Title of course-	: Thermal Engineering		
Subject Code-	: PCME203		
Weekly Load	:4	LTP-3-1-0	
Credit	: 4		

COURSE OUTCOMES:

After successful completion of course, the students should be able to

CO1: To understand Different Gas law, Thermal properties of gaseous and different system. **CO2:** To learn about Thermodynamics equilibrium, zeroth and other thermodynamics law and different thermal process.

CO3: To understand basics concept of Steam formation and study of boilers.

CO4: To study Engine cycles, SI and CI Engine and their performance.

CO's	PO1	PO2	PO3	PO4	PO5	PO6	PO7	PSO1	PSO2
CO1	3	1	2	2	3	1	2	3	1
CO2	3	2	2	2	3	1	1	2	1
CO3	2	2	2	1	3	1	2	2	1
CO4	3	2	2	2	3	1	1	3	2
Avg.	2.75	1.5	2	1.75	3	1	1.5	2.5	1.25

	Lecture(s
Unit-I	
Introduction:	
Boyle"s Law, Charle"s Law, characteristics gas equation, universal gas constant Properties; intrinsic and extrinsic, system; open, closed and isolated.	
Laws of thermodynamics:	
Thermodynamic equilibrium, Zero th law of thermodynamics, first law of thermodynamics, concepts of enthalpy, internal energy, specific heat, work and heat, concept of entropy, caluses and Kelvin plank statement of second law of thermodynamics, Equivalence of Kelvin plank and clausius statements. Throttling and free expansion, non-flow work done under isothermal, polytropic, adiabatic, isobaric, isochoric processes, simple problems steady flow energy and its applications	07
Formation of Steam	
Steam formation, wet steam, dry steam and saturated steam, dryness fraction, superheated steam; degree of superheat, latent heat of vaporization, Enthalpy of steam, entropy; entropy increase during evaporation, temperature entropy diagram mollier diagram (H-S diagram)	08
Steam Boilers	
Steam generator, Classifications, comparison of fire tube and water tube boilers, construction and features of Lancashire boiler, locomotive and Babcock and Wilcox Boilers, Introduction to modern boilers. Rankine cycle.	08
Unit-II	(S)
Engine Cycles	
Carnot cycle, Otto Cycle, diesel and dual cycle, derivation of efficiency and comparison of these cycles.	
I.C Engine	
Types, classification, CI and SI engines, Mechanical constructional details of two stroke petrol engine and diesel engine, four stroke petrol and diesel engines, valve timing diagrams.	06
Performance of IC engines	
Brake, indicated, frictional powers, brake mean effective pressure, indicated map, engine	07
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efficiencies, air standard, brake, indicated, mechanical, volumetric ,scavenging, efficiency, characteristics of power, fuel consumption with engine speed, calculation of powers, efficiency and SFC for two and four stroke engine. LCV, HCV

Total: 48

Recommended Books:

- 1. Thermal Engineering RK Rajput Laxmi publication.
- 2. Heat and thermodynamics PL Ballany Khanna Publisher
- 3. Thermal Scienec Domkundwar S.Chand Publisher
- 4. Heat Engineering Kumar and Vasandani S.Chand Publisher.
- 5. I.C Engine Ganesan McGraw Hill

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(a)

Unit-I Introduction

Boyle's Law

 \rightarrow It states that, the specific volume is inversely proportional to absolute pressure for a gas undergoing a constant temperature process, i.e.

$$v = \frac{1}{p}$$

or $pv = C$

where C is the constant of proportionality.

 \rightarrow For an ideal gas undergoing a constant temperature process from state 1 to state 2;

$$p_1v_1 = p_2v_2$$

- → Boyle's law represents a rectangular hyperbola curve on the p-v diagram. It is also referred to as an *isotherm*.
- \rightarrow The process occurring at constant temperature is known as an *isothermal process*.

Charle's Law

→ It states that, the change in specific volume is directly proportional to the change in absolute temperature of gas undergoing a constant pressure process, i.e.

 \rightarrow Where, C is the constant of proportionality at constant pressure.

 \rightarrow For an ideal gas undergoing a constant pressure process from state 1 to state 2;

$$\frac{v_1}{T_1} = \frac{v_2}{T_2}$$

Charle's law also states that the absolute pressure varies directly with absolute temperature for an ideal gas undergoing a constant volume process, i.e

$$p \ \mathsf{a} \ T$$

 $\frac{p}{T} = C$

Similarly, for an ideal gas undergoing a constant volume process,

$$\frac{p_1}{T_1} = \frac{p_2}{T_2}$$

Avogadro's Law

- → Avogadro's law states that, the molecular mass of all perfect gases occupies the same volume at NTP (i.e. 1 atm, 0°C).
- \rightarrow The average volume for 1 kg mol of any perfect gas at N.T.P is 22.413 m³.
- \rightarrow For a certain gas of mass *m* in kg and molecular weight μ , the number of 'kg mol' of the gas *n*, is given by,

$$m = \frac{m}{\mu} \text{kg mol}$$

 \rightarrow The molar volume, $\overline{v_{i}}$ is given by,

$$v = \frac{1}{n} \frac{m^3}{kgmol}$$

 \rightarrow Where, V is the total volume of the gas in m³.

Equation of State

 \rightarrow It is the functional relationship among the thermodynamic properties such as, pressure p, molar or specific volume v, and absolute temperature T.

 \rightarrow It is expressed in the form,

$$f(p, v, T) = 0 \qquad \qquad v a$$

 \rightarrow If any of the two properties are specified, the third property can be determined by a functional relation, i.e.

$$p = f(v, T)$$

 $v = g(p, T)$

T = h(p, v)

→ As for any thermodynamic system the properties vary simultaneously, the equation obtained by combining Boyle's and Charle's law is given by,

$$v =$$

→ Where, R is the *characteristic gas constant* or *specific gas constant*.

→ Hence the above relation is called the *characteristic gas equation* for an ideal gas or *ideal gas equation of state*.

Ideal Gas

Universal Gas Constant

→ From Avogadro's law, when p = 760 mmHg = 1.013 × 10⁵ N/m², T = 273.15 K, and v =

22.4 $m^3/kgmol$

$$R = \frac{1.013 \times 10^5 \times 22.4}{273.15}$$

= 8314.3 Nm/kgmolK
= 8.3143 kJ/kgmolK

 \rightarrow Also,

$$R = -\frac{\mu}{\mu}$$
$$R = -\mu$$

or

Characteristic Gas Constant

It is given by $R = \stackrel{R}{=}$, where μ is the molecular weight. μ $= \stackrel{8.3143}{=} 0.262 \text{ kJ/kgK}$ For oxygen, $RO_2 = \frac{32}{32}$ $= \stackrel{8.3143}{=} 0.287 \text{ kJ/kgK}$ For air, $\frac{28.96}{Rair}$

THERMODYNAMIC CONCEPT AND TERMINOLOGY

Thermodynamics

Thermodynamics is defined as the branch of science which deals with concept of heat, work and their interconversion.

<u>Origin</u>

Thermodynamics is the result of man's constant effort to convert heat into work. Developed in the nineteenth century due to joule, Clausius, Kelvin, and Carnot.

The name thermodynamics comes from the Greek words *therme* (heat) and *dynamics* (power) which is most descriptive of the early efforts to convert heat into power.

The term thermodynamics was first used in a publication by Lord Kelvin in 1849. The first textbook in thermodynamics was written in 1859 by William Rankine, a professor at the University of Glasgow.

What is Thermodynamics?

- Thermodynamics is a science dealing with energy and its transformation.
- It deals with equilibrium and feasibility of a process.
- Deals with relation between heat and work and the

properties of a system. The principle of thermodynamics are

summarized in four laws, they are

- 1. Zeroth law of thermodynamics deals with thermal equilibrium and provides a means of measuring temperature.
- 2. The first law of thermodynamics tells about the conservation of energy and introduces the concept of internal energy.
- 3. The second law of thermodynamics shows the limit of converting internal energy into work and introduces the concept of entropy.
- 4. The third law of thermodynamics provides a datum for the measurement of entropy.

The laws of thermodynamics cannot be directly proved. They were deduced from experimental results through logical reasoning. The validity of the laws of thermodynamics rests upon the fact that till date no experimental evidence is available to disprove them.

Application area of thermodynamics

All activities in nature involve some interaction between energy and matter; thus, it is hard to imagine an area that does not relate to thermodynamics in some manner.

<u>Thermo</u>

<u>dynamic</u>

<u>s system</u>

<u>System</u>

It is defined as a definite quantity of matter or region in space considered for thermodynamic study. A system may be very simple like a gas contained in a cylinder or it may be complex like a thermal power plant. The choice of a system may differ from person performing the analysis.

Surrounding

The mass or region outside the system is called surrounding. A system can exchange energy in the form of work and heat with its surrounding.

Boundary

The real and imaginary surface that separates the system from its surrounding is called the boundary.



Closed System-

The closed system also known as **Control Mass** is one, in which the boundaries are closed so that no substance may enter or leave the system. In such a system, the mass of the substance within the system remain constant. A transfer of energy in the form of heat and work may take place at the boundaries and the volume of a closed system does not have to be fixed. Ex Sun

Open system-

The open system or a **Control Volume** is one where the boundaries are not closed so that both mass and energy can cross the boundary of an open system. It usually encloses a device that involves mass flow such as a compressor, turbine and nozzle.

Isolated System- It is the system, in which no mass and energy

interaction takes place. Ex- universe, ice box, thermo flask.

Adiabatic System

A thermodynamic system in which mass can cross the boundary, but energy in the form of heat can't cross the boundary is called as adiabatic system.

Ex throttle valves, water pumps, water turbines heat exchanger.

Homogeneous System

A thermodynamic system consists of single phase is called as homogeneous system.

Heterogeneous System

A thermodynamic system consists of two or more than two phases is called as heterogeneous system.

Macroscopic Approach-

In this approach a certain quantity or matter is considered without considering the events occurring at molecular level. In this approach simple mathematical formulae are required for analyzing the system. A few properties are needed to describe the system.

Microscopic Approach

In this approach a certain quantity of matter is considered with taking into account the events occurring at molecular level. In this approach advanced statistical and mathematical methods are used for analyzing the system. Large number of variables required to describe the system.

Concept of Continuum

It is the concept which explains about the continuity and homogeneity of matter in a thermodynamic system. In a continuous system the matter is present without any void in it, and it is homogeneous throughout the system. This concept is not applicable when the negligible number of molecules present in matter.

Thermodynamic Properties

The characteristic of a system is called as thermodynamic property. The properties like pressure, temperature, volume, enthalpy and entropy describes the state of thermodynamic system.

Types of properties

Intensive Properties-

The properties those are independent of the mass of a system are known as intensive properties such as temperature, pressure and density.

Extensive properties-

The properties whose value depend upon the mass of a system are called as extensive properties. Such as mass, volume and momentum.

State

A thermodynamic state is the condition of a system which is characterized by thermodynamic properties.

represents path where the state changes from 1 to 2

Path is the locus of series of states through which a thermodynamic process occurs.



Processes

The transformation of thermodynamic system from one thermodynamic state to another is called a process.

Non Flow Process

A process undergone by a fluid in a closed system is referred as a non- flow process.

Flow Process

A process undergone by a fluid in an open system is referred as flow process.

Quasi-static Process

When a process proceeds in such a manner that the system remains almost infinitesimally close to equilibrium such a process is called a quasi-static Process.

Reversible Process

A reversible process is that, which can be take place between two states once and again act in reverse manner to reach the initial state of the system without changing the effect on the surrounding. It passes through a series of equilibrium states. Exfrictionless relative motion, expansion and compression of spring.

Irreversible process

An irreversible process is that which can't be reversed in the same path & also unidirectional. It passes through a series of non equilibrium states. Ex expansion, free expansion.

Adiabatic process

A process is called adiabatic process if there is no heat exchange between the system and surrounding. That is heat transfer (Q) = 0.

Isothermal Process

A Process is called isothermal process if there is no temperature change during the process. t= constant

Isobaric Process

A process is called isobaric process if there are no pressure changes during the process. P = constant

Isochoric process

A process is called process if there are no volume changes during the process. V = constantIsentropic Process A process is called an isentropic process if there is no entropy changes during the process. i.e s = constant

Isenthalpic process

A process is called isenthalpic process if there is no enthalpy change during the process. i.e h= constant

Macroscopic Approach-

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Microscopic Approach

In this approach a certain quantity of matter is considered with taking into account the events occurring at molecular level. In this approach advanced statistical and mathematical methods are used for analyzing the system. Large number of variables required to describe the system.

Cycle

A cycle or cyclic process is that, in which the initial and final states of a system are identical. The cycle follows a series of process in such a way that the sequence of process begins and ends at same state.

Point Function

There are certain properties which depend on states but don't depend on the these properties are called as point or state functions.

Ex Pressure, temperature, volume etc.

Path function

There are certain properties which depend upon the path between two ends state but don't depend upon the state only. These properties are called as path function.

Thermodynamic equilibrium

Thermodynamics deals with equilibrium states. The word equilibrium implies a state of balance. That is in equilibrium state there is no unbalanced force present in a system,

and the system experience no change.

There are different types of equilibrium

Thermal equilibrium

When a body is brought into contact with another body that is at a different temperature heat is transferred from a body at higher temperature to lower temperature until both bodies attain same temperature. At that point the heat transfer stops, and the two bodies are said to have reached thermal equilibrium. The equality of temperature is the only requirement for thermal equilibrium.

Mechanical equilibrium

A system is said to be in mechanical equilibrium in the absence of any unbalance force. The force is directly related to pressure. Thus if there is no pressure difference throughout the system then the system is said to be in mechanical equilibrium.

Chemical equilibrium

A system is said to be in chemical equilibrium if its chemical composition does not change with time, that is no chemical reaction occur within a system

<u>Phase equilibrium</u>

If a system involves with two phases and the mass of each phase reaches an equilibrium phases and stays there it is said to be in phase equilibrium.

A system is not in thermodynamic equilibrium unless the condition of all the types of equilibrium is satisfied.

Pressure

It is defined as the normal force exerted by a fluid per unit area. We speak about pressure only when we deal with a gas or liquid. The counterpart of pressure in solids is normal stress. **Unit** It has the unit of N/m^2 which is called a **Pascal** 1 Pa = $1N/m^2$

Three other pressure units commonly used in practice are bar, standard atmosphere and kilogram-force per square centimeter.

1 bar = 10⁵ Pa = 0.1MPa = 100kPa 1 atm= 101.325kPa,

1.01325bars 1kgf/cm² = 9.807 N/cm² = 9.807 * 10^4 N/m² =

 $9.807 * 10^4 Pa = 0.9807 bar 1 torr = 1 mm of hg column =$

133.33 pa

Absolute Pressure

It is the actual pressure measured in a system.

Gauge Pressure It is the Positive pressure measured by the pressure gauge, when pressure is above 1 atmospheric pressure.

Vacuum Pressure It is the negative pressure measured by the pressure gauge when pressure is 1 atmospheric pressure.

<u>**Relation**</u> $P_{abs} = P_{atm+} P_{gauge} P_{abs} = P_{atm} - V_{acuum}$

Conceptual Explanation of energy and its Sources

Definition of Energy - The capacity for doing work. It may exist in potential, kinetic, thermal, electrical, chemical, nuclear, or other various forms. There are, moreover, heat and work—i.e.

energy in the process of transfer from one body to another. After it has been transferred, energy is always designated according to its nature.

Definition of Work and heat

<u>Work</u>- in physics, measure of energy transfer that occurs when an object is moved over a distance by an external force at least part of which is applied in the direction of the displacement.

Mathematically, the above statement is expressed as follows:

W = F. d

Unit of Work

The SI unit of work is the **joule (J)**, which is defined as the work done by a force of 1 Newton in moving an object through a distance of 1 meter in the direction of the force.

Heat, energy is transferred from one body to another as the result of a difference in temperature. If two bodies at different temperatures are brought together, energy is transferred—i.e., heat flows—from the hotter body to the colder.

<u>Unit of Heat</u>

Units of Heat		
Calorie	1 cal	4184 J
Joules	1 J	0.000239006 kcal / 0.000947817Btu
BTU	1 Btu	1055.06 J

Units of Heat

	Work (W)	Heat (Q)
Interaction	Mechanical	Thermal
Requires	Force and Displacement	Temperature difference
Process	Macroscopic pushes and pulls	Microscopic collisions
Positive value	W > 0 when a gas is compressed. Energy is transferred into system.	Q > 0 when the environment is at a higher temperature than the system. Energy is transferred into system.
Negative value	W < 0 when a gas expands. Energy is transferred out of system.	Q < 0 when the system is at a higher temperature than the environment. Energy is transferred out of system.
Equilibrium	A system is in mechanical equilibrium when there is no net force or torque on it.	A system is in thermal equilibrium when it is at the same temperature as the environment.

Work transfer and Displacement work (PdV) work

- Let us consider the following arrangement of cylinder and piston. Cylinder contained with gas and displayed here the two equilibrium state of the system by state 1 and state 2. At state 1, gas will be at high pressure and will have lower volume and state of the system is displayed here by the co-ordinate P1V1.
- Let piston moves to its final position which is displayed here as state 2. Gas will be at lower pressure and will have higher volume as compared to state 1. Condition of the system at state 2 is displayed here by the co-ordinate P2V2.
- Let us consider one intermediate point with pressure p and volume v during travelling of piston from state 1 to state 2. We must note it here that this intermediate point must also be equilibrium state as thermodynamic properties such as pressure p and volume v are only significant for equilibrium states.
- Let area of the piston is A and piston moves by infinitesimal distance ds due to the pressure force of the gas acting over the piston.

- What will be the pressure force acting over the piston? Pressure force exerted by gas over the piston will be calculated as F= P. A
- Let us concentrate the infinitesimal amount of work carried out by gas over the piston in order to move the piston by infinitesimal distance i.e. dl and it will be calculated as mentioned here

Because (A. dS) will the infinitesimal displacement volume i.e. dV So the Displacement work done in a closed system is $W = P^*dV$

LAWS OF THERMODYNAMICS

ZEROTH LAW OF THERMODYNAMICS

Zeroth law of thermodynamics tells us the concept of temperature. This law states that if two bodies are each in thermal equilibrium with a third one, then they are in thermal equilibrium with each other.

When a body $_A'$ is in thermal equilibrium with another body $_b'$, and also separately in thermal equilibrium with a body $_C'$, then body $_B'$ and $_C'$ will also be in thermal equilibrium with each other. This statement defines the Zeroth law of thermodynamics. The law is based on temperature measurement.



Zeroth Law of Thermodynamics

First Law of Thermodynamics

The first law of thermodynamics states that the quantity of the heat absorbed, when some amount of heat is given to a system that is capable of doing external work, is equal to the sum of the increase in internal energy of the system due to a rise in temperature and external work done during expansion.

The first law of thermodynamics is generally represented by the equation-

U=Q-W

Where U=change in internal energy of the

thermodynamic system Q=heat given to the system

W=work done on the system

Differential form of the first law of thermodynamics equation-

dU - dQ = dW

The first law of Thermodynamics is also called _Law of Conservation of Energy'. The law of conservation of energy states that —Energy can neither be destroyed nor be created; it can only be transferred from one form to anotherll

Significance of First Law of Thermodynamics

Significances that the first law of thermodynamics has are as follows-

- The relation between heat and work is established by the first law of thermodynamics.
- Both Work and Heat are equivalent to each other.
- The exact equivalent amount of energy of the surrounding will be lost or gained, if any system gains or losses energy.
- Applied heat is always equal to the sum of work done and change in internal energy.

Applications of First Law of Thermodynamics

- The first law of thermodynamics is commonly used in heat engines.
- Refrigerators are another example where the first law of thermodynamics is used.
- Sweating is a great example of the first law of thermodynamics since the heat of the body is transferred to sweat.
- When an ice cube is put in a drink, the ice cubes absorb the heat of the drink which makes it cool.

Limitations of First Law of Thermodynamics

- 1. The first law of thermodynamics does not state anything about the heat flow direction.
- 2. The process is not reversible.

STEADY FLOW ENERGY EQUATION

A flow is said to be steady flow if the properties like pressure, volume and temperature don't vary with respect to time.

Such type of flow can be observed when a mass entering and leaving in a system is same



Consider an open system in which the working fluid flow at a steady rate

- The working substance enters the system at section 1-1 and leaves the system at section 2-2
- Let M= mass flow rate of the working fluid in (kg/sec)
- P_1 and P_2 are the absolute pressure of the working substance in (N/m²)
- C₁ and C₂ are the velocity of the working substance (m/sec)
- Z_1 and Z_2 are elevation above the datum line at entrance and exit respectively.
- U_1 and U_2 are the internal energy of the working substance (J/kg)
- Q_{cv} Amount of heat added to the system (J)

W- Work done by the system (J)

Energy out=
$$\frac{1}{2}mc^2 + mgz + u + W$$

$$W = -P_1V_1 + W_{CV} + P_2V_2$$

Where

 $-P_1V_1$ is the flow work done by the surrounding.

 W_{CV} - Work done by the control volume

 P_2V_2 - flow work done by the system.

Since we know that energy is conserved, so inlet energy = outlet energy

$$= \frac{1}{2} mc_{1}^{2} + mgz_{1} + u + Q = \frac{1}{2} mc_{2}^{2} + mgz_{1} + u + W$$

$$= \frac{1}{2} mc_{1}^{2} + mgz_{1} + u + Q = \frac{1}{2} mc_{2}^{2} + mgz_{1}^{2} + u - p v + W = \frac{1}{2} v + \frac$$

$$=H+\frac{1}{2} \frac{mc}{2} + \frac{mgz}{1} + \frac{Q}{1} = H+\frac{1}{2} \frac{mc}{2} + \frac{mgz}{2} + W$$

Dividing by m on both the sides

$$\underbrace{h}_{1} + \frac{1}{2} \underbrace{c^{2}}_{1} + \underbrace{gz}_{1} + \underbrace{Q_{cv}}_{m} = h_{2} + \frac{1}{2} \underbrace{c^{2}}_{2} + \underbrace{gz}_{2} + \underbrace{W_{cv}}_{m}$$
(a)

Steady flow energy equation for nozzle

<u>Nozzle</u> it is a device used to increase the velocity of fluid.

According to SFEE

$$(COP)_{R} = \frac{Q_{L}}{W_{in}}$$
$$W_{in} = Q_{H} - Q_{L}$$
$$(COP)_{R} = \frac{Q_{L}}{Q_{-H}Q_{-L}}$$



Here heat transfer $Q_{ck}=0$ (As perfectly insulated)

Work done W=0

Potential energy $E_p=0$ (Z₁=Z₂=Z)

So the equation becomes

$$h_{1} + \frac{v_{1}^{2}}{2} = h_{2} + \frac{v_{2}^{2}}{2}$$
Then $h_{1} = h_{2} + \frac{v_{2}^{2}}{2}$

$$V_{2} = \sqrt{2(h_{1} - h_{2})}$$
(1)

Second Law of Thermodynamics

Kelvin Planck Statement

It states that "It is impossible to construct a device which operates on a cycle and produces no other effect than the transfer of heat from a single body in order to produce work." This means that it is impossible to construct an engine whose sole purpose is to convert the heat from a high-temperature source/reservoir into an equal amount of work.



Clausius Statement

It is impossible to design a device which works on a cycle and produce no other effect other than heat transfer from a cold body to a hot body.

APPLICATION OF SECOND LAW OF THERMODYNAMICS

HEAT ENGINE

A heat engine is a device which operates on a cycle.

It receives heat energy from a high temperature reservoir convert some of heat energy into work and reject the remaining heat to a low temperature reservoir.

A steam power plant best fits into the definition of heat engine

It receives heat from the high temperature reservoir

(Source) at T_H It converts part of heat supplied into

useful work as Wnet

It rejects the remaining heat QL to a low temperature reservoir

(sink) at TL The net work output of a heat engine

Wnet=Wout-Win or Wnet=QH-QL

Thermal Efficiency

It is defined as the ratio of desired output to the energy input

Thermal efficiency (η_{ob}) = net work output/energy input

$$n = \frac{W_{nel}}{Q_H}$$

Or
$$\eta_{th} = \frac{Q_H - Q_L}{Q_H} = 1 - \frac{Q_L}{Q_H}$$
 (@)

HEAT PUMP

A heat pump is a device, operating in a cycle that maintains a space at a higher temperature than the surrounding.

The heat pump supply heat continuously to the controlled space and thus maintained at higher temperature than surrounding



The refrigerator and heat pump are operated on same thermodynamic cycle but they differ in their objective

The heat pump absorbs heat from low temperature surrounding and supplied it to a higher temperature space at the cost of work input to the compressor.

Let an amount of heat Q_L be absorbed from a low temperature region and W_{in} be the work input. Then the heat supply Q_H to the room is the desired effect for a heat pump

The Co-efficient of performance of a heat pump is expressed as

$$(COP)_{HP} = \frac{\text{Heat Supplied}}{\text{Work input}}$$

$$(COP)_{HP} = \frac{Q_H}{W_{in}}, Q = Q + W_{in}$$

$$(COP)_{HP} = \frac{Q_L + W_{in}}{W_{in}}$$

$$(COP)_{HP} = 1 + \frac{\varphi_L}{W_{in}} = 1 + (COP)_{R} - ----(a)$$

REFRIGERATOR

A refrigerator is a device operating in a cycle that maintains a body at lower temperature than its surroundings

A refrigerator extract heat continuously from a controlled space thus it maintained at lower temperature than surroundings.

The most frequently refrigeration cycle is the vapor

compression cycle. Co efficient of performance (cop)

The performance of a refrigerator is measured in term of co-efficient of

performance. It is defined as the ratio of refrigerating effect to the energy

input.

Consider an amount of heat Q_L is removed from refrigerated space at temperature $\underline{T}_{L,L}$. The work input is \underline{W}_{in} and heat rejected to consider is Q_H .

 $(COP)_{R} = \frac{\text{Refrigerating Effect}}{\text{Work input}} \frac{Q_{L}}{W_{ln}}$

 $W_{in} = Q_H - Q_L$



Heat capacity -

As the body absorbs heat the temperature of the body rises, but when heat is withdrawn from the body it cools down, so the body heat decreases. The temperature of any body is the measure of its <u>molecules' kinetic</u> energy. Heat capacity is the ratio of heat absorbed by a material to the temperature change. Therefore, the temperature change in a body is directly proportional to the heat transferred to the given body.

HEAT CAPACITY C, Cp, and Cv

Definition of molar heat capacity, C:

The total amount of energy in form of heat needed to increase the temperature of 1 mole of any substance by 1 unit is called molar heat capacity (C) of that substance.

It also depends greatly on the nature, size and composition of a substance in a system.

 $q = n C \Delta T$

This Formula Represents:

- q is the heat supplied or needed to bring about a change in temperature (ΔT) in 1 mole of any given substance
- n is the amount in moles
- The constant C is known as the molar heat capacity of the body of the given substance.

Specific heat at constant pressure (CP)

The amount of heat energy released or absorbed by a unit mass of the substance with the change in temperature at a constant pressure. In another words, under a constant pressure it is the heat energy transfer between a system and its surrounding.

Specific heat at constant volume (CF)

It is the amount of heat energy absorbed/released per unit mass of a substance where volume does not change. In other words, <u>Cv</u> is the heat energy transfer between a system and its surrounding without any change in the volume of that system.

Relationship Between Cp and Cv

According to the first law of thermodynamics: $\Delta Q = \Delta U + \Delta W$ where, ΔQ is the amount of heat that is given to the system, ΔU is the change in internal energy ΔW is the work done. Putting the value of P ΔV in equation (1) $nc_{R} \Delta T = nc_{X} \Delta T + nR\Delta T$

$$\underline{nc_p}\,\Delta T = \underline{n\Delta T}\,(C_V + R)$$

We can write

 $\Delta Q = \Delta U + P\Delta V, \text{ as } \Delta W = P\Delta VSince \quad \Delta Q = nc_P \Delta T \text{ and } \Delta U = nc_V \Delta T$ Therefore $nc_P \Delta T = nc_V \Delta T + P\Delta V1$) We know that PV = nRTAt T_1 Kelvin: $PV_1 = nRT_1$ ------(a) At T_2 Kelvin: $PV_2 = nRT_2$ ------(b) Subtracting (a) from (b): $PV_2 - PV_1 = nRT_2 - nRT_1 P (V_2 - V_1) = n R(T_2 - T_1)$

Where $V_2 - V_1 = \Delta V$ and $T_2 - T_1 = \Delta T$ Therefore, $P\Delta V = \underline{nR\Delta T}$

 $C_p = C_v + R$

 $C_P - \underline{C}_{\Sigma} = R....(A)$

Non flow process:

It is the one in which there is no mass interaction across the system boundaries during the occurrence of process. Different type of non-flow process of perfect gas is given:

- (1) Constant volume process
- (2) Constant pressure process
- (3) Isothermal process
- (4) Adiabatic process
- (5) Polytrophic process

Constant volume process (Isochoric Process)

A thermodynamic process taking place at constant volume is known as the isochoric process.

It is also sometimes called as an isometric process or constant-volume process. The term isochoric has been derived from the Greek words —isol meaning —constantl or —equall and

-choricl meaning -spacel or -volume.

An isochoric process is one for which,

$$V_i = V_i (\Delta v = 0, \, dv = 0)$$

In such a process, the work done is zero (since dW = pdy = 0 when V = constant). Hence

from the first law of thermodynamics

dQ = dU (isochoric process)

The total heat supplied or rejected is also equal to the increase or decrease in the internal energy of the system.

Constant Temperature process (Isothermal Process)

It is a thermodynamic process in which the temperature of the system remains constant. The transfer of heat into or out of the system happens so slowly that thermal equilibrium is maintained.

We know an isothermal process is the one in which the pressure and volume of the gas changes at constant temperature.

Hence $\Delta T = 0$

The total work done by a gas in expanding from $V_1 to V_2$

$$W = \int_{v_1}^{v_2} \frac{Pdy}{(1)}$$

By ideal gas law $PV = RT$
Therefore, $P = \frac{RT}{V}$

Hence by substituting the value of P in equation -- (1)

$$W = RT \int_{v_1}^{v_2} \frac{dv}{v}$$

Since <u> R^{\cdot} </u> is universal gas constant and <u> T^{\cdot} </u> is also constant because it is isothermal process, we can simplify the equation as

$$W = RT \int_{v_1}^{u_2} \frac{1}{v}$$

Since, $\int_{v_2}^{\frac{1}{2}} \frac{dx}{dx} = \log_e x$ the equation can be simplified further as,

$$W = RT \left[\log_{e} V \right]^{\frac{1}{2}}$$
$$W = RT \left[\log_{e} V - \log_{e} V \right]$$
$$W = 2.306RT \log_{e} V^{2}$$

Constant Pressure process (Isobaric Process)

An Isobaric process is a thermodynamic process taking place at constant pressure. The term isobaric has been derived from the Greek words —isol and —barosl meaning equal pressure. As such, the constant pressure is obtained when the volume is expanded or contracted.

In an isobaric process, when the heat is transferred to the system some work is done. However, there is also a change in the internal energy of the system

Work done in Constant Pressure Process

An isobaric process is also called constant pressure process.

$$p_{f} = p_{I}(\Delta P = 0 \text{ and } dP = 0)$$

The work done is found from the equation; $W = \int_{M}^{\infty} P dV$

Since the pressure is constant in an isobaric process, the integral becomes

$$W = \int_{\mathcal{M}}^{\mathcal{U}_{f}} P dV_{s} P_{i}(V_{f} - V_{i}) = P_{i} \Delta V$$

If the gas expands, $V_f \succ V_i$, so $\Delta V \succ 0$ and the work done by the gas is positive.

Adiabatic Process

An adiabatic process is defined as

The thermodynamic process in which there is no exchange of heat from the system to its surrounding neither during expansion nor during compression.

Reversible Adiabatic Process

Reversible adiabatic process is also called an Isentropic Process. It is an idealized thermodynamic process that is adiabatic and in which the work transfers of the system are frictionless; there is no transfer of heat or of matter and the process is reversible. Such an idealized process is useful in engineering as a model of and basis of comparison for real processes.

What is Adiabatic Expansion

Adiabatic expansion is defined as an ideal behaviour for a closed system, in which the pressure is constant and the temperature is decreasing.

What is Adiabatic Compression

Adiabatic compression of the air is defined as the compression in which no heat is added or subtracted from the air and the internal energy of the air is increased which is equal to the external work done on the air. The pressure of the air is more than the In adiabatic process $PV^{\gamma} = K$

So
$$P = KV^{-\gamma}$$

Work done $W = \int P dv$
Or $W = \int KV^{-\gamma} dv$
Or $\int W = K \times \begin{bmatrix} V^{-\gamma+1} \\ 1-\gamma \end{bmatrix}_{V_1}^{V_2}$
Or $W = \frac{K}{2} \times \begin{bmatrix} V^{-\gamma+1} - V^{-\gamma+1} \\ 1-\gamma \end{bmatrix}_{V_1}^{V_2}$
Or $W = \frac{1}{1-\gamma} \times \begin{bmatrix} KV^{-\gamma+1} - KV^{-\gamma+1} \\ 1 \end{bmatrix}$
Or $W = \frac{1}{1-\gamma} \times \begin{bmatrix} PV\gamma V^{-\gamma+1} - PV\gamma V^{-\gamma+1} \\ 1 \end{bmatrix}$
Or $W = \frac{1}{1-\gamma}$
Or $W = \frac{P_2V_2 - P_1V_1}{1-\gamma}$
(A)

Polytropic Process

A polytropic process is any thermodynamic process that can be expressed by the following

equation:

 $PV^n = Cons \tan t$

The polytropic process can describe gas expansion and compression which include heat transfer. The exponent n is known as the polytropic index and it may take on any value from 0 to ∞ , depending on the particular process.

There are some special cases of n, which corresponds to particular processes:

- The case n = 0, p= constant, corresponds to an isobaric (constant-pressure) process.
- The case n= 1, pV=constant, corresponds to an isothermal (constant-temperature) process.
- The case n =, pV = constant, corresponds to an isentropic (constant-entropy) process.
- The case *n* → ∞ corresponds to an isochoric (constant-volume) process.

Work done in polytropic process

In Polytropic process $PV^n = K$ So $P = KV^{-n}$ Work done $W = \int Pdy$ Or $W = \int KV^{-n}dy$ Or $\int W = K \times \begin{bmatrix} V^{-n+1} & V^2 \\ 1-n & J_p \end{bmatrix}$ Or $W = \frac{K}{1-n} \times \lfloor V^{-n+1} - V^{-n+1} \rfloor$ I - nOr $W = \frac{1}{1-n} \times \lfloor KV^{-n+1} - KV^{-n+1} \rfloor$ Or $W = \frac{1}{1-n} \times \lfloor PV^nV^{-n+1} - PV^nV^{-n+1} \rfloor$ Or $W = \frac{1}{1-n} \times \lfloor PV^nV^{-n+1} - PV^nV^{-n+1} \rfloor$ (A)

Free Expansion and Throttling Process

Throttling Process

This is an expansion process at constant enthalpy. That it exists in refrigeration and airconditioning. The liquid throttles in the expansion valve. Further, process exists in the liquefaction of gases. Throttling is an irreversible process. No work is obtainable with decrease of pressure. Thus, it is not a useful process. This expansion is not possible in a turbine because of phase change in throttling.

Free Expansion Process

In free expansion process gas is allowed to expand in vacuum. This is happened quickly so there is no heat transferred and no work is done because the gas doesn't displace anything. There is also no change in internal energy so temperature doesn't change.

Formation of steam

Some important terms

Compressed Liquid and Saturated Liquid

Liquid that is not about to vaporize, is called Compressed liquid.

Liquid that is about to vaporize, is called Saturated liquid.





superior (summer injuit).

Saturated Vapor and Superheated Vapor

A vapour that is about to condense is called Saturated

A vapor that is not about to condense (i.e., not a saturated vapor) is called a superheated vapor.



At 1 atm pressure, the temperature remains constant at 100°C until the last drop of liquid is vaporized (saturated vapor).



As more heat is transferred, the temperature of the vapor starts to rise (*superheated vapor*).

Saturation Temperature and Saturation Pressure

At a given pressure, the temperature at which a pure substance changes phase is called the saturation temperature *Tsat.*

saturation temperature **Tsat.** Likewise, at a given temperature, the pressure at which a pure substance changes phase is called the saturation pressure **Psat.**



PROPERTY DIAGRAMS FOR PHASE-CHANGE PROCESSES





P-V diagram



P-v-T surface





Graphical representation of formation of steam

h-s Diagram or Mollier Diagram

From the first and second laws of thermodynamics



Fig. 9.15 Phase equilibrium diagram on h-s coordinates (Mollier diagram)

- Sensible heat of water (h_r) It is defined as the quantity of heat absorbed by 1 kg of water when it is heated from 0°C (freezing point) to boiling point. It is also called total heat (or enthalpy) of water or liquid heat invariably.
- Latent heat or hidden heat (h_{fg}). It is the amount of heat required to convert water at a given temperature and pressure into steam at the same temperature and pressure. It is expressed by the symbol h_{fg}.

• Total heat or enthalpy of wet steam (h). It is defined as the quantity of heat required to convert 1 kg of water at 0°C into wet steam at constant pressure. It is the sum of total heat of water and the latent heat and this sum is also /called enthalpy.

If steam is dry and saturated, then x = 1 and $h_g = h_f + h_{fg}$.

 Superheated steam. When steam is heated after it has become dry and saturated, it is called superheated steam and the process of heating is called superheating. Superheating is always carried out at constant pressure. The additional amount of heat supplied to the steam during superheating is

called The total heat of superheated steam is given by

$$h_{sup} = h_f + h_{fg} + c_{ps} \left(T_{sup} - T_s \right)$$

Where $C_{\mbox{\tiny ps}}$ is the specific heat of superheated steam at constant pressure.

Dryness fraction or Quality (x). The term dryness fraction is related with wet steam. It is defined as the ratio of the mass of water vapour in steam to the mass of steam containing it. It is usually expressed by the symbol 'x' or 'q'. m_a

$$x = \frac{m_g}{m_g + m_l}$$

Where m_g and m_l are the masses of vapour and liquid 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 the vapour is said to be *dry saturated*.

Let V be the total volume of a liquid vapour mixture of quality x, V_f the volume of the saturated liquid, and V_g the volume of the saturated vapour, the corresponding masses being m, m_f , and m_g respectively.

Now $m = m_f + m_g$ and $V = V_f + V_g$ $mv = m_f v_f + m_g v_g$

$$= (m - m_g) v_f + m_g v_g$$
$$v = \left(1 - \frac{m_g}{m}\right) v_f + \frac{m_g}{m} v_g$$
$$v = (1 - x) v_f + x v_g$$

where $x = \frac{m_g}{m}$, v_f = specific volume of saturated liquid, v_g = specific volume of saturated vapour, and u = specific volume of the mixture of quality x

saturated vapour, and v = specific volume of the mixture of quality x. Similarly $s = (1 - x) s_f + x s_g$

We can also write

 $h = (1 - x) h_{f} + xh_{g}$ $u = (1 - x) u_{f} + xu_{g}$ $v = (1 - x) v_{f} + x v_{g}$ $= v_{f} + x(v_{g} - v_{f})$ $= v_{f} + x, v_{fg}$ $v = v_{f} + x v_{fg}$ $h = h_{f} + x h_{fg}$

or Similarly





Constant quality lines

Steam Tables

Steam table is a tabular presentation of properties such as specific enthalpy, entropy, internal energy and specific volume at different saturation pressures and temperatures. Steam table may be on pressure basis or on temperature basis. The table on pressure basis has continuous variation of pressure and corresponding to it : saturation temperature (Tsat), enthalpy of saturated liquid (h_i), enthalpy of saturated vapour (h_g), entropy of saturated liquid (s_i), entropy of saturated vapour (sg), specific volume of saturated liquid (v_i),

specific volume of saturated vapour (vg), internal energy of saturated liquid (u), internal energy of
Similar to above the temperature based table which gives continuous variation of temperature and corresponding to it saturation pressure and other properties as h_f , h_g , h_{fg} , s_f , s_g , s_{fg} , v_f , v_g , u_f , u_g and u_{fg} are given.

Similarly, steam properties for superheated steam are also estimated and tabulated at some discrete pressures for varying degree of superheat. Super heated steam table are available for getting enthalpy, entropy, specific volume and internal energy separately.

Temp. (°C)	Absolute pressure (bar)	te Specific enthalpy re (kJ/kg)			Specific entropy (hJ/kg K)			Specific volume (m ² /kg)	
t	p	hr	hin	h_g	8r	a fat	**	v,	v_{g}
0	0.0061	-0.02	2501.4	2501.3	-0.0001	9.1566	9,1565	0.0010002	206.3
0.01	0.0061	0.01	2501.3	2501.4	0.000	9.156	9.156	0.0010002	206.2
1	0.0065	4.2	2499.0	2503.2	0.015	9.115	9.130	0.0010002	192.6
2	0.0070	8.4	2496.7	2505.0	0.031	9.073	9.104	0.0010001	179.9
3	0.0076	12.6	2494.3	2506.9	0.046	9.032	9.077	0.0010001	168.1
4	0.0081	16.8	2491.9	2508.7	0.061	8.990	9.051	0.0010001	157.2
5	0.0087	21.0	2489.6	2510.6	0.076	8.950	9.026	0.0010001	147.1
6	0.0093	25.2	2487.2	2512.4	0.091	8.909	9.000	0.0010001	137.7
7	0.0100	29.4	2484.8	2514.2	0.106	8.869	8.975	0.0010002	129.0
8	0.0107	33.6	2482.5	2516.1	0.121	8.829	8.950	0.0010002	120.9
9	0.0115	37.8	2480.1	2517.9	0.136	8,789	8.925	0.0010003	113.4
10	0.0123	42.0	2477.7	2519.7	0.151	8.750	8.901	0.0010004	106.4
11	0.0131	46.2	2475.4	2521.6	0.166	8.711	8.877	0.0010004	99,86
12	0.0140	50.4	2473.0	2523.4	0.181	8.672	8.852	0.0010005	93.78

Saturated Water and Steam (Temperature) Tables

Saturated	Water	and	Steam	(Pressure)	Tables

Absolute pressure (bar)	Temp. (°C)	mp. Specific enthalpy C) (kJ/kg)			Specific entropy (hJ/kg K)			Specific volume (m ³ /hg)	
p	t,	h_f	h_{fg}	h_{g}	s _f	s _{fe}	^S g	v_f	U _g
0.006113	0.01	0.01	2 501.3	2 501.4	0.000	9.156	9.156	0.0010002	206.14
0.010	7.0	29.3	2 484.9	2514.2	0.106	8.870	8.976	0.0010000	129.21
0.015	13.0	54.7	2470.6	2525.3	0.196	8.632	8.828	0.0010007	87.98
0.020	17.0	73.5	2 460.0	2 533.5	0.261	8.463	8.724	0.001001	67.00
0.025	21.1	88.5	2 451.6	2540.1	0.312	8.331	8.643	0.001002	54.25
0.030	24.1	101.0	2444.5	2545.5	0.355	8.223	8.578	0.001003	45.67
0.035	26.7	111.9	2 438.4	2 550.3	0.391	8.132	8.523	0.001003	39.50
0.040	29.0	121.5	2 4 3 2.9	2554.4	0.423	8.052	8.475	0.001004	34.80
0.045	31.0	130.0	2428.2	2558.2	0.451	7.982	8.433	0.001005	31.13
0.050	32.9	137.8	2423.7	2561.5	0.476	7.919	8.395	0.001005	28.19
0.055	34.6	144.9	2419.6	2565.5	0.500	7.861	8.361	0.001006	25.77

$\downarrow p (bar)$ (t_g)	$t (^{\circ}C) \rightarrow$	50	100	150	200	250	300	400	500
	U	149.1	172.2	195.3	218.4	241.5	264.5	310.7	356.8
0.01	u	2445.4	2516.4	2588.4	2661.6	2736.9	2812.2	2969.0	3132.4
(7.0)	h	2594.5	2688.6	2783.6	2880.0	2978.4	3076.8	3279.7	3489.2
	5	9.242	9.513	9.752	9.967	10.163	10.344	10.671	10.960
	v	29.78	34.42	39.04	48.66	48.28	52.9	62.13	71.36
0.05	u	2444.8	2516.2	2588.4	2661.9	2736.6	2812.6	2969.6	3133.0
(32.9)	h	2593.7	2688.1	2783.4	2879.9	2977.6	3076.7	3279.7	3489.2
	S	8.498	8.770	9.009	9.225	9.421	9.602	9.928	10.218

Superheated Steam at Various Pressures and Temperatures

Dryness fraction measurement:

In the measurement of quality, the object is always to bring the state of the substance from the two-phase region to the single-phase or superheated region, where both pressure and temperature are independent. It can be measured either by adiabatic throttling or electric heating.

Steam Boiler

INTRODUCTION

STEAM GENERATOR OR BOILER

A steam generator or boiler is usually a closed vessel made of steel. Its function is to transfer the heat produced by the combustion of fuel to water and ultimately to generate steam.

BOILER PROPERTIES:

- (i) <u>Safety</u>. The boiler should be safe under operating conditions.
- (ii) <u>Accessibility</u>. The various parts of the boiler should be accessible for repair and maintenance.
- (iii) <u>Capacity</u>. Should be capable of supplying steam according to the requirements.

- (iv) <u>Efficiency</u>. Should be able to absorb a maximum amount of heat produced due to burning of fuel in the furnace.
- (v) It should be simple in construction .
- (vi) Its <u>initial cost</u> and <u>maintenance cost</u> should be low.
- (vii) The boiler should have <u>no joints exposed to</u> <u>flames.</u>
- (viii) Should be <u>capable of quick starting and</u> <u>loading.</u>

Requirements of a boiler

> Generate maximum steam.

> Light in weight and not occupy large space.

> Proper safety regulations.

> Cheaper in cost.

Easy cope up with fluctuating demands of requirements.

FUEL

The source of heat for a boiler are :

> WOOD

> COAL

> DIESEL

NATURAL GAS

> NUCLEAR ENERGY

CLASSIFICATION OF STEAM BOILERS



- Though there are many classifications of steam boilers, yet the following are important.
- ACCORDING TO THE CONTENTS IN THE TUBE:
- a) fire tube or smoke tube boiler
- b) water tube boiler.

FIRE – TUBE BOILERS



WATER TUBE BOILERS



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> ACCORGING TO POSITION OF FURNACE:

- a) Internally fired boilers
- b) Externally fired boilers

> ACCORDING TO AXIS OF FURNACE:

- a) Vertical boilers
- b) Horizontal boilers

> ACCORDING TO NUMBER OF TUBES:

- a) Single tube boilers
- b) Multi tube boilers

ACCORDING TO METHOD OF CIRCULATION OF WATER:

- a) Natural circulation boilers
- b) Forced circulation boilers

➤ ACCORDING TO THE USE

- a) Stationary boilers
- b) Mobile boilers

FACTORS AFFACTING TO SELECTION OF BOILER

Following factors should be considered

- Quality of steam required
- Steam Generation rate
- Accessibility of repair and inspection
- Area
- Cost
- Erection facility
- Fuel and Water available

COMPONENTS OF A BOILER

- > Boiler shell
- Combustion chamber
- > Furnace
- > Grate
- Heating surface
- Mounting
- > Accessories

BOILER MOUNTINGS

- Pressure Gauge
- Water level indicator
- > Safety valve
- > Fusible plug
- Blow of cock
- Steam stop valve

BOILER ACCESSORIES

Air preheater : It utilize the heat of exhaust gases.

Economizer: Heat is used to raise the temperature of feed water supplied to the boiler.

<u>Steam super heater:</u> Used to super heat the steam.

Feed pump: Raise the pressure of water and force it into the boiler.

Injector: Used to feed water in boilers.

WORKING OF COCHRAN BOILER

- Considered to be one of the most efficient type multi tubular boilers.
- Consists of external cylindrical shell and fire box. The shell and fire box both are hemispherical.
- The fire box and combustion chamber is connected through a short pipe.
- The flue gases from the combustion chamber flow to the smoke box through a number of smoke tubes.

WORKING OF COCHRAN BOILER

- The gases from the smoke box pass to the atmosphere through a chimney
- The external diameter of pipe is 62.5mm and are 165in number.
- >Manhole is provided for cleaning.

SIMPLE VERTICLE

BOILER



COCHRAN BOILER



LANCASHIRE BOILER



LANCASHIRE BOILER

- The boiler consists of a long cylindrical external shell
 (1) built of steel plates in sections riveted together.
- It has two large internal flue tubes (2).
- A fire grate (3) is also called furnace is provided at one end of the flue tubes on which solid fuel is burnt.
- At the end of the fire grate there is a brick arch (5) to deflect the flue gases upwards.
- The hot flue gases leaving internal flue tubes passes through the bottom tube(6).

LANCASHIRE BOILER

- These flue gases move to the front of the boiler where they divide and flow into side tube (7).
- The flue gases then enter the main flue (9) which leads them to chimney.
- The damper (8) is fitted at one side flues to control the draught and thus regulate the rate of generation of steam.
- A spring loaded safety valve (10) and stop valve (11) are mounted.

LOCOMOTIVE BOILER

 Locomotive boiler is a horizontal fire tube type mobile boiler. The main requirement of this boiler is that it should produce steam at a very high rate. Therefore, this boiler requires a large amount of heating surface and large grate area to burn coal at a rapid rate. In order to provide the large heating surface area, a large number of fire tubes are setup and heat transfer rate is increased by creating strong draught by means of steam jet



ADVANTAGES

- Large rate of steam generation per square metre of heating surface. To some extent this is due to the vibration caused by the motion.
- It is free from brickwork, special foundation and chimney. This reduces the cost of installation.
- It is very compact.

The pressure of the steam is limited to about 20 bar.



- 1. This is an example of water tube boiler and is used in stationary and marine engine.
- 2. The efficiency of this boiler is much greater than that of the fire tube boiler.
- 3. This boiler is used when pressure is above 10bar and steam generating capacity is required higher then 7000kg/hr.

BOILER MOUNTINGS

- SAFETY MOUTINGS
- Safety valves (2 Nos)
- Fusible plug
- Control mountings
- Water level indicator
- Pressure Gauge
- Blow of cock
- Steam stop valve
- Feed check valve
- Inspection Mountings
- Man hole
- > Mud hole

BOILER ACCESORIES

- Air preheater : It utilize the heat of exhaust gases.
- <u>Economizer</u>: Heat is used to raise the temperature of feed water supplied to the boiler.
- <u>Steam super heater</u>: Used to super heat the steam.
- <u>Feed pump</u>: Raise the pressure of water and force it into the boiler.
- Injector: Used to feed water in boilers.

BOILER ACCESORIES



BOILER ACCESORIES

• Economizer



BOILER ACCESORIES

Steam super heater



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BOILER PERFORMENCE

- 1. Evaporative capacity
- 2. Equivalent evaporation
- 3. Factor of evaporation
- 4. Boiler efficiency

1. Evaporate capacity

- Ability to evaporate water.
- · Generally it is expressed in terms of
- A. Kg of steam/hour
- B. Kg of steam /hour/area of heating surface
- C. Kg of steam/kg of fuel is fired

2. Equivalent evaporation

- It can be defined as the amount of water evaporated from water at 100 deg C to dry and saturated steam at 100 deg C.
- Simply it means that the capacity of boiler to generate same evaporation.

3. Factor of evaporation

- Ratio of heat received by 1kg water under working condition to that received by 1kg of water evaporated from and at 100deg C.
- Fc=h-hf/2257

4. Boiler efficiency

- Ratio of heat utilized to the heat supplied.
- Efficiency= ma (h hf)/c
- Where ma=mass of water actual evaporated to the system
- C= calorific value to the fuel
- hf=enthalpy of water at given feed temp.
- h=enthalpy of fuel.

Unit-2

Carnot Cycle



The Carnot cycle consists of four reversible processes,

- 1. Reversible isothermal expansion
- 2. Reversible adiabatic (isentropic) expansion
- 3. Reversible isothermal compression, and
- 4. Reversible adiabatic (isentropic) compression

Analysis

For process 1-2

$$Q_1 = p_1 V_1 \ln \frac{V_2}{V_1}$$

The work done during the process is,

$$W_{1-2} = Q_1 = mRT_1ln ()_{V_1}$$

For process 2-3

Heat Transfer,

$$Q_{2-3} = 0$$

The work done on the gas,

$$W_{2-3} = \frac{p_3 V_3 - p_2 V_2}{\gamma - 1} = \frac{mR(T_1 - T_3)}{\gamma - 1}$$

For process 3-4

Heat rejection during the process,

$$Q_2 = p_3 V_3 \ln \left(\underbrace{ V_3 }_{V_4} \right) = mRT_3 ln \left(\underbrace{ V_3 }_{V_4} \right)$$

The work done on the gas,

$$W_{3-4} = Q_2 = p_3 V_3 \ln \left(\frac{V_3}{L} \right)$$

 V_4

For process 4-1

Heat transfer during the process,

$$Q_{4-1} = 0$$

The work done on the gas,

$$W_{4-1} = \frac{p_1 V_1 - p_4 V_4}{\gamma - 1} = \frac{mR(T_1 - T_3)}{\gamma - 1}$$

Thermal Efficiency of the Carnot Engine

The efficiency for a Carnot engine is given by,

$$\eta_{th} = \frac{\text{Net Work done}}{\text{Heat Supplied}} = \frac{W_{net}}{Q}$$

For a cyclic heat engine,

$$W_{net} = Q_1 - Q_2$$

Therefore,

$$\eta_{th} = \frac{Q_1 - Q_2}{Q_1} \\ = 1 - \frac{Q_2}{Q_1}$$

Also,

$$\eta_{th} = 1 - \frac{mRT_3ln(V_3/V_4)}{\frac{mRT_ln(V_2/V_4)}{2}}$$

Considering the isentropic process 2-3

and
$$p \frac{V_{2}}{2} = p \frac{V_{2}}{33}$$
$$\frac{T_{1}}{T_{3}} = \frac{T_{2}}{T_{3}} = \left(\frac{V_{3}}{V_{2}}\right)^{\gamma-1}$$

Similarly, for isentropic process 4-1,

and
$$p V^{\gamma} = p V^{\gamma} V^{\gamma} = \frac{1}{4} \frac{1}{4} \frac{T_1}{T_3} = \frac{T_1}{T_4} = \left(\frac{V_4}{V_1}\right)^{\gamma-1} V_1$$

and
$$\frac{\underline{V}_3}{V_2} = \frac{V_4}{V_1}$$
$$\frac{\underline{V}_3}{V_4} = \frac{V_2}{V_1}$$

Therefore,

$$\eta_{th} = 1 - \frac{T_3}{T_1}$$

 \rightarrow The Carnot cycle efficiency is independent of the working substance.

 \rightarrow It depends on source and sink temperatures.

 \rightarrow The efficiency becomes maximum when, the sink temperature T_3 approaches zero. Since, it violates the Kelvin-Planck's statement in this condition, thus it is not possible.

Otto Cycle



- \rightarrow The Otto cycle is an ideal air standard cycle for the gasoline engine.
- \rightarrow The cycle consists of four processes:
 - a. Process 1-2: Isentropic Compression
 - b. Process 2-3: Reversible constant volume heat addition
 - c. Process 3-4: Isentropic Expansion
 - d. Process 4-1: Reversible constant volume heat rejection

Analysis

For Otto cycle, per unit mass of air

Heat supplied,

$$q_{in} = q_{2-3} = c_v(T_3 - T_2)$$

Heat rejected,

$$q_{out} = q_{4-1} = c_v(T_4 - T_1)$$

Net work done for a cycle is given by,

$$w_{net} = q_{in} - q_{out}$$

= $c_v(T_3 - T_2) - c_v(T_4 - T_1)$

The thermal efficiency of the cycle,

$$w_{net}$$

$$\eta_{th} = \frac{w_{net}}{q_{in}}$$

$$= 1 - \frac{q_{out}}{q_{in}}$$

$$= 1 - \frac{c_v(T_4 - T_1)}{c_v(T_3 - 2)}$$

$$= 1 - \frac{(T_4 - T_1)}{(T_3 - T_2)}$$

$$= 1 - \frac{T(\frac{T_4}{T_1} - 1)}{T_3}$$

$$= 1 - \frac{T(\frac{T_4}{T_3} - 1)}{T_2(T_2 - 1)}$$

Considering the isentropic process 1-2,

$$\begin{array}{ccc} T_2 & \underline{\nu}_1 & \gamma^{-1} \\ & - \end{pmatrix} = (& \gamma^{-1} & r \\ T_1 & \nu_2 & r \end{array}$$

Where, $r = \frac{v_1}{v_2}$, is called the compression ratio.

For the isentropic process 3-4,

$$\frac{\underline{T_3}}{T_4} = (\underbrace{\overset{\nu_4}{\longrightarrow}}_{\nu_3})^{\nu_1} = (\underbrace{\overset{\nu_1}{\longrightarrow}}_{\nu_2})^{\nu_1} = r^{\gamma-1}$$

Hence, the efficiency is given by,

$$\eta_{0tto} = 1 - \frac{T_1}{T_2} \\ = 1 - \frac{1}{T_2/T_1} \\ \eta_{0tto} = 1 - \frac{1}{(r)^{\gamma - 1}}$$

The ratio of specific heats (γ) is assumed to be constant and hence the efficiency for Otto cycle is the function of compression ratio only.

The Otto cycle efficiency increases with increase in temperature.

Diesel Cycle



- → In petrol engines, the air-fuel mixture is compressed during the compression stroke, and thus the compression ratio is limited by engine knock.
- → In case of Diesel engines, the air is compressed during the compression stroke, thus eliminating the possibility of auto-ignition.
- \rightarrow The Diesel engines are designed to operate at high compression ratios (i.e. between 12 and 24)
- \rightarrow The processes included in the Diesel cycle are:
 - a. Process 1-2: Isentropic Compression
 - b. Process 2-3: Reversible constant pressure heat addition
 - c. Process 3-4: Isentropic Expansion
 - d. Process 4-1: Reversible constant volume heat rejection

Analysis

For 1 kg mass of air undergoing a Diesel cycle,

Heat supplied,

$$q_{in} = q_{2-3} = c_p(T_3 - T_2)$$

Heat rejected,

$$q_{out} = q_{4-1} = c_v(T_4 - T_1)$$

Net work done for a cycle is given by,

$$w_{net} = q_{in} - q_{out}$$

= $c_v(T_3 - T_2) - c_v(T_4 - T_1)$

The thermal efficiency of the cycle,

$$\eta_{th} = q_{in}$$

$$= 1 - \frac{q_{out}}{q_{in}}$$

= $1 - \frac{c_p(T_4 - T_1)}{c_v(T_3 - T_2)}$
 $\eta_{Diesel} = 1 - \frac{(T_4 - T_1)}{\gamma(T_3 - T_2)}$

The efficiency of the Diesel cycle can also be expressed in terms,

а.	Compression ratio:	$r = \frac{V_1}{V_2} = \frac{v_1}{v_2} = \frac{\text{Volume before compression}}{\text{Volume after compression}}$
b.	Cut-off ratio:	$\rho = \frac{V_3}{V_2} = \frac{v_3}{v_2} = \frac{\text{Volume after expansion}}{\text{Volume before expansion}}$
C.	Expansion ratio:	$r = \frac{V_4}{V_4} = \frac{v_4}{v_4} = \frac{V_6}{V_6}$

It can be proved that

$$r = r_e \rho = \left(\begin{array}{c} \frac{v_4}{v_3} & v_3 & v_1 \\ v_3 \times \underline{-} = & \underline{-} = r \right) |$$

Now for isentropic process 1-2,

$$\begin{array}{l} T_2 \\ T_1 \\ T_1 \end{array} = \begin{pmatrix} v_1 \\ v_2 \end{pmatrix}^{\gamma-1} = r_{\gamma-1} \\ T_2 = T_1 r^{\gamma-1} \end{array}$$

Where, $r = \frac{v_1}{v_2}$, is called the compression ratio.

For constant pressure heat addition process 2-3,

$$\frac{T_3}{T_2} = \frac{v_3}{v_2} = \rho$$
$$T_3 = \rho T_2 = \rho r^{\gamma - 1} T_1$$

For the isentropic process 3-4,

$$\begin{array}{l} \frac{T_4}{T} = (\overset{\mathcal{V}_3}{\underset{\mathcal{V}_4}{}} \overset{\gamma-1}{\underset{\mathcal{V}_4}{}} \\ = \overset{1}{\underset{\mathcal{V}_e}{}} \overset{\gamma-1}{\underset{r_e}{}} \\ T_4 = (\overset{\rho}{\underset{\mathcal{T}}{}}) \overset{\gamma-1}{T} T_3 \\ T_4 = (\overset{\rho}{\underset{\mathcal{T}}{}}) \rho r^{\gamma-1} T_1 \\ T_4 = \rho T_1 \end{array}$$

Using the value of T_2 , T_3 , and T_4 and putting in the efficiency relation, we get

$$\begin{split} \eta_{Diesel} &= 1 - \frac{(\rho^{\gamma}T_1 - T_1)}{\gamma(\rho r^{\gamma - 1}T_1 - T_1r^{\gamma - 1})} \\ &= 1 - \frac{(\rho^{\gamma} - 1)T_1}{\gamma(\rho r^{\gamma - 1} - r^{\gamma - 1})T_1} \\ \eta_{Diesel} &= 1 - \frac{1}{r^{\gamma - 1}} [\frac{\rho^{\gamma} - 1}{\gamma(\rho - 1)}] \end{split}$$

Dual Cycle



→ Since the air standard Diesel cycle does not simulate the exact pressure-volume variation in a compression ignition engine, as the fuel injection starts before the end of compression stroke, the variation is approximated in the form of limited pressure cycle. Such a cycle is referred as *dual cycle* or *mixed cycle*.

→ Here some part of heat is added to air at constant volume, and the remainder at constant pressure.

Analysis

Heat supplied,

$$q_{in} = c_v(T_3 - T_2) + c_p(T_4 - T_3)$$

Heat rejected,

$$q_{out} = c_v(T_5 - T_1)$$

So, efficiency is given by,

$$\eta_{dual} = 1 - \frac{(T_5 - T_1)}{(T_3 - T_2) + \gamma(T - T_3)}$$

The efficiency of Dual cycle can be expressed considering the following ratios;

Compression ratio,	$r = \frac{v_1}{v_2}$
Cut-off ratio,	$\rho = \frac{v_4}{v_3}$
Pressure ratio,	$= \frac{p_3}{p_2}$
r_p Expansion ratio,	$r_e = \frac{v_5}{v_4}$

For isentropic process 1-2,

$$T_2 = T_1 r^{\gamma - 1}$$

For constant volume process 2-3,

$$\frac{T_3}{T_2} = \frac{p_3}{p_2} = r_p$$
$$T_2 = \frac{p_2}{T_3} = r_p r^{\gamma - 1} T_1$$

For constant pressure process 3-4,

$$\frac{\underline{v}_4}{T_4} = \frac{\underline{v}_3}{T_3}$$
$$\frac{\underline{v}_4}{T_4} = \frac{\underline{v}_4}{\underline{v}_3}T_3 = \rho T_3$$
$$= \rho r^{\gamma - 1}T$$
$$p \qquad 1$$

$$\begin{array}{l} \frac{T_{5}}{T} = (\underbrace{\frac{\nu_{4}}{\nu_{5}}}_{r})^{\gamma-1} \\ = \underbrace{() }_{r_{e}}^{\gamma-1} \\ T_{5} = (\underbrace{- }_{r})^{\gamma-1} T_{4} \\ T_{5} = (\underbrace{- }_{r})^{\gamma-1} \rho r_{p}^{\gamma-1} T_{1} \\ T_{5} = \rho^{\gamma} r_{p} T_{1} \end{array}$$

Using the value of T_2 , T_3 , T_4 , and T_5 and putting in the efficiency relation, we get

$$\begin{split} \eta_{dual} &= 1 - \frac{T_1(\rho^{\gamma}r_p - 1)}{T_1(r_p r^{\gamma-1} - r^{\gamma-1}) + \gamma T_1(\rho r_p r^{\gamma-1} - r_p r^{\gamma-1})} \\ \eta_{dual} &= 1 - \frac{1}{r^{\gamma-1}} \frac{\rho^{\gamma}r_p - 1}{(r_p - 1) + \gamma r_p(\rho - 1)} \end{split}$$

Therefore, the efficiency of Dual cycle is a function of r, ρ , r_p , and γ .

When,

- $\rightarrow r_p = 1$, then $\eta_{dual} = \eta_{Diesel}$
- $\rightarrow \rho = 1, r_p = 1, \eta_{dual} = \eta_{Otto}$

 \rightarrow For same compression ratio and cut-off ratio, as pressure r_p increases, η_{dual} increases

INTERNAL COMBUSTION ENGINES

Explain and Classify IC Engines

An internal combustion engines is a machine that converts chemical energy in a fuel into mechanical energy.

Classification

According to piston strokes in the working cycle

- 1. Four stroke engine
- 2. Two stroke engine

According to the fuel used in the cycle

- 1. Petrol engine
- 2. Diesel engine
- 3. Gas engine
- 4. Multi fuel engine

According to method of ignition

- 1. Spark ignition
- 2. Compression ignition

According to fuel feeding system

- 1. Carbureted engine
- 2. Engine with fuel injection

According to charge feeding system

- 1. Naturally aspirated engine
- 2. Supercharged engine

According to cooling engine

- 1. Air cooled engine
- 2. Water cooled engine

According to the number of cylinders

- 1. Single cylinder engine
- 2. Multi cylinder engine



According to speed of the engine

- 1. Low speed engine
- 2. Medium speed engine
- 3. High speed engine

According to the position of engine

- 1. Horizontal engine
- 2. Vertical engine
- 3. V engine

Terminologies

Cylinder

- → The engine cylinder is made from cast iron which provides with a cylinder liner on the inner side and a cooling arrangement on the outer side.
- \rightarrow For two stroke engines, it houses exhaust and transfer port.

Cylinder Head

- \rightarrow The top cover of the cylinder, towards TDC, is called cylinder head.
- \rightarrow It houses the spark plug in petrol engines and fuel injector in diesel engines.
- \rightarrow For four stroke cycle engines, the cylinder head has the housing of inlet and exhaust valves.

Piston

- \rightarrow It is the reciprocating member of the cylinder which is housed in the cylinder.
- \rightarrow It's usually made of cast iron or aluminium alloys.
- \rightarrow The top surface is called *piston crown* and bottom surface is called *piston skirt*.

Piston Rings

→ The piston rings seal the space between the cylinder liner and piston in order to prevent leakage of high pressure gases, from cylinder to crank case.

Crank

- \rightarrow It is rotating member of the engine housed in the crank case.
- → Its one end is connected with the crankshaft and the other end is connected with a connecting rod.

Crank Case: It is the housing of the crank and body of the engine.

Connecting Rod

 \rightarrow The connecting rod transmits power developed on the piston to a crank shaft through crank.

 \rightarrow It's usually made of medium carbon steel.

Crank Shaft

Working Principle of SI and CI Engines

Two Stroke Petrol Engine



- → Here essential operations are carried out in one revolution of the crankshaft or two strokes of the piston. Hence the engine is called two stroke or two stroke cycle engine.
- \rightarrow Construction
- → it consists of a cylinder cylinder head piston piston rings connecting rod crank crankcase crankshaft et cetera
- \rightarrow The carburettor prepares the air fuel mixture outside the cylinder
- \rightarrow It consists of inlet and exhaust ports which are regulated by piston displacement.
- \rightarrow A suction pot with Reed type valve is used for induction of charge into the crankcase
- \rightarrow The transfer port is used for the transfer of charge from the crankcase to the cylinder
- \rightarrow the exhaust port discharges the burnt gases from the cylinder
- \rightarrow The spark plug is located in the cylinder head

Cycle of operation





(b) Start of compression



The following operation takes place in a two stroke or in one revolution of the engine

Charge transfer and scavenging

- \rightarrow The transfer and exhaust ports are uncovered as the piston gets nearer to the crankcase.
- → The compressed air fuel mixture from the crankcase enters through the transfer port and drives out the burnt gases of the previous cycle through the exhaust port.
- → The piston top is made deflected so that the incoming charge is directed upwards and helps in expelling the burnt gases from the cylinder. This process is called scavenging

Compression and suction

- → The transfer and exhaust port are covered by the piston and the charge gets compressed as the piston moves upward.
- → Simultaneously a personal vacuum is created into the crankcase. The suction port opens by the crank movement allowing the fresh charge into the crankcase.

Combustion

- \rightarrow At the end of the stroke the piston reaches the top dead centre.
- → A high intensity spark from the spark plug ignites the air fuel mixture thereby resulting in combustion.

Power and exhaust

- → The burning gases apply pressure on the top of the piston, and the piston is forced downward as a result of pressure generated.
- → As the piston descends through about 80% of the expansion stroke, the exhaust port E is uncovered by the piston, and the combustion gases leave the cylinder by pressure difference.
- → At the same time, the underside of the piston causes compression of charge taken into crank case.

Charging

→ The slightly compressed charge in the crank case passes through the transfer port and enters the cylinder as soon as it is uncovered by the descending piston and when it approaches the bottom dead centre, the cycle is completed.

Four-Stroke Cycle Petrol Engine



All operations are carried out in four strokes the piston, i.e., two revolutions of the crank Therefore, the engine is called a four stroke engine.

Constructional Details

- → Similar to a two-stroke engine, it also consists of a cylinder, cylinder head attached with spark plug, piston attached with piston ring, connecting rod, crank, crank shaft, etc.
- \rightarrow In a four-stroke engine, valves are used instead of ports. Those are suction and exhaust valves.
- → These valves are operated by cams attached on a separate shaft, called a cam shaft. It is rotated at half the speed of a crank shaft.

Operation



The travel of the piston from one dead centre to another is called piston stroke and a four stroke cycle consists of four strokes as suction, compression, expansion and exhaust strokes

Suction Stroke

- \rightarrow The suction valve opens, exhaust valve remains closed.
- → The piston moves from the top dead centre to the bottom dead centre, the charge is drawn into the cylinder.
THERMAL ENGINEERING, I

Compression Stroke

- → When the piston moves from the bottom dead centre to top dead centre, and the suction valve is closed, exhaust valve remains closed.
- \rightarrow The trapped charge in the cylinder is compressed by the upward moving piston.
- \rightarrow As the piston approaches the top dead centre, the compression stroke completes.

Expansion Stroke

- → At the end of the compression stroke, the compressed charge is ignited by a high intensity spark created by a spark plug, combustion starts and the high-pressure burning gases force the piston downward.
- \rightarrow The gas pressure performs work, therefore, it is also called working stroke or power stroke.
- → When the piston approaches the bottom dead centre in its downward stroke then this stroke is completed. In this stroke, both valves remain closed.

Exhaust Stroke

- → When the piston moves from the bottom dead centre to the top dead centre, only exhaust valve opens and burnt gases are expelled to surroundings by upward movement of the piston.
- → This stroke is completed when the piston approaches the top dead centre. Thus, one cycle of a four stroke petrol engine is completed.
- \rightarrow The next cycle begins with piston movement from the top dead centre to the bottom dead centre.

DIESEL ENGINES

Two-stroke Diesel Engine

- → The operation of a two-stroke Diesel engine is similar to a petrol engine, except it takes air as charge and fuel is injected at the end of the compression stroke.
- → It uses a high compression ratio and hence the injected fuel is self ignited.

Operation

Both inlet and exhaust take place through the cylinder ports which are covered and uncovered by the piston.

Charge Transfer and Scavenging



- → When the piston is nearer to the crank case (bottom dead centre), the transfer port and exhaust port are uncovered by the piston.
- → The slightly compressed air enters into the cylinder through the transfer port and helps to scavenge the remaining burnt gases from the cylinder.

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→ The charge transfer and scavenging continue till the piston completes its downward stroke and further, it moves upward and covers the transfer port.





(b) Start of compression



Compression and Suction

- \rightarrow After covering the transfer port, the exhaust port is also covered by the upward moving piston.
- → As both ports are covered by the piston, the air trapped in the cylinder is compressed during the forward stroke of the piston.
- → As the piston moves towards the cylinder head, a partial vacuum is created in the crank case, the inlet port opens and fresh air enters the crank case.

Combustion and Power

- → Near the end of the compression stroke, the fuel is injected at a very high pressure with the help of the fuel pump and injector.
- \rightarrow The injected fuel is self ignited in the presence of hot air and combustion starts.
- → The piston is forced downward by very high pressure of burnt gases and power is transmitted to the crank shaft.

Exhaust

→ Near the end of the power stroke, the exhaust port is uncovered first by the piston and the products of combustion start leaving the cylinder as a result of pressure difference.

Charging

THERMAL ENGINEERING, I

→ The slightly compressed air in the crank case passes through the transfer port and enters the cylinder as soon as it is uncovered by the descending piston and when it approaches the bottom dead centres, the cycle is completed.

Four-stroke Diesel Engine

- → A four-stroke Diesel engine contains a fuel injector, fuel pump, cylinder, cylinder head, inlet and exhaust valves, piston attached with piston rings, connecting rod, crank shaft, cams, camshaft, etc.
- → One cycle of a four-stroke Diesel engine is completed in four strokes of the piston or two revolutions of the crank shaft

Suction Stroke

→ The inlet (suction) valve opens, the exhaust valve remains closed, only air is drawn into the cylinder as the piston moves from the top dead centre to the bottom dead centre.



 \rightarrow This stroke ends as the piston approaches the bottom dead centre.

Compression Stroke

- → As the piston moves from the bottom dead centre to the top dead centre, the inlet valve closes, exhaust valve remains closed.
- → The air trapped into the cylinder is compressed in the cylinder till the piston approaches the top dead centre.
- \rightarrow The air temperature reaches about 800°C by compression.
- → At the end of the compression stroke, the fuel is injected at very high pressure into the compressed hot air.
- \rightarrow The temperature of hot compressed air is sufficient to ignite the injected fuel.
- \rightarrow Thus, ignition takes place inside the cylinder.

Expansion Stroke

- \rightarrow During this stroke, both valves remain closed.
- \rightarrow The piston the top dead centre is pushed by expansion of burning gases.
- → Actual work is obtained during this stroke due to the force obtained by high pressure burning gases.
- \rightarrow Therefore, this stroke is called power stroke or working stroke.

Exhaust Stroke



Theoretical Valve Timing Diagram

Actual Valve Timing Diagram

Actual Valve Timing For 4-Stroke Diese Engine

- I.V.O. \rightarrow 25° Before T.D.C.
- I.V.C. \rightarrow 30° After B.D.C.
- F.V.O. \rightarrow 5° Before T.D.C.
- F.V.C. \rightarrow 25° After T.D.C.

E.V.O. \rightarrow 45° Before B.D.C.

E.V.C. \rightarrow 15° After T.D.C.

Valve Overlap \rightarrow 30°



Theoretical Valve Timing Diagram

Actual Valve Timing Diagram

Actual Valve Timing For 4-Stroke Petrol

Engine

I.V.O. $\rightarrow 20^{\circ}$ Before T.D.C. I.V.C. $\rightarrow 35^{\circ}$ After B.D.C. F.V.O. $\rightarrow 35^{\circ}$ Before T.D.C. E.V.O. $\rightarrow 35^{\circ}$ Before B.D.C. E.V.C. $\rightarrow 10^{\circ}$ After T.D.C. Valve Overlap $\rightarrow 30^{\circ}$

1.8 ENGINE PERFORMANCE PARAMETERS

The engine performance is indicated by the term *efficiency*, η . Five important engine efficiencies and other related engine performance parameters are:

(i)	Indicated thermal efficiency	(η_{ith})
(ii)	Brake thermal efficiency	(η_{bth})
(iii)	Mechanical efficiency	(η_m)
(iv)	Volumetric efficiency	(η_v)
(v)	Relative efficiency or Efficiency ratio	(η_{rel})
(vi)	Mean effective pressure	(p_m)
(vii)	Mean piston speed	(\overline{s}_p)
viii)	Specific power output	(P_s)
(ix)	Specific fuel consumption	(sfc)
(x)	Inlet-valve Mach Index	(Z)
(x)	Fuel-air or air-fuel ratio	(F/A or A/F)
(xi)	Calorific value of the fuel	(CV)

Figure 1.15 shows the diagrammatic representation of energy distribution in an IC engine.

1.8.1 Indicated Thermal Efficiency (η_{ith})

Indicated thermal efficiency is the ratio of energy in the indicated power, ip, to the input fuel energy in appropriate units.



1.8.2 Brake Thermal Efficiency (η_{bth})

Brake thermal efficiency is the ratio of energy in the brake power, bp, to the input fuel energy in appropriate units.

$$\eta_{bth} = \frac{bp}{\text{Mass of fuel/s} \times \text{ calorific value of fuel}}$$
(1.5)

1.8.3 Mechanical Efficiency (η_m)

Mechanical efficiency is defined as the ratio of brake power (delivered power) to the indicated power (power provided to the piston) or can be defined as the ratio of the brake thermal efficiency to the indicated thermal efficiency.

$$\eta_m = \frac{bp}{ip} = \frac{bp}{bp+fp} \tag{1.6}$$

$$fp = ip - bp \tag{1.7}$$

1.8.4 Volumetric Efficiency (η_v)

This is one of the very important parameters which decides the performance of four-stroke engines. Four-stroke engines have distinct suction stroke, volumetric efficiency indicates the breathing ability of the engine. It is to be noted that the utilization of the air is that determines the power output of the engine. Intake system must be designed in such a way that the engine must be able to take in as much air as possible.

Volumetric efficiency is defined as the ratio of actual volume flow rate of **air** into the intake system to the rate at which the volume is displaced by the system.

$$\eta_v = \frac{\dot{m}_a/\rho_a}{V_{\rm disp}N/2} \tag{1.8}$$

where ρ_a is the inlet density.

An alternative equivalent definition for volumetric efficiency is

$$\eta_v = \frac{m_a}{\rho_a V_d} \tag{1.9}$$

It is to be noted that irrespective of the engine whether SI, CI or gas engine, *volumetric rate of air flow is what to be taken into account* and not the mixture flow.

If ρ_a is taken as the atmospheric air density, then η_v is the pumping performance of the entire inlet system. If it is taken as the air density in the inlet manifold, then η_v is the pumping performance of the inlet port and valve only.

The normal range of volumetric efficiency at full throttle for SI engines is between 80 to 85% where as for CI engines it is between 85 to 90%. Gas engines have much lower volumetric efficiency since gaseous fuel displaces air and therefore the breathing capacity of the engine is reduced.

1.8.5 Relative Efficiency or Efficiency Ratio (η_{rel})

Relative efficiency or efficiency ratio is the ratio of thermal efficiency of an actual cycle to that of the ideal cycle. The efficiency ratio is a very useful criterion which indicates the degree of development of the engine.

$$\eta_{rel} = \frac{\text{Actual thermal efficiency}}{\text{Air-standard efficiency}}$$
(1.10)

1.8.6 Mean Effective Pressure (p_m)

Mean effective pressure is the average pressure inside the cylinders of an internal combustion engine based on the calculated or measured power output. It increases as manifold pressure increases. For any particular engine, operating at a given speed and power output, there will be a specific indicated mean effective pressure, *imep*, and a corresponding brake mean effective pressure, *bmep*. They are derived from the indicated and brake power respectively. For derivation see Chapter 16. Indicated power can be shown to be

$$ip = \frac{p_{im}LAnK}{60 \times 1000} \tag{1.11}$$

then, the indicated mean effective pressure can be written as

$$p_{im} = \frac{60000 \times ip}{LAnK} \tag{1.12}$$

Similarly, the brake mean effective pressure is given by

$$p_{bm} = \frac{60000 \times bp}{LAnK} \tag{1.13}$$

where ip = indicated power (kW)

$$p_{im}$$
 = indicated mean effective pressure (N/m²)

- L = length of the stroke (m)
- $A = \text{area of the piston } (\mathrm{m}^2)$
- N = speed in revolutions per minute (rpm)
- n =Number of power strokes N/2 for 4-stroke and N for 2-stroke engines
- K = number of cylinders

Another way of specifying the indicated mean effective pressure p_{im} is from the knowledge of engine indicator diagram (*p*-*V* diagram). In this case, p_{im} , may be defined as

$$p_{im} = \frac{\text{Area of the indicator diagram}}{\text{Length of the indicator diagram}}$$

where the length of the indicator diagram is given by the difference between the total volume and the clearance volume.

1.8.7 Mean Piston Speed (\overline{s}_p)

An important parameter in engine applications is the mean piston speed, \overline{s}_p . It is defined as

$$\bar{s}_p = 2LN$$

where L is the stroke and N is the rotational speed of the crankshaft in rpm. It may be noted that \overline{s}_p is often a more appropriate parameter than crank rotational speed for correlating engine behaviour as a function of speed.

1.8.8 Specific Power Output (P_s)

Specific power output of an engine is defined as the power output per unit piston area and is a measure of the engine designer's success in using the available piston area regardless of cylinder size. The specific power can be shown to be proportional to the product of the mean effective pressure and mean piston speed.

Specific power output,
$$P_s = bp/A$$
 (1.14)

$$= \operatorname{constant} \times p_{bm} \times \overline{s}_p \qquad (1.15)$$

1.8.9 Specific Fuel Consumption (sfc)

The fuel consumption characteristics of an engine are generally expressed in terms of specific fuel consumption in kilograms of fuel per kilowatt-hour. It is an important parameter that reflects how good the engine performance is. It is inversely proportional to the thermal efficiency of the engine.

$$sfc = \frac{Fuel \text{ consumption per unit time}}{Power}$$
 (1.16)

Brake specific fuel consumption and indicated specific fuel consumption, abbreviated as bsfc and isfc, are the specific fuel consumptions on the basis of bp and ip respectively.

1.8.11 Fuel-Air (F/A) or Air-Fuel Ratio (A/F)

The relative proportions of the fuel and air in the engine are very important from the standpoint of combustion and the efficiency of the engine. This is

The ratio of actual fuel-air ratio to stoichiometric fuel-air ratio is called equivalence ratio and is denoted by ϕ .

$$\phi = \frac{\text{Actual fuel-air ratio}}{\text{Stoichiometric fuel-air ratio}}$$
(1.19)

Accordingly, $\phi = 1$ means stoichiometric (chemically correct) mixture, $\phi < 1$ means lean mixture and $\phi > 1$ means rich mixture.

1.8.12 Calorific Value (CV)

Calorific value of a fuel is the thermal energy released per unit quantity of the fuel when the fuel is burned completely and the products of combustion are cooled back to the initial temperature of the combustible mixture. Other terms used for the calorific value are heating value and heat of combustion. 1.1 The cubic capacity of a four-stroke over-square spark-ignition engine is 245 cc. The over-square ratio is 1.1. The clearance volume is 27.2 cc. Calculate the bore, stroke and compression ratio of the engine.

Solution

Cubic capacity,
$$V_s = \frac{\pi}{4}d^2L = \frac{\pi}{4}\frac{d^3}{1.1} = 245$$

 $d^3 = 343$
Bore, $d = 7 \text{ cm}$
Stroke, $L = \frac{7}{1.1} = 6.36 \text{ cm}$
Compression ratio, $r = \frac{V_s + V_c}{V_c}$
 $= \frac{245 + 27.2}{27.2} = 10$

1.2 The mechanical efficiency of a single-cylinder four-stroke engine is 80%. The frictional power is estimated to be 25 kW. Calculate the indicated power (ip) and brake power (bp) developed by the engine.

Solution

$$\frac{bp}{ip} = 0.8$$

$$ip - bp = 25$$

$$ip - 0.8 \times ip = 25$$
Indicated power, $ip = \frac{25}{0.2} = 125 \text{ kW}$
Brake power, $bp = ip - fp = 125 - 25 = 100 \text{ kW}$

1.3 A 42.5 kW engine has a mechanical efficiency of 85%. Find the indicated power and frictional power. If the frictional power is assumed to be constant with load, what will be the mechanical efficiency at 60% of the load?

Solution

$$ip = \frac{bp}{\eta_m} = \frac{42.5}{0.85} = 50 \text{ kW}$$

Frictional power, fp = ip - bp = 50 - 42.5 = 7.5 kW \Leftarrow Brake power at 60% load = $42.5 \times 0.6 = 25.5$ kW Mechanical efficiency $\eta_m = \frac{bp}{bp + fp} = \frac{25.5}{25.5 + 7.5}$ = 0.773 = 77.3% \triangleq 1.4 Find out the speed at which a four-cylinder engine using natural gas can develop a brake power of 50 kW working under following conditions. Air-gas ratio 9:1, calorific value of the fuel = 34 MJ/m^3 , Compression ratio 10:1, volumetric efficiency = 70%, indicated thermal efficiency = 35% and the mechanical efficiency = 80% and the total volume of the engine is 2 litres.

Solution

Total volume/cylinder, $V_{tot} = \frac{2000}{4} = 500 \text{ cc}$ Swept volume/cylinder, $V_s = \frac{9}{10} \times 500 = 450$ cc Volume of air taken in/cycle = $\eta_v \times V_s = 0.7 \times 450 = 315$ cc Volume of gas taken in/cycle = $\frac{315}{9} = 35$ cc Energy supplied/cylinder, $E = 35 \times 10^{-6} \times 34 \times 10^{3}$ = 1.19 kJ (1)

Indicated thermal efficiency, $\eta_{ith} = \frac{bp/\eta_m}{\text{Energy supplied/cylinder/s}}$

Indicated thermal efficiency,
$$\eta_{ith} = \frac{bp/\eta_m}{\text{Energy supplied/cylinder/s}}$$

Energy supplied/cylinder/s,
$$E_1 = \frac{50/0.8}{0.35 \times 4} = 44.64 \text{ kJ}$$

Now, energy supplied per cylinder in
$$kJ = \frac{E_1}{N/120}$$

= $\frac{44.64 \times 120}{N} = \frac{5356.8}{N}$ (2)

Equating (1) and (2)
$$\frac{5356.8}{N} = 1.19$$

 $N \approx 4500 \text{ rpm}$

1.5 A four-stroke, four-cylinder diesel engine running at 2000 rpm develops 60 kW. Brake thermal efficiency is 30% and calorific value of fuel (CV)

is 42 MJ/kg. Engine has a bore of 120 mm and stroke of 100 mm. Take $\rho_a = 1.15 \text{ kg/m}^3$, air-fuel ratio = 15:1 and $\eta_m = 0.8$. Calculate (i) fuel consumption (kg/s); (ii) air consumption (m³/s); (iii) indicated thermal efficiency; (iv) volumetric efficiency; (v) brake mean effective pressure and (vi) mean piston speed

Solution

Fuel consumption,
$$\dot{m}_f$$
 = $\frac{bp}{\eta_{bth} \times CV} = \frac{60}{0.3 \times 42000}$
= $4.76 \times 10^{-3} \text{ kg/s}$ $\stackrel{\text{Ans}}{\longleftarrow}$
Air consumption = $\frac{\dot{m}_f}{\rho_a} \frac{A}{F} = \frac{4.76 \times 10^{-3}}{1.15} \times 15$
= $62.09 \times 10^{-3} \text{ m}^3/\text{ s}$ $\stackrel{\text{Ans}}{\longleftarrow}$
Air flow rate/cylinder = $\frac{62.09 \times 10^{-3}}{4} = 15.52 \times 10^{-3} \text{ m}^3/\text{s}$
Indicated power = $\frac{bp}{\eta_m} = \frac{60}{0.8} = 75 \text{ kW}$

$$\eta_{ith} = \frac{75}{4.76 \times 10^{-3} \times 42000}$$
$$= 0.37515 = 37.51\%$$

=

Ans

Volumetric efficiency =

Mean

Actual volume flow rate of air Volume flow rate of air corresponding to displacement volume $\times 100$ $= \frac{15.52 \times 10^{-3}}{\frac{\pi}{4} \times 0.12^2 \times 0.10 \times \frac{2000}{2 \times 60}} \times 100$ η_v Ans 82.3% =Brake mean effective pressure, 1

$$p_{bm} = \frac{bp}{LAnK}$$

$$= \frac{60}{0.1 \times \frac{\pi}{4} \times 0.12^2 \times \frac{2000}{2 \times 60} \times 4} \times 10^3$$

$$= 7.96 \times 10^5 \text{ N/m}^2 = 7.96 \text{ bar} \qquad \stackrel{\text{Ans}}{\Leftarrow}$$
piston speed
$$= \frac{2 \times 0.1 \times 2000}{60} = 6.67 \text{ m/s} \qquad \stackrel{\text{Ans}}{\Leftarrow}$$

1.6 A single-cylinder, four-stroke hydrogen fuelled spark-ignition engine delivers a brake power of 20 kW at 6000 rpm. The air-gas ratio is 8:1 and the calorific value of fuel is 11000 kJ/m³. The compression ratio is 8:1. If volumetric efficiency is 70%, indicated thermal efficiency is 33% and the mechanical efficiency is 90%, calculate the cubic capacity of the engine.

Solution

Energy input
$$= \frac{bp/\eta_m}{\eta_{ith}} = \frac{20}{0.8 \times 0.33}$$
$$= 75.76 \text{ kJ/s}$$
Number of power strokes/s
$$= \frac{N}{2 \times 60} = \frac{6000}{120} = 50$$
Energy input/power stroke
$$= \frac{75.76}{50} = 1.52 \text{ kJ}$$
Actual volume of H₂ × CV
$$= 1.52$$
Actual volume of hydrogen taken in
$$= \frac{1.52 \times 10^6}{11000} = 138.18 \text{ cc}$$
Actual volume of air take in
$$= \frac{A}{F} \times 138.18 = 8 \times 138.18$$

Actual volume of air take in
$$= \frac{A}{F} \times 138.18 = 8 \times 138.18$$
$$= 1105.44 \text{ cc}$$
Swept volume, $V_s = \frac{\text{Actual volume of air taken in}}{\eta_v}$
$$= \frac{1105.44}{0.7} = 1579.2 \text{ cc}$$
Cubic capacity of the engine
$$= V_s \times K = 1579.2 \times 1$$
$$= 1579.2 \text{ cc}$$