Basic Mechanical Engineering

(RGPV-2011)

BE 203

Bachelor of Engineering B.E. (Common to all Disciplines)

About the Authors

Dr P K Nag had been with the Indian Institute of Technology, Kharagpur, for about forty years, almost since his graduation. After retirement from IIT, he was an Emeritus Fellow of AICTE, New Delhi, stationed at Jadavpur University, Kolkata, till June 2005. He was a Visiting Professor in the Technical University of Nova Scotia (now Dalhousie University), Halifax, Canada, for two years during 1985–86 and 1993–94. He has authored four books, apart from this one, and about 150 research papers in several national and international journals and proceedings. His research areas include circulating fluidized bed boilers, combined cycle power generation, second law analysis of thermal systems and waste heat recovery. He was the recipient of the President of India medal (1995) from the Institution of Engineers (India). He is a Fellow of the National Academy of Engineering (FNAE) and a Fellow of the Institution of Engineers (India). He is a Life Member of the Indian Society for Technical Education, Indian Society for Heat and Mass Transfer, and the Combustion Institute, USA (Indian Section). He was formerly a member of the New York Academy of Sciences, USA.

Other books from the author

- Power Plant Engineering, 2/e
- Basic and Applied Thermodynamics
- Heat Transfer
- Engineering Thermodynamics

Kartikeya Tripathi is Associate Professor in the Department of Mechanical Engineering at Shri G S Institute of Technology and Science, Indore (MP). He graduated from the same institute, in Mechanical Engineering in 1988 and obtained his M.Tech. degree in Mechanical Design Engineering from IIT Bombay, Mumbai, in 1990. Currently he is in the process of obtaining a doctorate degree in the area of system dynamics and automation.

Tripathi has 18 years experience in teaching at UG and PG levels. He has taught the subjects of Mechanics of Solids, Machine Design, Measurement and Control, Mechatronics, and Automobile Engineering. He has guided about 50 UG projects and 25 PG students. He has published 45 research papers in International and National Journals and Conferences. He was awarded 'The Corps of Electrical and Mechanical Engineers Prize (2008)' of the Institution of Engineers for best research paper. He was the faculty adviser of his institute's teams for SAE Mini BAJA events for the years 2007 and 2009. He is a member of The Institution of Engineers (India), Indian Society of Technical Education, Association for Machines and Mechanisms, Indian Society of Tribology, and Society of Automotive Engineers (India). He has been a member of the institute's management committee for World Bank sponsored Technical Education Quality Improvement Program (TEQIP). Currently, he is working in the areas of Mechanical Design, Control and Automation, Mechatronics, and CAD.

C B Pawar is Associate Professor in the Department of Mechanical Engineering at Shri G S Institute of Technology and Science, Indore (MP). He graduated from the same institute in Mechanical Engineering in the year 1981 and also obtained his degree of ME in Industial Engineering and Management from here. He also secured an M.Tech degree in Mechanical Design Engineering from IIT Madras, Chennai, in 1991 with a specialization in IC Engines. Currently, he is in the process of obtaining a doctorate degree in the area of enhancement of heat transfer by artificial roughness.

Pawar has 24 years experience in teaching at UG and PG levels. He has been teaching the subjects of Basic Mechanical Engineering, Thermodynamics, Heat and Mass Transfer, Refrigeration and Air-conditioning, IC Engines and Gas Turbines and has been working in the areas of IC Engines, Refrigeration and Air-Conditioning, and Heat Transfer. He has also guided many students in completing UG and PG projects. He is a member of the Indian Society of Technical Education, and the Indian Society of Heating Refrigration and Air-Conditioning Engineers. He has also started the student chapter of ISHRAE at his Institute.

Pawar has published/presented about ten research papers in journals and conferences at the national and international levels. He has also received the Institution of Engineers award in the year 1991 for his paper.

Basic Mechanical Engineering

(RGVP-2011)

Fourth Edition

BE 203

Bachelor of Engineering B.E. (Common to all Disciplines)

P K Nag
Emeritus Fellow (AICTE)
Jadavpur University

Former Professor
Department of Mechanical Engineering
Indian Institute of Technology
Kharagpur

Kartikeya Tripathi
Associate Professor, Department of Mechanical Engineering
Shri G S Institute of Technology and Science
Indore

C B Pawar
Associate Professor, Department of Mechanical Engineering
Shri G S Institute of Technology and Science
Indore

Tata McGraw Hill Education Private Limited
NEW DELHI

McGraw-Hill Offices
New Delhi New York St Louis San Francisco Auckland Bogotá Caracas
Kuala Lumpur Lisbon London Madrid Mexico City Milan Montreal
San Juan Santiago Singapore Sydney Tokyo Toronto

Tata McGraw Hill

Published by the Tata McGraw Hill Education Private Limited,
7 West Patel Nagar, New Delhi 110 008.

Basic Mechanical Engineering, 4e

ISBN (13): 978-0-07-133323-8
ISBN (10): 0-07-133323-1

Vice President and Managing Director—MHE: Asica Pacific Region: *Ajay Shukla*

Head—Higher Education Publishing and Marketing: *Vibha Mahajan*
Publishing Manager—SEM & Tech Ed: *Shalini Jha*
Associate Sponsoring Editor: *Tina Jajoriya*
Sr Editorial Researcher: *Manish Choudhary*
Executive—Editorial Services: *Sohini Mukherjee*
Sr Production Manager: *Satinder S. Baveja*
Proof Reader: *Yukti Sharma*
Sr Product Specialist—SEM & Tech Ed.: *John Mathews*

General Manager—Production: *Rajender P Ghansela*
Asst General Manager—Production: *B L Dogra*

Typeset at

Cover:

R

The McGraw·Hill Companies

Contents

Preface

Basic Mechanical Engineering is a course fundamental to all branches of engineering education. The objective of this course is to familiarize the students both with the core concepts as well as the scope of mechanical engineering. Mechanical engineering is a branch which has maintained and developed its links with other branches of engineering throughout the history of mankind. In the modern industrialized world, engineers from various branches of engineering work in unison to develop new technology and applications. Such collaborative contribution of mechanical engineering is manifest in the form of newer areas like automotive engineering, mechatronics, robotics, automation and control, automated manufacturing, rapid prototyping, flexible manufacturing systems, and so on.

This book attempts to cover the new syllabus in the best possible manner, without making the contents voluminous. The authors have tried their best to limit the size of the book, without compromising the quality of content or treatment of the basic concepts. This book is a natural evolution of the long teaching experience of the authors in their respective areas. Such experience is based not only on classroom and laboratory teaching, but also on conducting theoretical and practical examinations, students' projects, industrial interactions, and background material compiled through standard textbooks on individual subjects and other teaching resources.

This book is primarily targeted at the students of the first-year undergraduate course in all branches of engineering at Rajiv Gandhi Proudyogiki Vishwavidyalaya (RGPV) also known as Rajiv Gandhi Technical University (RGTU). The contents are common to the syllabi of most of the universities in the country. The basic concepts and information presented in this book should also be useful to students appearing in various technical examinations.

The chapters in the book are not strictly related to each other. Therefore, a student may read any particular chapter without much difficulty. However, reading the chapters in a serial manner would be helpful in correlating the subject matter and concepts. The authors therefore recommend the students to read the chapters in a serial manner only, at least when they read the book for the first time. The teachers having the basic knowledge of the subject can choose to start from any chapter.

The important technical terms have been italicized in the book. These terms are the keys for understanding the topic. Such terms are explained in the text immediately following the terms, or with the help of diagrams. The students are advised to pay special attention to such terms, and understand them properly, before proceeding further. The entire book is profusely illustrated. Extreme care has been taken to keep the diagrams as simple as possible, but complete in all manner. The students should refer to these diagrams while reading the text. The text and the diagrams have been presented in an integrated manner to deliver the subject matter. The questions at the end of each chapter are both conceptual and explanatory in nature. The students are advised to go through all of them to get a better comprehension of the subject. The solution of latest RGVP question papers are given at the end of the book.

Chapter 1 deals with engineering materials, basic mechanical properties, and basic mechanical testing methods. Chapter 2 discusses basic concepts involved in measurement of mechanical quantities. This chapter also deals with the basics of machine tools and basic machining operations. Chapter 3 deals with basic concepts of fluid mechanics and their applications. Chapter 4 deals with basic thermodynamics and its applications. Chapter 5 gives an elementary idea of heat engines and basic principles of their working.

Web Supplement:

The following additional information is available on the website at http://www.mhhe.com/nag/bme4/rgpv11

- Additional Solved Examples
- Viva-Voce Questions
- Solutions of Latest RGPV Question Paper
- Powerpoint Lecture Slide for Instructors.

The authors would like to express their gratitude to their colleagues, fellow teachers in other institutions, past students, and senior teachers for their support and motivation in taking up this task.

A note of acknowledgement is also due to the esteemed reviewers of this book.

Rahul Thakur	*Oriental Institute of Science and Technology, Bhopal*
Mohammad Ali	*Sanghvi Institute of Science and Technology, Indore*
Abhay Kakirde	*Truba College of Engineering and Technology, Indore*

The authors hope that this text would serve the basic objective of delivering the knowledge, information and basic concepts related to the branch of mechanical engineering. It is hoped that the book would serve as an important stepping stone for students of the mechanical engineering branch. The authors sincerely look forward to comments and suggestions towards improvements in the book.

P K Nag
Kartikeya Tripathi
C B Pawar

Publisher's Note

Remember to write to us. We look forward to receiving your feedback, comments and ideas to enhance the quality of this book. You can reach us at *tmh.corefeedback@gmail.com*. Please mention the title and author's name as the subject.

Roadmap to the Syllabus

Rajiv Gandhi Proudyogiki Vishwavidyalaya, Bhopal

I Year B.E.

L	T	P
3	1	2

Basic Mechanical Engineering (BE 203)

Unit I : Materials

Classification of engineering material, composition of cast iron and carbon steels on iron–carbon diagram and their mechanical properties.

Alloy steels and their application. Stress–strain diagram, Hooke's law and modulus of elasticity.

Tensile, shear, hardness and fatigue testing of materials.

GO TO **Chapter 1** Engineering Materials and their Mechanical Properties

Unit II : Measurement

Temperature, pressure, velocity, flow strain, force and torque measurements, concept of measurement error and uncertainty analysis.

Vernier calipers, micrometer, dial gauges, slip gauges, sinebar and combination set. Introduction to lath, drilling, milling and shaping machines.

GO TO **Chapter 2** Measurement and Machine Tools

Unit III : Fluids

Fluid properties pressure, density and viscosity. Pressure variation with depth, static and kinetic energy.

Bernauli's equation for incompressible fluids, viscous and turbulent flow, working principle of fluid coupling, pumps, compressors turbines, positive displacement machines and pneumatic machines.

Hydraulic power and pumped storage plants for peak load management as compared to base load plants.

GO TO **Chapter 3** Fluids

Unit IV : Thermodynamics

First and second law of thermodynamics, steam properties, steam processes at constant pressure, volume, enthalpy and entropy.

Classification and working of boilers, efficiency and performance analysis, natural and artificial draught and calculation of chimney height.

Refrigeration, vapor absorption and compression cycles, Coefficient of Perform (COP), refrigerant properties and eco-friendly refrigerants.

GO TO

Chapter 4

Thermodynamics

Unit V : Reciprocating Machines

Steam engines, hypothetical and actual indicator diagram, Carnot cycle and ideal efficiency, Otto and diesel cycles, working of two-stroke and four-stroke petrol and diesel IC engines.

GO TO

Chapter 5

Reciprocating Machines

Chapter 1

Engineering Materials and their Mechanical Properties

1.1 INTRODUCTION

A wide variety of materials are available to engineers to design and manufacture different objects and machine components for different applications. An engineer must learn about the basic characteristics of these materials. In order to understand the general behaviour of materials, they are classified into different groups. The materials falling in one group have similar properties and behaviour. This simplifies the task of an engineer to understand the behaviour and characteristics of a large number of materials at his or her disposal. In this chapter a basic classification of engineering materials is presented. More stress is given to the metallic materials. Since steels and alloys of iron are most widely used in engineering applications, they are discussed in detail. The basic composition, mechanical properties, and applications are introduced in this chapter. Later, few basic methods of determining the mechanical properties are also given in brief. A very detailed knowledge on the topics covered in this chapter has been accumulated over the centuries of engineering practice. This chapter gives only a very brief introduction of the subject.

1.2 CLASSIFICATION OF ENGINEERING MATERIALS

Engineering materials are classified as metallic and non-metallic. Metallic materials are further classified as ferrous and non-ferrous. Alternately, materials can also be classified as brittle or ductile. Usually all the brittle materials are weak in tension while the ductile materials are stronger. Brittle materials are generally stronger in compression. Ferrous materials are classified as cast iron and steels. These materials are basically alloys of iron and carbon, along with few other elements in small quantities. The important non-ferrous materials are stainless steels, aluminum and its alloys and copper and its alloys. Among the non-metallic materials many types of plastics, rubbers, and ceramics are used in engineering applications.

1.3 MECHANICAL PROPERTIES OF MATERIALS

When a material is subjected to load, its behaviour depends upon its mechanical properties. This behaviour includes deformation as well as rupture. The important mechanical properties of a material, which are useful in defining and understanding such behaviour, are as follows:

Elasticity Whenever a material is subjected to a load, it undergoes deformation. During deformation, internal forces are generated between the molecules of the material, which try to oppose the applied force. This tendency of a material to oppose the action of applied load is called elasticity. Due to elasticity, a material regains its original shape after the external load is removed. This property is important when a component has to bear external load.

Plasticity Plastic state of a material is the state when it gets permanently deformed under external load. The property to undergo permanent deformation is called plasticity. This property is important for some manufacturing operations like deep drawing, extrusion, etc. In these processes, the material is shaped by loading it so that it deforms permanently. Metals show some plasticity at normal temperatures. Most metals become plastic at high temperatures. Under this state it is easy to give any desirable shape to the material.

Strength Strength is the ability to bear external load without breaking. Strength of a material depends upon the manner in which the load is applied. Therefore, the strength is defined separately for each type of loading condition like tension, compression, shear, etc.

Ductility If a material is pulled, it gets elongated. If the magnitude of the pulling force is increased continuously, the material breaks. A material which undergoes a large elongation before breaking is called ductile material, and this property is called ductility. Metals usually have high ductility as compared to non-metals. Few non-metals, like rubber, also have high ductility. Ductility is important when a material is to be drawn into wire. It is also important when excessive deformation is desirable. Copper and aluminum have high ductility. Low carbon steel also has good ductility.

Brittleness A brittle material does not deform much when loaded. It simply breaks when the applied load reaches a certain limit. Brittle materials are weak in tension and stronger in compression. They cannot bear shock and impact loads. Cast iron, glass, ceramics, and thermosetting plastics are brittle materials.

Malleability A material is called malleable if it can be hammered to make thin sheets. A malleable material need not be ductile. Lead and aluminum have high malleability. Aluminum can be beaten into very thin foils, which are used for wrapping food items. Copper and iron also have good malleability.

Toughness When a material is subjected to load, it undergoes deformation. In this process, the external load does work on the material. The work done by the external load is absorbed by the material in the form of strain energy. The capacity of a material to absorb this energy per unit volume, before failure, is called toughness. This property is useful when a machine component is subjected to shock and impact loads. Medium carbon steels usually have good toughness.

Resilience This is the property of material to absorb energy without undergoing plastic deformation. Resilient material releases all the absorbed energy when the external load is removed. High carbon steels have good resilience. Springs are manufactured using high carbon steels.

Fatigue Strength When a machine component is subjected to repetitive or variable loading, it fails even when the applied load is not very high. Such failure takes places due to fatigue. All the materials have very small cracks inside them or at their surfaces. During repetitive loading these cracks become larger and larger progressively. Finally the component fails. Any material which has a tendency to resist development and propagation of such cracks is said to have good fatigue strength.

Hardness A hard material resists scratching, wear, abrasion, cutting, machining, penetration, indentation. All cutting tools must be hard so that they can cut other materials without wearing away rapidly. High carbon steels and steels alloyed with titanium and molybdenum have high hardness. Glass and ceramics also have high hardness.

Creep Ristance At higher temperatures, metallic materials have a tendency to undergo continuous deformation even when the applied load is maintained constant. This phenomenon is called creep. Those materials which resist the tendency of creep are said to have high creep resistance.

There are some properties which are important from the point of view of manufacturing of materials. They are listed below:

Machinability Many items and components are made by machining process. In machining process, material is removed from a block to obtain the desired geometrical shape. Various machining processes are performed on machine tools like lathe, drill, shaper, band saw, planer, grinder, etc. When a material can be machined easily by any of the machining processes, it is said to have good machinability. Soft materials like mild steel, aluminum, copper, etc., have good machinability. Hard materials like cast iron have poor machinability.

Formability Some items and components are manufactured by plastic deformation of the material. Mild steel and aluminum can be easily formed into desired shapes, and therefore have good formability.

Weldability Welding is the process of joining two components by bringing them into molten state, followed by cooling. During welding the mechanical properties, chemical properties and microstructure of the material change. Welded components should have good strength, homogeneous structure, and defect-free composition. Those materials which exhibit such properties are said to have good weldability.

1.4 IRON AND ITS ALLOYS

Pure iron is a soft material, and hence it has limited use for engineering applications. Therefore iron is used in manufacturing steels. Steel is the most widely used metal in the world. It is basically an alloy of iron and carbon. Few more elements are added to steel to improve certain properties of the basic iron–carbon alloy. In the manufacturing of steel, **Pig Iron** is obtained initially by reduction of iron ore in the furnace. Pig iron contains 3 to 4 % carbon, along with small percentages of silicon, manganese, phosphorous and Sulphur. Phosphorous and Sulphur are present as impurities. **Wrought Iron** is obtained by removing carbon from Pig Iron by burning it in molten state, followed by hammering and rolling. It is the purest form of iron, and contains iron in the range 99.5 to 99.9%. Wrought iron is malleable and ductile. It can be formed easily into different shapes. It is widely used to manufacture crane hooks, rivets, boiler tubes and steam piping. It is suitable for manufacturing these products mainly due to its ductility.

The mechanical properties of steel mainly depend upon the percentage of carbon in the alloy. This alloy of iron and carbon exists in different phases, depending upon the percentage of carbon and the temperature. The relationship between the phases, carbon percentage and temperature can be shown using a diagram known as Iron-Carbon Equilibrium Diagram.

1.4.1 Iron-Carbon Diagram

On this diagram, the carbon percentage is shown on the x-axis and temperature on the y-axis. Figure 1.1 shows the Iron-Carbon Equilibrium Diagram. In this diagram the lines indicate the boundaries where the alloy changes its phase. The different phases or mixtures of phases occur in different areas enclosed by these curves. *Pure iron* exists in two allotropic forms, α-iron and γ-iron, both in solid state. The α-iron exists below 910°C and also above 1392°C, and its crystal lattice is body-centred cubic. The α-iron which exists above 1392°C is also called δ-iron. The γ-iron exists in the range 910°C to 1392°C, and its crystal is face-centred cubic. The melting point of iron is 1539°C.

In the Fe-C system in the solid state, the different ***phases*** which are present are, *Ferrite* (Solid solution), *Austenite* (Solid solution), *Cementite* (Chemical compound iron carbide: Fe_3C), and free carbon in the allotropic form of graphite.

Ferrite is the solid solution of carbon in α-iron (below 910°C). In ferrite, solubility of carbon is up to 0.02%. In the FCC lattice of ferrite, carbon atom is located at the centre of a face of the cube. Carbon atoms are also present at dislocations and vacancies in the lattice. Ferrite has tensile strength of 250 N/mm^2, yield strength of 120 N/mm^2, and hardness 80 BHN. **Austenite** is the solid solution of carbon in γ-iron. The maximum solubility of carbon in γ-iron is 2.14%. In austenite, the carbon atom is located at the centre of the BCC structure of γ-iron. Austenite has high ductility and low strength. **Cementite** is chemical compound of iron and carbon, called iron carbide (Fe_3C). Its carbon content is 6.67%. It has very high hardness and low ductility. Carbon also exists in the Fe-C system in the form of Graphite. It has hexagonal layered lattice structure. Graphite is soft with low strength.

The *simplified* iron-carbon diagram is shown in Fig. 1.1. Point A is melting point of iron (1539°C). Along line AB, a *liquidus* line (a line representing the transition between liquid state and liquid + solid state), austenite begins to crystallize out from the liquid alloy. Along liquidus line BC, cementite begins to crystallize out of liquid alloy. Line DBE is a *solidus* line, representing transformation from one solid state to another solid state. The Fe-C alloy exists in solid form both below and above this line. Below this line ***Leduburite*** begins to separate out from the solid solution. Alloys containing up to 0.81% carbon solidify along the line AD. Their solidification results into formation of ***Austenite.*** When these alloys are cooled further, their composition changes to a mixture of *Austenite and Ferrite* along the line FG. Further cooling below 727°C results into a mixture of *Ferrite and Pearlite.* Alloys containing carbon up to 0.81% are called *Hypoeutectoid* alloys. For alloy containing 0.81% carbon, the final structure is of pure pearlite. This is called *Eutectoid* alloy. In case of alloys containing carbon in the range of 0.81 to 2.14%, cooling from liquid state first results into separation of austenite along the liquidus AB. Further cooling results into complete transformation into austenite along AD. After this, cooling results into formation of a mixture of austenite and cementite, along the line DG. Further cooling yields a mixture of cementite and pearlite, along the line GH.

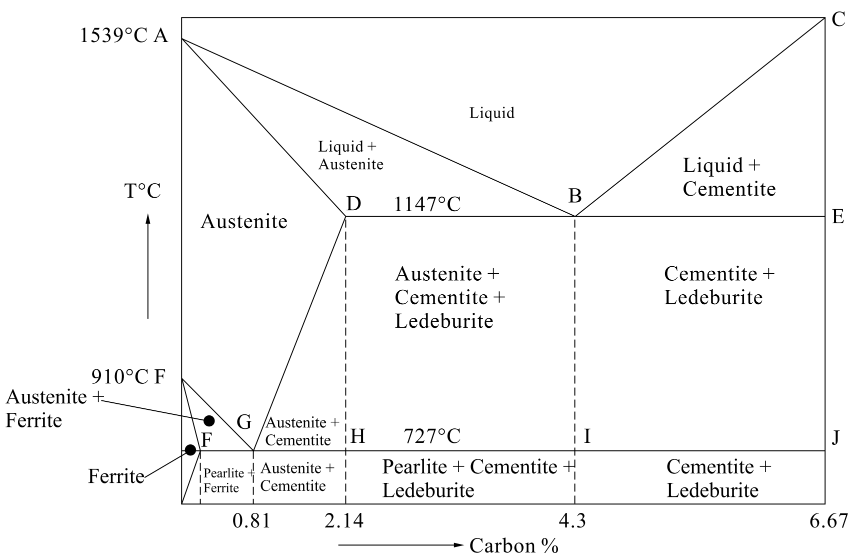


Fig. 1.1 *The Iron-carbon Diagram (Simplified)*

In case of alloys containing carbon in the range of 2.14 to 4.3% (called ***Hypo-eutectic*** alloys), cooling from liquid state results in to separation of austenite along the line AB. Further cooling results into a solid mixture of *Austenite + Cementite + Ledeburite*, along the line DB. This mixture finally transforms into a mixture of *Pearlite+Cementite+Ledeburite*, along the line HI. Alloy containing 4.3% carbon (called Eutectic alloy) finally gives pure Ledeburite. Line DBE represents the Eutectic temperature of 1147°C. Hypereutectic cast irons containing 4.3 to 6.67% carbon begin to solidify along liquidus line BC, when crystals of cementite begin to freeze. Solidified hypereutectic cast irons contain a mixture of ledeburite and cementite.

1.4.2 Cast Iron and Steels

Alloys of iron and carbon containing up to 2.14% carbon are called ***steels***, and those containing carbon above 2.14% are called ***cast irons***. This demarcation between steels and cast irons is based upon the maximum solubility of carbon in iron. In solidified state, steels do not contain ledeburite, which has low ductility. Also in heated conditions, steels have only austenitic structure which has high ductility. Therefore steels can be shaped easily during manufacturing processes, both at low and high temperatures. This is not the case with cast irons. However, cast irons have much better foundry properties, as compared to steels. They have low melting point and less shrinkage due to presence of low-melting ledeburite.

1.5 CAST IRON

Cast iron has carbon in excess of 2.14%. Carbon is present in cast irons in the form of either cementite, or graphite, or both. The classification of cast irons is based upon the form of graphite and the conditions under which it is formed. The general properties of cast irons are as follows:

(a) Low tensile strength, but high compressive strength.
(b) Good hardness and wear/abrasion resistance.
(c) Very low ductility and brittleness.
(d) They have low melting point and good castability.
(e) They cannot be formed, forged, or rolled.
(f) They have good damping quality.

Cast iron is a relatively cheap material. Also, the manufacturing process of casting is cheap too. Therefore, cast iron is widely used in industry. General applications of cast iron are:

(a) It is used for making frames, beds, guide-ways, and structures of machines.
(b) It is used for making wheels, flywheels, pulleys, levers and linkages.
(c) It is used for making cylinder blocks, piston rings, cylinder heads, valves, piston rings, crank cases, flywheels, and brake drums of IC engines.
(d) It is used for making hydraulic cylinders, steam pipes, valve bodies, and agricultural appliances.

1.5.1 Types of Cast Iron, Their Mechanical Properties and Applications

Cast irons can be broadly divided into Grey Cast Iron, White Cast Iron, Nodular Cast Iron, and Malleable Cast Iron.

Grey Cast Irons Presence of graphite gives a grey shade to the fractured surface of cast iron. Therefore, when all the carbon in cast irons is in the form of graphite, it is called Grey Cast Iron. Grey cast irons are most widely used in industry. Most of the carbon in them is in the form of graphite. This graphite is in the form of flakes. Grey cast iron with carbon content of 2.4 to 3.8% is most common. In general higher percentage of graphite reduces the mechanical properties of cast iron. Lower percentage of graphite makes the cast iron difficult to cast. Other elements present in grey cast iron are silicon, manganese, sulphur, and phosphorous. Grey cast iron has good machinability, weldability and corrosion resistance. Grey cast irons with ferritic and pearlitic composition, with medium to coarse graphite flakes, and carbon percentage in the range 3.1 to 3.6%, are used for low load applications. They can be used for agricultural machinery, structural applications, foundations, tractor fittings, etc. Cast irons with pearlitic structure have graphite in the form of fine curled inclusions. Due to its good lubricating properties it is used for making machine tool guide-ways, bearings, cylinder liners, piston rings and other similar items. It is also used for making machine frames, automobile cylinder blocks, valve bodies, gears, flywheels, pipe fittings, casings of compressors and pumps, and agricultural accessories.

White Cast Iron Presence of cementite gives a shiny light coloured surface to fractured cast iron. Therefore, cast irons which have all the carbon in the form of cementite are called White Cast Iron. White cast iron is obtained by rapid cooling of molten alloy. It is also called *chilled cast iron*. It is extremely hard and brittle. Its hardness ranges between 400 to 500 BHN. It is practically unmachinable, and for shaping it grinding is required. The alloying elements present in white cast iron are the same as those in grey cast iron. However, their percentages are a little different. White cast iron has limited applications in industry as a whole. However, it is used as upper layer with core of grey cast iron. This is achieved by chilling or rapid cooling, which gives a hard outer layer 12 to 30 mm deep. This provides a combination of good strength with excellent wear properties. It is used in applications requiring high abrasion resistance like rollers of rolling mills, jaws of crushers, railroad wheels, slurry pump impellers and casings, screw conveyors, tooling for earth moving and agricultural applications.

Malleable Cast Iron Due to hardness and brittleness of grey cast iron it is not suitable for making components subjected to shock and impact loads. For such applications malleable cast iron is used. It is obtained by annealing (prolonged heating) of castings made of white cast iron. In this process, the long flakes of graphite present in the cast iron are converted into round nodules. This results into cast iron having higher strength and good ductility. White cast iron, which is converted into malleable cast iron, has carbon in the range of 2.5 to 3%. Other alloying elements are same as those in grey cast iron. However, the percentage of sulphur and phosphorous are kept low. It is used for making components subjected to dynamic load, impact and vibrations. Typical applications are gears, gear box housings, axle housings, hubs, hooks, flanges and couplings. It is more ductile, tougher and stronger than grey cast iron. Its tensile strength is in the range 350 to 600 N/mm^2, percentage elongation in the range 2 to 8%, and hardness in the range 160 to 270 BHN. It has very good machinability and weldability.

Nodular Cast Iron It is also called *High Strength Cast Iron* or *Ductile Cast Iron*. It is obtained by adding small amount of alkali or alkali-earth metals to the alloy in liquid state. Mostly magnesium is used in quantity ranging from 0.03 to 0.07%. The carbon percentage is not over 3.3%. The other alloying elements are similar to those in grey cast iron. During solidification process, magnesium causes the graphite to precipitate in spherical nodular shape. Thus it prevents formation of flakes of graphite. Therefore, the weakening effect of long and sharp flakes of graphite is minimized. It has good machinability, castability, wear resistance, and damping properties. Its strength and ductility are better than grey cast iron. The tensile strength is in the range 500 to 600 N/mm^2 and percentage elongation up to 10%. It is used for making crankshafts, cylinder heads, forging and press working equipment, pump housings, valve bodies etc. The mechanical properties of cast irons depend mainly upon the structure and form of graphite. Cast iron can be considered as steel, with graphite present as impurity. Graphite acts as microscopic internal notches, which make the cast iron weak as compared to steel. Therefore, the mechanical properties of cast iron depend upon the amount, size, and distribution of graphite inclusions. If the graphite inclusions are small in size and distributed rarely, the mechanical properties of cast iron are better. Graphite flakes reduce the strength and ductility of the cast iron. Graphite, due to its layered structure, has a lubricating effect. Therefore, it reduces friction and gives wear resistance to cast irons. Also, due to the same reason it improves machinability of cast irons.

1.5.2 Effect of Alloying Elements in Cast Iron

The role of alloying elements in cast irons is discussed in this section.

Silicon Silicon reduces the solubility of carbon in γ-iron. Thus silicon promotes formation of graphite in cast iron. Its effect is similar to the effect of reduction in cooling rate. For castings with thin cross-section or depth, which cools at a faster rate, higher percentage of silicon is useful in completing the graphitization process. The percentage of silicon can go up to 4%, depending upon the structure required in the castings.

Manganese Manganese retards the precipitation of graphite during cooling. It results in structure like chilled or white cast iron. Its percentage is kept in the range 1.25 to 1.4%.

Sulphur Sulphur is an impurity in cast irons. It strongly retards graphitization and increases the size of graphite flakes. Thus it adversely affects the mechanical and casting properties of cast iron. Therefore, its percentage must be limited to 0.12% in cast irons.

Phosphorous It is also present in cast iron as an impurity. It does not affect the process of graphitization. However, it leads to formation of hard phosphides. Therefore, its percentage is kept to about 0.2%. Phosphorous improves fluidity, but increases brittleness.

1.6 CARBON STEELS

Carbon steels are alloys of carbon, with carbon ranging upto 2%. Carbon steel is manufactured by reducing the amount of carbon, silicon, manganese, sulphur, and phosphorous from pig iron in molten state. Sulphur and phosphorous are present as impurities, and must be controlled to very small quantities.

1.6.1 Types of Carbon Steels, Their Mechanical Properties and Applications

Steels are classified as *Low Carbon Steel (or Mild Steel), Medium Carbon Steel, High Carbon Steel, and Tool Steel*. These basic types of steels are classified according to percentage of carbon in them. Their mechanical properties are controlled mainly by the percentage of carbon in them. The mechanical properties of medium carbon steel and high carbon steel can be modified over a wide range through different heat treatment processes. Other special purpose steels are produced out of these basic types like, *Spring Steel, High Speed Steel, Alloy Steel*, etc. The principle alloying elements in carbon steel are silicon and manganese. Sulphur and phosphorous are also present as impurities.

Mild Steel Mild steel or low carbon steel is the most widely used form of steel. It has carbon in the range 0.08 to 0.3%. The important mechanical properties of mild steel are:

(a) It is soft, malleable, and very ductile. Its percentage elongation is as high as 40% for lower carbon percentage.
(b) It has good tensile strength, ranging between 250 to 350 N/mm^2.
(c) Due to low quantities of carbon its mechanical properties cannot be modified through heat treatment processes.
(d) It is very much suitable for a large variety of manufacturing operations due to high machinability, forgeability, and weldability.

Mild steel is used in a large number of applications:

(a) General purpose structural applications as steel rods, channel sections, I-beams, angle sections.
(b) Making nuts, bolts, keys, rivets, nails, screws, plain washers.
(c) Automobile sheet metal components, boilers, vessels, tanks, ships.
(d) For making shafts, gears, camshafts, axles for low load applications.

Medium Carbon Steel Medium carbon steels contain carbon in the range 0.3 to 0.6%. Its principal mechanical properties are:

(a) Its tensile strength is higher than that of mild steel.
(b) It is less ductile than mild steel. Its percentage elongation is usually in the range of 10 to 18%.
(c) It can be readily heat-treated to obtain a wide range of mechanical properties like tensile strength and hardness. The mechanical properties depend on both carbon percentage and the heat treatment process applied to it.
(d) It can be machined, forged and formed in annealed (softened) condition. After giving the desired shape in annealed condition, it can be heat-treated to obtain desirable mechanical properties.
(e) It is tough, and therefore it can be used for applications where shock and impact loads are expected.

The main applications of medium carbon steels are in making transmission shafts, axles, gears, connecting rods, rotor shaft, springs, spring washers and similar applications.

High Carbon Steel It has carbon in the range 0.6 to 1%. Its principal mechanical properties are:

(a) Its tensile strength is even higher than medium carbon steel.
(b) Its ductility is smaller than medium carbon steel. Its percentage elongation is below 10%.
(c) Due to high hardness it also has higher brittleness.
(d) It can be surface hardened, while retaining toughness at core. In this manner it can withstand substantial shock and impact loads.
(e) It is very resistant to wear and tear, and surface abrasion.
(f) It responds very well to heat treatment. It can be hardened to very high degree (BHN 600 and above).
(g) It is very hard and has springing quality in hardened condition.
(h) It is very difficult to machine, forge, or form. Most of the manufacturing operations are performed on it in softened and plastic condition, at higher temperatures.

The common applications of high carbon steel are:

(a) It is used for making a wide variety of tools for smithy, carpentry, and metal working.
(b) It is used for making knives, chisels, drill bits, cutting tools, shaper tools, milling cutters.
(c) It is used for making measuring tools like steel scale, calipers, etc.
(d) It is used for making dies for press-work, forming, blanking, shearing etc.
(e) It is used for making leaf springs and coil springs for automobiles and railways.
(f) It is used for making ball-bearings and other rolling element bearings.

One of the common categories of high carbon steels is ***Spring Steel***. It is used in making helical coil springs and leaf springs for automotive, railroad and other applications. It contains carbon in the range 0.6 to 0.9%. It is hard and has springing characteristics. In this manner components made of spring steel can store large energy per unit volume, in deformed condition, without the risk of permanent deformation. The important alloying elements in spring steels are silicon (upto 0.5%), manganese (upto 0.6%), chromium (upto 1%), and vanadium (upto 0.5%). These alloying elements improve corrosion resistance as well as hardness, while retaining the toughness.

Tool Steels During machining operation, a large amount of heat is generated, due to which ordinary steels get heated and lose their hardness. This results into rapid blunting of the cutting edge. The rate of heat generation is proportional to the cutting speed. Therefore, special steels are required for machining operations, which are able to cut at high cutting speeds, without losing their hardness. Tool steels are used in making tools and dies for various machining and forming operations. The percentage of carbon in these steels is in the range 0.8 to 1.2%. They are very hard and resistant to wear and abrasion. They can withstand their hardness even at elevated temperatures. For this property, tungsten, chromium, vanadium, cobalt and molybdenum are added to them as alloying elements.

One of the most common tool steel is ***High Speed Steel*** or **HSS**. It is used for making drill bits, lathe tools, shaper tools, milling cutters, reaming tools and other tools which are common in workshops and tool rooms. HSS can cut at cutting speeds of about 50 m/min. Its composition is 0.7 to 0.8% carbon, 12 to 20% tungsten, 3 to 5% chromium, 1 to 2% vanadium, and 5 to 10% cobalt. Carbon in the metal makes carbides with tungsten, which are very hard and wear resistant materials. Higher percentage of carbon can increase the hardness, but at the cost of toughness. Molybdenum improves hardenability, chromium improves resistance to oxidation at high temperatures, vanadium improves wear and abrasion resistance, and cobalt improves the ability to retain hardness at high temperatures.

Alloy Steel Alloy steels are derived from carbon steels by adding suitable alloying elements. The principal alloying elements used in steel are nickel, chromium, vanadium, molybdenum, and to some extent, copper, tungsten, cobalt, beryllium, boron, and silver. Alloying elements are used to improve strength, elastic ratio, and hardness. They are also helpful in improving machinability, castability, and weldability. They improve ductility, and yield more uniform grain structure. They also improve fatigue and corrosion resistance. The proper combination of these properties in steels depends upon both the presence and percentage of alloying elements, as well as the heat treatment cycle. Alloy steel can have mechanical properties much superior to plain carbon steels, with ultimate tensile strength of 2100 N/mm^2, and yield strength of 1750 N/mm^2. Alloy steels are expensive, and hence their use is limited.

Nickel improves strength of carbon steels without much reduction in ductility. It also retards grain growth, which makes it possible to have longer heat treatment and carburizing periods, without the risk of getting very coarse grain structure.

Chromium improves corrosion and oxidation resistance. It also improves hardenability, and gives strength at high temperatures. It helps in improving wear resistance, in combination with high carbon content.

Vanadium strengthens and toughens the steel. It helps in obtaining finer grain sizes. It also acts as a cleanser and degasifer. It improves life of tools, springs, IC engine components and components subjected to high temperatures.

Molybdenum has effects similar to those of chromium, but it is more powerful in action. It also helps in increasing depth of hardness during heat treatment.

Silicon and Manganese increase toughness and endurance strength, thereby improving fatigue life of components made of medium carbon steels.

Boron increases hardenability.

1.7 NON-FERROUS MATERIALS

Although a large portion of engineering applications employ steels and cast iron, there are specific applications where other non-ferrous materials have proved better. Some of the common metals and alloys used in engineering applications are aluminum and its alloys, copper, bronzes, etc.

1.7.1 Aluminum and Its Alloys

Aluminum is one of the lightest metals used in machines. Commercially obtained aluminum is soft and ductile. The most important aspects of aluminum and its alloys are their strength to weight ratio, corrosion resistance, and high thermal and electrical conductivity. Density of aluminum is 2770 kg/m^3, as compared to 7750 kg/m^3 of steels. Pure aluminum has tensile strength of 90 N/mm^2, but it can be increased substantially through cold working. Aluminum is commonly alloyed with copper, silicon, manganese, magnesium, iron, zinc, and nickel. While retaining the lightness of aluminum, these alloys have better machinability, hardness, and tensile strength. Their tensile strength in annealed or cast state may be twice that of commercial aluminum. Some alloys of aluminum have more strength comparable to that of structural steels (480 N/mm^2). The alloys of aluminum fall into two categories: first, those which can be hardened and strengthened only by cold working, and second, those which can be heat treated to improve mechanical properties.

The corrosion resistant properties of aluminum are due to formation of a tough and adherent layer of oxide on it surface. This layer retards further chemical decay due to environmental conditions. If this layer is removed due to some reason, it is formed again rapidly. Sulphuric acid, concentrated nitric acid and acetic acid are unable to attack aluminum due to this layer. However, hydrochloric acid and alkali dissolve this coating, thereby leading to rapid corrosion. The alloying elements added to aluminum tend to reduce its corrosion resistance. Anodizing in a sulphuric or oxalic acid electrolytic bath may increase the resistance to corrosion. In this process, aluminum is made the anode, and it gets a tough and resistant coating of oxide, which is not easily ruptured, even in bending.

Aluminum alloys are classified as *casting alloys* or *wrought alloys*. The casting alloys have higher percentage of alloying elements. These alloying elements improve castability, but make cold working difficult. Aluminum alloy castings made in sand moulds, permanent metal moulds, or in die-casting machines are generally stronger than poor grade cast iron. Permanent mould casting and die-casting give better surface finish, close dimensional tolerances, and better mechanical properties. They also help in reducing machining and finishing costs. These advantages justify the initial equipment cost, when mass production is required.

Mechanical properties of heat treatable alloys can be modified through solution or precipitation (aging) process at microstructure level. In solution process, the component is held at a high temperature for prolonged duration, and then quenched. In aging or precipitation process, the component is held at a lower temperature for prolonged duration. At room temperature, aging time is about 4 days, 18 hours at 160°C and 8 hours at 175°C. Annealing is used to reduce hardness of components, which have been hardened due to cold working. The rate of cooling is not as critical as in case of steels. However, too rapid cooling may cause distortion.

1.7.2 Copper and Its Alloys

Commercial copper is tough, ductile, and malleable. It contains less than 5% impurities, mainly tin, lead, nickel, bismuth, arsenic, and antimony. Strength of copper is lower than steels. The mechanical properties depend largely on mechanical treatment.

Cold working makes it stronger and brittle. Pure copper is not used much in machine components, except in castings, condenser tubes, water pipes, or sheet metal parts. In these applications its properties of corrosion resistance (weather, environmental and water), and excellent heat conductivity are used to advantage.

The alloys of copper have a wide range of properties. Some alloys have high strength, some have excellent wear properties (useful in bearings), some have high strength at high temperature, while some others have excellent corrosion resistance.

Brass Brasses are alloys of copper and zinc with 45–90% copper and small amount of iron, lead, and tin as impurities. These alloys have high corrosion resistance, good machinability, and good bearing properties. Alloys having 55–63% copper are brittle and difficult to work in cold condition. However, they can be forged, rolled, and extruded in hot condition. These are not used much commercially. Alloys containing copper over 64% are very ductile at room temperatures. They can be readily cold worked by rolling, upsetting, forming, stamping, deep drawing, or spinning. Cold working imparts hardness to brass. Such hardness increases with higher percentage of copper. Alloys with more than 85% copper have hardenability close to pure copper. After cold working they can be made malleable through annealing. Brasses with more than 80% copper can be hot forged, hot rolled, or hot worked easily, provided its lead impurity is below 0.03%. Addition of lead, upto 3%, increases machinability of brass. *Free cutting brasses* with copper content of 60–63% and small percentage of lead are used for automatic screw machine work. Addition of tin to brass improves its corrosion resistance. Some brasses are subject to *season cracking* due to corrosion, which produces short irregular cracks or long straight cracks of significant length. Season cracking is caused due to internal stresses. It can be avoided by stress relieving through low temperature annealing. It usually occurs in brasses with more than 15% zinc. Commercial brass with 90% copper has excellent cold working properties. It can be readily forged, upset, drawn, or spun. It is widely used in hardware, screws, rivets, and similar parts. Brass with 85% copper and 15% zinc has excellent cold working properties. It is used for severe cold drawing, stamping, and spinning work. It has better corrosion resistance than pure copper, and therefore is used for plumbing, in oil refineries, automobile radiators, and condenser tubes for inland use. However, it is not suitable for marine applications. It is relatively immune to season cracking.

Bronze Bronzes are alloys of copper, tin and small amount of phosphorus. They are more costly than brasses, and therefore are used only when cheaper alloys are not satisfactory. They are used in good quality thermostatic bellows, and similar other applications which require resistance to severe stretching and good tensile properties. Phosphorus is added to improve alloying of copper and tin. For this reason *phosphor bronze* is another trade name used for these alloys. When tin is added to molten copper, it forms tin oxide, which is insoluble. Since it has the same specific gravity as that of copper, it cannot be removed easily as slag. If tin oxide is not removed, it makes the cast ingots weak, brittle, and hence unfit for fabrication. Phosphorus reduces tin oxide to phosphorus pentoxide, which can be easily removed by skimming.

The bronzes are specially used where good corrosion resistance and fatigue properties are required. They are also useful for their spring characteristics due to high elastic limit (140–490 N/mm^2) and creep resistance at room temperature. As the percentage of tin increases up to 8%, strength and ductility of bronze increase rapidly. But, when it is increased further, ductility starts decreasing. Leaded phosphor bronze, with 4% lead, is free cutting.

Aluminum bronzes containing 5, 8 or 10% aluminum are golden yellow in color, have high corrosion resistance, high strength, good wear properties, and good fatigue properties. Aluminum bronzes are hard and are used as bearing materials where strength is important, i.e., where high pressures are encountered. They are used in aircrafts industry, bushings, gears, bearings, valve guides, shock absorbers, pistons, etc. They may be sand cast, centrifugally cast, rolled, forged, and extruded. They can also be heat-treated.

1.8 STRESS AND STRAIN

When an external load is applied to an object, its molecules generate an internal resistive force, which opposes the externally applied force. This resistive force per unit area is called ***stress***. In this manner, stress is the result of reaction of the molecules of the object, to the external force. Its basic unit is N/m^2 or Pascal. Thus,

Stress = Force/Area

The external force also causes the object to deform. The deformation per unit length is termed as ***strain***. Thus,

Strain = Change in Length/Original Length

1.8.1 Types of Stresses

The nature and type of stress depends upon the direction of the deforming force, relative to the orientation of the area on which it acts. Based upon this criterion, stress can be classified into *Normal Stress* and *Tangential Stress.* Normal stress can be *tensile* or *compressive*, depending upon whether the effect of the external force is to increase the length of the body, or to decrease it. Tangential stress is also called *shear stress.*

1.8.1.1 Normal Stress (Tensile and Compressive)

Stress is called normal stress, when the external force acts perpendicular to the area on which stress is being considered. When the effect of the external force is to increase the length of the body, the stress is called ***Tensile Stress***. This is shown in Fig. 1.2. In this figure, the external force acting on the body is F. A cross-section AA is considered on the body, which is perpendicular to the direction of force F. At this cross-section the molecules on the two parts of the body apply equal and opposite forces on each other. These forces are internal forces. The effect of the external force here is to elongate, i.e., increase the length of the body. The molecules at the cross-section AA, located on the two parts shown, pull each other. In this manner they try to oppose the elongating effect of the external forces. The magnitude of these internal forces, per unit area of the cross-section, is the tensile stress. Here it is denoted by σ_t. The subscript t indicates the tensile nature of the stress.

When the effect of the external force is to decrease the length of the body, it is called ***Compressive Stress***. This is shown in Fig. 1.3. Here it is denoted by σ_c. The

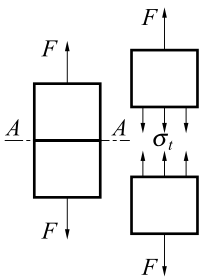


Fig. 1.2 *Tensile Stress*

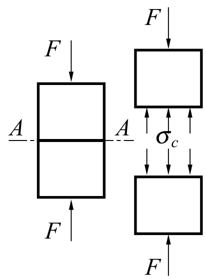


Fig. 1.3 *Compressive Stress*

subscript *c* indicates the compressive nature of the stress. In this case, the external force tends to decrease the length of the body. Here, the internal forces applied by the molecules, on the two parts of the body separated by the cross-section AA, try to push each other. In this manner the internal forces tend to oppose the compressive effect of the external force.

1.8.1.2 Tangential Stress (Direct Shear and Torsional Shear)

Figure 1.4 shows a rectangular body ABCD, fixed at its lower surface CD. A force F acts along its upper surface AB. The body may be considered as made of many layers as shown in the figure. The action of the external force F causes the different layers to slide relative to each other, as shown in Fig. 1.5. At each layer, equal and opposite force (and hence stress) is applied by the layers above and below it. This stress is called *shear stress*, and it is shown as τ in Fig. 1.5. The magnitude of shear stress is given by,

$\tau = F/a$; where a is the area of the layer in the direction perpendicular to the paper.

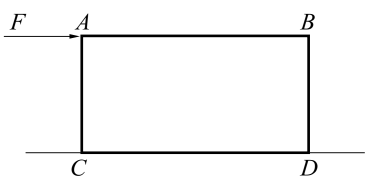


Fig. 1.4 *Body with Shear Load*

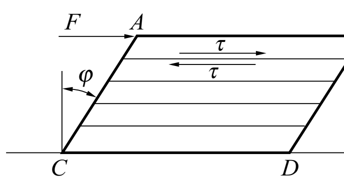


Fig. 1.5 *Concept of Shear Stress*

The *shear strain* is defined as the angular deformation of the face AC. It is equal to angle φ in Fig. 1.5.

Since this shear stress is induced due to action of a point force directly, it is called *direct shear stress.* Tangential stress (or shear stress) differs from normal stress in the sense that the direction of shear stress is parallel to the direction of the external force. Also the area on which the shear stress acts is parallel to the applied force. In case of normal stress, the stress is parallel to the applied force, but the area on which it acts is perpendicular to the applied force.

Now consider a rod with circular cross-section as shown in Fig. 1.6. One end of this rod is fixed. At the other end a torque (twisting moment) T is applied on the rod.

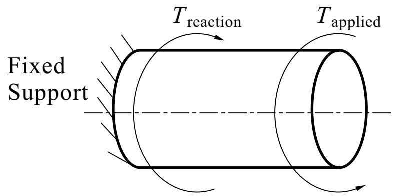


Fig. 1.6 *Round Bar Subjected to Torque*

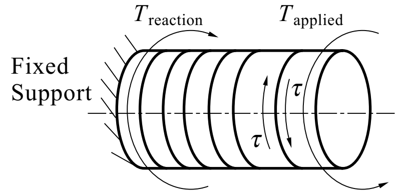


Fig. 1.7 *Concept of Torsional Shear Stress*

The fixed support applies a reaction torque on the rod, which is equal and opposite to the applied torque. The rod can be considered to be made of a large number of cross-section layers as shown in the Fig. 1.7. Under the action of the applied torque and the reaction torque, the cross-section layers undergo an angular slip relative to each other. Thus, at each cross-section, the adjoining layers apply equal and opposite torques. This gives rise to equal and opposite shear stresses on the cross-section, as shown in the figure. This shear stress is called *Torsional Shear Stress.*

1.8.2 Hooke's Law

The relationship between stress and strain was first investigated by Hooke. He observed that extension of a wire is proportional to the applied force. Further studies showed that stress is proportional to strain, up to certain limit. This relationship between load and extension, or more correctly, between stress and strain, is called *Hooke's Law*. Thus,

$$Strain \ \alpha \ Stress$$

or, $\quad Stress/Strain = E,$ a constant of proportionality.

1.8.3 Stress-Strain Diagram

When a tensile load is applied on a rod of uniform cross-section, it gets elongated. The elongation keeps on increasing as the magnitude of applied load is increased, and finally the rod breaks. Assuming the area of cross-section as constant, the applied load can be expressed as tensile stress. The magnitude of the tensile stress (denoted by σ), at any time during elongation, is given by the ratio of applied load to the original cross-section area of the rod. Similarly, the elongation of the rod can be expressed as strain (denoted by ε) . At any time during the elongation, the strain is equal to the ratio of total elongation and the original length of the rod. The variation of strain with applied stress is shown in Fig. 1.8. This diagram is called *Stress-Strain Diagram.* The diagram shown here is for ductile materials like mild steel.

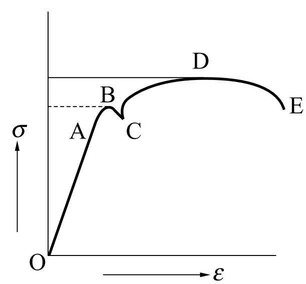


Fig. 1.8 *Stress-strain Curve for Ductile Material*

When the applied stress is gradually increased from zero, the strain increases proportionately (or linearly) with the stress. The point up to which this proportionality is observed is called the *Limit of Proportionality*, and it is shown as point A on the diagram. After this limit, if the stress is increased further, strain keeps on increasing up to another limit shown by point B. Between A and B strain is not proportional to stress. After point B, the curve starts to drop down. This is due to a phenomenon called *yielding*. Yielding is due to slippage between molecules of the material. The point B is called *Upper Yield Point*. Strain continues to increase between points A and B. The apparent reduction in stress continues up to another limit called *Lower Yield Point*. The value of stress at the yield point is called *Yield* Strength of the material. This is shown by point C on the curve. After this the stress again starts increasing. The strain also continues to increase. The stress reaches its maximum value at point D. This value of stress is called *Ultimate Tensile Strength* or simply *Tensile Strength* of the material. Up to this stress value the cross-section at any point in the rod is the same. Beyond the ultimate tensile strength, the cross-section area of the rod begins to reduce locally, i.e., at a particular location. This location can be anywhere in the rod. Simultaneously the magnitude of stress begins to reduce. However, the strain continues to increase. Due to local reduction in cross-sectional area, the load carrying capacity of the rod drops rapidly. Finally the specimen breaks. This point is shown as E on the diagram.

If the applied stress is less than the yield strength, the material regains its shape and size completely after the stress is removed. Therefore, the part of the curve OAB is said to be in *Elastic Zone* and the deformation observed in the material in this zone is called *Elastic Deformation*. If the material is loaded beyond the yield point, it does not regain its shape and size completely, when the applied stress is removed. Thus, there is a permanent deformation in the material, called *Plastic Deformation*. The part of the stress-strain curve BCDE is said to be in the *Plastic Zone*.

1.8.4 Resilience and Toughness on Stress-Strain Diagram

When the rod described above is loaded gradually, the elongation takes place under the action of the external force. Thus the external force does work on it. This work is stored in the rod in the form of strain energy. The area under the curve represents the product of stress and strain. This product is equal to strain energy stored per unit volume of the rod. As shown in Fig. 1.9, the strain energy stored in the rod up to the yield point is called *Resilience* of the material. In this figure resilience is the area enclosed inside OABFO. The energy stored by the rod, per unit volume, up to the point of fracture is called *Toughness* of the material. Toughness is the area enclosed by OABCDEGFO. Resilience and toughness are important properties for applications which require large storage of energy during deformation of the material. Components subjected to shock and impact load, and springs are examples of such applications.

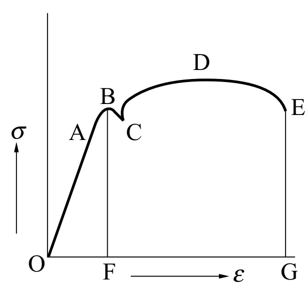


Fig. 1.9 *Resilience and Toughness*

1.8.5 Modulii of Elasticity

As discussed before, the stress and strain produced in a material during deformation are proportional with each other to some extent. In Figure 1.8, this limit is shown from point O to point A. For this part of the curve, stress is proportional to strain, i.e., *Strain α Stress*

or, *Stress/ Strain = E,*

Here, *E* is a constant of proportionality. This is called the *Modulus of Elasticity* or *Young's Modulus.* This constant is used to correlate stress and strain, when the material is subjected to normal stress, i.e., tension, compression and bending. It is the property of the material. Since strain is a ratio of lengths, therefore it has no unit. Hence, the units for the modulus of elasticity are the same as those for stress, i.e., N/m^2. For all types of carbon steels its value is about 2.1×10^5 N/mm^2.

When a component is subjected to shear stress, as shown in Fig. 1.5, similar relationship is observed between shear stress and shear strain.

Shear Strain α Shear Stress

or, *Shear Stress/Shear Strain = G,*

Here the constant of proportionality *G* is called the *Modulus of Shear* or *Modulus of Rigidity*. It is used to relate shear stress with shear strain, when components are subjected to direct or torsional shear stress.

In some cases a component is subjected to normal stresses from all directions. An example is a cube submerged in water. Due to pressure of water, all the faces of the cube shall experience normal (compressive) stress. In such situations the deformation in the cube shall be observed in the form of change in its volume due to all round compression. The volumetric deformation, per unit volume of the cube, is called the *Volumetric Strain*. The stress-strain relationship is given by,

Volumetric Strain α Stress

or, *Stress/ Volumetric Strain = K,*

Here, the constant of proportionality *K* is called the *Bulk Modulus of Elasticity.* It is used to relate volumetric strain with pressure for components subjected to hydrostatic condition of loading.

1.9 TESTING OF MATERIALS

The mechanical properties of materials are determined through different tests. These tests have been standardized all over the world. The important test methods are discussed in the following sections.

1.9.1 The Tensile Test

Tensile test is the most basic test performed on materials to determine their mechanical properties. The objectives of tensile test are to obtain ultimate tensile strength, yield strength, percentage elongation and percentage reduction in cross-sectional area (both indicators of ductility), resilience, and toughness. These basic mechanical properties are the most important properties which give information about the behaviour of the material under load.

Tensile test is performed on a specimen of circular cross-section, having shape like dumb-bells. Figure 1.10 shows the tensile test specimen. The parallel portion in the middle of the specimen is known as the *gauge length* (G.L.).

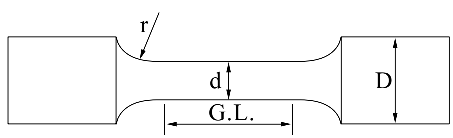


Fig. 1.10 *Dumb-bells Shaped Specimen for Tensile Test*

It is denoted by L_o. Circumferential marking is put on the specimen on both ends of the gauge length, before starting the test. The dumb-bell ends with larger diameter are gripped in the grips of the tensile testing machine.

The tensile testing machine has two grips; one fixed grip and other moving grip. The moving grip is powered hydraulically or by an electric motor and drive. After fixing the specimen in the grips, the specimen is pulled by applying a tensile load on it. The load is increased gradually. The load is measured and displayed continuously on a dial gauge or a digital display. The elongation is also measured continuously using extensometer, mechanical arrangement with graph paper, or LVDT. The stress and strain can be determined using this data. In some machines there is a facility to get the graph between load and elongation directly. The graph obtained for a ductile material is similar to Fig. 1.8.

Determination of Ultimate Tensile Strength and Yield Strength: As discussed in the previous sections, stress is obtained by dividing the load by original cross-section area A_o. Load at yield point and ultimate load are measured from the graph. Dividing them by area A_o gives yield strength and ultimate tensile strength of the material.

Determination of Percentage Elongation: After the specimen breaks, the two pieces are put together tightly, and the elongated gauge length is measured. It is denoted by L. The elongation in the test specimen is $(L - L_o)$. The percentage elongation is calculated using,

$$\begin{aligned} \textit{Percentage Elongation} &= \textit{(Change in Length/Original Length)} \times 100\ \% \\ &= 100(L - L_o)/L_o \end{aligned}$$

A ductile material shows percentage elongation more than 15%. Brittle materials like cast iron have percentage elongation below 5%.

1.9.2 Cross-Shear Test

The cross-shear test is performed to obtain the value of shear stress of any material. In this test the specimen is a cylindrical bar of about 10 mm diameter. The specimen is loaded such that direct shear stress is induced on its cross section. The mode of loading is in double shear, i.e., two cross-sections are loaded simultaneously by direct shear load, as shown in Fig. 1.11. If the applied load is P, the two supporting grips apply reaction loads of $P/2$ each. The two planes, where two cross-sections are simultaneously loaded in shear, are shown in the middle figure. The bottom figure shows the failure of the specimen. Due to double shear, the specimen shall break into three parts. At each plane of shear, the shear stress can be obtained as,

$$\text{Average Shear Stress } \tau = \textit{Load/Area} = P/2A$$

where A is cross-sectional area of the specimen.

1.9.3 Hardness Tests

Hardness is the property due to which a material can resist scratches, dents, wear and abrasion. Hardness is also related to tensile strength, especially in steels. There are a large number of methods for determining hardness of materials. They use different criteria to estimate hardness. The most common methods used for determining hardness of metals are Brinell test, Rockwell test and Vickers test. In all of these methods, an *indenter* is pressed against smooth and polished surface of the material, by applying

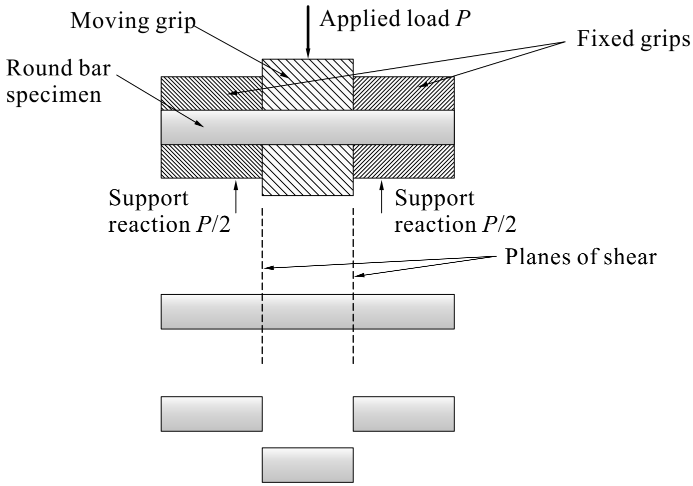


Fig. 1.11 *The Cross-Shear Test*
Top: *The Cross Shear Test Specimen and Setup for Holding it.*
Centre: *The Specimen in Double Shear at Two Cross-sections.*
Bottom: *The Specimen Failed at Two Cross-sections (Double Shear).*

specific load. Indenter is a hard object of definite geometry. The indenter penetrates into the surface of the material. The mark produced by such penetration is called *indentation.* The dimensions of the indentation, along with the magnitude of applied load, are used to calculate the hardness of the material. The value of hardness obtained by any of these tests is denoted by a number, which is referred to the corresponding *scale*. The hardness on any of the three scales can be converted into its corresponding value on the other scales. For this purpose standard conversion tables are available.

1.9.3.1 Brinell Hardness Test

This is the most fundamental method for determining hardness of metals. In this method, the indenter is a hard spherical ball, made of tungsten carbide. Diameter of this ball is generally 10 mm. This ball is pressed against the plane and polished surface of the material as shown in Figs 1.12 to 1.14. The applied load has a magnitude of 3000 kgf for steels and cast irons, 1000 kgf for copper and its alloys, and 250 kgf for soft materials like aluminum, aluminum alloys, and babbit. The indenter creates a crater-shaped impression on the material, as shown in Fig. 1.15. Geometrically this impression, or indentation, is part of surface of a sphere. The diameter of the indentation is measured. The value of hardness obtained by this method is denoted by *Brinell Hardness Number*. This number is determined by the formula,

$$BHN = \frac{2P}{\pi D(D - \sqrt{D^2 - d^2}}$$

Limitations of Brinell Test: The Brinell test in not accurate for specimen having hardness above 450 BHN. When the test specimen is too hard, the indenter ball gets

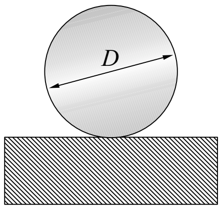


Fig. 1.12 *Ball Indenter*

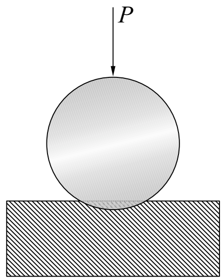


Fig. 1.13 *Load Application*

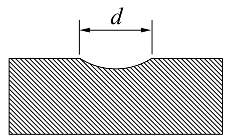


Fig. 1.14 *Indentation*

deformed, giving erroneous results. Also, it is not suitable for objects with small depths. For reliable results, the depth of the object should be more than 10 times the depth of the indentation. Also, in this test the size of indentation is significantly large. In case of some products, an indentation of this size may not be tolerable. So the tested specimen may not be further usable.

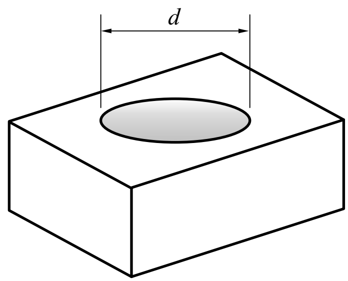


Fig. 1.15 *3-D View of Indentation*

1.9.3.2 Rockwell Hardness Test

Rockwell hardness test is considered as the most standard test in industry. The basis of determining the hardness is the depth of the indentation. For different types of applications there are different standards in this test. They are identified as A, B, C and so on. In Rockwell A and C, the indenter is a diamond cone, known as *Brale*. Accordingly, the Rockwell hardness numbers are denoted by R_A, R_B, and R_C respectively. The apex angle of the cone is 120°. In Rockwell B test, the indenter is a hardened steel ball having diameter of 1.5875 mm.

The load is applied in two steps, first the *Minor Load* P_o, followed by the *Major Load* P_m. The total load is the sum of the minor load and the major load. The minor load is 10 kgf. The major load is 50 kgf for A scale, 90 kgf for B scale, and 140 kgf for C scale. The minor load causes a small depression in the specimen, which is mostly elastic in nature. The major load enlarges the indentation by plastic deformation. The hardness is related to the plastic deformation part. The different stages of test are shown in Fig. 1.16. The vertical travel of the indenter, after application of the minor load is h_o, and it is h after both the major and minor loads have been applied. Therefore, the hardness value is based upon the difference of these two travels, which is due to plastic deformation in the specimen. Thus for calculation of hardness, the value of travel of the indenter is taken as $h - h_o$ in Rockwell test.

The travel of 0.002 mm of the brale is considered as one unit. The quantity corresponding to the travel of $h - h_o$ is calculated as

$$e = \frac{h - h_o}{0.002}$$

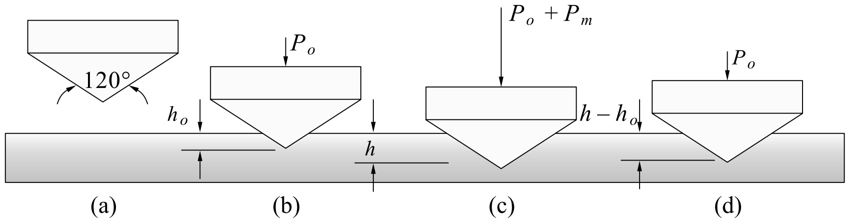


Fig. 1.16 *Rockwell Hardness Test*
(a) Diamond Cone Indenter
(b) Indenter Position when Minor Load is Applied.
(c) Indenter Position when Both Minor and Major Loads are Applied.
(d) Indenter Position when only the Major Load is Removed.

The Rockwell hardness is determined using the relations,

$$R_A = R_c = 100 - e \text{ (For A and C scales)}$$
$$R_B = 130 - e \text{ (For B scale)}$$

The indentation mark in Rockwell test is very small as compared to that in Brinell test. It may be removed easily during the final finishing processes. Sometimes it can be left as it is.

1.9.3.3 Vickers hardness test

In Vickers test the indenter is a square pyramid of diamond. Therefore the hardness number obtained by it is also known as *Diamond Pyramid Hardness* or *DPH*. The angle between the opposite lateral faces of the pyramid is 136°. This test is particularly suitable for components with very small thickness. For smaller thicknesses the load applied is also small. It is also used for determining hardness of thin layers on the parent metal. In this test, the indenter makes a square impression on the material. The two diagonals of the square are measured using a microscope. The average diagonal size d is then determined. The DPH is calculated using the formula,

$$DPH = \frac{2P \sin(\alpha/2)}{d^2} = 1.8544 \frac{P}{d^2}$$

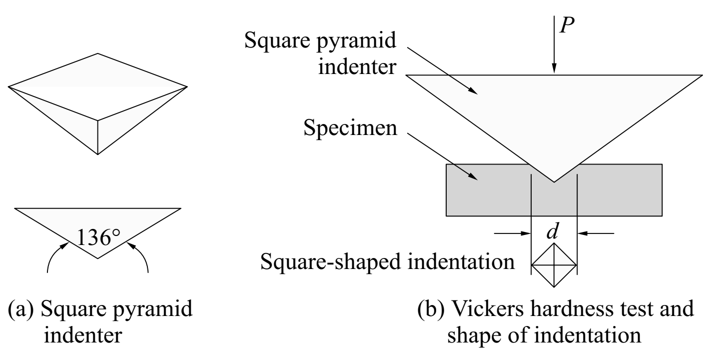


Fig. 1.17 *Vickers Hardness Test*

Here P is the applied load. It can be 5, 10, 20, 30, 100 or 120 kgf, α is the angle between the opposite faces of the pyramid, and d is the average length of the diagonals of the indentation.

1.9.4 Fatigue Failure

In many applications the machine components are subjected to a variable load. In such cases the load is of cyclic nature. It acts in an increasing decreasing manner, and reversal of load may also take place. Examples of such cases are rotating shafts mounted with gears and pulleys, axles of automobiles, springs, etc. Under such conditions the components fails at a stress which is much lower than the yield strength of the material. Such type of loading is called dynamic loading, and the failure is called *Fatigue Failure*. Fatigue failure starts at a microscopic defect in the component like a micro-crack, a cavity or an inclusion. Under repeated or reversed loading conditions the micro-crack is repeatedly opened and closed. Due to such opening and closing it starts to propagate over the cross-section of the material. The damage progresses gradually and without any observable signs. Finally, when the undamaged cross-section area of the component becomes too small, the component fails suddenly. Such sudden failure, without any prior indication, makes fatigue very dangerous and unpredictable. It leads to accidents and damage to property and life.

1.9.4.1 Fatigue Test

In fatigue failure, the component's life is defined in terms of the number of load cycles it can bear before failure. The fatigue life is closely related to the magnitude of load, and the manner in which it is applied. Fatigue test is performed on materials to determine the fatigue life for different magnitudes of load. Figure 1.18 shows the arrangement for fatigue test. The geometry of the specimen is similar to the specimen used for tensile test. It has a circular cross-section and dumb-bells shape. The specimen is supported on two sides on bearings B_3 and B_4. It is rotated by an electric motor. On the parallel part of the specimen, two bearings B_1 and B_2 are mounted. Through these bearings a load is suspended. This loading arrangement generates a bending moment in the parallel part of the specimen. In this manner, when the specimen is rotated, the direction of force due to suspended load is always downwards. When the specimen is rotated, any point on the specimen is subjected to alternating normal stress, varying from maximum tensile to maximum compressive. Due to such an alternating stress, the specimen is subjected to fatigue loading condition.

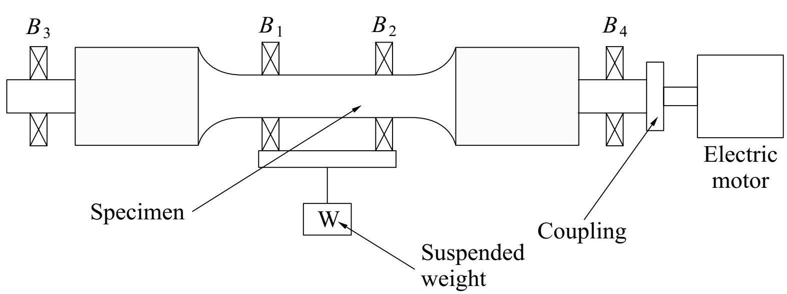


Fig. 1.18 *Arrangement for Fatigue Test*

The magnitude of the stress can be varied by changing the size of the suspended load. The test is carried out for different values of suspended loads. For each load value the stress induced in the specimen can be calculated. The number of cycles, at which the specimen fails, are recorded for different values of stress. The result is plotted as *S-N Diagram*, which has number of cycles on x-axis and stress magnitude on y-axis, as shown in Fig. 1.19. The life of the specimen in terms of number of cycles goes on increasing, as the magnitude of applied stress decreases. The *S-N* curves for ferrous materials have a typical 'knee' shape. This indicates that below a certain value of the applied stress, the life of the specimen is theoretically infinite. That is, it shall never fail. This limit is called *Endurance Limit*. In case of non-ferrous materials, such limit is not observed. The life of the specimen shall go on increasing, as the magnitude of the applied stress is reduced. The *S-N* curves are used to design machine components for finite life. Suitable value of stress can be used, based on the curve, to get desired life of the machine component.

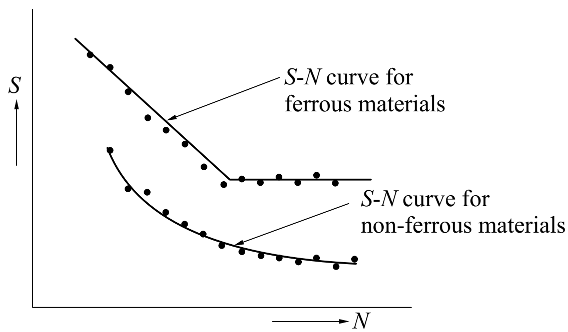


Fig. 1.19 *Stress-number of Cycles Curves*

REVIEW QUESTIONS

Answer the following questions:

1. What are the important mechanical properties of materials?
2. What are the merits and demerits of cast iron?
3. What are the different types of cast irons? What are their applications?
4. What is nodular cast iron?
5. What are the important alloying elements in cast iron? What are their roles?
6. What are the different types of steels? What are their applications?
7. What is spring steel?
8. What is tool steel? What are its important alloying elements?
9. What are the important alloying elements in carbon steels? What are their roles?
10. What are the applications of aluminum and its alloys as engineering materials?
11. What are the important alloys of copper? What are their applications?
12. What are the different types of stresses?

13. Draw the stress-strain diagram for a ductile material. Show the important points on this diagram.
14. Explain toughness and resilience on stress-strain diagram.
15. What are the different modulii of elasticity?
16. Explain the tensile testing of materials.
17. Explain the cross-shear test for materials.
18. How is Brinell hardness test performed on materials?
19. Explain the Rockwell hardness test procedure.
20. Describe the Vickers hardness test.
21. Draw the iron-carbon diagram. Indicate the different micro-structures on it.

Fill in the blanks:

1. The property due to which a material resists scratches and indentation is called ________. (hardness)
2. The energy absorbed by a material per unit volume, before failing under load, is called ________. (toughness)
3. Cementite contains _____ percent carbon. (6.67)
4. Presence of ______ gives a grey colour to the surface of fractured grey cast iron. (graphite)
5. White cast iron is also known as _______. (chilled cast iron)
6. _______ promotes formation of graphite in cast iron. (Silicon)
7. _____ and _______ are the main impurities in steels and cast irons. (Sulphur, phosphorus)
8. Mild steel has carbon upto _____ percent. (0.3)
9. _______ is used as structural steel. (Mild steel)
10. _______ steel does not respond to heat treatment. (Mild)
11. ______ steel is used for making shafts and axles. (Medium carbon)
12. Boron increases _______ of carbon steels. (hardenability)
13. The alloys of copper and tin are known as ______. (bronzes)
14. Brasses are alloys of copper and _____. (zinc)
15. The initial length marked on a tensile test specimen is called ______. (gauge length)
16. Percentage elongation is an indicator of _______ of a material. (ductility)
17. The shape of indenter in Brinell hardness test is ________. (spherical)
18. The diamond cone indenter used in Rockwell hardness test is also known as ______. (brale)
19. The indenter used in Vickers hardness test is a ________. (square pyramid)

Chapter 2

Measurement and Machine Tools

2.1 INTRODUCTION: MEASUREMENT OF ENGINEERING QUANTITITES

In engineering, measurement plays an important role. Measurement is required to assess the output, capacity and performance of machines and systems. Measurement is also required to control the machines and systems, so that they keep working within required limits. In engineering we come across a large number of physical and engineering quantities. The methods of their measurement differ from each other, due to the basic differences in their nature. In this section, the measurement techniques for some important engineering quantities are discussed in brief. For detailed information the reader should refer to specialized text books and hand books on the subject of measurement and measuring systems.

2.1.1 Measurement of Temperature

Temperature is an important parameter in many engineering systems. Measurement and control of temperature is essential in furnaces, processes, and proper functioning of machines and engineering systems. Different machines and processes work in different temperature ranges. Some systems like *cryogenic* systems work at extremely low temperatures, furnaces and nuclear systems work at very high temperatures, and many systems work at and around room temperature. For all of these systems the requirements of temperature measurement are different, and therefore, the measurement techniques and systems are also different.

Temperature cannot be measured by basic standards for direct comparison. Change in temperature is measured by measuring any of its effects like change in physical state of substance (melting, boiling), change in dimension (thermal expansion), change in electrical properties (change in resistance), change in radiation frequencies (change in colour), etc. The temperature standards are established using the change in physical state of materials. For example, the Celsius and Fahrenheit scales of temperature use the melting point of ice and boiling point of water as two datum points on the scale. For sub-zero temperatures the datum points used are freezing point of mercury, boiling point of nitrogen etc. For high temperatures, melting point of tin, lead, zinc, antimony, nickel, platinum, and tungsten, etc., are used.

Some of the basic instruments for measurement of temperature in engineering applications include *liquid-in-glass thermometers, pressure gage thermometers, bimetallic thermometers, thermocouples, resistance thermometers, thermistors, and pyrometers.*

Liquid-in-glass Thermometers The clinical thermometer is an example of this type. Liquid-in-glass thermometers have a large bulb at one end, a fine capillary tube in a glass rod (stem) having a scale, a small bulb at the other end, and *thermometric liquid* which is filled in the bulb and a part of the capillary. The remaining part of the capillary has either vacuum or it is filled with an inert gas like nitrogen. The scale is directly etched on the glass stem of the thermometer. When the temperature of the larger bulb of the thermometer is increased, the thermometric liquid starts to expand. The length of its column inside the capillary is the basis of measurement of temperature. The important properties of the thermometric liquid are:

(a) The expansion of the liquid should be linear with temperature, in the desired range of measurement.
(b) It should have low freezing point and high boiling point.
(c) It should have a large coefficient of thermal expansion.
(d) It should be visible as a fine line inside the capillary.
(e) It should not stick to the walls of the capillary.

For most of the applications around the room temperature, mercury satisfies the above-mentioned requirements. Mercury in glass thermometers have a range of –35°C to 500°C. Alcohol is used for measuring lower temperatures. It is used in the range –65°C to 75°C.

Most of the liquid-in-glass thermometers have some non-linearity over their working range, i.e., the length of liquid column is not proportional to change in temperatures. This may be due to non-linear characteristics of coefficient of thermal expansion, or due to variation in the diameter of the capillary. In general purpose applications the error due to this effect may be tolerable. If precise measurement is required, this factor should not be neglected. Error may also occur due to temperature variation over the body of the thermometer, i.e., from the bulb end to the other end. This error may be avoided if the whole thermometer is immersed inside the fluid whose temperature is to be recorded. However, it is not always possible to do so.

Pressure Thermometers Figure 2.1 shows the principle of operation of pressure thermometers. The bulb may be filled with liquid, gas or vapour. One end of the tube is connected to the bulb, and the other end is connected to a pressure gage. The length of the tube may be as long as 75 metres. When the temperature of the bulb changes, the pressure and volume of the fluid inside it also change. The change in pressure is recorded on the pressure gage. The scale of the pressure gage can be calibrated to give the temperature directly. The difference in temperature of the bulb and the long tube may cause error in measurement. This error can be minimized by keeping the volume of bulb much larger than volume of the tube. These thermometers are used in the range –200ºC to 500ºC.

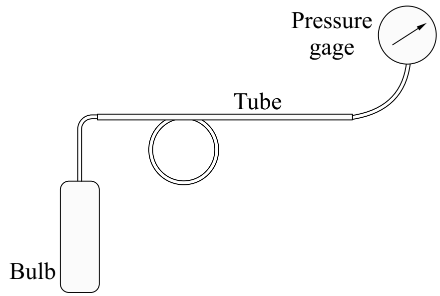


Fig. 2.1 *Pressure Thermometer*

Resistance Thermometers Electrical resistance in metals varies with temperature. For most metals and metallic alloys the resistance increases with increase in temperature (a positive relationship). This change is linear over a large range of temperature variation. Resistance thermometers work on this principle. The electrical element in these thermometers is made of nickel, copper, platinum, and silver. The temperature sensing element is made of a wire made of these metals, which is wound in a coil of multiple turns, around a solid silver core. The silver core is used for quick flow of heat from the end tip of the cover to the coil. The casing of the thermometer is made of glass, stainless steel, or brass. The temperature range of resistance thermometers is –200ºC to 600ºC.

The important requirements for materials to be used in resistance thermometers are:

(a) The resistivity of material should be high enough, so that the size of resistance element is not too large. A large size element will give sluggish response to temperature change.
(b) The thermal coefficient of resistivity should be high, so that magnitude of voltage change is measurable.
(c) The thermal coefficient of resistivity should be constant, so that the temperature-resistance relationship is linear over a sufficiently large range of temperature.
(d) The material should be corrosion resistant.
(e) The material should not undergo phase change within the operating temperature range.

For most materials, the temperature-resistance relationship can be defined by the following relation,

$$R_t = R_0\,(1 + AT + BT^2),$$

Where, R_t is resistance at temperature T; R_0 is resistance at 0ºC; T is the temperature; A and B are constants which depend upon the material.

Thermistors Thermistors are temperature measuring elements made of ceramic-based semiconductors. They also work on the principle of change in resistance with change in temperature. Compared to metals, the change in resistance is large in thermistors. In their case the resistance decreases with increase in temperature (a negative relationship). Thermistors are made of oxides of manganese, nickel and cobalt. They are available in different shapes like disk, rod, washer and bead. These may be used up to 300ºC. The temperature-resistance relationship for a thermistor is given by,

$$R_t = R_0 e^k;$$

where, $k = \beta\left(\frac{1}{T} - \frac{1}{T_o}\right)$; β is a material constant.

Thermocouples Seebeck discovered that an emf exists across a junction formed by two dissimilar metals. Peltier discovered that this emf depends upon the temperature of the junction (*Peltier Effect*). Thomson found that the emf also depends upon temperature gradient along the conductor wires (*Thomson Effect*). These principles are used in thermocouples for measurement of temperature. The emf due to Thomson Effect is quite small as compared to that due to Peltier effect.

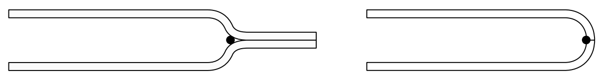


Fig. 2.2 *Common Methods of Making Thermocouple Joints*

The materials used in thermocouples are copper, iron, platinum, rhodium, iridium, constantan (60% Cu and 40% Ni), chromel (10% Cr and 90% Ni), and alumel (2% Al, 90% Ni, and remaining Si and Mn). The *copper-constantan* thermocouple is used in the temperature range –200°C to 350°C. It is relatively cheap. *Chromel-constantan* thermocouple is used in the range –20°C to 500°C. *Iron-constantan* thermocouple is used in the range –20°C to 800°C. *Chromel-alumel* thermocouple is used up to 1200°C, if used intermittently. *Platinum-10% rhodium* thermocouple is used in the range 700°C to 1500°C in continuous operation and up to 1750°C intermittently. *Iridium-rhodium* thermocouples are used up to 2000°C. Thermocouples are made by twisting two wires of dissimilar metals, and making a junction between them by brazing or welding. The voltage output of thermocouples is in milli-volts. Therefore, suitable circuitry is required for its amplification, display and recording.

Pyrometers It is well-known that any body having temperature above absolute zero gives out radiation. When a steel object is heated, it radiates energy in the infrared region. When the temperature is increased, the colour of radiation becomes dull red. On heating further, the colour of the body becomes red, bright red, orange and finally bluish. This change in colour is due to dominance of higher frequencies in the spectrum at higher temperatures. As the temperature increases, the frequency having the highest magnitude in the spectrum, goes on increasing as defined by *Wein's Law*. The pyrometers measure temperature on the basis of radiation from a hot body. There are two basic types of pyrometers: *total radiation pyrometer* and *optical pyrometer*. The total radiation pyrometer estimates the temperature of the body on the basis of the total radiation emitted by the body, i.e., taking into account all the frequency components in the radiation. Optical pyrometers use optical means for estimating the temperature. They use the radiation in the visible range of the spectrum of radiation from the hot body. Both of these types are non-contact instruments, i.e., they are not kept in contact with the body whose temperature is to be measured. A pyrometer must be calibrated for a particular application, before it is put to regular use.

Optical pyrometers match the colour of radiation from a hot body, with the colour of filament of a bulb. The current through the bulb's filament can be controlled through an electric circuit. When this current is varied, the colour of filament changes. The operator tries to adjust the current in such a manner that the colour of filament becomes the same as the colour of radiation from the hot body. In this condition the filament seems to merge with the background colour from the hot body. The current through the filament can be used as a measure of temperature of the hot body. Figure 2.3 shows the schematic diagram of an optical pyrometer.

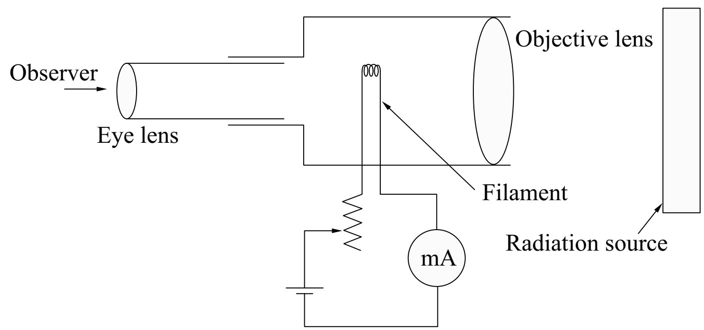


Fig. 2.3 *Working Principle of an Optical Pyrometer*

2.1.2 Measurement of Pressure

Pressure is the force exerted by a fluid on a unit area. This pressure is the *Absolute Pressure*. The measuring devices usually measure the difference of pressure between absolute pressure from a source and atmospheric pressure. This pressure is termed as *Gage Pressure*. The pressure below the atmospheric pressure is called *vacuum*. Vacuum is measured as the pressure difference between atmospheric pressure and absolute pressure. These terms are clarified diagrammatically in Fig. 2.4.

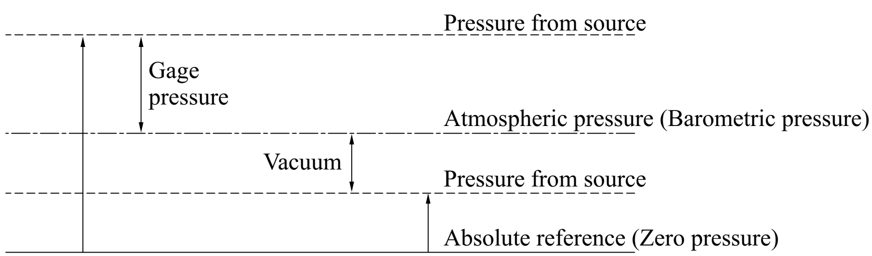


Fig. 2.4 *Relation between Absolute, Gage, and Atmospheric Pressures*

Pressure is measured by measuring deflection or displacement caused by it in the measurement device. Such devices may be gravitational type (manometers) or elastic elements (diaphragms, tubes, bellows). The commonly used manometers are *U-tube manometer, inclined manometer* and *two fluid type manometer.*

Glass Manometers The simple U-tube manometer has two glass tubes or *limbs* filled with a fluid called *manometric fluid*. One limb of the U-tube manometer is connected by a tube, to the system whose pressure is to be measured. The other limb is usually open to atmosphere. When the pressure of the system is equal to atmospheric pressure, the level of fluid in both the limbs is same. When pressure is applied to one limb, the liquid column goes down in that limb, and rises up in the other limb, as shown in Figure 2.5. In this case the relationship of pressures in the two limbs is given by,

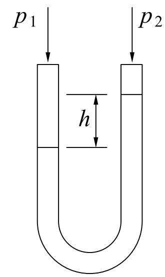


Fig. 2.5 *U-tube Manometer*

$$p_1 - p_2 = \rho gh;$$

where, ρ is density of manometric fluid, and h is difference in liquid columns in the two limbs.

For getting better resolution, one method is to use *inclined-tube manometer*. In this manometer, one limb is attached to a reservoir of large diameter. The single tube is inclined at an angle with the horizontal. A change in height h of liquid column in the inclined tube will cause the liquid to move by $h/\sin\alpha$. In this manner even a small change in the pressure, and therefore height of liquid column, will cause a significant movement of liquid column in the inclined tube. The inclined tube can be calibrated to give pressure with a much higher resolution, as compared to simple U-tube manometer. Since the cross-section area of the sump is many times the area of the inclined tube, the change is level of the sump is insignificant. Therefore, in most cases the reading of inclined tube alone can be used as a measure of applied pressure. Figure 2.6 shows the basic principle of an inclined tube manometer.

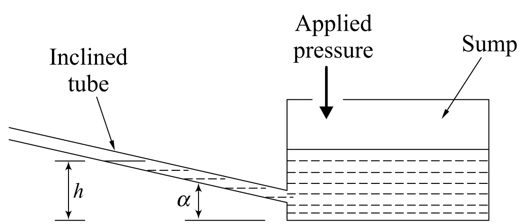


Fig. 2.6 *Inclined Tube Manometer*

Elastic Transducers Elastic transducers are based upon deflection of metallic transducers under the action of pressure. When pressure is applied, its effect is like applying a stress. When the transducer deforms under the action of externally applied stress (pressure), it deforms and this deformation gives rise to internal stresses as a reaction to deformation. The reaction forces (stresses) balance the applied forces (pressure) in the deformed state of the transducer. The deformation of the transducer is related to the applied pressure. The commonly used pressure transducers, based upon this principle, are *Bourdon tube pressure gage, elastic diaphragms (flat or corrugated),* and *bellows.*

Bourdon Tube Pressure Gage The Bourdon tube is a tube in the shape of an arc of a circle. Its cross-section is *oval* or *elliptical*, as shown in Fig. 2.7. The end A of the tube is connected to the pressure source. The end B is closed. When pressure is

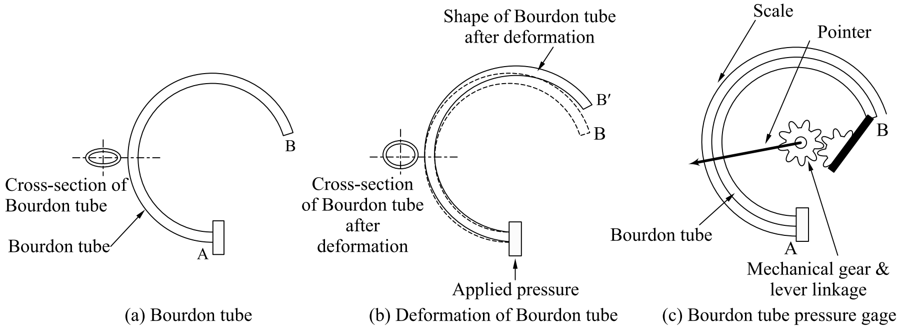


Fig. 2.7 *Working Principle of Bourdon Tube Pressure Gage*

applied at end A, the whole tube is subjected to internal pressure. Since the end B is closed, the oval cross-section of the tube deforms to become more circular. Due to such deformation in the cross-section, the whole tube tends to straighten out. This causes movement of end B, which is a function of the internal or applied pressure. The movement *BB'* of end B is amplified through a mechanical linkage consisting of gears and levers. The amplified movement is displayed on a circular scale through rotation of a pointer. The circular scale is calibrated to read pressure directly. In Bourdon tube pressure gages, the arc of Bourdon tube is usually less than 360°. However, when higher sensitivity is required, the tube is made with multiple turns. The Bourdon tube has the applied pressure on its inner side, and atmospheric pressure on the outside. Therefore, the measurement gives gage pressure, i.e., pressure difference between the applied pressure and atmospheric pressure.

Elastic Diaphragms The U-tube manometers and Bourdon tube pressure gages are suitable for small pressure ranges, low to medium sensitivity and when the variation in pressure is slow. For measurement of dynamic pressure, i.e., pressure changing very fast with time, they are not suitable. For such applications, pressure measurement is done using elastic diaphragms. These diaphragms are usually circular, and made of thin metallic sheet. The two basic types of diaphragms in use are *Flat Diaphragm* and *Corrugated Diaphragm*. The diaphragm (the sensing element, or transducer) is enclosed in a housing. The housing has threads for fitting on a suitable opening. It is fitted on the vessel or pipeline where pressure is to be measured. When pressure is applied on one side of the diaphragm, it gets deformed. This deformation is a function of applied pressure. The deformation is measured using a suitable device for measurement of displacement. Such devices, or *Secondary Transducers* work on an electrical principle like change in resistance, capacitance, or inductance. The output from the secondary transducer is recorded on a suitable recorder. In general, the pressure-deformation relationship of the diaphragm is linear when the deformation is within 30% of the thickness of the diaphragm. For measurement of higher pressure, the stiffness of diaphragm in increased by providing a *boss* at its centre, or by using a spring element. An arrangement is provided to restrict the deformation of diaphragm beyond a limit. Excessive deformation may induce stresses in the diaphragm which are above the yield point of its material. In such circumstances, the diaphragm gets permanently deformed and damaged. The diameter of a flat diaphragm is small. Its displacement range is also small. Comparatively, the corrugated diaphragms have larger diameters and also larger deflection. However, their dynamic response is not as fast as that of flat diaphragms.

2.1.3 Measurement of Velocity

Velocity is the rate of change of displacement. Velocity may be *Linear* or *Angular*. Direct measurement of linear velocity is not simple. Therefore, linear velocity is usually determined by determining linear or angular displacement. It can also be determined by first converting the linear displacement into angular displacement, and then measuring the angular velocity. Angular velocity can be measured by more direct methods.

Centrifugal Speedometers The centrifugal speed measuring devices use the principle of *fly-ball governors.* A schematic diagram to explain this principle is shown in Fig. 2.8. There is a rotating spindle, supported on bearings. Two arms are pivoted at the upper end of the spindle. Each arm carries a ball. The balls are attached to springs. The springs are attached with a sleeve. The sleeve can move up and down on the spindle. Each ball is restrained by a spring. One end of the spring is connected to one ball, and the other end is connected to the sleeve. When the spindle is rotated, the pivoted arms, balls, springs and the sleeve also rotate with it. Due to centrifugal action, the balls try to fly outwards, when the assembly is rotated. The springs provide the balancing force, and therefore, at a particular speed of rotation the balls keep rotating at a fixed radius from the axis of rotation. As the angular speed changes, the balls move in and out, and the sleeve moves up and down. The motion of the sleeve is related to the angular speed of rotation. The vertical position of the sleeve can thus be used for determining the angular speed. The motion of the sleeve can be transferred to a pointer and scale, through a suitable mechanism.

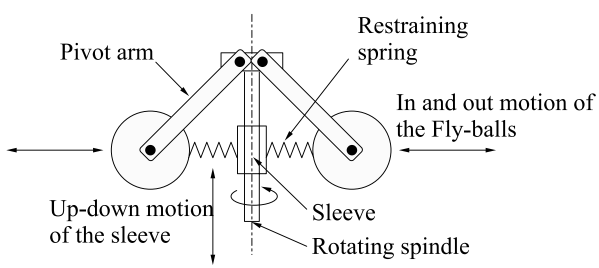


Fig. 2.8 *Centrifugal Speedometer*

Tachometers Tachometers have a permanent magnet type DC or AC generator, connected to a voltmeter. When the spindle of the tachometer rotates, an emf is induced whose magnitude is related to the speed of rotation. The voltmeter can be calibrated to read the angular speed directly. The output from the voltmeter can also be sent to a recording device or a digital display. DC generator needs a commutator like carbon brushes, whose wear and tear may pose problems over a long period. AC generator needs a rectifier circuit to give a DC voltage on the voltmeter.

Non-contact Methods Angular speed can also be measured without the need for direct contact between the rotating element and the measuring instrument. *Proximity sensors* and *optical sensors* are used in such cases.

A proximity sensor gives out a pulsed signal when an object is moved over it. A toothed disk is mounted on the rotating element. Every time a gear tooth passes over the sensor, a pulse is generated. A magnetic pickup is used as a proximity sensor. An optical sensor has a circular disk with large number of holes, at the same radius. Each time a hole passes over the optical sensor, a pulse is generated. These pulses are counted for a certain interval of time, and the count is used for calculating speed. An electronic circuit is used to count and convert the pulsed data into value of speed. Figure 2.9 shows the principle of measurement of angular speed using a magnetic pickup, and Fig. 2.10 shows the principle of optical pickup.

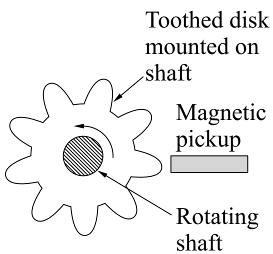


Fig. 2.9 *Magnetic Pickup*

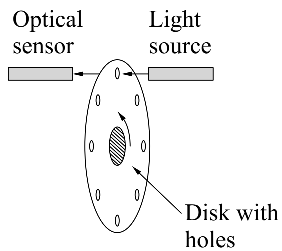


Fig. 2.10 *Optical Pickup*

2.1.4 Measurement of Flow

Flow rate is the quantity of a substance flowing across a certain cross-section per unit time. It is measured in terms of mass per unit time (Kg/sec), or volume per unit time (m^3/sec). A variety of principles and devices are in use for measurement of flow in engineering applications. Some of the basic devices are described in this section.

Volumetric Tanks This is a fundamental or *primary* method of flow measurement. In this method, the quantity of fluid flowing out of a pipe or conduit is collected in a tank, for measured time duration. The quantity of fluid is determined in terms of mass or volume by suitable measurement. Usually the tank has a graduated scale fixed on it, which gives the volume by direct reading. Then by dividing the quantity collected by time of measurement, we obtain the flow rate. This method is applicable only when the flow is steady. This method is used for laboratory based measurements, and for calibration of other flow measurement devices.

Obstruction Meters In this category of devices, the measuring device acts as an obstruction in the path of flow. This obstruction changes the flow velocity in a local region around it. The change in velocity causes a change in pressure, as governed by Bernoulli's theorem. At the cross-section where velocity is the maximum, the pressure is minimum. The pressure drop is measured by means of a suitable pressure measuring device, mostly a manometer. This pressure drop is used to calculate the velocity, which is then used to determine the flow rate. There are three basic devices which come under this category, *Venturimeter*, *Nozzle*, and *Orifice Meter*. These devices are shown in Fig. 2.11. In all of these devices, pressure begins to drop as the flow approaches the minimum area of restriction. After crossing this minimum area, the pressure again increases. The variation of pressure, along the length of the devices, is also shown below each device in Fig. 2.11.

The venturimeter and its pressure drop curve are shown in Figure 2.11(a). In case of the venturimeter, the *recovery* of pressure is the maximum, and it reaches about 98% of its value at the entry. This is due to gradual expansion of cross-section after the minimum area. Also the inner surface of venturimeter is very smooth. From this point of view, a venturimeter is the best obstruction type device, but it requires a long section in the pipe line, and also its cost is higher.

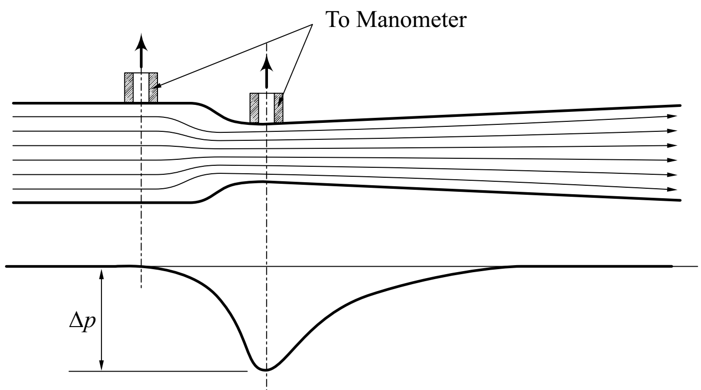


Fig. 2.11(a) *Venturimeter and its Pressure Drop Curve*

The nozzle and its pressure drop curve are shown in Fig. 2.11(b). The recovery of pressure in case of a nozzle is not as good as the venturimeter, but it is better than that in case of an orifice meter. Its length is shorter than that of a venturimeter. Its cost is also less. It is mounted on flanges in the pipe line.

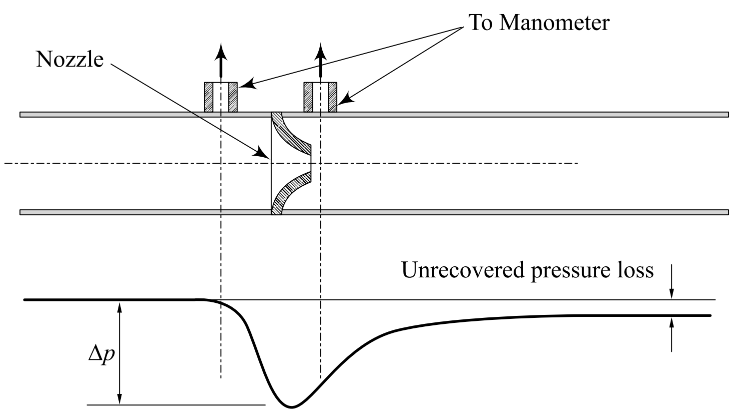


Fig. 2.11(b) *Nozzle Meter and its Pressure Drop Curve*

The orifice meter and its pressure drop curve are shown in Figure 2.11(c). The recovery of pressure is the poorest in case of orifice meter. However, it is very cheap and simple to fabricate. It is mounted on flanges in the pipe line.

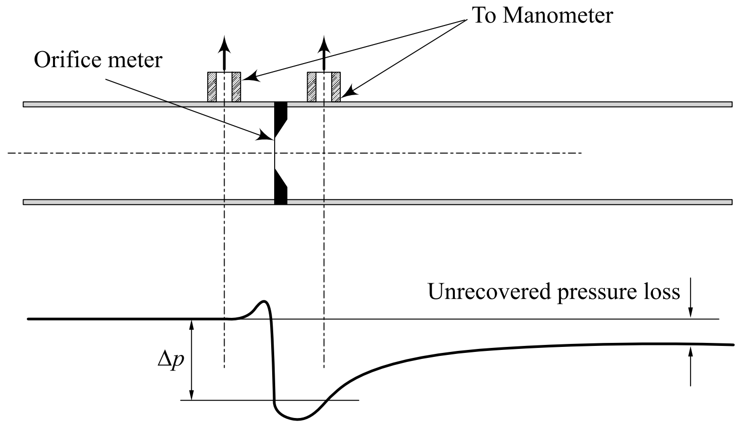


Fig. 2.11(c) *Orifice Meter and its Pressure Drop Curve*

Another type of flow measurement method is by using a *variable area device*. The most common device in this category is the *Rotameter*. In case of obstruction type devices, the *pressure loss* varies with square of the flow rate. So, the range of pressure measurement becomes quite large, if the range of flow measurement is large. In such a situation, the accuracy of the device at low flow rates will be poor. A rotameter overcomes this problem, because its indication is linear with flow rate. The pressure loss remains almost constant over the range of measurement. It consists of a tapered (variable area) tube, and a *float*. The float moves up and down the tapered tube. The flow inside the tube is from bottom to top. The height of the float inside the tube depends upon the flow rate. The tube is calibrated to read the flow rate directly. The major limitation of this device is that it has to be mounted vertically in the pipe line. Also, this device cannot be used when the fluid is not transparent enough due to visibility problems. It can also not be used if the fluid has suspended particles in it.

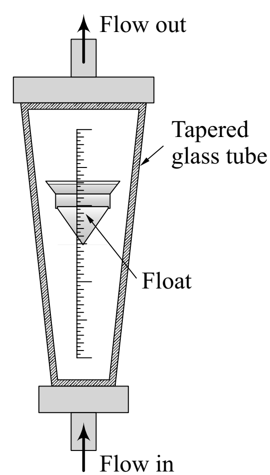


Fig. 2.12 *A Rotameter*

Figure 2.12 shows the basic construction of a rotameter.

Another category of flow measurement devices is *Pressure Probes*. This method is based on the fact that the flow rate is related to velocity of flow. This method attempts to measure the velocity at one or more points in the flow field. The probe is a sampling device, which is used to determine the velocity at a point in the flow, causing a minimum disturbance in flow pattern. The most common device in this category is a ***pitot tube***. The probe is a hollow tube of small diameter. The probe is placed in the flow, such that its axis is parallel to the flow direction. The fluid striking against the probe tip comes to a halt, and its momentum gives rise to pressure. Thus, the pressure at the tip of the probe is the sum of fluid pressure in the flow, and the pressure rise due to stopping of the flow at the probe's tip. At the same time, pressure is also measured at the wall of the probe. The difference of these two pressures gives the pressure component solely due to momentum (and hence the velocity) of the fluid. This value of pressure is used to determine the flow velocity. In most cases, the flow velocity is not constant across the cross-section of the pipe line. Therefore, the velocity is determined at many points over the cross-section, to obtain a *Velocity Profile*. Using this velocity profile, the flow rate can be determined.

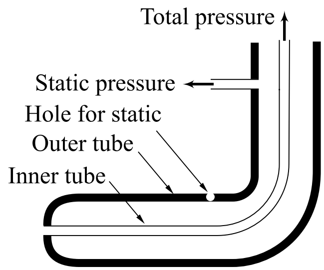


Fig. 2.13 *Pitot Tube*

2.1.5 Measurement of Strain

When an elastic body is subjected to load, internal stresses are generated in it. Along with this, the body also gets deformed. This deformation is measured in terms of strain. *Linear strain* is the change in length of an object, per unit original length. Strain can be determined by measuring the change in dimensions of the object. Such deformation can be measured by means of mechanical linkages using levers and gears, optical methods based upon deflection of light beam or interference, and electrical means by measuring changes in electrical resistance, capacitance and inductance. Based upon these principles, a large variety of sensors are available which can be used for measuring deformation and strain.

Measurement of strain is done for two major reasons. Firstly, strain is related to stress, and measurement of strain is done to determine stress in a machine component. This is very useful because there are hardly any means for measuring stress in an actual machine component directly. Secondly, measurement of strain is used for determining other physical quantities indirectly. It is well-known that change in dimensions (strain) is caused by many physical quantities like temperature, force, torque, pressure and motion. By measuring the strain produced by these physical quantities, their magnitude can also be determined. A large number of sensors, for measurement of a large number of physical quantities, use strain gages as a secondary transducer. The *Electrical Resistance Strain Gage* is one of the most widely used sensor for measurement of strain.

Electrical Resistance Strain Gage Consider an electrical wire element as shown in Fig. 2.14. The electrical resistance of the wire can be expressed as,

$$R = \rho L/A;$$

where ρ is electrical resistivity, L is length, A is cross-section area of wire.

When an axial force is applied on this wire, its length increases and diameter decreases. Due to these changes in its length and area of cross-section, its electrical resistance also changes. This is the principle on which electrical resistance strain gages work. This property of metals, due to which their resistance changes on applying stress, is called *Piezo-resistivity*.

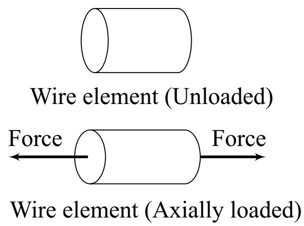


Fig. 2.14 *Deformation in a Wire*

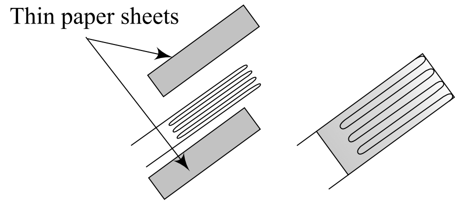


Fig. 2.15 *Electrical Wire Strain Gage*

The strain gage employed for measurement of strain is called *Bonded Resistance Gage*. Figure 2.15 shows the construction of a bonded wire flat strain gage. It consists of a grid of fine wire, sandwiched between two thin paper sheets. The strain gage is bonded on the surface, where stress is to be measured, by means of a suitable adhesive. The commonly used adhesives are based on nitro-cellulose, cyano-acrylate, or bakellite (phenolic).

The sensitivity of the strain gage is measured by its *Gage Factor*. Gage factor is defined as,

$$G = \frac{dR/R}{dL/L} = \frac{dR/R}{\varepsilon}$$

Here G is Gage Factor, dR is change in resistance, dL is change in length, and ε is linear strain. Typical resistance of a strain gage is 120 ohms. These strain gages can measure very small strains (0.000001 mm/mm).

Such type of strain gages can be used in the temperature range of –200°C to 200°C. However, the exact range for a particular gage and the bonding agent should be obtained from the manufacturer. The desirable properties of the metal used in resistance gages are, (a) High Gage Factor (b) High resistivity (c) Low temperature sensitivity (d) High yield point (e) High endurance limit (e) Good solderability and weldability (f) Good corrosion resistance.

Foil Strain Gage In foil strain gage, the resistive element is made of very thin metal foil (about 5 micron), mounted on a suitable base like epoxy resin or paper. Epoxy filled with fiber glass are used for high temperature applications. These gages are manufactured by printed circuit technology. Therefore, many configurations and shapes are possible in foil gages, which are not feasible with wire gages. Foil gages have almost replaced the wire gage. They are widely used as secondary transducers for load cells, torque sensors, pressure sensors etc. Figure 2.16 shows a typical foil gage.

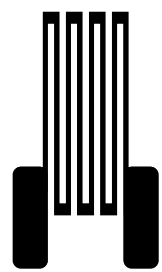


Fig. 2.16 *Foil Gage*

Semiconductor Gage Semiconductor materials like silicon and germanium possess piezo-resistive properties. Strain gages made from these materials are called semiconductor gages, or S-C gages. They are used in the form of very thin (10 micron) foil having very small width (0.1 mm). This gage element is cut from single crystal of doped silicon, using ultrasonic methods. Their length varies in the range of 1 to 10 mm.

They are extremely sensitive in comparison to metallic strain gages. Their sensitivity (Gage Factor) is about 100 times that of metallic gages. The major disadvantages of semiconductor gages are (a) Non-linear strain-resistance relationship (b) Higher sensitivity to temperature (c) High fragility (d) Lower maximum strain (e) High cost.

Advantages of Resistance Strain Gages The resistance strain gages have the following advantages, (a) Small size and mass (b) Ease of production over a range of sizes (c) Robustness (d) Good linearity over large strain range (e) Good sensitivity (f) Low cost (g) Suitable for measurement of static and dynamic strains (h) Suitable for remote measurements.

2.1.6 Measurement of Force

Force is measured using different types of *Elastic Transducers* and strain gages. When force is applied to an elastic body, it deflects. This deflection is related to the magnitude of force. Thus, by measuring the deflection caused by the force, its magnitude can be determined.

Spring Balance A spring balance is a common device used for measurement of force. It uses a helical coil spring with a scale. The force-deflection relationship for a helical spring is linear up to certain value of deflection in the spring. Therefore, the scale is a linear scale, and the maximum force which can be measured by a particular spring is limited by the linear range. The spring has two hooks, one on each end. One hook is used to hold it at a suitable fixed support. Force is applied to its other end. Figure 2.17 shows a typical spring balance with helical coil spring. The linear relationship of force-deflection can be expressed as,

$$F = K\,\delta;$$

where K is spring rate, and δ is deflection.

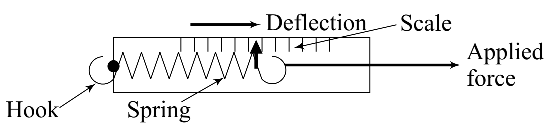


Fig. 2.17 *A Spring Balance using Helical Spring*

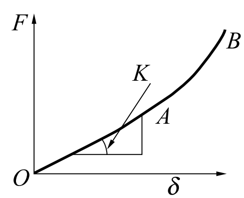


Fig. 2.18 *Force-deflection*

The spring rate is the magnitude of force for causing a unit deflection in the spring. The relationship between force and deflection is shown in Fig. 2.18. This relationship is linear in the range OA, and non-linear in the range AB. Therefore, for the purpose of mathematical modeling, the spring can be treated as a *Linear Spring* in the range OA and a *Non-linear Spring* in the range AB. The slope of the curve gives the spring rate.

Spring based for measuring devices are also available in the form of circular *Dial Gages*. These dial gages display the load on a circular dial.

Electrical Load Cells Electrical load cells have now become very common for measurement of load for both commercial and engineering applications. These load cells have strain gages mounted on an elastic element. There is a large variety of load cells, using different geometries of elastic elements, and different arrangements for mounting the strain gages. Figure 2.19 shows two basic shapes of elastic elements, commonly used load cells, along with arrangement for strain gages. In this figure only one strain gage is shown on each element. In actual cases, more gages are mounted on one elastic element. These elastic elements are enclosed in suitable housing. The housing has one upper and one lower casing, which can slide relative to each other, in the direction of applied force.

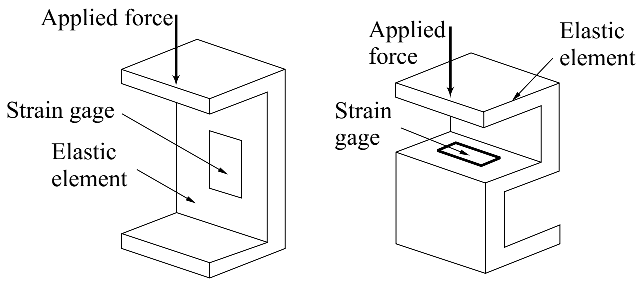


Fig. 2.19 *Elastic Elements for Load Cells*

Hydraulic and Pneumatic Load Cells Force can also be measured by measuring the pressure exerted by it, on a known area. This principle is used in hydraulic and pneumatic load cells. In these load cells, there is a piston or a plunger. External force is applied on them. The piston or plunger moves inside a cylindrical cavity, which is filled with either a hydraulic oil (in case of hydraulic load cells), or air (in case of pneumatic load cells). The cylindrical cavity is connected to a pressure measuring device. Since the area of the plunger is known, the display of the pressure measuring device can be directly calibrated to read the force. Figure 2.20 shows a hydraulic load cell.

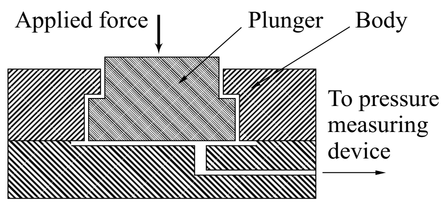


Fig. 2.20 *Hydraulic Load Cell*

2.1.7 Measurement of Torque

Torque is the moment applied by a force. The shafts of machines, electric motors, generators, pumps, IC engines, and other similar rotary equipment transmit power through angular motion and torque. The product of torque and angular velocity gives the mechanical power. Torque measuring devices are commonly known as *Dynamometers.* Thus, measurement of torque and angular velocity is essential for determination of mechanical power in rotary systems. Measurement of torque is also required to determine the induced stresses in mechanical components. This forms the basis of design of such components. Measurement of torque is possible through both mechanical means and electrical systems.

Prony Brake Dynamometer Prony brakes are one of the oldest devices for measurement of torque. The prony brakes fall into the category of *Absorption Dynamometers*.

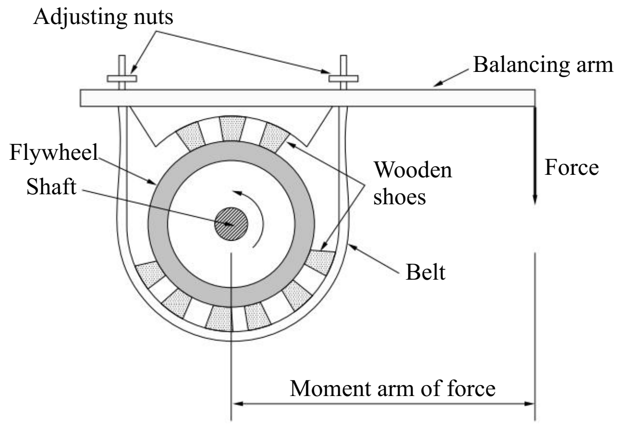


Fig. 2.21 *Prony Brake Dynamometer*

This is because the measurement is done by absorbing or dissipating the power. Figure 2.21 shows a simple prony brake dynamometer. In this dynamometer, a belt is wrapped around the flywheel mounted on the shaft. The belt is connected to a balancing arm through adjustable bolt and nut arrangements. Wooden shoes are mounted on the balancing arm and part of the belt. When the nuts are tightened, the wooden shoes press against the flywheel. A force is applied on the far end of the balancing arm. In the figure, the shaft tries to rotate the balancing arm in counter-clockwise direction due to torque generated by the prime-mover. The force applied on the balancing arm provides a clockwise moment which balances the torque due to the shaft. This moment can be calculated if the magnitude of the applied force, and the distance of its line of action from centre of the shaft are known. When the applied force is sufficient, its moment is equal to the torque applied by the shaft. The applied force is measured by a force measuring system. Dead weight or spring balance can be used for this purpose. The moment arm of the force can be measured directly. The product of these two quantities is the moment applied by the force, and it is equal to the torque applied by the shaft, when the balancing arm is steady.

Rope Dynamometer Figure 2.22 shows a rope dynamometer. Multiple turns of a rope are wound around the flywheel mounted on the shaft. One end of the rope is connected to a spring balance. The other end carries a weight. As the shaft rotates, the two ends of the rope apply moment of the flywheel due to tension produced in them. The tension in the upper part of the rope is measured by the spring balance. The tension in the lower part is equal to the force applied by the weight. The moment arm of these two forces is equal to distance of the rope

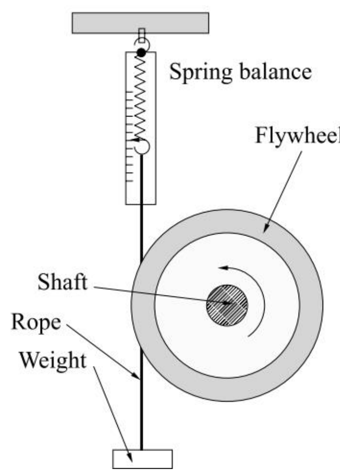


Fig. 2.22 *Rope Dynamometer*

from centre of the shaft. The moment applied by the rope is the product of the difference in the two tensions, and the moment arm. This moment is equal to the torque applied by the shaft.

Measurement of Torque Using Strain Gages When a shaft carries a torque, stresses are generated in its body. These stresses cause strain. Strain gages can be used to determine the strain. The strain is used to determine the stresses in the shaft. The magnitude of stress, and geometrical data of the shaft can be used to calculate the torque carried by the shaft.

2.2 ERROR AND UNCERTAINTY IN MEASUREMENT

Whenever experimental data is obtained from an experimental setup, errors enter into the results. Error is the difference between the actual value of a parameter, and the value obtained by measurement. Error leads to uncertainty in measurement. Errors may be caused by different reasons. In any practical situation the errors cannot be eliminated completely. Although the actual magnitude of error is not known, its effect can be minimized through systematic analysis and statistical methods. For this purpose, it is important to know the common sources of error. For this purpose, errors are classified into different categories.

2.2.1 Types of Errors

Figure 2.23 gives a classification of errors. Errors are broadly classified into three categories: (a) Systematic or fixed errors (b) Random or accidental errors, and (c) Illegitimate errors. Each of these classifications is divided into further types of errors, as shown in the figure.

Errors

- **Systematic or fixed errors**
  - *Calibration errors*
  - *Human errors*
  - *Experimental errors*
  - *Errors of technique*
  - *Loading errors*
- **Random or accidental errors**
  - *Errors of judgment*
  - *Variation of conditions*
  - *Definition*
- **Illegitimate errors**
  - *Blunders or mistakes*
  - *Computational errors*
  - *Chaotic errors*

Fig. 2.23 *Classification of Errors*

Systematic Errors These errors are of constant type. Also their sign remains the same. These errors are caused by factors which are consistent, i.e., they do not change over time. The magnitude and sign of systematic errors is the same for any measurement. The instrument may be responsible for such errors due to improper design, fabrication, or maintenance. Zero error, incorrect marking on dials and scales, defects in gears and lever mechanisms, non-linear behaviour of components (like electronic circuits, springs) are examples of such errors. These errors can also occur when a person consistently repeats the same mistake. This may happen due to improper training, incorrect technique and procedure, or lack of knowledge. When an instrument is introduced in a system for measurement of a parameter, it changes the characteristics of the system itself. For example, if an ammeter or voltmeter is used in a circuit, it will introduce its resistance and inductance in the system. A probe for measurement of velocity of flow will change the flow characteristics. This will change the characteristics of the system, and hence the output of the system. Such errors are called *loading errors*. In some cases the systematic errors can be controlled by calibration of the instrument. Systematic errors can also be caused by incorrect calibration of the instrument.

Random Errors Random errors are not consistent. Their magnitude and sign vary from measurement to measurement. A human being can introduce a random error if he is not consistent in method or judgement. For example, when a dial gage is used, the pointer may show a value between two marks. A person may sometimes record a higher value, and at other times a lower value. There are many external conditions (environmental conditions) which keep changing, and also affect the measurement. Such conditions are not in control of the person or system. Their effect is to introduce random errors into measurement. Ambient temperature and pressure, vibrations, wind, relative humidity, etc. are some of the factors of this type. Backlash and friction also give rise to random errors. Tolerances in dimensions and material are also responsible for random errors. Sometimes such errors occur due to poor definition. For example, a rectangular sheet of metal may have non-parallel edges. In such a situation its width or length cannot be defined, even when the measuring instrument is correct.

Random errors can be detected, and sometimes controlled, by using *Method of Symmetry* in taking the measurement. In this method, the parameter is first increased and then decreased. Magnitude of random errors can be estimated through statistical techniques.

Illegitimate Errors These are mistakes in conducting the experiment or following wrong procedures. They occur when proper care is not exercised. They can be eliminated by repeating the experiments or measurement. Chaotic errors occur due to very high level of vibrations, electrical interference (noise). The magnitude of these errors is high and it makes the test data meaningless. These errors can be taken care of by identifying their source and removing it.

2.2.2 Some Basic Concepts and Definitions Related to Measurement

Certain terms and definitions are useful in understanding the meaning of measurement, error and uncertainty. These are discussed in this section.

Data These are bits of information which are obtained by experiments. Usually data has numerical value.

Population This refers to all the set of all the data collected through an experiment.

Sample It is a part of the population. It is used for determining other quantities for stating the results of the experiment.

True Value V_a True value or actual value is the actual magnitude of the signal given to measurement system. Practically, the true value cannot be determined due to errors in measurement.

Indicated Value V_i This is the value indicated by the measuring system.

Result V_r This is the value obtained by applying all the corrections to the indicated value.

$$V_r = A\,V_i + B;$$

where A and B are correction factors.

Discrepancy This is the difference between two indicated values given by the measurement system, for the same input.

Error This is the difference between the true value and the result $(V_r - V_a)$. Practically the value of error is never known.

Accuracy It is the maximum amount by which the result differs from the true value. Thus, accuracy is the maximum error.

$$\text{Accuracy} = V_{r(max\ or\ min)} - V_a$$

Accuracy is usually expressed as percentage or either *Actual Reading* or *Full Scale*. Full scale is the maximum reading which can be obtained from the measurement system, for a particular setting.

Range It is the difference between the largest and the smallest result.

Dispersion It is the way in which the results are *scattered* about a mean value. It is a measure reliability of data.

Deviation It is the difference between a single result, and the mean value of many results.

Precision It is the degree of agreement between repeated results, for constant conditions of the system. When precision is high, the dispersion (measured by standard deviation) is low. Thus there is low *scatter* or *spread* in the data. Precision is totally independent from accuracy. An instrument with high precision may not be accurate. It may repeatedly show incorrect values, which themselves are very close to each other.

2.2.3 Uncertainty Analysis

Uncertainty It is the range or region in which error may vary. It is not the same as accuracy. Consider an example of manufacturing of shaft. On the drawing, the diameter of the shaft is shown as combination of a *nominal* value, and *tolerances*. Tolerances are the permissible deviations in the nominal size, both on higher and lower sides. Suppose that the nominal diameter of the shaft is 100 mm, and the acceptable diameter has the range of 99.5 mm to 100.5 mm. Then the diameter of the shaft is shown on the drawing as, $D = (100 \pm 0.5)$ mm. Here, 100 mm is the nominal diameter of the shaft, upper tolerance is +0.5 mm, and lower tolerance is –0.5 mm. Thus at the design stage, when the drawing is prepared, one knows that any particular shaft manufactured according to this drawing will have its diameter in the range 99.5 mm to 100.5 mm. Thus, at the design stage, the *range* of diameter is definitely known. However, at this stage the *exact diameter* of *a particular shaft* is not known, because the shaft has not been manufactured yet. Therefore, the range of diameter (99.5 mm to 100.5 mm) expresses the ***uncertainty*** that is expected in the diameter, when the shaft will be actually manufactured. When a shaft is actually manufactured, its actual dimension can be measured, and so it becomes known. Suppose the actual diameter of the shaft turns out to be 100.2 mm. The deviation of the actual diameter from the nominal diameter is 0.2 mm. This deviation is the measure of the shafts *accuracy*. In this manner, the tolerance expresses the uncertainty, which is different than accuracy.

Propagation of Uncertainty In many situations a value depends upon two or more measured values. For example, to determine the area of a rectangular sheet, one has to measure its width and length. Errors may occur in measurement of both the width and the length. These errors will introduce error in the value of area, when it is calculated by multiplying the values of length and width. Thus, the errors in measurement of length and width have *propagated* as error in value of area.

Consider that the scale which was used for measuring the length and width of the rectangular sheet had error in marking of graduations. This will cause error in both the values. Here, the errors in the two measurements are called *Dependent Errors*. The effect of the two errors, on the error in value of area, will be additive.

Now consider the case of a spring balance. There may be error in the stiffness of the spring, and also in the marking of the scale. The value of force shown on the scale depends upon both the stiffness and the scale's marking. If the stiffness of the spring is less than design value, the spring will undergo more deflection for a particular value of force. If the scale is correct, the value of force indicated on the scale will be more than the true value. However, if due to error in marking, the scale marks are cut at longer intervals than true value, the reading of spring's deflection will be reduced. Thus, the error in stiffness is tending to increase the measured value of force, but the error in scale is tending to reduce it. Therefore, the effect of these two errors, on the error in measurement of force, will be opposite. The error in stiffness is independent of the error in scale. In the present example they tend to *compensate* each other. Such errors are termed as *Independent Errors*. Dependent errors do not compensate one another, while independent errors may compensate one another.

The combined effect of independent errors can be obtained by the following relationship,

$$e_o = \sqrt{(e_1)^2 + (e_2)^2 + (e_3)^2 + \ldots + (e_n)^2}$$

Here, e_o is the overall error due to n independent errors e_1 to e_n, occurring in the n different parameters.

2.3 MEASURING INSTRUMENTS

Various measuring instruments are used for measurement of length dimension (length, diameter, depth, width), and angular dimensions. They are used in experiments, inspection, and quality control. They are also used to set the tools on machines, position the workpiece on a machine. A *Measuring Instrument* is used to determine the numerical value of a parameter. During inspection and quality control, it is sometimes sufficient to know whether a manufactured component is within the specified tolerances or not. In such cases, comparison of the component with a standard device is sufficient. The devices used in this manner are called *Gages*.

2.3.1 Vernier Calipers

Vernier caliper, is used to measure inside and outside dimensions of components. It has a *vernier scale* and a *main scale*. The main scale has markings at 0.5 mm or 1 mm. The vernier scale has marking slightly different than the main scale. The principle of vernier is based on difference of these two scales. This instrument has two jaws. The *fixed jaw* and the main scale form a single piece. The *moving jaw* slides on the main scale. It carries the vernier scale. This assembly is called the *vernier head*. The markings of the two scales are adjacent to each other. An *auxiliary head* is attached to the moving head. Both the vernier head and the auxiliary head have *lock screws*. The moving head and auxiliary head are connected to each other by a *Fine Adjustment Screw*. Figure 2.24 shows the details of a vernier calipers. Vernier calipers are available in the ranges 0 to 25 mm, 0 to 150 mm, 0 to 200 mm etc.

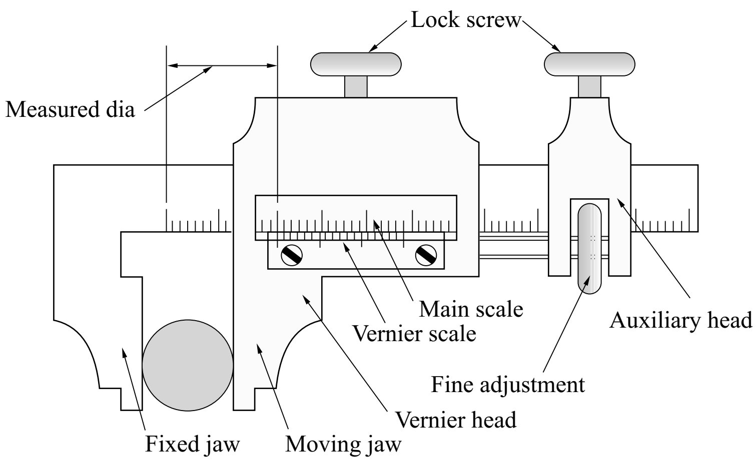


Fig. 2.24 *Vernier Calipers*

The Vernier Scale The principle of vernier scale is explained in Fig. 2.25. The main scale is graduated in centimetres, millimetres, and 0.5 mm. The major graduations on the main scale shown in Fig. 2.25 mark centimetres, and the smallest divisions mark 0.5 mm. The vernier scale, shown below the main scale, has 25 divisions. These 25 divisions are equal to 24 smallest divisions of main scale, i.e., 12 mm. Thus, each division of the vernier scale is equal to 12/25 mm = 0.048 mm. Therefore, the difference between the smallest division of main scale and the smallest division of vernier scale is 0.5 – 0.048 = 0.02 mm. This is the *Least Count* of the vernier calipers.

Reading the Vernier Scale Figure 2.26 explains how to read a vernier. Here the zero on the vernier scale is just after the main scale reading of 11.5 mm. This position is shown in the Fig. 2.26 by the dotted line on the left. We now move toward right on the vernier scale to find the division which coincides with a division on the main scale. The dotted line on the right shows this condition. The 15th division on the vernier scale is coinciding with a division on the main scale. This corresponds to a length equal to 15×0.02 mm = 0.3 mm. The overall reading of the instrument can be

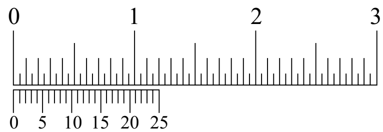


Fig. 2.25 *The Vernier Scale*

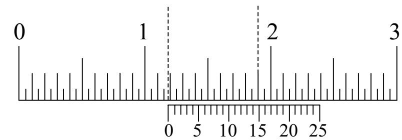


Fig. 2.26 *Reading the Vernier Scale*

determined by adding the reading on main scale and on the vernier scale. Hence, the reading for Fig. 2.26 becomes 11.5 mm + 0.3 mm = 11.8 mm.

2.3.2 Micrometer

The micrometer is used to measure the length and diameter of small components with an accuracy of 0.01 mm. It has a U-shaped *frame* made of alloy steel. At one end of the frame there is a hard *anvil* which protrudes about 3 mm from the frame. The anvil supports the component being measured on one side. A moving *spindle* moves in and out of the other end of the frame. The spindle has threads of pitch 0.5 mm. A *barrel* having graduations is attached to the frame. Graduations are marked on a line on the barrel. These marks are put at intervals of 0.5 mm and alternately above and below the line. A tubular cover called *thimble* is attached to the spindle. The thimble is divided into 50 divisions on its circumference. A *ratchet* is fixed on the thimble. The user turns the spindle-thimble assembly by turning the ratchet. This causes the spindle to move in and out relative to the frame. When the axial force on the spindle exceeds a certain limit, the ratchet begins to slip. This prevents excessive load on the spindle, and also maintains uniformity in measurement. Figure 2.27 shows the details of a micrometer. This type of micrometers are available in the *range* of 25 mm, with different starting values like, 0 to 25 mm, 25 to 50 mm, 50 to 75 mm, 75 to 100 mm, and so on up to the largest micrometer with 575 to 600 mm. Larger micrometers come with interchangeable anvils of different sizes, to obtain different starting values.

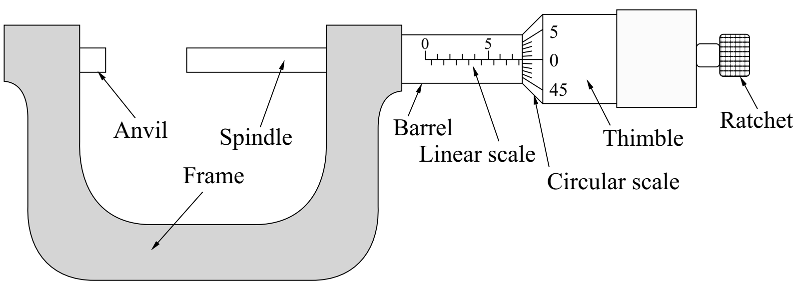


Fig. 2.27 *Details of a Micrometer*

Reading the Micrometer When the thimble of the micrometer is turned, it moves along the linear scale. This movement is due to threads on the spindle, which have a pitch of 0.5 mm. Therefore, for one complete rotation of the thimble, the spindle moves by 0.5 mm. The circular scale on the thimble is divided into 50 parts. Therefore, for rotation of thimble by on division on circular scale, the linear movement of spindle is 0.5/50 = 0.01 mm. This is the *Least Count* of the micrometer. On the linear scale the divisions above it show millimetres, and those below it show 0.5 mm. Therefore, first we have to take reading on the linear scale, corresponding to the division just to the left of the thimble. Then we read the division on the circular scale, which coincides with the linear scale.

In Fig. 2.28, the reading is determined as follows. First we determine the reading on the linear scale. On the upper scale, the last division to the left of thimble edge corresponds to 7 mm. On the lower scale, there is one division between this last division and the edge of the thimble. Therefore, we add 0.5 mm to the reading of upper scale. So the total reading of the linear scale becomes 7.5 mm. Now we determine the reading corresponding to the circular scale on the thimble. Here the 15th division of the circular scale coincides with the linear scale. Since each division on circular scale corresponds to 0.01 mm, the reading of the circular scale is 15 × 0.01 mm = 0.15 mm. Therefore the total reading, which is the sum of the readings of the linear scale and the circular scale, is 7.5 mm + 0.15 mm = 7.65 mm.

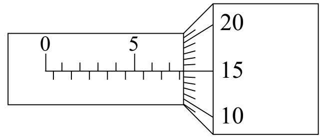


Fig. 2.28 *Reading the Micrometer*

2.3.3 Dial Gages

Dial gages, also known as *Dial Indicators*, have a circular dial with a pointer. A *plunger* is attached to the pointer through a gear train mechanism. The plunger moves in and out of the body of the dial gage. This linear motion of the plunger is magnified and converted into circular motion by the gear train. The circular dial is graduated in 100 divisions. Each division corresponds to displacement of 0.01 mm of plunger. This is the least count of the dial gage. One complete revolution of the pointer corresponds to displacement of 1 mm of the plunger. In normal condition the plunger remains extended out, due to force provided by a spring in the mechanism. Figure 2.29 shows external and internal schematic arrangement of a typical dial gage.

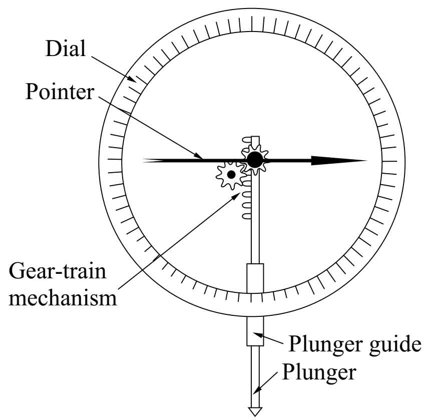


Fig. 2.29 *Dial Gage and its Internal Details*

For any position of the plunger (and therefore the pointer), the dial can be rotated to bring its zero on the pointer. Dial gages are used for alignment of shafts and tools, locating tools and work-pieces, inspection of manufactured components, etc. Dial gages are available in the ranges 0 to 3 mm, 0 to 5 mm, and 0 to 10 mm.

2.3.4 Slip Gages

Slip gages are also known as *Precision Gage Blocks*. They are a set of very accurate rectangular blocks, which are used for verifying and calibrating the measuring tools, limit gages and other quality control gages. They are made of alloy steels, with flat and super-smooth surface, and have high hardness to minimize wear and tear during use. They are made in five grades of accuracy: Grade I, Grade II, Grade 0, Grade 00, and Calibration Grade. Grade I is most commonly used in general engineering. The number of blocks or gages in one set varies from 32 to 112, for different applications. The most common is M 88 Grade I set, which has 88 gages in metric size. Table 2.1 shows the details of M 88 set. In this set any dimension can be obtained to an accuracy of 0.0005 mm.

Table 2.1 Details of M 88 slip gage set

Size Range, mm	*Increment, mm*	*Number of Pieces*
1.0005	—	1
1.001 to 1.009	0.001	9
1.01 to 1.49	0.01	49
0.5 to 9.5	0.5	19
10 to 100	10	10
	Total Number of Pieces	88

They are so accurately flat and smooth that they stick to each other when one block is slided over other. This is called *wringing*. This happens because during sliding almost no air is left between the surfaces of two blocks, and a partial vacuum is created between them. To obtain a particular thickness, the gages of different sizes are wrung together by slipping one over the other. For this reason slip gages are also known as *wringing* gages. Careful handling and cleanliness are very important in maintaining the accuracy of these gages.

2.3.5 Sine Bar

Sine Bar is used for determination of angles trigonometrically, by using measured linear dimensions. It is also used for setting angles and tapers. Slip gages are used to measure or set the linear dimensions. Sine bar is a steel bar with steps at both ends. It is made of steel and super-finished by lapping operation. At each end, a roller is attached at the step in the bar. The roller remains in contact with both faces of the step, as shown in Fig. 2.30. The distance between the centres of the two rollers L is known. Figure 2.31 shows the method for setting or determining the angle α with the help of sine bar. The two rollers are supported on sets of slip gages. The slip gages are placed on a flat and level surface. The height of each column of slip gages is obtained by adding their thicknesses. The difference in heights of the two columns H can be determined by taking the difference in heights of the two columns. The angle can now be determined by using,

$$\sin \alpha = \frac{H}{L} \Rightarrow \alpha = \sin^{-1} \frac{H}{L}$$

A sine bar is specified by the centre distance L between its rollers. Most common size is 100 mm. It is also available in 250 mm size. The two rollers must be of the same diameter. The accuracy of sine bar depends upon correctness of roller diameters, and

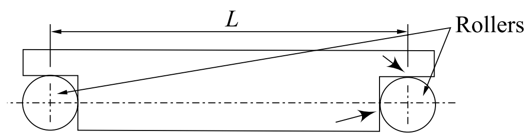


Fig. 2.30 *Sine Bar*

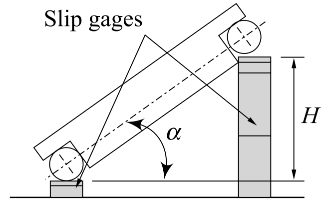


Fig. 2.31 *Measurement of Angle using Sine Bar*

centre distance between them. Also, the upper and lower edges of the sine bar, and the centre line of rollers must be parallel to each other.

2.3.6 Combination Set

Combination set is used in fitting and machine shops. It is a combination of three instruments, *square head, centre head,* and *bevel protractor*. These three heads are mounted on a common slotted beam, by means of nuts. The three heads can be slided along the beam to any desired position. The beam has graduations in mm, and acts as a rule. It is available in lengths ranging from 200 mm to 6000 mm. Figure 2.32 shows a combination set.

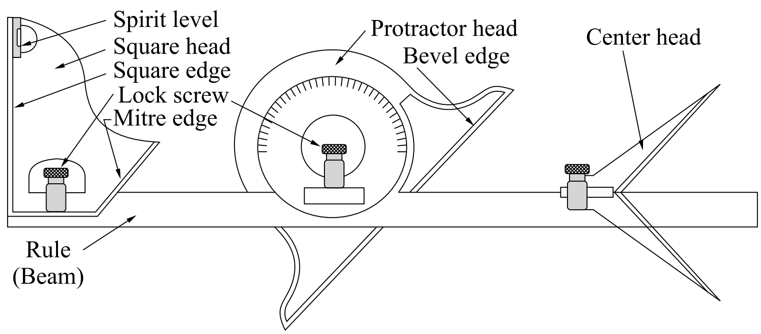


Fig. 2.32 *Combination Set*

Square Head It has one edge square (perpendicular) to the rule, and one edge forms a mitre (45°) with the rule. Thus, the square head can be used to test both 90° and 45° angles. The square head also carries a spirit level.

Centre Head It has two arms at right angle to each other. They are mounted on the rule in such a manner that the rule's edge divides the right angle in equal parts. The centre head is used for determining the centre of a round bar.

Protractor Head The protractor head is mounted on the beam through pin-joint, so that it can be tilted relative to the rule. In this manner the edge of the protractor head can be tilted to for any desired angle with the rule. The circular scale on the protractor is divided into degrees. For more precise angular measurement, a vernier scale is sometimes provided on the protractor. The vernier scale has a least count of 1/60 degree, i.e., one minute. The protractor head also carries a spirit level.

2.4 INTRODUCTION TO MACHINE TOOLS

In today's industrialized world, a large number of processes are employed for converting raw materials into finished products. Such processes are called *Manufacturing Processes*. In mechanical production engineering, the different types of processes in use are casting, machining, welding, forming, etc. Out of these processes, machining processes are very important, due to their versatility and application. In machining processes, unwanted material is removed from raw material (called *stock*), to obtain desired geometrical shape of a component. Machining process is essentially a process performed on the surface of the raw material. The machining processes are carried out on *Machine Tools*. The most common machine tools used in manufacturing industry are *lathe, shaper, drill*, and *milling* machine. These machine tools are called *general purpose* machine tools. For special type of machining processes, *Special Purpose Machine Tools* or *SPMs* are used.

2.4.1 The Lathe Machine

Lathe machine is the most basic, as well as most versatile machine tool. It is the backbone of any workshop or tool room. The basic arrangement in a lathe machine is to rotate or *turn* a work piece, while a cutting tool is moved along a straight line. The work piece can be held on the lathe in two ways (a) Holding it between the *live centre* and *dead centre*, and (b) Holding it on the *chuck*.

Basic Components of a Lathe The basic components of the lathe are shown in Fig. 2.32. The lathe machine is an assembly of sub-assemblies and components. The important parts and sub-assemblies are:

(a) The bed (b) The headstock assembly (c) The tailstock assembly (d) The carriage assembly (e)The quick-change gearbox.

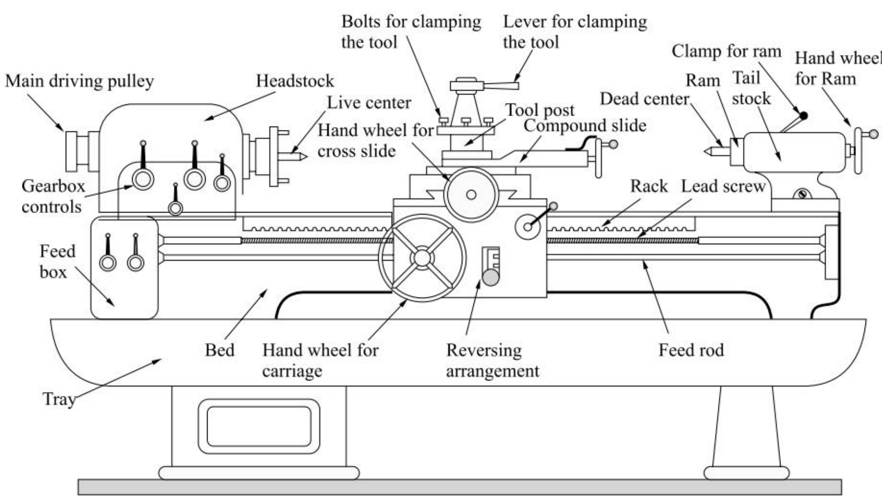


Fig. 2.33 *The Lathe Machine*

The Bed This is a rigid frame made of grey cast iron, on which all the sub-assemblies and parts of lathe are mounted. On its upper surface it has two pairs of guideways, one is a pair of inverted V-guides, and other is a pair of flat-guides. The V-guideways are for the carriage, and the flat guideways are for the tailstock. The guideways are machined with high precision, and their surface is hardened.

The Headstock Assembly The headstock has all the gear arrangements for transferring the power from the electric motor to the chuck and live centre. The headstock has a cast iron housing, mounted on the inner guideways at one end of the bed. It has a hollow spindle which is mounted on taper roller bearings. The headstock has a gear-box by which different rotational speed of work piece can be obtained. The number of speeds varies between 8 to 18, and the speed range is between 40 to 2500 RPM. The speeds are available in geometric progression. One end of the spindle projects out of the headstock housing, and different types of work-holding devices (chuck, dog plate, and face plate) can be mounted on it.

The Tailstock Assembly The tailstock assembly is mounted at the end of the bed, opposite to the headstock. The tailstock assembly has a hollow steel tube called *barrel*, which can be moved in and out of the tailstock housing, by a hand-wheel and screw arrangement. It can also be moved horizontally and perpendicular to the axis of the bed. The ram can hold a dead centre for supporting a long work-piece. It can also hold a tool (like a drill-bit, reamer, or a boring tool). The tailstock assembly is mounted on the inner guideways, and it can be slided over them.

The Carriage Assembly The carriage can be moved along the bed by means of a handwheel. It consists of a *saddle,* a *cross-slide*, a *compound slide*, a *tool post* and an *apron.* The function of the carriage and its components is to hold the tool and move it in different manners. The ***saddle*** is a H-shaped casting which moves along the bed on the outer guideways. The ***cross slide*** is mounted on the saddle. The cross slide can be moved horizontally and perpendicular to the bed. This motion is given by means of a screw and hand-wheel mounted on the saddle, and a nut mounted on the cross slide, which is engaged with the screw. A graduated circular scale is also attached with the hand-wheel. The ***compound slide*** is mounted on the cross slide. The compound slide can be rotated about a vertical axis. It can also be moved along its longitudinal axis by a screw and hand-wheel arrangement. The compound slide is used for *taper* turning. The ***tool post*** is mounted on the compound slide. The ***cutting tool*** is mounted on the tool post, by means of bolts. The ***apron*** is attached to the front part of the carriage assembly. It carries a hand-wheel to move the carriage along the bed. This motion is achieved by means of a ***rack and pinion*** arrangement. The rack is supported on the bed, and runs along the entire length of the bed. The pinion is mounted on the shaft of hand-wheel of the carriage. The apron also carries gear mechanism for giving powered motion to the carriage by means of a ***lead-screw***. The lead-screw, a long screw, is supported on bearings at the two ends of the bed. It is rotated about its own axis, by the main shaft of headstock, through a gear arrangement. The carriage has a ***half-nut*** which can be engaged or disengaged with the lead screw by means of a lever. When this half-nut is engaged with the lead screw, the linear motion of the carriage is powered through the lead screw. In this condition, the carriage moves along the bed by a fixed distance, per revolution of the lead screw.

2.4.1.1 Basic Operations on Lathe Machine

The lathe machine is a highly versatile machine. Using different types of tools and attachments, a variety of machining and cutting operations can be performed on it. Some of these operations are described here:

Straight Turning Operation In straight turning operation cylindrical surfaces are generated. In this operation the work piece is held in the rotating chuck. The cutting tool is moved parallel to the axis of the work piece, by moving the carriage along the bed. In this manner, the tip of the cutting tools generates a helix on the surface of the cylindrical work piece. The motion of the tool, called ***feed*** is kept slow, so that the helix has a very small pitch, and the surface generated after machining is smooth. Figure 2.34 shows straight turning operation.

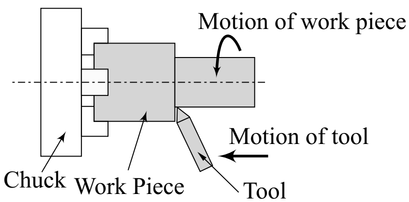


Fig. 2.34 *Straight Turning Operation*

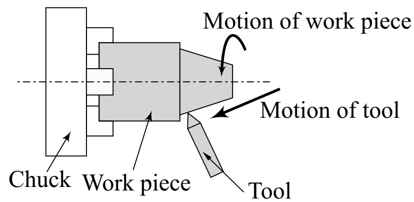


Fig. 2.35 *Taper Turning Operation*

Taper Turning Operation In the taper turning operation, the compound slide is set at required angle to axis of the work piece. The movement of tool is controlled by moving the compound slide, by rotating the wheel attached to it. This type of motion generates a conical surface on the work piece. Figure 2.35 shows taper turning operation.

Facing Operation In facing operation, the work piece is held in the chuck and rotated, while the tool is moved across its face, as shown in Fig. 2.36. This operation is used for obtaining a plane end face on the work piece, perpendicular to the axis.

Thread Cutting Operation Threads can be cut on a cylindrical work piece using lathe. The work piece is held in the chuck, and rotated. The cutting tool is moved parallel to its axis. The combined rotational motion of work piece, and linear motion of the tool, produces a helical groove on the surface of the cylindrical work piece. These two motions must be synchronized to obtain the required pitch of the thread. In thread cutting operation, the motion of carriage is achieved by engaging it with the lead screw, by engaging it to the half-nut on the carriage. Since the motion of lead screw is coupled to the rotation of main spindle through a gear train, the two motions become synchronized. By selecting a suitable combination of gears in the gear train, the desired pitch of threads can be obtained.

Drilling Operation Drilling operation is used for generating a cylindrical hole in a work piece. The cutting tool used for this purpose is called a *drill*. A drill tool is cylindrical in shape, and has helical *flutes* cut on its cylindrical surface. The cutting edges are at its one end, at certain angle to its axis. A typical drilling tool is shown in Figure 2.37.

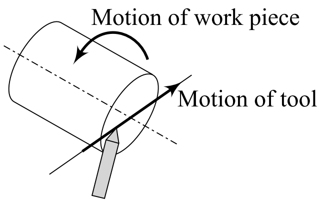


Fig. 2.36 *Facing Operation*

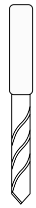


Fig. 2.37 *Drilling Tool*

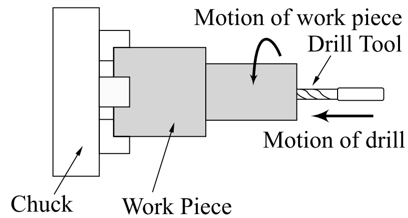


Fig. 2.38 *Drilling Operation*

For drilling operation, the work piece is held in the chuck mounted on the headstock spindle, and the drill is held in the tailstock. The work piece is rotated, and the drill is moved perpendicular to its surface, by slowly rotating the hand wheel in the tailstock. This operation is shown in Fig. 2.38. Sometimes when the component is of irregular shape, it is not possible to hold it in the chuck. In such cases, the drill tool is mounted on the chuck, and the component is held on the tailstock, using special holding arrangements.

Boring Operation Boring is the process of increasing the internal diameter of an existing hole. The work piece is held in the chuck, and the boring tool is mounted on the tailstock, like in a drilling operation. Figure 2.39 shows boring operation.

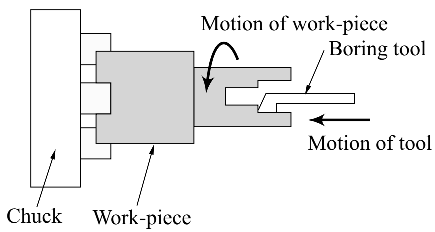


Fig. 2.39 *Boring Operation*

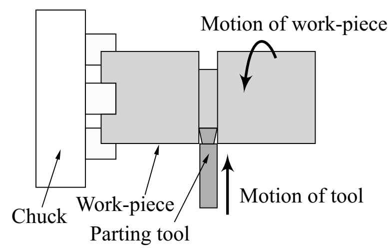


Fig. 2.40 *Parting Operation*

Parting Operation Parting operation is performed on a cylindrical work piece to cut it into two parts. The parting tool has a straight cutting edge, perpendicular to the axis. The width of the cutting edge is slightly more than the width of the tool body. The work piece is held in the chuck and rotated. The tool is moved perpendicular to the axis of the work piece. Figure 2.40 shows the parting operation.

Knurling Operation Many times a circular object is to be held or rotated by hand, like the ratchet of a micrometer. In such cases a plain surface of the object does not provide a good grip to fingers or hand. A cris-crossing pattern is machined on such surfaces to improve the grip. For this purpose as special tool, called knurling tool, is used. It has a cylindrical shape, with a cris-crossing pattern on its surface. The tool rotates freely on bearings. The work piece is mounted on the chuck and rotated. The tool is pressed against the work piece, keeping their axes parallel. It generates a cris-crossing pattern on the work piece. The knurling tool and knurling operation are shown in Fig. 2.41.

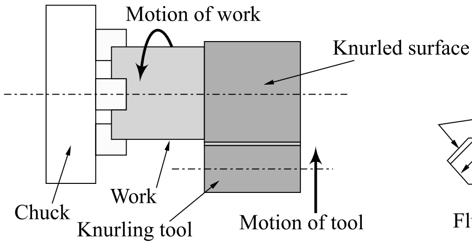


Fig. 2.41 *Knurling Operation*

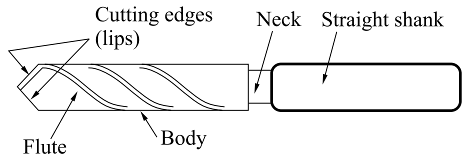


Fig. 2.42 *Details of a Drill Bit*

2.4.2 The Drilling Machine

Drilling machine is an essential part of any workshop. It is used for generating holes in the work pieces. In addition to this, other operations of similar nature are also performed using this machine like, counter-sinking, counter-boring, spot-facing, reaming, and trepanning. Figure 2.42 shows a typical drilling tool, called a *twist drill*. A twist drill has two cutting edges and two flutes.

2.4.2.1 Types of Drilling Machines

Several types of drilling machines are used in industry, like,

(a) Portable Drilling Machine.
(b) Sensitive Drilling Machine.
(c) Upright Drilling Machine.
(d) Radial Drilling Machine.

Portable Drilling Machine This type of drilling machine is used for components which cannot be mounted on a regular drilling machine, or which cannot be moved easily. The machine has a chuck to hold the drill tool, a spindle on which the tool is mounted, and a motor to rotate the spindle. The machine has holding and gripping arrangements. The power switch is located at the handle, so that it can be turned on or off without losing the grip. The machine and the drill tool are pressed perpendicular to the component to generate a hole. Since the maximum force which can be applied by hand is limited, this type of machine can drill holes with small diameters only. Also, since it is difficult to keep the machine steady during the drilling operations, the drilled holes may not be very accurate in terms of diameter. The judgement of perpendicularity is made by the operator, without any appropriate measuring tool or guide, so the hole's axis may not be truly perpendicular to surface of the work piece. Therefore, this type of drilling machine is not suitable where high precision and accuracy are required.

Sensitive Drilling Machine This type of drilling machine is either bench-mounted or floor-mounted. It has a heavy *base*, having a vertical *column*. The vertical column supports a *table* at its middle, on which the work piece is clamped. The table has *T-slots* for holding bolt heads for fastening the work piece. On the top of the column is the *head*. The head carries an electric motor, the driving mechanism, and a vertical *spindle* to hold the drilling tool. The spindle can be moved up and down by a turning *handle*, through a *rack and pinion* arrangement. The vertical motion of the spindle, and hence the drilling tool, is called *feed*. Since the feed is given by the operator, he

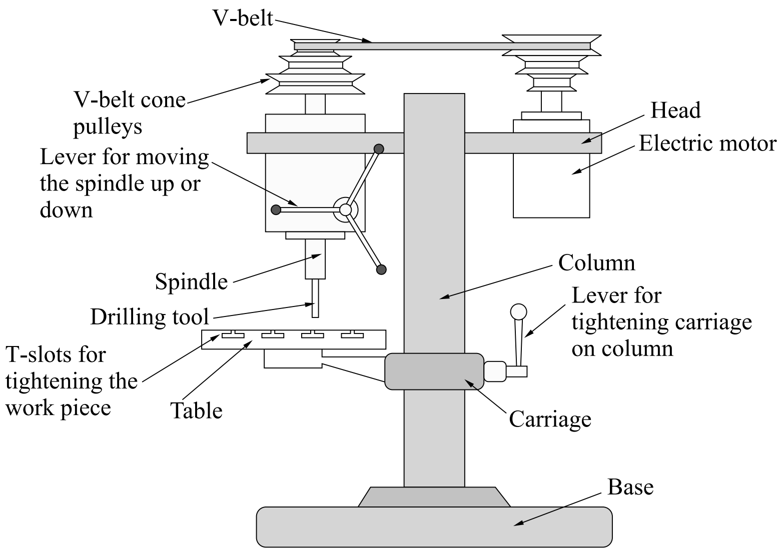


Fig. 2.43 *Sensitive Drilling Machine*

can feel the movement and force during the drilling operation. This is why this type of machine is called a *sensitive* drilling machine. If the machine jams, or cutting gets difficult due to blunting of the cutting edge of drill tool, the operator can sense it. During cutting operations a lot of heat is generated. The basic components of this drilling machine are shown in Fig. 2.43.

2.4.2.2 Basic Operations on Drilling Machine

There are many operations which can be performed on a drilling machine. Some of them are described here:

Reaming This operation is used to finish a previously drilled hole, and also to bring it to the final size. The tool for this purpose is called a *Reamer*. A reamer removes only a small amount of material from the work piece. Reaming operation is usually performed at half of the cutting speed used for drilling operation. Figure 2.44 shows a reaming tool.

Counter-sinking In this operation, a previously drilled hole is *chamfered* by 90^{o}. Such holes are used for *Countersunk Screws*. The head of a countersunk screw does not protrude out of the work piece. Figure 2.45 shows a typical counter-sinking tool, and Fig. 2.46 shows a countersunk hole and countersunk screw.

Counter-boring This operation is used to enlarge a hole diameter to limited depth. This is done to accommodate the heads of bolts and screws, or nuts. With this arrangement, the nuts and bolt heads do not protrude out of the surface of the work piece. Figure 2.47 shows a counter-boring tool, and Fig. 2.48 shows a counter-bored hole with a bolt.

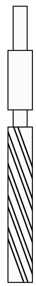


Fig. 2.44 *Reamer*

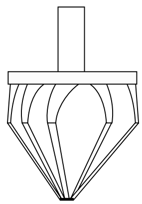


Fig. 2.45 *Counter-sinking Tool*

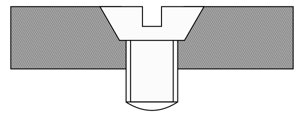


Fig. 2.46 *Counter-sunk Hole and Screw*

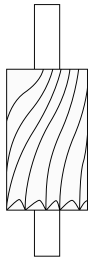


Fig. 2.47 *Counterboring Tool*

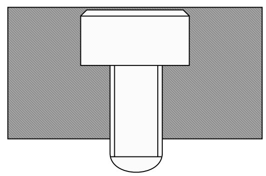


Fig. 2.48 *Counterbored Hole with Bolt*

A similar tool is used for ***spot facing*** operation. In this operation, a circular surface area on a component is finished to obtain flat surface. This is used for obtaining flat surfaces on rough castings, to seat nuts and bolts properly.

2.4.3 The Milling Machine

Milling machine uses a cutter with multiple teeth to obtain plane surfaces. This cutter is mounted on a spindle which is rotated by an electric motor. Each tooth of the cutter acts like a tool. The machine has a table with T-slots to hold the work piece. The cutter rotates at a fixed location, while the work piece is *fed* to it. Milling machines are very fast. The surface finish and accuracy obtained by a milling machine is very good. They are used for mass production of components. A milling machine is called *Horizontal Milling Machine* when the shaft carrying the cutter is horizontal. When this shaft is vertical, the machine is called a *Vertical Milling Machine.* Another more versatile type is *Universal Milling Machine*, in which the table can be inclined to desired angle. The important parts of a milling machine are described here,

Base and Column The base and column of the machine support all the other components. They are made of grey cast iron. They are rigid and have vibration damping nature. The column carries the *spindle*, and the spindle carries the *cutter*. The spindle is rotated by an electric motor. A gear box is used to obtain different rotational speeds of the cutter.

Knee A vertical guideway is provided on the front of the column. The knee is mounted this guideway. It can be moved up or down by a hand-wheel. In some cases it is moved by an electric motor, through a gearbox. The knee has guideways on its top, on which it supports a *saddle*. The knee can be clamped on the column at any position by a *clamping lever*.

Saddle The saddle in mounted on the guideways on top of the knee. The saddle has dovetail guideways on its upper surface on which it supports the *table*. The saddle and the table can be moved vertically along with the knee. This movement is achieved by a lead-screw and hand-wheel assembly and a nut mounted on the saddle. The saddle can be clamped on the knee by means of *clamping levers*.

Table The table is located on the dovetail guides on the saddle. The table moves perpendicular to the movement of the saddle. The table has many T-slots to clamp the work piece.

Spindle The spindle is rotated by the electric motor, through a gearbox, to obtain different speeds. Spindle is mounted on rigid and accurately machined supports. The cutter is mounted on the spindle.

A milling cutter is shown in Figure 2.49.

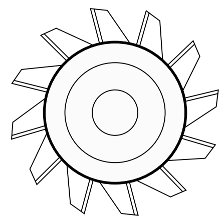


Fig. 2.49 *Milling Cutter*

2.4.3.1 Basic Operations on Milling Machine

The work piece is fed into the cutter in two ways. In the conventional or *Up-milling* operation, the work piece is pushed against the motion of the cutter teeth, as shown in Fig. 2.50. In *Climb-milling* or *Down-milling* process the work piece is moved along the direction of motion of the cutter teeth, as shown in Fig. 2.51. In up-milling process, the cutter teeth begin to cut in a previously cut area. Therefore, it is not loaded suddenly, especially when the work piece material has hard surface or surface scales on it. However, in this method the cutter teeth have a tendency to lift the work piece. Therefore, clamping of the work piece on table must be appropriate. Also there is a larger tendency of chatter and vibrations in up-milling process.

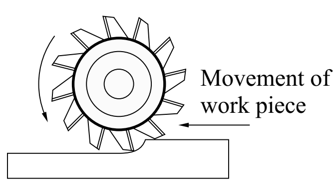


Fig. 2.50 *Up-milling*

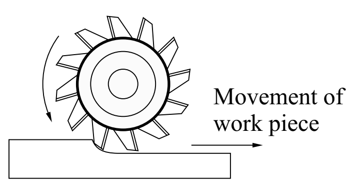


Fig. 2.51 *Climb-milling or Down-milling*

In climb milling the size of chip cut by each tooth is larger. The teeth push down the work piece. So clamping need not be very robust. Also the tendency of chatter and vibrations is less compared to up-milling.

The various common milling operations are end milling, corner rounding, slot cutting (T-slots and dovetail slots), cutting of keyways, face milling, etc. Some of the sections which can be produced on a milling machine are shown in Fig. 2.53.

2.4.4 The Shaper

The shaping machine or shaper, is used for producing flat surfaces. The cutting tool is a single point tool, like a turning tool of lathe machine. The tool moves in a straight line. One straight line cutting motion of the tool is called a *stroke*. After each stroke, the work piece is advance in a direction perpendicular to the line of stroke. In this way a plane surface can be produced by a series of parallel cutting strokes. Figure 2.52 shows the motion of the tool relative to the work piece, and the motion of work piece.

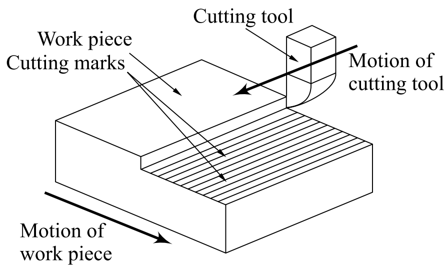


Fig. 2.52 *Cutting Operation on Shaper*

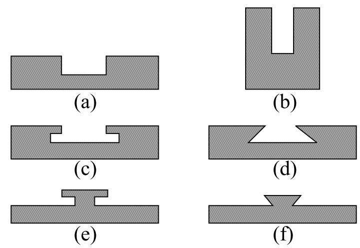


Fig. 2.53 *Sections Produced on Shaper*

2.4.4.1 Basic Operations on Shaper Machine

Various shapes can be produced on a shaper machine. Some of the common shapes are shown in Fig. 2.53. Figure (a) shows a slot in a plate, (b) shows a deep slot, (c) shows a T-slot, (d) shows a dovetail slot. T-slots and dovetail slots are used on tables of various machines to fasten the work piece, as described in previous sections. Figure (e) shows a projected T-section and (f) shows a projected dovetail. All these sections are used as guideways for tables, carriages and other heavy moving components on a machine.

REVIEW QUESTIONS

Answer the following questions:

1. What is the importance of measurement in engineering?
2. Temperature cannot be determined by direct comparison with basic standards. Discuss.
3. What are the important properties of thermometric fluid?
4. What are the probable sources of errors in a liquid-in-glass thermometer?
5. Describe the construction and working of a pressure thermometer.
6. What is a resistance thermometer? What are the requirements of material for a resistance thermometer?
7. What are the different types of thermocouples?
8. Describe the construction and working of an optical pyrometer.
9. Describe the construction and working of an inclined tube manometer.
10. Describe the construction and working of a Bourdon tube pressure gage.

11. Discuss the application of elastic diaphragms for measurement of pressure.
12. What are the different methods of measuring angular velocity?
13. What are obstruction type flow meters? Describe any one of them.
14. Compare venturi flow meter, nozzle, and orifice meter.
15. What is a rotameter? Explain its construction and working.
16. What are the advantages and limitations of a rotameter?
17. Explain the construction and working of a pitot tube.
18. What are strain gages? What are their applications?
19. What is gage factor of a strain gage?
20. What are the desirable properties of strain gage material?
21. What are semiconductor strain gages? What are their advantages?
22. What is a load cell?
23. Explain the construction and working of a prony brake dynamometer.
24. Explain the construction and working of a rope dynamometer.
25. What are the different types of errors encountered in measurement? Explain with suitable example.
26. What are random errors? Explain with suitable example.
27. Differentiate between accuracy and precision. Explain with suitable example.
28. What do you understand by uncertainty in measurement? Explain with suitable example.
29. How does uncertainty propagate in measurement? Explain with suitable example.
30. Describe the construction of a vernier caliper.
31. What is the principle of working of a vernier scale?
32. Describe the construction and working of a micrometer.
33. Describe the construction and working of a dial gage.
34. What are slip gages? What are their applications?
35. Explain measurement of angles using a sine bar.
36. What is a combination set? How is it useful on a shop floor?
37. What are the different types of machine tools? Why are they important?
38. Describe the construction and functions of the head stock of a lathe.
39. Describe the different parts of carriage of a lathe machine.
40. What are the different machining operations which can be performed on a lathe?
41. Draw a neat sketch of a drilling tool.
42. What are the major components of a drilling machine?
43. What are the different types of drilling machines?
44. Describe the different operations which can be performed on a drilling machine.
45. What are the basic components of a milling machine?
46. What types of components can be machined on a milling machine?

Fill in the blanks:

1. Clinical thermometer is an example of ________________type thermometers. (Liquid-in-glass)
2. In pressure thermometers, the volume of bulb should be _______ compared to volume of tube. (large)
3. For most metals, their electrical resistance __________ with increase in temperature. (increases)

4. Thermistors are made of ____________ semiconductors. (ceramic based)
5. When a junction of two dissimilar materials is made, the emf across the junction depends upon the junction's temperature. This effect is called _________. (Peltier effect)
6. The two basic types of pyrometers are ___________ and ____________. (total radiation pyrometer, optical pyrometer)
7. The difference between absolute pressure and atmospheric pressure is called _____ pressure. (gage)
8. The pressure indicated by a Bourdon tube pressure gage is _______ pressure. (gage)
9. Vacuum is the difference between atmospheric pressure and _______ pressure. (absolute)
10. The cross-section of the Bourdon tube is of ________ shape. (elliptical)
11. Magnetic pick up for measurement of shaft speed is a _________ type device. (non-contact)
12. A primary method of flow measurement is the use of _________. (volumetric tank)
13. Orifice meter is an _______________ type flow measurement device. (obstruction)
14. Among the different obstruction type flow measurement devices, the recovery of pressure is the maximum in case of __________. (venturi meter).
15. The cheapest obstruction type flow measurement device is _________. (orifice meter)
16. _________ is an example of variable area type flow measurement device. (Rotameter)
17. _________ is a commonly used device in the category of pressure probes. (Pitot tube)
18. The variation of flow velocity over the cross-section of a pipe is called ________. (velocity profile)
19. Electrical resistance strain gage is based on the principle of ________. (piezoresistivity)
20. Sensitivity of an electrical strain gage is given by its __________. (gage factor)
21. Devices used for measurement of torque in rotating shafts are called ________. (dynamometers)
22. The prony brake dynamometer is an ___________ type dynamometer. (absorption)
23. ________ errors are of consistent nature. (Systematic)
24. Zero error in a vernier falls under the category of __________ error. (systematic)
25. In case of ________ error, the magnitude and sign of measured quantity varies from one measurement to other. (random)
26. The method in which measurement is first taken in increasing direction, and then in the decreasing direction, is called __________. (method of symmetry)
27. ___________ is the difference between two indicated values given by the measurement system, for the same input. (Discrepancy)

28. The maximum amount by which the result of measurement differs from the true value is called ____________. (accuracy)
29. The way in which the measured data is scattered about the mean value is called _________. (dispersion)
30. The difference between any one result, and the mean of many results, is called ________. (deviation)
31. The range or region in which an error may occur is called __________. (uncertainty)
32. If the diameter of a shaft is given on the drawing as, 100 ± 0.5 mm, the mean diameter is _______ mm, and the tolerance is _______. (100, ± 0.5)
33. When the effect of two errors is additive, they are known as ___________ errors. (dependent)
34. The main scale of a vernier is marked in mm. Ten divisions of the vernier scale are equal to nine divisions on the mail scale. The least count of the vernier will be ______ mm. (0.1)
35. The pitch of the screw of a micrometer is 0.5 mm. The circular scale of the micrometer thimble is divided into 50 divisions. The least count of the micrometer will be ______ mm. (0.01)
36. Wringing gages is another name given to _________. (slip gages)
37. ________ are used for calibration of shop floor measuring instruments likeverniers and micrometers. (Slip gages)
38. A sine bar is used for measurement of _________. (angles)
39. The mitre edge of a combination set is at an angle of _______ with the rule. (45^{o})
40. _________ in the combination set is used for determining centres of rods and shafts. (Centre head)
41. ________ machine is the backbone of any workshop or tool room. (Lathe)
42. Chuck for holding work piece is mounted on _________ of the lathe machine. (spindle)
43. The frame of the machine tools is made of _________. (grey cast iron)
44. The dead centre in the lathe machine is housed in the _________. (tailstock)
45. The ________ slide of lathe machine is used for taper turning operation. (compound)
46. During threading operation, the power and motion is transferred to the carriage by the ______. (lead screw)
47. In _________ operation on a lathe, the motion of tool is synchronized with rotation of the work piece. (thread cutting)
48. A shaper machine can generate different types of ________ surfaces. (plane)

Chapter 3

Fluids

3.1 INTRODUCTION

Fluid mechanics is the study of physical behaviour of fluid and the laws governing this behaviour.

Hydrostatics The study of fluid at rest is called hydrostatics.

Kinematics The study of fluid in motion, without considering the pressure forces and energy causing motion is called fluid kinematics.

Dynamics Fluid dynamics is the study of fluid in motion, if the pressure forces and energy forces causing motion are considered.

3.2 PROPERTIES OF FLUID

Density It is defined as the mass of the fluid contained in a unit volume. Thus mass per unit volume is called density.

If, m is the mass in kg and v is the volume in m^3. Then, density

$$\rho = m/v \text{ kg/m}^3$$

If density is to be determined at a point in fluid, then consider a small element of volume δv at that point and let δm be the mass of the fluid contained within that elemental volume then

$$\rho = \lim_{\delta v \to 0} \frac{\delta m}{\delta v} \text{ kg/m}^3$$

Specific Weight It is defined as the weight of the fluid contained within a unit volume. Thus, weight per unit volume is called specific weight.

$$w = m.g/v = \rho\, g \text{ N/m}^3$$

Pressure It is defined as the force per unit area and is given as

$$p = F/A$$

where F is the force acting normal to the surface area A.

If the pressure is to be determined at a point in a fluid, then consider a small area dA in fluid and the force dF exerting on the area dA acting perpendicular to the surface. Then,

$$p = \lim_{\delta A \to 0} \frac{dF}{dA} \text{ N/m}^2 \text{ or Pascal, represented as Pa}$$

Another common unit of pressure is bar

$$1 \text{ bar} = 10^5 \text{ N/m}^2 = 10^5 \text{ Pa}$$

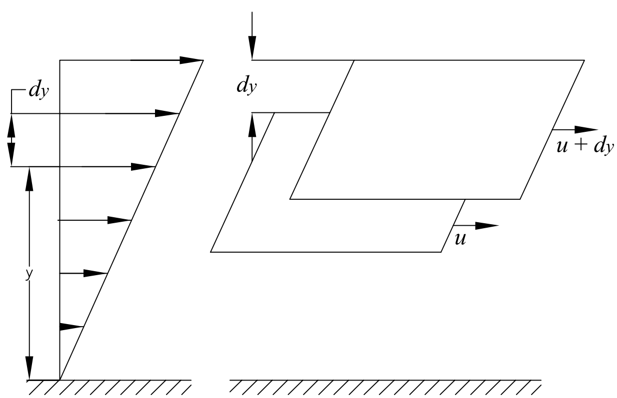
Specific Gravity It is defined as the ratio of the density of a substance to the density of water at 4^0C. It is a dimensionless quantity.

Viscosity It is defined as a property of a fluid which offers resistance to shear or angular deformation of one layer of the fluid over the another adjacent layer of the fluid.

Consider the two adjacent layers of the fluid flowing at a velocity u and $u + du$ respectively, moving one over the other steadily over a horizontal surface separated by a small distance dy (Fig. 3.1). The upper layer of fluid moving with the velocity $u + du$ tries to drag the lower layer along with it with a force F, while the lower layer moving with the velocity u tries to retard the motion of the upper layer by exerting a force equal and opposite to F. Thus these equal and opposite forces cause shear stress τ. This shear stress is proportional to the rate of change of velocity with respect to y in the normal direction or velocity gradient.

$$\tau \,\alpha\, du/dy$$

$$\tau = \mu\, du/dy \tag{3.1}$$



(a) Velocity profie (b) Two adjacent layers of fluid flow

Fig. 3.1

The above relationship is called *Newton's Law of Viscosity* where, μ is the constant of proportionality and is called the coefficient of dynamic viscosity or only viscosity.

Units of viscosity

$$\tau = \mu\, du/dy$$

$$\mu = \tau/(du/dy) = \text{shear stress/velocity gradient} = \frac{\text{N/m}^2}{(\text{m/s})(1/\text{m})}$$

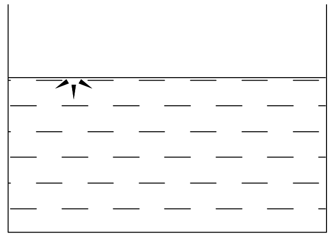
$$= \text{N–s/m}^2 = \text{Pa. s}$$

$$1 \text{ Ns/m}^2 = 10 \text{ poise}$$

Kinematic Viscocity It is defined as the ratio of dynamic viscosity of the fluid to the density of the fluid. It is denoted by v. Thus

$$v = \mu/\rho \text{ m}^2/\text{s}$$

Surface Tension Consider a liquid molecule A beneath the free surface of a liquid as shown in Fig. 3.2. The molecule A is acted upon by molecular forces of attraction by the other molecules surrounding it. All these forces being equal in all directions cancel out and there is no resultant force acting on it. Whereas a liquid molecule B on the surface have no molecules above it to counteract the molecular forces of attraction caused by the molecules below it. Hence, the molecules lying at the surface have net force of attraction tending to pull in the downward direction. Thus some work is expended to bring the molecule to the free liquid surface which then acts like an elastic or stretched membrane. This work done is called the surface energy.This work will give rise to force which has to be tensile on the surface. This tensile force acting on the surface has a tendency to contract or shrink the surface to have minimum surface area.



Thus, *surface tension* is the property of fluid by virtue of which the free surface of fluid at rest behaves like a stretched membrane tending to contract, to have a minimum surface area. The force of surface tension is the force acting perpendicular to a line and tangential to the liquid surface per unit length. It is denoted by σ (sigma). If F is the force acting on line of length l. Then

$$\sigma = F/l \text{ N/m} \tag{3.2}$$

3.3 TYPES OF FLUIDS

Fluids are classified as under:

1. Ideal fluid
2. Newtonian fluid
3. Non-Newtonian fluid
4. Real fluid
5. Ideal plastics

Ideal Fluid A fluid which is non-viscous in nature is known as an ideal fluid. It is an imaginary fluid. $\tau = 0$. It is shown by line ‘f ’ (Fig. 3.3) on shear stress–velocity gradient graph.

Newtonian Fluid A fluid in which shear stress is proportional to the velocity gradient is known as Newtonian fluid. Fluid, represented by curve a_1 and a_2 are Newtonian fluids, fluid represented by curve a_1 is more viscous than the fluid represented by curve a_2. (Fig. 3.3).

Example 2 Two plates are placed at a distance of 0.15 mm apart. The lower plate is fixed while the upper plate having a surface area of 1.0 m^2 is pulled with a speed of 0.3 m/s. Find the force and power required if the fluid placed between the two plates is having dynamic viscosity of 1.5 poise.

Solution

Viscosity μ = 1.5 poise = 0.15 N/m^2
Area of plate A = 1.0 m^2
Distance between the plates dy = 0.15 mm.= 0.15×10^{-3} m
Relative velocity of the upper plate w.r.t. lower plate du = 0.3 m/s.

Using the relation (3.1)

$$\tau = \mu\, du/dy$$
$$\tau = 0.15 \times 0.3/(0.15 \times 10^{-3})$$
$$= 300 \text{ N/m}^2$$

Force required to pull the plate = Shear stress × area of the plate

$$F = \tau \times A$$
$$= 300 \times 1.0 = 300 \text{ N}$$

Power = Force × distance moved in one second
= 300×0.3 = 90 J/s = 90 watts **Ans.** F= 300 N, P = 90 W

Example 3 The velocity distribution for a flow over a flat plate is given by the relation $u = (3/2)\, y - y^{3/2}$, where u is the velocity in m/s at a distance y meters above the plate. Calculate the shear stress at a distance of 9 cm. above the plate, assuming the dynamic viscosity of fluid 8 poise.

Solution

y = 9 cm. = 0.09 m.
Dynamic viscosity μ = 8 poise = 0.8 N/m^2
$u = (3/2)\, y - y^{3/2}$

Differentiating the above given equation with respect to y

$$du/dy = 3/2 - (3/2)y^{1/2}$$

using the relation
Shear stress $\tau = \mu\,(du/dy)$
τ at a distance y m above the plate = $0.8 \times ((3/2 - (3/2)\, y^{1/2})$
τ at a distance 0.09 m. above the plate = $0.8 \times ((3/2 - (3/2)0.09^{1/2})$
= 0.84 N/m^2 **Ans.** τ = 0.84 N/m^2

Example 4 A square plate of side 1.0 m weighing 390 N is sliding down an inclined plane with a uniform speed of 1.5 m/s. The gradient of the inclined plane is 5/12 (5 units vertical to 12 horizontal units). An oil film of 1.0 mm thickness is kept between the plate and an inclined plane. Determine the dynamic viscosity of oil.

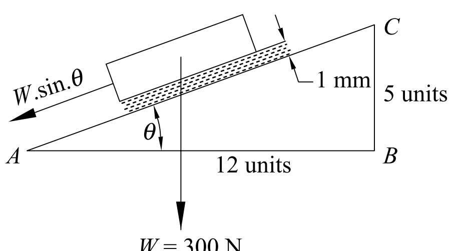


Fig. 3.4

Solution

Area of the plate A = 1.0 m^2
Speed of the plate moving down an inclined plane u = 1.5 m/s

As the inclined plane is stationary $du = 1.5$ m/s
Distance between the plate and an inclined plane $dy = 1.0$ mm = 0.001 m.
Weight of the plate $W = 390$ N
Component of the weight acting along an inclined plane in downward direction

$$F = W \sin\theta$$

$$AC = \sqrt{(AB)^2 + (BC)^2}$$

$$AC = \sqrt{12^2 + 5^2} = 13$$

$$F = 390 \times 5/13 = 150 \text{ N} \qquad [\because \text{Sin } \theta = BC/AC]$$

Shear stress $\tau = F/A$
$= 150\ \text{N/m}^2$

Shear stress $\tau = \mu\,(du/dy)$

$$\mu = \tau\,(dy/du)$$

$$\mu = 150\ (0.001/1.5) = 0.1\ \text{Ns/m}^2 = 1.0 \text{ poise.}$$

Ans. $\mu = 0.1$ Ns/m²

Example 5 Calculate the velocity of a central plate of area 5 m², if the force of 200 N is applied to it as shown in the Fig. 3.5. Take the viscosity of oil A as 0.1 Ns/m² and that of oil B as 0.4 Ns/m² respectively.

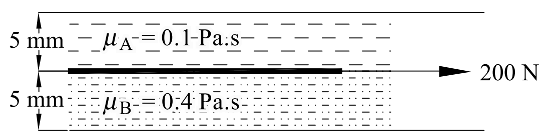


Fig. 3.5

Solution

Viscosity of oil A $\mu_A = 0.1$ Ns/m²
Viscosity of oil B $\mu_B = 0.4$ Ns/m²
Area of the plate $A_p = 5$ m²
Force $F = 200$ N, $dy = 0.005$ m

Using the relation

$$\tau = \mu\,(du/dy) \text{ and force} = \tau A_p$$

Let $du = U$ m/s;

$$F = F1 + F2$$

$$F = A_p\,[\mu_A(du/dy) + \mu_B(du/dy)]$$

$$200 = 5\,[\,0.1 \times (U/0.005) + 0.4 \times (U/.005)]$$

$$U = 0.4 \text{ m/s}$$

Ans. U = 0.4 m/s

3.4 PASCAL LAW

It states that the intensity of pressure at any point in a static fluid in all direction is equal.

Consider a wedge shape element of size dx, dy, ds respectively in a fluid at rest as shown in Fig. 3.6. Let p_x, p_y and p_θ be the pressure acting normal to the surfaces OACD, OABE, BEDC respectively. The element is also acted on by gravitational body force acting vertically in the downward direction.

If width dz of the wedge element perpendicular to paper is equal to unity, i.e., $dz = 1$

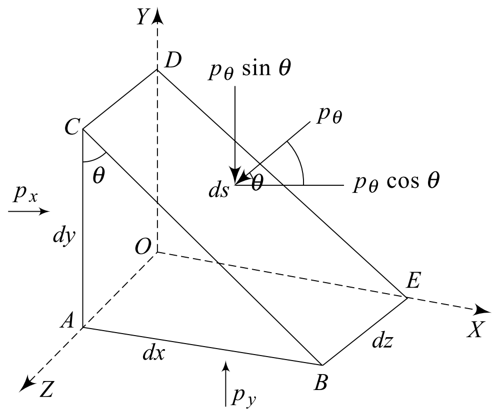


Fig. 3.6 *Forces on a Wedge Shape Element*

Then,

force acting on the face OACD = $p_x (dy.\ 1)$

force acting on the face OABE = $p_y\ (dx.\ 1)$

force acting on the face BEDC = $p_\theta\ (ds.\ 1)$

The weight of the fluid element = (Volume of an element) (density of fluid).(acceleration due to gravity)

$= dv.\ \rho.g$

$= 1/2\ (\text{AB.AC}).1.\rho.g$

As the fluid element is in equilibrium, the sum of forces in horizontal direction and in vertical direction must be zero.

Resolving the forces in X-direction

$$p_x dy.1 - p_\theta.ds.1.\cos\theta = 0$$

$$p_x dy.1 - p_\theta.dy.1 = 0 \qquad [\because ds \cos\theta = dy]$$

hence,

$$p_x = p_\theta \tag{3.3}$$

Resolving the forces in Y-direction

$$p_y\, dx.1 - p_\theta.ds.\sin\theta.1 - 1/2.(dx.dy.1)\ \rho\ g = 0$$

Let the size of the element approach smaller, then the gravitational force which is the product of *dx* and *dy* can be neglected.

$$p_y\, dx.1 - p_\theta.ds.\sin\theta.1 = 0$$

$$p_y\, dx.1 - p.\ dx.1 = 0 \qquad [\because ds \sin\theta = dx]$$

$$p_y = p_\theta \tag{3.4}$$

From Eqs (3.3) and (3.4)

$$p_x = p_y = p_\theta \tag{3.5}$$

The above relation shows that the pressure at any point x, y, z in a static fluid is independent of θ, it follows that the pressure in all the directions in a static fluid is same.

3.5 PRESSURE VARIATION IN A STATIC FLUID

Consider an imaginary infinitesimal cylindrical element in a fluid at rest at a distance y from the top surface of the fluid as shown in Fig. 3.7.

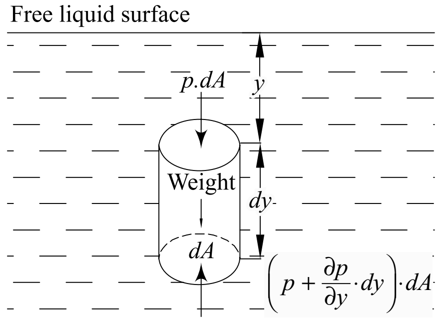


Fig. 3.7 *Forces on Cylindrical Fluid Element*

Let dA be the cross-sectional area, dy the height of the cylindrical element in the fluid.

The pressure forces acting on the cylindrical element are:

1. pressure force on the top surface of the cylindrical element
   $p \times dA$ acting in vertically downward direction.
2. pressure force at the bottom surface of the cylindrical element
   $(p + (\partial p/\partial y)\ dy) \times dA$ acting in vertically upward direction.
3. weight of the fluid element acting in the downward direction,
   $$dA \times dy \times \rho \times g,$$
   where ρ is the density of the fluid and g is the acceleration due to gravity.
4. Summation of pressure forces on the curved surface of the cylindrical fluid element is equal to zero.

As the fluid element is in equilibrium, the sum of downward forces must be equal to the sum of upward forces acting on it. Therefore,

$$p \times dA - (p + (\partial p/\partial y)\ dy) \times dA + dA \times dy \times \rho \times g = 0$$

$$-\partial p/\partial y + \rho \times g = 0$$

$$\partial p/\partial y = \rho \times g = w \text{ (specific weight of the fluid)} \tag{3.6}$$

since, the pressure is varying in only one direction, partial derivation can be replaced by an exact differential. Hence Eq. (3.6) reduces to.

$$\partial p/\partial y = dp/dy = \rho \times g = w$$

By integrating the above equation

$$\int dp = \int \rho \times g\ dy$$

$$p = \rho \times g \times y$$

where, p is the pressure intensity at a point, y distance from the free surface of the fluid. Thus, the pressure will be constant everywhere over the same level of surface in a continuous body of a static fluid. It also indicates that in a static fluid, pressure increases as the depth increases.

3.6 RELATIONSHIP BETWEEN ATMOSPHERIC, ABSOLUTE, GAUGE, AND VACUUME PRESSURE

The pressure measured above the absolute zero or zero vacuum is called absolute pressure. The pressure measured above the atmospheric pressure is called the gauge pressure Figure 3.8. Mathematically,

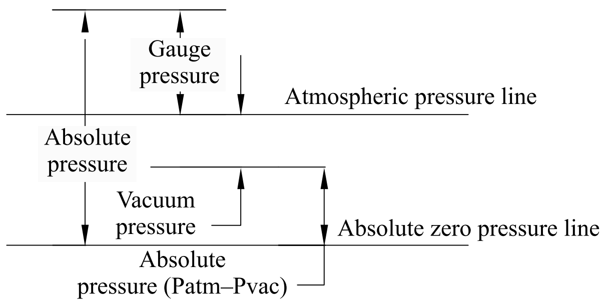


Fig. 3.8 *Relationship between Pressure*

Absolute pressure = gauge pressure + atmospheric pressure

$$P_{abs} = P_{gauge} + P_{atmos}$$

For pressure below atmospheric pressure

Vacuum pressure = Atmospheric pressure – Absolute pressure.

or $$P_{abs} = P_{atmos} - P_{vac}$$

3.7 MANOMETERS

A manometer is a device used to determine the pressure in a fluid by balancing it against the liquid column. Manometers are classified as under

1. Piezometer
2. U tube manometer
3. U tube differential manometer
4. Inverted U tube differential manometer
5. Single column manometer

3.7.1 Piezometer

Piezometer is the simplest of all types of manometers. It measures positive gauge pressure only. It consists of a vertical transparent tube. It is necessary that the diameter of the tube should be large enough to reduce the capillary effect. One end of the tube is connected to the point normal to the boundary where pressure is to be measured, while the other end is opened to free atmosphere Fig. 3.9. The liquid rises to a level in a vertical tube to a height equivalent to the pressure head at the point of connection. If p is the pressure of the fluid flow in a pipe and h is the height of the fluid level in manometer from the centre of pipe, then

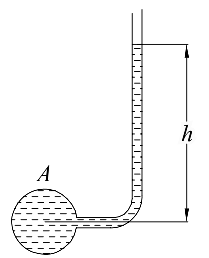


Fig. 3.9 *Piezometer*

$p = \rho g h$ where ρ is the density of the fluid flowing through the pipe

3.7.2 U tube Manometer

It is made up of a transparent U-tube filled with liquid of higher specific gravity as compared to the fluid whose pressure is to be measured. For high pressure range, mercury is preferred in the U-tube, whereas for moderate pressure carbon tetrachloride (specific gravity 1.59) or acetylene tetra-bromide (specific gravity 2.59) can be used as manometer fluid. One end of U-tube is connected to a point normal to the surface where pressure is to be measured, while the other end of the U-tube is opened to the

atmosphere. It can be used for measuring positive pressure or vacuum pressure. The reading of the mercury level in both the cases is as shown in the Fig. 3.10(a) and 10(b) respectively. If p_1 is the pressure of fluid, ρ_1 be the density of fluid flowing through the pipe, h_1 is the difference between centre of the pipe and the level of the manometer fluid in the limb connected to it. Then, pressure at section X-X
For positive pressure Fig. 3.10(a)

$$p_1 + \rho_1 g h_1 = p_{\text{atm}} + \rho_{\text{m}} g h_{\text{m}}$$

For vacuum pressure Fig. 3.10(b)

$$p_1 + \rho_1 g h_1 = p_{\text{atm}} + \rho_{\text{m}} g h_{\text{m}}$$

in the above equations, p_1 is absolute pressure, and if p_{atm} is considered as zero, then p_1 will be gauge pressure.

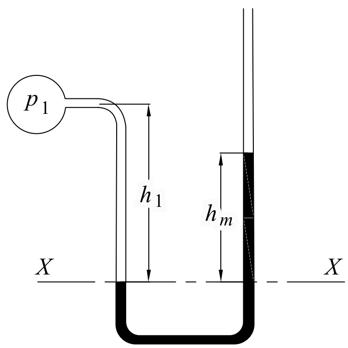


Fig. 3.10 *U-Tube Manometer*

3.7.3 U-tube Differential Manometer

A U-tube differential manometer is also made up of transparent material and is used for measuring the pressure difference between two points in a pipe line or in two different pipes or reservoirs. When the pressure of the fluid at points A and B in the pipe is greater than atmospheric pressure, U-tube is filled with manometric liquid of higher specific gravity compared to the fluid whose pressure difference is to be measured. The pressure difference of the fluid at points A and B flowing through two different pipes kept at same level or different level can be measured as shown in Figs 3.11(a) and (b).

For two pipes at the same level
Figure 11(a) shows a differential manometer, which connects the two pipes at same level where the pressure difference is to be measured. Balancing the pressure at section X-X, we get,

$$\rho_1 g h_1 + p_1 = p_2 + \rho_2 g h_2 + \rho_{\text{m}} g h_{\text{m}}$$

$$p_1 - p_2 = \rho_2 g h_2 + \rho_{\text{m}} g h_{\text{m}} - \rho_1 g h_1 \tag{3.7}$$

For two pipes at the different level
Figure 3.11(b) shows a differential manometer, which connects the two different pipes

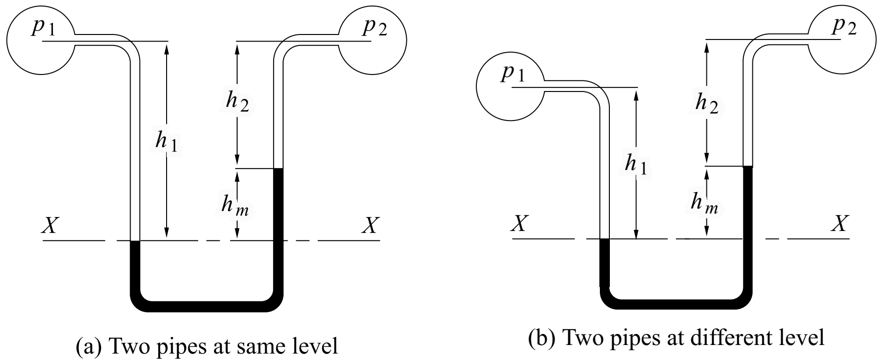


Fig. 3.11

at two different level where the pressure difference is to be measured. Balancing the pressure at section X-X, we get,

$$\rho_1 g\, h_1 + p_1 = p_2 + \rho_2 g\, h_2 + \rho_m g\, h_m$$

$$p_1 - p_2 = \rho_2 g\, h_2 + \rho_m g\, h_m - \rho_1 g\, h_1 \qquad (3.8)$$

The sensitivity of differential manometer depends on the difference of the densities of manometeric fluid and the fluid flowing through the pipes.

3.7.4 Inverted U- tube Differential Manometer

An inverted U-tube differential manometer is also made up of transparent material and is used for measuring the pressure difference between two points in a pipe or two different pipes, when the pressure at point in the pipe A and pipe B is less than the atmosphere. An inverted U-tube manometer is filled with manometric liquid of lower specific gravity as compared to the fluid whose pressure difference is to be measured. The pressure difference of the fluid flowing through two different pipes kept at different level can be measured as shown in Fig. 3.12.

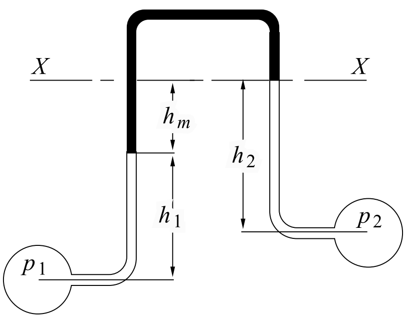


Fig. 3.12

Figure 3.12 shows an inverted U-tube differential manometer, which connects the two pipes at different level where the pressure difference is to be measured. Balancing the pressure at section X-X, we get,

$$p_1 - \rho_1 g\, h_1 - \rho_m g\, h_m = p_2 - \rho_2 g\, h_2$$

$$p_1 - p_2 = \rho_m g\, h_m + \rho_1 g\, h_1 - \rho_2 g\, h_2 \qquad (3.9)$$

3.7.5 Single Column Vertical Tube Manometer

For measuring small pressure generally single column vertical manometer is used. It consists of a large vessel of cross-section area roughly 100 times as compared to the cross-section area of the other limb B. It is connected to a vertical transparent tube of narrow cross section as shown in the Fig. 3.13. The vessel of bigger cross-section area

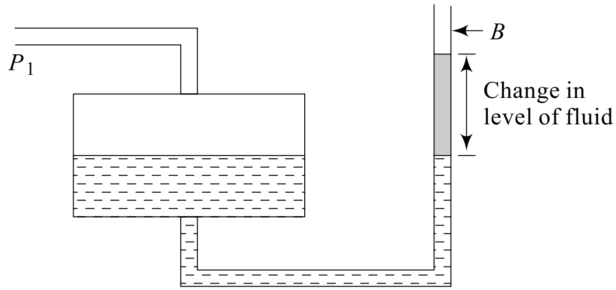


Fig. 3.13 *Single Column vertical Manometer*

is connected at a point where pressure is to be measured. A change of level of manometric liquid in the bigger vessel due to pressure change would be so small that it can be neglected. Pressure would then be indicated only by the height of the liquid column in the limb B as shown in Fig. 3.13.

Example 6 Determine the gauge and the absolute pressure at a point 2.5 m below the free surface of the fluid having density of 1600 kg/m³. Atmospheric pressure is 750 mm of mercury. Take specific gravity of mercury as 13.6 and density of water as 1000 kg/m³.

Solution Density of water $\rho = 1000$ kg/m³

Distance below the free surface of fluid $y = 2.5$ m.

Density of fluid $\rho_1 = 1600$ kg/m³

Sp. gr. of mercury = 13.6

Density of mercury $\rho_2 = 13.6 \times 1000$ kg/m³

Atmospheric pressure = 750 mm of Hg = 0.75 m of Hg.

$$= \rho_2\, g\, h \text{ N/m}^2$$

where ρ is the density of mercury, h is the atmospheric pressure in mercury column.

$$p_{atm} = (13.6 \times 1000) \times 9.81 \times 0.75 \text{ N/m}^2 = 100062 \text{ N/m}^2$$

Pressure at a point 2.5 m below the free surface of the fluid = $\rho_1\, g\, y$

$$p_{gauge} = 1600 \times 9.81 \times 2.5 = 39240 \text{ N/m}^2$$

$$p_{abs} = p_{atm} + p_{gauge}$$

$$p_{abs} = 100062 + 39240 = 139302 \text{ N/m}^2$$

Ans $p_{gauge} = 39240$; $p_{abs} = 139302$ Pa.

Example 7 The pressure intensity at a point in a given fluid is 49050 N/m². Find the corresponding height in the fluid, when the fluid is a) water b) oil of specific gravity 0.9.

Solution pressure intensity $p = 49050$ N/m²

$$p = \rho\, g\, h \text{ where,}$$

ρ is the density of fluid, h is the corresponding height and P is the pressure intensity.

For water $\rho = 1000$ kg m³

Substituting the values in the above equation

$$49050 = 1000 \times 9.81 \times h$$

$$h = 5.0 \text{ m.}$$

For oil of sp. gr. 0.9

Density of oil ρ_o = Sp. gr. of oil × Density of water

$= 0.9 \times 1000 = 900\ \text{kg/m}^3$

$$p = \rho_o g\, h_o$$

$$49050 = 900 \times 9.81 \times h_o$$

$$h_o = 5.55\ \text{m.}$$

Ans. $h = 5$ m; $h_o = 5.55$ m

Example 8 One end of a U-tube manometer containing mercury is open to atmosphere, while the other end of the tube is connected to a pipe in which a fluid of specific gravity 0.85 is flowing. The difference between centre of a pipe and the surface of mercury level in the other limb is 15 cm as shown in Fig. 3.14. Find the gauge pressure of the fluid flowing in the pipe if the difference in the mercury level of the two limbs is 20 cm.

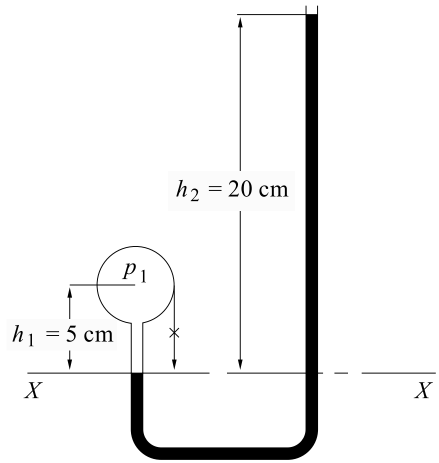


Fig. 3.14

Solution

Sp. gr of the fluid = 0.85

Density of the fluid $\rho_1 = 850\ \text{kg/m}^3$

Density of mercury $\rho_2 = 13600\ \text{kg/m}^3$

Difference between the mercury level = 0.2 m

Height of the fluid above the mercury level in the left limb $h_1 = 0.05$ m

Let the pressure of the fluid flowing in the pipe = p_1

Equating the pressure at section X-X

$$p_1 + \rho_1\, g\, h_1 = \rho_2\, g\, h_2$$

Substituting the values

$$p_1 = g(\rho_2\, h_2 - \rho_1\, h_1)$$

$$p_1 = 9.8(13600 \times 0.2 - 850 \times 0.05)$$

$$p_1 = 26239.5\ \text{N/m}^2$$

Ans $p_1 = 26239.5$ Pa gauge

Example 9 One end of a U-tube manometer containing mercury is open to atmosphere, while the other end of the tube is connected to a pipe in which a fluid of specific gravity 0.85, and having vacuum is flowing. Find the vacuum pressure of the fluid flowing in the pipe if the difference in the mercury level of the two limbs is 20 cm and the height of the mercury column in the left limb is 10 cm below the centre of pipe.

Solution See Fig. 3.15

Density of the fluid $\rho_1 = 850\ \text{kg/m}^3$

Density of mercury $\rho_2 = 13600\ \text{kg/m}^3$

Difference between the mercury level = 0.2 m

Height of the fluid mercury level below the centre of pipe in the left limb $h_1 = 0.1$ m

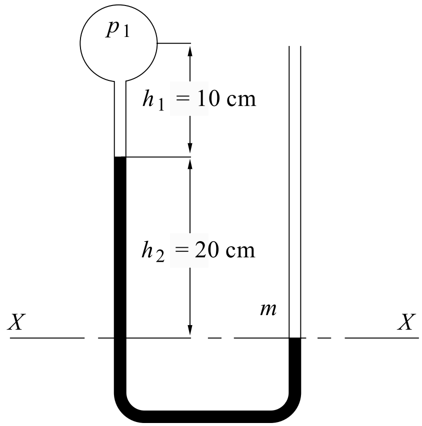


Fig. 3.15

Let the pressure of the fluid = p_1
Equating the pressure at section X-X

$$p_1 + \rho_1 g h_1 + \rho_2 g h_2 = 0$$
$$p_1 = -g(\rho_1 h_1 + \rho_2 h_2)$$
$$p_1 = -9.8(850 \times 0.1 + 13600 \times 0.2)$$
$$p_1 = -27489 \text{ N/m}^2$$

Ans. $p_1 = -27489$ Pa.

Example 10 Figure 3.16 shows a conical vessel having its outlet A to which U-tube manometer is connected. The reading of the manometer is indicated in the figure, when the conical vessel is empty, i.e., the water surface is at level A. Find the reading of the manometer when the conical vessel is completely filled with water.

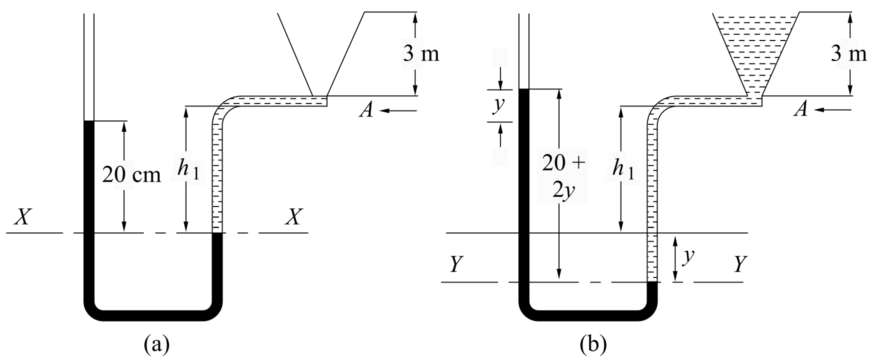


Fig. 3.16

Solution

Density of the fluid $\rho_1 = 1000$ kg/m^3
Density of mercury $\rho_2 = 13600$ kg/m^3
Difference between the mercury level $h_2 = 0.2$ m

Let height of the mercury level below the point A be h_1 m.
Equating the pressure at section X-X

$$\rho_1 g h_1 = \rho_2 g h_2$$
$$\rho_1 h_1 = \rho_2 h_2$$
$$h_1 = \rho_2 h_2/\rho_1$$

substituting the values

$$h_1 = 13600 \times 0.2/1000$$
$$h_1 = 2.72 \text{ m}$$

When the vessel is full of water, the pressure in the right limb will increase Fig. 3.16(b). Let the mercury level further go down by distance of y m. in the right limb, then the difference between the mercury level of two limbs will increase by further 2 y distance.
Equating the pressure at section Y-Y
Pressure in the left limb = pressure in the right limb

$$\rho_2 g (0.2 + 2y) = \rho_1 g (h_1 + 3 + y)$$

Substituting the values in the above equation

$$13600 (0.2 + 2y) = 1000 (2.72 + 3 + y)$$
$$y = 0.1145 \text{ m} = 11.45 \text{ cm}$$

Manometer reading = 20 + 11.45 × 2 = 42.9 cm

Ans. manometer reading after filling the conical vessel = 42.9 cm

3.8 ENERGIES POSSESSED BY FLUID

Fluid may possess the following three forms of energies: 1. Pressure energy 2. Kinetic energy 3. Potential energy

Pressure Energy It is the energy required to move the liquid mass across the control surface at the entry and exit cross section without imparting velocity to it.

Consider, one dimensional, incompressible fluid flow system in a control volume as shown in Fig. 3.17. At the entry, assume the pressure intensity p, velocity V and density of the fluid ρ to be uniform at the cross-section area A. During the small time dt this section move by a small distance ds such that the variation in the fluid properties can be neglected. Work done during the displacement of this fluid, i.e.

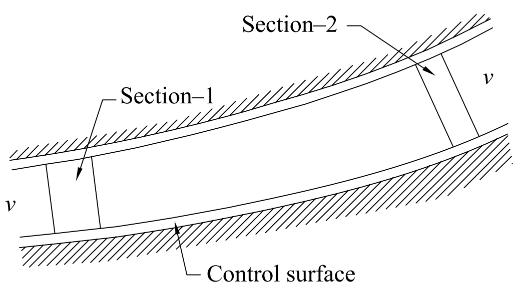


Fig. 3.17 *Flow Chart*

$$\text{Flow work} = p\,A\,ds$$
$$= p\,A\,V\,dt \qquad [\because ds = V\,dt]$$
$$\text{mass of the fluid} = A.ds.\rho \qquad (3.10)$$

Flow work per unit mass = p/ρ

Kinetic Energy Kinetic energy of the fluid is possessed by virtue of its motion. Consider a fluid of mass m having an acceleration dV/dt at that point
From second law of motion
Force = mass × acceleration

$$dF = m\, dV/dt$$

$$dW = dF.\, ds = m.\, ds.dV/dt = m\, V\, dV \qquad \left[\because V = \frac{ds}{dt}\right]$$

$$dW = mVdV$$

Integrating the above equation

$$W = m \int V\, dV$$

$$W = m\, [V^2/2] \tag{3.11}$$

The above relation indicates the work require to accelerate the fluid of mass m from rest to velocity V.

$$\text{Kinetic energy} = m\, [V^2/2]$$

Kinetic energy per unit mass = $[V^2/2]$ Joule

Potential Energy Potential energy is the energy possessed by the fluid by virtue of its position with reference to some arbitrary datum or reference plane. It represents the work required to move it against the gravitational force from the reference position.

$$\text{P.E.} = mgh \tag{3.12}$$

Or potential energy per unit mass = $g\, h$ Joule
where h is the height in metre above the reference level.

3.9 BERNOULLI'S EQUATION

In a streamline, steady flow of an ideal and incompressible fluid the sum of the pressure energy, kinetic energy and potential energy at any point in the fluid flow is constant.

(*Streamline is defined as an imaginary line drawn in a flow field such that tangent to it at any point gives the direction of velocity vector at that point, at an instant.*

Mathematically it can be expressed as $\dfrac{p}{\rho} + \dfrac{V^2}{2} + zg$ = constant.

or $\qquad p/\rho g + V^2/2g + z$ = constant

where $p/\rho g$ is pressure head
$V^2/2g$ velocity head
z is potential head
ρ density of fluid Kg/m^3
p pressure intensity at a point in the fluid N/m^2
V velocity of the fluid particle at that point m/s

Consider a cylindrical element along a streamline in a fluid flow as shown in the Fig. 3.18.

Let the area of cross section of the cylindrical element be dA; length of the cylindrical element be dS; let θ be the angle between the direction of the flow of fluid and the line of action of gravitational force on the element. Then,

1. the pressure forces along the direction of the flow = $p\, dA$
2. the pressure force opposite to the direction of the flow = $(p + (\partial p/\partial s)\, ds)\, dA$

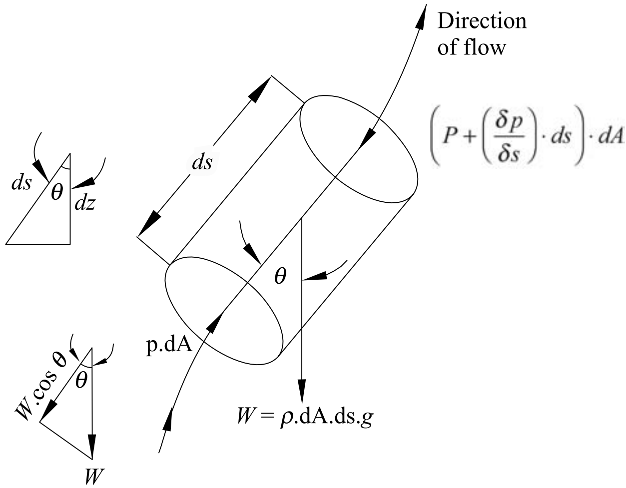


Fig. 3.18 *Forces on a Fluid Element*

3. Gravitational force on the cylindrical element = $\rho\, dA\, ds\, g$
4. Component of the gravitational force opposite to the direction of flow

$$= \rho\, dA\, ds\, g \cos\theta$$

The resultant force on the fluid element should be equal to the product of mass and the acceleration of the fluid element in the direction of the flow.

Net force in the direction of flow = (mass of the fluid element) × (acceleration of the fluid element in the direction of flow)

Hence,

$$p\, dA - (p + (\partial p/\partial s)\, ds)\, dA - \rho\, dA\, ds\, g \cos\theta = \rho\, dA\, ds.\, (dV/dt) \qquad (3.13)$$

V is a function of (s, t)

$$a_s = dV/dt = (\partial V/\partial s)\,(ds/dt) + (\partial V/\partial t)\,(dt/dt)$$

$$= (\partial V/\partial s)\,(ds/dt) + (\partial V/\partial t) \qquad [\text{for steady flow } (\partial V/\partial t) = 0]$$

$$dV/dt = (\partial V/\partial s)\, V \qquad [(ds/dt) = V]$$

or $$dV/dt = V.\, dV/ds \qquad (3.14)$$

Substituting the value of Eq. (3.14) in (3.13) and simplifying

$$-((\partial p/\partial s)\, ds)dA - \rho\, dA\, ds\, g \cos\theta = \rho\, dA\, ds.\; V.\; dV/ds$$

or $$-dp - \rho\, ds.\, \cos\theta.g - \rho\, V\, dV = 0$$

or $$dp + \rho\, dz.g + \rho\, V\, dV = 0 \qquad [\because \cos\theta = dz/ds] \qquad (3.15)$$

Integrating the above relation

$$\int dp + \int \rho g\, dz + \int \rho\, V\, dV = \text{constant}$$

$$p + \rho\, g\, z + V^2/2 = \text{constant}$$

Dividing the above relation by $\rho\, g$

$$p/(\rho\, g) + z + V^2/2\, g = \text{constant.} \qquad (3.16)$$

The following assumptions are made in deriving the Bernoulli's equation

1. The fluid flow is steady.

2. The fluid is ideal (non-viscous).
3. The fluid flow is incompressible.
4. The fluid flow is irrotational.
5. Velocity of the fluid particle across any cross section of the tube is constant.

[However, the fluid particles have maximum velocity along the axis and practically zero velocity along the wall of a pipe.]

In Eq. (3.16), the first term $p/(\rho\, g)$ is also called the pressure head;

z is called potential head;

$V^2/2\, g$ is called kinetic or velocity head.

The sum of pressure head and potential head is usually called *piezometric head*.

1. If there are losses due to change in the shape, a term h_L is to be added to the right side of the equation, where h is the energy loss per unit weight.

$$p_1/(\rho\, g) + z_1 + V_1^2/2\, g = p_2/(\rho\, g) + z_2 + V_2^2/2\, g + h_L \tag{3.17}$$

2. If E is the mechanical energy added or taken out per unit weight then

$$p_1/(\rho\, g) + z_1 + V_1^2/2\, g = p_2/(\rho\, g) + z_2 + V_2^2/2\, g \pm E \tag{3.18}$$

positive sign is used for turbines whereas negative sign is used for pumps.

If power is to be calculated

$$P = \rho\, g\, Q\, E/1000 \text{ kW} \tag{3.19}$$

Q is the quantity of fluid flowing per second in m^3/s

3.9.1 Applications of Bernoulli's Equation

1. Flow meters (a) Venturi meter (b) Orifice meter
2. Flow over an aero foil section

1. Flow meters

(a) Venturi meter It is a device used for measuring the amount of fluid flowing through a pipe in a steady flow. It consists of a converging section, a throat and a diverging section. The converging angle is normally 21° ± 2° and diverging angle is between 5 – 7° to accomplish maximum kinetic energy recovery. As the fluid flows through the throat, the velocity increases (continuity equation) and pressure decreases (Bernoulli's equation). The pressure difference between the inlet and the throat is measured with the help of a manometer as shown in the Fig. 3.19.

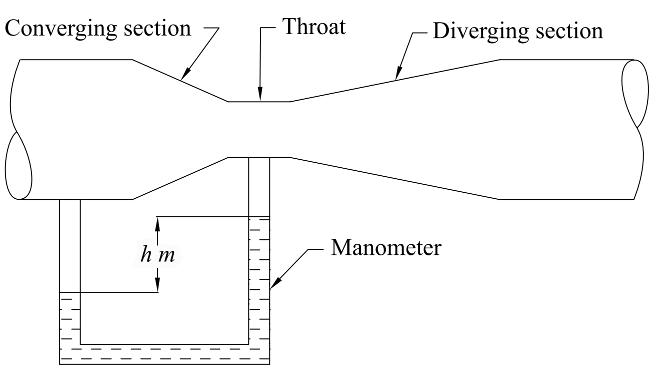


Fig. 3.19 *Venturi Meter*

If a_1 and a_2 are the areas of pipe and throat respectively in m^2
h is the pressure difference at the inlet and the throat in m
Then,

$$Q \text{ (discharge)} = [a_1.a_2/(\sqrt{a_1^2 - a_2^2}\,)]\ \sqrt{2gh}\ \ \text{m}^3/\text{s} \qquad (3.20)$$

where, $h = h_m\ [(S_m/S_p) - 1]$

(S_m and S_p are the specific gravity of fluid in the manometer and the fluid flowing through the pipe)

(b) Orifice Meter It is also used for measuring the flow of fluid through a pipe in a steady flow. It consists of a circular disc with a circular hole. The diameter of an orifice is usually kept between 0.4 – 0.8 of the pipe diameter. Some of the advantages of an orifice flow meter are its low cost, ease of installation and less space requirement.

If a_1 inlet area of pipe in m^2
a_o area of an orifice plate in m^2
h pressure difference across an orifice in m, as shown in Fig. 3.20

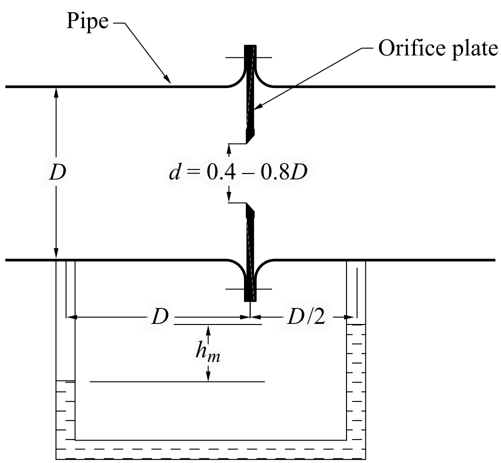


Fig. 3.20 *Orifice Meter*

Then,

$$Q = [a_1.a_o/(\sqrt{a_1^2 - a_0^2}\,)]\ \sqrt{2gh}\ \text{m}^3/\text{s} \qquad (3.21)$$

where, $h = h_m\ [(S_m/S_p) - 1]$

(S_m and S_p are the specific gravity of fluid in the manometer and the fluid flowing through the pipe)

2. Flow over an Aero Foil Section

When an aero foil moves through the air, the air flows in streamlines around the aero foil as shown in Fig. 3.21. The air splits into two parts at leading edge. The air molecules moving above the aero foil have to travel a larger distance than the air molecules moving below the aero foil at the same time. Hence, the velocity of the molecules moving on the upper side of the aero foil must have a higher velocity than the molecules of the air moving below the aero foil. Thus, as per Bernoulli's equation if velocity is more, the pressure will be less and vice-versa. This difference in pressure produces a normal thrust as shown in Fig. 3.21. The normal thrust can be divided into two components horizontal and vertical. The horizontal component is called drag, while the vertical component is called the lift. This vertical component gives the necessary force to lift an aero foil.

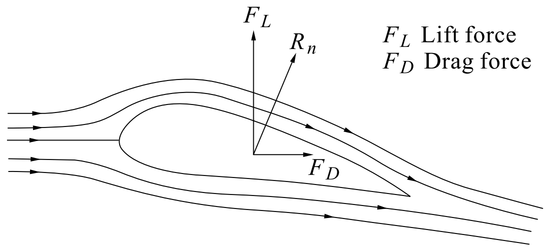


Fig. 3.21 *Flow Around an Aero Foil Section*

Example 11 50 lit/s water is flowing down through an inclined conical pipe of diameter 500 mm and 250 mm at the inlet and outlet respectively and the inlet is raised by 1 unit vertical for every 25 units of the pipe length. If the length of pipe is 100 m and the pressure at the inlet is 2.5 bar, determine the pressure at the outlet of the pipe.

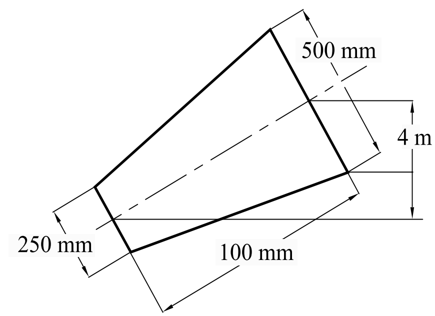


Fig. 3.22

Solution Figure 3.22

Length of pipe L = 100 m.

Discharge Q = 50 lit./s = 0.05 m³/s

Pressure at the inlet $p_1 = 2.5$ bar $= 2.5 \times 10^5$ N/m²

Let $z_1 = (1/25) \times 100 = 4$ m

$z_2 = 0.0$ m

Diameter of pipe at the inlet $d_1 = 500$ mm $= 0.500$ m

Area of the pipe at the inlet $a_1 = (\pi/4)d_1^2 = (\pi/4)(0.5)^2 = 0.196$

Diameter of pipe at the outlet $d_2 = 250$ mm $= 0.25$ m

Area of the pipe at the outlet $a_2 = (\pi/4)\, d_2^2 = (\pi/4)\,(0.25)^2 = 0.049$

Velocity at the inlet $V_1 = 0.255$ m/s

Velocity at the outlet $V_2 = 1.02$ m/s

Applying Bernoulli's equation

$$p_1/(\rho\, g) + z_1 + V_1^2/2\, g = p_2/(\rho\, g) + z_2 + V_2^2/2\, g$$

$$2.5 \times 10^5/(1000 \times 9.81) + 4.0 + (0.255)^2/2 \times 9.81$$
$$= p_2/1000 \times 9.81 + 0.0 + (1.02)^2/2 \times 9.81$$
$$25.48 + 4.0 + 3.3 \times 10^{-3} = p_2/1000 \times 9.81 + 0.053$$
$$p_2 = 2.887 \times 10^5 \text{ Pa.}$$

Ans $p_2 = 2.887 \times 10^5$ Pa

Example 12 For a turbine the inlet diameter and outlet diameter are 400 mm and 800 mm the pressure at the inlet is 300 kPa and the pressure at the outlet of the turbine is –50 kPa, if the discharge Q of water is 0.5 m³/s. Determine the power output of the turbine in kW, take the potential head at the inlet to the turbine as 2 m and that at the outlet 0 m.

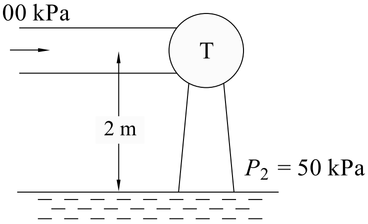


Fig. 3.23

Solution Given,

Discharge $Q = 0.5$ m³/s

Diameter at the inlet $d_1 = 400$ mm $= 0.4$ m

Area at the inlet $A_1 = (\pi/4)d_1^2 = \pi \times (0.4)^2/4$

Velocity at the inlet $V_1 = 3.978$ m/s

Diameter at the outlet $d_2 = 800$ mm $= 0.8$ m

Area at the outlet $A_2 = (\pi/4)d_2^2 = \pi \times (0.8)^2/4$

Velocity at the outlet = 0.995 m/s

Potential head at the inlet $Z_1 = 2$ m

Potential head at the outlet $Z_2 = 0.0$ m.

Pressure at the inlet $p_1 = 300$ kPa $= 3 \times 10^5$ Pa

Pressure at the oulet $p_2 = -50$ kPa $= -5 \times 10^4$ Pa

Substituting the values in the following equation

$$p_1/(\rho\, g) + z_1 + V_1^2/2\, g = p_2/(\rho\, g) + z_2 + V_2^2/2\, g + E$$
$$(3 \times 10^5)/1000 \times 9.81 + 2.0 + 3.978^2/2 \times 9.81$$
$$= (-5 \times 10^4)/1000 \times 9.81 + 0.0 + 0.995^2/2 \times 9.81 + E$$
$$30.58 + 2.0 + 0.806 = -5.09 + 0.050 + E$$
$$33.386 = -5.04 + E$$
$$E = 38.426 \text{ m}$$
$$\text{Power} = P = \rho\, g\, Q\, E/1000 \text{ kW}$$

Substituting the values in the above equation

$$P = 1000 \times 9.81 \times 0.5 \times 38.426/1000 \text{ kW}$$
$$P = 188.48 \text{ kW}$$

Ans $P = 188.48$ kW

Example 13 For a siphon shown in Fig. 3.24 determine the discharge through a pipe of 20 cm diameter.

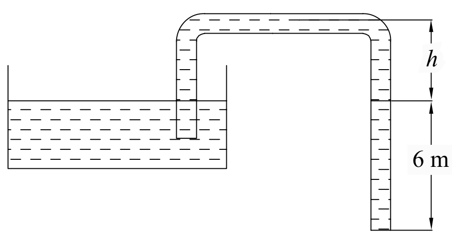


Fig. 3.24 *Siphon*

Solution

Diameter of pipe = 20 cm = 0.20 m

$$Z_1 = 6 \text{ m.}$$
$$Z_2 = 0.0 \text{ m}$$

Assume the velocity of water at inlet of the siphon tube $V_1 = 0$ m/s

Velocity of water at outlet be V_2 m/s

$$p_1 = p_2 = 0.0$$

Substituting the above values in the following equation

$$p_1/(\rho\, g) + z_1 + V_1^2/2\, g = p_2/(\rho\, g) + z_2 + V_2^2/2\, g$$
$$0.0 + 6.0 + 0.0 = 0.0 + 0.0 + V_2^2/2 \times 9.81$$
$$V_2 = \sqrt{6 \times 2 \times 9.81} = 10.85 \text{ m/s}$$

Discharge Q = area of pipe × velocity of fluid flowing through pipe

$$Q = a \times V_2 = (\pi/4)\, d^2$$
$$Q = (22/7) \times 0.2^2 \times 10.85 = 0.341 \text{ m}^3\text{/s}$$

Ans $Q = 0.341$ m^3/s

3.10 LAMINAR AND TURBULENT FLOW

To understand the laminar and turbulent flow, consider Reynold's experimental set up Fig. 3.25 consisting of the following essential parts:

- a tank containing water maintained at a constant head.
- a horizontal pipe made of glass tube and bell mouthed as shown in figure.
- a regulating valve for controlling the flow of water, connected at the end of glass tube.
- a small dye tank for injecting dye along the axis of the glass tube.

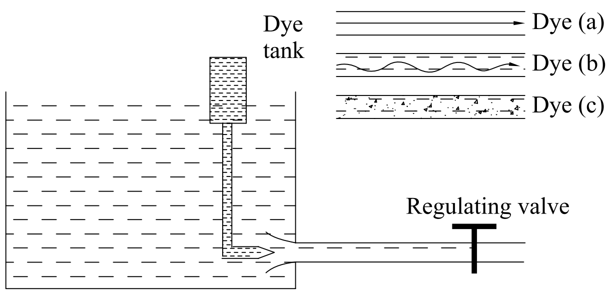


Fig. 3.25 *Reynold's Experiment*

The water from the tank is allowed to flow through the glass tube. A liquid dye (same specific weight) is injected in the centre of the glass tube along the axis. The valve is opened slowly. As the flow velocity is low initially, the dye filament injected in the glass tube is flowing in a straight line parallel to the glass tube, indicating it is a laminar flow Fig. (a).

With further opening of the valve, velocity of flow increases. The dye injected in the centre of the tube now no more follows a straight line path, but becomes wavy as shown in figure (b). This shows that the flow is no longer laminar. With further opening of the valve the velocity of flow further increases, a stage comes when the dye injected breaks up and finally diffuses in the water. This indicates that the fluid particles are moving in random fashion, in zig-zag path or disorderly manner causing the flow to become turbulent as shown in figure (c).

Laminar Flow In a laminar flow the fluid particles move along a well defined path or in streamline which are parallel and straight. Thus, the particles of fluid move in layers. The laminar flow is also called viscous or streamline flow.

Turbulent Flow In a turbulent flow the fluid particles move in zig-zag, erratic and unpredictable path due to which eddies are formed.

A non-dimensional Reynold's Number is used to determine whether the flow is laminar or turbulent. Reynold's Number is defined as the ratio of inertia forces to the viscous forces of the flowing fluid.

$R_e = \rho V d/\mu$ where, ρ is the density of flowing fluid kg/m^3
μ is the dynamic viscosity N-s/m^2
d diameter of the pipe m
v velocity of fluid m/s

In pipes, if
Reynold's Number $\leq$ 2000 Laminar flow
Reynold's Number is greater than 2000 and less than 3000; it is transition flow (neither laminar nor turbulent)
Reynold's Number $\geq$ 3000 Turbulent flow

3.11 FLUID COUPLING

The basic purpose of the fluid coupling is to transmit power from the driving shaft to the driven shaft without any mechanical coupling between them. It also serves the same purpose as served by the mechanical transmission systems like clutch assembly and gear train. In the mechanical power driven system, if the driver shaft rotates the driven shaft will rotate.

The operating principle can be understood by an illustration. Keep two electric fans face to face at a small distance. Start one of the fans so that the air thrown by it is towards the other stationary fan. When the air thrown by the running fan towards the stationary fan create sufficient torque so as to overcome the friction and inertia forces of the stationary fan, the stationary fan also starts rotating but in the opposite direction. In this the working medium was air.

Figure 3.26 shows the basic components of the fluid coupling. Normally, oil is used as a working medium due to its stability, non-corrosive and lubricating property. The pump impeller and the turbine runner are enclosed in a single housing. Both are mounted on two different shafts as shown. The only contact between the two is the working fluid contained in the casing. When the driving

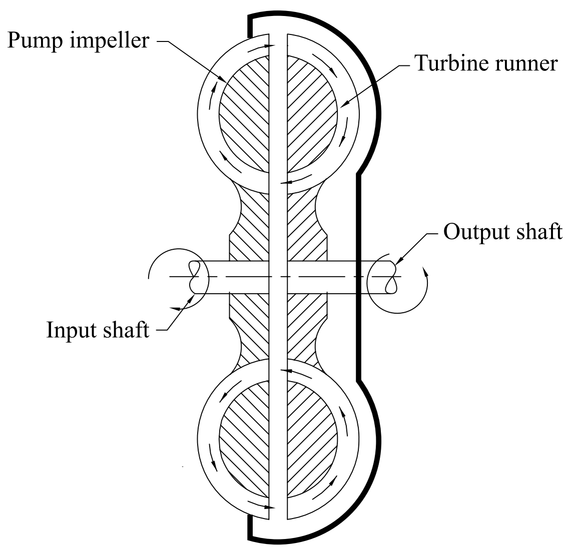


Fig. 3.26 *Fluid Coupling*

shaft is rotated, because of centrifugal action the fluid moves from inner radius of the pump impeller to outer radius and gains the kinetic and potential energy. This fluid, then enters the outer radius of the turbine runner towards the inner radius and exerts a force on the turbine runner (blade) causing it to rotate. The fluid from the turbine runner once again enters the pump impeller and the process is repeated.

The turbine speed should always be less than the pump speed. If N_p is the pump speed and N is the turbine speed then $(N_p - N)/N$ is called slip. The greater the slip the greater is the percentage of power input that is converted to torque by the turbine runner and transferred to the driven shaft. If the speed of both pump impeller and turbine runner are equal then their will be no circulatory motion of the fluid. Hence the turbine runner speed should always be 2% less than the pump impeller speed.

3.12 PUMPS

Pump is a device which converts the mechanical energy into the energy of the fluid. In other words, it is a device which gives energy to the fluid thereby increasing its pressure head or kinetic head or both. Pumps are used for agriculture purposes, water supply systems, hydraulic control systems, and in many engineering applications.

3.12.1 Classification of Pumps

Pumps are classified as shown in Fig. 3.27:

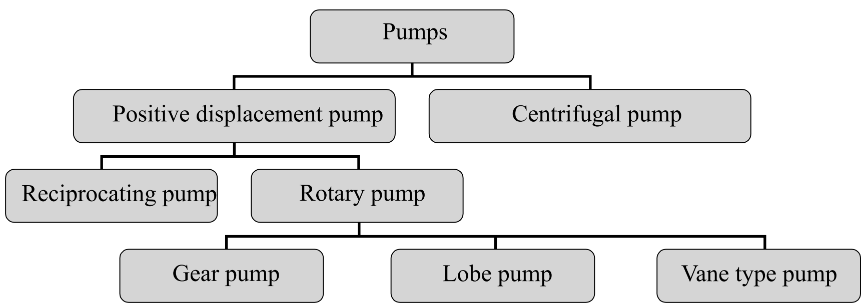


Fig. 3.27

3.12.1.1 Reciprocating Pump

Figure 3.28 shows the basic components of the reciprocating pump. The rotary motion given to the crank shaft by a prime mover is converted into reciprocating motion of the piston by the connecting rod. When the piston moves from the outer dead centre to the inner dead centre, the inlet valve opens and fluid is drawn in to the cylinder through the inlet valve through the suction pipe. When the piston moves from inner dead centre to outer dead centre, the pressure of fluid increases, this causes the pressure difference across the outlet valve and thereby opening it. As the outlet valve opens the fluid is forced out through the outlet valve to the delivery pipe. This cycle is

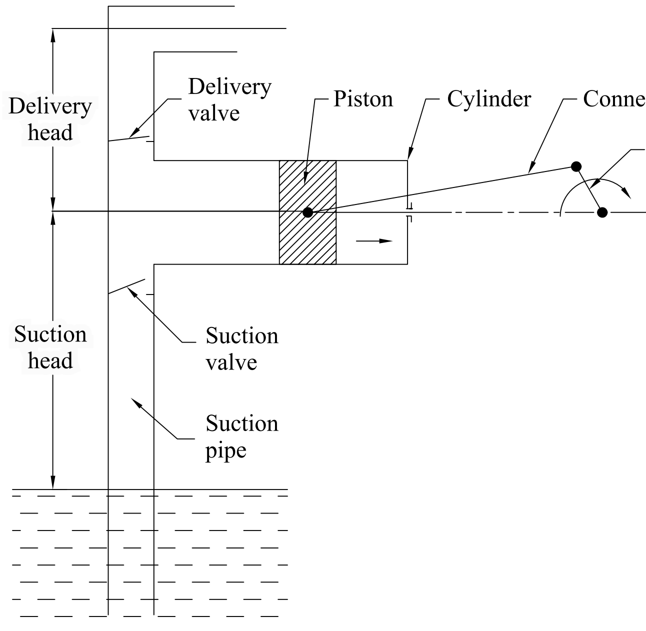


Fig. 3.28 *Main components of reciprocating pump*

repeated. If the fluid enters only from one side of the piston it is called single acting, if the fluid enters from both sides of the piston it is called double acting pump.

3.12.1.2 Rotary Pump

Gear Pump Figure 3.29 shows the basic components of the gear pump. It consists of two identical intermeshing spur gears. Both the gears are mounted on two different shafts and are placed in a stationary housing. One gear is keyed to the driving shaft while the other revolves idly.

The fluid entering the inlet port fills the space between the teeth. The fluid trapped between the teeth is carried forward by the revolving gears and finally pushed out of the discharge port. These are used in automobiles.

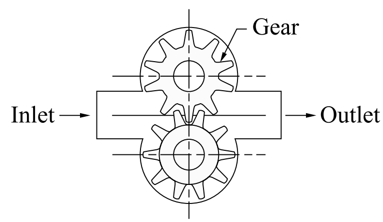


Fig. 3.29 *Gear Pump*

Lobe Pump Figure 3.30 shows the basic components of the lobe pump. It consists of two identical lobes. Both the lobes are mounted on two different shafts and are placed in housing. One lobe is keyed to the driving shaft while the other revolves freely on the shaft. The fluid entering the inlet port fills the space between the two lobes. The fluid trapped between the lobes is carried forward by the rotating lobes and finally pushed out of the outlet port.

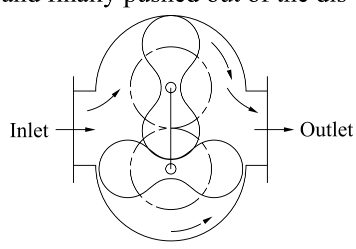


Fig. 3.30 *Lobe Pump*

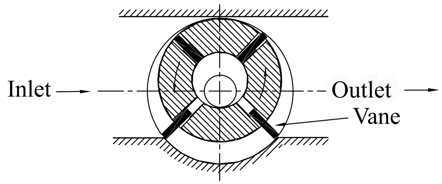


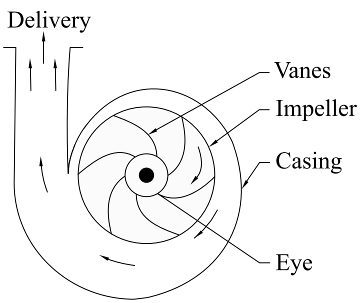
Fig. 3.31 *Vane pump*

Vane Type Pump It consists of a rotor mounted eccentrically in relation to the cylindrical housing Fig. 3.31. The rotor has slots cut radially in which the vanes slide. The vanes are spring loaded, i.e., the vanes are held tightly against the cylindrical housing by means of spring. It provides the leakproof joint between the suction and discharge connection. When the rotor rotates, the vane moves to and fro inside the slot of the rotor. During the suction, the space between the vanes increases. During the further movement of the rotor the space decreases and the fluid is discharged.

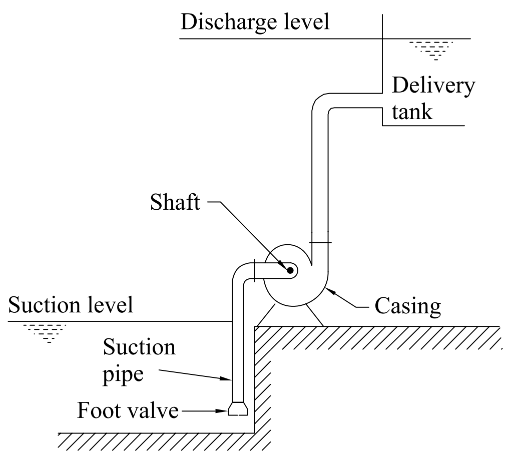
3.12.1.3 Centrifugal Pump

The essential parts of the centrifugal pump and centrifugal pump assembly are as follows and are shown in Fig. 3.32(a) and (b):

1. Impeller 2 Casing 3. Suction pipe, foot valve and strainer 4. Delivery pipe.



(a) Centrifugal pump



(b) Centrifugal pump layout

Fig. 3.32

Impeller: Impeller consists of series of curve blades mounted on the shaft as shown in figure. It is coupled to an electric motor or a prime mover.

Casing: The casing is air tight passage surrounding the impeller of a pump. The high kinetic energy imparted to the fluid at the outlet of the impeller is converted into pressure energy in a spiral casing of gradually increasing cross-section area.

Suction pipe: It is a pipe whose one end is connected to the inlet of a pump called an eye of the pump, while the other end is connected to the water sump. It is provided with a foot valve (one way valve) to prevent the back flow of water into the sump, when the pump is stopped. Below the foot valve a strainer is provided to prevent the entry of dust particles, debris, etc., into the pump.

Delivery pipe: Delivery pipe leads the fluid from the outlet of the pump to the point of use. Generally, a valve is provided to control the flow of fluid into the delivery pipe at the outlet.

3.12.2 Comparison between Reciprocating Pumps and Centrifugal Pumps

	Centrifugal pumps	*Reciprocating pumps*
1	The delivery is continuous and smooth	The delivery is pulsating and fluctuating
2	It is used for high discharge and low pressure head	It is used for small discharge and high pressure heads
3	Initial cost and running cost is low	Initial cost as well as maintenance cost is high
4	It can handle highly viscous fluids like sugar molasses, paper pulp, slurry, etc.	It can handle low viscous fluids
5	Its operation is smooth because of only rotary part which can be balanced more perfectly	Its operation is not smooth because of non uniform torque
6	Its efficiency is high	Its efficiency is low

3.13 AIR COMPRESSOR

3.13.1 Introduction

The function of compressor is to compress certain quantity of air or gas from the suction pressure to a required delivery pressure. In order to compress air or gas certain amount of energy is required, hence it is necessary that the air should be compressed with minimum expenditure of energy. A compressor requires a prime mover which can be electric motor or in some cases internal combustion engines. The compressed air finds many applications because of easy transmission of compressed air. Some of the applications of compressed air are in operation of pneumatic drill, hammers, hoist, control system, air brakes, sprays, blast furnaces, and lift gates. Compression of air plays a vital role in the performance of internal combustion engine and gas turbines. Compressors also find its application in refrigeration and air conditioning industries.

3.13.2 Air Compressor Terminology

1. Single acting compressor are those in which the suction, compression, and delivery of the air takes place from only one side of the piston.

   Double acting compressor are those in which the suction, compression, and delivery of the air takes place from both sides of the piston.
2. Single stage compressors are those in which the compression of air from suction pressure to delivery pressure takes place in one stage or one cylinder.

   Multi-stage compressors are those in which the compression of air from suction pressure to delivery pressure takes place in more than one cylinder. Air delivered by the first compressor at a higher pressure of first cylinder becomes the intake or suction of the second cylinder and so on.
3. Ratio of compression is defined as the ratio of the absolute delivery pressure to the absolute intake pressure.

4. Actual capacity of the compressor is the actual quantity of free air delivered i.e., quantity of air delivered at the intake condition.
5. The space between the top dead centre of the piston and the cylinder head is called clearance volume.

3.13.3 Classification of Compressors

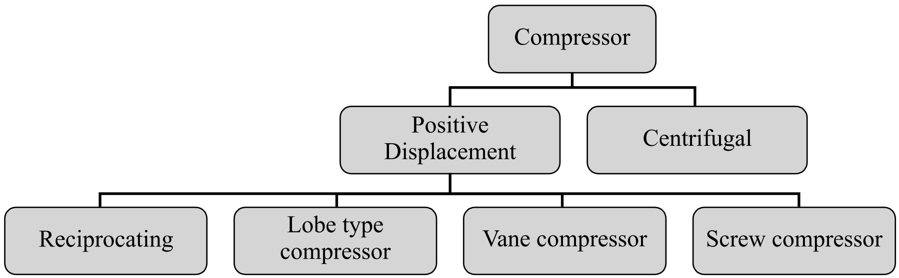


Fig. 3.33 *Classification of compressors*

3.13.3.1 Reciprocating Compressor

The basic components of reciprocating compressor are piston, cylinder and connecting rod whose one end is connected to the piston and the other big end connected to the crank Fig. 3.34. The inlet and outlet valves are also provided with the cylinder head which are operated by the pressure differences across them. In general, the piston reciprocates inside the cylinder which is either air cooled or water cooled.

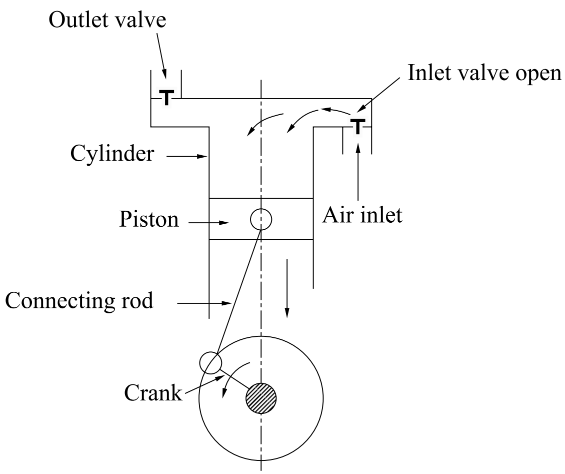


Fig. 3.34 *Reciprocating Compressor*

When the piston moves in the downward direction the air trapped between the piston and the cylinder in the previous stroke (air in the clearance volume) expands and the pressure inside the cylinder decreases. As soon as the pressure inside the cylinder reaches a value less than the intake manifold pressure the inlet valve opens. Thus a fresh charge of air is sucked inside the cylinder, for the remaining part of the suction stroke. During this process the delivery or the outlet valve remains closed. When the piston moves in the upward direction the pressure inside the cylinder increases, and as soon as the pressure inside the cylinder reaches a value more than the intake manifold pressure the inlet valve is closed. The further upward movement of the piston increases the pressure of the air trapped inside the piston and the cylinder. Eventually, a pressure will be reached when the pressure inside the cylinder becomes more than the delivery pressure. This pressure difference causes opening of the delivery valve and the compressed air is delivered to the receiver for the remaining part of the stroke. After completion of the compression stroke piston once again moves in the downward direction and the cycle is repeated.

3.13.3.2 Rotary Compressors

Lobe Type Root Blower Figure 3.35 shows the basic components of the lobe pump. It consists of two identical lobes. Both the lobes are mounted on two different shafts and are placed in housing. One lobe is keyed to the driving shaft while the other revolves freely on the shaft. The profile of the lobe is cycloid or involute. The air entering the inlet port fills the space between the two lobes. The air trapped between the lobes is carried forward by the rotating lobes and finally pushed out of the outlet port. As each side of the lobe faces a side of casing, the process is carried out four times per revolution of the driving shaft.

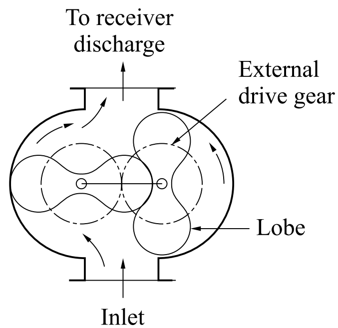


Fig. 3.35 *Lobe Type Blower*

Vane Type Blower It consists of a rotor mounted eccentrically in relation to the cylindrical housing Fig. 3.36. The rotor has slots cut radially in which the vanes slide. The vanes are spring loaded, i.e., the vanes are held tightly against the cylindrical housing by means of spring. It provides the leak-proof joint between the suction and discharge connection. When the rotor rotates the vane moves to and fro in the slot of the rotor. During the suction, the space between the vanes increases. During the further movement of the rotor the space and the casing decreases and air is discharged through the outlet. In this type of compression the compression is obtained before the trapped volume is opened to the delivery, and further compression is obtained by the back flow of air from the receiver.

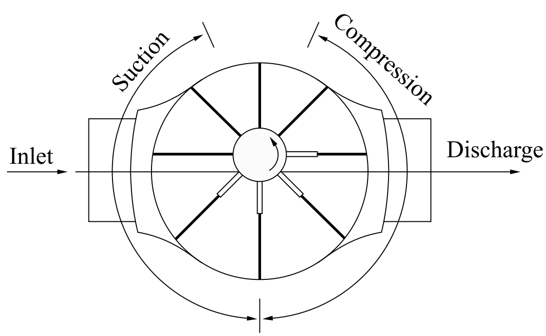


Fig. 3.36 *Vane Type Blower*

3.13.3.3 Centrifugal Compressor

The essential parts of the centrifugal pump are shown in Fig. 3.37 and are same as that of centrifugal pump. It consists of a rotor with a series of curved blades. Air is drawn in through an opening near the hub as shown in Fig. 3.37(a). The impeller rotates at high rotational speed. The static pressure of air increases from an eye to an impeller outlet. As the air leaving an impeller tip is passed through a diffuser provided around an impeller. The kinetic energy of the air is thus converted into the pressure energy. The centrifugal compressors are used for low pressure and high volume of air.

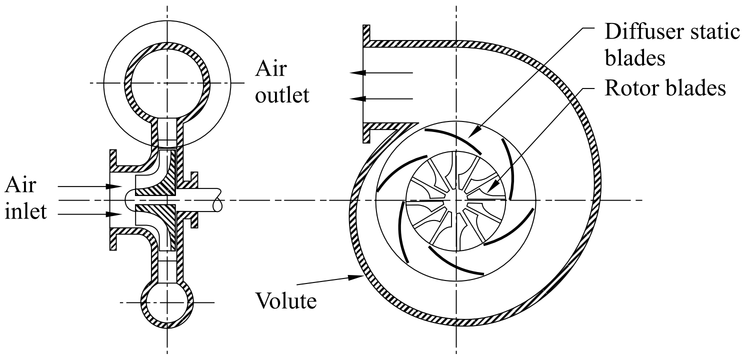


Fig. 3.37(a) *Centrifugal Compressor*

3.14 TURBINES

3.14.1 Introduction

A water turbine converts the available potential and kinetic energy of the water into useful mechanical energy. The rotary motion imparted to the turbine in turn is used to drive an electric generator. Thus, it converts mechanical energy into electric energy.

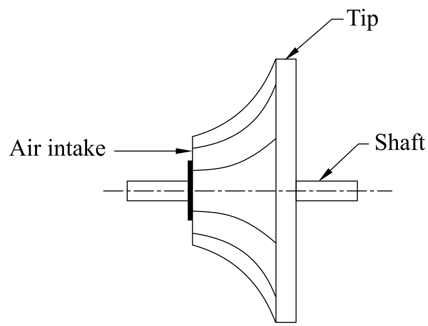


Fig. 3.37(b) *Rotor*

Turbines are classified as:

1. (a) Impulse turbine e.g., Pelton turbine
   (b) Reaction turbine e.g., Francis turbine, Kaplan turbine
2. According to available head
   (a) low head: lesss than 30 m e.g., Kaplan turbine
   (b) medium head: 30 m < head < 100 m Kaplan turbine, Francis turbine
   (c) high head: head > 100 m, Pelton turbine
3. According to the direction of flow of water
   (a) Tangential flow, e.g., Pelton turbine
   (b) Radial flow, e.g., Francis tyrbine
   (c) Axial flow, e.g., Kaplan turbine

3.14.1.1 Impulse Turbine

In an impulse turbine the available potential energy of water is first converted into kinetic energy by means of a nozzle. The high velocity of jet coming out of the nozzle strikes series of blades (bucket shaped) fixed around the periphery of the rim of a circular disc. The resulting change in the momentum of water forces the blades to move, which in turn, rotates the disc. (Newton's second law of motion)

3.14.1.2 Reaction Turbine

Figure 3.38 illustrates the basic principle of reaction turbine. Allow the water to flow through a pipe into a drum, which has radial opening. When water escapes through these openings at a higher velocity it produces an equal and opposite reaction causing drum to rotate in opposite direction of the flow. Similarly, when water slides over the runner blade the part of the pressure energy changes causing a reaction force on the blades, causing turbine to rotate. (Newton's third law of motion).

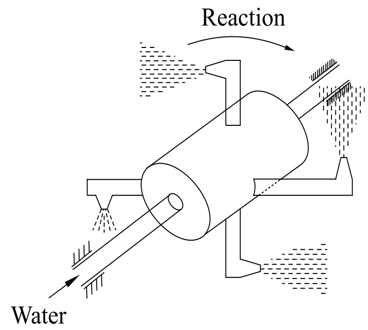


Fig. 3.38 *Principle of Reaction Turbine*

3.14.2 Pelton Turbine

Pelton turbine was invented by A. Pelton (1829–1908) and is based on the principle of impulse turbine (Fig. 3.39). Pelton turbine is a tangential flow impulse turbine, in which water flows along the tangent to the path of runner. The water flows from the reservoir into the penstock to the nozzle. The nozzle converts the available pressure head into the kinetic head. The high velocity of water coming out of the nozzle strikes the series of blades (bucket shaped) mounted on the periphery of the circular disc. As water flows into the bucket, the direction of water runner changes. In the process, the change in the momentum of water causes a force on the bucket to move. After doing useful work, the water discharges into the tail race.

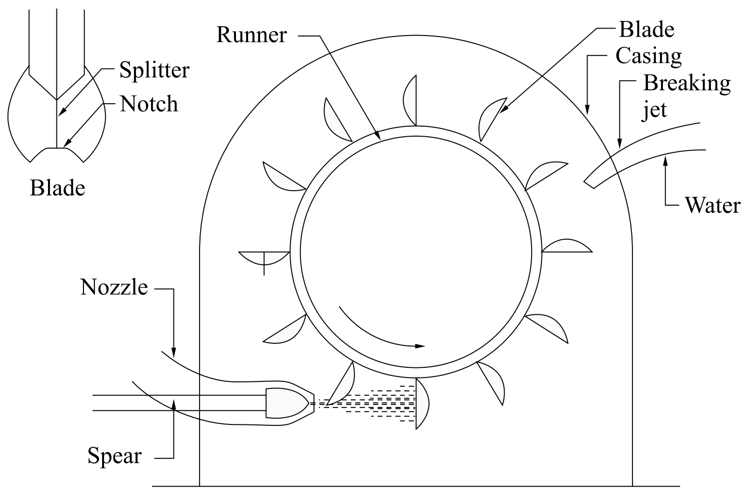


Fig. 3.39 *Pelton Turbine*

Essential components of Pelton turbine are:

1. Casing 2. Nozzle 3. Runner 4. Breaking jet.

Casing: Its basic function is to prevent the water splashing outside and discharging the water to the tail race.

Nozzle: The function of the nozzle is to convert the potential energy of water into the kinetic energy. The forward or backward movement of a spear provided in the nozzle regulates the amount of water striking the buckets. The movement of spear is controlled either manually or automatically by a governing mechanism.

Runner: Runner consists of series of buckets placed equidistantly along the periphery of a circular disc. The bucket is a cup shaped and has a splitter in the middle to distribute the water striking it symmetrically. A notch is provided in the bucket on the outer side so that the jet strike the bucket only when it comes in the proper position to the jet.

Breaking jet: When the nozzle is closed to stop the turbine, the runner due to inertia continues to rotate for a long time. To stop the runner in short time, a small nozzle is provided which directs the flow of the water jet on the back of the bucket see Fig. 3.39. This jet is called the breaking jet.

3.14.3 Reaction Turbine

In reaction turbine the entire flow of water from head water to tail water takes place in a closed conduit system, i.e., it is not opened to the atmosphere at any point in the passage. In reaction turbines the water entering the runner exerts an impulse force and at the discharge it exerts a reaction opposite to the direction of the flow. The reactive force is more than the impulsive force in reaction turbine.

1. Francis Turbine Francis turbine was invented by James B. Francis. It is a radial flow reaction turbine. In Francis inward flow turbine, water enters the spiral casing running around the runner. Its cross-section area gradually reduces so as to maintain the same velocity of water throughout the circumference of the runner at inlet. When the water flows over the blades, part of the pressure energy is converted to kinetic energy causing a reaction force on the blades, thereby rotating turbine (Fig. 3.40).

Essential components of Francis turbine are

1. Scroll casing 2. Guide vanes 3. Runner 4. Draft tube

Scroll casing: The water supplied through the penstock is fed to the spiral casing running around the runner (see Fig. 3.40). The cross-section area of the casing gradually reduces along the direction of the flow, so that the water enter the runner at constant velocity throughout the circumference of the runner.

Guide vanes: The guide vanes allow the water to strike the blades of the rotor without shock at the inlet. Guide vanes are fixed in a position. However, they can swing about their own axis to change the flow area between the two consecutive blades by means of the hand wheel or governor.

Runner: When the guide vanes are opened, a part of the potential energy of the flow is converted into kinetic energy and remaining is potential energy. After passing through the vanes it passes over the blades of the runner. While passing through these passages, the radial component of the flow gradually changes to axial flow, the tangential component of the flow is used for rotating the runner.

Draft tube: A considerable fraction of the available head would be wasted if the turbine were placed above the tail race level and the outgoing water leaving at atmospheric pressure. By providing a turbine above the tail race level and connecting the outlet to the tail race level by a tube called the draft tube can improve the turbine output and the efficiency.

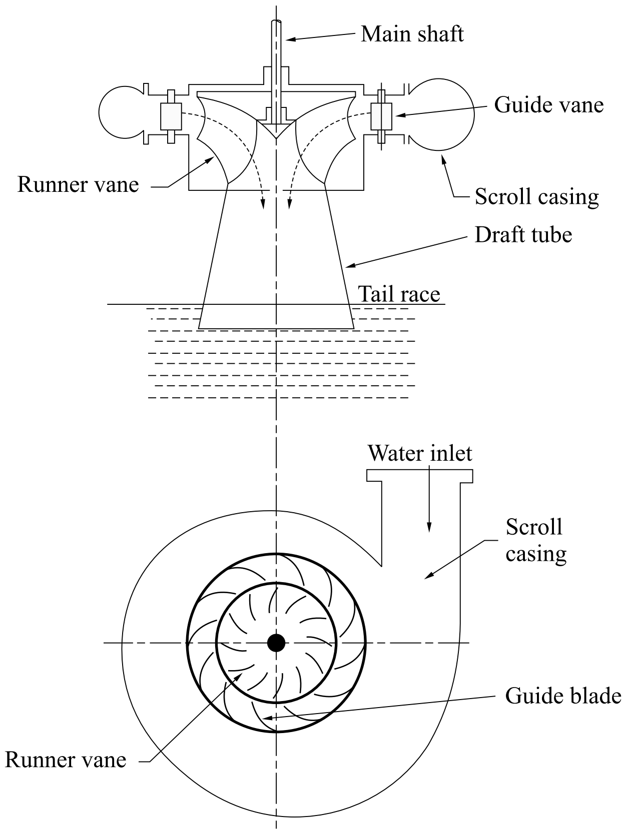


Fig. 3.40 *Francis Tturbine*

Thus, water after passing through the turbine is discharged to the tail race through a gradually expanding tube called draft tube. The most commonly type of draft tube is elbow type. *The function of the draft tube is to conserve for conversion of the energy remaining at the exit of the runner into power by the turbine.*

2. Kaplan Turbine It is purely an axial flow, low head turbine. The main components of the Kaplan turbine are as follows and are shown in Fig. 3.41.

1. Scroll casing 2. Guide vanes 3. Runner 4. Draft tube.

The function of scroll casing, guide vanes and the draft tube serve the same purpose as that of Francis turbine. The runner is like a propeller of the ship. The runner is in the form of a boss, i.e., the extension of the shaft in a bigger diameter. The blades on the runner are few in number usually 4, 6 or at most 10 of air foil shape. The runner blades are pivotally mounted on the hub so that their inclination can be adjusted during the change in the load for the best performance. In a fixed type of runner, blade angle cannot be varied. Some of the Kaplan turbine installation are Bhakra-Nangal project, Hirakund dam project, Orissa.

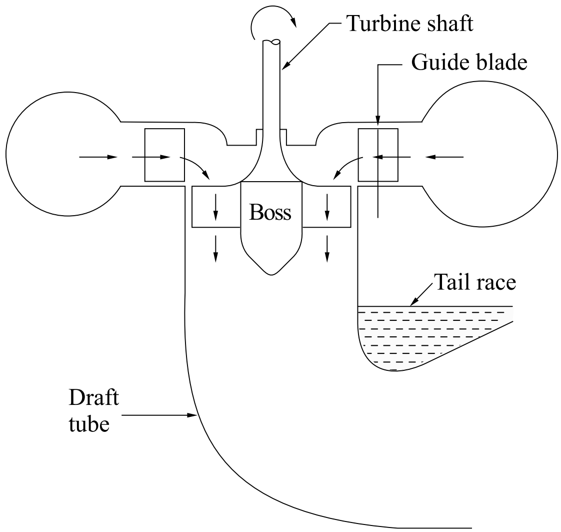


Fig. 3.41 *Kaplan Turbine*

3.14.4 Comparison between Francis turbine and Pelton turbine

Sr. No.	*Particular*	*Pelton turbine*	*Francis turbine*
1	Head	Used when high heads are available	Used for low and medium heads
2	Utilization of Head available	Pelton turbine has to be set at a higher level than the tail race, hence loss of available head	Full utilization of the available head by the use of draft tube
3	Performance under variation in the head available	For the efficient working the variation in the maximum head to the min. operating head should not vary more than 10%	It can operate even if the ratio of the max. to min. operating head is 2
4	Repair	It is easier to repair as the parts are accessible	Difficult to repair because the parts are not accessible
5	Speed	Low speed	Higher as compared to Pelton
6	Size	For the same operating head the size is large.	Size is small due to high speed
7	Control	Easier to regulate	Comparatively difficult to regulate
8	Sensitive	More sensitive to the variation in the diameter of nozzle	More sensitive to abrasive effect of sand and dirt.
9	Operating efficiency	Poor between half and full load	Better between half and full load compared to Pelton turbine

3.15 HDYRO-ELECTRIC POWER PLANTS

Hydro-power plants are installed, where the availability of water is in huge quantity and at a sufficient head. In hydro-electric power plants the available energy of the water is utilized to drive the turbine, which in turn drives the generator unit to produce electricity.

Nearly 20% of the power of the world is met by hydro-electric power plants.

Advantages of hydro-electric power plants are:

1. No fuel is required to generate electricity.
2. The running cost of the plant is very low as compared to thermal power plants.
3. The starting time and stopping time of these plants is very short as compared to thermal power plants, and hence are more suitable as peak load plants.
4. It has a greater life.
5. It does not pose any problem to pollution as compared to nuclear (disposal of nuclear waste) or thermal power plants.
6. It also provides other additional benefits like irrigation, fishery, and navigation.

Disadvantages of hydro-electric power plants:

1. Initial investment is very high.
2. The power capacity of the plant totally depends on the amount of water and head available.
3. The gestation period is large.
4. Big hydro-power plants disturb the ecology of the area by the way of deforestation.
5. It can only be installed, where large amount of water is available at high head.
6. It submerges huge area and uproots the large population.

3.15.1 Classification of Hydro-Electric Power Plants

Hydro-electric power plants can be classified as

- According to the water head available
  - low head: less than 30 m
  - medium head: 30 m to 100 m
  - high head: more than 100 m
- According to the type of load supplied
  - Base load plant
  - Peak load plant

3.15.2 Load Curve

The demand of electric power used by the residential colonies, industries and commercial places is not constant throughout the day or throughout the year. It increases during the summer due to the use of air cooling devices. The requirement of consumer plotted against the time period is called load curve. It is not desirable to built a power plant to meet the fluctuating demand. Hence, thermal power plants are designed to take up the average load whereas the additional load is taken by the peak load plant (Fig. 3.42).

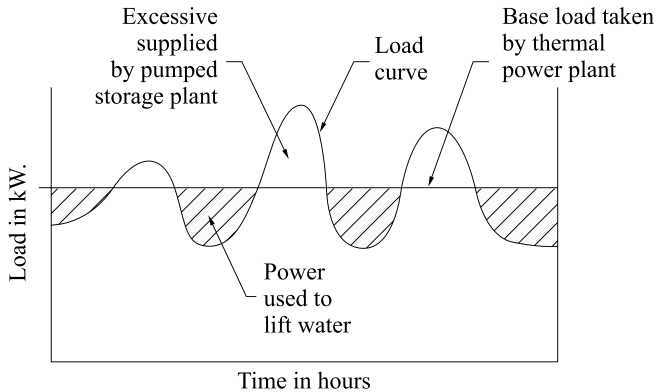


Fig. 3.42 *Load Curve*

3.15.3 Essential Elements of Hydro-Electric Power Plant

The schematic arrangement of a typical hydro-electric power plant is as shown in Fig. 3.43. Water flowing during the rainy season is stored in the reservoir and supplied to the turbine through the penstock, which in turn operates the generator to produce electricity.

The essential elements of hydro-electric power plant are as follows:

1. Catchment area
2. Reservoir
3. Dam
4. Spillway
5. Penstock
6. Surge tank
7. Draft tube
8. Power house

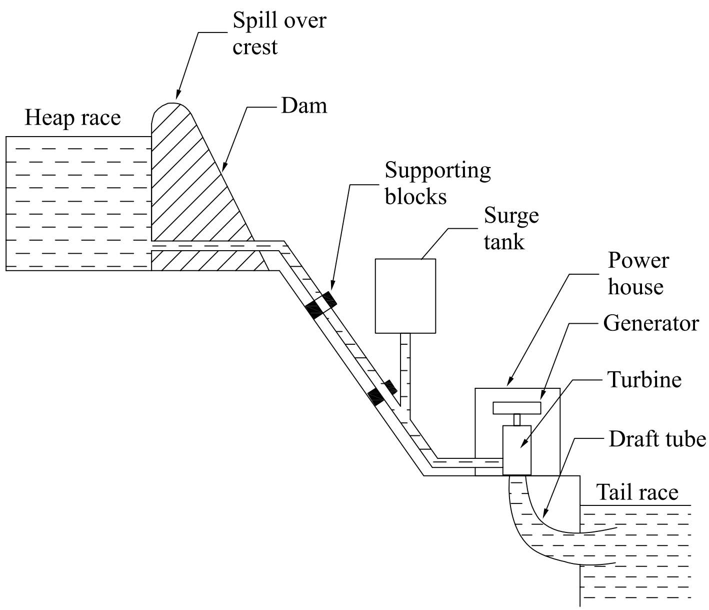


Fig. 3.43 *General Layout of a Hydro-power Plant*

Catchment Area The whole area behind the dam draining into stream, across which the dam is constructed is known as catchment area.

Reservoir Reservoir is a place to store large quantity of water. Its purpose is to store the water during the rainy season and supply the same to the turbine unit to produce electricity. It also provides the water during the lean period. The water in the reservoir can also be used for irrigation, fishery, etc. A reservoir can either be natural or artificial. Artificial reservoir can be built by constructing a dam across a river.

Dam The basic function of a dam is
(a) To develop a high capacity reservoir for storing water.
(b) To built a required head for the power generation.

Spillway It is made up of concrete structure. It provides stability to the dam structure when water level rises above the danger level in the reservoir. This condition mainly arises during the heavy rains or flood periods.

Forebay It serves as a regulating reservoir for storing the water temporarily when the load on the plant is reduced, and provides water for initial increment when the load increases, while water in the canal is accelerated.

Penstock It is basically a pipe or conduit used for connecting the prime mover with forebay or surge tank. It is mainly built of steel plates.

Draft Tube It is an air tight pipe connected to the outlet of the reaction turbine for discharging water into the tail race. By the use of draft tube the effective operating head is increased.

Power House It is a house which accommodates the prime mover, generator, control room and its accessories.

Surge Tank A change in the load on the generator unit causes the governor to regulate the water supply to the turbine causing the fluctuation of pressure in the penstock. Surge tank acts as a relief valve. When the load on the turbine is reduced the water flowing to the turbine is also reduced due to this there is sudden rise of pressure in the penstock giving rise to water hammer. The surge tank helps in stabilizing the pressure in the penstock. It also acts as a temporary reservoir to provide sufficient amount of water during increase in load on the turbine.(see Fig. 3.43)

3.15.4 Pumped Storage Power Plant

To meet the fluctuating demand at times, the thermal power plant has to operate at lower loads during the leaner period at lower efficiency thereby increasing the cost of generating the electricity. To reduce the cost of generating electricity the pumped storage plants are used in combination with thermal power or nuclear power plants. It improves the overall efficiency of the combined power plant unit. At times when there is low electric demand, the excess generating capacity of the base load plant (thermal power plant) is used to pump the water at a higher level reservoir to raise its potential energy (Fig. 3.44). When there is a large demand of power the thermal power plant takes up the base load and for meeting the excess load, water is released back into a lower level reservoir through a turbine unit (low head), to generate the electricity. Due

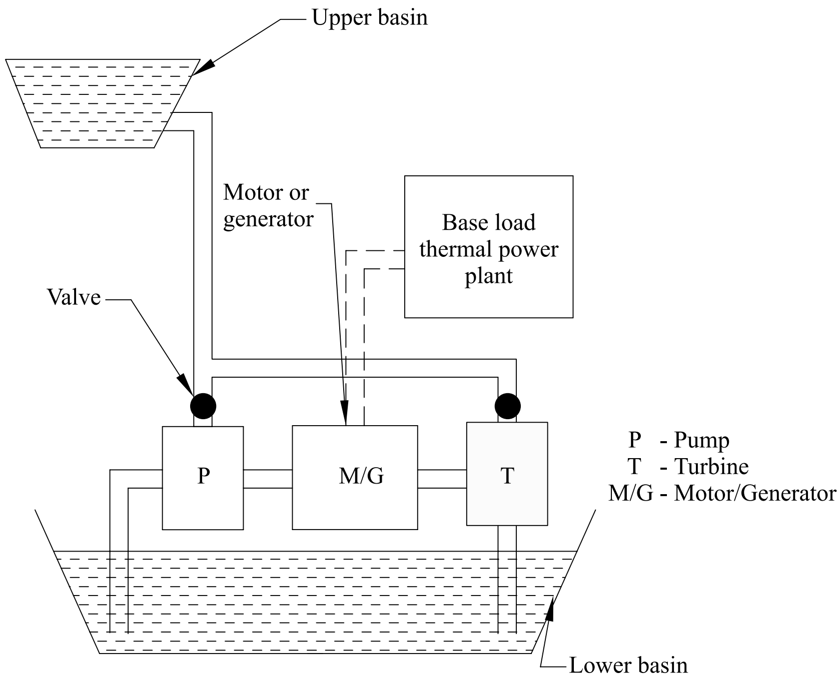


Fig. 3.44 *Schematic Diagram of Pumped Storage Power Plant*

to the exposed water surface and other losses approximately 70–85% of the electric energy used to pump the water in to the higher reservoir can be regained. The relatively low energy density requires large amount of water. For example, 1000 kg of water at the top of a 100 m tower has a potential energy of about 0.272 kWh. The only way to store a significant amount of energy is by having a large amount of water located on a hill relatively near, but as high as possible above the tail race. This system is economical because it flattens out load variations on the power grid, permitting thermal power stations such as coal-fired and nuclear power plants that provide base-load electricity to continue operating at peak efficiency, while reducing the need for 'peaking' power plants that use costly fuels. These plants are generally used during peak loads. Some of the pumped storage plants installed in India are Bhira (Maharashtra) pump storage unit 150 MW, Kadamparai, Tamil Nadu, (4*100)MW, Nagarjuna Sagar, Andhra Pradesh, 810 MW.

Some of the advantages of pumped storage power plants are as follows:

1. The cost of meeting the demand during peak period is less compared to thermal power plant.
2. The thermal power plant and nuclear power plant can operate on maximum efficiency to take up the base load.
3. As its starting and stopping time is short the spinning reserve requirement is reduced. It can take up the peak load immediately.
4. It flattens out the load variation on the power grid.

3.16 HYDRAULIC MACHINES

3.16.1 Hydraulic Press

Figure 3.45 shows a schematic sketch of a hydraulic press and its basic components. It consists of a cylinder C which is connected to a pump supplying oil under pressure. Inside the cylinder C a plunger P moves up and down with the application of oil pressure. On the plunger P, a platform A is attached which moves along with the plunger. A fixed plate D is secured firmly by connecting it to a cylinder by two vertical columns B. An object to be pressed is kept on the platform A and oil is supplied at high pressure to the cylinder C. Platform A which is guided by the vertical columns moves in the upward direction. The platform moves down by the gravitational force when the oil pressure is removed. The hydraulic press is used for pressing the cotton bales, embossing and shaping sheet metal.

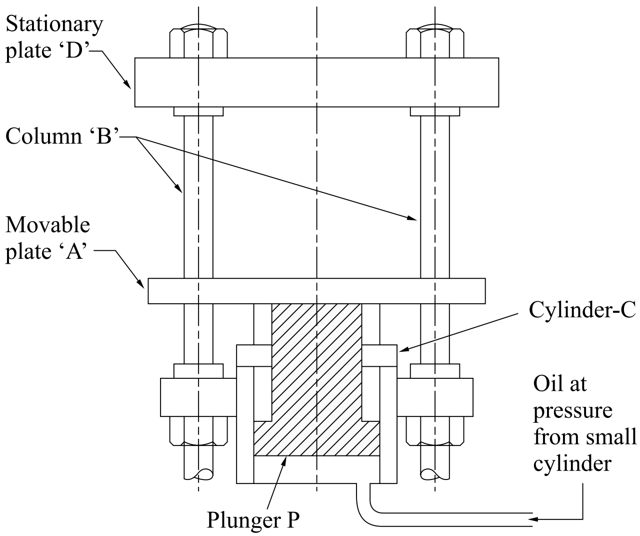


Fig. 3.45 *Hydraulic Press*

3.16.2 Hydraulic Intensifier

Figure 3.45 shows the basic components of a hydraulic intensifier. It works like a step up transformer that is it converts low pressure fluid into high pressure fluid. It consists of a big cylinder C in which fluid is filled. Inside the big cylinder a small cylinder D is placed which acts as plunger for the cylinder C. A plunger P is placed inside a smaller cylinder D. A weight W is attached to the plunger by two tie rods fixed firmly on the outer side of the cylinder C. When oil at lower pressure is supplied inside the cylinder C, it pushes the small cylinder D against the plunger P which is held stationary by weight W thus increasing the pressure. The pressure of the oil inside C is intensified in the small cylinder in the ratio of their cross section area. If p is the pressure of the oil in big cylinder and A is the cross-section area of the small cylinder, then the force acting on the small cylinder is $p\,A$. If A_1 is the area of the plunger F, then the pressure of the oil in the cylinder will be intensified to $p(A/A_1)$.

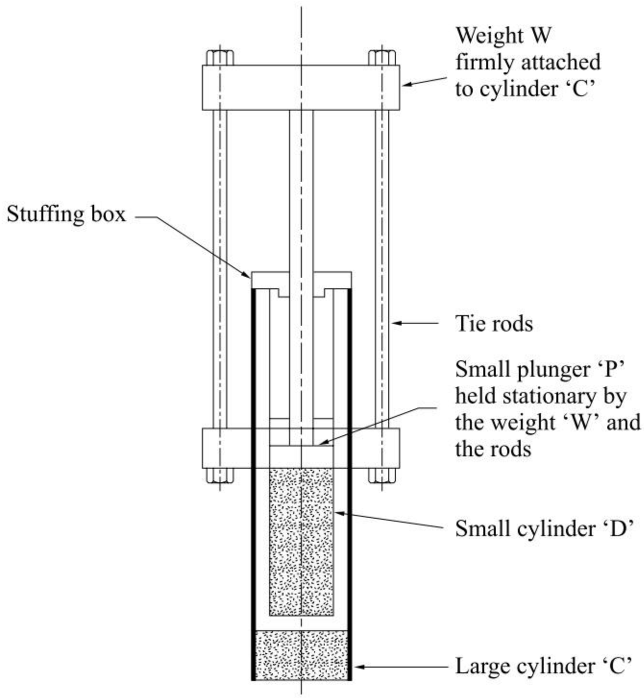


Fig. 3.46 *Hydraulic Intensifier*

3.16.3 Hydraulic Jigger

The basic components of the jigger are as shown in Fig. 3.47. Hydraulic jigger consists of a cylinder C. A number of pulleys are fixed both on the top of the ram and the bottom of the cylinder. A rope or chain is wound over the pulleys, one end of which is fixed to the cylinder and the other end of the rope is free to be tied to any load. The pulleys magnify the movement of the ram. Oil under pressure pushes the sliding arm thereby moving the pulleys apart. As one end of the rope is tied to the cylinder which is fixed and the other end free, the load tied to the free end moves up. If pressure of oil inside the cylinder is released the distance between the pulleys decreases and the free end which is tied to the load moves down. The jigger can be used in the vertical or in the horizontal position. Oil to the jigger is supplied through the hydraulic intensifier.

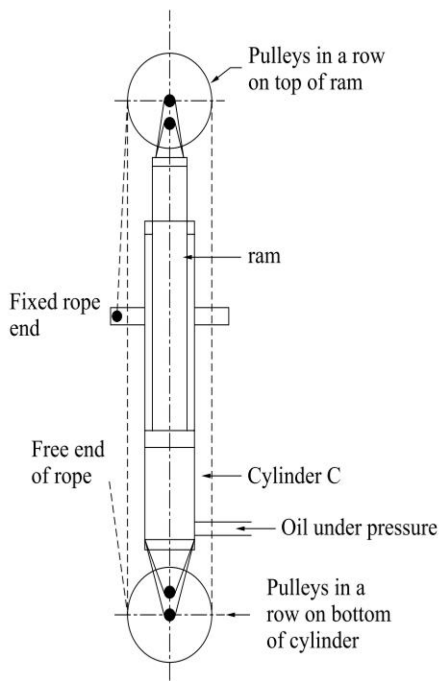


Fig. 3.47 *Hydraulic Jigger*

3.16.4 Hydraulic Crane

Hydraulic crane consists of a truss which is assembly of a column, tie rod and jib as shown in Fig. 3.48. The truss can be designed as per the requirement of the maximum load to be carried. The column is fixed on a platform. The platform can be fixed on the ground or it can be mounted on the chassis of the vehicle. If it is fixed on the chassis of the vehicle it is called movable crane. A pulley is fixed at the junction of tie rod and jib and the other pulley is mounted at the junction of the column and the tie rod. The wire rope or the chain carrying the load passes over these pulleys. The rope then passes through the hollow column and tied to jigger which is mounted horizontally. The jigger is connected to the hydraulic circuit which is operated by the electric motor or diesel engine. The relative displacement of the pulleys of jigger moves the load up or down.

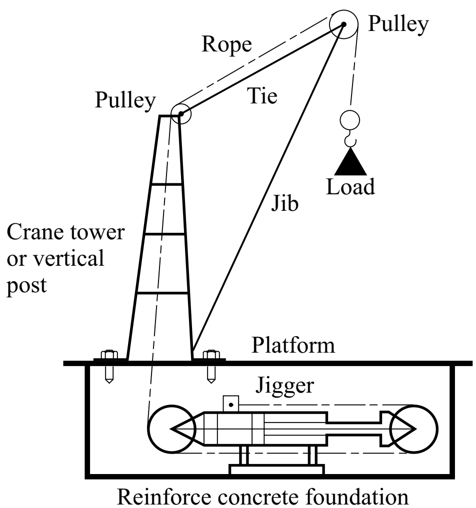


Fig. 3.48 *Hydraulic Crane*

REVIEW QUESTIONS

1. Define the following properties with their units:
   (a) specific weight (b) surface tension (c) dynamic viscosity
2. Distinguish between the following:
   (a) specific weight and mass density.
   (b) dynamic viscosity and kinematic viscosity.
3. Explain the various types of fluid flow with suitable examples?
4. A needle placed gently length-wise on the surface of water floats. Give reason?
5. Why does oil spreads when it is poured on water?
6. Arrange the following in order of increasing dynamic viscosity under the same condition air, water, glycerin, alcohol, castor oil?
7. How is the dynamic viscosity of gas affected by increase in temperature?

8. What is the difference between U-tube differential manometer and inverted U-tube differential manometer ? Where are they used?
9. State and prove Pascal's law.
10. Distinguish between the following:
    (a) steady and unsteady flow (b) uniform and non-uniform flow
    (c) laminar and turbulent flow?
11. How does the intensity of pressure at a point in the fluid varies with depth?
12. What is the normal range of blood pressure of human body?
13. Explain how Pascal's law is used in hydraulic press?
14. List all the assumptions applied in the derivation of Bernoulli's equation?
15. Enlist with brief description the various applications of Bernoulli's equation?
16. What is the difference between orifice meter and venturi meter?
17. Why light roofs are blowing during a wind storm?
18. Explain Reynold's number and give its significance?
19. Distinguish between pumps and turbines?
20. Explain the function of nozzle and spear in Pelton turbine?
21. Explain the following terms as applied to Pelton turbine:
    a. gross head b. net head
22. Differentiate between impulse and reaction turbine.
23. Explain the method of governing of Pelton turbine?
24. Explain the function of draft tube, surge tank.
25. Differentiate between radial and axial flow turbine?
26. Explain the factors which decide the choice for a particular turbine for hydro-power plant.
27. With a simple sketch explain the working of Francis and Kaplan turbine?
28. Explain the principle working of centrifugal pump with a neat sketch?
29. Explain priming of pump?
30. Explain the function of volute casing provided in centrifugal pump?
31. Explain the function of foot valve in pumps.
32. Draw the complete lay out of a hydro-power plant? Also explain the function of its major parts?
33. Explain the working of flexible coupling with a suitable sketch? Enlist its applications?
34. Explain the working of jigger. Give its application.
35. What are peak load plants? How does a pump storage plant serve the purpose of peak load plant.
36. List the advantages of peak load plant.

Numericals

1. A liquid has a relative density of 0.9 and kinematic viscosity of 2.5 centistokes. Calculate its (a) unit weight and (b) dynamic viscosity. Take the density of water as 998 kg/m^3. (**Ans.** w = 8.81 kN/m^3, μ =2.245 × 10^{-3} Pa.s)
2. Two plates are placed at a distance of 3 mm apart. The lower plate is fixed while the upper plate having a surface area of 1.0 m^2 is pulled with a speed of 2 m/s. Find the force and power required if the fluid placed between the two plates is having dynamic viscosity of 0.5 Pa.s. (**Ans.** 333.3 N; 666.6 J)

3. A square plate of side 1.0 m weighing 400 N is sliding down 30° inclined plane with a uniform speed of 1.5 m/s. An oil film of 1.0 mm of thickness is kept between plate and an inclined plane. Determine the dynamic viscosity of oil.
(**Ans.** 0.133 N-s/m^2)
4. A flat plate of area 0.2 m^2 is to be moved up an inclined plane of slope 1 vertical and 3 horizontal on a thin layer of oil of dynamic viscosity of 1 Pa.s. of thickness 0.4 mm. If the weight of the plate is 250 N, calculate the force required to pull the plate at 1.6 m/s. (**Ans.** 879 N)
5. A shaft of 96 mm diameter rotates about a vertical axis at a speed of 300 rpm inside a cylinder of internal diameter 100 mm and length 50 cm. The space between the shaft and the cylinder is filled with an oil of viscosity 2 poise. Determine the torque and power required to rotate a shaft at a given speed overcoming the viscous resistance. (**Ans.** T = 0.727 Nm; P = 22.8 W)
6. The gap between the two discs of diameter 30 cm is 1 mm. The gap is filled with an oil of viscosity 0.8 Pa.s. Determine the power required to rotate the upper disc at a speed of 600 rpm while holding the lower disc stationary.
(**Ans.** 2.51 kW)
7. Determine the force required to lift a thin ring of 5 cm diameter from water surface. Assume the surface tension of water = 0.0728 N/m. Neglect the weight of the wire. (**Ans.** F = 0.02287 N)
8. Determine the gauge and absolute pressure at a point 2.5 m^2 below the free surface of the fluid having density of 1.60 kg/m^3. Atmospheric pressure is 750 mm of mercury. Take specific gravity of mercury as 13.6 and density of water as 1000 kg/m^3.
9. A pipe line carrying oil of specific gravity 0.87, changes its diameter from 200 mm at a position A to 500 mm at B which is 2.0 m at a higher level than A. If the pressures at A and B are 19.62 kPa and 5.886 kPa respectively and the discharge is 200 litres/s. Determine the pressure loss of head and the direction of flow.
(**Ans.** head loss = 1.64 m)

Chapter 4

Thermodynamics

4.1 INTRODUCTION

Thermodynamics is the science of energy transfer and its effect on the physical properties of substances. It is based upon observations of common experience which have been formulated into thermodynamic laws. These laws govern the principles of energy conversion. The applications of the thermodynamic laws and principles are found in all fields of energy technology, notably in steam and nuclear power plants, internal combustion engines, gas turbines, air conditioning, etc.

4.1.1 Macroscopic Versus Microscopic Viewpoint

In the macroscopic approach, a certain quantity of matter is considered, without the events occurring at the molecular level being taken into account. From the microscopic point of view, matter is composed of myriads of molecules. If it is a gas, each molecule at a given instant has a certain position, velocity, and energy, and for each molecule these change very frequently as a result of collisions. The behaviour of the gas is described by summing up the behaviour of each molecule. *Macroscopic thermodynamics* is only concerned with the effects of the action of many molecules. For example, the macroscopic quantity, pressure, is the average rate of change of momentum due to all the molecular collisions made on a unit area. The macroscopic point of view is not concerned with the action of individual molecules.

4.1.2 Thermodynamic System and Control Volume

A thermodynamic *system* is defined as a quantity of matter or a region in space upon which attention is concentrated in the analysis of a problem. Everything external to the system is called the *surroundings* or the *environment*. The system is separated from the surroundings by the system boundary (Fig. 4.1). The boundary may be either *fixed* or *moving*. A system and its surroundings together comprise a *universe*.

There are three classes of systems: (a) closed system, (b) open system, and (c) isolated system. The *closed system* (Fig. 4.2) is a system of fixed mass. There is no mass transfer

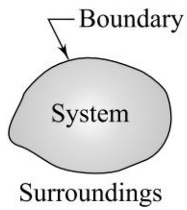


Fig. 4.1 *A Thermodynamic System*

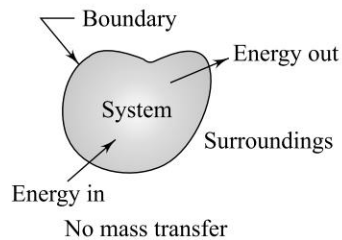
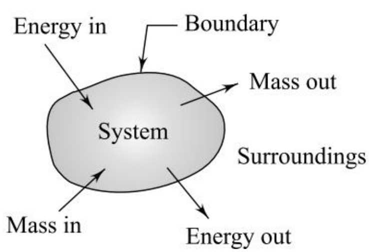
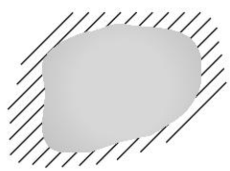


Fig. 4.2 *A Closed System*

across the system boundary. There may be energy transfer into or out of the system. A certain quantity of fluid in a cylinder bounded by a piston constitutes a closed system. The *open system* (Fig. 4.3) is one in which matter crosses the boundary of the system. There may be energy transfer also. Most of the engineering devices are generally open systems, e.g. an air compressor in which air enters at low pressure and leaves at high pressure and there are energy transfers across the system boundary. The *isolated system* (Fig. 4.4) is one in which there is no interaction between the system and the surroundings. It is of fixed mass and energy, and there is no mass or energy transfer across the system boundary.





the change of state is called a *process*, e.g. a constant pressure process. A thermodynamic *cycle* is defined as a series of state changes such that the final state is identical with the initial state (Fig. 4.5).

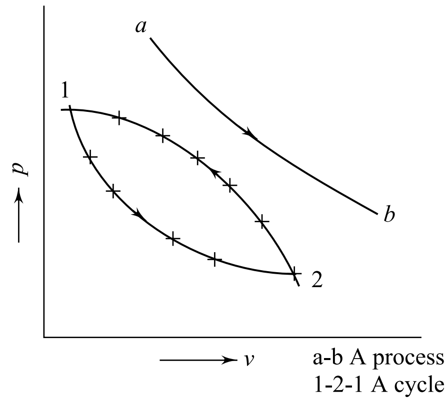


Fig. 4.5 *A Process and a Cycle*

Properties may be of two types. *Intensive properties* are independent of the mass in the system, e.g. pressure, temperature, etc. *Extensive properties* are related to mass, e.g. volume, energy, etc. Specific extensive properties, i.e. extensive properties per unit mass, are intensive properties, e.g. specific volume, specific energy, density, etc.

4.1.4 Thermodynamic Equilibrium

A system is said to exist in a state of *thermodynamic equilibrium* when no change in any macroscopic property is registered, if the system is isolated from its surroundings.

A system will be in a state of thermodynamic equilibrium, if the conditions for the following three types of equilibrium are satisfied:

(a) Mechanical equilibrium
(b) Chemical equilibrium
(c) Thermal equilibrium

In *mechanical equilibrium*, there is no unbalanced force within the system itself and also between the system and the surrounding.

In *chemical equilibrium*, there is no chemical reaction or transfer of matter from one part of system to another such as diffusion or solution.

Thermal equilibrium exists when a system existing in mechanical or chemical equilibrium is separated from its surrounding by a diathermic wall, and if there is no spontaneous change in any property of the system.

4.1.5 Quasi-Static Process

Let us consider a system of gas contained in a cylinder (Fig. 4.6). The system initially is in an equilibrium state, represented by the properties p_1, v_1, t_1. The weight on the piston just balances the upward force exerted by the gas. If the weight is removed, there will be an unbalanced force between the system and the surroundings, and under gas pressure, the piston will move up till it hits the stops. The system again comes to an equilibrium state, being described by the properties p_2, v_2, t_2. But the intermediate states passed through by the system are nonequilibrium states which cannot be described by thermodynamic coordinates.

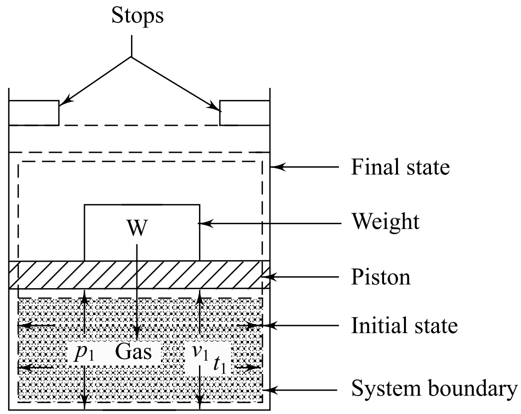


Fig. 4.6

Now if the single weight on the piston is made up of many very small pieces of weights, and these weights are removed one by one very slowly from the top of the piston, at any instant of the upward travel of the piston, if the gas system is isolated, *the departure of the state of the system from the thermodynamic equilibrium state will be infinitesimally small*. So every state passed through by the system will be an equilibrium state. Such a process, which is but a locus of all the equilibrium points passed through by the system, is known as a *quasi-static process* (Fig. 4.7), 'quasi' meaning 'almost'. *Infinite slowness is the characteristic feature of a quasi-static process*. A quasi-static process is thus a succession of equilibrium states. A quasi-static process is also called a *reversible process*.

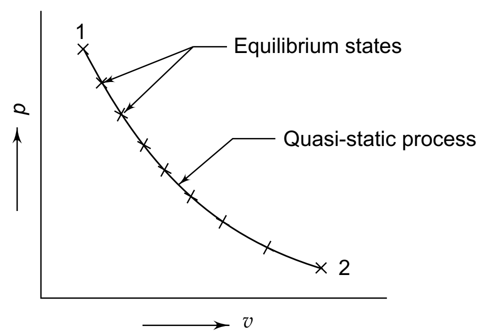


Fig. 4.7 *A Quasi-Static Process*

4.2 ZEROTH LAW OF THERMODYNAMICS

The property which distinguishes thermodynamics from other sciences is temperature. Temperature is associated with the ability to distinguish hot from cold. When two bodies at different temperatures are brought into contact, after some time they attain a common temperature and are then said to exist in thermal equilibrium.

When a body A is in thermal equilibrium with a body B, and also separately with a body C, then B and C will be in thermal equilibrium with each other.

This is known as the *zeroth law of thermodynamics*. It is the basis of temperature measurement.

4.3 WORK AND HEAT TRANSFER

A closed system and its surroundings can interact in two ways: (a) by work transfer, and (b) by heat transfer. These may be called *energy interactions* and these bring about changes in the properties of the system. Thermodynamics mainly studies these energy interactions and the associated property changes of the system.

4.3.1 Work Transfer

Work is one of the basic modes of energy transfer. In mechanics the action of a force on a moving body is identified as work. In mechanics work is defined as:

The work is done by a force as it acts upon a body moving in the direction of the force.

In thermodynamics, *work is said to be done by a system if the sole effect on things external to the system can be reduced to the raising of a weight*. The weight may not actually be raised, but the net effect external to the system would be the raising of a weight. Let us consider the battery and the motor in Fig. 4.8 as a system. The motor is driving a fan. The system is doing work upon the surroundings. When the fan is replaced by a pulley and a weight, as shown in Fig. 4.9, the weight may be raised with the pulley driven by the motor. The sole effect on things external to the system is then the raising of a weight.

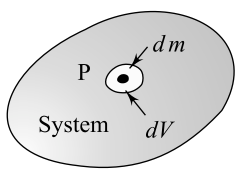


Fig. 4.8 *Battery-motor System Driving a Fan*

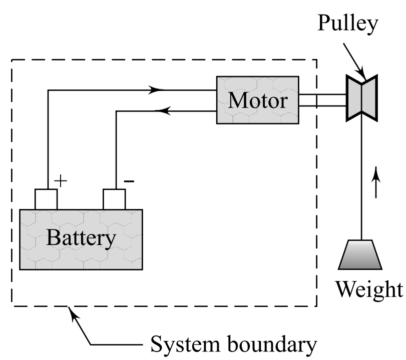


Fig. 4.9 *Work Transfer from a System*

When work is done by a system, it is arbitrarily taken to be positive, and when work is done on a system, it is taken to be negative.

The unit of work is N.m or Joule [1 Nm = 1 Joule].

4.3.2 *pdV*-Work or Displacement Work

Let the gas in the cylinder (Fig. 4.10) be a system having initially the pressure p_1 and volume V_1. The system is in thermodynamic equilibrium, the state of which is described by the coordinates p_1, V_1. The piston is the only boundary which moves due to gas pressure. Let the piston move out to a new final position 2, which is also a thermodynamic equilibrium state specified by pressure p_2 and volume V_2. At any intermediate point in the travel of the piston, let the pressure be p and the volume V. This must also be an equilibrium state. When the piston moves an infinitesimal distance dl, and if 'a' be the area of the piston, the force F acting on the piston $F = p.a.$ and the infinitesimal amount of work done by the gas on the piston

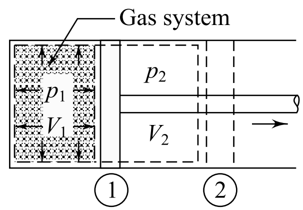


Fig. 4.10 *pdV Work*

$$dW = F \cdot dl = padl = pdV \tag{4.1}$$

where $dV = adl$ = infinitesimal displacement volume.

When the piston moves out from position 1 to position 2 with the volume changing from V_1 to V_2, the amount of work W done by the system will be

$$W_{1-2} = \int_{V_1}^{V_2} pdV$$

The magnitude of the work done is given by the area under the path 1–2, as shown in Fig. 4.11. *The integration* $\int pdV$ *can be performed only on a quasi-static path*.

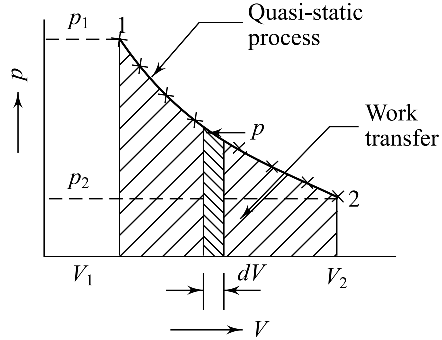


Fig. 4.11 *Quasi-Static pdV Work*

4.3.2.1 Path Function and Point Function

With reference to Fig. 4.12, it is possible to take a system from state 1 to state 2 along many quasi-static paths, such as A, B or C. Since the area under each curve represents the work for each process, the amount of work involved in each case is not a function of the end states of the process, and it depends on the path the system follows in going from state 1 to state 2. For this reason, work is called a *path function*, and $đW$ is an *inexact or imperfect differential*.

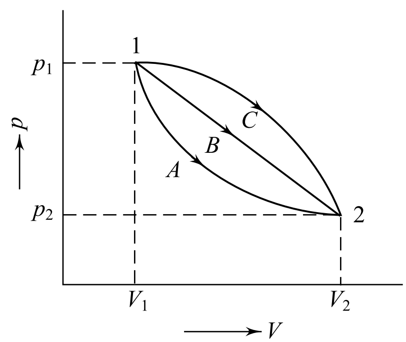


Fig. 4.12 *Work—A Path Function*

Thermodynamic properties are *point functions*, since for a given state, there is a definite value for each property. The change in a thermodynamic property of a system in a change of state is independent of the path the system follows during the change of state, and depends only on the initial and final states of the system. The differentials of point functions are *exact or perfect differentials*, and the integration is simply

$$\int_{V_1}^{V_2} dV = V_2 - V_1$$

The change in volume thus depends only on the end states of the system irrespective of the path the system follows.

On the other hand, work done in a quasi-static process between two given states depends on the path followed.

$$\int_1^2 đW \neq W_2 - W_1$$

Rather,

$$\int_1^2 đW = W_{1-2} \qquad \text{or} \qquad {}_1W_2$$

4.3.2.2 *pdV*-Work in Various Quasi-Static Processes

(a) Constant pressure process (Fig. 4.13) (isobaric or isopiestic process)

$$W_{1-2} = \int_{V_1}^{V_2} pdV = p(V_2 - V_1) \tag{4.2}$$

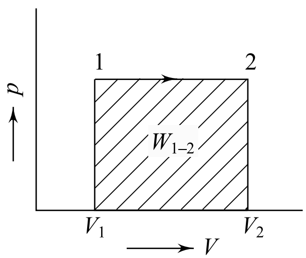


Fig. 4.13 *Constant Pressure Process*

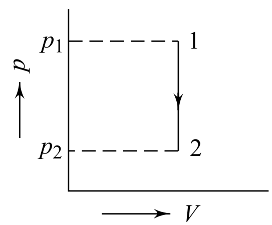


Fig. 4.14 *Constant Volume Process*

(b) Constant volume process (Fig. 4.14) (isochoric process)

$$W_{1-2} = \int pdV = 0 \tag{4.3}$$

(c) Process in which $pV = C$ (Fig. 4.15)

$$\therefore \qquad W_{1-2} = \int_{V_1}^{V_2} pdV \qquad pV = p_1 V_1 = C$$

$$p = \frac{(p_1 V_1)}{V}$$

$$W_{1-2} = p_1 V_1 \int_{V_1}^{V_2} \frac{dV}{V} = p_1 V_1 \ln \frac{V_2}{V_1}$$

$$= p_1 V_1 \ln \frac{p_1}{p_2} \tag{4.4}$$

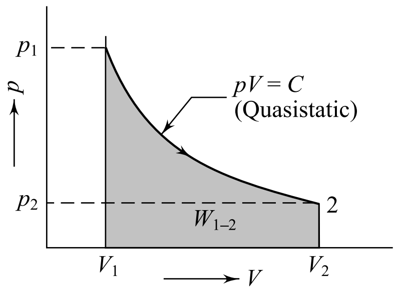


Fig. 4.15 *Process in Which pV = Constant*

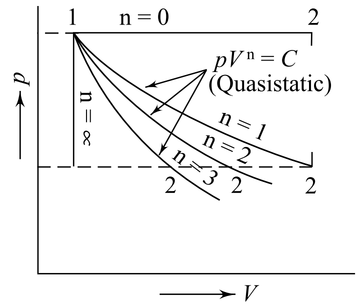


Fig. 4.16 *Process in which pV^n = Constant*

(d) Process in which $pV^n = C$, where n is a constant (Fig. 4.16).

$$pV^n = p_1 V_1^n = p_2 V_2^n = C$$

$$\therefore \qquad p = \frac{\left(p_1 V_1^n\right)}{V^n}$$

$$\therefore \qquad W_{1-2} = \int_{V_1}^{V_2} pdV = \int_{V_1}^{V_2} \frac{p_1 V_1^n}{V^n} \cdot dV = (p_1 V_1^n)\left[\frac{V^{-n+1}}{-n+1}\right]_{V_1}^{V_2}$$

$$= \frac{p_1 V_1^n}{1-n}(V_2^{1-n} - V_1^{1-n}) = \frac{p_2 V_2^n \times V_2^{1-n} - p_1 V_1^n \times V_1^{1-n}}{1-n}$$

$$= \frac{p_1 V_1 - p_2 V_2}{n-1} = \frac{p_1 V_1}{n-1}\left[1 - \left(\frac{p_2}{p_1}\right)^{n-1/n}\right] \tag{4.5}$$

4.3.3 Other Types of Work Transfer

There are forms of work other than pdV or displacement work. The following are the additional types of work transfer which may get involved in system-surroundings interactions.

(a) Shaft Work

When a shaft, taken as the system, is rotated by a motor, there is work transfer into the system. This is because the shaft can rotate a pulley which can raise a weight. If T is the torque applied to the shaft and $d\theta$ is the angular displacement of the shaft, the shaft work is

$$W = \int_1^2 Td\theta$$

and the shaft power is

$$W = \int_1^2 T\frac{d\theta}{d\tau} = T\omega$$

where ω is the angular velocity and T is considered a constant in this case.

(b) Flow Work

The flow work, significant only in a flow process or an open system, represents the energy transferred across the system boundary as a result of the energy imparted to the fluid by a pump, blower or compressor to make the fluid flow across the control volume. Flow work is analogous to displacement work. Let p be the fluid pressure in the plane of the imaginary piston, which acts in a direction normal to it (Fig. 4.17). The work done on this imaginary piston by the external pressure as the piston moves forward is given by

$$đW_{\text{flow}} = p\,dV, \tag{4.6}$$

where dV is the volume of fluid element about to enter the system.

$$\therefore \quad đW_{\text{flow}} = pv\,dm \tag{4.7}$$

where $dV = v\,dm$

Therefore, flow work at inlet (Fig. 4.17),

$$(dW_{\text{flow}})_{\text{in}} = p_1 v_1\,dm_1 \tag{4.8}$$

Similarly, flow work of the fluid element leaving the system is

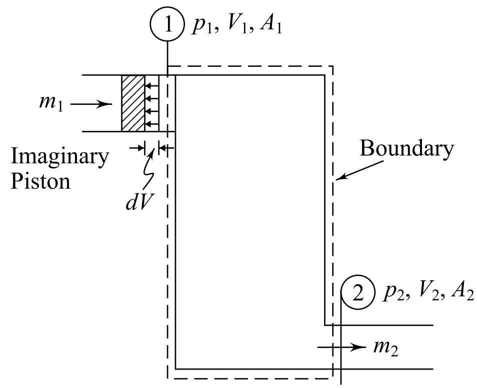


Fig. 4.17 *Flow Work*

$$(đW_{\text{flow}})_{\text{out}} = p_2 v_2\,dm_2 \tag{4.9}$$

The flow work per unit mass is thus

$$đW_{\text{flow}} = pv \tag{4.10}$$

It is the displacement work done at the moving system boundary.

4.3.4 Heat Transfer

Heat is defined as the form of energy that is transferred across a boundary *by virtue of a temperature difference*. The temperature difference is the 'potential' or 'force' and heat transfer is the 'flux'.

The direction of heat transfer is taken from the high temperature system to the low temperature system. *Heat flow into a system is taken to be positive, and heat flow out of a system is taken as negative* (Fig. 4.18). The symbol Q is used for heat transfer, i.e. the quantity of heat transferred within a certain time.

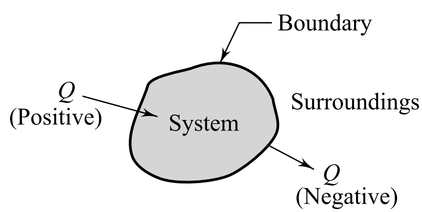


Fig. 4.18 *Direction of Heat Transfer*

The unit of heat is Joule in S.I. units.

The rate of heat transfer or work transfer is given in kW or W.

Heat Transfer—A Path Function

Heat transfer is a *path function*, that is, the amount of heat transferred when a system changes from state 1 to state 2 depends on the intermediate states through which the system passes, i.e. its path. Therefore dQ is an inexact differential, and we write

$$\int_1^2 đQ = Q_{1-2} \quad \text{or} \quad {}_1Q_2$$

4.3.5 Specific Heat

The *specific heat* of a substance is defined as the amount of heat required to raise a unit mass of the substance through a unit rise in temperature. The symbol c will be used for specific heat.

$$\therefore \qquad c = \frac{Q}{m \cdot \Delta t} \text{ J/kg K}$$

where Q is the amount of heat transfer (J), m, the mass of the substance (kg), and Δt, the rise in temperature (K).

Since heat is not a property, as explained later, so the specific heat is qualified with the process through which exchange of heat is made. For gases, if the process is at constant pressure, it is c_p, and if the process is at constant volume, it is C_v. For solids and liquids, however, the specific heat does not depend on the process.

4.4 LAWS OF THERMODYNAMICS

4.4.1 First Law for a Closed System Undergoing a Cycle

The transfer of heat and the performance of work may both cause the same effect in a system. Heat and work are different forms of the same entity, called energy, which is conserved. Energy which enters a system as heat may leave the system as work, or energy which enters the system as work may leave as heat.

Let us consider a closed system which consists of a known mass of water contained in an adiabatic vessel having a thermometer and a paddle wheel, as shown in Fig. 4.19. Let a certain amount of work W_{1-2} be done upon the system by the paddle wheel. The quantity of work can be measured by the fall of weight which drives the paddle wheel through a pulley. The system was initially at temperature t_1, the same as that of atmosphere, and after work transfer let the temperature rise to t_2. The pressure is always 1 atm. The process 1–2 undergone by the system is shown in Fig. 4.20 in generalized thermodynamic coordinates X, Y. Let the insulation now be removed. The system and the surroundings interact by heat transfer till the system returns to the original temperature t_1, attaining the condition of thermal equilibrium with the atmosphere. The amount of heat transfer Q_{2-1} from the system during this process, 2–1, shown in Fig. 4.20, can be estimated. The system thus executes a cycle, which consists of a

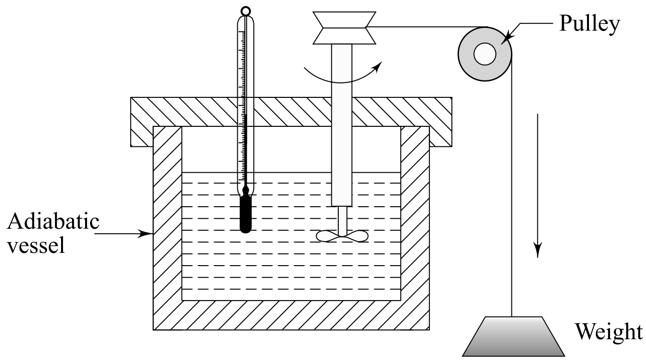


Fig. 4.19 *Adiabatic Work*

definite amount of work input W_{1-2} to the system followed by the transfer of an amount of heat Q_{2-1} from the system. It has been found that this W_{1-2} is always proportional to the heat Q_{2-1}, and the constant of proportionality is called the Joule's equivalent or the *mechanical equivalent of heat*. If the cycle involves many more heat and work quantities, the same result will be found. Expressed algebraically.

$$(\Sigma W)_{\text{cycle}} = J\,(\Sigma Q)_{\text{cycle}}$$

where J is the Joule's equivalent. This is also expressed in the form

$$\oint dW = J \oint dQ$$

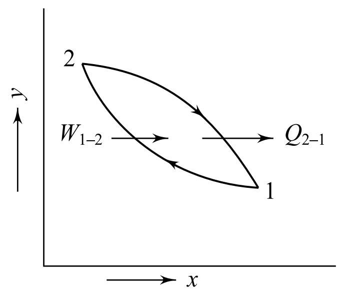


Fig. 4.20 *Cycle Completed by a System with Two Energy Interactions: Adiabatic Work Transfer W_{1-2} Followed by Heat Transfer Q_{2-1}*

where the symbol $\oint$ denotes the cyclic integral for the closed path. This is the *first law for a closed system undergoing a cycle*.

The constant of proportionality, J, is unity in S.I. system of units ($J = 1$ Nm/J).

4.4.2 First Law for a Closed System Undergoing a Change of State

The expression $(\Sigma W)_{\text{cycle}} = (\Sigma Q)_{\text{cycle}}$ applies only to systems undergoing cycles, and the algebraic summation of all energy transfer across system boundaries is zero. But if a system undergoes a change of state during which both heat transfer and work transfer are involved, the *net* energy transfer will be stored or accumulated within the system. If Q is the amount of heat transferred to the system and W is the amount of work transferred from the system during the process, the net energy transfer $(Q - W)$ will be stored in the system. Energy in storage is neither heat nor work, and is given the name *internal energy* or simply, the *energy* of the system.

Therefore $$Q - W = \Delta E$$

where ΔE is the increase in the energy of the system

or $$Q = \Delta E + W \tag{4.11}$$

Here Q, W, and ΔE are all expressed in the same units (in joules).

4.4.3 Different Forms of Stored Energy

In thermodynamics, energy can be in two forms: (i) Energy in transit, (ii) Energy in storage. Work and heat intractions are the forms of energy in transit, observed at the boundaries of a system. They are not properties of a system. They are path functions. Energy in storage, called internal energy, is a point or state function and hence a property of a system.

The symbol E refers to the total energy stored in a system. Basically there are two modes in which energy may be stored in a system:

(a) Macroscopic energy mode
(b) Microscopic energy mode

The macroscopic energy mode includes the macroscopic kinetic energy and potential energy of a system. Let us consider a fluid element of mass m having the centre of mass velocity $\overline{V}$ (Fig. 4.21). The macroscopic kinetic energy E_K of the fluid element by virtue of its motion is given by

$$E_K = \frac{m\overline{V}^2}{2}$$

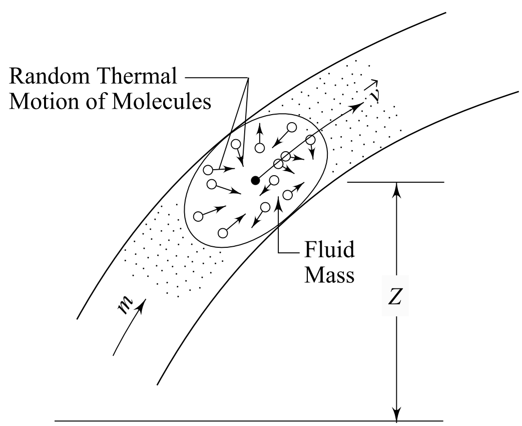


Fig. 4.21 *Macroscopic and Microscopic Energy*

If the elevation of the fluid element from an arbitrary datum is z, then the macroscopic potential energy E_p by virtue of its position is given by

$$E_p = mgz$$

The microscopic energy mode refers to the energy stored in the molecular and atomic structure of the system, which is called the *molecular internal energy* or *simply internal energy*, customarily denoted by the symbol U.

Other forms of energy which can also be possessed by a system are magnetic energy, electrical energy and surface (tension) energy. In the absence of these forms, the total energy E of a system is given by

$$E = \underbrace{E_K + E_P}_{\text{macro}} + \underbrace{U}_{\text{micro}}$$

where E_K, E_P, and U refer to the kinetic, potential and internal energy, respectively. In the absence of motion and gravity.

$$E_K = 0, \quad E_P = 0$$

$$E = U$$

and Eq. (4.11) becomes

$$Q = \Delta U + W \tag{4.12}$$

U is an extensive property of the system. The specific internal energy u is equal to U/m and its unit is J/kg.

In the differential forms, eqs (4.12) becomes

$$đQ = đU + đW \tag{4.13}$$

When only pdV work is present, the equation becomes

$$đQ = dU + pdV \tag{4.14}$$

or, in the integral form

$$Q = \Delta U + \int pdV \tag{4.15}$$

4.4.4 Specific Heat at Constant Volume

The specific heat of a substance at constant volume C_v is defined as the rate of change of specific internal energy with respect to temperature when the volume is held constant, i.e.

$$C_v = \left(\frac{\partial u}{\partial T}\right)_v$$

For constant volume process

$$(\Delta u)_v = \int_{T_1}^{T_2} C_v \cdot dT$$

The first law may be written for a closed stationary system composed of a unit mass of a pure substance for a process in the absence of work other than pdV work

$$đ\phi = dU + pdV$$

when the volume is held constant

$$(Q)_v = \int_{T_1}^{T_2} C_v \, dT \tag{4.16}$$

Heat transferred at constant volume increases the internal energy of the system.

4.4.5 Enthalpy

The enthalpy of a substance, h, is defined as

$$h = u + pv \tag{4.17}$$

It is an intensive property of a system (kJ/kg).

Internal energy change is equal to the heat transferred in a constant volume process involving no work other than pdV work. From Eq. (4.14), it is possible to drive an expression for the heat transfer in a constant pressure process involving no work other than pdV work. In such a process in a closed stationary system of unit mass of a pure substance

$$đQ = du + pdv$$

At constant pressure

$$pdv = d(pv)$$

$$\therefore \quad (đQ)_p = du + d(pv)$$

or

$$(đQ)_p = d(u + pv)$$

or

$$(đQ)_p = dh \tag{4.18}$$

where $h = u + pv$ is the *specific enthalpy*, a property of the system.

Heat transferred at constant pressure increases the enthalpy of a system.

For an ideal gas, the enthalpy becomes

$$h = u + RT$$

Since the internal energy of an ideal gas depends only on the temperature, the enthalpy of an ideal gas also depends on the temperature only, i.e.

$$h = f(T) \text{ only}$$

4.4.6 Specific Heat at Constant Pressure

The specific heat at constant pressure c_p is defined as the rate of change of enthalpy with respect to temperature when the pressure is held constant

$$c_p = \left(\frac{\partial h}{\partial T}\right)_p$$

Since h, T and p are properties, so c_p is a property of the system.

For a constant pressure process

$$(\Delta h)_p = \int_{T_1}^{T_2} c_p \, dT$$

The first law for a closed stationary system of unit mass

$$đQ = du + pdv$$

Again

$$h = u + pv$$

$$\therefore \quad dh = du + pdv + vdp$$

$$= dQ + vdp$$

$$\therefore \quad đQ = dh - vdp$$

$$\therefore \quad (đQ)_p = dh$$

or $$(Q)_p = (\Delta h)_p$$

$\therefore$ $$(Q)_p = \int_{T_1}^{T_2} c_p \, dT$$

c_p is a property of the system, just like c_v.

4.4.7 Perpetual Motion Machine of the First Kind—PMM1

The first law states the general principle of the conservation of energy. *Energy is neither created nor destroyed, but only gets transformed from one form to another.* There can be no machine which would continuously supply mechanical work without some other form of energy disappearing simultaneously (Fig. 4.22). Such a *fictitious machine* is called a *perpetual motion machine of the first kind*, or in brief, PMM1. *A PMM1 is thus impossible.*

The converse of the above statement is also true, i.e. there can be no machine which would continuously consume work without some other form of energy appearing simultaneously (Fig. 4.23).

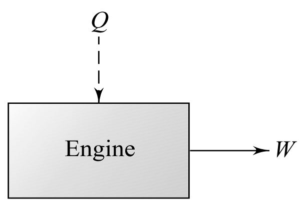


Fig. 4.22 *A PMM1*

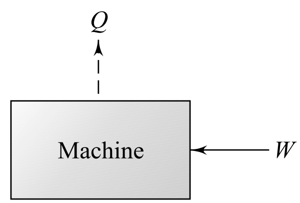


Fig. 4.23 *The Converse of PMM1*

4.4.8 First Law Applied to Flow Processes

4.4.8.1 Control Volume

For any system and in any process, the first law can be written as

$$Q = \Delta E + W$$

where E represents all forms of energy stored in the system.

When there is mass transfer across the system boundary, the system is called an open system. Most of the engineering devices are open systems involving the flow of fluids through them.

In the analysis of open system, instead of concentrating attention upon a certain quantity of fluid, which constitutes a moving system in flow processes, attention is focused upon a certain fixed region in space called a *control volume* through which the moving substance flows.

The broken line in Fig. 4.24 represents the surface of the control volume which is known as the *control surface*. Sections 1 and 2 allow mass transfer to take place, and Q and W are the heat and work interactions respectively.

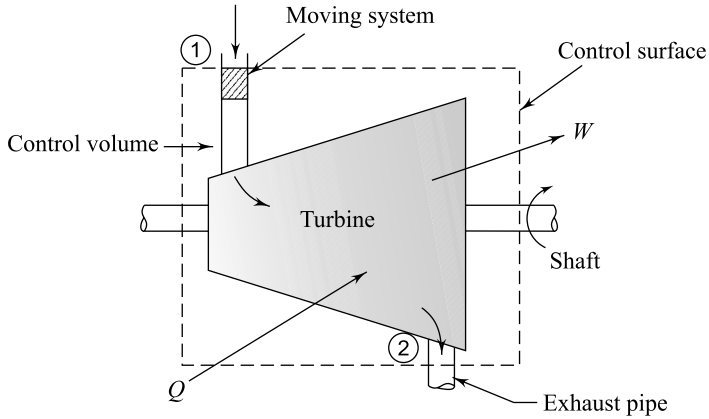


Fig. 4.24 *Flow Process Involving Work and Heat Interactions*

4.4.8.2 Steady Flow Process

'Steady flow' means that the rates of flow of mass and energy across the control surface are constant.

At the steady state of a system, any thermodynamic property will have a fixed value at a particular location, and will not alter with time. Thermodynamic properties may vary along space coordinates, but do not vary with time. 'Steady state' means that the state is steady or invariant with time.

4.4.8.3 Mass Balance and Energy Balance in a Simple Steady Flow Process

In Fig. 4.25, a steady flow system has been shown in which, one stream of fluid enters and an another stream leaves the control volume. There is no accumulation of mass or energy within the control volume, and the properties at any location within the control volume are steady with time. Sections 1.1 and 2.2 indicate, respectively, the entrance and exit of the fluid across the control surface. The following quantities are defined with reference to Fig. 4.25.

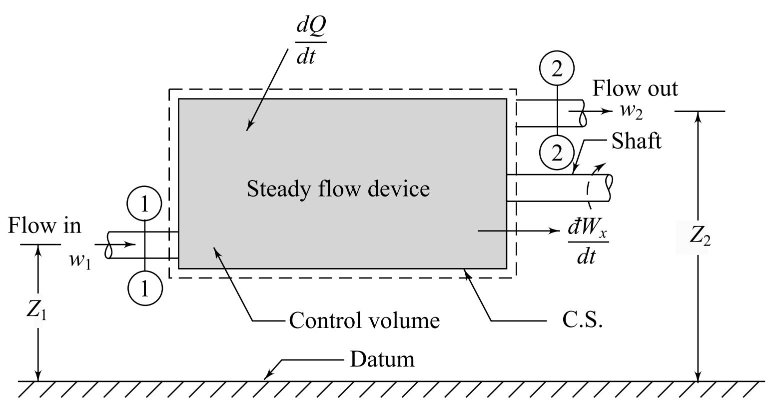


Fig. 4.25 *Steady Flow Process*

A_1, A_2—cross-section of stream, m^2
w_1, w_2—mass flow rate, kg/s
p_1, p_2—pressure, absolute, N/m^2
v_1, v_2—specific volume, m^3/kg
u_1, u_2—specific internal energy, J/kg
$\mathbf{V}_1, \mathbf{V}_2$—velocity, m/s
Z_1, Z_2—elevation above an arbitrary datum, *m*
$\frac{đQ}{d\tau}$—net rate of heat transfer through the control surface, J/s
$\frac{đW_x}{d\tau}$—net rate of work transfer through the control surface, J/s
exclusive of work done at Sections 1 and 2 in transferring the fluid through the control surface.
τ—time, s.
Subscripts 1 and 2 refer to the inlet and exit sections.

Mass Balance By the conservation of mass, if there is no accumulation of mass within the control volume, the mass flow rate entering must equal the mass flow rate leaving, or

$$w_1 = w_2$$

or
$$\frac{A_1\mathbf{V}_1}{v_1} = \frac{A_2\mathbf{V}_2}{v_2}$$

This equation is known as the *equation of continuity.*

Energy Balance In a flow process, the work transfer may be of two types: the *external work* and the *flow work*. In engineering thermodynamics the only kinds of external work of importance are *shear* (shaft or stirring) *work* and *electrical work*. In Fig. 4.25 the only external work occurs in the form of shaft work, W_x. The flow work, is the displacement work done by the fluid of mass dm_1 at the inlet Section 1 and that of mass dm_2 at the exit Section 2, which are $(-p_1v_1\, dm_1)$ and $(+p_2v_2\, dm_2)$ respectively. Therefore, the total work transfer is given by

$$W = W_x - p_1v_1dm_1 + p_2v_2dm_2$$

In the rate form,

$$\frac{đW}{d\tau} = \frac{đW_x}{d\tau} - p_1v_1\frac{dm_1}{d\tau} + p_2v_2\frac{dm_2}{d\tau}$$

or
$$\frac{đW}{d\tau} = \frac{đW_x}{d\tau} - w_1p_1v_1 + w_2p_2v_2 \tag{4.19}$$

Since there is no accumulation of energy, by the conservation of energy, the total rate of flow of all energy streams entering the control volume must equal the total rate of flow of all energy streams leaving the control volume. This may be expressed in the following equation

$$w_1 e_1 + \frac{đQ}{d\tau} = w_2 e_2 + \frac{đW}{d\tau}$$

Substituting for $\frac{đW}{d\tau}$ from Eq. (4.19)

$$\therefore \qquad w_1 e_1 + w_1 p_1 v_1 + \frac{đQ}{d\tau} = w_2 e_2 + w_2 p_2 v_2 + \frac{đW_x}{d\tau} \qquad (4.20)$$

where e_1 and e_2 refer to the energy carried into or out of the control volume with unit mass of fluid.

The specific energy e is given by

$$e = e_k + e_p + u$$

$$= \frac{\mathbf{V}^2}{2} + Zg + u$$

Substituting the expression for e in Equation (4.20)

$$w_1 \left(\frac{\mathbf{V}_1^2}{2} + Z_1 g + u_1 \right) + w_1 p_1 v_1 + \frac{đQ}{d\tau}$$

$$= w_2 \left(\frac{\mathbf{V}_2^2}{2} + Z_2 g + u_2 \right) + w_2 p_2 v_2 + \frac{đW_x}{d\tau}$$

or

$$w_1 \left(h_1 + \frac{\mathbf{V}_1^2}{2} + Z_1 g \right) + \frac{đQ}{d\tau}$$

$$= w_2 \left(h_2 + \frac{\mathbf{V}_2^2}{2} + Z_2 g \right) + \frac{đW_x}{d\tau} \qquad (4.21)$$

where $h = u + pv$.

And, since $\quad w_1 = w_2$, let $w = w_1 = w_2 = \frac{dm}{d\tau}$

Dividing Equation (4.21) by $\frac{dm}{d\tau}$

$$h_1 + \frac{V_1^2}{2} + Z_1 g + \frac{đQ}{dm}$$

$$= h_2 + \frac{V_2^2}{2} + Z_2 g + \frac{đW_x}{dm} \qquad (4.22)$$

Equations (4.21) and (4.22) are known as *steady flow energy equations* (S.F.E.E.), for a single stream of fluid entering and a single stream of fluid leaving the control volume.

4.4.8.4 Some Examples of Steady Flow Processes

The following examples illustrate the applications of the steady flow energy equation in some of the engineering systems.

(a) Nozzle and Diffusor A nozzle is a device which increases the velocity or K.E. of a fluid at the expense of its pressure drop, whereas a diffusor increases the pressure of a fluid at the expense of its K.E. Figure 4.26 shows a nozzle which is insulated. The steady flow energy equation of the control surface gives

$$h_1 + \frac{\mathbf{V}_1^2}{2} + Z_1 g + \frac{đQ}{dm} = h_2 + \frac{\mathbf{V}_2^2}{2} + Z_2 g + \frac{đW_x}{dm}$$

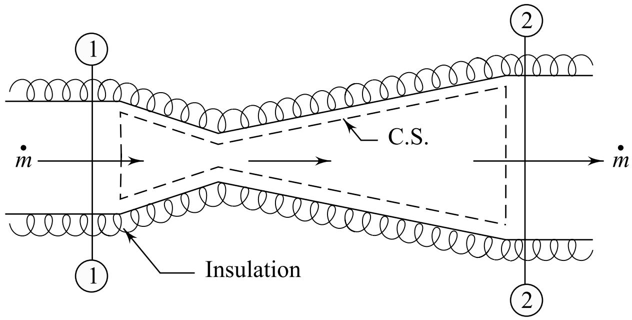


Fig. 4.26 *Steady Flow Process Involving Two Fluid Streams at the Inlet and Exit of the Control Volume*

Here $\frac{đQ}{dm} = 0$, $\frac{đW_x}{dm} = 0$, and the change in potential energy is zero. The equation reduces to

$$h_1 + \frac{\mathbf{V}_1^2}{2} = h_2 + \frac{\mathbf{V}_2^2}{2} \tag{4.23}$$

When the inlet velocity or the 'velocity of approach' $\mathbf{V}_1$ is small compared to the exit velocity $\mathbf{V}_2$, Eq. (4.23) becomes

$$h_1 = h_2 + \frac{\mathbf{V}_2^2}{2}$$

or

$$\mathbf{V}_2 = \sqrt{2(h_1 - h_2)} \text{ m/s}$$

where $(h_1 - h_2)$ is in J/kg.

(b) Throttling Device When a fluid flows through a constricted passage, like a partially opened valve, an orifice, or a porous plug, there is an appreciable drop in pressure, and the flow is said to be throttled. Figure 4.27 shows the process of throttling by a partially opened valve on a fluid flowing in an insulated pipe. In the steady-flow energy Eq. (4.22),

$$\frac{đQ}{dm} = 0, \quad \frac{đW_x}{dm} = 0$$

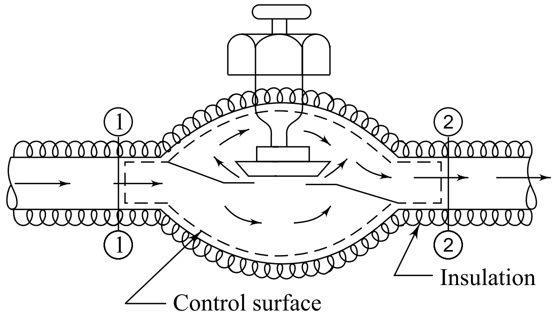


Fig. 4.27 *Flow Through a Valve*

and the changes in P.E. are very small and ignored. Thus, the S.F.E.E. reduces to

$$h_1 + \frac{\mathbf{V}_1^2}{2} = h_2 + \frac{\mathbf{V}_2^2}{2}$$

Often the pipe velocities in throttling are so low that the K.E. terms are also negligible. So

$$h_1 = h_2$$

or the enthalpy of the fluid before throttling is equal to the enthalpy of the fluid after throttling.

4.5 SECOND LAW OF THERMODYNAMICS

4.5.1 Qualitative Difference Between Heat and Work

The first law of thermodynamics states that a certain energy balance will hold when a system undergoes a change of state or a thermodynamic process. But it does not give any information on whether that change of state or the process is at all feasible or not. The first law cannot indicate whether a metallic bar of uniform temperature can spontaneously become warmer at one end and cooler at the other. All that the law can state is that if this process did occur, the energy gained by one end would be exactly equal to that lost by the other. *It is the second law of thermodynamics which provides the criterion as to the probability of various processes.*

Spontaneous processes in nature occur only in one direction. Heat always flows from a body at a higher temperature to a body at a lower temperature, water always flows downward, time always flows in the forward direction. The reverse of these never happens spontaneously. This directional law puts a limitation on energy transformation other than that imposed by the first law.

Joule's experiments amply demonstrate that energy, when supplied to a system in the form of work, can be completely converted into heat (work transfer $\rightarrow$ internal energy increase $\rightarrow$ heat transfer). But the complete conversion of heat into work in a cycle is not possible. *So heat and work are not completely interchangeable forms of energy.*

When work is converted into heat, we always have

$$W \underset{\rightarrow}{=} Q$$

but when heat is converted into work in a complete closed cycle process

$$Q \underset{\longrightarrow}{>} W$$

The arrow indicates the direction of energy transformation. Thus work is said to be a *high grade energy* and heat a *low grade energy. The complete conversion of low grade energy into high grade energy in a cycle is impossible.*

4.5.2 Cyclic Heat Engine

A heat engine cycle is a thermodynamic cycle in which there is a net heat transfer to the system and a net work transfer *from* the system. The system which executes a heat engine cycle is called a *heat engine*.

If heat Q_1 is transferred to the system, work W_E is done by the system, work W_c is done upon the system, and then heat Q_2 is rejected from the system. The system is brought back to the initial state through all these four successive processes which constitute a heat engine cycle.

The net heat transfer in a cycle to either of the heat engines

$$Q_{\text{net}} = Q_1 - Q_2$$

and the net work transfer in a cycle

$$W_{\text{net}} = W_E - W_C$$

By the first law of thermodynamics, we have

$$\sum_{cycle} Q = \sum_{cycle} W$$

$$\therefore \qquad Q_{\text{net}} = W_{\text{net}}$$

$$\text{or} \qquad Q_1 - Q_2 = W_E - W_C$$

The efficiency of a heat engine or a heat engine cycle is defined as follows:

$$\eta = \frac{\text{Net work output of the cycle}}{\text{Total heat input to the cycle}}$$

$$= \frac{W_{net}}{Q_1}$$

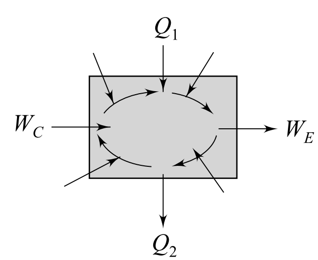


Fig. 4.28 *Cyclic Heat Engine with Energy Interactions Represented in a Block Diagram*

$$\eta = \frac{W_{\text{net}}}{Q_1} = \frac{Q_1 - Q_2}{Q_1}$$

$$\eta = 1 - \frac{Q_2}{Q_1}$$

This is also known as the *thermal efficiency* of a heat engine cycle.

4.5.3 Thermal Energy Reservoirs

A thermal energy reservoir (TER) is defined as a large body of infinite heat capacity, which is capable of absorbing or rejecting an unlimited quantity of heat without suffering appreciable changes in its thermodynamic coordinates. The changes that do take place in the large body as heat enters or leaves are so very slow and so very minute that all processes within it are quasi-static.

The thermal energy reservoir TER_H from which heat Q_1 is transferred to the system operating in a heat engine cycle is called the *source*. The thermal energy reservoir TER_L to which heat Q_2 is rejected from the system during a cycle is the *sink*. A typical source is a constant temperature furnace where fuel is continuously burnt, and a typical sink is a river or sea or the atmosphere itself.

4.5.4 Refrigerator and Heat Pump

A *refrigerator* is a device which, operating in a cycle, maintains a body at a temperature lower than the temperature of the surroundings. Let the body A (Fig. 4.29) be maintained at t_2, which is lower than the ambient temperature t_1. In order to maintain body A at the constant temperature t_2, heat has to be removed from the body at the same rate at which heat is leaking into the body. In a refrigerator cycle, attention is concentrated on the body A. Q_2 and W are of primary interest. Just like efficiency in a heat engine cycle, there is a performance parameter in a refrigerator cycle, called the *coefficient of performance*, abbreviated to COP, which is defined as

$$\text{COP} = \frac{\text{Desired effect}}{\text{Work input}} = \frac{Q_2}{W}$$

$$\therefore \qquad [\text{COP}]_{\text{ref}} = \frac{Q_2}{Q_1 - Q_2} \tag{4.24}$$

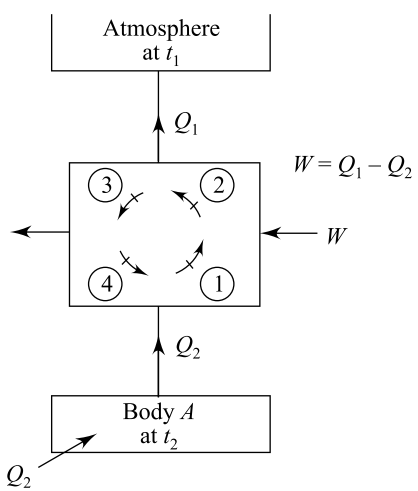


Fig. 4.29 *A Cyclic Refrigeration Plant*

Similarly, a *heat pump* is a device which, operating in a cycle, maintains a body, say B (Fig. 4.30), at a temperature higher than the temperature of the surroundings. The attention is here focussed on the high temperature body B.

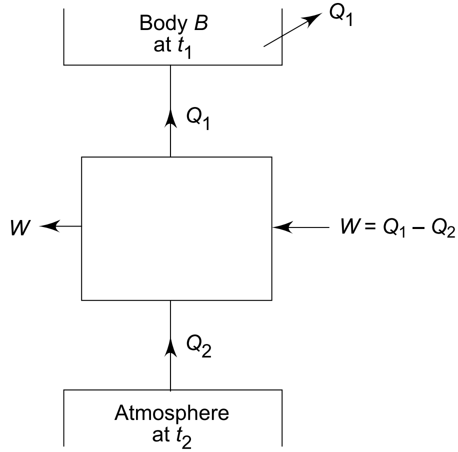


Fig. 4.30 *A Cyclic Heat Pump*

Here Q_1 and W are of primary interest, and the COP is defined as

$$\text{COP} = \frac{Q_1}{W}$$

$$\therefore \qquad [\text{COP}]_{H.P.} = \frac{Q_1}{Q_1 - Q_2} \tag{4.25}$$

From Eqs. (4.24) and (4.25), it is found that

$$[\text{COP}]_{H.P.} = [\text{COP}]_{\text{ref}} + 1$$

4.5.5(a) Kelvin-Planck Statement of Second Law

The efficiency of a heat engine is given by

$$\eta = \frac{W_{net}}{Q_1} = 1 - \frac{Q_2}{Q_1}$$

Experience shows that $W_{\text{net}} < Q_1$, since heat Q_1 transferred to a system cannot be completely converted to work in a cycle. Therefore, η is less than unity. A heat engine can never be 100% efficient. Therefore, $Q_2 > 0$, i.e. there has always to be a heat rejection. To produce net work in a thermodynamic cycle, a heat engine has thus to exchange heat with two reservoirs, the source and the sink.

The *Kelvin-Planck statement* of the second law states: *It is impossible for a heat engine to produce net work in a complete cycle if it exchanges heat only with bodies at a single fixed temperature.*

If $Q_2 = 0$ (i.e. $W_{net} = Q_1$, or $\eta = 1.00$), the heat engine will produce net work in a complete cycle by exchanging heat with only one reservoir, thus violating the Kelvin-Planck statement (Fig. 4.30). Such a heat engine is called a *perpetual motion machine of the second kind*, abbreviated to PMM2. A PMM2 is impossible.

A heat engine has, therefore, to exchange heat with two thermal energy reservoirs at two different temperatures to produce net work in a complete cycle. So long as there is a difference in temperature, motive power (i.e. work) can be produced. If the bodies with which the heat engine exchanges heat are of finite heat capacities, work will be produced by the heat engine till the temperatures of the two bodies are equalized.

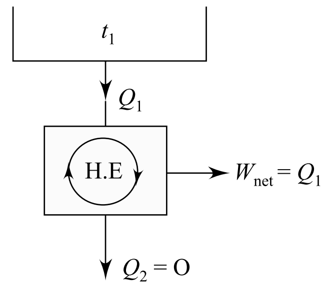


Fig. 4.31 A *PMM2*

4.5.5(b) Clausius' Statement of the Second Law

Heat always flows from a body at a higher temperature to a body at a lower temperature. The reverse process never occurs spontaneously.

Clausius' statement of the second law gives: *It is impossible to construct a device which, operating in a cycle, will produce no effect other than the transfer of heat from a cooler to a hotter body.*

Heat cannot flow of itself from a body at a lower temperature to a body at a higher temperature. Some work must be expended to achieve this.

4.5.6 Carnot Cycle

A reversible cycle is an ideal hypothetical cycle in which all the processes constituting a cycle are reversible. Carnot cycle is a reversible cycle. For a stationary system, as in piston and cylinder machine, the cycle consists of the following four successive processes. (Fig. 4.31)

(a) A reversible isothermal process 1-2 in which heat Q_1 enters the system at temperature t_1 reversibly from a constant temperature source at t_1 and the fluid expands isothermally and reversibly at the same temperature when the cylinder cover is in contact with the diathermic cover *A*.

$$Q_{1\text{-}2} = W_{1\text{-}2} = mRT_1 \log[V_2 / V_1]$$

(b) A reversible adiabatic process 2-3 in which the diathermic cover *A* is replaced by adiabatic cover *B*, and work *W* is done by the system adiabatically and reversibly at the expense of internal energy. The temperature decreases from T_1 to T_2.

(c) A reversible isothermal process 3-4 in which insulated cover *B* is replaced by the diathermic cover A and heat Q_2 leaves the system at T_2 to a constant temperature sink T_2 while the fluid is compressed isothermally and reversibly.

$$Q_{3\text{-}4} = W_{3\text{-}4} = mRT_2 \log[V_3 / V_4]$$

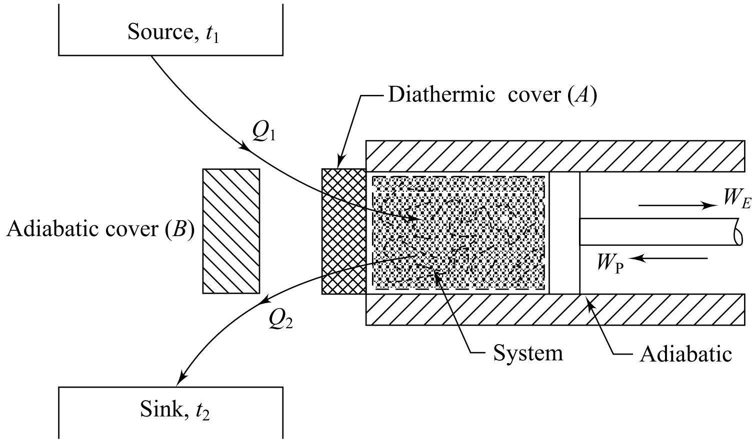


Fig. 4.32 *Carnot Heat Engine—Stationary System*

(d) A reversible adiabatic process 4-1 in which the adiabatic cover B replaces the cover A, and the work W is done on the system reversibly and adiabatically, and the internal energy of the system further increases and the temperature further increases form T_2 to T_1.

The process 2-3 and 4-1 are reversible adiabatic processes

$$T_2 / T_3 = [V_3 / V_2]\gamma^{-1} = T_1 / T_2$$

And

$$T_1 / T_4 = [V_4 / V_1]\gamma^{-1} = T_1 / T_2$$

From the above equation

$$[V_3 / V_2] = [V_4 / V_1]$$
$$[V_3 / V_4] = [V_2 / V_1]$$

The efficiency of reversible engine = work done / heat supplied

$$\eta = WD/HS = [Q_{1\text{-}2} - Q_{3\text{-}4}] / Q_{1-2}$$
$$\eta = (Q_1 - Q_2)/Q_1 = 1 - (T_2/T_1)$$
$$\eta = (T_1 - T_2)/T_1$$

It is observed here that as T_2 decreases and T_1 increases, the η of the reversible cycle increases.

Since η is always less than unity therefore T_2 is always greater than zero.

The COP of a refrigerator is given by

$$[COP_{\text{ref}}]_{\text{rev}} = Q_2/(Q_1 - Q_2) = T_2 / (T_1 - T_2)$$

for reversible heat pump

$$[COP_{\text{HP}}]_{\text{rev}} = Q_1/(Q_1 - Q_2) = T_1 / (T_1 - T_2)$$

4.6 ENTROPY

The first law of thermodynamics was stated in terms of cycles first and it was shown that the cyclic integral of heat is equal to the cyclic integral of work. When the first law was applied for thermodynamic processes, the existence of a property, the internal energy, was found. Similarly, the second law was also first stated in terms of cycles executed by systems. When applied to processes, the second law also leads to the definition of a new property, known as entropy. If the first law is said to be the law of internal energy, then second law may be stated to be the law of entropy. In fact, *thermodynamics is the study of three E's, namely, energy, equilibrium and entropy*.

If the system is taken from an initial equilibrium state i to a final equilibrium state f by an *irreversible path*, since entropy is a point or state function, and the entropy change is independent of the path followed, the non-reversible path is to be replaced by a reversible path to integrate for the evaluation of entropy change in the irreversible process (Fig. 4.33).

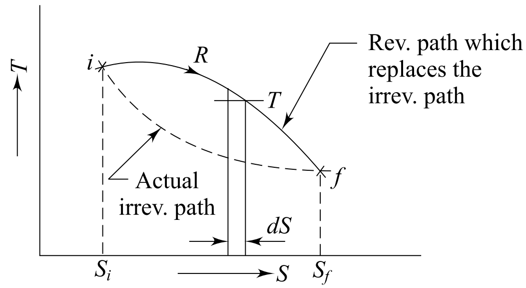


Fig. 4.33 *Integration can be Done Only on a Reversible Path*

$$S_f - S_i = \int_i^f \frac{đQ_{\text{rev}}}{T} = (\Delta S)_{\text{irrev path}}$$

Integration can be performed only on a reversible path.

$$Q_{\text{rev}} = T(S_f - S_i)$$

Example 4.1 A stationary mass of gas is compressed without friction from an initial state of 0.3 m^3 and 0.105 MPa to a final state of 0.15 m^3 and 0.105 MPa, the pressure remaining constant during the process. There is a transfer of 37.6 kJ of heat from the gas during the process. How much does the internal energy of the gas change?

Solution: First law for a stationary system in a process gives

$$Q = \Delta U + W$$

or
$$Q_{1-2} = U_2 - U_1 + W_{1-2} \tag{1}$$

Here
$$W_{1-2} = \int_{V_1}^{V_2} pdV = p(V_2 - V_1)$$

$$= 0.105\ (0.15 - 0.30)\ \text{MJ} = -\ 15.75\ \text{kJ}$$

$$Q_{1-2} = -\ 37.6\ \text{kJ}$$

∴ Substituting in Eq. (1)

$$-\ 37.6\ \text{kJ} = U_2 - U_1 - 15.75\ \text{kJ}$$

∴
$$U_2 - U_1 = \mathbf{-\ 21.85\ kJ}$$

The internal energy of the gas decreases by 21.85 kJ in the process.

Example 4.2 When a system is taken from state *a* to state *b*, in Fig. 4.34 along path *acb*, 84 kJ of heat flow into the system, and the system does 32 kJ of work. (a) How much will the heat that flows into the system along path *adb* be, if the work done is 10.5 kJ? (b) When the system is returned from *b* to *a* along the curved path, the work done on the system is 21 kJ. Does the system absorb or liberate heat, and how much of the heat is absorbed or liberated? (c) If $U_a = 0$ and $U_d = 42$ kJ, find the heat absorbed in the processes *ad* and *db*.

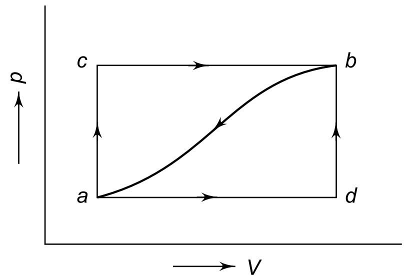


Fig. 4.34

Solution:

$$Q_{acb} = 84 \text{ kJ}$$
$$W_{acb} = 32 \text{ kJ}$$

We have

$$Q_{acb} = U_b - U_a + W_{acb}$$

$$\therefore \quad U_b - U_a = 84 - 32 = \mathbf{52\ kJ}$$

(a) $$Q_{adb} = U_b - U_a + W_{adb}$$
$$= 52 + 10.5 = \mathbf{62.5\ kJ}$$

(b) $$Q_{b-a} = U_a - U_b + W_{b-a}$$
$$= -52 - 21 = \mathbf{-73\ kJ}$$

The system liberates 73 kJ of heat

(c) $$W_{adb} = W_{ad} + W_{db} = W_{ad} = 10.5 \text{ kJ}$$

$$\therefore \quad Q_{ad} = U_d - U_a + W_{ad}$$
$$= 42 - 0 + 10.5 = 52.5 \text{ kJ}$$

Now $$Q_{adb} = 62.5 \text{ kJ} = Q_{ad} + Q_{db}$$

$$\therefore \quad Q_{db} = 62.5 - 52.5 = \mathbf{10\ kJ}$$

Example 4.3 A piston and cylinder machine contains a fluid system which passes through a complete cycle of four processes. During a cycle, the sum of all heat transfers is – 170 kJ. The system completes 100 cycles per min. Complete the following table showing the method for each item, and compute the net rate of work output in kW.

Process	Q (kJ/min)	W (kJ/min)	ΔE (kJ/min)
a–b	0	2,170	—
b–c	21,000	0	—
c–d	–2,100	—	–36,600
d–a	—	—	—

Solution: Process *a–b*:

$$Q = \Delta E + W$$
$$0 = \Delta E + 2170$$
$$\therefore \quad \Delta E = -2170 \text{ kJ/min}$$

Process *b–c*:

$$Q = \Delta E + W$$
$$21{,}000 = \Delta E + 0$$
$$\therefore \quad \Delta E = 21{,}000 \text{ kJ/min}$$

Process *c–d*:

$$Q = \Delta E + W$$
$$-2100 = -36{,}600 + W$$
$$\therefore \quad W = 34{,}500 \text{ kJ/min}$$

Process *d–a*:

$$\sum_{\text{cycle}} Q = -170 \text{ kJ}$$

The system completes 100 cycles/min.

$$\because \quad Q_{ab} + Q_{bc} + Q_{cd} + Q_{da} = -17{,}000 \text{ kJ/min}$$
$$0 + 21{,}000 - 2100 + Q_{da} = -17{,}000$$
$$\therefore \quad Q_{da} = -35{,}900 \text{ kJ/min}$$

Now $\oint dE = 0$, since cyclic integral of any property is zero.

$$\therefore \quad \Delta E_{a-b} + \Delta E_{b-c} + \Delta E_{c-d} + \Delta E_{d-a} = 0$$
$$-2170 + 21{,}000 - 36{,}600 + \Delta E_{d-a} = 0$$
$$\therefore \quad \Delta E_{d-a} = 17{,}770 \text{ kJ/min}$$
$$\therefore \quad W_{d-a} = Q_{d-a} - \Delta E_{d-a}$$
$$= -35{,}900 - 17{,}770 = \mathbf{-53{,}670 \text{ kJ/min}}$$

The table becomes

Process	Q (kJ/min)	W (kJ/min)	ΔE (kJ/min)
a–b	0	2170	– 2170
b–c	21,000	0	21,000
c–d	–2100	34,500	– 36,600
d–a	–35,900	– 53,670	17,770

Since $\sum_{\text{cycle}} Q = \sum_{\text{cycle}} W$

Rate of work output

$$= -17{,}000 \text{ kJ/min} = \mathbf{-283.3 \text{ kW}}$$

Example 4.4 A cyclic heat engine operates between a source temperature of 800°C and a sink temperature of 30°C. What is the least rate of heat rejection per kW net output of the engine?

Solution: For a reversible engine, the rate of heat rejection will be minimum (Fig. 4.35).

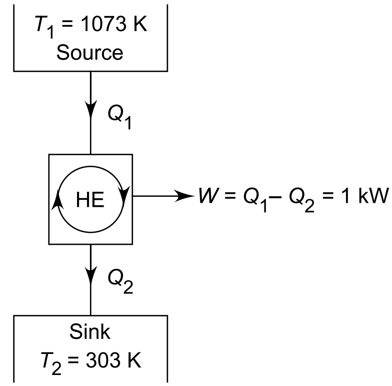


Fig. 4.35

$$\eta_{\max} = \eta_{\text{rev}} = 1 - \frac{T_2}{T_1}$$

$$= 1 - \frac{30 + 273}{800 + 273}$$

$$= 1 - 0.282 = 0.718$$

Now $$\frac{W_{\text{net}}}{Q_1} = \eta_{\max} = 0.718$$

$\therefore$ $$Q_1 = \frac{1}{0.718} = 1.392 \text{ kW}$$

Now $$Q_2 = Q_1 - W_{\text{net}} = 1.392 - 1 = \mathbf{0.392\ kW}$$

This is the least rate of heat rejection.

Example 4.5 A domestic food freezer maintains a temperature of – 15°C. The ambient air temperature is 30°C. If heat leaks into the freezer at the continuous rate of 1.75 kJ/s what is the least power necessary to pump this heat out continuously?

Solution: Freezer temperature,

$$T_2 = -15 + 273 = 258 \text{ K}$$

Ambient air temperature,

$$T_1 = 30 + 273 = 303 \text{ K}$$

The refrigerator cycle removes heat from the freezer at the same rate at which heat leaks into it (Fig. 4.36).

For minimum power requirement

$$\frac{Q_2}{T_2} = \frac{Q_1}{T_1}$$

$\therefore$ $$Q_1 = \frac{1.75}{2.8} \times 303 = 2.06 \text{ kJ/s}$$

$\therefore$ $$W = Q_1 - Q_2$$

$$= 2.06 - 1.75 = 0.31 \text{ kJ/s} = \mathbf{0.31\ kW}$$

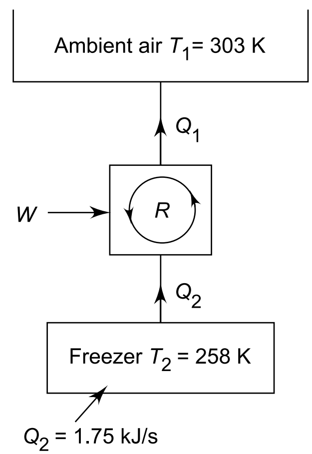


Fig. 4.36

4.7 PROPERTIES OF PURE SUBSTANCE (WATER)

4.7.1 Introduction

A pure substance is defined as one that is homogeneous and invariable in chemical composition throughout its mass. The relative proportions of the chemical elements constituting the substance are also constant. Atmospheric air, steam water mixture and combustion products of fuel are regarded as pure substances.

4.7.2 Heat Addition During the Steam Formation

Consider unit mass of ice at –10° and 1 atm contained in a cylinder and a piston assembly. And the piston is loaded so that the pressure is held constant Fig. 4.37. Let the change in temperature be plotted on temperature and heat addition diagram. The distinct regimes of heating , are as shown in Fig. 4.38.

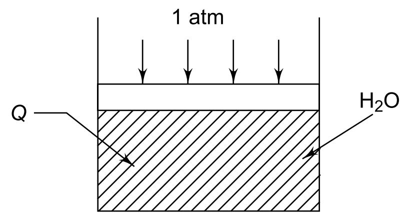


Fig. 4.37 *Heating of H_2O at a Constant Pressure of 1 Atm*

- 1-2 the temperature of ice increases from -10°C to 0 °C during the heat addition. At state 2 the ice starts melting.

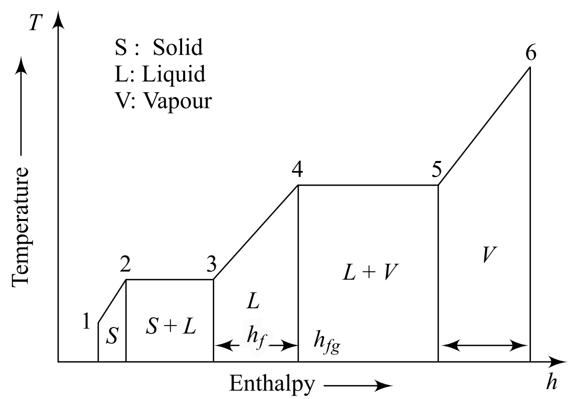


Fig. 4.38

- 2-3 with the further addition of heat, ice melts into water at a constant temperature. At state 3, the complete conversion of ice into water takes place. The quantity of heat required, to convert one kg of ice at 0 °C to water at 0 °C i.e. at the same temperature and at constant pressure is called *latent heat of fusion*. It is represented by a line 2-3.
- 3-4 the temperature of water increases with further addition of heat from 0 °C to 100 °C i.e. upto the boiling point. The boiling point depends upon the pressure. The quantity of heat required to heat water from state 3 to state 4 is called *sensible heat*.

- 4-5 when further heat is added, the water starts boiling at state 4 and continuous up to state 5. This phase change from liquid to vapor occurs at constant temperature of 100 °C (the pressure being held constant at 1 atm). Then, the quantity of heat required to convert 1 kg of water at 100 °C (boiling point or saturation temperature) to steam at the same temperature is called *latent heat of vaporization*. The steam at state 5 is dry and saturated.
- 5-6 when further heat is added to dry and saturated steam at state 5, once again the temperature increases. The steam obtained during 5-6 is called *superheated steam*.

4.7.3 *p*-*v* Diagram for a Pure Substance

Again consider a unit mass of ice at – 10°C and 1 atm contained in a cylinder and piston assembly (Fig. 4.36). Let the ice be heated slowly so that its temperature is always uniform. The changes which occur in the mass of water would be traced as the temperature is increased while the pressure is held constant. Let the state changes of water be plotted on *p*–*v* co-ordinates. The distinct regimes of heating, as shown in Fig. 4.398, are:

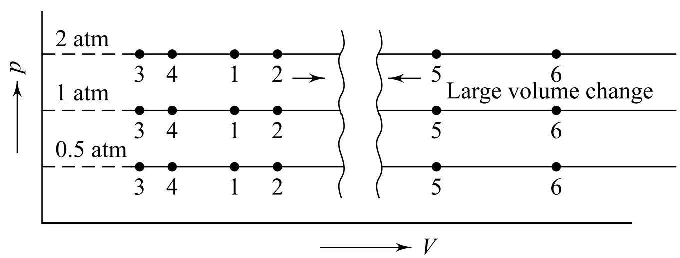


Fig. 4.39 *Changes in the Volume of Water During Heating at Constant Pressure*

1–2 The temperature of ice increases from – 10°C to 0°C. The volume of ice would increase, as would be the case for any solid upon heating. At state 2, i.e. 0°C, the ice would start melting.

2–3 Ice melts into water at a constant temperature of 0°C. At state 3, the melting process ends. *There is a decrease in volume, which is a peculiarity of water*.

3–4 The temperature of water increases, upon heating, from 0°C to 100°C. The volume of water increases because of thermal expansion.

4–5 The water starts boiling at state 4 and boiling ends at state 5. This phase change from liquid to vapour occurs at a constant temperature of 100°C (the pressure being constant at 1 atm). There is a large increase in volume.

5–6 The vapour is heated to, say, 250°C (state 6). The volume of vapour increases from state 5 to state 6.

Water existed in the solid phase between 1 and 2, in the liquid phase between 3 and 4, and in the gas phase beyond 5. Between 2 and 3, the solid changed into the liquid phase by absorbing the latent heat of fusion and between 4 and 5, the liquid changed into the vapour phase by absorbing the latent heat of vaporization, both at constant temperature and pressure.

The states 2, 3, 4 and 5 are known as *saturation states*. A saturation state is a state from which a change of phase may occur without a change of pressure or temperature. State 2 is a *saturated solid state* because a solid can change into liquid at constant pressure and temperature from state 2. States 3 and 4 are both saturated liquid states. In state 3, the liquid is saturated with respect to solidification, whereas in state 4, the liquid is saturated with respect to vaporization. State 5 is a *saturated vapour state*, because from state 5, the vapour can condense into liquid without a change of pressure or temperature.

If the heating of ice at – 10°C to steam at 250°C were done at a constant pressure of 2 atm, similar regimes of heating would have been obtained with similar saturation states 2, 3, 4 and 5, as shown in Fig. 4.40. All the state changes of the system can similarly be plotted on the *p-v* coordinates, when it is heated at different constant pressures. All the saturated solid states 2 at various pressures are joined by a line, as shown in Fig. 4.40.

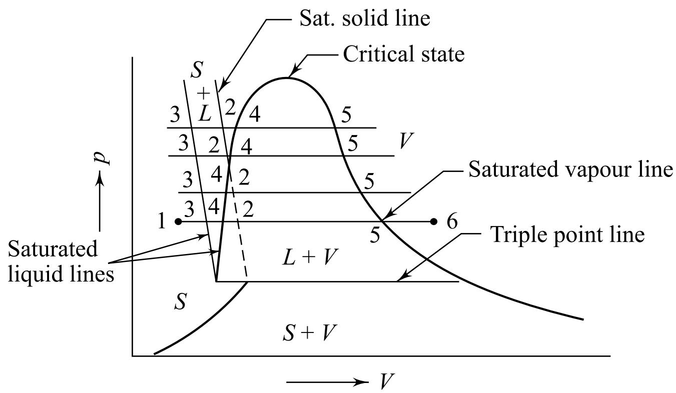


Fig. 4.40 *p-v Diagram of Water, Whose Volume Decreases on Melting*

Similarly, all the saturated liquid states 3 with respect to solidification, all the saturated liquid states 4 with respect to vaporization, and all the saturated vapour states 5, are joined together.

Since, Liquid is, most often, the working fluid in power cycles, etc. and interest is often confined to the liquid-vapour regions only. So to locate the state points, the solid regions from Figs 4.40 can be omitted. The *p-v* diagram then becomes as shown in Fig. 4.41. If the vapour at state *A* is compressed slowly and isothermally, the pressure will rise until there is saturated vapour at point *B*. If the compression is continued, condensation takes place, the pressure remaining constant so long as the temperature remains constant. At any point between *B* and *C*, the liquid and vapour are in equilibrium. Since a very large increase in pressure is needed to compress the liquid, line *CD* is almost vertical. *ABCD* is a typical *isotherm* of a pure substance on a *p-v* diagram. Some isotherms are shown in Fig. 4.41. As the temperature increases, the liquid-vapour transition, as represented by *BC*, decreases, and becomes zero at the critical point. Below the critical point only, there is a liquid-vapour transition zone, where a saturated liquid, on heating, absorbs the latent heat of vaporization, and becomes saturated vapour at a constant pressure and temperature. Similarly, a saturated vapour, on cooling, releases the latent heat of condensation at constant pressure and temperature to become saturated liquid. Above the critical point, however, a liquid, upon heating, suddenly *flashes* into vapour, or a vapour, upon cooling, suddenly condenses into liquid. There is no distinct transition zone from liquid to vapour and vice versa. The isotherm passing through the critical point is called the *critical isotherm*, and the corresponding temperature is known as the *critical temperature* (t_c). The pressure and volume at the critical point are known as the *critical pressure* (p_c) and the *critical volume* (v_c) respectively. For water

$$p_c = 221.2 \text{ bar}$$
$$t_c = 374.15°\text{C}$$
$$v_c = 0.00317 \text{ m}^3/\text{kg}$$

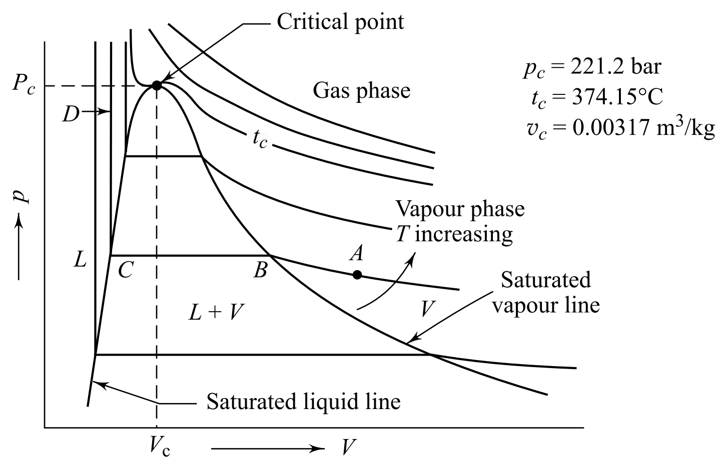


Fig 4.41 *Saturation Curve on p-v Diagram*

4.7.4 *p-T* Diagram for a Pure Substance (Water)

The state changes of a pure substance, upon slow heating at different constant pressures, are shown on the *p-v* plane, in Figs. 4.40, and 4.41. If these state changes are plotted on *p-T* coordinates, the diagram, as shown in Fig. 4.42, will be obtained. If the heating of ice at – 10°C to steam at 250°C at the constant pressure of 1 atm is considered, 1–2 is the solid (ice) heating, 2–3 is the melting of ice at 0°C, 3–4 is the liquid heating, 4–5 is the vaporization of water at 100°C, and 5–6 is the heating in the vapour phase. The process will be reversed from state 6 to state 1 upon cooling. The curve passing through the 2, 3 points is called the *fusion curve*, and the curve passing through the 4, 5 points (which indicate the vaporization or condensation at different temperatures and pressures) is called the *vaporization curve*. If the vapour pressure of a solid is measured at different temperatures, and these are plotted, the *sublimation curve* will be obtained. The fusion curve, the vaporization curve, and the sublimation curve meet at the triple point.

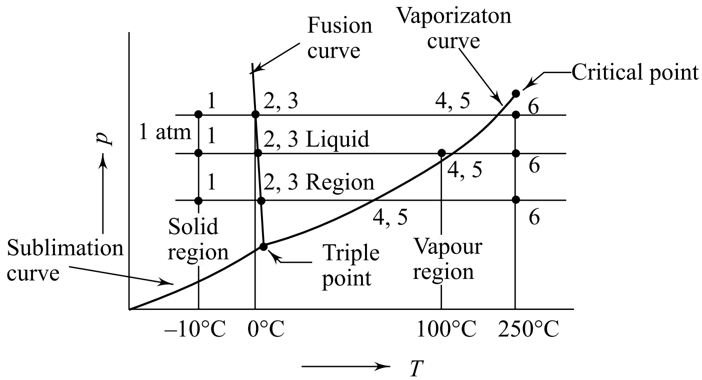


Fig. 4.42 *Phase Equilibrium Diagram on p-T Coordinates*

The slopes of the sublimation and vaporization curves for all substances are positive. The slope of the fusion curve for most substances is positive, but for water, it is negative. The temperature at which a liquid boils is very sensitive to pressure, as indicated by the vaporization curve which gives the saturation temperatures at different pressures, but the temperature at which a solid melts is not such a strong function of pressure, as indicated by the small slope of the fusion curve.

The triple point of water is at 4.58 mm Hg and 273.16 K, whereas that of CO_2 is at 3885 mm Hg (about 5 atm) and 216.55 K. So when solid CO_2 ('dry ice') is exposed to 1 atm pressure, it gets transformed into vapour directly, absorbing the latent heat of sublimation from the surroundings, which gets cooled or 'refrigerated'.

4.7.5 Quality or dryness fraction of steam

If in 1 kg of liquid and vapour (steam) mixture, x kg is the mass of vapour (steam) and 1-x kg is the mass of liquid (water), then x is known as the quality or dryness fraction of *water* vapour mixture. Therefore quality indicates the mass fraction of vapour (steam) in liquid vapour mixture or

$$x = m_s/(m_s + m_w)$$

m_s and m_w are the mass of steam and mass of water respectively in the mixture. The value of x varies between 0 and 1. For saturated water, when water just starts boiling, $x = 0$, and for saturated vapour, when vaporization is complete, $x = 1$ for which vapour is said to be dry and saturated.

Let v_f be the volume saturated water in m³/kg
v_g be the volume saturated steam in m³/kg
x be the dryness fraction of steam

specific volume of water vapour mixture of quality x is

$$v = (1 - x)v_f + x\, v_g$$

At low pressure v_f can be neglected in comparision to v_g i.e $v_g >> v_f$

Hence, $v = x\, v_g$
similarly,
enthalpy of wet steam
if h_f is the enthalpy of saturated water in kJ/kg
h_g is the enthalpy of saturated steam in kJ/kg
h_{fg} is the enthalpy or latent heat of vaporization in kJ/kg
then specific enthalpy of water vapour mixture of dryness fraction x is

$$h = h_f + x\, h_{fg} \text{ kJ/kg} \quad \text{or} = (1-x)h_f + x\, h_g$$

Internal energy of wet steam

$$u = u_f + x\, u_{fg} \qquad \text{or } (1-x)u_f + x\, u_g$$

Entropy of wet steam

$$s = s_f + x\, s_{fg} \text{ or } (1-x)s_f + x\, s_g$$

Where h, u and s refers to the mixture quality x, suffix f and suffix g indicate the condition of saturated liquid and saturated vapour.

4.7.6 Superheated steam

When the temperature of the vapour is greater than the saturation temperature corresponding to the given pressure, the vapour is said to be superheated. The difference between the temperature of superheated and saturated vapour is called degree of super saturated steam.

Degree of superheat = $t_{sup} - t_{sat}$

In superheated vapour at a given pressure, the temperature may have different values greater than the saturation temperature.

Specific enthalpy of superheated steam h_{sup} kJ/kg

$$h_{sup} = h_g + C_s\,(t_{sup} - t_{sat}) \text{ kJ/kg}$$

where C_s is the specific heat of superheated steam at low pressure it can be assumed that the steam behaves as a perfect gas and the volume of the superheated steam can be found out by the gas equations.

$$(p.\, v_g)/t_{sat} = (p\, v_{sup})/t_{sup}$$

or

$$v_{sup} = (v_g\, t_{sup})/t_{sat}$$

4.7.7 *T-s* Diagram for a Pure Substance

The heating of the system of 1 kg of ice at – 5°C to steam at 250°C is again considered, the pressure being maintained constant at 1 atm. The entropy increases of the system in different regimes of heating are given as follows.

1. The entropy increase of ice as it is heated from – 5°C to 0°C at 1 atm. (c_{pice} = 2.093 kJ/kg K).

$$\Delta s_1 = s_2 - s_1 = \int \frac{đQ}{T} = \int_{T_1=268}^{T_2=273} \frac{mc_p\, dT}{T} = mc_p \ln \frac{273}{268}$$

$$= 1 \times 2.093 \ln \frac{273}{268} = 0.0398 \text{ kJ/kg K}$$

2. The entropy increase of ice as it melts into water at 0°C (latent heat of fusion of ice = 334.96 kJ/kg)

$$\Delta s_2 = s_3 - s_2 = \frac{334.96}{273} = 1.23 \text{ kJ/kg K}$$

3. The entropy increase of water as it is heated from 0°C to 100°C ($c_{p_{\text{water}}}$ = 4.187 kJ/kg K)

$$\Delta s_3 = s_4 - s_3 = mc_p \ln \frac{T_3}{T_2} = 1 \times 4.187 \ln \frac{373}{273} = 1.305 \text{ kJ/kg K}$$

4. The entropy increase of water as it is vaporized at 100°C, absorbing the latent heat of vaporization (2257 kJ/kg)

$$\Delta s_4 = s_5 - s_4 = \frac{2257}{273} = 6.05 \text{ kJ/kg K}$$

5. The entropy increase of vapour as it is heated from 100°C to 250°C at 1 atm

$$\Delta s_5 = s_6 - s_5 = \int_{373}^{523} mc_p \frac{dT}{T} = 1 \times 2.093 \ln \frac{523}{373}$$

$$= 0.706 \text{ kJ/kg K}$$

assuming the average specific heat of steam in the temperature range of 100°C to 250°C as 2.093 kJ/kg K.

These entropy changes are shown in Fig. 4.43. The curve 1-2-3-4-5-6 is the isobar of 1 atm. If, during the heating process, the pressure had been maintained constant at 2 atm, a similar curve would be obtained. The states 2, 3, 4, and 5 are saturation states. If these states for different pressures are joined, the phase equilibrium diagram of a pure substance on the *T-s* coordinates, would be obtained.

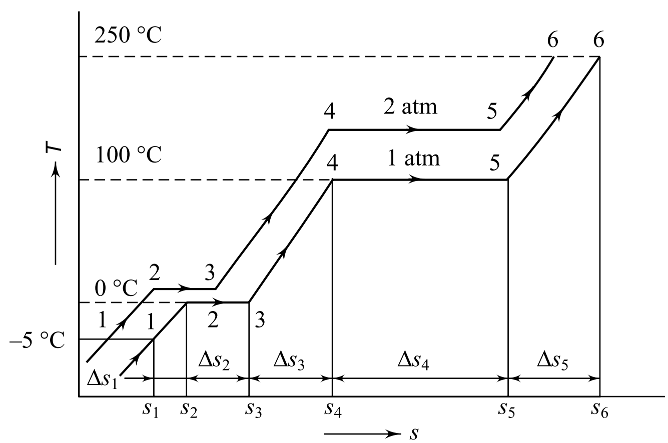


Fig. 4.43 *Isobars on T-s Plot*

Most often, liquid-vapour transformations only are of interest, and Fig. 4.44 shows the liquid, the vapour, and the transition zones only. At a particular pressure, s_f is the specific entropy of saturated water, and s_g is that of saturated vapour. The entropy change of the system during the phase change from liquid to vapour at that pressure is s_{fg} $(= s_g - s_f)$. The value of s_{fg} decreases as the pressure increases, and becomes zero at the critical point.

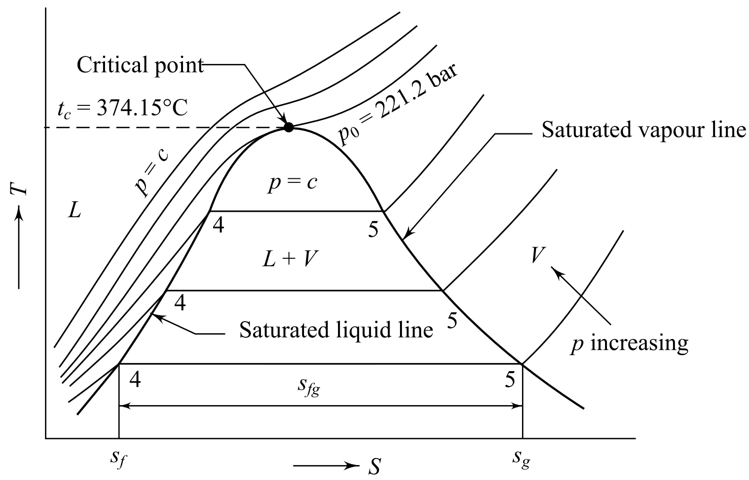


Fig. 4.44 *Saturation (or vapour) Dome for Water*

4.7.8 *h-s* Diagram or Mollier Diagram for a Pure Substance

From the first and second laws of thermodynamics, the following property relation was obtained.

$$Tds = dh - vdp$$

or
$$\left(\frac{\partial h}{\partial s}\right)_p = T \tag{4.70}$$

This equation forms the basis of the *h-s* diagram of a pure substance, also called the Mollier diagram. The slope of an isobar on the *h-s* coordinates is equal to the absolute saturation temperature ($t_{sat} + 273$) at that pressure. If the temperature remains constant the slope will remain constant. If the temperature increases, the slope of the isobar will increase.

Figure 4.45 is the *h-s* or the Mollier diagram indicating only the liquid and vapour phases. As the pressure increases, the saturation temperature increases, and so the slope of the isobar also increases. Hence, the *constant pressure lines diverge from one another*, and the critical isobar is a tangent at the critical point, as shown. In the vapour region, the states of equal slopes at various pressures are joined by lines, as shown, which are the *constant temperature lines*. Although the slope of an isobar remains continuous beyond the saturated vapour line, the isotherm bends towards the right and its slope decreases asymptotically to zero, because in the ideal gas region it becomes horizontal and the constant enthalpy implies constant temperature. As the pressure increases, h_{fg} decreases, and at the critical pressure, h_{fg} becomes zero.

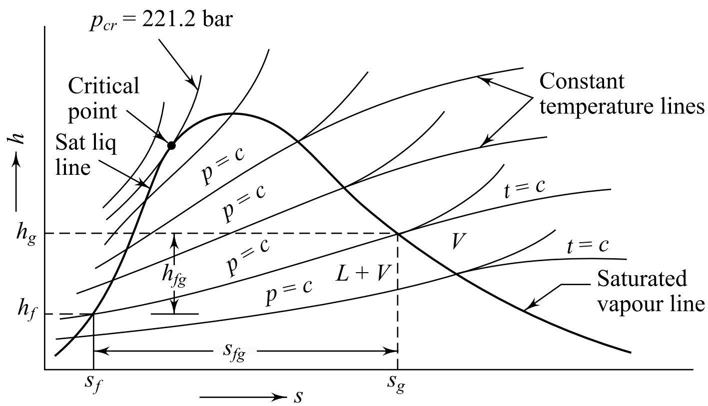


Fig. 4.45 *Enthalpy-entropy Diagram of Water*

Example 4.6 Find the saturation temperature, the changes in specific volume and entropy during evaporation, and the latent heat of vaporization of steam at 1 MPa.

Solution: At 1 MPa, from steam table

$$t_{sat} = 179.91°\text{C}$$
$$v_f = \mathbf{0.001127\ m^3/kg}$$
$$v_g = 0.19444\ \text{m}^3/\text{kg}$$
$$\therefore \quad v_{fg} = v_g - v_f = 0.1933\ \text{m}^3/\text{kg}$$
$$s_f = 2.1387\ \text{kJ/kg K}$$
$$s_g = 6.5865\ \text{kJ/kg K}$$
$$\therefore \quad s_{fg} = s_g - s_f = \mathbf{4.4478\ kJ/kg\ K}$$
$$h_{fg} = h_g - h_f = \mathbf{2015.3\ kJ/kg}$$

Example 4.7 Saturated steam has an entropy of 6.76 kJ/kg K. What are its pressure, temperature, specific volume, an enthalpy?

Solution: Form steam table, when s_g = 6.76 kJ/kg K

$$p = 0.6\ \text{MPa}, \quad t = 158.85°\text{C}$$
$$v_g = 0.3157\ \text{m}^3/\text{kg}, \quad \text{and} \quad h_g = \mathbf{2756.8\ kJ/kg}$$

Example 4.8 Find the enthalpy and entropy of steam when the pressure is 2 MPa and the specific volume is 0.09 m^3/kg.

Solution: From steam table, when p = 2 MPa, v_f = 0.001177 m^3/kg and v_g = 0.09963 m^3/kg. Since the given volume lies between v_f and v_g, the substance will be a mixture of liquid and vapour, and the state will be within the vapour dome. When in the two-phase region, the composition of the mixture or its quality has to be evaluated first. Now,

$$v = v_f + x\,v_{fg}$$
$$0.09 = 0.001177 + x\,(0.09963 - 0.001177)$$

or $x = 0.904$ or 90.4%

At 2 MPa, $h_f = 908.79$ and $h_{fg} = 1890.7$ kJ/kg

$s_f = 2.4474$ and $s_{fg} = 3.8935$ kJ/kg K

$$h = h_f + x\,h_{fg}$$
$$= 908.79 + 0.904 \times 1890.7 = \mathbf{2618.79\ kJ/kg}$$
$$s = s_f + x\,s_{fg}$$
$$= 2.4474 + 0.904 \times 3.8935$$
$$= \mathbf{5.9534\ kJ/kg\ K}$$

Example 4.9 Find the enthalpy, entropy, and volume of steam at 1.4 MPa, 380°C.

Solution: At $p = 1.4$ MPa, in steam table, $t_{sat} = 195.07$°C. Therefore, the state of steam must be in the superheated region. For properties of superheated steam,

at 1.4 MPa, 350°C $v = 0.2003$ m³/kg

$h = 3149.5$ kJ/kg

$s = 7.1360$ kJ/kg K

and at 1.4 MPa, 400°C $v = 0.2178$ m³/kg

$h = 3257.5$ kJ/kg

$s = 7.3026$ kJ/kg K

∴ By interpolation

at 1.4 MPa, 380°C $v = 0.2108$ m³/kg

$h = 3214.3$ kJ/kg

$s =$ **7.2360 kJ/kg K**

Example 4.10 A vessel of volume 0.04 m³ contains a mixture of saturated water and saturated steam at a temperature of 250°C. The mass of the liquid present is 9 kg. Find the pressure, the mass, the specific volume, the enthalpy, the entropy, and the internal energy.

Solution: From Table A.1(a), at 250°C, $p_{sat} = 3.973$ MPa

$v_f = 0.0012512$ m³/kg, $v_g = 0.05013$ m³/kg

$h_f = 1085.36$ kJ/kg, $h_{fg} = 1716.2$ kJ/kg

$s_f = 2.7927$ kJ/kg K, $s_{fg} = 3.2802$ kJ/kg K

Volume of liquid, $V_f = m_f v_f$

$$= 9 \times 0.0012512 = 0.01126 \text{ m}^3$$

Volume of vapour, $V_g = 0.04 - 0.01126 = 0.02874$ m³

∴ Mass of vapour

$$m_g = \frac{V_g}{v_g} = \frac{0.02874}{0.05013} = 0.575 \text{ kg}$$

∴ Total mass of mixture,

$$m = m_f + m_g = 9 + 0.575 = \mathbf{9.575\ kg}$$

Quality of mixture,

$$x = \frac{m_g}{m_f + m_g} = \frac{0.575}{9.575} = 0.06$$

$\therefore$

$$v = v_f + xv_{fs}$$
$$= 0.0012512 + 0.06\,(0.05013 - 0.0012512)$$
$$= \mathbf{0.00418\ m^3/kg}$$
$$h = h_f + xh_{fg}$$
$$= 1085.36 + 0.06 \times 1716.2 = \mathbf{1188.32\ kJ/kg}$$
$$s = s_f + xs_{fg}$$
$$= 2.7927 + 0.06 \times 3.2802 = \mathbf{2.9895\ kJ/kg\ K}$$
$$u = h - pv$$
$$= 1188.32 - 3.973 \times 10^3 \times 0.00418 = \mathbf{1171.72\ kJ/kg}$$

Also, at 250°C, $u_f = 1080.39$ and $u_{fg} = 1522.0$ kJ/kg

$\therefore$

$$u = u_f + xu_{fg}$$
$$= 1080.39 + 0.06 \times 1522 = \mathbf{1071.71\ kJ/kg}$$

4.8 STEAM BOILERS

4.8.1 Introduction

According to the Indian Boiler Act, a boiler or steam generator is a closed pressure vessel with a capacity of about 5 gallons used for generating steam at a pressure higher than atmospheric pressure. The steam generated has large heat capacities and may be used for:

1. Electrical power generation
2. Bleaching, sizing and in weaving sections in textile industries.
3. In industries like sugar, soya, rubber and other chemical industries for various processes.
4. For heating buildings in cold weather conditions.

4.8.2 Classification of boilers

Boilers can be classified on various points. Some of the important basis of classifications are as follows:

1. Content of the Tubes

(a) Fire Tube In fire-tube boilers, hot flue gases are allowed to flow inside the tubes and water surrounds the tubes, e.g., simple vertical, Cochran, and Lancashire boilers.

(b) Water Tube In water-tube boilers, water is allowed to flow inside the tubes and the hot flue gases surrounds the tube, e.g., Babcock and Wilcox, Sterling, and Lamont boilers.

2. Steam Pressure

(a) Low-pressure Boilers The boilers which produce steam at a pressure lower than 30 bars are called low-pressure boilers, e.g. simple vertical, Cochran, Babcock and Wilcox , and Lancashire boilers etc.

(b) Medium-pressure Boilers The boilers which produce steam at a pressure in the range of 30 bars to 80 bars are called medium pressure boilers.

(c) High-pressure Boilers The boilers which produce steam at a pressure higher than 80 bars are called high pressure boilers, e.g. Velox, Lamount, and Benson boilers.

3. Type of Water Circulation in the Boiler

(a) Natural Water Circulation In natural water circulation, the circulation of water takes place by the convection currents caused due to temperature difference of water, e.g., simple vertical, Cochran, Babcock and Wilcox , and Lancashire boilers.

(b) Forced Water Circulation In forced water circulation , water is circulated inside the boiler with the help of a pump. (at high pressure the natural convection becomes ineffective and hence force water circulation is adopted). Examples Lamount, Velox, and Benson boilers.

4. Furnace Position

(a) Internally Fired In internally fired boilers, the furnace is located inside the boiler shell, e.g., Cochran, and Lancashire boilers.

(b) Externally Fired In externally fired boilers, the furnace is located outside the shell of the boiler, e.g., Babcock and Wilcox, and Stirling boilers.

5. Use

(a) Stationary Boilers These boilers are mounted on a fixed platform and are stationed in only one place. These are generally used in steam power plants and in other industries for producing process steam.

(b) Portable Boilers Portable boilers are small boilers and can be carried from one place to another, e.g., simple vertical boilers.

(c) Mobile Boilers Mobile boilers are mounted on a moving platform like locomotive, marine, etc.

6. Position of the Boiler Shell

(a) Horizontal If the position of the axis of the boiler shell is horizontal then it is called horizontal boiler, e.g., Lancashire, and Babcock and Wilcox boilers.

(b) Vertical If the axis of the boiler shell is vertical then it is called vertical boiler, e.g., simple vertical, and Cochran boiler.

7. Type of the Fuel Used

(a) Coal fired
(b) Oil fired
(c) Gas fired

8. Type of Fuel Firing

(a) Hand Fired In hand fired boilers the fuel is fired manually into the furnace. This is normally employed in small boilers, e.g., simple vertical, and Lancashire boilers.

(b) Stoker Fired In a stoker-fired system, the stoker (conveyor made of chain links on which coal is fed through a hopper) moves at a constant speed into the furnace. Thus, it is a continuous coal-feeding device. These are normally used in Babcock and Wilcox, and Stirling boilers.

(c) Pulverized Fuel Fired In pulverized fuel firing system the coal is ground to a fine powder form and then it is supplied with compressed air through the nozzle into the furnace. These are normally used in thermal power plants. Pulverized fuel fired boilers can meet the fluctuating demand of steam.

4.8.3 Terms commonly used with boiler

Shell The shell of a boiler is made up of one or more steel plates bent into a cylindrical form and riveted or welded together. The shell is closed at the ends by means of flat or curved plates called boiler heads. The purpose of the shell is to store water for heating. A shell along with a boiler head is called a boiler drum.

Settings Settings are made of brickwork and forms walls of the furnace and combustion chamber. In case of Lancashire boiler, it provides support to it and also forms passage for the hot flue gases. It also confines the heat to the boiler shell.

Grate It is made up of iron bars placed at a distance upon which solid fuel is burnt. The space between the bars allows the air to pass through it for supporting combustion of fuel. It also allows the ashes to fall down.

Furnace The furnace is the space above the grate and below the boiler shell in which the combustion of fuel takes place. In the furnace the combustion of volatile matter takes place.

Water Space The water space is the volume occupied by water in the shell.

Steam Space The steam space is the remaining volume of the shell not occupied by water and tubes.

Heating Surface It is that surface of the boiler which is exposed to hot flue gases.

Mountings In accordance with the Indian Boiler Regulation Act, the mountings are the essential items to be fitted on the boiler for its safe working, like safety valve, water level indicator, fusible plug, etc.

Accessories Accessories are the items used along with the boiler for improving its efficiency and performance. Some of the accessories used along with a boiler are economizer, air pre-heater, super-heater, etc.

Working Pressure It is the pressure of the steam generated inside the boiler.

4.8.4 Factors to be Considered While Selecting a Boiler

1. Working pressure
2. Steam generation rate at the required working pressure

3. Type and quality of the fuel used in a boiler
4. Type of load, i.e., demand of steam whether steady or fluctuating
5. Floor and grate area
6. Quality and the availability of water at site
7. Operating and maintenance cost
8. Accessibility of repair and inspection
9. Initial cost

4.8.5 Boiler Mountings

According to the Indian Boiler Regulation Act, the boiler must be fitted with the following mountings for its proper and safe functioning.

Safety Valves Safety valves are placed on the top of the boiler .

The function of the safety valve is to blow off the excess quantity of steam if the pressure of the steam exceeds the working pressure limit of the boiler.

Water Level Indicator Generally, two water level indicators are provided along the two sides of the boiler. One end of the water level indicator is connected to the steam space while the other end is connected to the water space. The water-level indicator is mounted in front of a boiler so that it is easily visible to the attendant.

The function of the water level indicator is to show the level of water inside the boiler.

Pressure Gauge The pressure gauge is mounted in a place such that the operator can read it conveniently. Its end is connected to the steam space through a U tube (siphon tube) in which water is filled. The purpose of this siphon tube is to avoid the live steam coming in direct contact with the Bourdon tube used in a Bourdon pressure gauge.

The function of the pressure gauge is to indicate the pressure of the steam inside a boiler.

Steam Stop Valve The steam stop valve is mounted on the top part of the steam space of the boiler.

The function of the steam stop valve is to stop or to regulate the flow of steam from the boiler to the main steam pipe.

Feed Check Valve The feed check valve is fitted on the boiler just below the working level of the water in the boiler.

The function of a feed check valve is to supply the water from the feed pump to the boiler. It also prevents the water escaping from the boiler in case of the failure of the feed pump or when the feed pump is stopped, i.e. it acts as one way valve.

Blow-off Cock A blow-off cock is fitted on the boiler shell at the bottom-most part of the water space.

The function of the blow-off cock is to remove the sediments, mud, scale collected at the bottom of the water space periodically by opening the valve, when the boiler is in operation. It is also used to empty the boiler at the time of inspection, cleaning and maintenance.

Fusible Plug The fusible plug is fitted at the top of the crown of furnace or on the top of the combustion chamber. In normal working conditions, the fusible plug is dipped inside the water.

The function of the fusible plug is to prevent the boiler from overheating by extinguishing the fire inside the furnace when the water level falls below the unsafe level.

4.8.6 Accessories

The boiler accessories are used either to increase the efficiency of a boiler or to increase the performance.

Economiser An economizer is installed or erected in the passage of hot flue waste gases between the boiler and the chimney.

An economizer is used for heating feed water by the hot flue waste gases. It recovers part of the heat being carried away by the flue gases to the chimney.

Greens's vertical economizer is shown in Fig. 4.46. It consists of a large number of vertical tubes. The vertical tubes are connected at the two ends with two horizontal headers, one at the bottom and one at the top. The hot gases move around the vertical tubes in the direction opposite to the direction of feed water. Scrappers are provided on the outer surface of the vertical tubes to make the external surface of the vertical tubes soot free (deposition of soot on the outer surface reduces the heat transfer). The scrappers move slowly and continuously up and down on the outer surface of the tubes with the help of chain and sprocket arrangement. The feed water flows from the bottom header into the vertical tube to the upper header and then to the boiler. The heat transfer from hot gases to the water takes place in the vertical tubes thereby increasing the feed water temperature.

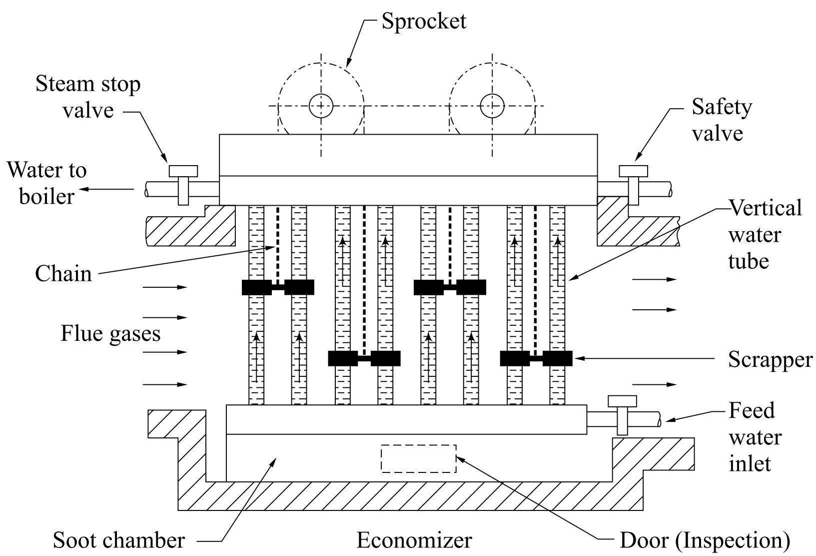


Fig. 4.46

Economizers are also provided with a safety valve, a blow-off cock and a pressure gauge for its safe working.

The advantages gained by the use of an economizer are as follows:

1. It improves the fuel economy
2. Improves evaporative capacity
3. Increases the efficiency of boiler

Air Pre-heater An air pre-heater is also installed in the passage of the waste hot flue gases between an economizer and the chimney.

An air pre-heater also recovers part of the heat being carried away by the flue gases, leaving the economizer to the chimney. An air pre-heater heats fresh air to be fed to the furnace. The tubular type of air heater consists of number of tubes arranged in bundles. Hot flue gases are allowed to pass through these tubes. The fresh air to be supplied to the combustion chamber of the boiler is allowed to pass over the tubes a number of times by baffles. Thus air gets heated before it is fed to the furnace.

The advantages gained by the use of an air pre heater are as follows

1. It improves the fuel economy.
2. It accelerates the rate of combustion of fuel.
3. It also helps in the combustion of low grade fuel.

4.8.7 Cochran Boiler

A Cochran boiler is a vertical, multi-tubular, fire-tube type of a boiler. It is made in sizes up to a diameter of 2.75 m and a height of 5.8 m. The maximum steam generating capacity of Cochran boiler is 3600 kg/hr and heating area of 112.5 sq. m.

A Cochran boiler is made up of a cylindrical shell with a hemispherical top. It also has a hemispherical furnace (it is the strongest structure under compression). The furnace and fire tubes are surrounded by the water on all sides except the opening for the fire door and an opening for the combustion chamber. The grate is arranged inside the furnace on which coal is burnt. The ashpit is provided below the grate by a mere extension of boiler shell at the bottom for collecting the ash. It also has a combustion chamber which is lined inside with fire bricks. A number of horizontal tubes are provided, whose one end is connected with combustion chamber plate and the other end is connected with the smoke box plate. The tubes are simply pushed inside the holes of the plates of the combustion chamber and fire box and expanded at the ends to form seam-tight joints. Sufficient space between the tubes and shell is provided for natural convection currents of water. A stack is provided at the top of the fire box for allowing the hot gases to leave in to the atmosphere. A damper is also provided at the base of the chimney to regulate the rate of combustion of fuel.

Various mountings are fitted on the Cochran boiler as shown in Fig. 4.47.

Working

The hot flue gases pass from the grate to the combustion chamber through a short flue pipe. After the combustion chamber, it passes through the horizontal tubes in to the smoke box and then to the stack as shown. The water surrounding the tubes and the combustion chamber gets heated by the natural circulation. The steam formed from heating water inside the boiler is collected in the steam space.

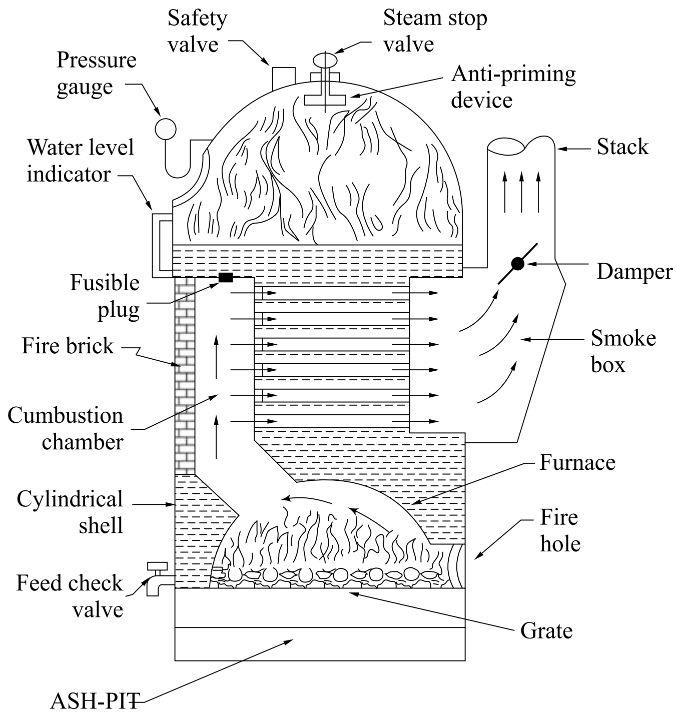


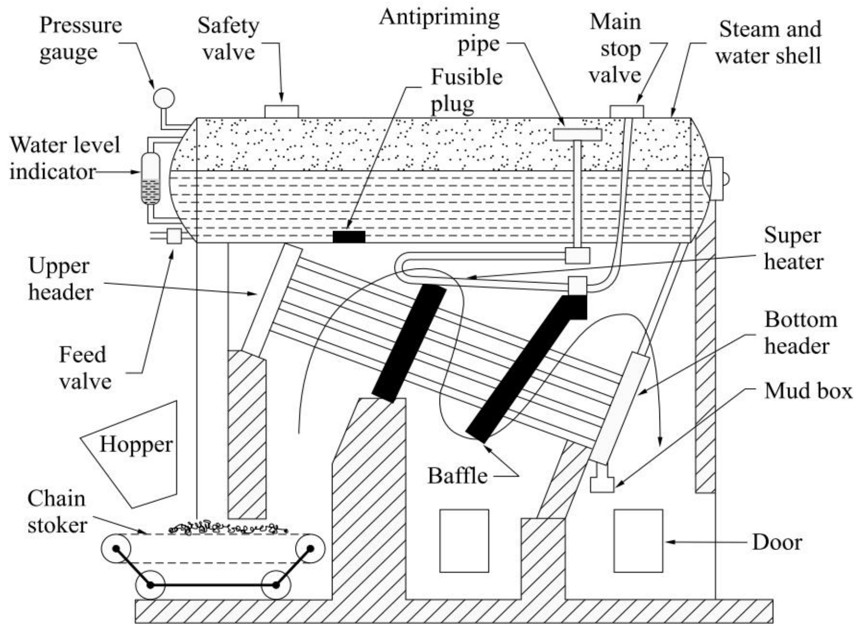
Fig. 4.47 *Cochran Boiler*

4.8.8 Babcock and Wilcox Boiler

A Babcock and Wilcox boiler (Fig. 4.48) is a horizontal, water tube boiler. The final pressure of steam of these boilers is in between 25-30 bars. It consists of a horizontal cylindrical drum made up of steel plates. The entire boiler is suspended from steel girder structures. The slings pass around the drum and are entirely independent of brick work. Thus, the boiler is free to expand and contract without affecting the settings.

The furnace space is divided into three compartments by baffle plates or brick walls that force the hot flue gases to take the definite path. The maximum temperature occurs in the first pass. The volumetric size of the pass decreases from furnace to exit in order to maintain constant velocity of the flue gases.

The front end of the boiler is connected to the upper header and the rear end of the boiler is connected to the bottom header through nipples. These two headers are connected by a number of small-diameter tubes expanded in the header and flared at the ends. The inclination of tubes varies from 10° to 20° from the horizontal to promote natural circulation system of water. A mud box is attached at the bottom of the lower header. In mud box any matter held in suspension in water is blown off periodically with the help of a blow off-valve connected to the mud box.



BABCOCK–WILCOX BOILER

Fig. 4.48

A super-heater consisting of number of U tubes secured at each end to a box is placed in the combustion chamber. The upper box of the superheater is connected to the steam space inside the drum through an anti-priming device. The steam gets super-heated in the super-heater and is led into the main steam pipe.

A mechanical stoker is provided for feeding coal in the furnace. Coal is fed through a hopper on the chain grate stoker. The chain of the stoker acts as a grate for the boiler. A damper is provided at the rare end of the combustion chamber to regulate the quantity of fresh air required for the combustion of fuel. Doors are provided for the access and cleaning purpose.

As per the IBR, various mountings like steam stop valve, safety valve, fusible plug, blow off cock, etc., are mounted on the boiler for its proper and safe working.

The water is supplied to the boiler through a feed-check valve up to the prespecified level. When the combustion of fuel takes place, the hot flue gases rise up. The hot flue gases are compelled to pass in the upward direction between the tubes towards the upper header, then in the downward direction between the tubes and then once again in the upward direction and then finally to the chimney by the baffles provided, as shown in the figure. The hot gases heat the water flowing through the water tubes. The water flows from the rear boiler shell to the bottom header and then to the upper header through the inclined tubes into the drum. The water then moves from front of the drum to the rear of the drum and then to the bottom header.

4.8.9 Boiler Draught

Boiler draught is defined as the pressure difference which causes a flow of gases to take place. In case of a boiler, the function of a draught is to force the air to flow over the furnace, combustion chamber, flue gas passage and finally through the chimney. It provides sufficient quantity of fresh air for the proper combustion of fuel.

Classification of Draught

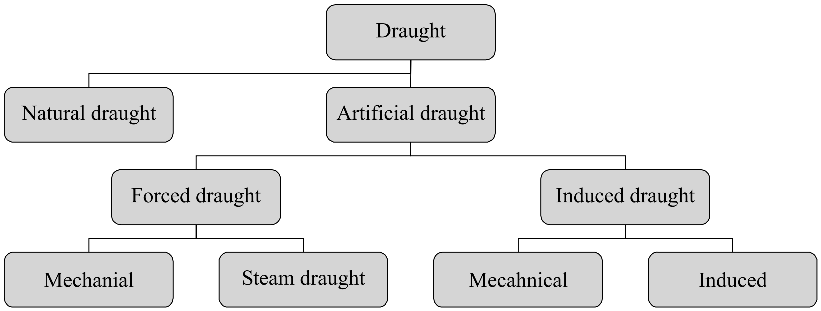


Fig. 4.49

4.8.9.1 Natural Draught

In a boiler, natural draught is obtained by the installation of a chimney. The chimney provided in the boiler performs one or more of the following functions: (1) It produces sufficient draught so that the air and the flue gases are forced through the fuel bed , furnace, boiler passes and then to the chimney. (2) It carries the products of combustion to such a height before discharging so that it is not objectionable or injurious to surroundings.

The chimney is a vertical tubular structure made up of brick and masonry structure, while the stack is made up of steel structure.

The figure shows the schematic arrangement of a chimney and a boiler. When fire is not lighted, the pressure at all points is same, i.e., at grate level and the chimney base. The pressure (p_a) at all points at a horizontal level of the height of the chimney H is also same.

Let p_1 the pressure at the grate level

p_2 the pressure at the base of the chimney created by the hot gases, i.e., when fire is lighted in the boiler

p_a the pressure at the height of chimney due to cold air column

ρ_g density of hot flue gas

ρ_a density of air outside the chimney.

The pressure at grate level near the combustion chamber $p_1 = p_a$ + pressure due to cold air column of height H

$$p_1 = p_a + \rho_a g H$$

The pressure at the base of a chimney $p_2 = p_a$ + pressure due to hot gas column of height H

$$p_2 = p_a + \rho_g g H$$

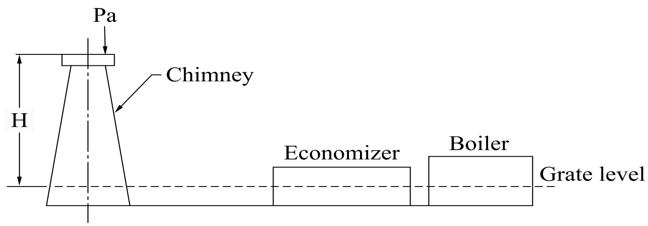


Fig. 4.50

The pressure p_1 is greater than p_2 owing to the density difference of the outside cold air and the hot flue gases inside the chimney at the same level. The pressure difference between p_1 and p_2 is called the static draught which causes the flow of flue gases.

4.8.9.2 Artificial Draught

The application of an economizer, air pre-heater and super-heater increases the draught requirement of the boiler for proper combustion of fuel. Besides, resistance to flow is also offered by the combustion equipment. It would not be practical to build a chimney high enough to produce draught of such a large magnitude. To meet the desired requirement independent of the climatic condition, an artificial draught is created. For small installation, steam draught is preferred while for power plants and bigger installation, mechanical draught is preferred.

Advantages of Artificial Draught

1. Increases the steam-generating capacity of the boiler—increasing the draught increases the fuel combustion rate thereby increasing the steam generating capacity
2. Easy control over the rate of fuel combustion and evaporation of steam
3. Reduces the height of chimney
4. Prevention of smoke
5. Low-grade fuel can be used
6. Improves the efficiency of a boiler plant: Several heat recovery systems can be incorporated in the boiler plant thereby increasing the efficiency of the boiler plant

Disadvantages of Artificial Draught

1. Increases the initial investment cost
2. Increases the wear and tear of the plant
3. Increases the regular maintenance cost of the plant

Forced Draught In mechanical forced draught system, a fan or a blower is installed near the base of the boiler grate. Force draught maintains a higher pressure than the atmosphere in the furnace, settings, and the passage of the flue gases, etc., since the pressure is positive the flue gas may be force to move out through the cracks.

Induced Draught In the induced draught system, a fan or a blower is installed near or at the base of the chimney. Induced draught maintains a lower pressure than the atmosphere in the furnace, settings, and the passage of the flue gases, economizer, etc.

It produces a partial vacuum in the furnace and flue passages, thereby the products of combustion are drawn from the main flue and they pass up the chimney. Induced draught system is used usually when an economizer and air pre-heater are installed in the system. It is used alone for gas, oil and pulverized fuel firing systems.

Balance Draught Balance draught uses the combination of forced and the induced draught systems. In balance draught the force draught fan overcomes the resistance offered by the fuel bed (chain grate under feed stoker) and the combustion chamber, while the induced draught overcomes the resistance offered by the economizer, air pre heater and connecting flues.

Steam Jet Draught Artificial draught can also be produced by a steam jet. It can be used as forced draught or induced draught depending upon the location of the steam jet. The steam used for producing steam jet draught can be live steam or dead steam (steam from the exhaust of steam engine). In induced steam jet draught, the steam jet is provided in the smoke box near the stack. The air is induced through the ash pit to the grate, flue tubes and then to the smoke box.

In forced jet draught the steam jet is located near the grate, air is forced to flow over the fuel bed then to the combustion chamber, flue tubes and then to chimney.

Advantages of Steam Jet Draught

1. Simple and economical
2. Less space is occupied
3. In forced steam jet draught the grate bars are kept cool thus preventing the clinker formation
4. Low maintenance cost
5. Low grade of fuel can be burnt

4.8.10 Height of a Chimney to Produce a given Static Draught

Let m_a be the mass of air supplied per kg of fuel

$m_a + 1$ the mass of the flue gases per kg of fuel burnt

T_o Temperature of air at 0° C = 273 K

T_a Temperature of atmosphere air outside the chimney in K

T_g Temperature of hot flue gases inside the chimney in K

P atmospheric pressure N/m²

The volume of air per kg, i.e., (sp. vol.) at T_o

$$= v = (R\,T_o)/P = (287 \times T_o)/1.01325 \times 10^5 = T_o/353 \qquad (1)$$

Volume of one kg of atmospheric air at temperature $T_a = T_a/\,353$ m³

Volume of m kg of air supplied per kg of fuel burnt $= m \times T_a/353$

Density of atmospheric air $= \rho_a = 353/T_a$ kg/m³ (2)

Volume of hot flue gases $= V_g = m \times T_g/353$

Density of hot flue gases $= (m + 1)/V_g$

$$\rho_g = [353 \times ((m + 1)/m)]/(T_g) \text{ kg/m}^3 \qquad (3)$$

Since the total static pressure difference is due to the weights of the hot flue gases inside the chimney of height H and the weight of the cold air column outside the chimney due to the height H, let p_1 pressure owing to cold air column of height H meter

p_2 pressure owing to hot air column of height H meter

$$p_1 = \rho_a g H \tag{4}$$

$$p_2 = \rho_g g H \tag{5}$$

$$p_1 - p_2 = \rho_a g H - \rho_g g H = gH [\rho_a - \rho_g] \tag{6}$$

Substituting the values from Eqs (2) and (3)

$$p_1 - p_2 = \Delta p = 353\ gH [(1/T_a) - ((m+1)/m)/T_g] \text{ N/m}^2 \tag{7}$$

The pressure difference can be represented in terms of water column

$$\Delta p = \rho_w g h_w \text{ [if } h \text{ is the height of water column in mm]}$$

$$\Delta p = 1000 \times g \times h/1000$$

$$= gh$$

$$h = 353 \text{ H } [(1/T_a) - ((m+1)/m)/T_g] \text{ mm of water column} \tag{8}$$

Thus the theoretical natural draught is directly proportional to the height of chimney. The naural draught also increases as the temperature of exhaust gases leaving the chimney increases.

The draught in terms of hot gas column H'

$$\Delta p = \rho_g g H'$$

Using equations (3) and (7)

$$\Delta p = g H' [353 \times ((m+1)/m)]/(T_g) = 353\ gH [(1/T_a) - ((m+1)/m)/T_g]$$

$$H' = H[(T_g/T_a)(m/(m+1)) - 1] \text{ meter of hot gas column} \tag{9}$$

Diameter of Chimney

The theoretical velocity of the hot gases passing through the chimney

$$V = \sqrt{2}\ \text{g H}' \tag{10}$$

Mass of the hot flue gases = $A\ V \rho_g$, (11)

where A is the cross sectional area of chimney in m^2,

V is the velocity of hot gases in m/s, and

ρ_g is the density of hot flue gases going through the chimney is kg/m^3.

If D is the diameter of the chimney and m_g is the mass of hot gases going through the chimney then

$$(\pi/4) D^2\ V \rho_g = m_g$$

$$D = 1.128 \sqrt{m_g/(V\ \rho g)} \text{ meter}$$

Condition for Maximum Discharge through a Chimney

From Eq. (10)

$$V = \sqrt{2}\ g H'$$

Substituting the value of H' from Eq. (9)

$$V = \sqrt{2}\ g H[(T_g/T_a)(m/(m+1)) - 1] \text{ m/s} \tag{12}$$

Mass of hot gases going through chimney

$$m_g = A\ V \rho_g$$

Using Eq. (12)

$$m_g = A\,[\rho/RT_g]\ \sqrt{2}\ \ g\,H[(T_g/T_a)(m/(m+1)) - 1]$$

$$= (K/T_g)\ \sqrt{(T_g/T_a)(m/(m+1)) - 1]}$$

where K is the constant of proportionality, i.e., $K = (A\rho/R)\sqrt{(2gH)}$

$$= K\ \sqrt{(1/T_g T_a)(m/(m+1)) - 1/T_g^2]} \qquad (13)$$

To get maximum discharge, differentiate the above equation with respect to T_g and equate it to zero,
i.e., $dm_g/dT_g = 0$

$$= K(1/2)[(1/T_a)(m/(m+1))(-1/T_g^{2}) + 2/T_g^{3}]/\sqrt{(1/T_a T_g)(m/(m+1)) - 1/T_g^2]}$$

$$= [(1/T_a)(m/(m+1))(-1/T_g^{2}) + 2/T_g^{3}] = 0$$

$$= (1/T_a)(m/(m+1))(1/T_g^{2}) = 2/T_g^{3}$$

$$T_g = 2T_a(m+1)/m \qquad (14)$$

Thus for maximum discharge of the hot gases leaving the chimney, the temperature of the hot gases should be 2(m+1)/m times the absolute temperature of the outside air (T_a).

Substituting the values of Eq. 14 in Eq. 9

$$H' = H$$

Thus, for maximum discharge the height of the hot gas column would produce a draught equal to the height of the chimney.

Example 4.11 Calculate the height of a chimney to produce a static draught of 30 mm of water column if the mean flue gas temperature is 250° C and the out side temperature is 30 °C. Take the mass of fresh air supplied for combustion to be 20 kg/kg of fuel.

Solution:

h = 30 mm of water column , T_g = 250° C = 523 K, T_a = 30 °C = 303 K ,
m = 20 kg/kg of fuel, H = ?

$h = 353\ \mathrm{H}\ [1/T_a - ((m+1)/m)/T_g]$ where, h is in mm

$30 = 353\ H\ [1/303 - (21/20)/523]$

$H = 30/0.4563$

H = 65.74 m *Ans*

Example 4.12 To provide a natural draught a boiler is equipped with a chimney of 25-m height. The temperature of the outside air is 30 °C and the mean flue gas temperature is 300 °C. If the amount of air supplied per kg of fuel fired is 20 kg. Determine the (a) the theoretical draught produced in mm of water column and in Pa, (b) the velocity of flue gases leaving the chimney if 50 % of the theoretical draught is lost in friction at the grate and in the flue passages.

Solution:

$T_g = 300^{\circ}$ C = 573 K, $T_a = 30$ °C = 303 K, $m = 20$ kg/kg of fuel, $H = 25$ m.

$h = ?$

$h = 353$ H $[1/T_a - ((m + 1)/m)/T_g]$ where h is in mm

$h = 353 \times 25$ [1/ 303 – (21/20)/573]

$h = 12.95$ mm

$p = 12.95 \times 9.8 = 127.08$ Pa *Ans*

(b) Velocity of flue gases = $V = \sqrt{2g}\ (H_1 - hf)$

$$H_1 = H\,[(m/(m + 1)(\mathrm{T_g}/\,\mathrm{T_a}) - 1\,]$$

$$= 25\,[(20/21)(573/303) - 1] = 20.02 \text{ m}$$

$$h_f = 0.5 \times H_1 \text{ m}$$

$$V = \sqrt{2g\,(H_1 - 0.5H_1)}$$

$$= \sqrt{gH_1}$$

$$V = \sqrt{9.81 \times 24.64} = 14 \text{ m/s } \textit{Ans}$$

Example 4.13 Determine the quantity of air required per kg of fuel burnt in a boiler having a chimney of 30-m height to create a 17-mm draught of water column. Take the mean flue gas temperature as 350 °C and the boiler house temperature as 30 ° C.

Solution:

$h = 17$ mm of water column; $H = 30$ m; $T_g = 350^{\circ}$ C = 623 K, $T_a = 30$°C = 303 K , $m = ?$

$$h = 353\,H\,[1/T_a - ((m + 1)/m)\,/T_g]$$

$$17 = 353 \times 30[1/303 - ((m + 1)/m)/623]$$

$$(m + 1)/m = 1.056$$

$$m = 17.85 \text{ kg of air /kg of fuel}$$

Example 4.14 Determine the height of a chimney to produce a natural draught of 18mm of water column. Take the mean flue gas temperature as 300 °C and the ambient temperature of air as 25 °C. The mass of the flue gas formed per kg of fuel burnt is 23 kg. Also, find the mass of the flue gases flowing through the chimney if the diameter of the chimney is 2 m.

Solution: $h = 18$ mm of water column; $T_g = 300^{\circ}$ C = 573 K, $T_a = 25$ °C = 298 K , $m = 22$ kg/kg of fuel. $D = 2$ m; $H = ?$

$$18 = 353 \text{ H } [1/298 - (23/22)/573]$$

$$H = 33.3 \text{ m}$$

$$H_1 = H\,[(m/(m + 1)(T_g/T_a) - 1]$$

$$= 33.3\,[(22/23)(573/298) - 1]$$

$$= 27.95 \text{ m}$$

$$V = \sqrt{2gH_1}$$
$$= V = \sqrt{2(9.81)27.95}$$
$$= 23.4 \text{ m/s}$$

Density of gas $\rho_g = 353[((m + 1)/m)(1/T_g)]$

$353[(23/22)(1/573)]$

$\rho_g = 0.644 \text{ kg/m}^3$

Mass of gases leaving the chimney = $A\,V\,\rho_g$ where A is the cross sectional area of the chimney

Mass of the gases leaving the chimney = $(\pi/4) \times D^2 \times 22.89 \times 0.644$

$(\pi/4) \times 2^2 \times 22.89 \times 0.644$

47.35 kg/s

4.8.11 Performance of boilers

The comparison between two boilers is possible only when they work under the same operating condition, i.e., they generate steam at the same working pressure, use the same quality of fuel, have the same feed water temperature, etc. Since the boilers work under different operating conditions, it becomes imperative to provide a common base so that water gets evaporated under the same standard reference conditions. The standard reference conditions adopted are: feed water temperature of 100 °C, and working pressure of 1.01325 bar. Under these conditions, 1 kg of water at 100 °C requires 2257 kJ of heat energy to get converted to dry and saturated steam at 100°C and is called the *standard evaporation unit*.

Equivalent Evaporation

In a boiler, the feed-water temperature and the working pressure are different from the standard conditions. Let H be the heat in kJ required for raising W kg of steam in a boiler. If the same quantity of heat is applied to the feed water at standard condition and produces W_e quantity of steam then W_e is said to be equivalent evaporation.

Heat gained by the steam from boiler

$$W(h - h_{\text{feed}}) \text{ kJ}$$

Equivalent evaporation = $W_e = W(h - h_{\text{feed}})/2257$ kg

$(h - h_{\text{feed}})/2257$ is called the factor of evapoaration, F_e

If W is the amount of steam generated per kg of coal fire then
W_e is the equivalent evaporation per kg of coal.
Where enthalpy

$h = h_f + x\,h_{fg}$ for wet steam kJ/kg

$h = h_g$ for dry and saturated steam kJ/kg

$h = h_g + C_s(T_{\text{sup}} - T_{\text{sat}})$ for super heated steam kJ/kg

h_{feed} = sensible heat of feed water temperature

x = dryness fraction of steam

h_f =sensible heat of water at working pressure kJ/kg

h_{fg} = is the latent heat of vapourization kJ/kg

h_g = is the total heat $(h_f + h_{fg})$ kJ/kg

In this type of comparision the quality of fuel is not taken into account.

Boiler Efficiency

Boiler efficiency is defined as the ratio of actual quantity of heat utilized by the steam to the amount of heat liberated by the fuel in the same time period.

$$\eta_{\text{boiler}} = W(h - h_{\text{feed}})/\text{CV}$$

where CV : calorific value of fuel kJ/Kg

Example 4.15 A boiler produces 8 kg of steam per kg of coal at a pressure of 1 Mpa absolute from a feed water temperature of 40 °C . Calculate the equivalent evaporation assuming dryness fraction of steam to be 0.95. Also, find out the efficiency of boiler if the calorific value of coal used is 32000 kJ/kg.

Solution: $x = 0.95$; $T_{\text{feed}} = 40$ °C; CV = 32000 kJ/kg
Properties of steam at pressure of 1 Mpa;

$$h_f = 762.79 \text{ kJ/kg}; \; h_{fg} = 2015.3$$
$$h = h_f + x\,h_{fg} \text{ kJ/kg}$$
$$h = 762.79 + 0.95 \times 2015.3 = 2677.3 \text{ kJ/kg}$$
$$h_{\text{feed}} = 4.18\,(40) = 167.2 \text{ kJ/kg}$$
$$W_e = W(h - h_{\text{feed}})/2257$$
$$W_e = 8(2677.3 - 167.2)/2257 = 8.897 \text{ kg/kg of coal } \textit{Ans.}$$
$$\eta_{\text{boiler}} = W(h - h_{\text{feed}})/\text{CV}$$
$$= [8(2677.3 - 167.2)/32000] \times 100 = 62.75 \text{ \% } \textit{Ans}$$

Example 4.16 In a boiler trial, 1200 kg of coal is consumed in 24 hours of duration. If the boiler generates 11500 kg of dry and saturated steam at a pressure of 0.8MPa from a feed water of 35 °C, calculate the (a) equivalent evaporation /kg of coal and (b) efficiency of boiler. Take CV of fuel as 30000kJ/kg , specific heat of water = 4.18 kJ/kg K.

Solution: $T_{\text{feed}} = 35$ °C ; $p = 0.8$ MPa ; CV = 30000 kJ/kg ;
Mass of steam generated in 24 hours = 11500 kg
Mass of coal consumed in 24 hours = 1200 kg
Mass of steam generated per kg of coal burnt = 11500/1200 = 9.583 kg/kg of coal
Properties of steam at pressure 0.8 MPa:

$$h_g = 2769.1 \text{ kJ/kg}$$
$$h_{\text{feed}} = 4.18(35) = 146.3 \text{ kJ/kg}$$

(a) $W_e = W(h - h_{\text{feed}})/2257$

$$= 9.583(2769.1 - 146.3)/2257 = 11.136 \text{ kg /kg of coal } \textit{Ans}$$

(b) $\eta_{\text{boiler}} = W(h - h_{\text{feed}})/\text{CV}$

$$= [9.583(2769.1 - 146.3)/30000] \times 100 = 83.78\% \; \textit{Ans}$$

Example 4.17 A boiler produces 8 kg steam per kg of fuel at a pressure of 11 bar from the feed water temperature of 75 °C. If the efficiency of the boiler is 80% and the factor of utilization is 1.13, determine (a) temperature of steam and degree of super heat, (b) calorific value of coal, and (c) equivalent evaporation/ kg of coal. Take C_s= 2.2 kJ/kgK

Solution:

$W = 8$ kg/kg of fuel; $p = 11$ bar ; $T_{feed} = 75$ °C ; factor of utilization = 1.15;

$\eta_{boiler} = 80\%$; $h_{feed} = 4.18 \times 75 = 313.5$ kJ/kg

Properties of steam from steam table at $p = 11$ bar

$T_{sat} = 184.09$ °C; $h_f = 781.32$ kJ/kg; $h_{fg} = 2000.4$ kJ/kg; $h_g = 2781.7$ kJ/kg

Factor of evaporation = 1.15 = $(h - h_{feed})/2257$

$$1.13 = (h - 313.5)/2257$$

$$h = 2863.91 \text{ kJ/kg}$$

Since h is greater than h_g, the steam is superheated

$$h = h_g + C_s (T_{sup} - T_{sat})$$

$$2863.91 = 2781.7 + 2.2(T_{sup} - T_{sat})$$

$$(T_{sup} - T_{sat}) = 37.37 \text{ °C}$$

$$T_{sup} = 221.46 \text{ °C}$$

(b) $$\eta_{boiler} = W(h - h_{feed})/\text{CV}$$

$$0.8 = [8(2863.91 - 313.5)/\text{CV}]$$

$$\text{CV} = 25504.1 \text{ kJ/kg}$$

(c) $$W_e = W(h - h_{feed})/2257$$

$$= W \times F_e$$

$$= 8 \times 1.13 = 9.04 \text{ kg /kg of coal}$$

4.9 REFRIGERATION

4.9.1 Refrigeration by Non-Cyclic Processes

Refrigeration is the cooling of a system below the temperature of its surroundings.

The melting of ice or snow was one of the earliest methods of refrigeration and is still employed. Ice melts at 0°C. So when ice is placed in a given space warmer than 0°C, heat flows into the ice and the space is cooled or refrigerated. The latent heat of fusion of ice is supplied from the surroundings, and the ice changes its state from solid to liquid.

4.9.2 Applications of Refrigeration System

1. In cold storage—for preservation of fruits, vegetables, food and beverages and dairy products.
2. In air conditioning of offices, theaters, hospitals etc.
3. In air conditioning automobiles, trains, buses and aircrafts.
4. It is used for liquification of gases.
5. It is used in manufacturing units e.g. precision instruments, electronic industries etc.
6. It is used in pharmaceutical units.
7. It is used for manufacturing of ice and icecream.

4.9.3 Vapour Compression Refrigeration Cycle

The basic components used in vapour compression refrigeration cycle are as shown in Fig. 4.51.

1. Compressor

2. Condenser
3. Expansion valve
4. Evaporator

The basic operation involved in vapour compression refrigeration plant are represented in the flow diagram Fig. 4.51 and property diagram Fig. 4.52.

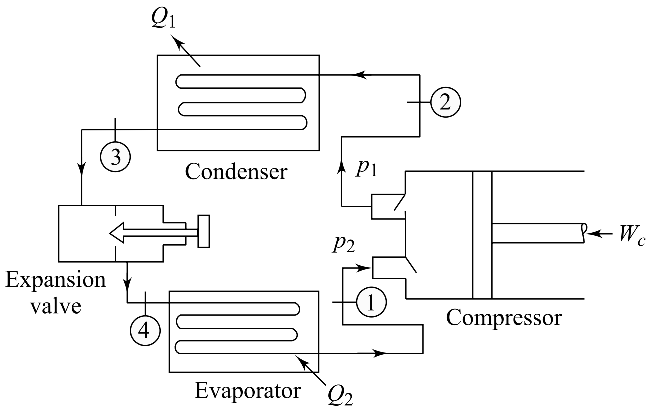


Fig. 4.51 *Vapour Compression Refrigeration Plant-flow Diagram*

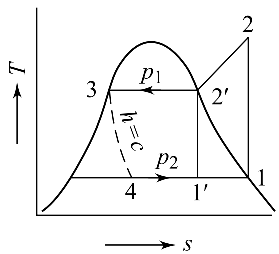


Fig. 4.52 *Vapour Compression Refrigeration Cycle-Property Diagrams*

The operations represented are as follows for an idealized plant:

1. *Compression* A reversible adiabatic process 1–2 or 1′–2′ either starting with saturated vapour (state 1), called *dry compression*, or starting with wet vapour (state 1′), called *wet compression*. Dry compression (1-2) is always preferred to wet compression (1′-2′), because with wet compression there is a danger of the liquid refrigerant being trapped in the head of the cylinder by the rising piston which may damage the valves or the cylinder head, and the droplets of liquid refrigerant may wash away the lubricating oil from the walls of the cylinder, thus accelerating wear.

2. *Cooling and Condensing* A reversible constant pressure process, 2-3, first desuperheated and then condensed, ending with saturated liquid. Heat Q_1 is transferred out.

3. *Expansion* An adiabatic throttling process 3-4, for which enthalpy remains unchanged. States 3 and 4 are equilibrium points. Process 3-4 is adiabatic (then only $h_3 = h_4$ by S.F.E.E.), but not isentropic.

Hence it is irreversible and cannot be shown in property diagrams. States 3 and 4 have simply been joined by a dotted line.

4. *Evaporation* A constant pressure reversible process, 4-1, which completes the cycle. The refrigerant is throttled by the expansion valve to a pressure, the saturation temperature at this pressure being below the temperature of the surroundings. Heat then flows, by virtue of temperature difference, from the surroundings, which gets cooled or refrigerated, to the refrigerant, which then evaporates, absorbing the heat of evaporation. The evaporator thus produces the cooling or the *refrigerating effect*, absorbing heat Q_2 from the surroundings by evaporation.

In refrigeration practice, enthalpy is the most sought-after property. The diagram in *p-h* coordinates is found to be the most convenient. The constant property lines in the *p-h* diagram for the vapour compression cycle in Fig. 4.53.

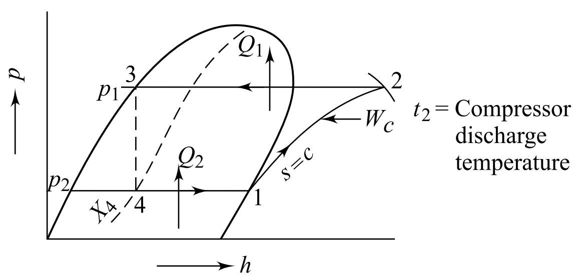


Fig. 4.53 *Vapour Compression Cycle on p-h Diagram*

4.9.3.1 Performance and Capacity of a Vapour Compression Plant

Figure 4.54 shows the simplified diagram of a vapour compression refrigeration plant.

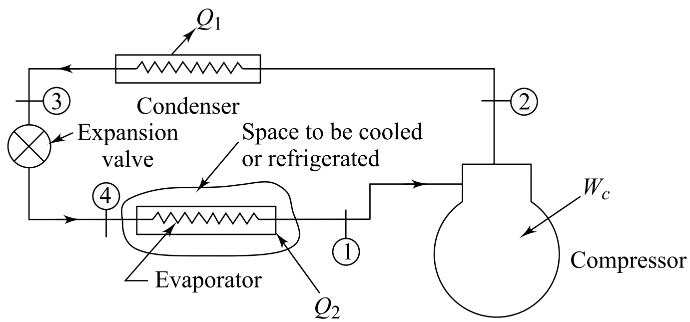


Fig. 4.54 *Vapour Compression Plant*

When steady state has been reached, for 1 kg flow of refrigerant through the cycle, the steady flow energy equations (neglecting K.E. and P.E. changes) may be written for each of the components in the cycle as given as follows.

Compressor $\quad h_1 + W_c = h_2$

$\therefore \quad W_c = (h_2 - h_1)$ kJ/kg

Condenser $\quad h_2 = Q_1 + h_3$

$\therefore \quad Q_1 = (h_2 - h_3)$ kJ/kg

Expansion valve $h_3 = h_4$

Evaporator

$$h_4 = Q_2 = h_1$$

$\therefore$ $Q_2 = (h_1 - h_4)$ kJ/kg

This is known as the *refrigerating effect*, the amount of heat removed from the surroundings per unit mass flow of refrigerant.

If the *p-h* chart for a particular refrigerant is available with the given parameters, it is possible to obtain from the chart the values of enthalpy at all the cardinal points of the cycle. Then for the cycle

$$\text{COP} = \frac{Q_2}{W_c} = \frac{h_1 - h_4}{h_2 - h_1} \tag{4.75}$$

If w is the mass flow of refrigerant in kg/s, then the rate of heat removal from the surroundings

$$= w(h_1 - h_4) \text{ kJ/s} = w(h_1 - h_4) \times 3600 \text{ kJ/h}$$

One tonne of refrigeration is defined as the rate of heat removal from the surroundings equivalent to the heat required for melting 1 tonne of ice in one day. If the latent heat of fusion of ice is taken as 336 kJ/kg, then 1 tonne is equivalent to heat revoval at the rate of (1000 × 336)/24 or 14,000 kJ/h

$\therefore$ Capacity of the refrigerating plant

$$\frac{w(h_1 - h_4) \times 3600}{14{,}000} \text{ tonnes}$$

4.9.3.2 Actual Vapour Compression Cycle

In order to ascertain that there is no droplet of liquid refrigerant being carried over into the compressor, some superheating of vapour is recommended after the evaporator.

A small degree of subcooling of the liquid refrigerant after the condenser is also used to reduce the mass of vapour formed during expansion, so that too many vapour bubbles do not impede the flow of liquid refrigerant through the expansion valve.

Both the superheating of vapour at the evaporator outlet and the subcooling of liquid at the condenser outlet contribute to an increase in the refrigerating effect, as shown in Fig. 4.55. The compressor discharge temperature, however, increases, due to superheat, from t_2' to t_2, and the load on the condenser also increases.

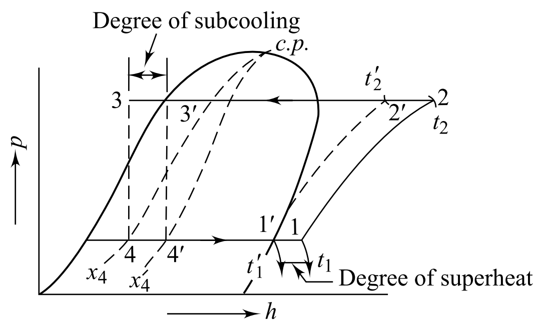


Fig. 4.55 *Superheat and Subcooling in a Vapour Compression Cycle*

Sometimes, a liquid-line heat exchanger is used in the plant, as shown in Fig. 4.56. The liquid is subcooled in the heat exchanger, reducing the load on the condenser and improving the COP.

$$Q_2 = h_6 - h_5,\ Q_1 = h_2 - h_3$$
$$W_c = h_2 - h_1 \text{ and } h_1 - h_6 = h_3 - h_4$$

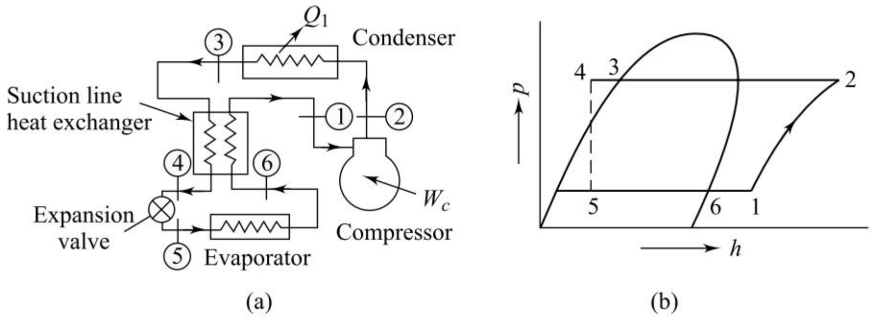


Fig. 4.56 *Vapour Compression Cycle with a Suction-line Heat Exchanger*

4.9.4 Absorption Refrigeration Cycle

The absorption refrigeration system is a *heat operated unit* which uses a refrigerant that is *alternately absorbed and liberated from the absorbent*. In the basic absorption system, the compressor in the vapour compression cycle is *replaced by an absorber-generator assembly* involving less mechanical work. Figure 4.57 gives the basic absorption refrigeration cycle, in which *ammonia is the refrigerant and water is the absorbent*. This is known as the *aqua-ammonia absorption* system.

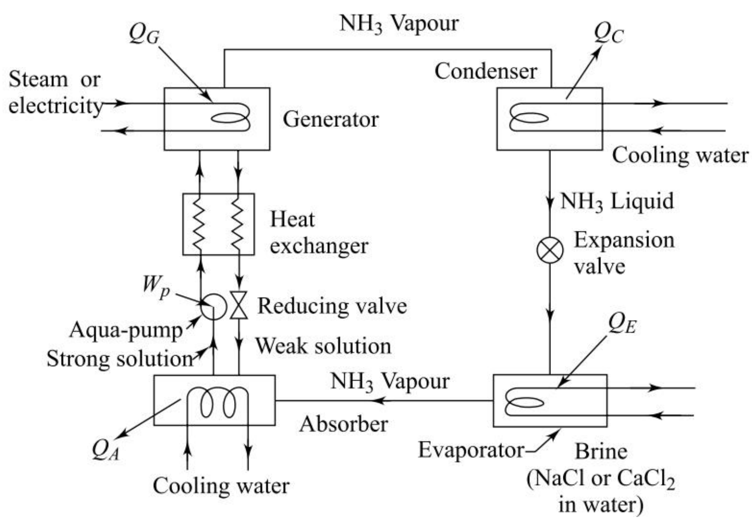


Fig. 4.57 *Vapour Absorption Refrigeration Plant-flow Diagram*

Ammonia vapour is vigorously absorbed in water. So when low-pressure ammonia vapour from the evaporator comes in contact in the absorber with the weak solution (the concentration of ammonia in water is low) coming from the generator, it is readily absorbed, releasing the latent heat of condensation. The temperature of the solution tends to rise, while the absorber is cooled by the circulating water, absorbing the *heat of solution* (Q_A), and maintaining a constant temperature. Strong solution, rich in ammonia, is pumped to the generator where heat (Q_G) is supplied from an external source (steam, electricity, gas flame, etc.). Since the boiling point of ammonia is less than that of water, the ammonia vapour is given off from the aqua-ammonia solution at high pressure, and the weak solution returns to the absorber through a pressure reducing valve. The heat exchanger preheats the strong solution and precools the weak solution, reducing both Q_G and Q_A, the heat to be supplied in the generator and the heat to be removed in the absorber respectively. The ammonia vapour then condenses in the condenser, is throttled by the expansion valve, and then evaporates, absorbing the heat of evaporation from the surroundings or the brine to be chilled.

In driving the ammonia vapour out of the solution in the generator, it is impossible to avoid evaporating some of the water. This water vapour going to the condenser along with the ammonia vapour, after condensation, may get frozen to ice and block the expansion valve. So an *analyzer-rectifier combination* (Fig. 4.58) is used to eliminate water vapour from the ammonia vapour going into the condenser.

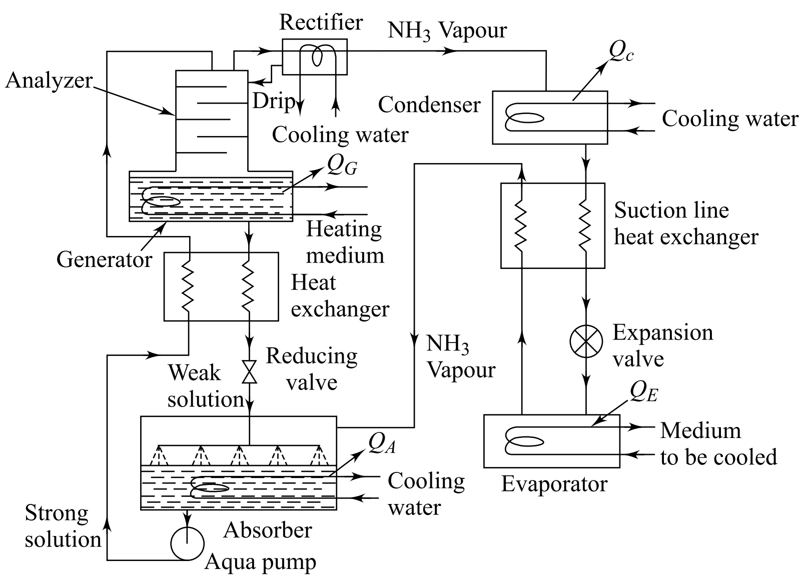


Fig. 4.58 *Actual Vapour Absorption Refrigeration Plant with Analyzer and Rectifier*

The analyzer is a direct-contact heat exchanger consisting of a series of trays mounted above the generator. The strong solution from the absorber flows downward over the trays to cool the outgoing vapours. Since the saturation temperature of water is higher than that of ammonia at a given pressure, it is the water vapour which condenses first. As the vapour passes upward through the analyzer, it is cooled and enriched by ammonia, and the liquid is heated. Thus the vapour going to the condenser is lower in temperature and richer in ammonia, and the heat input to the generator is decreased.

The final reduction in the percentage of water vapour in the ammonia going to the condenser occurs in the rectifier which is a water-cooled heat exchanger which condenses water vapour and returns it to the generator through the drip line, as shown in Fig. 4.89. The use of a suction-line heat exchanger is to reduce Q_A and increase Q_E, thus achieving a double benefit. In the absorber the weak solution is sprayed to expose a larger surface area so as to accelerate the rate of absorption of ammonia vapour.

4.9.5 Refrigerants

The most widely used refrigerants now-a-days are a group of halogenated hydrocarbons, marketed under the proprietary name of freon. These are either methane-based or ethane-based, where the hydrogen atoms are replaced by chlorine or fluorine atoms. Methane-based compounds are denoted by a number of two digits, where the first digit minus one is the number of hydrogen atoms and the second digit indicates the number of fluorine atoms, while the other atoms are chlorine. For Refrigerant-12 (R–12), e.g. the number of hydrogen atoms is zero, the number of fluorine atoms is two, and hence the other two atoms must be chlorine. Therefore, the compound is CCl_2F_2, dichloro-difluoro methane. Similarly, for R-22, it is $CHClF_2$, monochloro-difluoro methane; for R-50, it is methane, CH_4; for R-10, it is CCl_4, carbon tetrachloride, and so on. If the compound is ethane-based, a three-digit number is assigned to the refrigerant, where the first digit is always 1, the second digit minus one is the number of hydrogen atoms, and the third digit indicates the number of fluorine atoms, all other atoms in the hydrocarbon being chlorine. For example, R-110 is C_2Cl_6, R-113 is $C_2Cl_3F_3$, R-142 is $C_2H_3ClF_2$, and so on.

In broader sense, any substance that absorbs heat through expansion or vaporization is called refrigerant . it is also applied to secondary cooling medium such as cold water or brine solution.

4.9.5.1 Classification of Refrigerant

The refrigerants are classified as follows:

1. Primary refrigerant
2. Secondary refrigerants

Primary refrigerants: primary refrigerant is the working medium of refrigeration cycle which absorbs heat at lower temperature by the absorption of latent heat of evaporation from its surroundings and rejecting the same at higher temperature e.g. ammonia, Freon group, carbon di-oxide etc.

Secondary refrigerant: Secondary refrigerants are the substances which do not flow in the refrigerating cycle. It first gets cooled with the help of primary refrigerant and subsequently takes the cooling load. e.g. ice, brine solution etc.

The primary refrigerants are further grouped as follows:

1. *Halocarbons*: The most widely used refrigerants now-a days are a group of halogenated hydrocarbons, marketed under the propriety name of Freon. These are either methane based, where the hydrogen atoms are replaced by chlorine or fluorine atoms.
2. *Azeotropes*: The azeotrope refrigerants are the mixture of different refrigerants which cannot be separated in to its components by distillation. The azeotropes, possesses fixed thermodynamic properties and does not under go any separation while undergoing different temperature and pressure. e.g. R-500 (73.8% R-!2 and 26.2% R-152)
3. *Inorganic compounds:* Some of the inorganic compounds which acts as refrigerants are ammonia, air, carbon dioxide, sulpur dioxide etc.
4. *Hydrocarbons*: Some of the hydrocarbons which are used as refrigerants have favourable thermodynamic properties but are highly inflammable are as follows methane, ethane, propane, butane etc.

4.9.5.2 Selection of Refrigerants

The most important parameters that need to be considered in the selection of refrigerant are as follows:

1. The temperatures of the two media (the refrigerated space and the envoirnment), with which the refrigerant exchanges the heat. To have reasonable heat transfer rate, a temperature difference of 5-10 °C should be maintained between the refrigerant and the medium.
2. If single refrigerant cannot meet the desired temperature, then two cycles with two different refrigerant can be used in series.
3. the other desirable characteristics of the refrigerant are that it should be non-toxic, non- flammable, non-corrosive, chemically stable and should have large enthalpy of vaporization to minimize the mass flow rate.

4.9.5.3 Properties of Refrigerants

The properties of refrigerant can be categorized in to the following heads:

1. thermodynamic property
2. physical property
3. chemical property

Thermodynamic property:

1. Freezing temperature: As the refrigerant has to operate in the cycle above its freezing temperature hence, it is evident that, it must have freezing temperature well below the evaporator temperature.
2. Critical temperature and pressure: the critical temperature should be high so that the condenser temperature line is well below the critical temperature, while critical pressure should be low.
3. Condensing and evaporator pressure: An evaporator pressure should be positive and near atmospheric value. The positive pressure also eliminates the possibility of leakage of air into the system.

4. Latent heat of vaporization: A refrigerant should posses a large latent heat of vaporization to have a larger refrigerating effect per kg of refrigerant there by reducing the mass of refrigerant flowing in the system per tonne of refrigeration.

Chemical property:

1. Flammability: Refrigerants should neither be explosive nor inflammable. Hydrocarbon refrigerants are highly inflammable.
2. Toxicity: Refrigerants should not be toxic. Ammonia because of toxicity and flammability is not used in domestic refrigerators and comfort air conditioners.
3. Action with water: the solubility of fluorocarbon water is low even then the presence of the moisture is very critical in refrigeration system operating below 0 °C, as it can cause choking of tubes.
4. Action with material: The material should be selected depending upon the refrigerant . As ammonia attacks copper and copper bearing material hence should not be used with ammonia.

Physical property:

1. Viscosity: Low viscosity is desirable for better heat transfer.
2. Thermal conductivity: A high thermal conductivity is desirable for high heat transfer.
3. Leak tendency: the leak tendency of refrigerant should be low. At the same time in case of leak it should be easily detectable.
4. Cost of refrigerant: the cost of refrigerant should be low. Ammonia being the cheapest is used in cold storages.

4.9.6 Ozone Depletion Potential and Global Warming

The ozone layer is present in the upper part of atmosphere called stratosphere, which is about 11-50 km above the surface of the earth. The ozone layer in the stratosphere blocks the UV radiation from the sun reaching the earth. The CFC because of their stability and long life migrate in to the upper atmosphere by molecular diffusion. It was hypothesized that the chlorine atom splits off by the action of sunlight. The free chlorine atom from CFC reacts with the ozone present in the stratosphere, thus depleting the ozone layer. A single atom of chlorine released from CFC reacts out about 100,000 molecules of ozone. Hence, even a small concentration of CFC becomes important in the atmosphere.

The presence of CFC not only allows more UV radiation in to the earth surface but also prevents the Infra red radiation escaping the earth to the outer surface. This contributes to green house effect and global warming.

As a result, the use of some CFCs is banned by Montreal Protocol, 1987, and phased out in many countries. Fully halogenated CFCs such as R-11, R-12 and R-115 do the most damage to the ozone layer. The partially halogenated refrigerants such as R-22 has about 5% of the ozone depletion potential (ODP) compared to R-12.

The chlorine free refrigerant R-134a is presently replacing R-12, the most widely used refrigerant, particularly in refrigerators and freezers and automobile air conditioners.

4.9.7 Comparasion between Vapour Compression and Vapour Absorption System

Sr.No.	*Particular*	*Vapour compression system*	*Vapour absorption system*
1	Energy input	Electrical or mechanical for driving the compressor	Heat energy – low grade energy. Waste or exhaust steam can be used.
2	Effect of evaporator pressure and temperature	The refrigerating capacity decreases with decrease in evaporator pressure	Refrigerating capacity is less affected by decrease in evaporator pressure.
3	Wear and tear for same cooling capacity	More	Less (moving part is a small aqua pump)
4	COP	More	Less
5	Refrigerant charging	Easy	difficult
6	Effect on performance due to Load variation	Poor	Not affected by variation of load.
7	suitability	Suitable at all loads	Not suitable for lower loads.
8	Capacity	Maximum capacity for single compressor is 1000 TR	Can be built in capacity above 1000 TR

Example 4.18 A refrigerator working on Carnot cycle requires 1.2 kW per tonnne of refrigeration to maintain a lower temperature of –35 °C . Calculate the COP and heat rejection temperature.

Solution: $T_2 = 273+(-35)\ K = 238\ K$

Power require = 1.2 kW

Refrigerating effect = 14000 kJ/hr

$$COP = \text{Refrigerating effect / work done}$$

$$\text{Work done} = 1.2 \times 3600 = 4320 \text{ kJ/hr}$$

$$COP = 14000/4320 = 3.24$$

$$(COP)_{ideal} = T_2/(T_1 - T_2)$$

$$3.24 = 238/(T_1 - 238)$$

$$T_1 = 311.45 \text{ K}$$

Example 4.19 A refrigeration plant operates on a reversed Carnot cycle operating between the temperature of -10 °C, 30 °C.If the capacity of the refrigerator is 200 tonnes of refrigeration, determine 1. the quantity of ice formed per hour when the water supplied is at 25 C. 2 minimum power required.

Solution: Take latent heat of fusion of ice = 336 kJ/kg.,

Specific heat of water = 4.18 kJ/kg K

$$T_1 = 273 + 30 = 303 \text{ K}, \quad T_2 = 273 + (-10) = 263 \text{ K}$$

Heat to be removed from water at 25 C per kg to convert in to ice at 0 C

$$= 4.18 \times 25 + 336 = 440.5 \text{ kJ/kg}$$

refrigerating effect = $14000 \times 200 = 2800000$ kJ/hr let m be the mass of ice formed per hour

m = 2800000/ 440.5 = 6.356 Tonnes of ice /hr Ans.

COP = T_2 / ($T_1 - T_2$) = 263/ (40) = 6.57

COP = Refrigerating effect per second / work done

6.57 = 14000 ×200/ (3600 ×W)

W = 118.38 kJ/s = 118.38 kW *Ans.*

Example 4.20 A cold storage is to be maintained at – 5 °C while the surroundings are at 35 °C. The heat leakage from the surroundings into the cold storage is estimated to be 29 kW. The actual COP of the refrigeration plant used is one-third that of an ideal plant working between the same temperatures. Find the power required (in kW) to drive the plant.

Solution: COP (Ideal) = $\dfrac{T_2}{T_1 - T_2} = \dfrac{268}{308 - 268} = 6.7$

$\therefore$ Actual COP = $1/3 \times 6.7 = 2.23 = \dfrac{Q_2}{W}$

$\therefore$ Power required to drive the plant (Fig. 4.95)

$$W = \frac{Q_2}{2.23} = \frac{29}{2.23} = \mathbf{13\ kW}$$

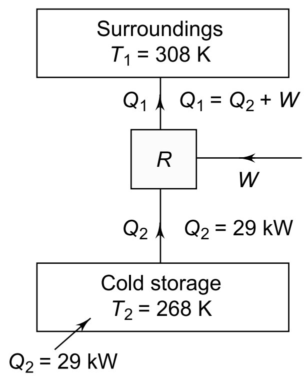


Fig. 4.59

Example 4.21 A house hold refrigerator produces a refrigerating effect of 100 kJ/min. If the COP of the system is 2.5 , determine the power consumed and heat rejected to the surroundings.

Solution: COP = 2.5 , Refrigerating effect = 100 kJ/min.

COP = refrigerating effect/ work done

5.5 = 100/ (W)

W = 40 kJ/min = 0.667 kW *Ans.*

Heat rejected to the surrounding = refrigerating effect + work done

= 100 + 40 =140 kJ/min = 2.33 kJ/s *Ans.*

Example 4.22 A refrigeration plant produces 0.139 kg/s of ice at –5 °C from water at 30 °C . if the power required to drive the plant is 22 kW, determine the capacity of the ice plant in tonnes and actual COP. (C_p of ice =2.1 kJ/kg K, Sp. heat of water = 4.18 kJ/kg K, Latent heat of fusion of ice = 336 kJ/kg)

Solution: Mass of ice produced 0.139 kg/s
Power required to drive the plant = 22 kW
Heat to be extracted from water to produce ice at -5 °C per kg =

$\times 30 + 336 + 2.1 \times 5 = 471.9$ kJ/kg

since the plant is producing 0.139 kg/s of ice ,
the refrigerating effect = 0.139 ×471.9 kJ/s = 65.59 kJ/s

COP = Refrigerating effect / work done
= 65.59/22 = 2.98 *Ans.*

Capacity of plant in tonnes = 65.59 ×3600/14000 = 16.866 TR *Ans.*

REVIEW QUESTIONS

4.1 What do you understand by macroscopic and microscopic viewpoints?
4.2 What is the difference between a closed system and an open system?
4.3 Distinguish between the terms ‘change of state’, ‘path’, and ‘process’.
4.4 What are intensive and extensive properties?
4.5 What is a quasi-static process? What is its characteristic feature?
4.6 What is displacement work?
4.7 What do you understand by path function and point function? What are exact and inexact differentials?
4.8 State and explain the first law for a closed system undergoing a cycle.
4.9 Define enthalpy. Why does the enthalpy of an ideal gas depend only on temperature?
4.10 What is a steady flow process?
4.11 Write the steady flow energy equation for a single stream entering and a single stream leaving a control volume and explain the various terms in it.
4.12 Define the thermal efficiency of a heat engine cycle. Can this be 100%?
4.13 What is a thermal energy reservoir? Explain the terms ‘source’ and ‘sink’.
4.14 Give the Kelvin-Planck statement of the second law.
4.15 Give the Clausius’ statement of the second law.
4.16 Define the COP of a refrigerator.
4.17 What do you understand by triple point ?
4.18 What is the critical point? Explain the term critical pressure and critical temperature and critical volume of water?
4.19 Draw the phase equilibrium diagram on *p-v* coordinates for a substance which shrinks in volume on melting.

4.20 Draw the phase equilibrium diagram for a pure substance on *p-T* coordinates. Why does the fusion line for water have negative slope?
4.21 Draw the phase equilibrium diagram for a pure substance on *T-s* plot with relevant constant property lines.
4.22 Draw the phase equilibrium diagram for a pure substance on *h-s* plot with relevant constant property lines.
4.23 How are steam boilers classified?
4.24 Explain in brief the functions of various important mountings with which a boiler can operate safely.
4.25 Give a brief description of a Cochran boiler with a neat sketch with the position of essential mountings.
4.26 Give the merits and demerits of water-tube boilers over fire-tube boilers.
4.27 Explain the function of fusible plug, and where is it located in a Babcock and Wilcox boiler.
4.28 Give the benefits of periodic blowing of water in the boiler.
4.29 Why is forced water circulation used in a high pressure boiler?
4.30 What are the advantages of using a super heater in the boiler.
4.31 Explain the function of an air pre-heater. Also give its location in the passage of flue gases.
4.32 Explain pulverized fuel-fired system.
4.33 Why are water-tube boilers used for large power station?
4.34 Why is economizer fitted with the scrappers?
4.35 Why is pressure gauge fitted with a U-tube filled with water.
4.36 Explain draught and give its importance.
4.37 Discuss the merits and demerits of artificial draught and natural draught.
4.38 Derive an expression between the height of a chimney and the static draught it produces, flue gas temperature, and atmospheric temperature.
4.39 Establish the relationship for maximum discharge of hot flue gases leaving through a chimney.
4.40 Explain the difference between forced draught and induced draught.
4.41 Explain the significance of equivalent of evaporation.
4.42 Explain the importance of boiler thermal efficiency.
4.43 What do you understand by dry and wet compression? Which is preferred and why?
4.44 What is refrigerating effect?
4.45 What is a tonne of refrigeration?
4.46 Explain the function of various components of simple vapour compression refrigeration system
4.47 Why is the use of halogenated hydrocarbons as refrigerants now discouraged?
4.48 What are the effects of CFCs on the environment? How do they affect the ozone layer?
4.49 What is ODP?
4.50 What are the parameters to be considered in the selection of a refrigerant?
4.51 What is an absorption refrigeration cycle? How does it differ from a vapour compression cycle?
4.52 What are the functions of the analyzer and the rectifier?

PROBLEMS

4.1 A mass of 1.5 kg of air is compressed in a quasi-static process from 0.1 MPa to 0.7 MPa for which pv = constant. The initial density of air is 1.16 kg/m^3. Find the work done by the piston to compress the air. **Ans.** 251.62 kJ

4.2 A mass of gas is compressed in a quasi-static process from 80 kPa, 0.1 m^3 to 0.4 MPa, 0.03 m^3. Assuming that the pressure and volume are related by pv^n = constant, find the work done by the gas system. **Ans.** –11.83 kJ

4.3 In a cyclic process, heat transfers are + 14.7 kJ, – 25.2 kJ, – 3.56 kJ and + 31.5 kJ. What is the net work for this cyclic process? **Ans.** 17.34 kJ

4.4 A domestic refrigerator is loaded with food and the door closed. During a certain period the machine consumes 1 kW h of energy and the internal energy of the system drops by 5000 kJ. Find the net heat transfer for the system.
Ans. – 8.6 MJ

4.5 A system composed of 2 kg of the above fluid expands in a frictionless piston and cylinder machine from an initial state of 1 MPa, 100°C to a final temperature of 30°C. If there is no heat transfer, find the net work for the process.
Ans. 100.52 kJ

4.6 A mass of 8 kg gas expands within a flexible container so that the p–v relationship is of the form $pv^{1.2}$ = const. The initial pressure is 1000 kPa and the initial volume is 1 m^3. The final pressure is 5 kPa. If specific internal energy of the gas decreases by 40 kJ/kg, find the heat transfer in magnitude and direction. **Ans.** + 2615 kJ

4.7 A rigid vessel of volume 0.86 m^3 contains 1 kg of steam at a pressure of 2 bar. Evaluate the specific volume, temperature, dryness fraction, internal energy, enthalpy, and entropy of steam.

4.8 The steam is heated to raise its temperature to 150°C. Show the process on a sketch of the p–v diagram, and evaluate the pressure, increase in enthalpy, increase in internal energy, increase in entropy of steam, and the heat transfer. Evaluate also the pressure at which the steam becomes dry saturated.
Ans. (a) 0.86 m^3/kg, 120.23°C, 0.97, 2468.54 k/kg,
2640.54 kJ/kg, 6.9592 kJ/kg K
(b) 2.3 bar, 126 kJ/kg, 106.6 kJ/kg, 0.2598 kJ/kg K, 106.6 kJ/K

4.9 Ten kg of water at 45°C is heated at a contant pressure of 10 bar until it becomes superheated vapour at 300°C. Find the change in volume, enthalpy, internal energy and entropy.
Ans. 2.569 m^3, 28627.5 kJ, 26047.6 kJ, 64.842 kJ/K

4.10 A rigid closed tank of volume 3 m^3 contains 5 kg of wet steam at a pressure of 200 kPa. The tank is heated until the steam becomes dry saturated. Determine the final pressure and the heat transfer to the tank. **Ans.** 304 kPa, 3346 kJ

4.11 A refrigerated plant produces 10 tonnes of ice per day at -4 C using water at a room temperature of 25 C Estimate the power of the compressor in kW if COP of the refrigeration plant is 2.5. Take the latent heat of fusion of ice = 336 kJ/kg, specific heat of water = 4.18 kJ/kg K, Specific heat of ice = 2.1 kJ/kg K.

Ans. Power of compressor = 20.78 kW

4.12 A refrigerator produces a refrigerating effect of 8.5MJ/min.If the COP of the refrigeration system is 3, determine the power required to run the compressor.

Ans. power = 47.2 kW

4.13 The condenser and evaporator temperature of a refrigeration system operating on a reversed Carnot cycle is 40 C and -5 C. Determine the (a) the COP of the system (b) the refrigerating effect per kW of work input and (c) the heat rejected to the condenser.

Ans. COP= 5.956, Q_2 =5.955 kJ/s, Q_1= 6.956 kJ/s

Chapter 5

Reciprocating Machines

Reciprocating machines like heat engines are used for converting heat energy into mechanical energy. Heat obtained from combustion of fuels is used to heat the *working substance*. In case of *internal combustion engines (IC engines)*, the fuel is burned directly inside the engine. The combustion gases reach high temperature and pressure. The heat energy of the combustion gases is utilized in moving the reciprocating parts of the engine like the piston. In case of *steam engines* the heat energy obtained from combustion of fuel is first transferred to water. Water is heated in a boiler to obtain steam at high pressure and temperature. This steam is then supplied to the steam engine, where it expands to move the piston. The reciprocating motion of the piston is converted into rotary motion by means of a suitable mechanism like *slider crank mechanism*.

5.1 STEAM ENGINES

A steam engine uses steam as working substance. In a steam engine steam at high pressure and temperature is expanded to move the piston. The reciprocating motion of the piston is converted into rotary motion by a slider crank mechanism. Steam engine was invented in 1712. James Watt developed it in its present form in 1770. The steam engine was the centre of the industrial revolution in the 18th century. It has been the work horse of industry for more than a century. It was used as a *prime-mover* for industrial machines, generators, ships, and locomotives. However, it has been largely replaced by IC engines, steam turbines, and gas turbines.

5.1.1 Construction of Steam Engine

The schematic diagram of a steam engine and its essential components are shown in Fig. 5.1. A basic steam engine has a *frame* which supports all the stationary components

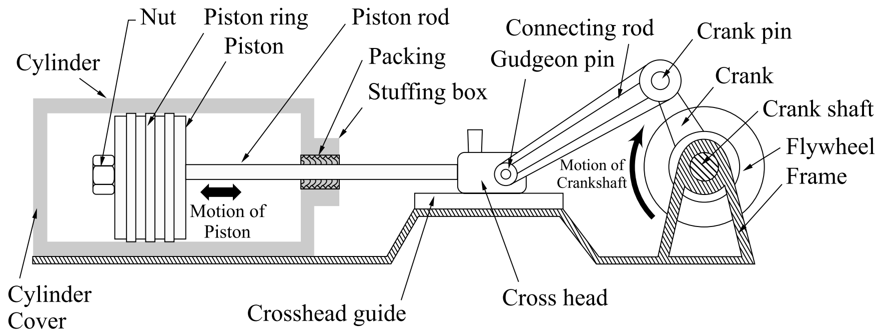


Fig. 5.1 *Steam Engine*

of the engine. The frame is a strong and rigid structure made of cast iron. A hollow cast iron *cylinder* is supported rigidly on the frame. One end of the cylinder is closed by a *cylinder cover*. An enclosed cast iron chamber is attached to the cylinder, called *steam chest*. The steam chest is cast integral with the cylinder. On its back it is closed by a cover called *steam chest cover*. The steam pipeline from the boiler is connected to the steam chest cover. Steam is supplied first into this chamber. Inside the steam chest, there is a sliding valve which controls the supply of steam into the cylinder. Steam enters into the cylinder through openings in its wall, called *ports*. A cast iron a *piston* moves to and fro inside the cylinder. The piston is cylindrical in shape and has circumferential grooves cut on it. Circular rings made of cast iron are inserted in these grooves. These rings are called the *piston rings*. The piston rings remain in contact with the cylinder walls. They prevent leakage of steam from around the piston. They also take the wear due to rubbing, and should be replaced from time to time. A cylindrical *piston rod*, made of mild steel, is attached with the piston, which passes out of the cylinder through a *stuffing box*. Thus, the cylinder is covered by cylinder cover on one end, and the stuffing box on the other. The stuffing box contains tightly packed *packing*, which prevents leakage of steam from the cylinder. The piston rod is connected to a *cross-head*, which moves to and fro on *cross-head guides*. These guides are made of soft materials like brass or gun metal. Sometimes they are made of cast iron. The piston rod is connected to the cross-head by a *cotter joint* or threaded joint. A *connecting rod* is also joined to the cross-head by means of a *gudgeon pin*. This pin joint allows oscillation of the connecting rod about the gudgeon pin. This pin is made of medium carbon steel. The connecting rod is joined to a *crank*, by means of a *crank pin*. The crank is connected to a shaft, called the *crank shaft*. It is made of medium carbon steel. The connecting rod converts the reciprocating motion of the piston into rotary motion of the crank shaft. The crank shaft is supported on *main bearings*. The part of the crank shaft which is supported on the bearing is called *journal*. The crank shaft carries a *flywheel*. Fly wheel has a circular *rim* which is joined to a central *hub* by means of *arms*. The rim, arms and the hub are cast as a single casting in small and medium sized engines. The flywheel absorbs mechanical energy during the *power stroke* and returns it back during the *return stroke*. The power stroke and return stroke are explained in the next section. In this manner the flywheel reduces the fluctuations in rotational speed of the crank shaft during every *cycle* of the engine. A *governor* is used to maintain the speed of the crank shaft when the load on the engine changes. This control is done by either controlling the quantity of steam supplied to the engine, or by control on the pressure of steam supplied.

The flow of steam into and out of the cylinder is controlled by a *valve gear mechanism*, as shown in Fig. 5.2. This mechanism consists of an *eccentric* mounted on the crank shaft. The eccentric is a circular disc, called *sheave* with a hole that does not coincide with its geometrical centre. The crank shaft passes through this hole of the disc. A casing covers the eccentric. The sheave and the casing are made of cast iron. A rod is bolted to this casing, called the *eccentric rod*. The other end of this rod is joined with a *cross-head* by means of a pin. The cross-head for eccentric rod moves inside straight *guide ways*. Thus, when the crank shaft rotates, the eccentric cover undergoes an rotational motion, and the cross-head undergoes a linear oscillatory motion. In this manner, the eccentric converts the rotary motion of the crank shaft into linear oscillatory motion of the cross-head. The cross-head is connected by a *valve rod* to a D-shaped valve called *D-slide valve*. The eccentric rod, the valve rod, and the valve are made of cast iron. The D-slide valve is housed inside the steam chest. It slides in a reciprocating manner against the cylinder wall to open and close the ports. The valve slides on the *valve seat*. The movement of the slide valve is synchronized with the rotation of the crank shaft.

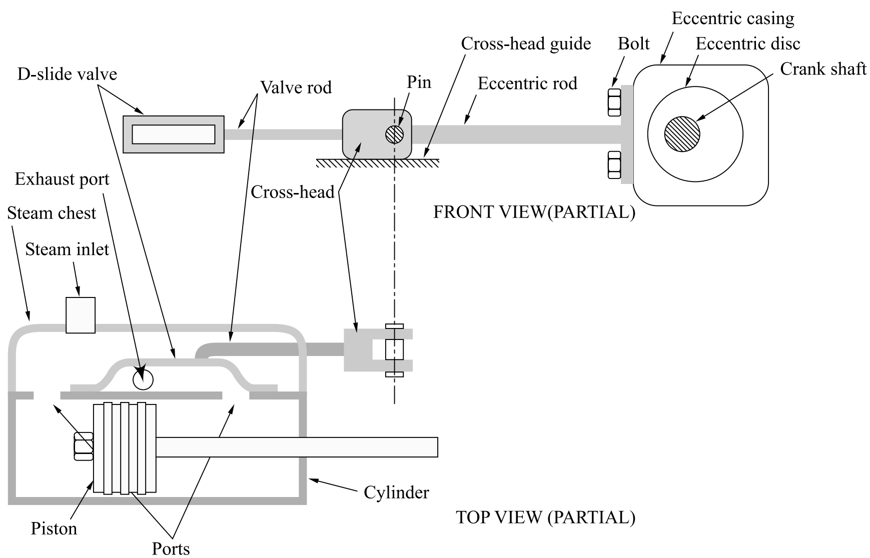


Fig. 5.2 *Valve Gear Mechanism for Steam Engine*

The ***stationary parts*** of the steam engine are frame, cylinder, steam chest, stuffing box, cross-head guide, and crank shaft bearings. The ***reciprocating parts*** are piston, piston rings, piston rod, and cross-head assembly. The ***rotating parts*** are crank, crank shaft, eccentric, and bearings. The connecting rod and eccentric rod move with a combination of linear and angular oscillatory motion.

5.1.2 Classifications of Steam Engine

Steam engines may be classified according to different criteria, as follows:

1. *Orientation of axis of cylinder:* (a) Vertical (b) Horizontal (c) Inclined.
2. *Direction of steam inlet:* (a) Single acting (b) Double acting. In single acting engines the steam is supplied on one side of piston only. Thus, we get one *power stroke* and one *idle stroke* in each cycle. In double acting engines steam is supplied on one side of piston during forward stroke and on its other side during the return stroke. Thus, we get two power strokes in each cycle.
3. *Number of cylinders:* (a) Simple steam engine (b) Compound steam engine. In simple steam engine the steam expands in one cylinder only. In compound cylinder, steam is allowed to expand partly in one cylinder, and partly in second or third cylinders.
4. *Exhaust of steam:* (a) Condensing (b) Non-condensing. In condensing engines, the steam coming out of the cylinder, after expansion, is sent to an enclosed chamber called *condenser*. Inside the condenser pressure is maintained below atmospheric pressure. Here, the steam is condensed by *cooling water*. In non-condensing engines, the steam is exhausted directly to the atmosphere. Condensing engines are more efficient, as more work output is obtained from the steam.
5. *Application:* (a) Stationary (b) Locomotive (c) Marine. Stationary engines are used in plants for generation of mechanical or electrical power, and to drive pumps, shafts, machines, etc. Locomotive engines are used in railroad applications. Marine engines are used in ships.
6. *Speed:* (a) Low speed—below 100 rpm (b) Medium speed—100 to 300 rpm (c) High speed—above 300 rpm.

5.1.3 Working of Steam Engine

Working of a single acting steam engine is explained here. As shown in Fig. 5.3 (a), in the beginning the piston is at its innermost position. This is called the *inner dead centre (IDC)*. The steam chest is connected to *live steam* line. Therefore, it is always filled with high pressure steam. In the initial position, the D-slide valve uncovers the inlet port. Steam enters into the cylinder and pushes the piston. The piston moves outwards towards the *outer dead centre (ODC)*. When the piston reaches ODC, as shown in Fig. 5.3(b), the D-slide valve covers the inlet port. Therefore, steam supply into the cylinder stops. Also, the valve uncovers the outlet port. Steam escapes from the cylinder through the outlet valve. In this position the outlet valve is also connected to the exhaust valve. Therefore, the steam leaves the engine. It is discharged into atmosphere if the engine is non-condensing type, or sent to the condenser, if it is a condensing type. The piston is returned to IDC by inertia of the flywheel.

5.1.4 Indicator Diagram

The indicator diagram shows variation of pressure against motion of the piston in the cylinder. It represents the sequence of events during working of the engine. Figure 5.4 shows the *hypothetical* indicator diagram. Pressure on the piston is shown by the

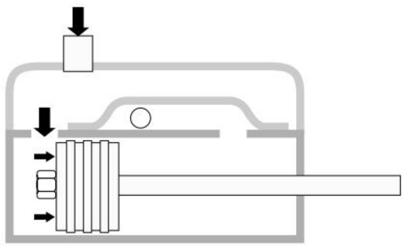


Fig. 5.3 *Working of D-slide Valve*

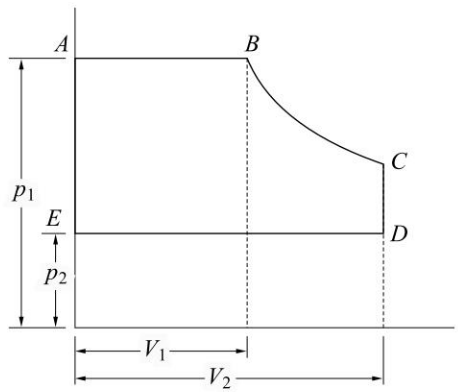


Fig. 5.4 *Hypothetical Indicator Diagram for Steam Engine*

ordinate and motion of piston is shown on the abscissa. It is customary to represent the motion of piston in terms of volume of space between the piston and cylinder head.

In this diagram, point A represents the instant when steam starts entering the cylinder through the inlet port. At this point the piston is at IDC. The pressure of steam is p_1. The piston starts moving from IDC to ODC, indicated by line AB. The steam continues to enter at a constant pressure, while the inlet port remains open. At point B the steam supply is stopped by the valve by closing the inlet port. This point is called the *cut-off point*. The high pressure steam trapped inside the cylinder expands along the curve BC. The curve BC follows the law pV = *Constant.* The piston reaches the ODC, represented by point C. The piston has completed the forward stroke. At this point the valve opens the outlet port, and the steam is exhausted out of the cylinder. The pressure drops to p_2, which is equal to the atmospheric pressure in case of non-condensing engines, and equal to condenser pressure in case of condensing engines. Line CD represents this event. The piston now starts to return to the IDC. The return stroke is shown by the line DE. During the return stroke the pressure on piston is maintained constant. At the end of the stroke the piston reaches the IDC again, shown by point E. In this manner, the piston has completed one forward stroke and one return stroke. This completes one cycle of the engine.

The phenomena discussed above are in fact ideal or theoretical. The actual working and nature of events during the cycle differs from those mentioned above. The actual events and the variation of pressure during the cycle are shown by actual indicator diagram shown in Fig. 5.5.

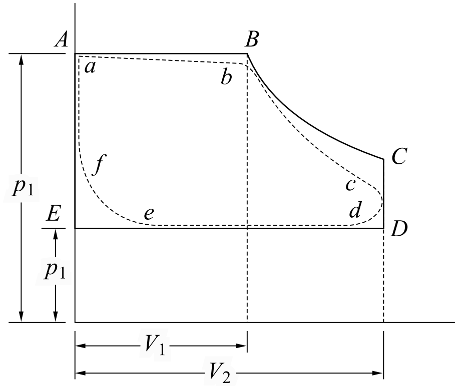


Fig. 5.5 *Actual Indicator Diagram*

In Fig. 5.5, the differences between the actual and hypothetical indicator diagrams are obvious. A comparison between the hypothetical and actual indicator diagrams is given in Table 5.1.

Table 5.1 Comparison Between Hypothetical and Actual Indicator Diagrams

Hypothetical Indicator Diagram	*Actual Indicator Diagram*
It is assumed that there is no clearance between the piston and cylinder head, when the piston is at IDC. The point A lies on the pressure axis, indicating zero volume at IDC.	Some clearance must be provided due to mechanical reasons. The IDC is indicated by point *a*.
Stroke length is defined by points A and C.	Stroke length is defined by points *a* and *C*. Therefore, actual stroke length is smaller than that shown in hypothetical diagram.
Steam pressure is assumed to be constant between point A and B.	Steam pressure drops as the piston takes the forward stroke. This is shown by line *ab*.
Cut-off of steam supply is instantaneous, as shown by the sharp change at point B.	Cut-off of steam is gradual due to gradual closing of the inlet valve. This effect is shown at point *b* on the curve.
Expansion of steam after cut-off is hyperbolic, as shown by the curve BC.	Expansion of steam after cut-off is not hyperbolic, as shown by curve *bc*.

(*Contd.*)

(*Contd.*)

The exhaust of steam is assumed to be instantaneous at ODC, and pressure drop is sudden as shown by line CD.	The exhaust port starts opening gradually before the piston reaches ODC. The exhaust of steam is gradual, as shown by curve *cd*.
The pressure is assumed to fall to minimum value when piston is at ODC. Therefore, the entire return stroke is at this minimum pressure.	The pressure does not fall to minimum value, even when the piston starts the return stroke, as shown by the curve at point *d*.
The exhaust is at constant pressure, corresponding to the pressure in the condenser (or atmosphere).	In the exhaust stroke pressure remains slightly above the condenser (or atmospheric) pressure. This is shown by line *de*, which remains above line DE.
The exhaust port closes suddenly when the piston reaches IDC, after completing the return stroke.	The exhaust port closes a little before the piston reaches IDC. Therefore, the steam trapped in the cylinder undergoes compression, as shown by the curve *ef*. This provides a *cushioning effect* on the piston.
The total area enclosed by the diagram is more.	The total area enclosed by the diagram is smaller. Therefore, the work obtained per cycle is smaller than that indicated by the hypothetical indicator diagram.

5.2 THERMODYNAMIC CYCLES

Heat engines convert heat energy into mechanical energy. Heat engines like steam engines or internal combustion engines (***IC Engines***), work in a cyclic manner. A ***cycle*** is a sequence of steps or processes which occur repeatedly, in a fixed order. For a cycle to be completed successfully, it is necessary that all of its processes must get completed in proper time duration and in the proper order.

A ***thermodynamic cycle*** is a sequence of thermodynamic processes like compression (isothermal, adiabatic or isentropic) and expansion ((isothermal, adiabatic or isentropic), heat addition at constant pressure, heat addition at constant volume etc. Every thermodynamic cycle is made of such processes, which occur in a proper order and in a repetitive manner. The thermodynamic processes common to all IC engine cycles are heat addition, heat rejection, compression of air or air-fuel mixture (charge), and expansion of burnt gases.

5.2.1 Carnot Cycle and Ideal Efficiency

Different thermodynamic cycles can be synthesized using combination of various thermodynamic processes. However, these cycles differ from each other in terms of performance and efficiency. In 1824, Sadi Carnot attempted to find the factors which lead to maximum efficiency of a thermodynamic cycle. He discovered that a thermodynamic cycle working on reversible processes has the highest efficiency. He proposed an ideal cycle as shown in Fig. 5.6.

This cycle theoretically has the maximum possible efficiency, but cannot be applied in actual practice. Still, its main importance is that it provides the designer with the ideal goal which he or she has to achieve, while designing an engine. As shown in Fig. 5.6, Carnot cycle is made up of four thermodynamic processes, out of which two are *isothermal* and two are *isentropic*. It operates between two temperature limits T_1 and T_2, which are measured on absolute temperature scale. The efficiency of the Carnot cycle is a function of these two temperatures only, and it is determined by,

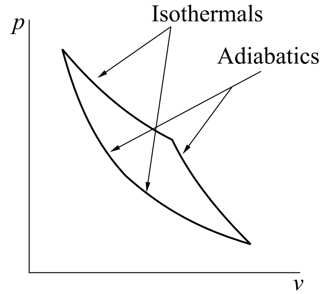


Fig. 5.6 *Carnot Cycle*

$$\eta = \frac{T_1 - T_2}{T_1} \qquad (5.\ )$$

This efficiency is called the ***Carnot Efficiency*** or ***Ideal Efficiency***. The Carnot efficiency does not depend upon the working substance. It can be shown that no engine, working between the same temperatures, can have efficiency higher than the Carnot efficiency. For an actual heat engine to be more efficient, the difference between the two temperatures must be as high as possible. In case of steam engines the lower temperature cannot be below 40°C and not below 400°C in case of IC engines. The major problem in achieving lower temperatures is the requirement of very long exhaust stroke, and very slow rate of heat transfer. Since the heat engines are required to work at high speeds, to obtain larger *power*, the exhaust temperature must be kept high. With these limitations, another way to improve the efficiency is to increase the upper temperature. Most IC engines go up to 2300^{0}C. However, there are limits to it due to limited strength of materials at higher temperatures.

5.2.2 Otto Cycle

This cycle was first proposed and used by a German engineer N.A. Otto in 1878. This cycle is also known as ***constant volume cycle***. Figure 5.7 shows an Otto cycle. It consists of four *processes*:

(a) Adiabatic Compression of the working substance
(b) Addition of heat to working substance at constant volume

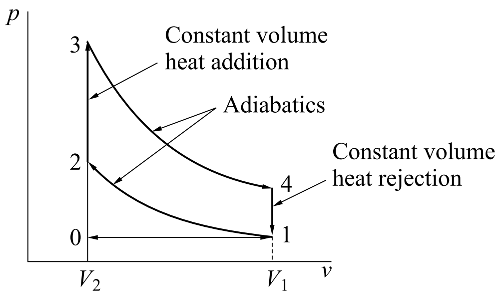


Fig. 5.7 *Otto Cycle*

(c) Adiabatic Expansion of working substance
(d) Rejection of heat at constant volume

As shown in Fig. 5.7, process 0-1 indicates intake of working substance into the engine, 1-2 represents adiabatic compression of working substance, 2-3 indicates addition of heat at constant volume, 3-4 indicates adiabatic expansion, 4-1 represents rejection of heat constant volume, and 1-0 represents exhaust of the working substance out of the engine.

In the ideal cycle, the intake and exhaust processes are not considered. It is assumed that the working substance works in a *closed cycle*. Also, the compression and expansion processes are assumed to be ideal. The specific heats and their ratio are considered to be constant throughout the cycle. The ideal Otto cycle is represented by the closed curve 1-2-3-4. The expression for efficiency of an *ideal* Otto cycle is derived here.

Let us consider that the mass of the working substance is m. Let the temperature of the working substance corresponding to points 1, 2, 3, and 4 be T_1, T_2, T_3, and T_4 respectively. The temperature of the working substance increases from T_2 to T_3 during the heat addition process 2-3. Then,

Heat addition to the working substance during process 2-3 is given by, $m\,C_v\,(T_3 - T_2)$, where C_v is the specific heat of the working substance at constant volume.

The amount of heat rejection during the process 4-1 is given by, $m\,C_v\,(T_4 - T_1)$

No heat is added of rejected during the adiabatic processes 1-2 and 3-4.

Then, the thermal efficiency of Otto cycle is given by,

$$\eta = \frac{\text{Heat Input} - \text{Heat rejected}}{\text{Heat Input}}$$

$$= 1 - \frac{\text{Heat rejected}}{\text{Heat Input}}$$

$$= 1 - \frac{mC_v\left(T_4 - T_1\right)}{mC_v\left(T_3 - T_2\right)} = 1 - \frac{\left(T_4 - T_1\right)}{\left(T_3 - T_2\right)}$$

For the adiabatic process 1-2 and 3-4, we have the relations,

$$\frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{\gamma-1} \text{ and } \frac{T_3}{T_4} = \left(\frac{V_4}{V_3}\right)^{\gamma-1}$$

Or, $$\frac{T_2}{T_1} = \frac{T_3}{T_4} = r^{\gamma-1}\text{, because } V_1 = V_4 \text{ and } V_2 = V_3$$

Here, γ is the ratio of specific heats of the working substance, and r is the *compression ratio*. Compression ratio is the ratio of volume of working substance at start of compression process, to that at the end of compression,

$$r = \frac{\text{Volume before compression}}{\text{Volume after compression}} = \frac{V_1}{V_2}$$

Therefore,

$$\frac{T_2}{T_1} = \frac{T_3}{T_4} \Rightarrow \frac{T_4}{T_1} = \frac{T_3}{T_2} \Rightarrow \frac{T_4}{T_1} - 1 = \frac{T_3}{T_2} - 1 \Rightarrow \frac{T_4 - T_1}{T_1} = \frac{T_3 - T_2}{T_2}$$

$$\Rightarrow \frac{T_4 - T_1}{T_3 - T_2} = \frac{T_1}{T_2} = \left(\frac{1}{r}\right)^{\gamma - 1}$$

Hence, the efficiency of ideal Otto cycle is given by,

$$\eta = 1 - \left(\frac{1}{r}\right)^{\gamma - 1}$$

The above relation indicates that the efficiency of the Otto cycle depends only on the compression ratio, and it increases as the compression ratio is increased. For comparing the efficiencies of different cycles, it is assumed that the working substance is pure air. It is also assumed that the ratio of specific heats, γ, does not change during the cycle. The thermal efficiency of a cycle determined in this manner is called the **Air Standard Efficiency**. It is also known as Ideal Efficiency or Theoretical Efficiency. For a given compression ratio, the Otto cycle has the highest air standard efficiency among various cycles used for IC engines.

In an actual engine working on Otto cycle, the air-fuel mixture is sucked into the cylinder by the downward motion of the piston. This is called the suction stroke. This process takes along 0-1, at atmospheric pressure. Then the mixture is compressed adiabatically along 1-2. This process takes place during the compression stroke of the engine. When the mixture attains sufficiently high temperature at point 2, the combustion is initiated by a spark. Thus, heat addition process takes place along 2-3 at constant volume. At the end of this process, the pressure reaches its maximum value. Then the adiabatic expansion process takes place along 3-4. Power is generated in this process. This process takes place during the power stroke of the engine. At the end of power stroke, the burnt gases are discharged through process 4-1. This process is equivalent to heat rejection process of the ideal cycle. Lastly, the burnt gases are purged out of the cylinder through exhaust stroke 1-0.

5.2.3 Diesel Cycle

Diesel cycle is named after a German engineer Rudolf Diesel. This cycle is also called constant pressure cycle. In this cycle, the working substance is compressed adiabatically and heat is added through constant pressure process 2-3, as shown in Figure 5.8.

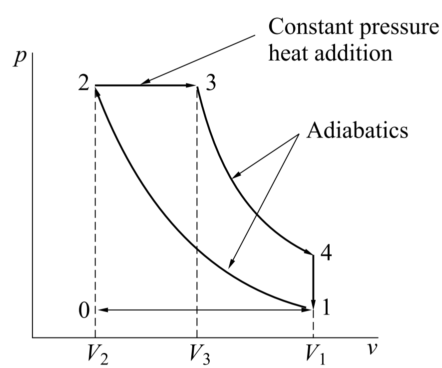


Fig. 5.8 *Diesel Cycle*

In an engine, air is sucked into the cylinder by the suction stroke 0-1. It is then compressed adiabatically along 1-2. Heat is then added to the working substance along the constant pressure process 2-3. This is accomplished by *injection* of fuel to the heated air during this process. The adiabatic expansion process is completed along 3-4. Heat is released during the exhaust process 4-1. The burnt gases are *scavenged* out of the cylinder in the process 1-0.

In the analysis of ideal cycle, it is assumed that the working substance works in a closed cycle. Thus, there are no suction or exhaust process. Such an ideal cycle is represented by the cycle 1-2-3-4. The thermodynamic efficiency of such a cycle is derived here.

The constant pressure heat addition process is shown by 2-3 on cycle. Heat addition to the working substance is $mC_p(T_3 - T_2)$, where C_p is the specific heat at constant volume.

Heat is rejected by the constant volume process 4-1. Therefore, the amount of heat rejected is $mC_v(T_4 - T_1)$.

Work done during the cycle = Heat input – Heat rejected. Therefore, work done during the cycle is given by,

$$m\,C_p(T_3 - T_2) - m\,C_v(T_4 - T_1)$$

Thermal efficiency of ideal Diesel cycle is,

$$\eta = \frac{\text{Heat Input} - \text{Heat rejected}}{\text{Heat Input}}$$

$$= \frac{mC_p(T_3 - T_2) - mC_v(T_4 - T_1)}{mC_p(T_3 - T_2)} = 1 - \frac{C_v}{C_p}\frac{(T_4 - T_1)}{(T_3 - T_2)} = \frac{1}{\gamma}\frac{(T_4 - T_1)}{(T_3 - T_2)}$$

In the Diesel cycle we define the ratio of volumes V_3 and V_2 as the *cut-off ratio*, and express it by ρ. The compression ratio is denoted by r.

Thus, $\rho = V_3/V_2$ and $r = V_1/V_2 = V_4/V_2$.

For the adiabatic compression process 1-2, $\dfrac{T_2}{T_1} = r^{\gamma-1}$

For the constant pressure process 2-3, $T_3 = \rho\, T_2$

Therefore, $T_3 = \rho r^{\gamma-1} T_1$

For the adiabatic expansion process 3-4 we can write, $\dfrac{T_4}{T_3} = \left(\dfrac{\rho}{r}\right)^{\gamma-1}$

Therefore, $T_4 = \left(\dfrac{\rho}{r}\right)^{\gamma-1} T_3 \Rightarrow T_4 = \rho^{\gamma} T_1$

Combining the equations obtained above, the expression for the thermal efficiency of Diesel cycle is given by,

$$\eta = 1 - \frac{1}{\gamma}\left(\frac{\rho^{\gamma} - 1}{\rho - 1}\right)\left(\frac{1}{r}\right)^{\gamma-1}$$

The efficiency of Diesel cycle increases with compression ratio. Also, for the same compression ratio, the efficiency of Diesel cycle is less than Otto cycle.

5.2.4 Comparison Between Otto and Diesel Cycles

1. Heat addition process in Otto cycle is a constant volume process, while in case of Diesel cycle it is a constant pressure process.
2. For the same compression ratio, the efficiency of Otto cycle is more than the Diesel cycle.
3. Otto cycle is used in petrol engines while Diesel cycle is used in diesel engines.
4. In case of petrol engines working on Otto cycle, the compression ratio has to be kept below 12 due to problem of ***knocking***. There is no such limitation in case of diesel engines working on Diesel cycle. Therefore, the compression ratio in diesel engines is as high as 24. Hence, although the Otto cycle is more efficient for the same compression ratio, in actual practice diesel engines are more efficient because they work on higher compression ratio.

5.3 IC ENGINES

5.3.1 Classification of IC Engines

Internal combustion engines may be classified in many different ways, as given below:

1. *Number of Cylinders:* (a) Single cylinder engines (b) Multi-cylinder engines
   Most of the two-wheeler automobiles like mopeds, scooters and motor-cycles have a single cylinder engine. Single cylinder engines are used in small agricultural pumps, portable generators, or small machines. Multi-cylinder engines are used where power requirement is large like, sports bikes, cars, trucks, locomotives, ships, boats, large generators and power plants.
2. *Arrangement of Cylinders:* (a) Horizontal (b) Vertical (c) V-engine (d) In-line (e) Radial
   Two wheeled automobiles have horizontal or inclined cylinders. This is to facilitate cooling by air striking on cylinder cover. Industrial engines may be horizontal or vertical. When small floor space is available, a vertical engine is a better choice. The engines of four-wheeled automobiles like cars or trucks are vertical in-line engines. In this case the cylinders are arranged side by side. Diesel locomotives used in railways have V-engines, where the cylinders are arranged in two *banks.* Both the banks have cylinders arranged in-line, and the two banks are inclined with each other at a certain angle. Sports cars or larger automobiles also have V-engines. Radial engines are used in propeller-driven aircrafts.
3. *Thermodynamic Cycle:* (a) Otto (b) Diesel (c) Dual
   Engines running on Liquefied Petroleum Gas (LPG) and Petrol work on Otto cycle. For diesel engines the theoretical cycle is Diesel cycle, but these engines work on dual cycle, which is a modification of Diesel cycle. Engines running on Compressed Natural Gas (CNG) also work on dual cycle. Most of industrial, marine and large automobile engines are diesel engines. Petrol and LPG engines are used in cars. CNG engines are used in heavy automobiles like buses, and industrial applications where continuous supply of this fuel is available.

4. *Method of Ignition:* (a) Compression ignition (b) Spark ignition
In engines running on diesel, combustion is achieved through adiabatic compression, which results into very high temperature. In case of petrol, CNG, and LPG engines ignition is done by a spark plug.
5. *Number of Strokes per Cycle:* (a) Two stroke engines (b) Four stroke engines
Engines of small two-wheeled automobiles are two-stroke engines. In these engines, the power to weight ratio is high, because one power stroke is obtained for each revolution of the cranks shaft. However, in these engines combustion is not so efficient. This leads to pollution problems, and it is not possible to design such engines which can meet current *emission norms* like EURO II and III. Therefore in most countries, including India, the production of such engines is being stopped due to government regulations. Four-stroke engines are invariably used in all modern automobiles like scooters, bikes, cars, trucks as well as in boats, ships and aircrafts.
6. *Method of Cooling:* (a) Air-cooled (b) Water-cooled
Small two-stroke engines used in mopeds, scooters, and bikes are air-cooled. High power bikes use water or liquid-cooled engines. All the multi-cylinder engines used in cars, trucks, boats, ships, etc. are water-cooled. Aircraft engines are air-cooled.
7. *Speed:* (a) Low (b) Medium (c) High
The engines used for industrial applications, large generators, locomotives and large automobiles, medium-sized boats, and ships are low speed engines. Medium speed engines are used in medium-sized automobiles like cars, light trucks, and medium sized generators, pumps etc. High speed engines are used in small two-wheeled automobiles, racing vehicles and aircrafts.
8. *Application:* (a) Stationary (b) Locomotive (c) Marine (d) Automobile (e) Aero engine
Stationary engines are used in agricultural pumps, industrial machines and power generation applications. Locomotive engines are used in railways. Marine engines are used in boats, ships and barrages. The design of engines for different applications differs greatly, on the basis of performance parameters and environmental conditions.

5.3.2 Working of IC Engines

Figure 5.9 shows the basic details of an IC engine. In Fig. 5.10 the schematic diagram of a typical IC engine is shown. Here, O is the *piston pin* which connects the piston with the *connecting rod* OP. The connecting rod oscillates about point O. The connecting rod is connected to the *crank* CP by *crank* pin at P. The crank rotates about C. The crank rotates the *crank shaft*. Point C is fixed with respect to the frame of the engine. In Fig. 5.10 (a) the piston is at the topmost position, called the ***top dead centre (TDC)***. As the crank rotates, the piston begins to move downwards as shown in Fig. 5.10 (b). After 180° rotation of crank the piston reaches its bottom-most position, called the ***bottom dead centre (BDC)***, as shown in Fig. 5.10 (c). The movement of piston from TDC to BDC makes one ***stroke***. When the crank rotates further, the piston begins to move upwards, as shown in Fig. 5.10 (d). After a rotation of 180° of the

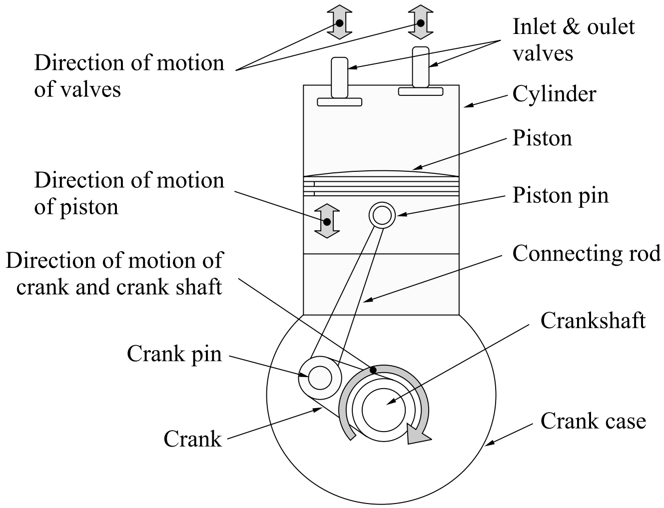


Fig. 5.9 *Typical IC Engine and its Components*

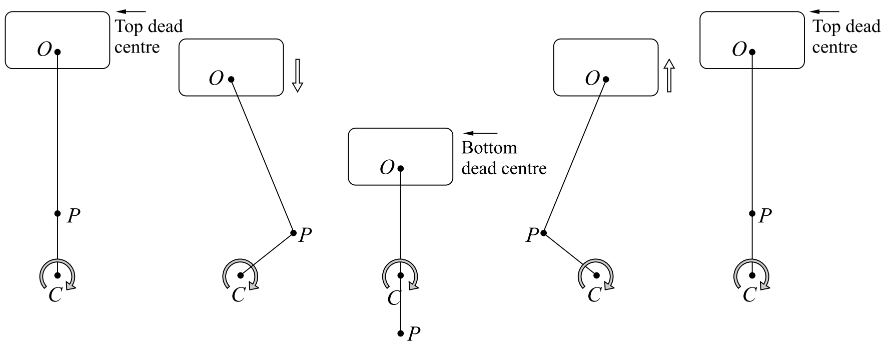


Fig. 5.10 *Working of IC Engine*

crank, from BDC, the piston again reaches the TDC. The movement of the piston from BDC to TDC also makes one stroke. Thus, two strokes are completed in 360° rotation of the crank.

For completion of one cycle (Otto or Diesel) in an IC engine, the following processes are to be completed:

(a) Intake of air or charge into the cylinder
(b) Compression of air or charge
(c) Combustion of charge
(d) Expansion of burnt charge
(e) Exhaust of the burnt charge out of the cylinder

These processes can be accomplished in either two strokes, or in four strokes. Accordingly, we have engines working on ***two stroke cycle*** or ***four stroke cycles***.

5.3.3 Four Stroke Cycle

Schematic diagram of an engine working on four stroke cycle is shown in Fig. 5.11. The following events take place during one complete cycle:

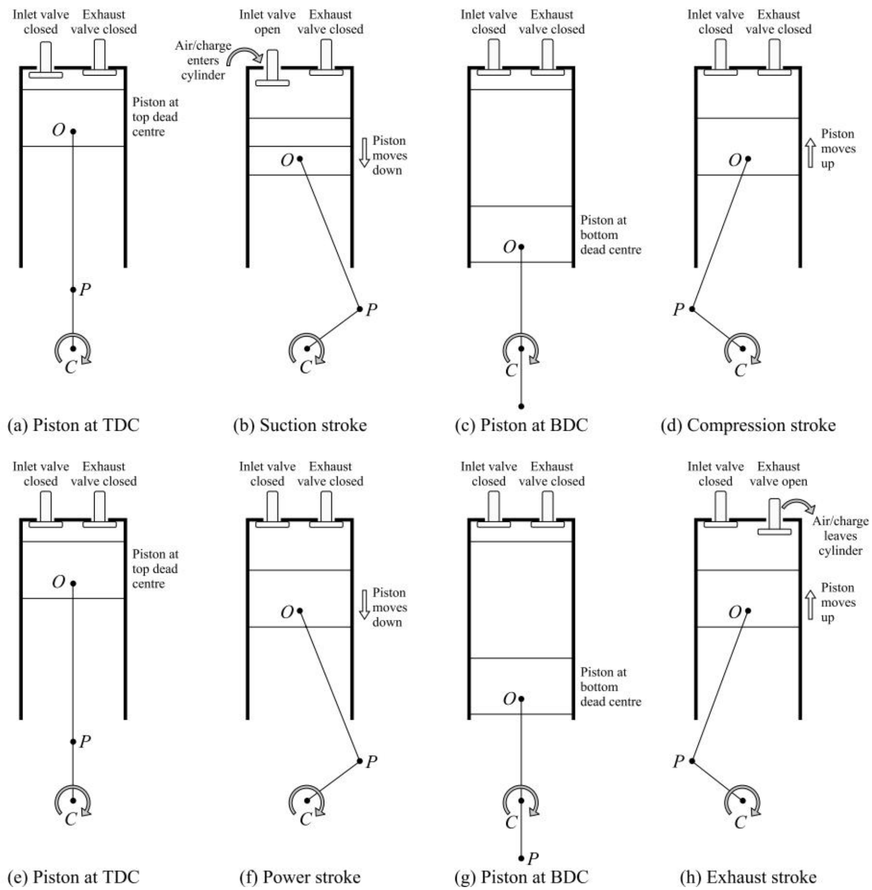


Fig. 5.11 *Working of Four-stroke Engine*

(a) At the beginning of the cycle, the piston is at TDC, as shown in Fig. 5.11(a). It begins to move downward and the air or charge is taken into the cylinder, as shown in Fig. 5.11(b). During the event the *intake valve* is kept open. This process is completed when the piston reaches the BDC, as shown in Fig. 5.11(c). This stroke is called ***suction stroke***.

(b) The intake valve is now closed, and the piston moves upwards, as shown in Fig. 5.11(d). This stroke is called the ***compression stroke***. In this stroke the air or charge is compressed adiabatically to high temperature and pressure. At the end of compression stroke the piston reaches TDC, as shown in Fig. 5.11(e).

(c) After completion of compression stroke, combustion of charge begins. In petrol engines, a spark is produced by a *spark plug* to ignite the compressed charge. In diesel engines, fuel is injected in the form of a fine spray from a *nozzle* called fuel injector. The combustion results into very high pressure and temperature above the piston. The piston is pushed downwards due to high pressure and the ***expansion stroke*** begins, as shown in Fig. 5.11(f). The piston applies force on the connecting rod through piston pin. The connecting rod applies force on the crank through the crank pin. In this manner a torque is generated by the crank, which rotates the crank shaft. The expansion stroke is also called ***power stroke***. During the expansion stroke, the piston moves from TDC to BDC. At the end of this stroke, the piston reaches the BDC, as shown in Fig. 5.11(g). During this stroke, both the intake and exhaust valves remain closed.

(d) The exhaust valve is opened near the end of expansion stroke. The high pressure burnt gases rapidly come out of the cylinder. The last stroke in the cycle is the ***scavenging stroke***. In this stroke the burnt gases remaining in the cylinder are pushed out, as shown in Fig. 5.11(h). During this stroke, the exhaust valve remains open. The piston moves from BDC to TDC.

In this manner the four stroke cycle is completed.

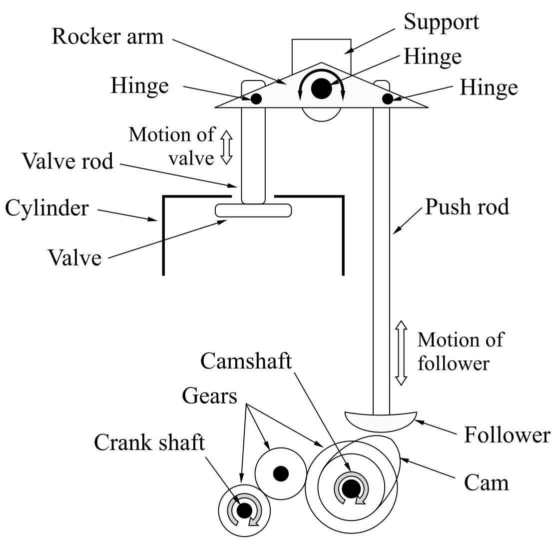


Fig. 5.12 *Valve Gear Mechanism for Four-stroke Engine*

In four stroke cycle, the crank makes two complete turns, i.e., through 720°. In a four-stroke engine, the intake and exhaust of gases is controlled by mechanical motion of valves. The valves are operated by a *valve gear mechanism*. The crank shaft is connected to a *camshaft* through gears. The rotational speed of the camshaft is half of the crank shaft. Thus, during one complete cycle of a four-stroke engine, the crank shaft rotates through 720° but the camshaft rotates through 360° only. The camshaft carries two *cams*, one for each of inlet and exhaust valves. Each cam on the camshaft is in contact with one *follower*. The follower moves to and fro inside *guideways*. The cam converts the rotary motion of camshaft into translational motion of the follower.

The stem of the follower is called *push rod*. Each push rod is connected to one end of a *rocker arm*. The rocker arm is a lever pivoted in its middle. The other end of the rocker arm is connected to a *valve rod*. Valve rod is a cylindrical rod which carries the valve on its other end. In this manner, the motion of the crank shaft is *synchronized* with the motion of the valves. The angular position of the cams on the camshaft decide the timing of opening and closing of the valves.

5.3.4 Two-Stroke Cycle

In two-stroke cycle, all the processes are completed in two strokes, i.e., one complete rotation of the crank shaft. A typical engine working on two-stroke cycle is shown in Fig. 5.13. A two-stroke engine does not have any valves. Instead, it has ***ports***. Ports are openings or passages in the cylinder wall through which air or charge comes into the cylinder or leaves it. When the piston is over a port, it gets closed. Thus, the opening and closing of the ports is regulated by the motion of the piston. A two-stroke engine has three ports located in the cylinder wall. The ***inlet port*** and ***exhaust port*** are located on the same side, while the ***transfer port*** is located opposite to the exhaust port. Fresh charge enters through the inlet port *below* the piston, and goes to the crank case. It is compressed slightly by the downward motion of the piston. There is a connection between the crank case and the transfer port in cylinder. The charge is transferred from crank case to the cylinder by the transfer port.

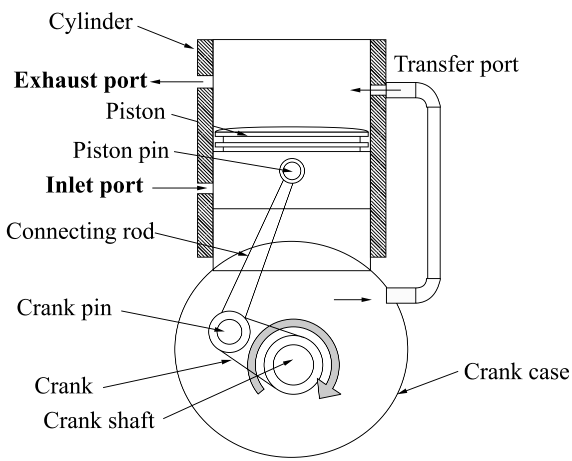


Fig. 5.13 *Details of a Two-stroke Engine*

Schematic diagrams of the working of such an engine are shown in Fig. 5.14. The sequence of events and processes is as follows:

(a) When the piston is at TDC, the inlet port is open, while the exhaust port and transfer ports are closed.
(b) When the piston starts moving downwards, the inlet port is also closed, and the charge in the crank case gets slightly compressed.
(c) When the piston reaches near the BDC, the exhaust port and transfer port open. The exhaust port opens a little before the transfer port. This is to ensure that the

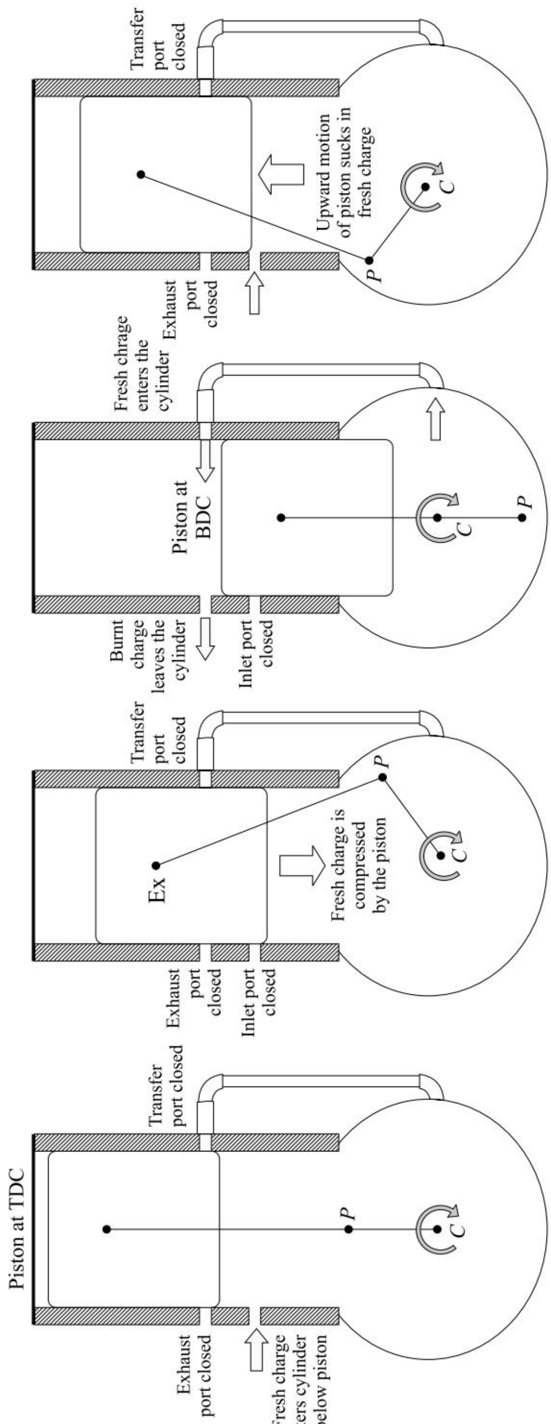


Fig. 5.14 *Working of Two-stroke Engine*

burnt charge starts leaves the cylinder before the fresh charge starts enters it. However, for some duration both of these events take place simultaneously; while the burnt charge is leaving the cylinder through exhaust port, the fresh charge keeps entering through the transfer port.

(d) When the piston starts moving upwards, the exhaust port and transfer port get closed. The fresh charge is now trapped in the space above the piston. It gets compressed adiabatically.

(e) When the piston reaches near the TDC, the temperature and pressure of the charge are sufficiently high. At this time in *two-stroke petrol engines*, a spark is produced to initiate combustion. In case of *two-stroke diesel engines*, fuel is injected into the cylinder and combustion starts due to high temperature of the air.

5.3.5 Comparison Between Petrol and Diesel Engines

The following are the main points of comparison between petrol and diesel engines:

(a) Both petrol and diesel engines have the same basic mechanism. Both of them have a cylinder, a piston, a piston pin (or *gudgeon pin*), a connecting rod, a crank and a crank shaft.

(b) Both of them can be two-stroke or four-stroke engines.

(c) In petrol engines, a mixture of air and fuel is supplied into the cylinder. This mixture is produced in *carburetor* by mixing petrol and air. This mixture is compressed inside the cylinder during compression stroke. After compression, a spark is produced inside the cylinder by a spark plug. This results into combustion of the mixture. The spark is produced due to very high voltage generated by a magneto coil which rotates with the crank shaft.

(d) In diesel engines, only air is supplied into the cylinder. This air is compressed during the compression stroke. At the end of compression, when the temperature of the air reaches a very high level, fuel is injected in form of fine spray. This spray inside the cylinder is produced by a nozzle. A fuel pump is used to supply the fuel to the nozzle at a very high pressure.

(e) A petrol engine works on Otto cycle. Combustion of air-fuel mixture in a petrol engine is very rapid, and takes place like a constant volume process (similar to the constant volume heat addition process in an Otto cycle).

(f) A diesel engine works on Diesel cycle. The heat addition process is a constant pressure process. Combustion is not as instantaneous as in an Otto cycle. The combustion of fuel is a prolonged process, because fuel is supplied over a large part of the power stroke.

(g) Compression ratio in petrol engines is below 12, due to problem of knocking. In diesel engines the compression ratio is as high as 24.

(h) The Otto cycle is more efficient than Diesel cycle for a given compression ratio. But diesel engines are more efficient because they work with much higher compression ratio than petrol engines. Also, at present in our country the cost of commercially available diesel is lower than petrol. Hence, due to higher thermal efficiency and lower fuel cost, diesel engines are more economical.

(i) Due to higher compression ratio, the peak pressure in a diesel engine is higher than that in a petrol engine. Therefore, all the components like cylinder, piston, connecting rod, and crank are heavier in construction.

5.3.6 Comparison Between Two-Stroke and Four-Stroke Engines

The important points of comparison between two-stroke and four-stroke engines are as follow:

(a) In two-stroke engines, the cycle (Otto or Diesel) is completed in one revolution of the crank. In four-stroke engines, the cycle is completed in two revolutions of the crank.

(b) In two-stroke engines, there are two strokes (compression stroke and expansion stroke). In four-stroke engines, there are four strokes (suction, compression, expansion and exhaust).

(c) In two-stroke engines, the intake of charge (or air) into the cylinder takes place simultaneously with exhaust of burnt charge. Also, these processes take place when the piston is at BDC. Therefore, there is no need for suction or exhaust strokes in two-stroke engines.

(d) In two-stroke engines, one power stroke is obtained for every revolution of the crank. In four-stroke engines, one power stroke is obtained for every *two* revolutions of the crank. Thus, the average torque and power output are more in case of two-stroke engines, for the same size of engines. A heavier flywheel is required in four-stroke engines, to reduce the fluctuation of speed during the cycle.

(e) In two-stroke engines, the intake and exhaust of gases is through ports. A two-stroke engine has three ports (inlet, exhaust, and transfer ports). In four-stroke engines the intake and exhaust of gases is through valves. A basic four-stroke engine has two valves (inlet valve and exhaust valve).

(f) The opening and closing of ports in two-stroke engines is managed by movement of piston. The piston covers and uncovers the ports as it moves up and down the cylinder. In four-stroke engines, the opening and closing of the valves is done by means of valve gear mechanism.

(g) The number of moving components in two-stroke engines is less (piston, connecting rod, crank, and crankshaft). The four-stroke engine has additional moving components (valves, push rod, rocker arm, camshaft, follower, gears). Thus, a two-stroke engine is simpler in design and easy in maintenance.

(h) In case of two-stroke *petrol* engine, the intake of fresh charge and exhaust of burnt charge takes place simultaneously. For this, the exhaust port and transfer port are opened simultaneously when the piston is at BDC. In this situation some fresh charge goes out of the cylinder along with the burnt gases. This results into loss of fuel and reduction in efficiency. In case of two-stroke *diesel* engine, although there is no loss of fuel because only air is taken into the cylinder, the mixing of fresh air with burnt charge does reduce the power output. It also reduces efficiency of combustion.

Such problems are not present in case of four-stroke engines because there are separate strokes for intake and exhaust.

5.3.7 Two-Stroke Petrol Engine and its Working

The construction and working of two-stroke petrol engine can be understood with the help of Fig. 5.15. The main components of a two-stroke petrol engine are cylinder, cylinder head, piston, piston rings, piston pin (or gudgeon pin), connecting rod, crank pin, crank, crank shaft, and flywheel. The cylinder wall has three ports: intake port, exhaust port, and transfer port. This engine works on Otto cycle.

(a) Mixture of petrol and air is made in the *carburetor*. This mixture is supplied to the cylinder through the intake port, via the *intake manifold*.

(b) The mixture enters the cylinder below the piston, as shown in Fig. 5.15(a). This process takes place when the piston is near TDC at the end of compression stroke. In this position it uncovers the inlet port.

(c) When the piston moves down during the expansion stroke, the charge is compressed in the crank case. This phenomenon is shown in Fig. 5.15 (b). The crank case has a connection with the transfer port in the cylinder wall. When the piston reaches near the BDC, at the end of expansion stroke, it uncovers the exhaust and transfer ports as shown in Fig. 5.15(c). The exhaust port is opened a little before the transfer port, so that most of the burnt gases escape out of the cylinder before entry of fresh charge begins. However, for some time near the BDC, both the exhaust port and transfer port are open simultaneously. Thus, when the piston is near the BDC, the fresh charge moves from the crank case into the cylinder through the transfer port.

(d) When piston starts moving towards the TDC in the compression stroke, as shown in Fig. 5.15(d), it again covers the exhaust port and transfer port. So the fresh charge gets trapped in the space above the piston. Near the end of compression stroke, when the charge is heated sufficiently, a spark is produced to ignite the charge, as shown in Fig. 5.15(a).

(e) High pressure of the burnt charge pushes the piston downwards. This force is transferred to the crank through the connecting rod. The force on the crank produces a torque on the crank shaft. This results into rotation of the crank shaft and generation of power. This cycle repeats itself.

In two-stroke petrol engines, the efficiency is reduced due to loss of fresh charge through the exhaust port. This happens because at BDC both the exhaust port and transfer port are open simultaneously for some time. Some part of the incoming fresh charge escapes out of the cylinder with the outgoing burnt charge. This loss can be controlled to some extent by providing a special shape to the piston top, as shown in Fig. 5.16. This figure also shows the details of piston rings.

5.3.8 Two-Stroke Diesel Engine and its Working

The main components of a two-stroke diesel engine are cylinder, cylinder head, piston, piston rings, piston pin (or gudgeon pin), connecting rod, crank pin, crank, crank shaft, and flywheel. The cylinder wall has three ports: intake port, exhaust port, and transfer port. This engine works on Diesel cycle.

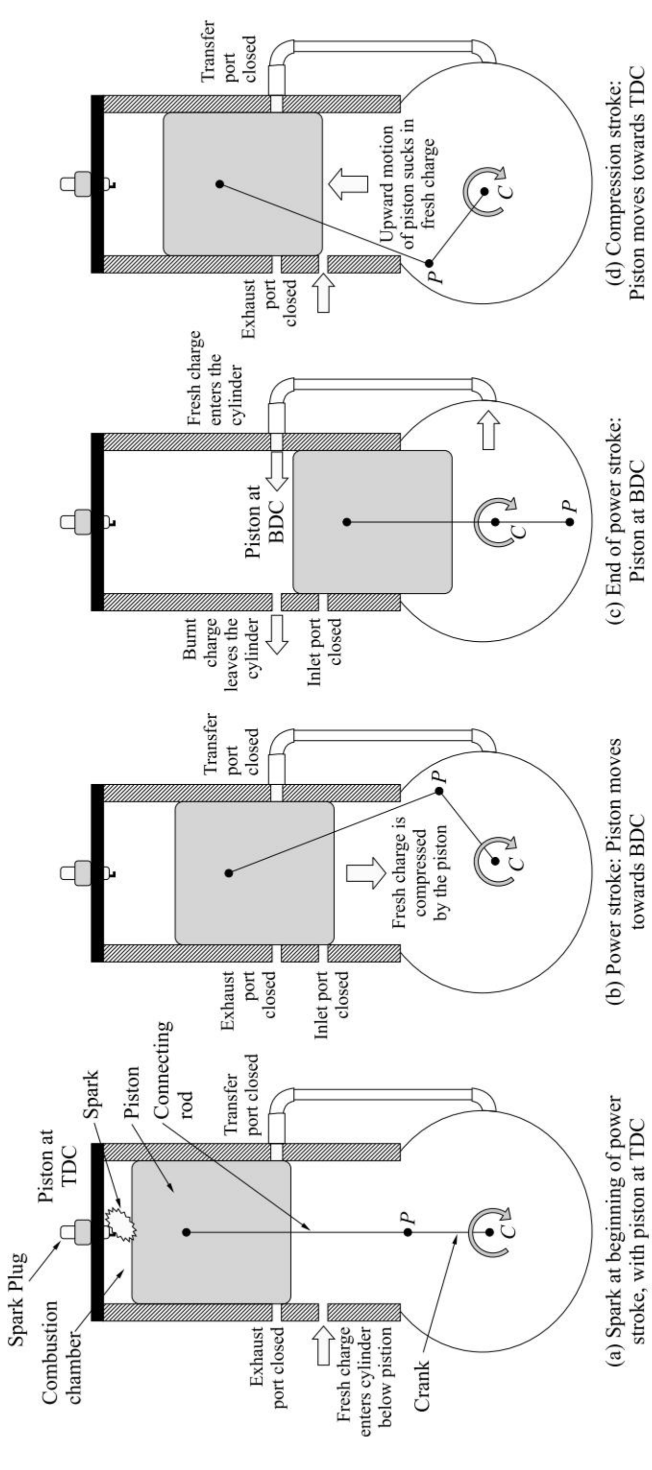


Fig. 5.15 *Working of Two-stroke Petrol Engine*

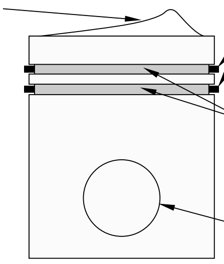


Fig. 5.16 *Shape of Two-stroke Petrol Engine Piston*

The working of two-stroke diesel engine is explained below, with the help of Fig. 5.17.

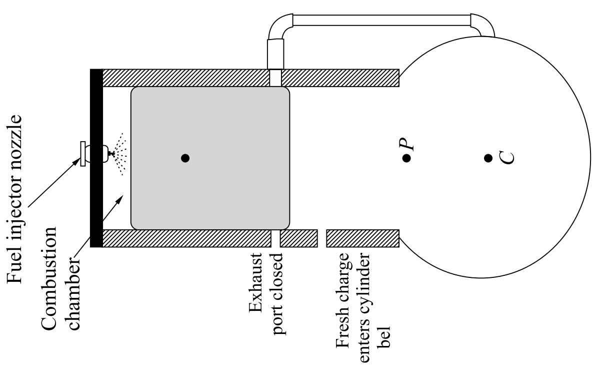
(a) Air is supplied to the cylinder through the intake valve, via the *intake manifold*. This air enters the cylinder below the piston. This process takes place when the piston moves up as shown in Fig. 5.17(a). In this position, the piston uncovers the inlet port. The air above the piston is already compressed and heated. Fuel is injected in this air and combustion starts. The piston starts moving downwards due to high pressure of the combustion gases.

(b) When the piston moves down during the expansion stroke, as shown in Fig. 5.17(b), the air is compressed in the crank case. The crank case has a connection with the transfer port in the cylinder wall.

(c) When the piston reaches near the BDC, at the end of expansion stroke, it uncovers the exhaust and transfer ports. This position is shown in Fig. 5.17(c). The exhaust port is opened a little before the transfer port, so that most of the burnt gases escape out of the cylinder before entry of fresh air begins. However, for some time near the BDC, both the exhaust port and transfer port are open simultaneously. Thus, when the piston is near the BDC, the fresh air moves from the crank case into the cylinder through the transfer port.

(d) When piston starts moving towards the TDC in the compression stroke, it again covers the exhaust port and transfer port. This is shown in Fig. 5.17(d). The fresh air gets trapped in the space above the piston. Near the end of compression stroke, when the air is heated sufficiently, fuel is injected into the cylinder through a nozzle, as shown in Fig. 5.17(a). This injection of fuel is done at a high pressure. The nozzle generates a spray of fine droplets of fuel. Since the compression ratio is very high, the compressed air is at a very high temperature. Therefore, the injected fuel is ignited immediately.

(e) High pressure of the burnt charge pushes the piston downwards. This force is transferred to the crank through the connecting rod. The force on the crank produces a torque on the crank shaft. This results into rotation of the crank shaft and generation of power. This cycle repeats itself.


Fuel injector nozzle
Combustion chamber
Exhaust port closed
Fresh charge enters cylinder bel
P
C

5.3.9 Four-Stroke Petrol Engine and its Working

The construction and working of four-stroke petrol engine is explained in this section. Like all IC engines it has a cylinder, cylinder head, piston, piston rings, piston pin, connecting rod, crank, crank shaft, and flywheel. A basic four-stroke petrol engine has two valves: the inlet valve and the exhaust valve. These valves are mounted on the cylinder head. The opening and closing of these valves is controlled by a valve gear mechanism. Details of the valve gear mechanism are given in Section 5.3.3, and Figure 5.12. The air-fuel mixture is prepared in the carburetor and supplied into the cylinder through the intake valve, via the inlet manifold. The products of combustion are expelled out of the cylinder through the exhaust valve, and discharged into the atmosphere by the exhaust manifold.

The working of a four-stroke petrol engine is as follows, as shown in Fig. 5.18.

(a) The engine works on Otto cycle. One cycle is completed in two revolutions of the crank shaft, i.e., four strokes of the piston.

(b) At the beginning of the cycle, the piston is at the TDC, as shown in Fig. 5.18(a). The intake valve is opened and the piston begins to move downwards for the suction stroke, as shown in Fig. 5.18(b). Fresh charge of air-fuel mixture is taken into the cylinder. The intake valve closes as the piston reaches BDC, and the suction stroke is complete, as shown in Fig. 5.18(c).

(c) The piston begins to move upwards towards the TDC and the compression stroke begins, as shown in Fig. 5.18(d). Both intake and exhaust valves are closed during the compression stroke. The charge is compressed adiabatically to high pressure and temperature.

(d) When the piston reaches near the TDC towards the end of compression stroke, a spark is produced by the spark plug to ignite the high temperature mixture. This is shown in Fig. 5.18(e). The mixture burns and the pressure and temperature of combustion gases become very high. Under the heavy pressure, the piston begins to move downwards and the expansion (or power) stroke begins, as shown in Fig. 5.18(f).

With completion of suction and compression strokes, one revolution of the crank shaft is complete.

(e) During the power stroke, the piston continues to move from TDC to BDC. Both the valves remain closed. The force applied on the piston by the combustion gases is transferred to the connecting rod through the piston pin. The connecting rod applies force on the crank through the crank pin. The force on crank produces a torque on the crank shaft. The crank shaft rotates and power is produced. When the piston reaches the BDC, the power stroke is over, as shown in Fig. 5.18(g).

(f) The piston begins to move up from the BDC towards the TDC, and the exhaust stroke begins, as shown in Fig. 5.18(h). The exhaust valve opens, and remains open during the whole exhaust stroke. The burnt gases are expelled out of the cylinder. When the piston reaches TDC, the exhaust stroke is complete, and the exhaust valve is closed. This stroke is also called *scavanging* stroke.

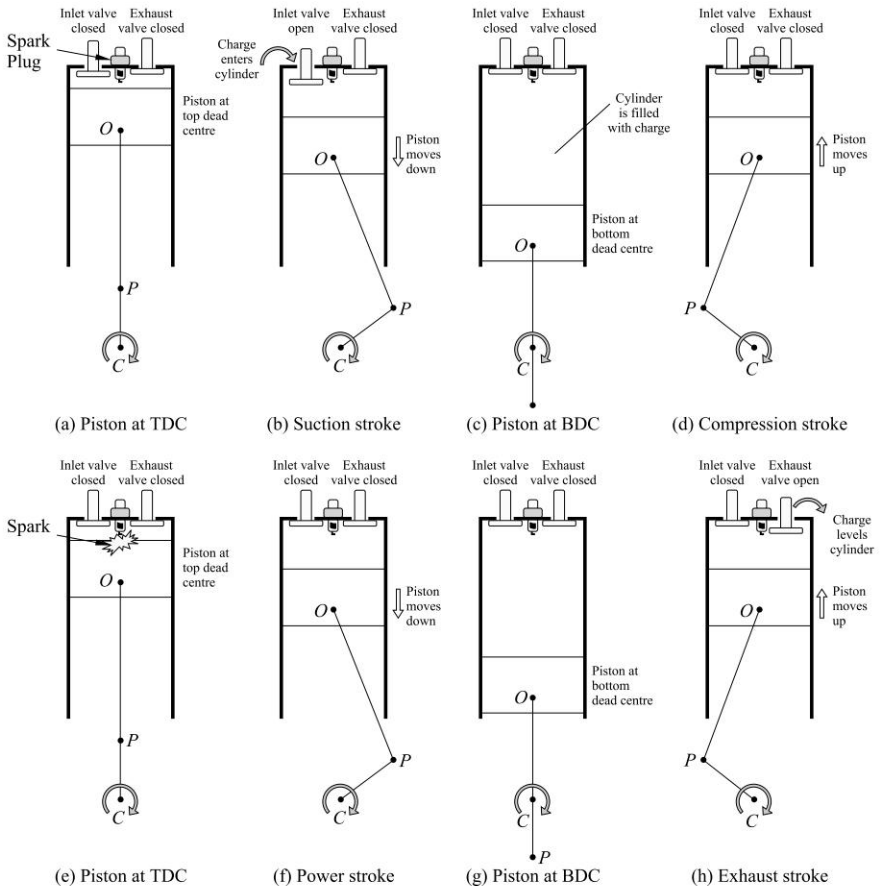


Fig. 5.18 *Working of Four-stroke Petrol Engine*

With completion of power and exhaust strokes, second revolution of the crank shaft is complete.

(g) In this manner the cycle is completed in four strokes, or two revolutions of the crank shaft. When the piston reaches TDC, the next cycle begins.

5.3.10 Four-Stroke Diesel Engine and Its Working

The construction and working of four-stroke diesel engine is explained in this section. Like all IC engines it has a cylinder, cylinder head, piston, piston rings, piston pin, connecting rod, crank, crank shaft, and flywheel. In addition, a basic four-stroke diesel engine has two valves: the inlet valve and the exhaust valve. These valves are mounted on the cylinder head. The opening and closing of these valves is controlled by a valve gear mechanism. Details of the valve gear mechanism are given in Section 5.3.3, and Fig. 5.12. Fresh air is supplied into the cylinder through the intake valve, via the inlet manifold. The products of combustion are expelled out of the cylinder through the exhaust valve, and discharged into the atmosphere by the exhaust manifold.

The working of a four-stroke diesel engine is explained below, with the help of Fig. 5.19.

(a) The engine works on Diesel cycle. One cycle is completed in two revolutions of the crank shaft, i.e., four strokes of the piston.

(b) At the beginning of the cycle, the piston is at the TDC, as shown in Fig. 5.19(a). The intake valve is opened and the piston begins to move downwards for the suction stroke, as shown in Fig. 5.19(b). Fresh air is taken into the cylinder. The intake valve closes as the piston reaches BDC, and the suction stroke is complete, as shown in Fig. 5.19(c).

(c) The piston begins to move upwards towards the TDC and the compression stroke begins, as shown in Fig. 5.19(d). Both intake and exhaust valves are closed during the compression stroke. The air is compressed adiabatically to high pressure and temperature.

(d) When the piston reaches near the TDC towards the end of compression stroke, fuel is injected into the cylinder by a fuel injector nozzle. This is shown in

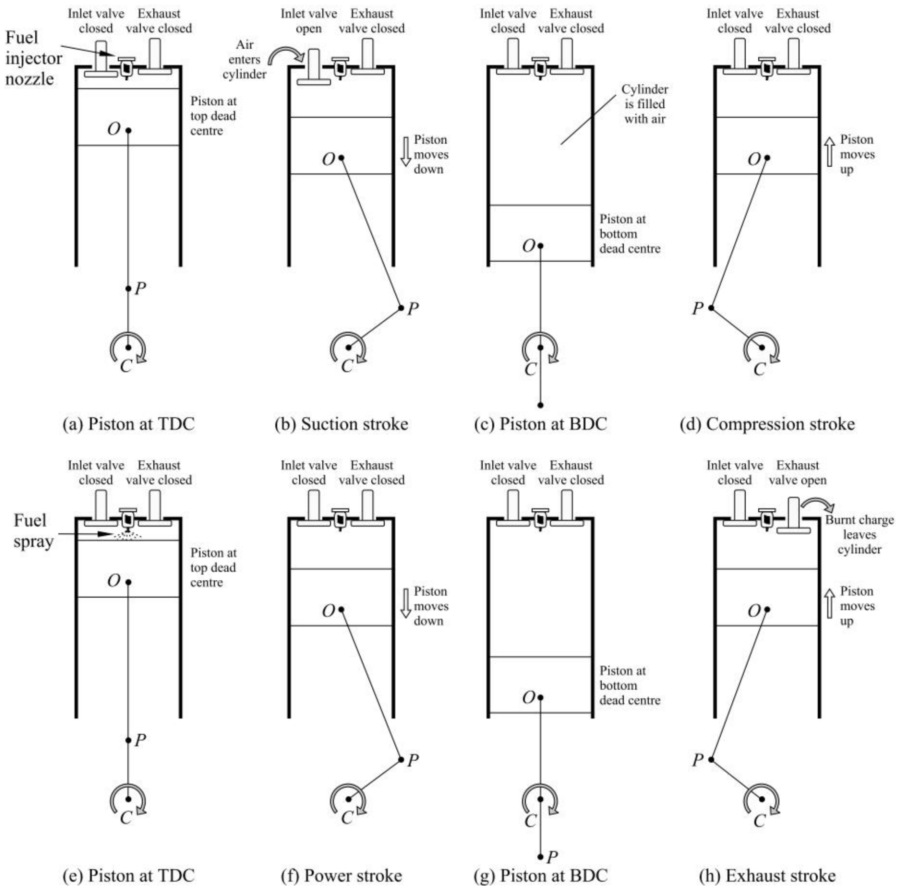


Fig. 5.19 *Working of a Four-stroke Diesel Engine*

Fig. 5.19(e). The fuel is supplied at a high pressure from a fuel pump, and the nozzle creates a spray of fine droplets. The droplets of fuel are ignited due to the high temperature of the compressed air. The fuel burns and the pressure and temperature of combustion gases become very high. Under the heavy pressure the piston begins to move downwards and the expansion (or power) stroke begins, as shown in Fig. 5.19(f).

With completion of suction and compression strokes, one revolution of the crank shaft is complete.

(e) During the power stroke, the piston continues to move from TDC to BDC. Both the valves remain closed. The force applied on the piston by the combustion gases is transferred to the connecting rod through the piston pin. The connecting rod applies force on the crank through the crank pin. The force on crank produces a torque on the crank shaft. The crank shaft rotates and power is produced. When the piston reaches the BDC, the power stroke is over, as shown in Fig. 5.19(g).

(f) The piston begins to move up from the BDC towards the TDC, and the exhaust stroke begins as shown in Fig. 5.19(h). The exhaust valve opens, and remains open during the whole exhaust stroke. The burnt gases are expelled out of the cylinder. When the piston reaches TDC, the exhaust stroke is complete, and the exhaust valve is closed.

(g) With completion of power and exhaust strokes, second revolution of the crank shaft is complete.

(h) In this manner the cycle is completed in four strokes, or two revolutions of the crank shaft. When the piston reaches TDC, the next cycle begins.

SOLVED EXAMPLES

Example 5.1 A four-stroke engine has a stroke of 90 mm and bore of 100 mm. The clearance volume is 70 cc. The engine works on Otto cycle. Determine theoretical efficiency of the engine.

Solution: The swept volume of the piston is given by $\frac{\pi}{4}D^2L$, where, D is the bore (diameter) of engine cylinder, and L is the stroke of piston.

Here, Bore = 100 mm = 10 cm, and Stroke = 90 mm = 9 cm.

Therefore, the swept volume $V_s = \frac{\pi}{4}10^2 \times 9 \text{ cm}^3$ = 706.86 cu. cm.

The clearance volume V_c is given as 70 cu. cm.

Hence, the compression ratio $r = \frac{V_c + V_s}{V_c} = \frac{70 + 706.86}{70} = \frac{776.86}{70} = 11.1$

The theoretical efficiency of Otto cycle is given by,

$$\eta = 1 - \left(\frac{1}{r}\right)^{\gamma - 1}$$

Since theoretical efficiency of a cycle is determined considering air as the working substance, we take $\gamma = 1.4$.

$$\eta = 1 - \left(\frac{1}{11.1}\right)^{1.4-1} = 1 - 0.3818 = 61.82\% \quad \textit{Answer.}$$

Example 5.2 Over the past few decades the compression ratios of IC engines have been improved considerably through design improvement and material and manufacturing technologies. A few decades back the compression ratio in a typical petrol engine used to be 6.5:1, and today it is about 11:1. Find out the improvement achieved in the efficiency of petrol engines due to this.

Solution: Efficiency of Otto cycle is given by,

$$\eta = 1 - \left(\frac{1}{r}\right)^{\gamma-1}$$

For $r = 6.5$,

$$\eta = 1 - \left(\frac{1}{r}\right)^{\gamma-1} = 1 - \left(\frac{1}{6.5}\right)^{1.4-1} = 1 - 0.4730 = 52.7\%$$

For $r = 11$,

$$\eta = 1 - \left(\frac{1}{r}\right)^{\gamma-1} = 1 - \left(\frac{1}{11}\right)^{1.4-1} = 1 - 0.3832 = 61.68\%$$

Thus, the improvement in efficiency is about 9% .

Example 5.3 Typical compression ratio of modern petrol engines is about 11:1, and that of diesel engines is about 24:1. Compare their ideal efficiencies, assuming that petrol engines work on ideal Otto cycle, and diesel engines work on ideal Diesel cycle.

Solution: Air standard efficiency of Otto cycle for compression ratio of 11:1 is 61.68% (as shown in Problem 5.2). The air standard efficiency of Diesel cycle is given by,

$$\eta = 1 - \frac{1}{\gamma}\left(\frac{\rho^{\gamma} - 1}{\rho - 1}\right)\left(\frac{1}{r}\right)^{\gamma-1}$$

In case of Diesel cycle, we should also know the cut-off ratio. The cut-off ratio depends upon the duration of fuel injection. In diesel engines, the power output is controlled by controlling the fuel injection time, i.e., cut-off ratio. For maximum power, the cut-off ratio is also at the maximum. Typically, this cut-off ratio is about 3.

Therefore, for $r = 24$, and $\rho = 3$, the efficiency of Diesel cycle is,

$$\eta = 1 - \frac{1}{1.4}\left(\frac{3^{1.4} - 1}{3 - 1}\right)\left(\frac{1}{24}\right)^{1.4-1} = 1 - \left(0.7143 \times \frac{3.655}{2} \times 0.04167^{0.4}\right)$$

$$= 1 - 0.3661 = 63.38\%$$

In this manner, it is clear that in spite of a large difference in the compression ratios of modern petrol and diesel engines, their ideal efficiencies are almost the same. *Considering the difference in prices of petrol and diesel in India at present, the diesel engines are more economical. This is the reason that most of the* ***commercial*** *engines are diesel engines. What about pollution?*

Example 5.4 A diesel engine working on Diesel cycle has stroke of 95 mm and bore of 100 mm. The compression ratio of the engine is 23. Find the efficiency of the air standard cycle, if the injection of fuel is done for (a) 5%, and (b) 10% of the stroke.

Solution: The swept volume $V_s = \frac{\pi}{4} D^2 L = \frac{\pi}{4} 10^2 \times 9.5 = 746.13$ cu. cm.

The relation between swept volume, clearance volume, and compression ratio is,

$$r = \frac{V_c + V_s}{V_c} \Rightarrow r = 1 + \frac{V_s}{V_c} \Rightarrow V_c = \frac{V_s}{(r-1)}$$

Since compression ratio is 23, the clearance volume $V_c = \frac{746.13}{(24-1)} = 32.44$ cu. cm.

Now, for fuel injection of 5% of stroke, the volume at the end of fuel injection,

$$V_3 = V_c + \left(V_s \times \frac{5}{100}\right) \Rightarrow V_3 = 32.44 + \left(746.13 \times \frac{5}{100}\right) = 69.75 \text{ cu. cm.}$$

Therefore, the cut-off ratio $\rho = \frac{V_3}{V_c} = \frac{69.75}{32.44} = 2.15$

Hence, the air standard efficiency is,

$$\eta = 1 - \frac{1}{\gamma}\left(\frac{\rho^\gamma - 1}{\rho - 1}\right)\left(\frac{1}{r}\right)^{\gamma-1} = 1 - \frac{1}{1.4}\left(\frac{2.15^{1.4} - 1}{2.15 - 1}\right)\left(\frac{1}{23}\right)^{1.4-1}$$

$$= 1 - 0.7143 \times \frac{2.92 - 1}{1.15} \times 0.0435^{0.4} = 66\%$$

Similarly, for fuel injection of 10% of stroke, volume at the end of fuel injection,

$$V_3 = V_c + \left(V_s \times \frac{5}{100}\right) \Rightarrow V_3 = 32.44 + \left(746.13 \times \frac{10}{100}\right) = 107.05 \text{ cu. cm.}$$

Therefore, the cut-off ratio $\rho = \frac{V_3}{V_c} = \frac{107.05}{32.44} = 3.3$

Hence, the air standard efficiency is,

$$\eta = 1 - \frac{1}{\gamma}\left(\frac{\rho^\gamma - 1}{\rho - 1}\right)\left(\frac{1}{r}\right)^{\gamma-1} = 1 - \frac{1}{1.4}\left(\frac{3.3^{1.4} - 1}{3.3 - 1}\right)\left(\frac{1}{23}\right)^{1.4-1}$$

$$= 1 - 0.7143 \times \frac{5.32 - 1}{2.3} \times 0.0435^{0.4} = 61.72\%$$

Thus, as the cut-off ratio increases, the efficiency decreases. Since, a higher cut-off ratio indicates higher power output, it is economical to run the engine at less than full load. This expressed in another terms is that *the part load efficiency of a diesel engine is high*. This is why it is better to run transport vehicles at steady speeds much lower than they can attain owing to their power. Higher power in these vehicles is not meant for higher speeds, but for climbing up the gradients or starting under fully loaded conditions.

REVIEW QUESTIONS

Answer in brief

1. What are heat engines? What are their types?
2. Draw a neat sketch of a steam engine.
3. Explain working of D-slide valves in a steam engine.
4. Differentiate between hypothetical and actual indicator diagrams for a steam engine.
5. Describe the construction of a single acting steam engine.
6. How are steam engines classified?
7. What is Carnot cycle? What is its importance?
8. Explain the Otto cycle. What type of engines use it?
9. Draw the ideal and actual indicator diagrams for Otto cycle.
10. What is air standard efficiency? What are the assumptions behind it?
11. Derive an expression for air standard efficiency of Otto cycle.
12. Explain Diesel cycle. What types of engines use it?
13. Derive an expression for air standard efficiency of Diesel cycle.
14. Draw the ideal and actual indicator diagrams for Diesel cycle.
15. What do you understand by Indicated Horse Power and Brake Horse Power?
16. How are IC engines classified?
17. Explain working of a typical IC engine.
18. What are the main parts of an IC engine? Explain with a neat sketch.
19. Explain the working of a four stroke cycle with the help of neat sketches.
20. Explain the working of a two stroke cycle with the help of neat sketches.
21. Explain the construction and working of valve gear mechanism in four-stroke engines.
22. Compare two-stroke and four-stroke engines.
23. Explain the working of a two-stroke petrol engine with the help of neat sketches.
24. Explain the working of a two-stroke diesel engine with the help of neat sketches.
25. Explain the working of a four-stroke petrol engine with the help of neat sketches.
26. Explain the working of a four-stroke diesel engine with the help of neat sketches.

Solve the following problems:

1. Find the air standard efficiency of an engine working on Otto cycle if the stroke is 90 mm and bore is 95 mm. The compression ratio of the engine is 10.

2. An engineer has made an improvement in a petrol engine due to which its compression ratio can be increased from 8:1 to 12:1. What shall be the gain in terms of air standard efficiency?
3. An engine working on Otto cycle has piston displacement of 800 cc and clearance volume of 120 cc. Determine its air standard efficiency.
4. A mechanical engineering student had a 100 cc motorcycle equipped with a four-stroke petrol engine, with original compression ratio of 10:1. He thought of welding some metal on the cylinder head, to reduce the clearance volume. What volume of metal should he deposit, in order to increase the compression ratio to 12:1? How much gain in air standard efficiency should he expect?
5. An engine working on Diesel cycle has a bore of 200 mm and stroke of 220 mm. The compression ratio is 22:1, and the fuel is injected up to 10% of the stroke. Determine the air standard efficiency.

Fill in the blanks:

1. A heat engine converts ______________ energy into ______________ energy. (heat, mechanical)
2. The most important heat engine in the beginning of industrial revolution was ______________. (steam engine)
3. The connecting rod and crank convert ______________ motion of piston into ______________ motion. (reciprocating, rotary)
4. In a steam engine, the steam first enters into the ______________. (steam chest)
5. D-slide valves are used in ______________ engines. (steam)
6. The motion of D-slide valves is controlled by ______________ mounted on the crank shaft. (eccentric)
7. The area of indicator diagram represents ______________ obtained in one cycle. (mechanical work)
8. The area of hypothetical indicator diagram is ______________ than that of actual indicator diagram. (more)
9. In a double acting steam engine, there are ______________ power stroke/s in each cycle. (two)
10. Engines used in ships are known as ______________ engines. (marine)
11. The maximum theoretical efficiency of a cycle cannot be more than that of ______________ cycle. (Carnot)
12. The efficiency of Carnot cycle depends only on ______________. (maximum and minimum temperatures)
13. The temperatures in the expression for Carnot efficiency are measured on ______________ scale. (absolute)
14. The efficiency of air standard Otto cycle depends only on ______________. (compression ratio)
15. The Otto cycle is used by engines running on ______________ fuels. (petrol or LPG)
16. For the same compression ratio, the air standard efficiency of Otto cycle is ______________ than that of Diesel cycle. (more)
17. The efficiency of diesel cycle depends upon compression ratio and ______________. (cut-off ratio)

18. The efficiency of diesel cycle ______________ with increase in cut-off ratio. (decreases)
19. Two banks of cylinders are found in ______________ engines. (V)
20. In ______________ engines, the cylinders are arranged in a circular fashion. (radial)
21. The regulation of flow of charge/ air in two-stroke engines is done through ______________. (ports)
22. The regulation of flow of charge/ air in four-stroke engines is done through ______________. (valves)
23. IC engines do not have a piston rod, but ______________ engines have it. (steam)
24. The ratio of BHP to IHP gives the ______________ efficiency of the engine. (mechanical)
25. The opening and closing of valves in a four-stroke engine is controlled by ______________ shaft. (cam)
26. There is/ are ______________ number of cams in a typical four-stroke engine. (two)
27. There is/ are ______________ number of crank shafts in a six-cylinder engine. (one)
28. A four-cylinder four-stroke engine must have minimum ______________ number of valves. (eight)
29. In a two-stroke engine, intake and ______________ take place simultaneously. (exhaust)
30. In a two-stroke engine, exhaust and ______________ ports are open simultaneously. (transfer)
31. In a two-stroke engine, the air/charge goes into ______________ before entering the cylinder. (crank case)
32. A ______________ engine does not have a separate suction stroke. (two-stroke)
33. A ______________ engine does not have a separate scavenging stroke. (two-stroke)
34. A fuel injector nozzle is found in ______________ engines. (diesel)
35. The mixture of air and petrol is made in ______________. (carburetor)
36. In a diesel engine a ______________ is used to supply fuel to the injector nozzle at high pressure. (fuel pump)
37. In a four-stroke engine, during ______________ and ______________ strokes both the valves remain closed. (compression, power)
38. The efficiency of two-stroke engines is ______________ than that of four-stroke engines. (less)
39. For the same size, a two-stroke petrol engine would generate more ______________ as compared to a four-stroke petrol engine. (power)
40. In small two-wheeler automobiles, the engines are ______________ cooled. (air)
41. Larger IC engines are ______________ cooled. (water).

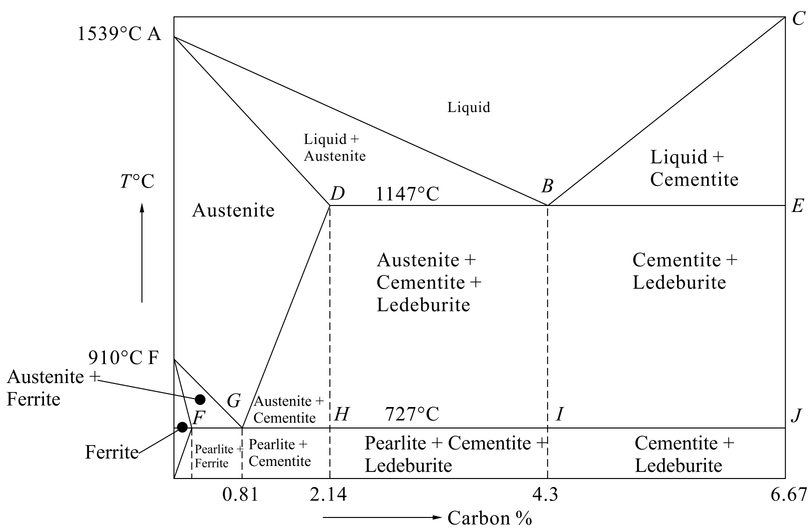
Solved Question Paper 2008

UNIT I

1. (a) Draw a neat sketch of the iron–carbon equilibrium diagram and explain the following reactions:
(i) Eutectic reaction
(ii) Eutectoid reaction
(iii) Peritectic reaction **(10)**

(b) Give the composition, properties and uses of mild steel and high-carbon steels. **(10)**

Ans. 1(a) Iron–carbon diagram



The Iron–Carbon Diagram (Simplified)

Ans. 1(b)

Mild steel or low carbon steel is the most widely used form of steel. It has carbon in the range of 0.08 to 0.3%. The other alloying elements are silicon and manganese (both in the range of 0.5%). Sulphur and phosphorous are present as impurities (both below 0.05%).

The important mechanical properties of mild steel are the following:

(a) It is soft, malleable, and very ductile. Its percentage elongation is as high as 40 % for lower carbon percentage.
(b) It has good tensile strength, ranging between 250 to 350 N/mm^2.
(c) Due to low quantities of carbon, its mechanical properties cannot be modified through heat treatment processes.
(d) It is very much suitable for a large variety of manufacturing operations due to high machinability, forgeability, and weldability.

Mild steel is used for a large number of applications:

(a) General-purpose structural applications as steel rods, channel sections, I-beams, angle sections
(b) Making nuts, bolts, keys, rivets, nails, screws, plain washers
(c) Automobile sheet-metal components, boilers, vessels, tanks, ships
(d) For making shafts, gears, camshafts, axles for low load applications

2. Write short notes on the following:

(i) Cast iron
(ii) Carbon steels
(iii) Alloy steels
(iv) Classification of engineering materials **(5 marks each)**

Ans. 2.

(i) Cast iron Cast iron has carbon in excess of 2.14 %. Carbon is present in cast irons in the form of either cementite or graphite, or both. The classification of cast irons is based upon the form of graphite and the conditions under which it is formed. The general properties of cast irons are as follows:

(a) Low tensile strength, but high compressive strength
(b) Good hardness and wear/ abrasion resistance
(c) Very low ductility and are brittle
(d) They have low melting point and good castability
(e) They cannot be formed, forged, or rolled
(f) They have good damping quality

Cast iron is a relatively cheap material. Also, the manufacturing process of casting is cheap too. Therefore, cast iron is widely used in industry. General applications of cast iron are the following:

(a) It is used for making frames, beds, guide-ways, and structures of machines.
(b) It is used for making wheels, flywheels, pulleys, levers and linkages.
(c) It is used for making cylinder blocks, piston rings, cylinder heads, valves, piston rings, crank cases, flywheels, and brake drums of IC engines.
(d) It is used for making hydraulic cylinders, steam pipes, valve bodies, and agricultural appliances.

(ii) Carbon steels Carbon steels are alloys of carbon, with carbon ranging up to 2%. Carbon steel is manufactured by reducing the amount of carbon, silicon, manganese, sulphur, and phosphorous from pig iron in the molten state. Sulphur and phosphorous are present as impurities, and must be controlled to very small quantities.

Steels are classified as *low-carbon steel* (or *mild steel*), *medium-carbon steel, high-carbon steel,* and *tool steel*. These basic types of steels are classified according to the percentage of carbon in them. Their mechanical properties are controlled mainly by the percentage of carbon in them. The mechanical properties of medium-carbon steel and high-carbon steel can be modified over a wide range through different heat-treatment processes. Other special-purpose steels are produced out of these basic types like *spring steel, high-speed steel, alloy steel,* etc. The principal alloying elements in carbon steel are silicon and manganese. Sulphur and phosphorous are also present as impurities.

(iii) Alloy steels Alloy steels are derived from carbon steels by adding suitable alloying elements. The principal alloying elements used in steel are nickel, chromium, vanadium, molybdenum, and to some extent, copper, tungsten, cobalt, beryllium, boron, and silver. Alloying elements are used to improve strength, elastic ratio, and hardness. They are also helpful in improving machinability, castability, and weldability. They improve ductility, and yield more uniform grain structure. They also improve fatigue and corrosion resistance. The proper combination of these properties in steels depends upon both the presence and percentage of alloying elements, as well as the heat-treatment cycle. Alloy steel can have mechanical properties much superior to plain carbon steels, with an ultimate tensile strength of 2100 N/mm^2, and a yield strength of 1750 N/mm^2. Alloy steels are expensive, and hence their use is limited. The principal alloying elements in alloy steels are nickel, chromium, vanadium, molybdenum, silicon, manganese, and boron.

(iv) Classification of engineering materials Engineering materials are classified as metallic and non-metallic. Metallic materials are further classified as ferrous and non-ferrous. Alternately, materials can also be classified as brittle or ductile. Usually all the brittle materials are weak in tension while the ductile materials are stronger. Brittle materials are generally stronger in compression. Ferrous materials are classified as cast iron and steels. These materials are basically alloys of iron and carbon, along with a few other elements in small quantities. The important non-ferrous materials are stainless steels, aluminum and its alloys, and copper and its alloys. Among the non-metallic materials, many types of plastics, rubbers, and ceramics are used in engineering applications.

UNIT II

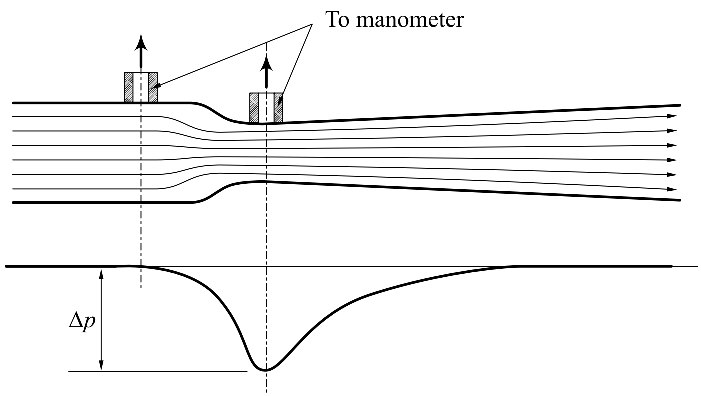
3. Explain the construction, working and uses of the following:

(5 marks each)

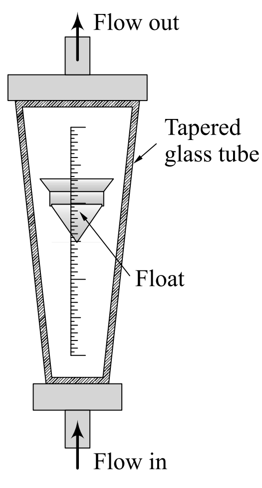
(i) Venturimeter (ii) Rotameter (iii) Prony brake dynamometer (iv) Vernier calipers

Ans. 3.

(i) Venturimeter Venturimeter is used for measurement of flow. It acts as an obstruction in the path of flow. This obstruction changes the flow velocity in a local region around it. The change in velocity causes a change in pressure, governed by Bernoulli's theorem. At the cross section where velocity is the maximum, the pressure is the minimum. The pressure drop is measured by means of a suitable pressure measuring device, mostly a manometer. This pressure drop is used to calculate the velocity, which is then used to determine the flow rate. The pressure begins to drop as the flow approaches the minimum area of restriction. After crossing this minimum area, the pressure again increases. The venturimeter and its pressure-drop curve are shown below. In case of the venturimeter, the *recovery* of pressure is the maximum, and it reaches about 98 % of its value at the entry. This is due to gradual expansion of cross section after the minimum area. Also, the inner surface of a venturimeter is very smooth. From this point of view, a venturimeter is the best obstruction type device, but it requires a long section in the pipeline, and its cost is higher too.

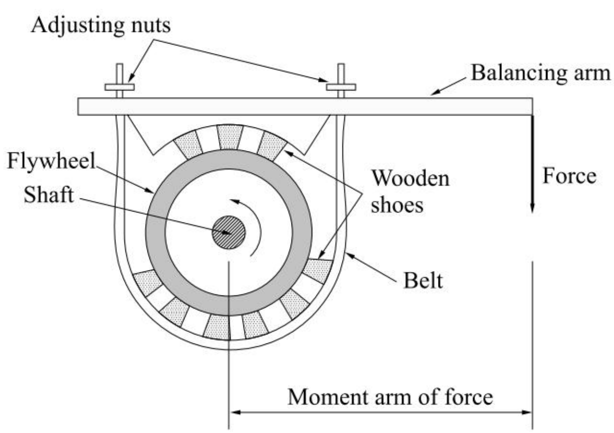


Venturi meter and its pressure-drop curve



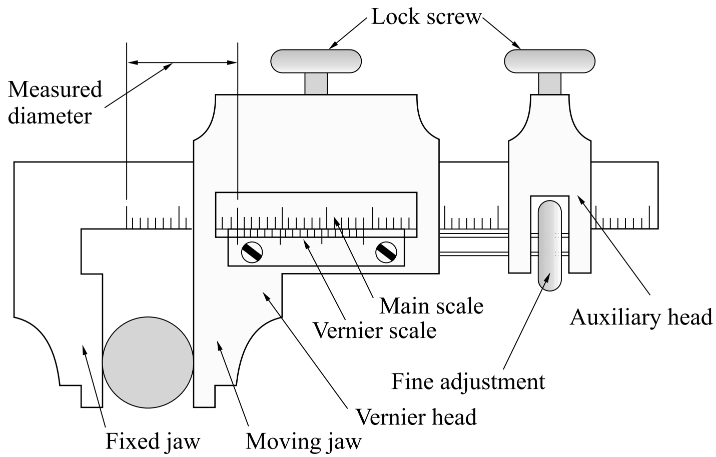
(ii) Rotameter A rotameter is a variable area device. In case of obstruction-type devices, the pressure loss varies with the square of the flow rate. So, the range of pressure measurement becomes quite large if the range of flow measurement is large. In such a situation, the accuracy of the device at low flow rates will be poor. A rotameter overcomes this problem, because its indication is linear with flow rate. The pressure loss remains almost constant over the range of measurement. It consists of a tapered (variable area) tube, and a float. The float moves up and down the tapered tube. The flow inside the tube is from bottom to top. The height of the float inside the tube depends upon the flow rate. The tube is calibrated to read the flow rate directly. The major limitation of this device is that it has to be mounted vertically in the pipeline. Also, this device cannot be used when the fluid is not transparent enough due to visibility problems. It can also not be used if the fluid has suspended particles in it. The basic construction of a rotameter is shown in the figure below.

(iii) Prony brake dynamometer A prony brake is an absorption dynamometer because the measurement is done by absorbing or dissipating the power. A simple prony brake dynamometer is shown in the figure below. In this dynamometer, a belt is wrapped around the flywheel mounted on the shaft. The belt is connected to a balancing arm through adjustable bolt-and-nut arrangements. Wooden shoes are mounted on the balancing arm and part of the belt. When the nuts are tightened, the wooden shoes press against the flywheel. A force is applied on the far end of the balancing arm. In the figure, the shaft tries to rotate the balancing arm in a counterclockwise direction due to torque generated by the prime-mover. The force applied on the balancing arm provides a clockwise moment which balances the torque due to the shaft. This moment can be calculated if the magnitude of the applied force, and the distance of its line of action from the centre of the shaft are known. When the applied force is sufficient, its moment is equal to the torque applied by the shaft. The applied force is measured by a force measuring system. Dead weight or spring balance can be used for this purpose. The moment arm of the force can be measured directly. The product of these two quantities is the moment applied by the force, and it is equal to the torque applied by the shaft, when the balancing arm is steady.



Prony brake dynamometer

(iv) Vernier Calipers A vernier calipers is used to measure the inside and outside dimensions of components. It has a vernier scale and a main scale. The main scale has a markings at 0.5 mm or 1 mm. The vernier scale has a marking slightly different than the main scale. The principle of a vernier is based on the difference of these two scales. This instrument has two jaws. The fixed jaw and the main scale form a single piece. The moving jaw slides on the main scale. It carries the vernier scale. This assembly is called the vernier head. The markings of the two scales are adjacent to each other. An auxiliary head is attached to the moving head. Both the vernier head and the auxiliary head have lock screws. The moving head and auxiliary head are connected to each other by a fine-adjustment screw. The figure below shows the details of a vernier calipers. Vernier calipers are available in the ranges 0 to 25 mm, 0 to 150 mm, 0 to 200 mm, etc. The least count of the common vernier calipers is 0.1 mm or 0.02 mm.



Vernier calipers

4. (a) **Explain the principal of temperature measurement.** **(5)**
   (b) **Explain the working of thermocouples and radiation pyrometers with a neat sketch.** **(10)**
   (c) **Explain the working of a Bourdon-tube pressure guage with a neat sketch.** **(5)**

Ans. 4(a).

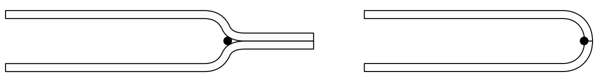
Temperature is an important parameter in many engineering systems. Measurement and control of temperature is essential in furnaces, processes, and proper functioning of machines and engineering systems. Different machines and processes work in different temperature ranges. Some systems like cryogenic systems work at extremely low temperatures, while furnaces and nuclear systems work at very high temperatures, and many systems work at and around room temperatures. For all of these systems, the requirements of temperature measurement are different, and therefore, the measurement techniques and systems are also different.

Temperature cannot be measured by basic standards for direct comparison. Change in temperature is measured by measuring any of its effects—like change in physical state of substance (melting boiling), change in dimension (thermal expansion), change in electrical properties (change in resistance), change in radiation frequencies (change in colour), etc. The temperature standards are established using the change in the physical state of materials. For example, the Celsius and Fahrenheit scales of temperature use the melting point of ice and boiling point of water as two datum points on the scale. For sub-zero temperatures, the datum points used are the freezing point of mercury, and the boiling point of nitrogen. For high temperatures, melting points of tin, lead, zinc, antimony, nickel, platinum, and tungsten, etc., are used.

Some of the basic instruments for measurement of temperature in engineering applications include liquid-in-glass thermometers, pressure guage thermometers, bimetallic thermometers, thermocouples, resistance thermometers, thermistors, and pyrometers.

Ans. 4(b).

Thermocouples Seebeck discovered that an emf exists across a junction formed by two dissimilar metals. Peltier discovered that this emf depends upon the temperature of the junction (Peltier effect). Thomson found that the emf also depends upon temperature gradient along the conductor wires (Thomson effect). These principles are used in thermocouples for measurement of temperature. The emf due to Thomson effect is quite small as compared to that due to Peltier effect.

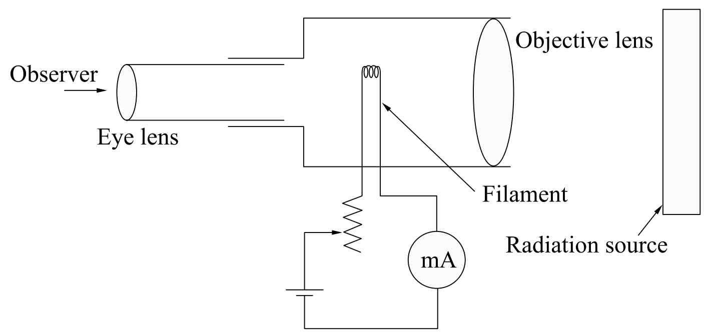


Common methods of making thermocouple joints

The materials used in thermocouples are copper, iron, platinum, rhodium, iridium, constantan (60 % Cu and 40 % Ni), chromel (10 % Cr and 90 % Ni), and alumel (2 % Al, 90 % Ni, and remaining Si and Mn). The copper–constantan thermocouple is used in the temperature range of 200°C to 350°C. It is relatively cheap. The chromel–constantan thermocouple is used in the range of 20°C to 500°C. The iron–constantan thermocouple is used in the range of 20°C to 800°C. The chromel–alumel thermocouple is used up to 1200°C, if used intermittently. The platinum–10% rhodium thermocouple is used in the range 700°C to 1500°C in continuous operation and up to 1750°C intermittently. Iridium–rhodium thermocouples are used for up to 2000°C. Thermocouples are made by twisting two wires of dissimilar metals, and making a junction between them by brazing or welding. The voltage output of a thermocouple is in millivolts. Therefore, suitable circuitry is required for its amplification, display and recording.

Pyrometers It is well known that any body having a temperature above absolute zero gives out radiation. When a steel object is heated, it radiates energy in the infra-red region. When the temperature is increased, the colour of the radiation becomes dull red. On heating further, the colour of the body becomes red, bright red, orange and finally bluish. This change in color is due to dominance of higher frequencies in the spectrum at higher temperatures. As the temperature increases, the frequency having the highest magnitude in the spectrum goes on increasing as defined by Wein's law. Pyrometers measure temperature on the basis of radiation from a hot body. There are two basic types of pyrometers: *total radiation pyrometer* and *optical pyrometer*. The total radiation pyrometer estimates the temperature of the body on the basis of the total radiation emitted by the body, i.e., taking into account all the frequency components in the radiation. Optical pyrometers use optical means for estimating the temperature. They use the radiation in the visible range of the spectrum of radiation from the hot body. Both of these types are non-contact instruments, i.e., they are not kept in contact with the body whose temperature is to be measured. A pyrometer must be calibrated for a particular application, before it is put to regular use.

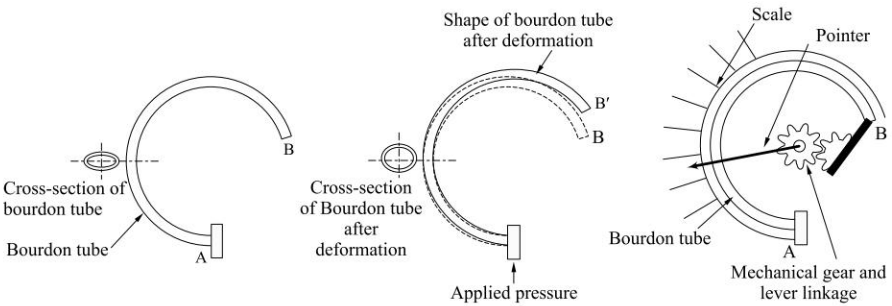
Optical pyrometers match the colour of radiation from a hot body, with the colour of filament of a bulb. The current through the bulb's filament can be controlled through an electric circuit. When this current is varied, the colour of the filament changes. The operator tries to adjust the current in such a manner that the colour of the filament becomes the same as the colour of radiation from the hot body. In this condition, the filament seems to merge with the background colour from the hot body. The current through the filament can be used as a measure of temperature of the hot body. The figure below shows the schematic diagram of an optical pyrometer.



Working principle of an optical pyrometer

Ans. 4(c).

Bourdon-Tube Pressure Guage The Bourdon tube is a tube in the shape of an arc of a circle. Its cross section is *oval* or *ellptical*, as shown in the figure below. The end *A* of the tube is connected to the pressure source. The end *B* is closed. When pressure is applied at the end *A*, the whole tube is subjected to internal pressure. Since the end *B* is closed, the oval cross section of the tube deforms to become more circular. Due to such deformation in the cross-section, the whole tube tends to straighten out. This causes movement of the end *B*, which is a function of the internal or applied pressure. The movement *BB'* of the end *B* is amplified through a mechanical linkage consisting of gears and levers. The amplified movement is displayed on a circular scale through rotation of a pointer. The circular scale is calibrated to read pressure directly. In Bourdon tube pressure guages, the arc of a Bourdon tube is usually less than 360°. However, when higher sensitivity is required, the tube is made with multiple turns. The Bourdon tube has the applied pressure on its inner side, and atmospheric pressure on the



(a) Bourdon tube (b) Deformation of Bourdon tube (c) Bourdon tube pressure gage

Working principle of bourdon tube pressure gage

outside, the measurement gives guage pressure, i.e., pressure difference between the applied pressure and atmospheric pressure.

UNIT III

5. (a) How turbines are classified? Explain. (10)

(b) A pipe 200 m long has a slope of 1 in 100 and tapers from 1 m diameter at the high end to 0.4 m at the low end. Rate of water flow is 4,000 litres per minute. If the pressure at high end is 50 kPa, find the pressure at low end. (10)

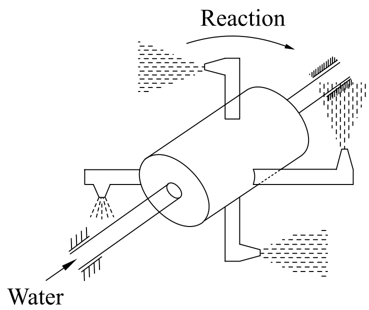
Ans. 5 (a).

Turbines are classified as

1. (a) Impulse turbine, e.g., Pelton turbine
   (b) Reaction turbine, e.g., Francis turbine, Kaplan turbine
2. According to available head
   (a) low head , lesss than 30 m, e.g., Kaplan turbine
   (b) medium head , 30 m < head < 100 m, Kaplan turbine , Francis turbine
   (c) high head , head > 100 m, Pelton turbine
3. According to the direction of flow of water
   (a) Tangential flow , e.g., Pelton turbine
   (b) Radial flow, e.g., Francis turbine
      (i) radial outward flow, e.g., Francis turbine
      (ii) radial inward flow
   (c) Axial flow, e.g., Kaplan turbine

Impulse turbine In an impulse turbine, the available potential energy of water is first converted into kinetic energy by means of a nozzle. The high velocity of the jet coming out of the nozzle strikes a series of blades (bucket shaped) fixed around the periphery of the rim of a circular disc. The resulting change in the momentum of water forces the blades to move, which in turns rotates the disc. (Newton’s second law of motion).

Reaction turbine The following figure illustrates the basic principle of a reaction turbine. Allow the water to flow through a pipe into a drum, which has radial opening. When water escapes through these openings at a higher velocity, it produces an equal and opposite reaction causing the drum to rotate in the opposite direction of the flow. Similarly, when water slides over the runner blade, the part of the pressure energy

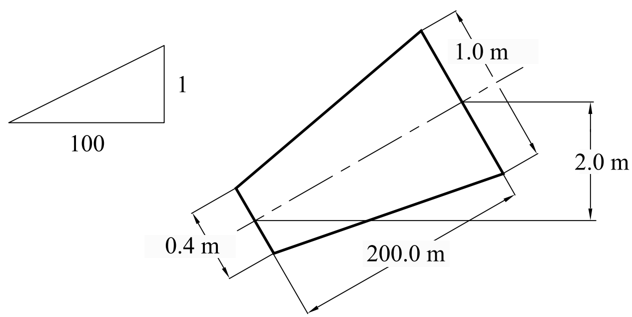


changes causing a reaction force on the blades, causing the turbine to rotate. (Newton's third law of motion).

Ans. 5 (b).

A 200-m long pipe has a slope of 1 in 100 and tapers from 1-m diameter at the high end to 0.4 m at the lower end. The rate of water flow is 4000 litres/min. If the pressure at the high end is 50 kPa, find the pressure at the low end.

Solution:



Assumption density of water = 1000 kg/m^3

Given,

Length of pipe, $L = 200$ m.

Discharge = 4000 litres/min = 4000/60 × 1000 m^3/s [1000 litres = 1 m^3]

$Q = 0.2/3$ m^3/s

Pressure at the inlet $p_1 = 50$ kPa $= 5 \times 10^4$ N/m^2

Pressure at the outlet $p_2 = ?$

$z_1 = (1/100) \times 200 = 2$ m

$z_2 = 0.0$ m

Diameter of pipe at the inlet $d_1 = 1$ m

Area of the pipe at the inlet $a_1 = (\pi/4)\, d_1^2 = (\pi/4)\,(1)^2 = 0.7854$ m^2

Diameter of pipe at the outlet $d_2 = 0.4$ m

Area of the pipe at the outlet $a_2 = (\pi/4)\, d_2^2 = (\pi/4)\,(0.4)^2 = 0.1257$ m^2

$V = Q/\text{area}$

Velocity at the inlet $V_1 = 0.2/(3 \times 0.7854) = 0.0849$ m/s

Velocity at the outlet $V_2 = 0.2/(3 \times 0.1257) = 0.5304$ m/s

Applying Bernoulli's equation

$p_1/(\rho g) + z_1 + V_1^2/2g = p_2/(\rho g) + z_2 + V_2^2/2g$

$$5 \times 10^4/(1000 \times 9.81) + 2.0 + (0.0849)^2/2 \times 9.81$$
$$= p_2/1000 \times 9.81 + 0.0 + (0.5304)^2/2 \times 9.81$$
$$5.0968 + 2.0 + 3.673 \times 10^{-4} = p_2/1000 \times 9.81 + 0.0143$$
$p_2 = 69482.9$ Pa. $= 69.4829$ kPa **Ans** $p_2 = 69.4829$ kPa

6. Describe the construction and working principle of the following: (10 each)

(i) Pelton wheel

(ii) Kaplan turbine

Ans. 6 (a).

Pelton turbine The Pelton turbine was invented by A Pelton (1829–1908) and is based on the principle on impulse momentum transfer.

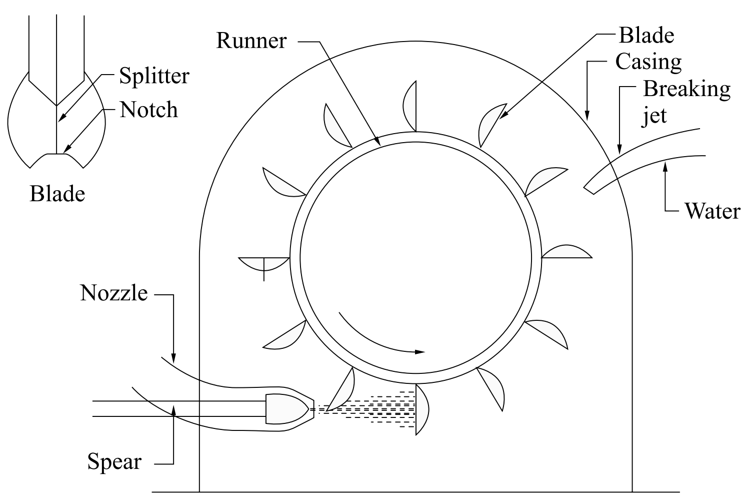
Construction Essential components of Pelton turbine are as shown in the figure and their functions are as follows:

Casing Its basic function is to prevent the water from splashing outside. It also helps in discharging the water to the tail race.

Nozzle The function of the nozzle is to convert the potential energy of water into the kinetic energy (available potential head into kinetic head). Inside the nozzle, a spear is provided for regulating the amount of water striking the blades attached to the runner. The forward movement of a spear decreases the amount of water while the backward movement of a spear increases the amount of water striking the bucket-shape a blades The movement of the spear is controlled either manually or automatically by a governing mechanism.

Runner The runner consists of series of buckets placed equidistantly along the periphery of a circular disc. The bucket is cup-shaped and has a splitter in the middle to distribute the water striking it symmetrically. A notch is also provided in the bucket on the outer side so that the jet strikes the bucket only when it comes in the proper position.

Breaking jet When the nozzle is closed to stop the turbine, due to inertia the runner continues to rotate for a long time. To stop the runner in a short time, a small nozzle is provided which directs the flow of the jet on the backside of the bucket as shown in the figure. This jet is called the breaking jet.



Working The Pelton turbine is a tangential flow impulse turbine, in which water flows along the tangent to the path of the runner. The water flows from the reservoir into the penstock (a pipe connecting the reservoir and nozzle) to the nozzle. The nozzle converts the available pressure head into the kinetic head. The high velocity of water coming out of the nozzle strikes the series of blades (bucket shaped) mounted on the periphery of the circular disc (rotor). As water flows into the bucket, the direction of water velocity changes. In the process, the change in the momentum of water causes a force on the bucket to move. After doing useful work, the water discharges into the tail race.

Ans. 6 (b).

Kaplan turbine The Kaplan turbine was invented by Kaplan an Austrian engineer. It is a low-head, axial-flow reaction turbine. It is also called propeller turbine.

Construction The main components of the Kaplan turbine are as follows:

1. Scroll casing 2. Guide vanes 3.Runner 4. Draft tube

The functions of the main components are as follows.

Scroll casing The water supplied through the penstock is fed to the spiral casing running around the runner as shown in the figure. The cross section area of the casing gradually reduces along the direction of the flow, so that the water enters the runner at constant velocity throughout the circumference of the runner.

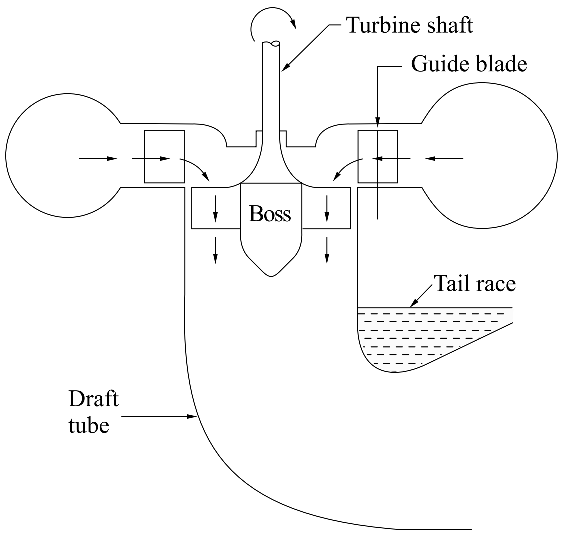
Guide vanes The guide vanes allow the water to strike the blades of the rotor without shock at the inlet. Guide vanes are fixed in a position. However, they can swing about their own axis to change the flow area between two consecutive blades by means of a hand wheel or governor. The water from guide vanes turns through 90 degrees and flows axially along the runner.

Runner The runner of a Kaplan turbine is like a propeller of the ship. The runner is in the form of a boss, i.e., the extension of the shaft in a bigger diameter. The blades on the runner are of an aerofoil shape. The number of blades are usually 4, 6 or at most 10. The runner blades are pivotally mounted on the hub so that their inclination can be adjusted during the change in the load for the best performance. In a fixed type of runner, the blade angle cannot be varied.

Draft tube A considerable fraction of the available head would be wasted if the turbine were placed above the tail race level and the outgoing water was leaving at atmospheric pressure. By providing a turbine above the tail race level and connecting the outlet to the tail race level by a tube called the draft tube, improves the turbine output and the efficiency.

Thus, water after passing through the turbine is discharged to the tail race through a gradually expanding tube called the draft tube. The most common type of draft tube is the elbow type. *The function of the draft tube is to conserve for conversion of the energy remaining at the exit of the runner into power by the turbine.*

Working The water from the reservoir enters the scroll casing through the penstock. After the scroll casing, the water enters the guide vanes at the exit of the guide vanes, turns through 90 degree and flows parallel to the axis of rotation of the runner. When the guide vanes are opened, a part of the potential energy of the flow is converted into kinetic energy and the remaining is potential energy. When water flows over the blades of the runner, the radial component of the flow gradually changes to axial flow, and the tangential component of the flow rotates the runner.



Some of the Kaplan turbine installations are the Bhakra–Nangal project in Himachal Pradesh, and Hirakund Dam project in Orissa.

UNIT IV

7. (a) State and explain First Law of Thermodynamics.

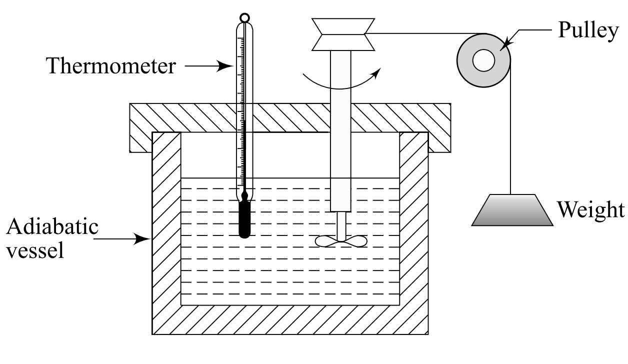
(b) Write the short notes on the following:

1. Boiler classification

2. Eco-friendly refrigerants

Ans. 7 (a).

The first law of thermodynamics is based on the law of conservation of energy. It states that the energy can neither be created nor destroyed but can be converted from one form to another. Heat and work are different forms of the same entity called the energy. Energy which enters the system as heat may leave the system as work, or energy which enters the system as work may leave the system as heat. This can be shown by Joules experimental set up as shown in the following figure.



It consists of an adiabatic vessel filled with known mass of water. The adiabatic vessel has a thermometer and a stirrer as shown in the figure. When weight moves down, it rotates the paddle wheel (stirrer) through a pulley which churns the water. The amount of work W can be measured by the fall of weight. The system was initially at a temperature t_1, the same as that of atmosphere, but after the transfer of work, the temperature rises to t_2. Let the insulation now be removed. The system and the surroundings interact by heat transfer till the system reaches to the original temperature t_1, attaining thermal equilibrium. The system thus executes a cycle. It was found that the amount of heat transfer $Q_{1\text{-}2}$ is proportional to the amount of work transfer $W_{1\text{-}2}$ and the proportionality is called the Joules equivalent or the mechanical equivalent of heat. If the system involves many more heat and work quantities, the same result is obtained and mathematically for a closed cycle it is written as

$$\int \delta q = \mathrm{J} \int \delta w$$

The value of Joules equivalent J in S.I. unit is unity.

$$\int \delta q = \int \delta w$$

i.e. for the system going under a cyclic process, the net heat transfer is equal to the amount of work transfer.

Ans. 7 (b).

(i) Boiler Classification

The boilers may be classified as follows:

1. According to position of boiler shell:
   (i) *Horizontal boiler:* If the axis of the boiler is horizontal, the boiler is called as horizontal boiler. Examples: Lancashire, Babcock and Wilcox boiler, Locomotive boiler, etc.
   (ii) *Vertical boiler:* If the axis of the boiler is horizontal, the boiler is called as vertical boiler. Examples: Simple vertical boiler, Cochran boiler, etc.
2. According to position of furnace:
   (i) *Externally Fired:* If the fire is outside the shell or the furnace is located outside the boiler shell, it is known as externally fired boiler. Examples: Stirling boiler, Babcock & Wilcox boiler.
   (ii) *Internally Fired:* If the furnace is located inside the boiler shell, it is known as internally fired boiler. Examples: Lancashire, Cochran boiler, etc.
3. According to content of tubes:
   (i) *Water Tube boiler:* In this type, the water flows inside the tubes and hot gases surrounds them. Examples: Stirling boiler, Babcock and Wilcox boiler, etc.
   (ii) *Fire Tube boiler:* In this type, the hot gases pass through the tubes and the water surround the tubes. Example: Cochran boiler, Locomotive boiler and Lancashire.
4. According to circulation of water:
   (i) *Natural circulation:* The circulation of water takes place due to natural convection currents produced by application of heat or due to density difference of hot and cold water. Examples: Lancashire, Babcock and Wilcox boiler, etc.

(ii) *Forced circulation:* The circulation of water is done by a forced pump. Examples: Cochran boiler, Velox, Lamount, etc.

5. According to pressure of steam:
   (i) *Low pressure boiler:* Steam pressure upto 30 bar. Examples: Cochran boiler, Cornish, Lancashire, etc.
   (ii) *Medium pressure boiler:* Steam pressure 30 bar to 75 bar.
   (iii) *High pressure boiler:* Steam pressure 80 bar and above. Examples: Lamount, Velox, Loeffler boiler, etc.
6. According to number of tubes:
   (i) *Single tube boiler:* It consists of single fire tube. Examples: Simple Vertical boiler and Cornish.
   (ii) *Multi tube boiler:* It consists of more than one tube (fire or water tubes). Examples: Babcock and Wilcox boiler, Lancashire, Locomotive boiler, Stirling boiler, Cochran boiler, etc.
7. According to the use:
   (i) *Stationary boiler:* These are mounted on a fixed platform and do not move from one place to another. Examples: Lancashire, Locomotive boiler, Cornish, Babcock and Wilcox boiler, etc.
   (ii) *Mobile boiler (Marine and Locomotives):* They are used to drive the sea vehicles, railway engines, etc.
8. According to fuel feeding method:
   (i) *Hand Fired boiler:* Like Simple Vertical boiler, Locomotive boiler, Cochran boiler, etc.
   (ii) *Stoker fired boiler:* Like Babcock and Wilcox boiler, Stirling boiler, etc.
   (iii) *Pulverized fuel boiler:* The coal is ground to a fine powder and it is blown with combustion air into furnace.

Ans. 7 (b).

(ii) Eco friendly Refrigerants

The earth's ozone layer in the upper atmosphere (stratosphere) is needed for the absorption of harmful UV rays from the sun. These cause skin cancer. Chlorofluorocarbous (CFCs) have been linked to the depletion of this ozone layer. They have varying degrees of ozone depletion potential (ODP). In addition, they also act as greenhouse gases. Hence they have global warming potential (GWP) as well. It is established that it is the chlorine atom in the molecule which is responsible for the ODP. According to the following reactions,

$$CCl_2F_2 \xrightarrow{\text{sunlight}} CClF_2 + Cl$$

$$O_3 + C \xrightarrow{\text{sunlight}} ClO + O_2$$

Thus, O_3 will be depleted to O_2. The problem with CFCs is of their chain reactions. A single atom of Cl released from a CFC reacts taking out 100,000 O_3 molecules. That is why even a small concentration of CFC becomes very important.

CFC substitutes fall into four categories: those based on N_2, F, hydrocarbons and inert gases.

Hydroflurocarbons (HFCs) provide an alternative to fully halogenated CFC refrigerants. They contain no chlorine atom at all and, therefore, have zero ODP. The HFCs on the other hand, because of their H-content, may be flammable to some extent. This depends upon the number of H-atoms in the molecule. Pure HCs are, of course, highly flammable.

At present, the following substitutes are available:

— HCFC R-123 ($CHCl_2$-CF_3) in place of CFC R-11 (CCL_3F)
— HFC R-134a (CH_2F-CF_3) and Isobutane in place of CFC R-12 (CCl_2F_2)
— R-69s in place of R-22 and R-502.

8. (a) Describe the classification, construction and working of a Cochran boiler. (10)

(b) Explain vapour absorption system with a neat sketch. (10)

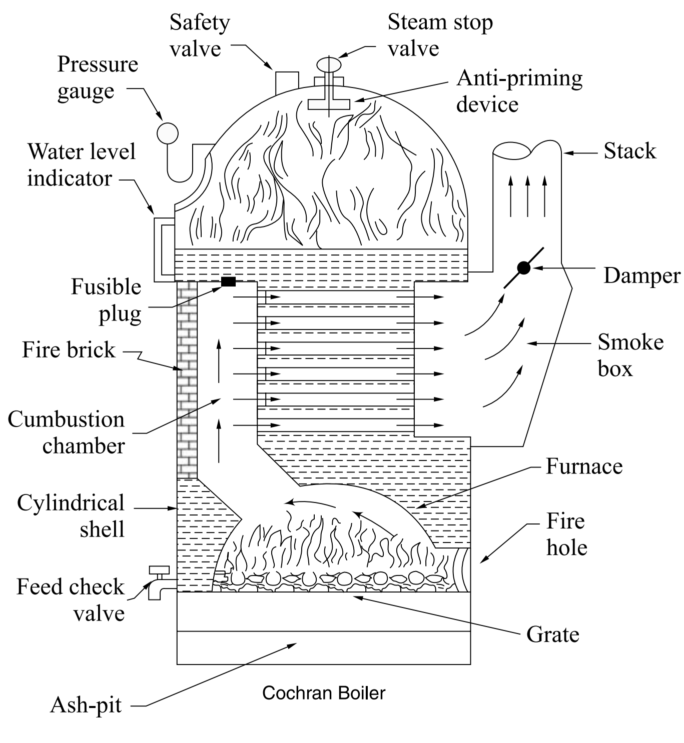
Ans. 8(a)

(a) Cochran Boiler

It is a steam generator having the following characteristics:

— It is a vertical boiler.
— It is a fire tube, multitubular boiler.
— It is a low pressure boiler.
— It is a stationary and internally fired boiler.

It consists of a cylindrical shell with hemispherical top. It also has a hemispherical furnace. It has a combustion chamber lined inside with fire bricks. A number of horizontal fire tubes are provided whose one end is connected with the combustion chamber plate and the other end is connected to the smoke box plate. The various mountings fitted on the boiler are as shown in the figure.



Cochran Boiler

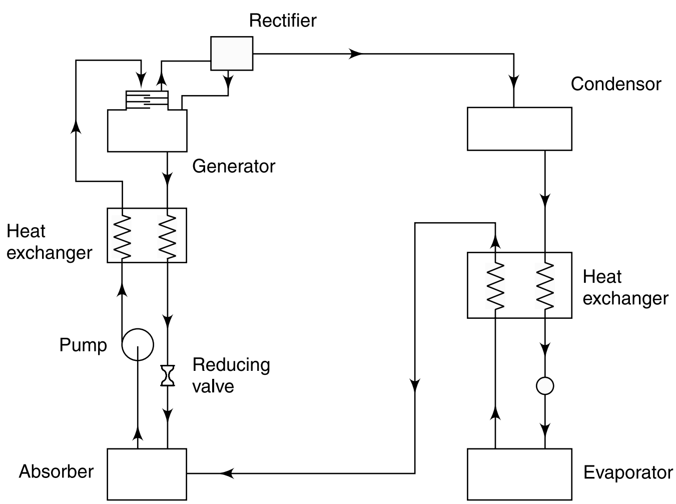
Working: The fuel is burnt on the grate in the fire box, and the ash collected is disposed off from the ash pit. The hot gases of combustion pass through a short flue to the combustion chamber and then through the fire tubes (which are surrounded by water), into the smoke box. These gases are then discharged into the atmosphere through the stack. The manhole is provided for cleaning and maintenance. A mud hole is provided at the bottom for draining out the unwanted water or muddy water from the boiler. A water gauge, pressure gauge, blow-off cock, feed-check valve, feed pump, fusible plug and chimney are provided for proper functioning of the boiler.

On heating, the water is vapourized and converted to steam. This steam is then collected in the steam space. The steam from the steam space passes through an antipriming device into the steam stop valve for use.

Ans 8 (b)

Vapour Absorption System The vapour-absorption refrigeration system is a heat-operated system which uses a refrigerant that is alternatively absorbed and liberated from the absorbent. It is quite similar to the mechanical vapour compression system which employs a compressor, condenser, expansion device and an evaporator. In the vapour-absorption refrigeration system, the compressor is replaced by an absorber generator assembly. The system in which ammonia is used as a refrigerant and water is used as an absorber is called aqua-ammonia absorption system.

The basic flow diagram of vapour-absorption system is as shown in the figure.



A practical vapour-absorption system consists of an *absorber*, a *pump*, a *generator*, and a *pressure-reducing valve* to replace the compressor of the vapour compression system. The other components being a *condenser*, *expansion valve* and *evaporator* are same as that of the vapour-compression refrigeration system. In order to improve the performance and working of the plant, the accessories fitted are an *analyzer*, a *rectifier* and *heat exchangers*.

Ammonia-Water Absorption Refrigeration System
In the absorber, the ammonia vapour coming out of the evaporator is absorbed by liquid water. The formation of this liquid solution is exothermic, thus heat is released. The solvency of ammonia in the water decreases as temperature increases. Thus cooling is required in the absorbent to absorb the energy released due to the absorption of ammonia in the water. The strong aqua-ammonia solution is pumped to the generator through a heat exchanger, where it is preheated with the help of a hot, weak solution returning to the absorber, thereby, reducing the heat supply in the generator. In the generator, the ammonia is driven out of the solution (endothermic process), leaving a weak ammonia solution in the generator. The ammonia vapour liberated passes through the analyzer-rectifier assembly to remove the water vapour going into the condenser, thereby avoiding ice formation in the system. It also reduces the heat input to the generator. The remaining weak solution present in the generator returns back to the absorber through a pressure-reducing valve. The condensed ammonia is passed first through a heat exchanger, further reducing the temperature of the liquid ammonia. It is then expanded through an expansion valve and then enters the evaporator, where it absorbs heat from the surroundings or the brine to be chilled.

UNIT V

9. (a) Explain the working of a two-stroke petrol engine. (10)

(b) Explain Otto cycle and derive an expression for the effciency of an Otto cycle. (10)

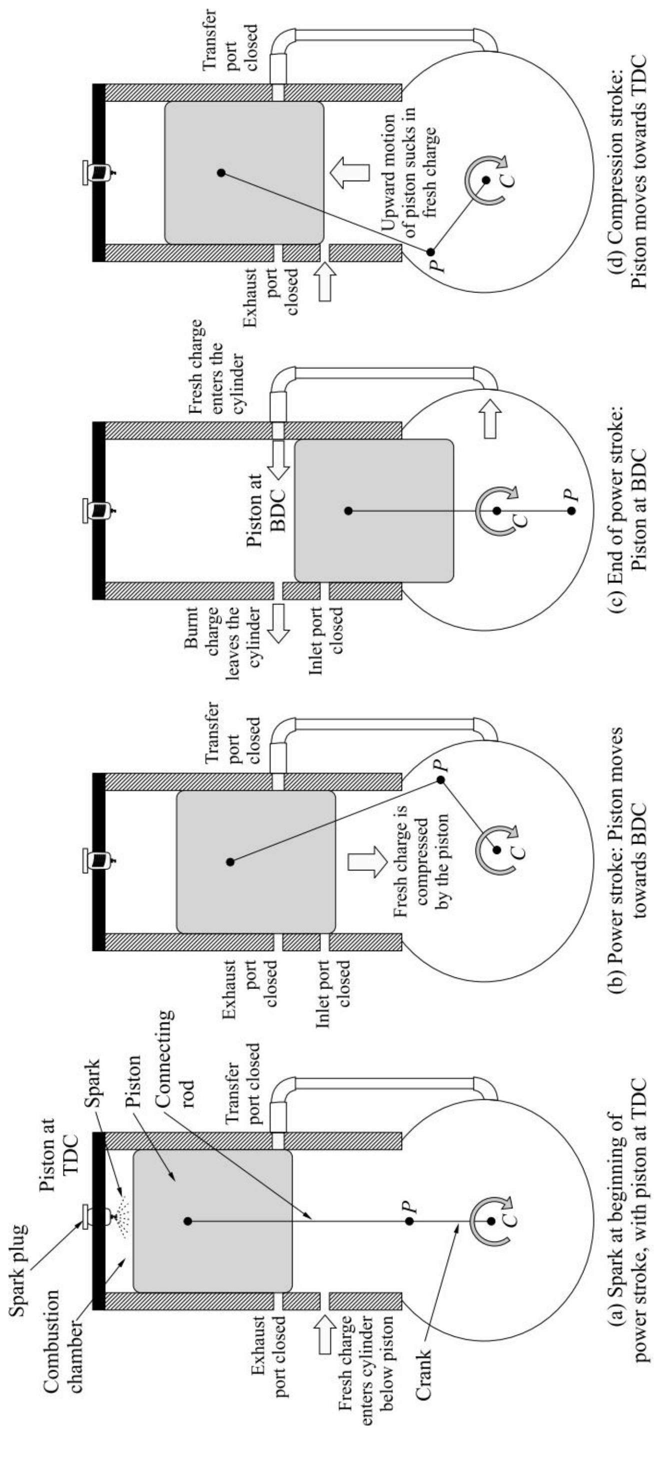
Ans.

(a) ***Two-Stroke Petrol Engine and its Working*** The construction and working of a two-stroke petrol engine is explained here. The main components of a two-stroke petrol engine are cylinder, cylinder head, piston, piston rings, piston pin (or gudgeon pin), connecting rod, crank pin, crank, crank shaft, and flywheel. The cylinder wall has three ports: intake port, exhaust port, and transfer port. This engine works on the Otto cycle.

(a) A mixture of petrol and air is made in the *carburetor*. This mixture is supplied to the cylinder through the intake valve, via the *intake manifold*.

(b) The mixture enters the cylinder below the piston. This process takes place when the piston is near TDC at the end of the compression stroke. In this position, it uncovers the inlet port.

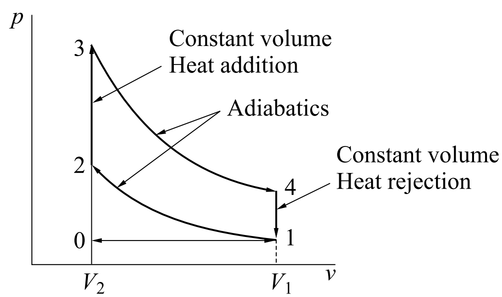
(c) When the piston moves down during the expansion stroke, the charge is compressed in the crank case. The crank case has a connection with the transfer port in the cylinder wall. When the piston reaches BDC, at the end of the expansion stroke, it uncovers the exhaust and transfer ports. The exhaust port is opened a little before the transfer port, so that most of the burnt gases escape out of the cylinder before the entry of fresh charge begins. However, for some time near BDC, both the exhaust port and transfer port are open simultaneously. Thus, when the piston is near BDC, the fresh charge moves from the crank case into the cylinder through the transfer port.



Working of two-stroke petrol engine

(d) When piston starts moving towards TDC in the compression stroke, it again covers the exhaust port and transfer port. So the fresh charge gets trapped in the space above the piston. Near the end of compression stroke, when the charge is heated sufficiently, a spark is produced to ignite the charge.
(e) High pressure of the burnt charge pushes the piston downwards. This force is transferred to the crank through the connecting rod. The force on the crank produces a torque on the crank shaft. This results into rotation of the crank shaft and generation of power. This cycle repeats itself.

(b) This cycle was first proposed and used by a German engineer NA Otto in 1878. This cycle is also known as constant volume cycle. It consists of four processes:
(a) Adiabatic compression of the working substance
(b) Addition of heat to working substance at constant volume
(c) Adiabatic expansion of working substance
(d) Rejection of heat at constant volume



In an actual engine working on the Otto cycle, the air–fuel mixture is sucked into the cylinder by the downward motion of the piston. This is called the suction stoke. This process takes place along 0–1, at atmospheric pressure. Then the mixture is compressed adiabatically along 1–2. This process takes place during the compression stroke of the engine. When the mixture attains sufficiently high temperature at the point 2, the combustion is initiated by a spark. Thus, heat addition process takes place along 2–3 at constant volume. At the end of this process, the pressure reaches its maximum value. Then the adiabatic expansion process takes place along 3–4. Power is generated in this process. This process takes place during the power stroke of the engine. At the end of the power stroke, the burnt gases are discharged through the process 4–1. This process is equivalent to heat rejection process of the ideal cycle. Lastly, the burnt gases are purged out of the cylinder through the exhaust stroke 1–0.

Let us consider that the mass of the working substance is m. Let the temperature of the working substance corresponding to points 1, 2, 3, and 4 be T_1, T_2, T_3, and T_4 respectively. The temperature of the working substance increases from T_2 to T_3 during the heat-addition process 2–3. Then,

Heat addition to the working substance during the process 2–3 is given by, $m\ C_v t_{rp}$ $(T_3 - T_2)$, where C_v is the specific heat of the working substance at constant volume.

The amount of heat rejection during the process 4–1 is given by , $m\ C_v\ (T_4 - T_1)$

No heat is added or rejected during the adiabatic processes 1–2 and 3–4.

Then, the thermal efficiency of the Otto cycle is given by

$$= 1 - \frac{\text{Heat rejected}}{\text{Heat input}}$$

$$= 1 - \frac{mC_v(T_4 - T_1)}{mC_v(T_3 - T_2)} = 1 - \frac{(T_4 - T_1)}{(T_3 - T_2)}$$

For the adiabatic processes 1–2 and 3–4, we have the relations

$$\frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{\gamma-1} \quad \text{and} \quad \frac{T_3}{T_4} = \left(\frac{V_4}{V_3}\right)^{\gamma-1}$$

Or, $$\frac{T_2}{T_1} = \frac{T_3}{T_4} = r^{\gamma-1}$$

Here, γ is the ratio of specific heats of the working substance, and r is the *compression ratio*. Compression ratio is the ratio of the volume of the working substance at the start of the compression process to that at the end of compression,

$$r = \frac{\text{Volume before compression}}{\text{Volume after compression}} = \frac{V_1}{V_2}$$

Therefore,

$$\frac{T_2}{T_1} = \frac{T_3}{T_4} \Rightarrow \frac{T_4}{T_1} = \frac{T_3}{T_2} \Rightarrow \frac{T_4}{T_1} - 1 = \frac{T_3}{T_2} - 1 \Rightarrow \frac{T_4 - T_1}{T_1} = \frac{T_3 - T_2}{T_2}$$

$$\Rightarrow \frac{T_4 - T_1}{T_3 - T_2} = \frac{T_1}{T_2} = \left(\frac{1}{r}\right)^{\gamma-1}$$

Hence, the efficiency of an ideal Otto cycle is given by

$$\eta = 1 - \left(\frac{1}{r}\right)^{\gamma-1}$$

10. (a) Explain the working of a four-stroke Diesel engine. (10)

(b) In an air-standard Diesel cycle with compression ratio 14, the conditions of air at the start of the compression stroke are 1 bar and 300 K. After addition of heat at constant pressure, the temperature rises to 2775 K. Determine the thermal efficiency of the cycle, net work done per kg of air and the mean effective pressure. (10)

Ans.

(a) *Four-Stroke Diesel Engine and its Working*

The construction and working of a four-stroke diesel engine is explained in this section. Like all IC engines, it has a cylinder, cylinder head, piston, piston rings, piston pin, connecting rod, crank, crank shaft, and flywheel. In addition, a basic four-stroke diesel engine has two valves: the inlet valve and the exhaust valve. These valves are mounted on the cylinder head. The opening and closing of these valves is controlled by a valve gear mechanism. Details of the valve-gear mechanism are given in Section

5.3.3, and Figure 5. Fresh air is supplied into the cylinder through the intake valve, via the inlet manifold. The products of combustion are expelled out of the cylinder through the exhaust valve, and discharged into the atmosphere by the exhaust manifold.

The working of a four-stroke diesel engine is as follows:

(a) The engine works on the Diesel cycle. One cycle is completed in two revolutions of the crankshaft, i.e., four strokes of the piston.

(b) At the beginning of the cycle, the piston is at TDC. The intake valve is opened and the piston begins to move downwards for the suction stroke. Fresh air is taken into the cylinder. The intake valve closes as the piston reaches BDC, and the suction stroke is complete.

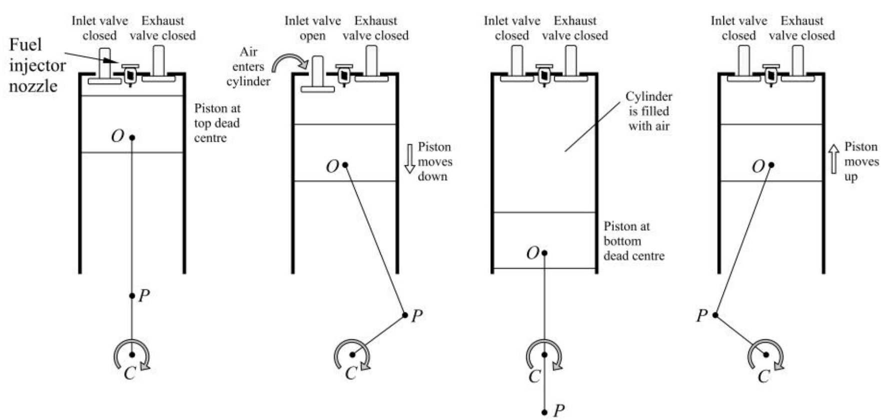
(c) The piston begins to move upwards towards TDC and the compression stroke begins. Both intake and exhaust valves are closed during the compression stroke. The air is compressed adiabatically to high pressure and temperature.

(d) When the piston reaches near TDC towards the end of the compression stroke, fuel is injected into the cylinder by a nozzle. The fuel is supplied at a high pressure from a fuel pump, and the nozzle creates a spray of fine droplets. The droplets of fuel are ignited due to the high temperature of the compressed air. The fuel burns and the pressure and temperature of combustion gases become very high. Under the heavy pressure, the piston begins to move downwards and the expansion (or power) stroke begins.

(e) With completion of suction and compression strokes, one revolution of the crank shaft is complete.

(f) During the power stroke, the piston continues to move from TDC to BDC. Both the valves remain closed. The force applied on the piston by the combustion gases is transferred to the connecting rod through the piston pin. The connecting rod applies force on the crank through the crank pin. The force on the crank produces a torque on the crank shaft. The crank shaft rotates and power is produced. When the piston reaches BDC, the power stroke is over.

(g) The piston begins to move up from BDC towards TDC, and the exhaust stroke begins. The exhaust valve opens, and remains open during the whole exhaust



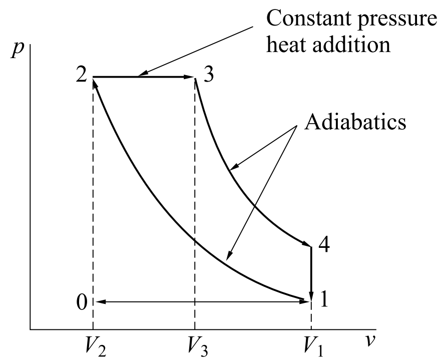
(a) Piston at TDC (b) Suction stroke (c) Piston at BDC (d) Compression stroke

stroke. The burnt gases are expelled out of the cylinder. When the piston reaches TDC, the exhaust stroke is complete, and the exhaust valve is closed.

(h) With the completion of the power and exhaust strokes, the second revolution of the crank shaft is complete.

(i) In this manner the cycle is completed in four strokes, or two revolutions of the crank shaft. When the piston reaches TDC, the next cycle begins.

(b) The Diesel cycle is shown in the figure below:



Given that $T_1 = 300$ K, $T_3 = 2775$ K, $p_1 = 1$ bar $= 10^5$ Pascal, and compression ratio $r = V_1/V_2 = 14$. Assume that $C_p = 1.005$ kJ/Kg-K, and $C_v = 0.718$ kJ/Kg-K.

Hence, $\dfrac{T_2}{T_1} = r^{\gamma-1} = 14^{0.4} \Rightarrow T_2 = 862.13\text{K}$

The cut-off ratio, $\rho = V_3/V_2 = T_3/T_2 = 3.22$

And, $\dfrac{T_4}{T_3} = \left(\dfrac{V_3}{V_4}\right)^{\gamma-1} = \left(\dfrac{V_3}{V_2}\dfrac{V_2}{V_4}\right)^{\gamma-1} = \left(\dfrac{V_3}{V_2}\dfrac{V_2}{V_1}\right)^{\gamma-1} = \left(\dfrac{\rho}{r}\right)^{\gamma-1} = 0.555$

Therefore, $T_4 = 1541.5$ K

Since work done = heat supplied – heat rejected,

$$W = C_p (T_3 - T_2) - C_v (T_4 - T_1)$$
$$= 1.005(2775 - 862.13) - 0.718(1541.5 - 300) = 1031 \text{ kJ.}$$

Heat supplied = 1922.4 kJ

Therefore, efficiency = work done/heat supplied = 1031/1922.4 = 53.63%

For 1-kg air,

$$pV = mRT$$
$$V = mRT/p = (1 \times 287 \times 300)/\ 10^5 = 0.86 \text{ m}^3$$

Therefore, $V_2 = V_1/r = 0.86/14 = 0.0614$ m^3

Then, swept volume $= V_1 - V_2 = 0.86 - 0.0614 = 0.7986$ m^3

Then,

mean effective pressure = work done/swept volume

$= 1031 \times 10^3$ J/ 0.7986 m^3 = 1.29 MPa

Solved Question Paper 2009

BME APRIL 2009 EXAMINATION

Q. 1. Discuss the composition, specific properties and main applications of the following materials:

(i) Mild steel
(ii) High-carbon steel
(iii) High-speed steel
(iv) Stainless steel

(5 marks each)

Ans: Refer Section 1.6.1.

OR

Q. 1. Describe the following mechanical properties of materials:

(i) Tensile strength
(ii) Hardness
(iii) Fatigue strength
(iv) Modulus of Elasticity
(v) Toughness

(4 marks each)

Ans: Refer Section 1.3.

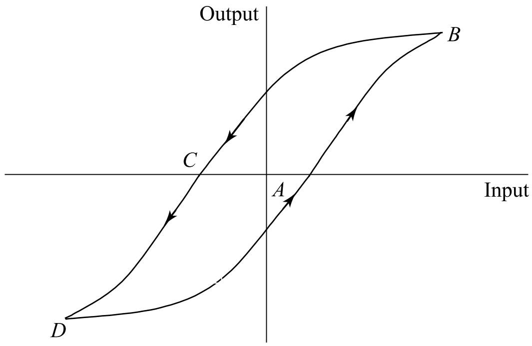
Q. 2. Explain the following properties of any measuring instrument:

(i) Hysteresis
(ii) Sensitivity
(iii) Response time
(iv) Precision and accuracy

(5 marks each)

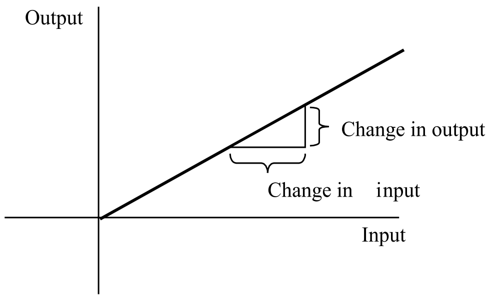
Ans:

(i) Hysteresis Hysteresis is a performance characteristic of a measuring instrument. When a measuring instrument has hysteresis, the relationship between input and output is as shown below:



When the input is increased, the output follows the curve DAB; and when the input is decreased, the output follows the curve BCD. In this way, the output of the system is different at the time of *loading* than at the time of *unloading*. Such behaviour is mainly due to the presence of friction in the mechanism of the instrument.

(ii) Sensitivity Sensitivity of an instrument is representative of *gain* or *amplification*. It is defined as the ratio of *change in output to change in input*. Thus, it can also be represented as the slope of an input-output curve, as shown below:

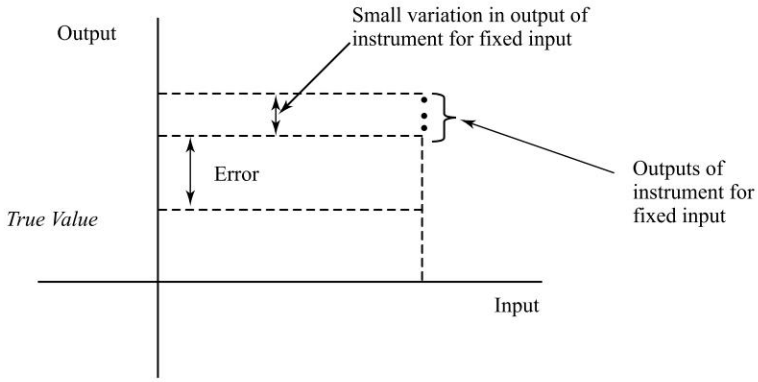


Sensitivity of an instrument

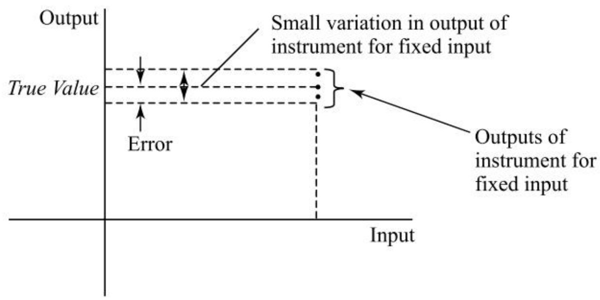
(iii) Response time Measuring instruments show *sluggishness* to different degrees. When an input is applied to an instrument, it takes some time to show the output. Such sluggishness is due to inertia and damping characteristics present in the components of the instrument. Inertia is mainly due to moving masses and also due to inductance in an electrical system. Damping is due to viscous damping or friction in the mechanical components or due to capacitors in the electrical system. Response time is usually the time elapsed from the instant of application of input to the instant when the output reaches about 98% per cent of its maximum value.

(iv) Precision and accuracy Precision is the measure of *repeatability* of an instrument. When the variation of output for a fixed input is small, the instrument is said to have high precision. Accuracy is a measure of closeness of the instrument's output with the actual value of the measured quantity.

Figure below shows a comparison between a precise and an accurate instrument:



Precise but inaccurate instrument



Precise and inaccurate instrument

OR

Q. 2. With the help of a simple diagram, explain various parts of a lathe machine and also enumerate various operations which can be performed on it.

Ans: Refer to Figure 2.33 and Section 2.4.1.1.

Q. 3. What is Newton's law of viscosity?

A plate requires 2 N force per unit area or 2 N/m^2 to move with a velocity of 60 cm/s over a fixed plate. The distance between the two plates is 0.03 mm. Determine the fluid viscosity between the plates.

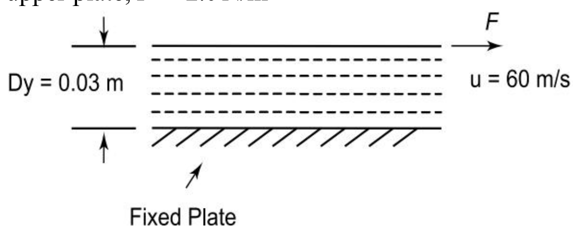
Ans: Newton's law of viscosity: Refer Section 3.2.

Given,

Distance between plates, $dy = 0.03 \text{ mm} = 0.03 \times 10^{-3} \text{ m}$

Velocity of upper plate, $u = 60 \text{ cm/s} = 0.6 \text{ m/s}$

Force on upper plate, $F = 2.0 \text{ N/m}^2$



This is the value of the shear stress i.e., τ
Let the fluid viscosity between the plates be μ.

We have $\tau = \mu\,(du/dy)$

where, du = change of velocity $= u - 0 = u = 0.60$ m/s

dy = change of distance $= 0.03 \times 10^{-3}$ m

τ = force per unit area $= 2.0$ N/m^2

Therefore, $$2.0 = \mu \frac{0.60}{0.03 \times 10^{-3}}$$

Thus, $$\mu = \frac{2.0 \times 0.03 \times 10^{-3}}{0.60} = 1 \times 10^{-4}\ \text{Ns/m}^2$$

$\mu = 1 \times 10^{-4} \times 10$ poise $= 1 \times 10^{-3}$ poise. **Ans.**

OR

Q. 3 Derive Bernoulli's equation from Euler's equation for an ideal flow.
The water is flowing through a pipe having diameters of 20 cm at the inlet section 1 and 10 cm at the outlet section 2. The rate of flow through the pipe is 35 lit/s. The section 1 is 6 m above the datum and the section 2 is 4 m above the datum. If pressure at the section 1 is 39.24 N/cm^2, find the intensity of pressure at the section 2.

Euler's equation of motion is given by

$$\int (\partial/c) + fgd_2 + fv\,dv = \text{constant}$$

If
1. the flow is incompressible, i.e, Q is constant
2. the flow is steady
3. the fluid is ideal
4. the flow is 1-D

Integrating the above equation we get,

$$(p/Q) + gz + (v^2/2) = \text{constant}$$

Or,

$$(p/Qg) + (v^2/2g) + z = \text{constant}$$

The above equation is Bernoulli's equation in which

(p/Qg) = pressure head

$(v^2/2g)$ = kinetic head

z = potential head

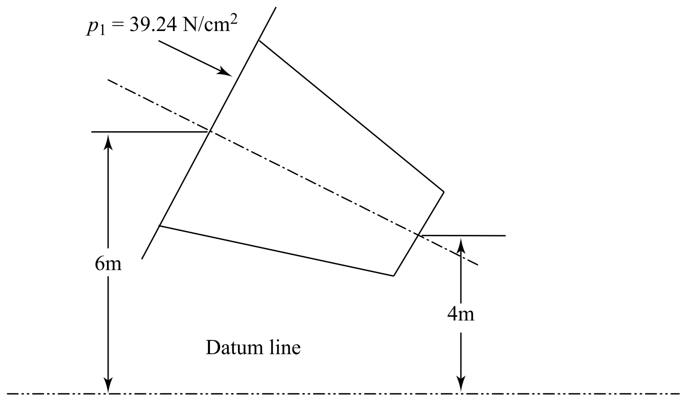
Given,

At the section 1, $D_1 = 20\ \text{cm} = 0.2$ m

$A_1 = (\Pi/4) \times (0.2)^2 = 0.0314$ m^2

$$p_1 = 39.24\ \text{N/cm}^2 = 39.24 \times 10^4\ \text{N/m}^2$$
$$z_1 = 6.0\ \text{m}$$

At the section 2,
$$D_2 = 0.10\ \text{m}$$
$$A_2 = (\Pi/4) \times (0.1)^2 = 0.00785\ \text{m}^2$$
$$z_2 = 4.0\ \text{m}$$
$$p_2 = ?$$



Rate of flow, $Q = 35\ \text{lit/s} = 0.035\ \text{m}^3/\text{s}$

As per the continuity equation, $Q = A_1V_1 = A_2V_2$

Therefore, $V_1 = Q/A_1 = 0.035/0.0314 = 1.114\ \text{m/s}$

and $V_2 = Q/A_2 = 0.035/0.00785 = 4.458\ \text{m/s}$

Applying Bernoulli's equation at sections 1 and 2, we get

$$(p_1/Qg) + (V_1^2/2g) + z_1 = (p_2/Qg) + (V_2^2/2g) + z_2$$

Substituting the values in the above equation,

$$\frac{39.24 \times 10^4}{1000 \times 9.81} + \frac{(1.114)^2\ + 6.0}{2 \times 9.81} = \frac{p^2}{1000 \times 9.81} + \frac{(4.458)^2\ + 4.0}{2 \times 9.81}$$

Therefore, $p_2 = 9810 \times 41.051\ \text{N/m}^2 = \dfrac{9810 \times 41.051}{10^4}\ \text{N/cm}^2 = 40.27\ \text{N/cm}^2$. **Ans.**

Q. 4. Explain the first law of thermodynamics with suitable examples.

In a gas turbine, the gas enters at the rate of 5 kg/s with a velocity of 50 m/s and an enthalpy of 900 kJ/kg and leaves the turbine with a velocity of 150 m/s and an enthalpy of 400 kJ/kg. The loss of heat from the gases to the surroundings is 25 kJ/kg. Assume for gas, R = 0.285 kJ/kg K and C_p = 1.004 kJ/kg K and the inlet conditions to be at 100 kPa and 27°C. Determine the power output of the turbine and the diameter of the inlet pipe.

Ans: First law of Thermodynamics : page 4.10, Section 4.4.1

Given, in a gas turbine,

At entry,

$$\text{Mass flow rate} = w_1 = 5 \text{ kg/s}$$
$$\text{Velocity} = V_1 = 50 \text{ m/s; Enthalpy} = h_1 = 900 \text{ kJ/kg}$$
$$\text{Pressure at inlet} = p_1 = 100 \text{ kPa} = 100 \times 103 \text{ N/m}^2$$
$$\text{Temperature} = T_1 = 27°\text{C} = 27 + 273 = 300 \text{ K}$$

At exit,

$$\text{Mass flow rate} = w_2 = 5 \text{ kg/s}$$
$$\text{Velocity} = V_2 = 150 \text{ m/s}$$
$$\text{Enthalpy} = h_2 = 400 \text{ kJ/kg}$$

Heat loss from the gases to the surrounding = $Q_1 = -25$ kJ/kg
Also for gas,

$$R = 0.285 \text{ kJ/kg K and } c_p = 1.004 \text{ kJ/kg K}$$

The power output of the turbine and the diameter of the inlet pipe =?
Applying SFEE,

$$w(h_1 + V_1^2/2 + Q_1) = w(h_2 + V_2^2/2) + W$$
$$5[(900 \times 1000) + (50)^2/2) - (25 \times 1000)] = 5[(400 \times 1000) + ((150)^2/2)] + W$$
$$\mathbf{W = 2325 \text{ kW}}$$

Now applying gas equation we get,
At inlet,

$$p_1 v_1 = \text{mRT}_1$$
$$100 \times 10^3 \times v_1 = 5 \times 0.285 \times 1000 \times 300$$

Therefore, $v_1 = 4.275 \text{ m}^3/\text{s}$

We know that ,

$$v_1 = A_1 V_1$$

Thus, $v_1 = (\Pi/4) \times (d_1)^2 \times V_1$

Therefore, $d_1 = 0.33$ m.

OR

Q. 4. Give two statements of the second law of thermodynamics.

Which is amore effective way to increase the efficiency of a Carnot engine?

To increase T_1 keeping T_2 constant

or

To decrease T_2 keeping T_1 constant

where, T_1 is the source temperature and T_2 is the sink temperature.

Answer:

Kelvin-Planck statement of second law of thermodynamics It is impossible for a heat engine to produce net work in a complete cycle if it exchanges heat only with the bodies at a single fixed temperature.

Clausius' statement of second law of thermodynamics It is impossible to construct a device which, operating in a cycle, will produce no other effect other than transferring heat from a cooler to a hotter body.

Solution to the second part is on pages 132 and 133, Example 6.4, of Engineering Thermodynamics by P K Nag (third edition).

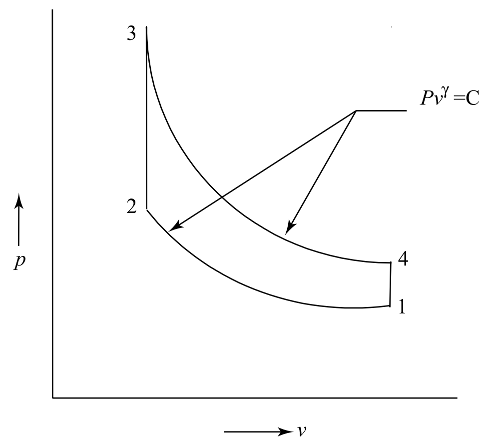
Q. 5. Show that the efficiency of the Otto cycle depends only on the compression ratio.

In an SI engine working on the ideal Otto cycle, the compression ratio is 5.5. The pressure and temperature at the beginning of compression are 1 bar and 27°C respectively. The peak pressure is 30 bars. Determine the pressure and temperature at the salient points, the air standard efficiency and the mean effective pressure. Assume ratio of specific heats to be 1.4 for air.

Ans: Efficiency of Otto cycle Refer Section 5.2.2.

$\eta = 1 - [1/r^{(\gamma-1)}]$

If the ratio of specific heat (cp/cv) of air as assumed constant then the efficiency of an air standard Otto cycle is only a function of compression ratio, and the efficiency increases as the compression ratio is increased. But because of the practical problems in an SI engine, the maximum compression ratio is limited to 12.



Given,

$$\text{compression ratio} = r = 5.5 = v_1/v_2$$

$$p_1 = 1 \text{ bar} = 1 \times 10^5 \text{ N/m}^2$$

$$T_1 = 27°\text{C} = 27 + 273 = 300 \text{ K}$$

$$p_3 = \text{peak pressure} = 30 \text{ bar} = 30 \times 10^5 \text{ N/m}^2$$

γ for air is 1.4

We know, $\eta \text{ cycle} = 1 - [1/r^{(\gamma-1)}] = 1 - [1/5.5^{(1.4-1)}] = 0.494$ or 49.4 %

Now, $(v_1/v_2) = 5.5$

We know that R, c_p and c_v for Air are 0.287 kJ/kgK, 1.005 kJ/kgK and 0.718 kJ/kgK respectively.

$$v_1 = \text{RT}_1/p_1 = \frac{0.287 \times 1000 \times 300}{10^5} = \mathbf{0.861\ m^3/kg} = \boldsymbol{v_4}$$

Therefore, $v^2 = 0.861/5.5 = 0.156\ \text{m}^3/\text{kg} = v^3$

Now, $T_2/T_1 = (v_1/v_2)^{(\gamma-1)} = (5.5)^{(\gamma-1)}$

$\boldsymbol{T_2} = 300 \times 1.98 = \mathbf{594\ K}$

Also, $p_2/p_1 = (v_1/v_2)^{(\gamma)} = (5.5)^{1.4}$

Therefore, $p_2 = 10.88 \times 1\ \text{bar} = \mathbf{10.88\ bar}$

Again, $p_3\ v_3/T_3 = p_2\ v_2/T_2$

Thus, $\boldsymbol{T_3} = \mathbf{1638\ K}$

We know that, $T_3/T_4 = (v_4/v_3)^{(\gamma-1)} = (v_1/v_2)^{(\gamma-1)}$ [since $v_1 = v_4$ and $v_2 = v_3$]

Therefore, $T_4 = 828\ \text{K}$

Now, heat supplied can be calculated by the relation

$$Q_1 = cv\,(T_3 - T_2)\ \text{kJ/kg} = 0.718\,(1638 - 594) = 750\ \text{kJ/kg}$$

Therefore, $\text{W}_{\text{net}} = Q_1 \times \eta\,\text{cycle} = 370.5\ \text{kJ/kg}$

Mean effective pressure can be calculated as

$$p_m = W_{\text{net}}/(v_1 - v_2) = \frac{370.5}{(0.861 - 0.156)} = 525.5\ \text{kN/m}^2 = 5.25\ \text{bar}$$

OR

Q. 5 What is the basic difference between an Otto cycle and a Diesel cycle?
Derive the expression for the efficiency and mean effective pressure of a Diesel cycle.

Ans: Difference between an Otto cycle and Diesel cycle:

	Otto cycle	*Diesel Cycle*
1	Heat is added at constant volume.	Heat is added at constant pressure.
2	The efficiency is high for the same compression ratio and same heat input.	The efficiency is low for the same compression ratio and heat input.
3	Petrol engine works on Otto cycle.	Diesel engine works on Diesel cycle.
4	The maximum compression ratio is limited to 12, due to detonation in SI engines.	The compression ratio is as high as 24 as Only air is inducted in a Diesel engine.

Expression for the efficiency of efficiency of Diesel cycle Refer Section 5.2.3.

B.E. (First Semester) EXAMINATION, Dec., 2010
(Common to all Branches)
BASIC MECHANICAL ENGINEERING

Q. 1. (a) Discuss the effect of carbon, silicon, phosphorus on the behaviour of cast iron.

(b) Draw stress-strain diagram for mild steel, clearly showing various points.

Ans. (a) Refer Page 1.8, Section 1.5.2 (Effect of Alloying Elements in Cast Iron).

(b) Refer Page 1.16, Section 1.8.3 (Stress-Strain Diagram)

Q. 2. (a) What are the functions, properties and uses of high speed steel? State its various types.

(b) Draw a neat sketch of Iron-carbon equilibrium diagram and explain various reactions involved.

Ans. (a) Refer Page 1.9, Section 1.6.1 (Types of Carbon Steels, Their Mechanical Properties and Application)

(b) Refer Page 1.4, Section 1.4.1 (Iron-Carbon Diagram)

Q. 3. (a) Draw a simple diagram of lathe machine and discuss any *five* operations, that can be performed on it.

(b) Discuss the measurement by vernier calliper with neat sketch.

Ans. (a) Refer Page 2.26, Section 2.4.1 (The Lathe Machine)

(b) Refer Page 2.21, Section 2.3.1 (Vernier Calipers)

Q. 4. (a) Draw a neat sketch of radial drilling machine, discuss its various operations.

(b) Define the following measurement terms :

(i) Accuracy

(ii) Sensitivity

(iii) Precision

(iv) Hysteresis

(v) Error

Ans. (a) Refer Page 2.30, Section 2.4.2 (The Drilling Machine)

(b) Refer Page 2.18, Section 2.2.2 (Some Basic Concepts and Definitions Related to Measurement)

Q. 5. (a) State and prove Bernoulli's equation for incompressible fluids. State its assumptions.

(b) Draw a neat sketch of hydraulic power plant. State the function of any five important components.

Ans. (a) Refer Page 3.16, Section 3.9 (Bernoulli's Equation)

(b) Refer Page 3.36, Section 3.15.3 (Essential Elements of Hydro-Electric Power Plant)

Q. 6. (a) Discuss the working of fluid coupling and state its applications.

(b) Describe the construction and working of Pelton turbine.

Ans. (a) Refer Page 3.23, Section 3.11 (Fluid Coupling)

(b) Refer Page 3.31, Section 3.14.2 (Pelton Turbine)

Q. 7. (a) Draw a neat sketch of a Cochran boiler. State the function of any five important parts.

(b) Using steam tables, determine the mean specific heat for superheated steam at 1 bar between temperatures of 150°C and 200°C.

Ans. (a) Refer Page 4.45, Section 4.8.7 (Cochran Boiler)

(b) From properties of superheated steam tables: At pressure 1 bar

$T_s = 99.62°C$; $h_g = 2675.5$ kJ/kg

150°C : $h_{sup} = h_{150} = 2776.4$kJ/kg

200°C : $h_{sup} = h_{200} = 2875.3$ kJ/kg

Where, h_{150} and h_{200} are the specific enthalpy of superheated steam at temperatures 150 and 200 °C respectively.

If C_m is the mean specific heat

$h_{sup} = h_g + C_m (T_{sup} - T_{sat})$

$h_{150} = h_g + C_m (150 - T_{sat})$ ----- (1)

$h_{200} = h_g + C_m (200 - T_{sat})$ ------ (2)

From 1 and 2

$C_m = (h_{200} - h_{150})/ (\Delta T)$ [ΔT = 200-150]

C_m =1.978 kJ/kg K **Ans**

Q. 8. (a) Calculate the equivalent evaporation of boiler per kg of coal fired, if the boiler produces 50000 kg of wet steam per hour with a dryness fraction of 0.95 and operating at 10 bar. The coal burnt per hour in furnace is 5500 kg and feed wafer temperature is 40°C.

(b) Define Refrigeration. Draw a layout of vapor absorption refrigeration system. State the function of each component.

Ans. (a) Mass of steam produced M_s = 50,000 kg/hr;

Mass of coal used M_f= 55,00 kg/hr;

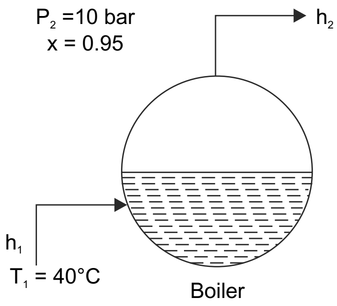
Mass of steam produced per kg of coal fired = $m_s = M_s / M_f$

= 50,000/5500 = 9.09 kg/kg of coal fired;

Feed water temperature T_1= 40°C

$h_1 = C_w \times 40 = 4.187 \times 40 = 167.48$ kJ/kg; (C_w is the specific heat of water)

Dryness fraction of steam x = 0.95



From steam tables the properties of steam at pressure of 10 bar.

$t_s = 179.9°C$; $h_f = 762.8$ kJ/kg ; $h_{fg} = 2015.3$ kJ/kg;

as the steam is wet the enthalpy of steam leaving the boiler

$h = h_f + x\, h_{fg}$

Hence $h_2 = 762.8 + 0.95 \times 2015.3 = 2677.3$ kJ/kg;

Heat energy supplied by boiler per kg of steam produced

$= h_2 - h_1 = 2677.3 - 167.48 = 2509.8$ kJ/kg

Equivalent evaporation per kg of coal fired = $m_s \times (h_2 - h_1)/\ 2257$

$= 9.09 \times 2509.8/2257 =$ **10.11 kg/kg of coal fired. Ans.**

(b) Refer Page 4.56 & 4.60, Section 4.9.1 (Refrigeration by Non-Cyclic Process) and 4.9.4 (Absorption Refrigeration Cycle)

Q. 9. (a) Explain the working of two stroke petrol engine.

(b) Draw a neat sketch of steam engine. State the function of any five important components.

Ans. (a) Refer Page 5.21, Section 5.3.7 (Two-Stroke Petrol Engine and its Working)

(b) Refer Page 5.1 and Page 5.4, Section 5.1.1 (Construction of Stream Engine) and 5.1.3 (Working of Steam Engine)

Q. 10. (a) Explain the working of four stroke petrol engine.

(b) Differentiate between an Otto cycle and a Diesel cycle.

Ans. (a) Refer Page 5.25, Section 5.3.9 (Four-Stroke Petrol Engine and its Working)

(b) Refer Page 5.12, Section 5.2.4 (Comparison Between Otto and Diesel Cycles)