INSTITUTE OF TEXTILE TECHNOLOGY CHOUDWAR

3rd Semester Mechanical Engg.

Thermal Engineering-I

Chapter-1

Thermodynamic concept & Terminology

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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, refrigeration, gas dynamics, jet propulsion, compressors, chemical process plants, and direct energy conversion devices.

1.1 MACROSCOPIC Vs MICROSCOPIC VIEWPOINT

There are two points of view from which the behaviour of matter can be studied: the macroscopic and the microscopic. 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. Such a study is made in *microscopic or statistical thermodynamics*. *Macroscopic thermodynamics* is only concerned with the effects of the action of many molecules, and these effects can be perceived by human senses. 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 effects of pressure can be felt. The macroscopic point of view is not concerned with the action of individual molecules, and the force on a given unit area can be measured by using, e.g., a pressure gauge. These macroscopic observations are completely independent of the assumptions regarding the nature of matter. All the results of classical or macroscopic thermodynamics can, however, be derived from the microscopic and statistical study of matter.

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. 1.1). 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. 1.2) is a system of fixed mass. There is no mass transfer 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. 1.3) 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. 1.4) 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.

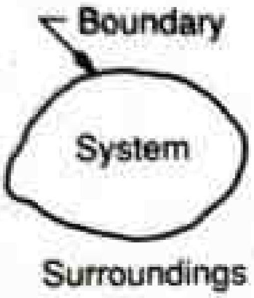


FIG. 1.1 *A thermodynamic system*

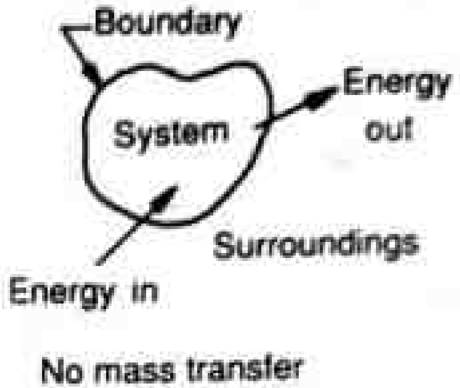


FIG. 1.2 *A closed system*

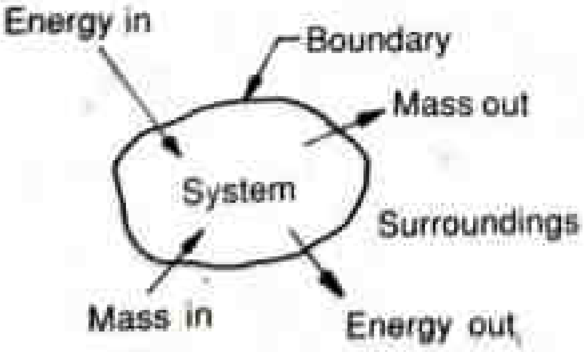


FIG. 1.3 *An open system*

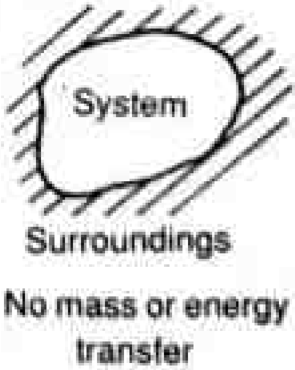


FIG. 1.4 *An isolated system*

If a system is defined as a certain quantity of matter, then the system contains the same matter and there can be no transfer of mass across its boundary. However, if a system is defined as a region of space within a prescribed boundary, then matter can cross the system boundary. While the former is called a closed system, the latter is an open system.

For thermodynamic analysis of an open system, such as an air compressor (Fig. 1.5), attention is focussed on a certain volume in space surrounding the compressor, known as the *control volume*, bounded by a surface called the *control surface*. Matter as well as energy crosses the control surface.

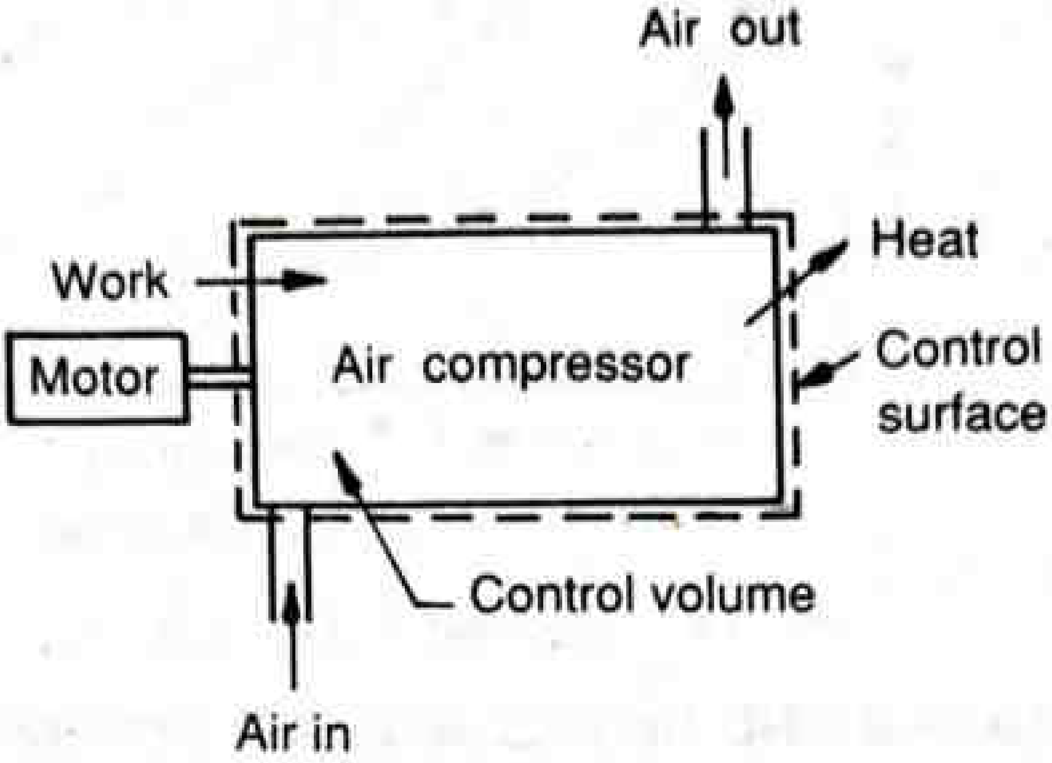


FIG. 1.5 *Control volume and control surface*

A closed system is a system closed to matter flow, though its volume can change against a flexible boundary. When there is matter flow, then the system is considered to be a volume of fixed identity, the control volume. There is thus no difference between an open system and a control volume.

1.1 THERMODYNAMICS

Thermodynamics can be defined as the 'science of energy'. In fact, the name 'thermodynamics' originates from two Greek words, *threme* (heat energy) and *dynamics* (motion or power). Thus, the subject of thermodynamics deals with energy and its transformation, including heat, work and physical properties of substances. It also deals with thermodynamic equilibrium and feasibility of processes.

Every engineering activity involves an interaction between energy and matter, and it is hard to find an area which does not relate to thermodynamics in some respect. An ordinary house has a gas stove, an electric iron, fans, a cooler, a refrigerator, pressure cooker and televisions. The design of each item requires the knowledge of thermodynamics.

In the engineering field, thermodynamics plays an important role in the design of automobile engines, compressors, turbines, refrigerators, rockets, jet engines, solar collectors, conventional and nuclear power plants. An energy-efficient home is designed for minimum heat loss in winter and minimum heat gain in summer. The size, location and power input to an air-conditioner is decided after thermodynamic analysis of a room.

1.2 THERMODYNAMIC SYSTEM

A thermodynamic system, or simply a ***system***, is defined as *a certain quantity of matter* or *a prescribed region in space considered for thermodynamic study.*

The region outside the system is called the ***surroundings or environment***. The real or imaginary surface that separates the system from its surroundings is called the ***boundary***. The boundary of the system may be fixed or movable. The system and its surroundings constitute the ***universe***. These terms are illustrated in Fig 1.1.

Types of Systems The thermodynamic systems can be classified as

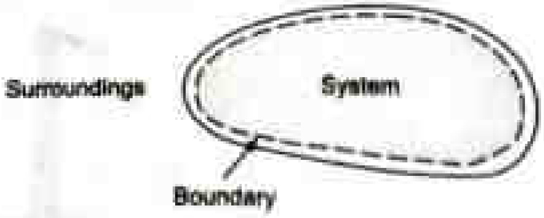


Fig. 1.1 *System, surroundings and boundary*

1. Closed and open systems
2. Homogeneous and heterogeneous systems

1.2.1 Closed System

A closed system (also known as ***control mass***) has the following characteristics:

- (i) It consists of a fixed amount of mass, and no mass can cross its boundary, i.e., no mass can enter or leave a closed system.
- (ii) The volume of a closed system may vary and hence its boundary is movable.
- (iii) The energy in the form of heat or work can cross the boundary.

Figure 1.2 shows the representation of a close a system. Some examples of closed system are discussed below.

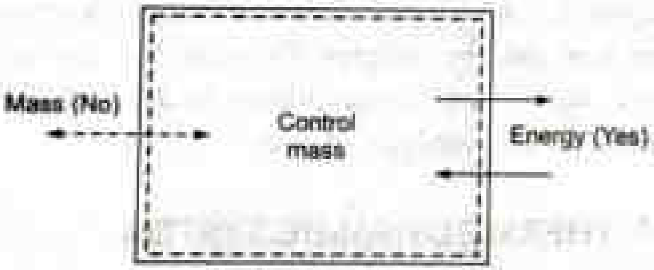


Fig. 1.2 *Representaion of a closed system*

1. Gas Trapped within a Piston-cylinder Device, Fig. 1.3

- (i) The inside surface of the cylinder and piston forms the boundary.
- (ii) With the movement of the piston, a part of the boundary can move.
- (iii) The movement of the piston is restricted by a stopper, so no mass of gas can leave the system.
- (iv) The energy, as heat and work, can cross the boundary.

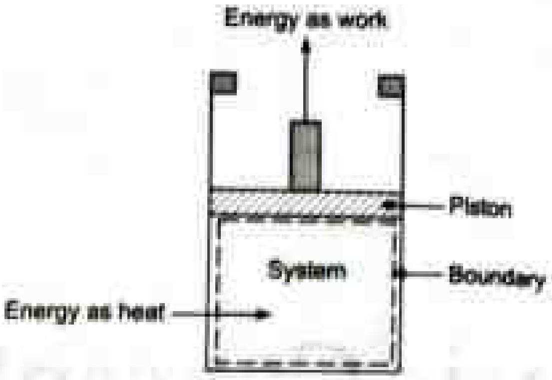


Fig. 1.3 *Gas trapped in a cylinder-piston device*

2. Food Items in a Pressure Cooker, Fig. 1.4

- (i) The inside surface of the pressure cooker and its cover forms the boundary.
- (ii) The boundary of the system is fixed.
- (iii) No mass of the food can cross the boundary, unless by the process of whistling.
- (iv) Energy as a heat can leave or enter the boundary of the system.

Fig. 1.4 *Pressure pan and pressure cooker*

3. Refrigerator and Ice-cream Freezer Figure 1.5 (b) shows the basic components of a refrigerator as a system along with its boundary. The working substance is the *refrigerant*.

- (i) The compressor, condenser, capillary tube and condenser together constitute a system.
- (ii) No mass of the working substance can leave the system.
- (iii) The boundary of the system is fixed.
- (iv) The energy as electrical work enters the compressor, and energy as heat leaves the condenser and enters the evaporator. Thus, energy crosses the boundary.

Hence, the refrigerator is a *closed system*.

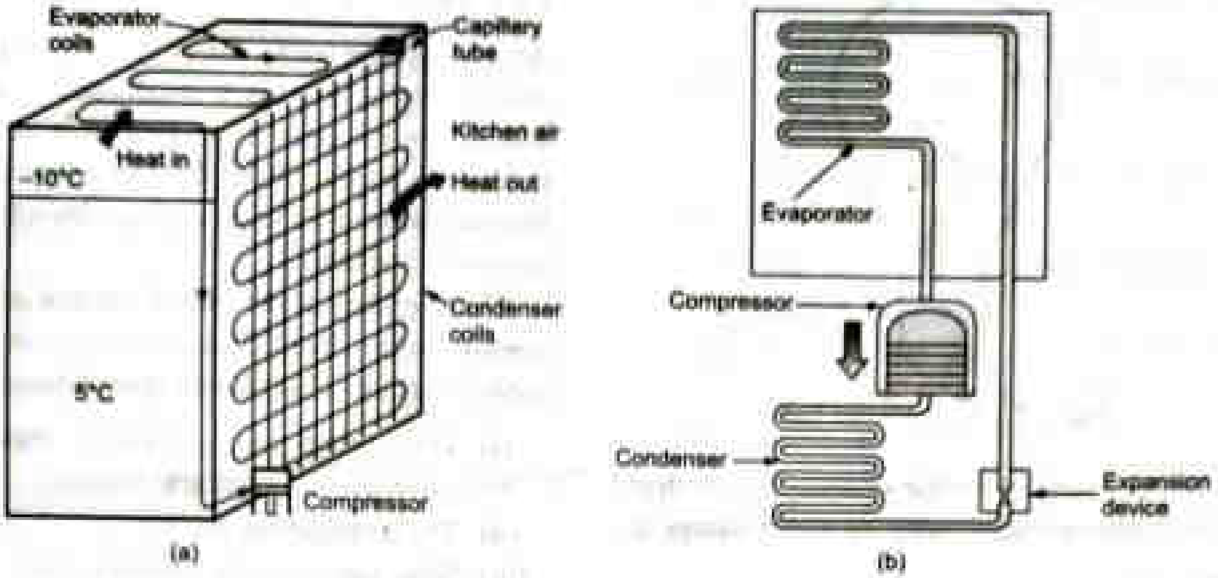


Fig. 1.5 *Schematic and basic components of a refrigerator*

4. *Steam (Thermal) Power Plant* Figure 1.6 shows the basic components of a steam power plant as a closed system along with its boundary. The working substance is water vapour.

(i) The boiler, turbine, condenser, and feed pump together constitute a system.
(ii) No mass of the working substance can leave the system.
(iii) The boundary of the system is fixed.
(iv) The energy as heat and work can cross the boundary of the system.

Thus, the steam power plant is a closed system.

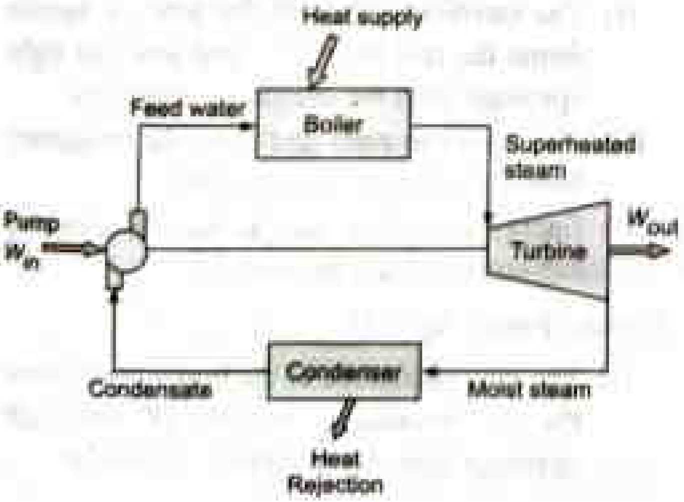


Fig. 1.6 *Steam power plant*

5. *Electrolytic Battery, Fig. 1.7*

(i) The acid and lead plates in a plastic box make up the system.
(ii) The boundary of the system is fixed.
(iii) No mass of the acid can leave the boundary.
(iv) Energy in electrical form can leave or enter the boundary of the system.

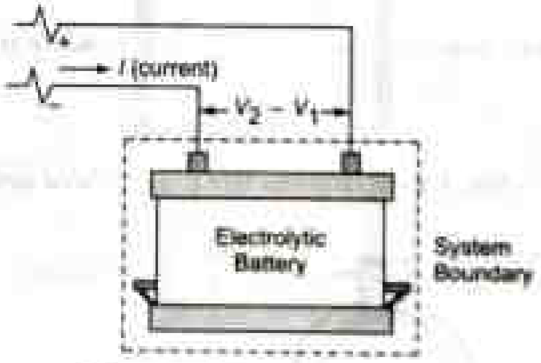


Fig. 1.7 *Electrolytic battery*

6. *Bulbs and Lamps, Fig. 1.8*

(i) The mass of the inert gas remains fixed inside bulbs and lamps.
(ii) The boundary of the system is fixed.
(iii) Energy as electricity, heat and light can cross the boundary of the system.

Isolated System An *isolated system* is a special case of a closed system, in which energy can also

Fig. 1.8 *Incandescent bulb*

not cross the boundary of the system. This system is not in communication with its surroundings in any way.

Thus, an **isolated system** neither exchanges energy in any form nor any mass with the surroundings. Hence, by definition, the *universe* can be considered as an isolated system. The representation of an isolated system is shown in Fig. 1.9. Other examples are thermos flask (Fig. 1.10) and ice box.

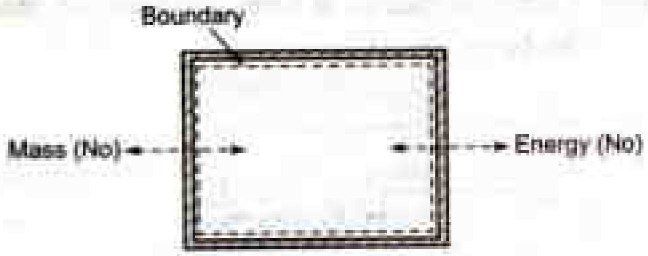


Fig. 1.9 *Representation of an isolated system*

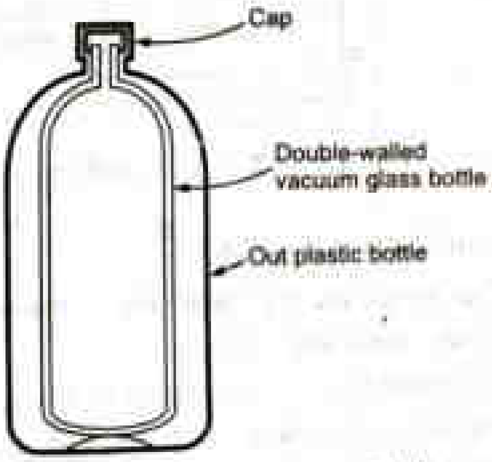


Fig. 1.10 *Thermos flask*

1.2.2 Open System

An *open system* (or a *control volume*) is a properly selected region in space. It usually encloses a device which involves mass flow, such as a compressor, turbine or nozzle. Flow through these devices is best studied by selecting a region within the devices as control volume.

The boundary of the control volume is called the *control surface*. Both mass and energy can cross the control surface. Thus, for an open system:

(i) The system has a selected region (fixed volume), called control volume.
(ii) The boundary of an open system is fixed.
(iii) Mass can cross the control surface.
(iv) The energy, in the form of heat and work, can cross the control surface.

An open system can be represented by Fig. 1.11. Some examples of open systems are discussed below.

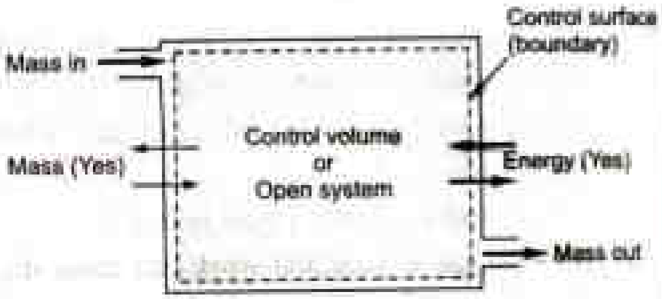


Fig. 1.11 *Representation of open system*

1. Flow through Tubes and Nozzles, Fig. 1.12

(i) The interior surface of the tube or nozzle forms the real boundary, and left and right openings form the imaginary boundary.
(ii) The mass can enter and leave the imaginary boundary of the control volume.
(iii) Energy as well as mass across the boundary can enter or leave the system.

2. Water Boiler, Fig. 1.13

(i) The interior surface of the boiler shell forms the real boundary, and the left and right openings form the imaginary boundary.

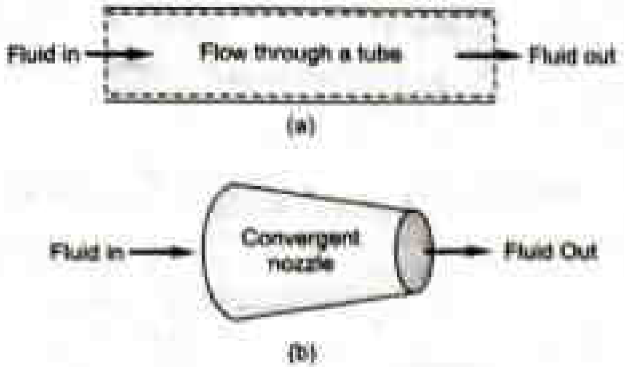


Fig. 1.12 *Flow through (a) Tube, and (b) Nozzle*

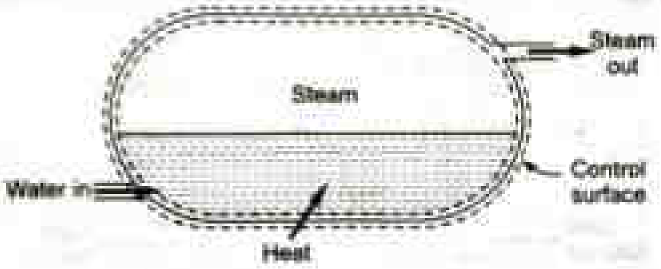


Fig. 1.13 *Water boiler*

(ii) The mass of the water enters, and the mass of steam comes out the control surface.

(iii) Energy as heat enters the control surface.

(iv) The energy in the form of heat or work can cross the boundary.

3. ***Reciprocating Air Compressor*** Figure 1.14 shows the reciprocating air compressor as an open system.

(i) The interior surface of cylinder and piston forms the control surface.

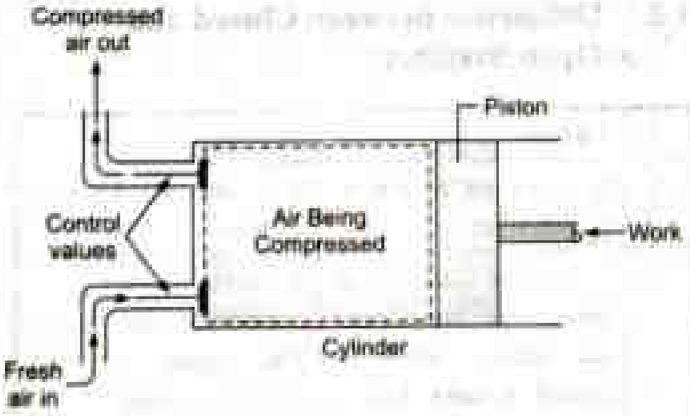


Fig. 1.14 *Reciprocating air compressor*

(ii) Mass of air can enter and leave the control volume through the valves.

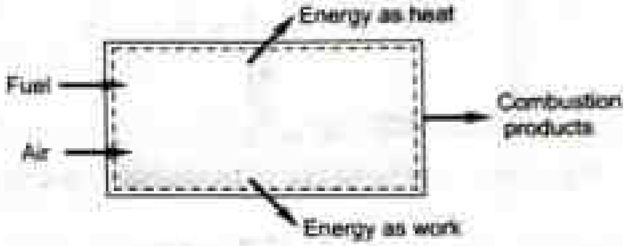
(iii) Energy as work and heat can cross the control surface.

4. ***Internal combustion engines, gas turbine, Fig. 1.15***

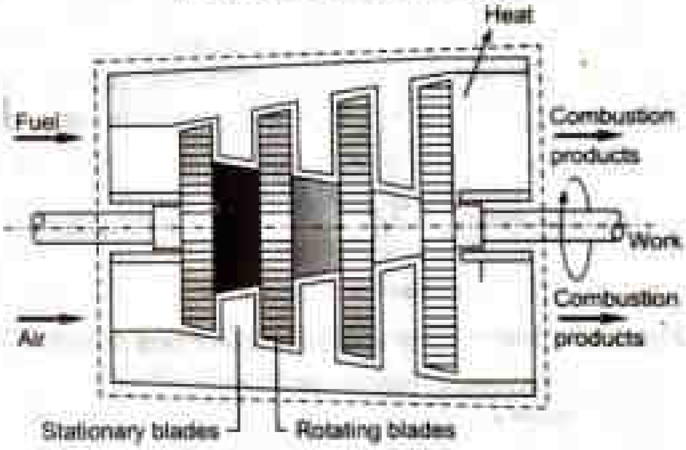
(i) The interior surface and openings form the control surface.

(ii) Mass as air and fuel mixture enters and leaves as combustion products.

(iii) Some part of the combustion heat is converted into work and the remaining is discharged as waste heat from the system.



(a) Internal combustion engine



(b) Gas turbine engine

Fig. 1.15

Adiabatic System An *adiabatic system* is a special case of an open system, in which mass can cross the control surface, but energy in the form of heat is not allowed to cross the control surface of the system. However, energy in other forms can enter and leave the system. Insulated turbines, throttle valves, water pumps, water turbines, insulated heat exchangers, etc., are some examples of adiabatic systems.

Some common features of these devices are the following:

(i) The interior surface of the device forms the control surface.
(ii) Fluid enters and leaves the control surface.
(iii) The energy other than heat energy can enter or leave the control surface.
(iv) Heat transfer is negligible at its outer control surface.

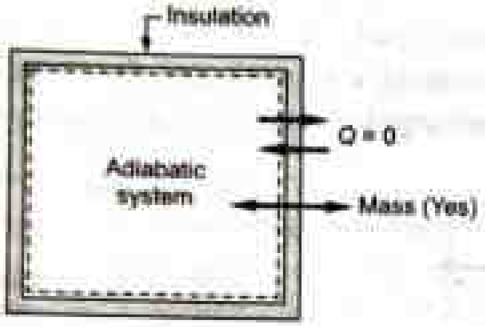


Fig. 1.16 *Representation of an adiabatic system*

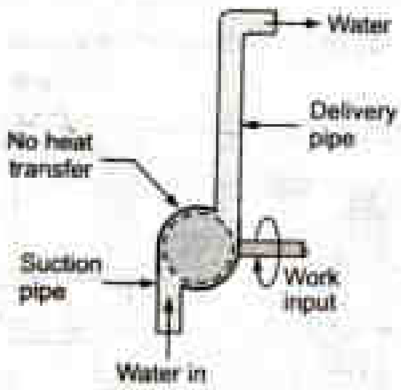


Fig. 1.17 *Water pump does not involve heat transfer*

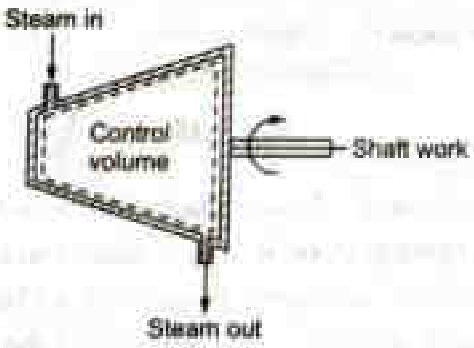


Fig. 1.18 *Insulated turbine*

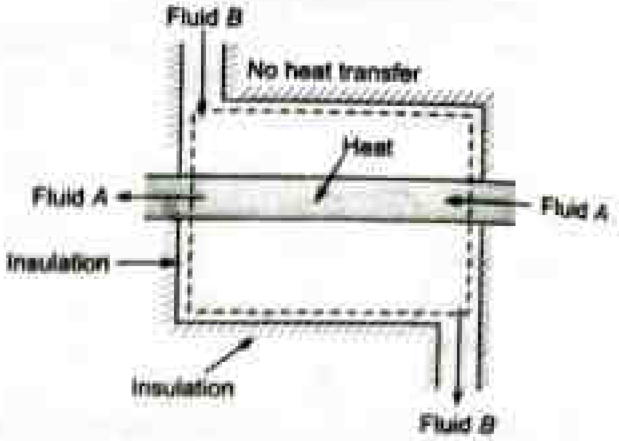


Fig. 1.19 *Heat exchanger insulated at its outer surface*

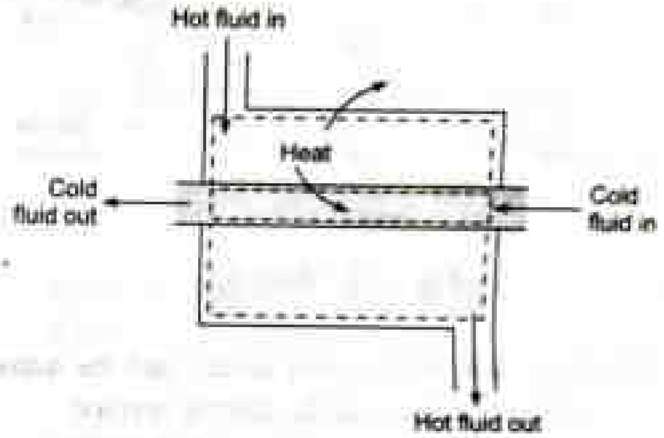


Fig. 1.20 *Heat exchanger which involves heat transfer at the outer boundary*

If the heat exchanger considered above in Fig. 1.19 is not insulated at its outer boundary then the heat transfer will take place across its boundary as shown in Fig.1.20 and it will not be treated as an adiabatic system.

The thermodynamic relations that are applicable to closed and open systems are different. Therefore, it is important that we must recognise the type of system before analysing it.

1.2.3 Difference Between Closed and Open Systems

	Closed system	*Open system*
1.	It is also called a *non-flow system.*	It is also called a *flow system.*
2.	A certain quantity of matter is considered for study. Thus, a closed system has a control mass.	A certain region is considered for study. This region is called control volume.

Contd.

3.	The system is surrounded by a real boundary, which may be fixed or movable.	An open system is surrounded by a control surface, which is a combination of real and imaginary boundaries.
4.	No mass can cross the boundary, while energy can enter or leave the boundary of the system.	Mass as well as energy can enter or leave the control surface of the system.
5.	If energy transfer does not take place across the boundary then the closed system is called an *isolated system*.	If heat transfer does not take place across the control surface then an open system is called an *adiabatic system*.
6.	Examples of a closed system are pressure cooker and refrigerator.	Examples of an open system are scooter engine, air compressor and gas turbine.

1.2.4 Difference Between Isolated and Adiabatic Systems

	Isolated system	*Adiabatic system*
1.	It is a special type of a closed system.	It is a special type of an open system.
2.	Mass and energy do not cross the boundary of the system.	Mass and energy, except heat energy, can cross the boundary of the system.
3.	It is a closed system, which is insulated at its boundaries, thus it becomes isolated from its surroundings.	It is an open system, which is insulated at its real boundaries, thus heat cannot cross it.
4.	Examples of an isolated system are ice box and thermos flask, etc.	Examples of an adiabatic system are water pump, throttle valve and insulated steam turbine etc.

1.2.5 Homogeneous System

A system is called a **homogeneous system**, if it consists of a single *physical phase*, either solid, liquid or gas phase only. It is treated as one constituent for its analysis. Thus, analysis becomes simple, for example, ice, water and steam (three distinct phases of water), sugar or salt dissolved in water, air, oxygen gas and nitrogen gas.

1.2.6 Heterogeneous System

When a system is a mixture of two or more than two phases of matter, it is called a **heterogeneous system**.

Since each constituent present in the system has its own properties independent of each other, the system cannot be analysed as a single constituent, for examples, mixture of ice and water; mixture of water and steam; dal, rice and water in a pressure cooker, etc.

1.3 MACROSCOPIC V/S MICROSCOPIC VIEWS

It is well known that every substance is composed of a large number of molecules. The properties of the substance depend on the behavior of these molecules. In the *macroscopic approach*, a certain quantity of matter is considered without the events occurring at the molecular level. The macroscopic approach in the study of thermodynamics is also called *classical thermodynamics*. It provides a direct and easy way to the solution of engineering problems. In the macroscopic approach,

1. The structure of the matter is not considered,
2. Only a few variables are needed to describe the state of the system,
3. The values of these variables can be measured.

The *microscopic approach* is more elaborate. We know that every system is composed of a large number of molecules. All have the same mass but each moves with a velocity independent of others. Similarly, each molecule has its own position, temperature, etc. The microscopic approach of such a system will involve a large number of equations, specifying three location coordinates and three velocity components for each molecule. It is

1.3 THERMODYNAMIC PROPERTIES, PROCESSES AND CYCLES

Every system has certain characteristics by which its physical condition may be described, e.g., volume, temperature, pressure, etc. Such characteristics are called *properties* of the system. These are all *macroscopic* in nature. When all the properties of a system have definite values, the system is said to exist at a definite *state*. Properties are the coordinates to describe the state of a system. They are the state variables of the system. Any operation in which one or more of the properties of a system changes is called a *change of state*. The succession of states passed through during a change of state is called the *path* of the change of state. When the path is completely specified, 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. 1.6).

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. If mass is increased, the values of the extensive properties also increase. Specific extensive properties, i.e., extensive properties per unit mass, are intensive properties, e.g., specific volume, specific energy, density, etc.

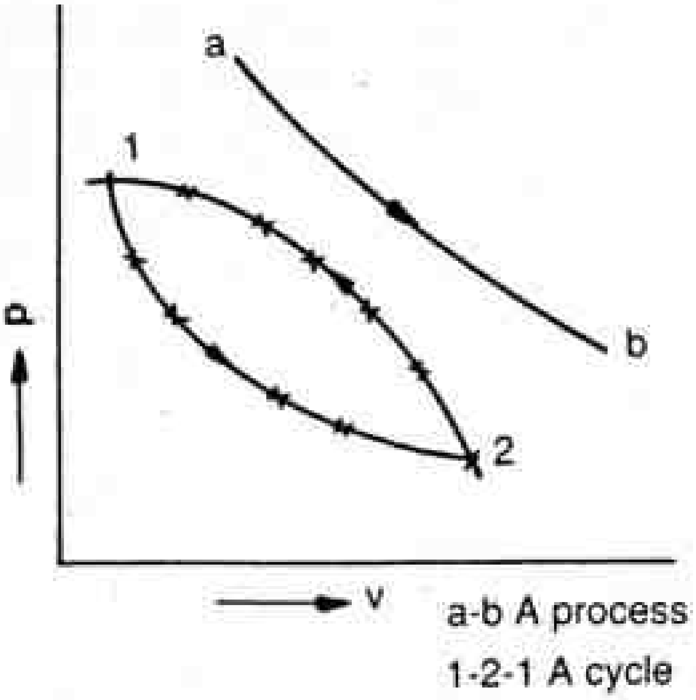


FIG. 1.6 *A process and a cycle*

1.4 HOMOGENEOUS AND HETEROGENEOUS SYSTEMS

A quantity of matter homogeneous throughout in chemical composition and physical structure is called a *phase.* Every substance can exist in any one of the three phases, viz., solid, liquid and gas. A system consisting of a single phase is called a *homogeneous system*, while a system consisting of more than one phase is known as a *heterogeneous system*.

very difficult to adopt in practice even with high-speed computers. The properties of the system are based on the average behavior of a large group of molecules under consideration. Thus, this approach is also called *statistical thermodynamics*. In the microscopic approach,

1. The knowledge of the structure of the matter is necessary
2. A large number of variables are needed to describe the state of the system
3. The values of the variables cannot be measured easily.

1.4 WORKING FLUID

The matter contained within the system boundaries is called *working fluid*. It is used in thermodynamic devices as a medium for energy transport between the system and surroundings, while undergoing a thermodynamic process or cycle. A working fluid may be gas, vapour, liquid or any non-reactive mixture of these constituents. The working fluids frequently absorb, store or release energy. For examples, water vapour is the working fluid in a steam power plant, and a refrigerant is the working fluid in a refrigerator.

1.5 CONTINUUM

Matter is made up of discrete particles, called *atoms*. These atoms are widely spaced (free path) in a gaseous phase and matter may also have some voids. The macroscopic approach is applicable when the smallest unit of the matter is large enough compared to the mean free path of the atoms. Under such circumstances, the matter in a system is considered as continuous and homogeneous without any hole. This is called the concept of *continuum*.

Let us consider the mass Δm in a volume ΔV surrounded the point P as shown in Fig. 1.21. The ratio of $\Delta m/\Delta V$ is the average mass density of the system within the volume ΔV. The volume $\Delta V'$ is the smallest volume about the point P, for which the mass can be considered continuous. Any volume smaller than this volume will lead to disconti in the particles, atoms and electrons, etc., and t density becomes unpredictable.

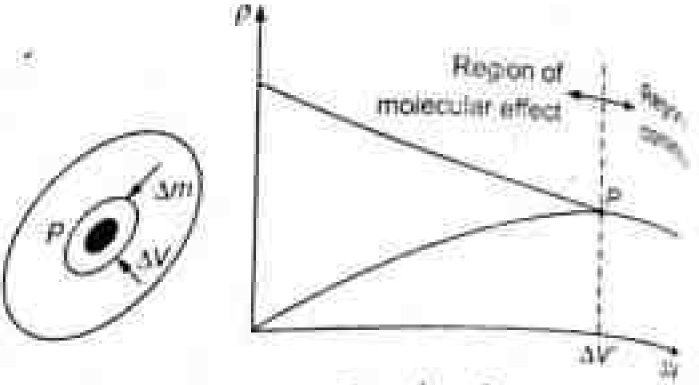


Fig. 1.21 *Concept of continuum*

The variation in density is tentatively shown i Fig. 1.21. When the volume approaches zero, t density becomes uncertain.

$$\rho = \lim_{\Delta V \to \Delta V'} \left(\frac{\Delta m}{\Delta V} \right) \qquad \text{...(1.1)}$$

Similarly, the definition of pressure is als required for a minimum area $\Delta A'$ at the which forc ΔF_n acts.

$$\rho = \lim_{\Delta A \to \Delta A'} \left(\frac{\Delta F_n}{\Delta A} \right) \qquad \text{...(1.2)}$$

The continuum is not applicable when the number of molecules in a system becomes negligible, e.g., a system under high vacuum.

1.6 THERMODYNAMIC PROPERTIES OF A SYSTEM

Any characteristic of a system is called a ***property***. Every system has certain characteristics by which its physical condition may be described, e.g., volume, temperature, pressure, etc. The list can be extended to include velocity, viscosity, thermal conductivity, modulus of elasticity, coefficient of thermal expansion, resistivity and elevation, etc.

The salient features of a thermodynamic property are the following:

(a) A property is a measurable characteristic, describing the state of a system.

(b) It has a definite value when the system is in a particular state.

(c) It also helps to distinguish one system from another.

(d) The magnitude of a property depends on the state of the system, and it is independent of the path or route followed by a system during a process.

(e) A property is an exact differential.

The differential quantity of a property P is designated as dP, and its integral between states 1 and 2 of the system is

$$\int_1^2 dP = P_2 - P_1 \qquad \ldots(1.3)$$

For a given expression of a property,

$$dP = Mdx + Ndy$$

A simple check can be a useful tool to recognize whether a quantity is a property or not.

$$\left(\frac{\partial M}{\partial y}\right)_x = \left(\frac{\partial N}{\partial x}\right)_y \qquad \ldots(1.4)$$

Types of Properties Properties may be classified as

1. Intrinsic and extrinsic properties according to their origin, and
2. Intensive and extensive properties according to their dependability.

1.6.1 Intrinsic and Extrinsic Properties

Intrinsic Properties These are the basic properties, and cannot be defined in terms of other properties. Their values can be assigned independently for example, length, mass, time, area volume, pressure, temperature, electric current, etc.

Extrinsic Properties These are those properties whose values cannot be assigned independently. These are characteristic of the motion or position of a system and are measured in reference to certain datum such as velocity, acceleration, potential energy, kinetic energy, enthalpy, entropy, etc.

1.6.2 Intensive and Extensive Properties

Intensive Properties These the properties that do not depend on the extent of the system. These properties are independent of the mass also. Properties such as pressure, temperature, density, velocity, etc., are examples of intensive properties.

Extensive Properties These are properties that vary directly with the extent of the system. These properties depend on the mass of the system. The properties such as mass, area, volume, total energy, etc., are examples of extensive properties.

An easy way to distinguish whether a property is intensive or extensive is to divide the system into two equal parts with a partition as shown in Fig. 1.22.

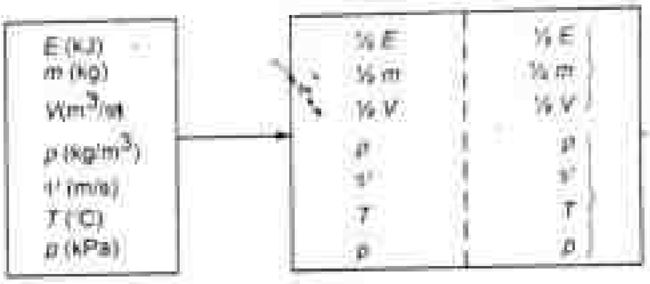


Fig. 1.22 *Recognition of intensive and extensive properties*

After partition, each part will have the same value for the intensive properties as of the original system, but half the value for extensive properties.

1.6.3 Density and Specific Gravity

Specific Property An extensive property expressed per unit mass of the system is called a specific property. Examples include specific volume, specific energy, specific enthalpy, specific internal energy, etc. and thus are intensive properties.

Mass density or simply *density* is a measure of the amount of working substance contained in a given volume and is defined as mass per unit volume.

$$\rho = \frac{\text{Mass of substance}}{\text{Volume occupied}} = \frac{m}{V}\ (\text{kg/m}^3) \qquad \ldots(1.5)$$

Similarly, *specific gravity*, or relative density, is defined as the ratio of density of a substance (ρ_s) to the density of water at 4°C ($\rho_{water} = 1000$ kg/m^3). It is designated by SG.

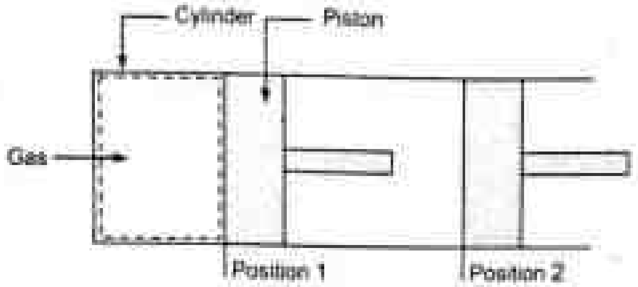
1.7 STATE, PATH, PROCESS AND CYCLE

1.7.1 State

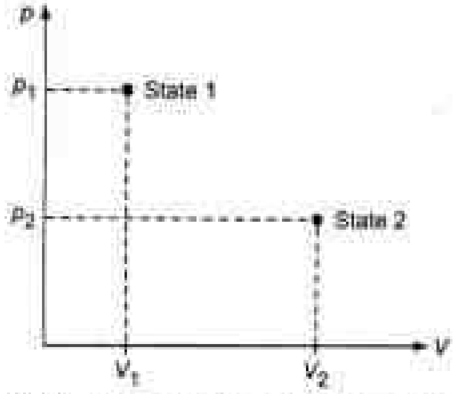
The thermodynamic *state* is the *condition of the system* as characterised by certain thermodynamic properties like pressure, temperature, specific volume, etc.

If any system is not undergoing any change then all of its properties can be measured or calculated, which gives us a set of properties that completely describe the condition or state of the system. At this state, all thermodynamic properties of the system have the same value throughout the system. If the value of even one property changes, the system will change its state to a different one.

Consider a certain quantity of a gas as a system in a piston–cylinder device as shown in Fig.1.23 (a). At the position 1 of the piston at any instant, the condition of the system can be described by pressure p_1, temperature T_1 and volume V_1. The system is said to exist at the state 1. After expansion of the gas, the system will reach a new position 2 (state 2) as shown in Fig.1.23 (b).



(a) Piston at two positions within a cylinder



(b) Representation of states on a plot

Fig. 1.23

1.7.2 Path

When a gas expands in the cylinder, the piston moves outward, the properties of a system change and the system reaches to the new state 2. It is called a *change of state*. *A locus of series of states through which a system passes between initial and final states* is called a *path* as shown in Fig.1.24.

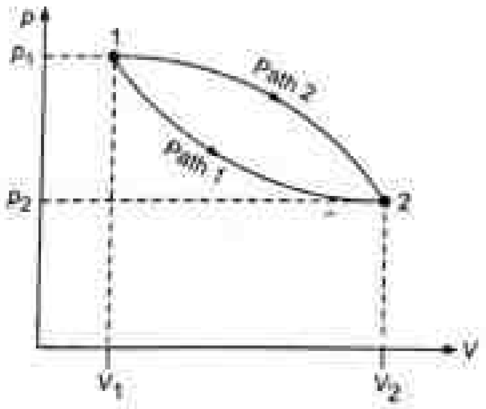


Fig. 1.24 *Two paths between initial and final states*

The system may reach from state 1 to state 2 by a number of paths depending on the type of expansion.

1.7.3 Process

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

A series of states through which a system passes during a process is called the *path of the process*. The processes are classified as follows:

1. A process undergone by a fluid in a closed system, is referred as a *non-flow process*.
2. A process undergone by a fluid in an open system is referred as a *flow process*.
3. 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***.
4. A process is called a *reversible process* if it once has been taken place between two states, can be reversed to restore the system to initial conditions without leaving any effect on the surroundings. It passes through a series of equilibrium states.
5. A process which cannot be reversed by the same path, and follows in one direction only is called an *irreversible process*. It passes through a series of non equilibrium states.
6. When a system undergoes a process, while enclosed by an adiabatic wall (ideal insulator), the system does not experience any heat exchange between the system and its surroundings. Such a process is called an *adiabatic process*.

The prefix *iso-* is often used to designate a type of process for which a particular property remains constant.

(i) An Isothermal Process The *temperature* remains constant during the process.

(ii) An Isobaric Process The *pressure* remains constant during the process.

(iii) An Isochoric (Isometric) Process The *volume* remains constant during the process.

(iv) An Isentropic Process The *entropy* remains constant during the process.

(v) An Isenthalpic Process The *enthalpy* remains constant during the process.

1.7.4 Cycle

If a system undergoes a series of processes in such a way that its *initial* and *final* states are identical then the system is said to have undergone a *cyclic process* or simply a *cycle*. A thermodynamic cycle is a sequence of processes that begins and ends at the same state as shown in Fig. 1.25. At the conclusion of a cycle, all properties of the fluid have the same values as they had at the initial state.

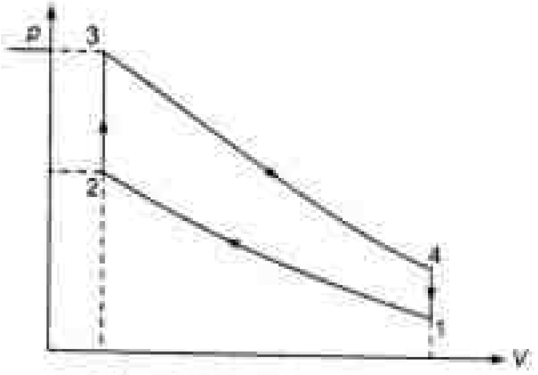


Fig. 1.25 *Cyclic process*

1.8 POINT FUNCTION AND PATH FUNCTION

When a system undergoes a change from one state to another, the properties of the system also change, which depend only on end states and not on the path followed between these two states. Therefore, these properties are called state functions or point functions. *Point functions* can be represented by a point on any plot, e.g., temperature, pressure, volume, etc. These properties have exact differentials designated by the symbol *d*. Therefore, change in volume or pressure is represented by dV or dp, respectively.

A quantity, whose value depends on the particular path followed during the process is called a *path function*. It requires a particular path and direction to represent the quantity on any plot, e.g. heat, work, etc. The path functions have inexac differentials represented by the symbol δ Therefore, a differential amount of work or hea is written as δW or δQ. A typical representation of expansion work (a path function quantity) is shown in Fig. 1.26.

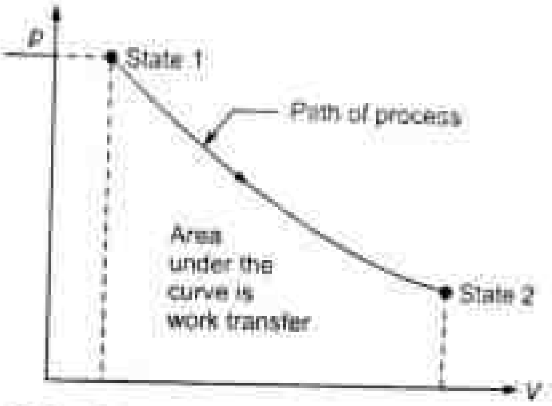


Fig. 1.26 *Reprsentation of path function quantity*

1.9 QUASI-STATIC PROCESS

When a process proceeds in such a manner that the system remains infinitesimally close to an equilibrium state at all times, it is called a *quasi-static*, or *quasi-equilibrium* process. A quasi-static process is viewed as a sufficiently slow process in which system changes its state very slowly under the influence of an infinitesimally small driving force. The system adjusts itself internally, so that the properties in one part of the system do not change any faster than those in the other part.

Figure 1.27 illustrates a quasi-static process. The system consists of a gas initially at equilibrium under the piston in a cylinder. The piston is loaded by a number of small masses. As one mass is removed, the gas expands slightly, allowing the piston to move slowly upward. During such expansion, the molecules get sufficient time to redistribute, and thus the gas would depart only slightly from equilibrium and as the pressure and other intensive properties become uniform, it will attain a new equilibrium state. Moreover, if the same mass is put on the piston, the gas would be restored to its initial state.

An isolated system has no interaction with its surroundings and is always in internal equilibrium. When any one of the above conditions of equilibrium are not satisfied, the system is not considered to be in thermodynamic equilibrium.

1.11 DIMENSIONS AND UNITS

Any physical quantity may be characterized by *dimensions*. The reference standard used to measure the dimensions of a physical quantity is called a *unit*. In the *tenth* and *eleventh General Conference of Weight and Measures*, it was decided to use the single universally accepted system of units throughout the world and a system of measurement called the *International System of Units* was introduced. This system of units is called *Système International d 'Unités* and is abbreviated as *SI units*.

The seven units used for the seven fundamental quantities, considered as basic units, are given in Table 1.1.

Table 1.1 *Basic or primary dimensions, units and symbols in SI units*

Qunatity	*Unit*	*Symbol*
Length	metre	m
Mass	kilogram	kg
Time	second	s
Electric current	ampere	A
Temperature	kelvin	K
Amount of light	candela	cd
Amount of matter	mole	mol

A list of some derived physical quantities, their symbols, units and dimensions are given in Table 1.2.

Table 1.3 shows a list of some secondary units and their expressions in terms of basic units.

Guidelines for Writing Units and their Symbols
The following guidelines should strictly be followed for writing correct units and their dimensions:

1. All unit names derived from scientist's names are not to be written with an initial capital letter. For example, the unit of force named after Sir Isaac Newton is written as 'newton' (not Newton). Similarly, the unit of temperature named after Lord Kelvin is written as 'kelvin' (not Kelvin).
2. Symbols of unit names derived after scientist's names are always written with an initial capital letter. For example, the symbol 'N' is used for newton and 'K' for kelvin.
3. If the symbol of a unit is not derived from a scientist's name, it is written with a small letter. For example, 'm' for *metre* and 'kg' for *kilogram*.
4. The symbols of units do not take a plural form. However, the full name of the unit

Table 1.2 *Derived quantities, their units and symb*

Qunatity	*Unit*	*Symbol*
Acceleration	metre per second square	m/s^2
Angular acceleration	radian per second square	rad/s^2
Angular velocity	radian per second	rad/s
Area	square metre	m^2
Electric resistance	ohm	Ω
Frequency	hertz	Hz or 1/s
Specific volume	kilogramme per cubic metres	kg/m^3
Velocity	metre per second	m/s
Volume	cubic metre	m^3

Table 1.3 *Secondary units, their symbols an expressions in terms of basic units*

Qunatity	*Unit*	*Symbol*	*Expression in terms of basic units*
Force	newton	N	$kg \cdot m/s^2$
Pressure	pascal	Pa	$kg/m \cdot s^2$
Energy, work, heat	joule	J	$kg \cdot m^2/s^2$
Power	watt	W	$kg \cdot m^2/s^3$

may be pluralized. For example, the length of an object can be written as 5 m or 5 metres but not 5 ms. Similarly, the mass of an object can be written as '5 kg' or '5 kilograms' but not '5 kgs'.

5. No full stop or other punctuation mark is placed after symbols, unless they appear at the end of a sentence. For example, metre is written as 'm' not 'm.'.
6. For better appearance, a single space must always be provided between a numerical value and a symbol of a unit.

1.12 PRESSURE

Pressure is defined as the *normal force exerted by a fluid per unit area*. We speak of pressure only when we deal with a gas or liquid. The counterpart of pressure in a solid is *stress*. If F is the force normal to the area A, then

$$p = \frac{F}{A} \text{ (N/m}^2\text{)} \qquad \text{...(1.10)}$$

where force, F = mass (m) × acceleration due to gravity (g)

mass, m = volume × density = area (A) × depth (h) × density (ρ)

or $$F = Ah\rho g$$

and $$\text{pressure, } p = \frac{Ah\rho g}{A} = \rho\, g\, h \text{ (N/m}^2\text{)} \qquad \text{...(1.11)}$$

1.12.1 Units of Pressure

Pressure is measured in newtons per square metre, which is called ***pascal*** **(Pa).** The pressure unit pascal being too small, very often kilopascal (kPa), megapascal (MPa), bar and standard atmosphere (atm) are used. These are related as

$$1 \text{ kPa} = 10^3 \text{ Pa}$$
$$1 \text{ MPa} = 10^6 \text{ Pa} = 10^3 \text{ kPa}$$
$$1 \text{ bar} = 100 \text{ kPa} = 10^5 \text{ Pa}$$
$$1 \text{ atm} = 101,325 \text{ Pa} = 101.325 \text{ kPa}$$
$$1 \text{ Torr} = 133.32 \text{ Pa}$$

1.12.2 Atmospheric, Absolute and Gauge Pressures

(i) Atmospheric Pressure It is the pressure exerted by the envelope of air surrounding the earth's surface. The standard atmospheric pressure is equal to the pressure produced by a 760 mm high column of mercury, the density of mercury being 13,595 kg/m^3 and the acceleration due to gravity being 9.80665 m/s^2 at sea level.

$$p_{atm} = 101325 \text{ N/m}^2 = 1.01325 \text{ bar}$$

(ii) Absolute Pressure The actual pressure at a given position is called *absolute pressure*. It is designated as p_{abs}, or simply p, and it is measured by a barometer above the absolute zero pressure.

(iii) Gauge Pressure All pressure-measuring instruments and gauges are calibrated to read zero at atmospheric pressure, and so they indicate the difference between the actual (absolute) pressure and local atmospheric pressure (p_{atm}). This difference is called *gauge pressure*. It is denoted by p_{gauge} and is expressed as

$$p_{gauge} = p_{abs} - p_{atm} \qquad \text{...(1.12)}$$

The pressure measured below atmospheric pressure is called **vacuum (gauge) pressure** and

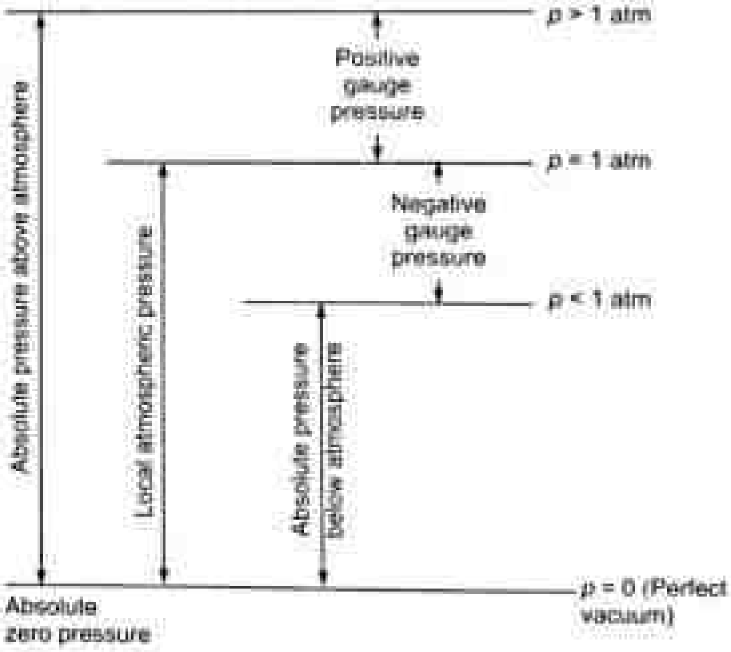


Fig. 1.28 *Relation between atmospheric, absolute and gauge pressures*

is measured by *vacuum gauges*, which indicate the difference between the atmospheric pressure and actual (absolute) pressure. It is expressed as

$$p_{vacuum} = p_{atm} - p_{abs} = -p_{gauge} \qquad ...(1.13)$$

1.13 TEMPERATURE AND ZEROTH LAW OF THERMODYNAMICS

1.13.1 Temperature

Temperature can be defined as a measure of hotness or coldness, but it is not the exact definition. Temperature is a basic property, such as mass, length and time thus cannot be defined precisely.Based on our sensation, we express the level of temperature qualitatively with words like 'cold', 'freezing cold', 'warm', 'hot' and 'red hot'. However, a numerical value cannot be assigned to these feelings, because our sensations may be misleading. For example, a metal chair will feel much colder than a wooden one, even when both are at the same temperature.

1.17 ENTROPY

It is an abstract property of the second law of thermodynamics. It is considered as a measure of degree of the molecular disorder in the matter. The change in value is calculated as

$$\Delta S = \int_1^2 \frac{\delta Q}{T} = \int_1^2 mC\frac{dT}{T} \qquad \text{...(1.22)}$$

(iii) An Isochoric (Isometric) Process The *volume* remains constant during the process.

(iv) An Isentropic Process The *entropy* remains constant during the process.

(v) An Isenthalpic Process The *enthalpy* remains constant during the process.

1.7.4 Cycle

If a system undergoes a series of processes in such a way that its *initial* and *final* states are identical then the system is said to have undergone a *cyclic process* or simply a *cycle*. A thermodynamic cycle is a sequence of processes that begins and ends at the same state as shown in Fig. 1.25. At the conclusion of a cycle, all properties of the fluid have the same values as they had at the initial state.

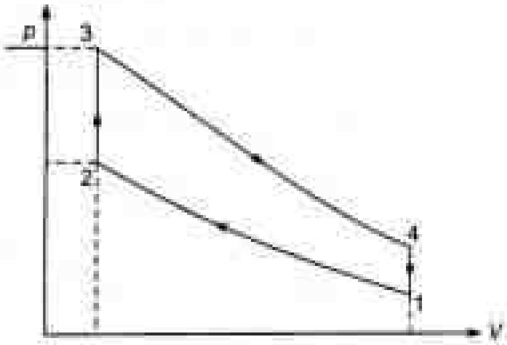


Fig. 1.25 *Cyclic process*

1.8 POINT FUNCTION AND PATH FUNCTION

When a system undergoes a change from one state to another, the properties of the system also change, which depend only on end states and not on the path followed between these two states. Therefore, these properties are called state functions or point functions. *Point functions* can be represented by a point on any plot, e.g., temperature, pressure, volume, etc. These properties have exact differentials designated by the symbol *d*. Therefore, change in volume or pressure is represented by dV or dp, respectively.

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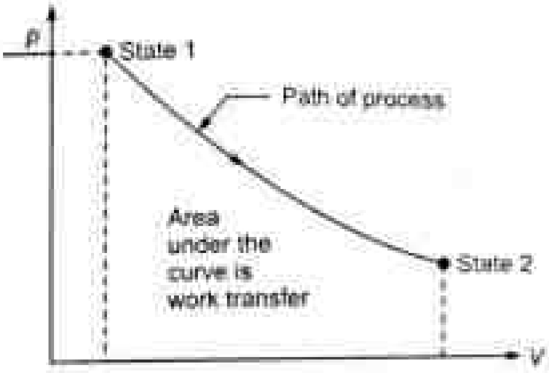

Fig. 1.26 *Reprsentation of path function quantity*

1.9 QUASI-STATIC PROCESS

When a process proceeds in such a manner tha the system remains infinitesimally close to an equilibrium state at all times, it is called a *quasi-static*, or *quasi-equilibrium* process. A quasi-static process is viewed as a sufficiently slow process in which system changes its state very slowly unde the influence of an infinitesimally small drivin force. The system adjusts itself internally, so tha the properties in one part of the system do no change any faster than those in the other part.

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1.5 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.

An isolated system always reaches in course of time a state of thermodynamic equilibrium and *can never depart from it spontaneously*.

Therefore, there can be no *spontaneous change in any macroscopic property* if the system exists in an equilibrium state. Thermodynamics studies mainly the properties of physical systems that are found in equilibrium states.

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 the absence of any unbalanced force within the system itself and also between the system and the surroundings, the system is said to be in a state of *mechanical equilibrium*. If an unbalanced force exists, either the system alone or both the system and the surroundings will undergo a change of state till mechanical equilibrium is attained.

If there is no chemical reaction or transfer of matter from one part of the system to another, such as diffusion or solution, the system is said to exist in a state of *chemical equilibrium*.

When a system existing in mechanical and chemical equilibrium is separated from its surroundings by a diathermic wall (diathermic means 'which allows heat to flow') and if there is no spontaneous change in any property of the system, the system is said to exist in a state of *thermal equilibrium*. When this is not satisfied, the system will undergo a change of state till thermal equilibrium is restored.

When the conditions for any one of the three types of equilibrium are not satisfied, a system is said to be in a *nonequilibrium state*. If the nonequilibrium of the state is due to an unbalanced force in the interior of a system or between the system and the surroundings, the pressure varies from one part of the system to another. There is no single pressure that refers to the system as a whole. Similarly, if the nonequilibrium is because of the temperature of the system being different from that of its surroundings, there is a nonuniform temperature distribution set up within the system and there is no single temperature that stands for the system as a whole. It can thus be inferred that when the conditions for thermodynamic equilibrium are not satisfied, the states passed through by a system cannot be described by thermodynamic properties which represent the system as a whole.

Thermodynamic properties are the macroscopic coordinates defined for, and significant to, only thermodynamic equilibrium states. Both classical and statistical thermodynamics study mainly the equilibrium states of a system.

1.6 QUASI-STATIC PROCESS

Let us consider a system of gas contained in a cylinder (Fig. 1.7). The system initially is in 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

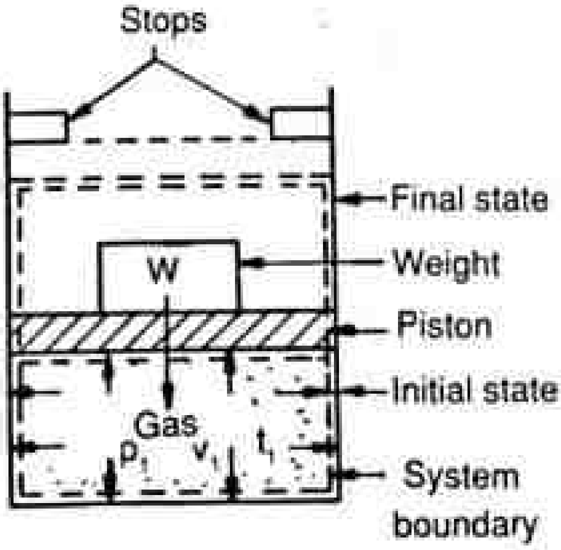


FIG. 1.7 *Transition between two equilibrium states by an unbalanced force*

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. Figure 1.8 shows points 1 and 2 as the initial and final equilibrium states joined by a dotted line, which has got no meaning otherwise. Now if the single weight on the piston is made up of many very small pieces of weights (Fig. 1.9), 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. 1.10), '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.*

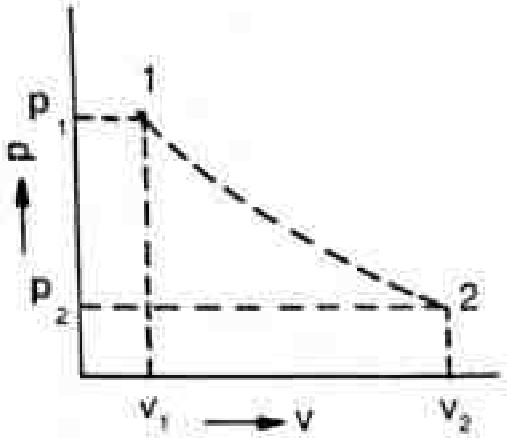


FIG. 1.8 *Plot representing the transition between two equilibrium states*

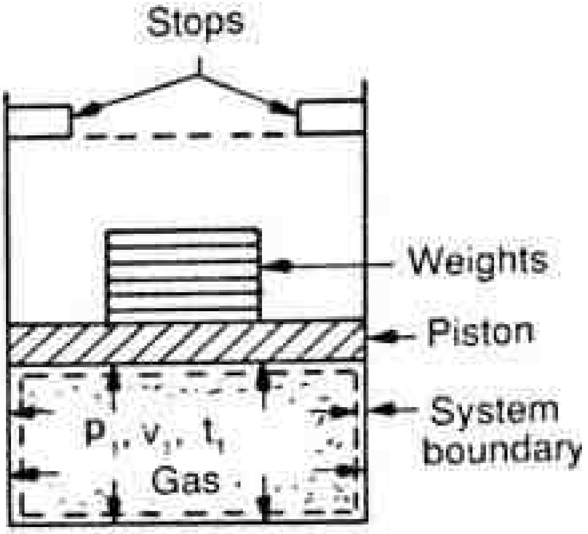


FIG. 1.9 *Infinitely slow transition of a system by infinitesimal force*

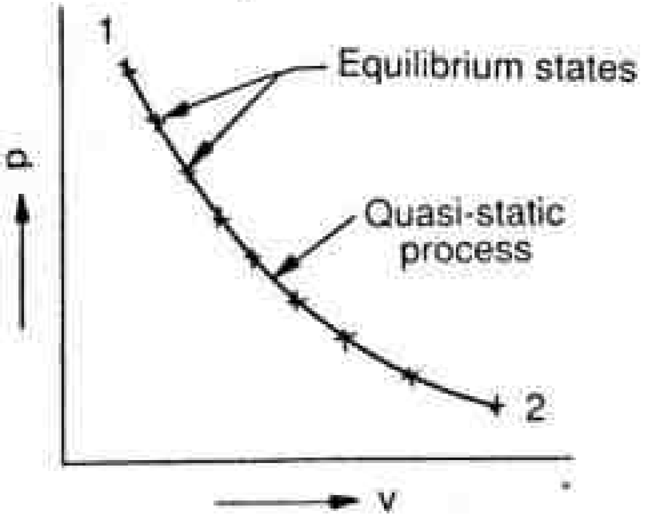


FIG. 1.10 *A quasi-static process*

Energy and Work Transfer

Introduction

Energy is one of the major inputs for the economic development of any country. In the case of developi countries, the energy sector assumes a critical importance in view of the ever-increasing energy nee requiring huge investments to meet them.

Work is a high-grade energy and of prime interest as it is the output from a system, when energy is t input. The rate of work transfer is referred as *power*. High power generation is the need of any developin country.

Sources and forms of energy, enthalpy, forms of work transfer, concept of thermodynamic work transfe heat, specific heat, sign convention for work and heat transfer are discussed in this chapter as a foundati to the following chapters. The first law of thermodynamics is explained with the help of Joule's experimer and other examples.

2.1 ENERGY

Energy is defined as the *capacity to do work*. It is a scalar quantity. It is measured in kJ in SI units, and kcal in MKS units. Energy can have many forms as shown in Fig. 2.1.

2.2 SOURCES OF ENERGY

The sources of energy can be divided into fou categories according to their availabilty:

(i) Transitional Energy The energy in motion, i.e. wind energy, hydel energy, etc.

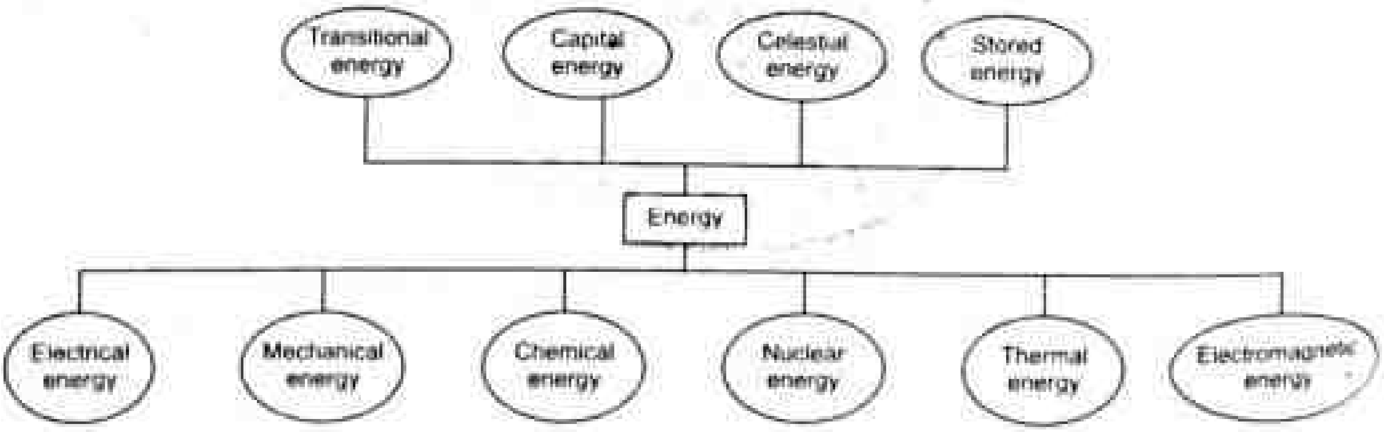


Fig. 2.1 *Sources and forms of energy*

(ii) Capital Energy The energy derived from fuels existing in the earth, i.e., fossile fuels, nuclear fuels, etc.

(iii) Celestial Energy The energy coming from outer atmosphere, i.e., sun, moon, etc.

(iv) Stored Energy The energy existing in various masses, i.e., flywheel, tides, geothermal, hydraulic energy, etc.

2.3 CLASSIFICATION OF ENERGY SOURCES

The sources and forms of energy can be classified into several types based on the following criteria:

- Primary and secondary energy
- Commercial and non-commercial energy
- Renewable and non-renewable energy

2.3.1 Primary and Secondary Energy

Primary forms of energy are those that are either found or stored in nature. Common primary energy sources are coal, oil, natural gas, and biomass (such as wood). Other primary energy sources available include nuclear energy from radioactive substances, thermal energy stored in the earth's interior (geothermal energy), and potential energy due to the earth's gravity.

Secondary forms of energy are those forms which are derived from the primary forms of energy; for example, coke, oil or gas converted into steam and electricity.

2.3.2 Commercial Energy and Non-Commercial Energy

Commercial forms of energy are available in the market for a definite price. The most important forms of commercial energy are electricity, coal and refined petroleum products. Commercial energy serves the basis of industrial, agricultural, transport and commercial development in the modern world.

Non-commercial forms of energy are not available in the commercial market for a definite price. Non-commercial energy sources include fuels such as firewood, cattle dung and agricultural wastes, which are traditionally gathered, and not bought at a price, and used especially in rural households. These are also called *traditional fuels*. Non-commercial energy is often ignored in energy accounting.

2.3.3 Renewable and Non-Renewable Energy

Renewable energy is obtained from sources that are not exhaustible. These are freely available in nature and can be continuously used.

Examples of renewable resources include wind power, solar power, geothermal energy, tidal power, ocean thermal energy, fuel cells, energy from biomass and hydraulic energy. The most important feature of renewable energy is that it can be harnessed without the release of harmful pollutants.

Non-renewable energy is obtained from conventional fossil fuels such as coal, oil and gas, nuclear fuels, and heat traps which are accumulated in the earth crust. These have been in use for several decades. The sources of non-renewable energy are depleting at a fast rate and may not be sufficient to meet the inceasing energy demand in future. Therefore, these sources are also called *exhaustible sources of energy* and they cannot be replenished immediately.

2.3.4 Comparison between Renewable and Non-Renewable Energy Sources

Renewable sorces of energy

These are inexhaustible.

These are freely available.

These are environment-friendly.

Energy concentration varies from region to region.

Cost of equipments for harnessing energy is high, but maintenance and operational costs are minimum.

- Perfect energy utilization equipments are yet to be designed.

Non-renewable sources of energy

- These are exhaustible.
- These are available at definite prices.
- These are hazardous to the environment.
- Energy concentration does not vary.
- Cost of equipments, maintenance and operation are high.
- Competitive designs are progressing satisfactorily.

2.4 FORMS OF ENERGY

Energy can exist in numerous forms, such as internal, thermal, electrical, mechanical, kinetic, potential, wind, and nuclear energy.

In thermodynamic analysis, all forms of energy can be put into two groups:

(a) Stored energy, and
(b) Transit energy.

(a) Stored Energy The stored form of energy can further be classified as

(i) Macroscopic forms of energy: *potential energy* and *kinetic energy*, and
(ii) Microscopic forms of energy: *internal energy*.

The macroscopic forms of energy are defined as energy with respect to some outside reference.

The microscopic forms of energy are those which are related to the molecular structure of a system and degree of molecular activities and are independent of the outside reference.

(b) Transit Energy Transit energy means energy in transition. It is the energy possessed by a system, which is capable of crossing the boundaries. Heat energy and work transfer are transit forms of energy.

2.4.1 Potential Energy

The energy that a system possesses as a result of its elevation in a gravitational field is called *potential energy* (*PE*) and is expressed as

$$PE = mgz \text{ (joules)} \qquad \ldots(2.1)$$

on unit mass basis $\quad pe = gz \text{ (J/kg)} \qquad \ldots(2.2)$

where g is the acceleration due to gravity and z is the elevation of the system relative to some outside reference.

2.4.2 Kinetic Energy

The energy that a system possesses, as a result of motion relative to some reference is called *kinetic energy* (*KE*). When all parts of a system move with the same velocity, the kinetic energy is expressed as

$$KE = \frac{1}{2} m\mathcal{V}^2 \text{ (joule)} \qquad \ldots(2.3)$$

on unit mass basis $\quad ke = \dfrac{1}{2}\mathcal{V}^2 \text{ (J/kg)} \qquad \ldots(2.4)$

where $\mathcal{V}$ is the velocity of the system with respect to some reference.

2.4.3 Internal Energy

The sum of all the microscopic forms of energy is called *internal energy*. The internal energy of a system is the energy stored within the body resulting from the kinetic and potential energy of its molecules. Thus, it is related to molecular structure and degree of molecular activities. The molecules of any system may possess both kinetic and potential energy. Thus, the internal energy of any system may be viewed as the sum of kinetic and potential energy of molecules. It is denoted by U and is measured in joules.

$$U = K + P \text{ (joules)} \qquad \ldots(2.5)$$

where K = internal kinetic energy of molecules and
P = internal potential energy of molecules

(a) Internal Kinetic Energy All molecules in a system move around with some velocity, vibrate about each other, and rotate about an axis during their random motion as shown in Fig. 2.2. The *internal kinetic energy* is the sum of all these motions of molecules. When energy passes into a

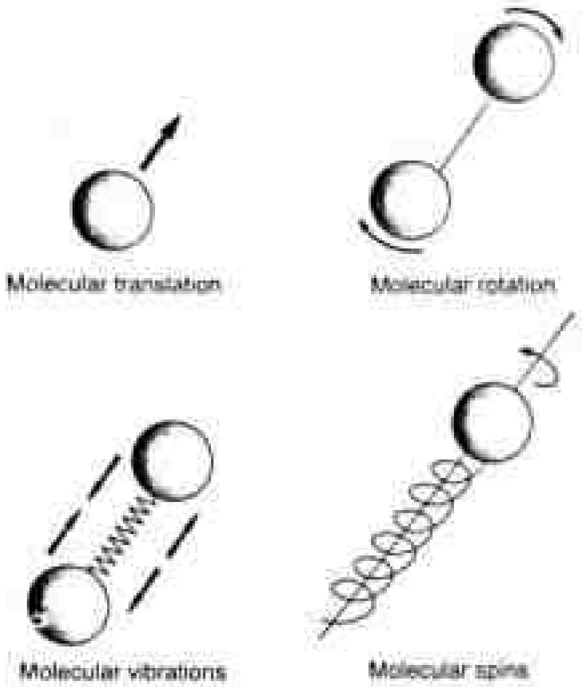


Fig. 2.2 *Molecular motions*

system, it increases the motion of molecules, thus the internal kinetic energy of system is increased, and this change is reflected by an increase in temperature of the system. Sometimes, kinetic internal energy of molecules is referred as *sensible energy*. The average velocity and the degree of activities of molecules are proportional to the temperature of a gas. Thus, at higher temperature, a system will possess higher internal energy.

(b) Internal Potential Energy Internal potential energy of a system is the energy of molecular separation. It is the energy that the molecules have as a result of their position in relation to one another. The greater the degree of molecular separation, the greater is the internal potential energy.

When a system expands or changes its physical state with addition of energy, a rearrangement of molecules takes place that increases the mean distance between them. An internal work is required to pull the molecules against the forces of attraction between them. An amount of internal potential energy equal to the amount of internal work done for rearrangement of molecules is called *latent energy* or *latent heat*.

2.4.4 Mechanical Energy

Mechanical energy can be defined as a form of energy that can be converted directly and completely into mechnical work by an ideal mechanical device such as an ideal turbine or pump. The kinetic and potential energies are the common forms of mechanical energy. Thermal (heat) energy is not a form of mechanical energy since it cannot be converted to work directly and completely.

An ideal turbine extracts mechanical energy from a flowing fluid by reducing its pressure, while a pump transfers mechanical energy to a fluid by raising its pressure. The pressure force acting on a fluid through a distance produces flow work (pv per unit mass). It is the energy of a flowing fluid, and is thus called *flow energy*. Therefore, the mechanical energy of a flowing fluid on a unit mass basis is viewed as

$$e_{mech} = pv + \frac{V^2}{2} + gz \qquad \ldots(2.6)$$

where pv is the flow energy, $\frac{V^2}{2}$ is the kinetic energy and gz is the potential energy of unit mass of a fluid. It can also be expressed in the rate form as

$$\dot{E}_{mech} = \dot{m}\left(pv + \frac{V^2}{2} + gz\right) \qquad \ldots(2.7)$$

where $\dot{m}$ is the mass flow rate of fluid. The mechanical energy change of a fluid is

$$\Delta e_{mech} = (p_2v_2 - p_1v_1) + \left(\frac{V_2^2 - V_1^2}{2}\right) + g(z_2 - z_1) \qquad \ldots(2.8)$$

and $\Delta \dot{E}_{mech}$

$$= \dot{m}\left[(p_2v_2 - p_1v_1) + \left(\frac{V_2^2 - V_1^2}{2}\right) + g(z_2 - z_1)\right] \qquad \ldots(2.9)$$

In the absence of any losses, the mechanical energy change represents the mechanical work supplied to the fluid (if $\Delta e_{mech} > 0$); or extracted from the fluid (if $\Delta e_{mech} < 0$). The shaft work, spring work, acceleration work, gravitational work, work done on a solid elastic bar are also some mechanical forms of work.

In *electrical work*, the force is voltage (potential difference) and displacement is electrical current; in *magnetic work*, the force is the magnetic field strength and displacement is magnetic dipole moment and are not mechanical forms of work.

2.5 ENTHALPY

The sum of the internal energy U and the product of pressure p and volume V appears frequently in many thermodynamic analyses. Therefore, it is convenient to give a name to this combination, *enthalpy*. It is also called *total enthalpy* and is designated by H. By definition,

$$H = U + pV \qquad ...(2.10)$$

Since U, p and V all are properties, the enthalpy is also a property of the system. It is measured in units of internal energy, i.e., kJ in SI units. The enthalpy for unit mass system is referred as *specific enthalpy* and is denoted by h (kJ/kg),

$$h = u + pv \qquad ...(2.11)$$

The enthalpy per mole basis is expressed as

$$\bar{h} = \bar{u} + p\bar{v} \qquad ...(2.12)$$

It should be noted that the enthalpy is a combination of other properties and it is not a form of energy.

2.6 HEAT

It is a *transfer form* of energy that flows between two systems (or a system and its surroundings) by virtue of the temperature difference between them. The temperature difference is the potential for heat transfer. There would be no heat transfer between two systems if they are at the same temperature.

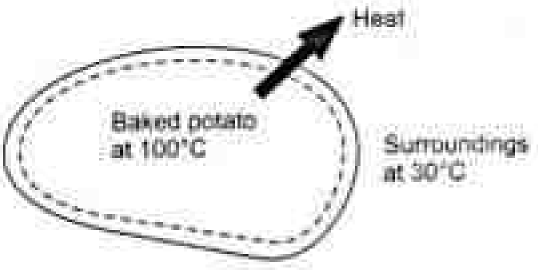
The amount of heat transferred from the state 1 to the state 2 is designated Q_{1-2} or Q and it is measured in joules (J) or kilojoules (kJ) in SI units and calories (cal) or kilocalories (kcal) in MKS units.

Heat transfer per unit mass of a system is denoted by q and is expressed as

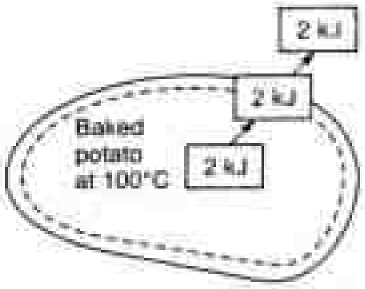
$$q = \frac{Q}{m} \text{ (kJ/kg)} \qquad ...(2.1$$

2.6.1 Heat Supply and Heat Rejection

The heat or heat energy is generally referred a *heat transfer*. The transfer of heat into a system i called *heat addition* or *heat supply* and the transfe of heat from the system is called *heat rejection*. I is recognized as it crosses the system boundary. Fo example, a hot potato rejects its internal energy a heat at its boundary to its surroundings as shown i Fig. 2.3(b).



(a) Heat transfer by virtue of temperature differenc



(b) Energy as heat crossing the boundary

Fig. 2.3

A process during which there is no heat transf is called an *adiabatic process* as shown in Fig. 2. In an adiabatic process, energy content and the tem perature of a system can be changed by other pro cesses, such as work.

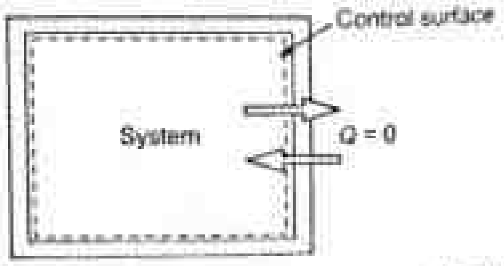


Fig. 2.4 *A system exchanging no heat with surroun ings is an adiabatic system*

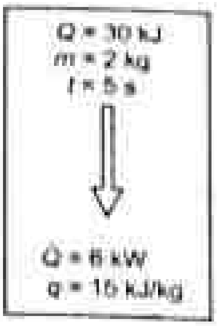


Fig. 2.5 *Relation between Q and q*

2.6.2 Heat-Transfer Rate

The quantity of heat transferred in unit time is called *heat-transfer rate*. It is designate as $\dot{Q}$ and is measured in kJ/s or kW. It is given as

$$\dot{Q} = \frac{Q}{\Delta t} \qquad \text{... (2.14)}$$

2.6.3 Heat vs Internal Energy

In thermodynamics, heat and internal energy are two different forms of energy. Internal energy is a property, while heat is not. A body may contain energy (in stored form) but not heat. The internal energy is associated with a state, while heat is associated with a process. Therefore, *heat or heat energy is defined as a form of energy in transit*. Heat is a path function. It requires a specific direction in its representation on a plot.

2.6.4 Sign Convention for Heat

Heat is a directional quantity, and its specification requires magnitude and direction. Universally accepted sign conventions for heat energy are shown in Fig. 2.6:

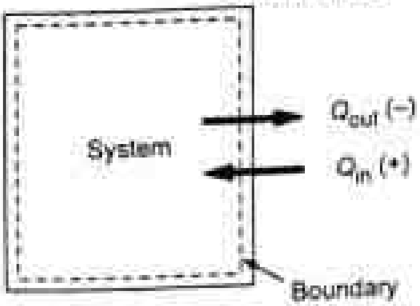


Fig. 2.6 *Sign convention for heat transfer*

1. Heat transferred to a system (heat supply) is considered *positive*.
2. Heat transferred from a system (heat rejection) is considered *negative*.

In other words, the quantity of heat which increases the energy content of a system is positive and any heat transfer that decreases the energy content of a system is negative.

2.7 SPECIFIC HEAT

It is defined as *heat energy required to change the temperature of the unit mass of a substance by one degree*. It is designated as C and is measured in kJ/kg·K or kJ/kg·°C in SI units and kcal/kg·K in MKS units. In general, the specific heat can be calculated as

$$C = \frac{1}{m}\left(\frac{\delta Q}{dT}\right) = \frac{\delta q}{dT} \qquad \text{...(2.15)}$$

Since the heat transfer is a path function, the specific heat also becomes path function and it depends on how the process is executed. The value of energy storage capacity of the substance depends upon specific heat. The value of specific heat depends upon

(i) molecular arrangement of the system,
(ii) Condition under which change of state occurs,
(iii) How the system executes the process

2.7.1 Specific Heats of Solids and Liquids

Essentially, gases have two specific heats: C_p and C_v. But for liquids and solids, the specific volume is very small and its change with pressure and temperature is negligible. Consequently, the term $d(pv)$ is neglected from the differential form of Eq. (2.11), and thus

$$dh = du$$

It indicates that for solids and liquids, the enthalpy is equal to internal energy. Thus they have only one specific heat designated as C. Therefore, for any process of solids and liquids,

$$dq = dh = du \equiv C\,dT \qquad \text{...(2.16)}$$

2.7.2 Heat Capacity

The product of mass and specific heat is defined as *heat capacity* of the system. It is measured in kJ/K or kJ/°C.

Example 2.1 *4 kg of solid material is heated from 15°C to 115°C with addition of 750 kJ of heat in a furnace. Calculate its specific heat.*

Solution

Given Mass of system, $m = 5$ kg
Initial temperature, $T_1 = 15°\text{C}$
Final temperature, $T_2 = 115°\text{C}$,
Heat added $Q = 750$ kJ

To find The specific heat of the solid system

Analysis The heat supplied to a system is expressed as

$$Q = mC(T_2 - T_1)$$

$$\therefore \quad C = \frac{Q}{m(T_2 - T_1)}$$

$$= \frac{750\ \text{kJ}}{(1\ \text{kg}) \times (115°\text{C} - 15°\text{C})}$$

$$= \mathbf{7.5\ kJ/kg \cdot °C}$$

Example 2.2 *Estimate the rise in temperature of water when it falls through a height of 50 m. Assume that all the heat generated stays in water. The specific heat of water may be taken as 4.2 kJ/kg·°C.*

Solution

Given A running automobile vehicle is brought to rest
Height of water $h = 100$ m,
Specific heat of water $C = 4.2$ kJ/kg·°C
$= 4200$ J/kg·°C.

To find The temperature rise of water

Assumption Acceleration due to gravity is 9.81 m/s^2.

Analysis The potential energy change of water when it falls through 100 m

$$\Delta PE = mgh = m \times (9.81\ \text{m/s}^2) \times (100\ \text{m}) = 981m\ \text{J}$$

Decrease in potential energy will convert into heat energy, thus

$$Q = \Delta PE = 981m\ \text{J}$$

and $$Q = mC\Delta T$$

or $$\Delta T = \frac{Q}{mC} = \frac{981m}{m \times 4200} = \mathbf{0.233°C}$$

Example 2.3 *An automobile vehicle of 1500 kg running at a speed of 60 km/h. The brakes are suddenl applied and the vehicle is brought to rest. Calcula the rise in temperature of brake shoes, if their mas 15 kg. Take the specific heat of brake shoe material 0.46 kJ/kg·K.*

Solution

Given A running automobile vehicle is brought to res
Initial vehicle speed, $V_1 = 60$ km/h $= 16.67$ m/s
Final vehicle speed $V_2 = 0$
Mass of vehicle, $m_{vehicle} = 1500$ kg.
Mass of brake shoes, $m_{brake} = 5$ kg.
Specific heat $C = 0.46$ kJ/kg·K

To find The temperature rise of brake shoes

Assumption All the heat generated is absorbed b brake shoes.

Analysis The deceleration work of vehicle

$$W_{deceleration} = \Delta KE = \frac{1}{2} m_{\text{vehicle}} (V_2^2 - V_1^2)$$

$$= \frac{1}{2} \times (1500\ \text{kg}) \times ((0\ \text{m})^2 - (16.67\ \text{m})^2)$$

$$= -208417\ J = -208.417\ \text{kJ}$$

When brakes are applied, this deceleration work converts into heat energy and is transferred to brake shoe That is,

$$Q = 208.417\ \text{kJ}$$

and $$Q = m_{brake} C\Delta T$$

$$\therefore \quad \Delta T = \frac{(208.417\ \text{kJ})}{(15\ \text{kg}) \times (0.46\ \text{kJ/kg·K})}$$

$$= \mathbf{30.2°C}$$

Example 2.4 *During a certain process, the spec heat capacity of a system is given by $C = (0.4 + 0.004T$ kJ/kg°C. Find the heat transferred and mean spec heat of gas, when the temperature changes from 25°C t 125°C. The mass of the system is 5 kg.*

Solution

Given Initial temperature, $T_1 = 25°\text{C}$
Final temperature, $T_2 = 125°\text{C}$

Relation, $C = (0.4 + 0.004T)$ kJ/kg °C
Mass of system, $m = 5$ kg

To find The heat-transfer rate

Analysis The relation for specific heat is given as

$$C = (0.4 + 0.004T) \text{ kJ/kg°C}$$

The heat transfer can be calculated as

$$Q = m\int_{T_1}^{T_2} C\,dT$$

$$= 5 \times \int_{25}^{125} (0.4 + 0.004T)\,dT$$

$$\text{or} \quad Q = 5 \times \left[0.4T + 0.004 \times \frac{T^2}{2}\right]_{25}^{125}$$

$$= 5 \times \left[0.4 \times (125 - 25) + 0.004 \times \frac{(125)^2 - (25)^2}{2}\right]_{25}^{125}$$

$$= 5 \times (40 + 30) = \mathbf{350\ kJ}$$

The heat transfer can also be expressed in terms of mean specific heat as

$$Q = mC(T_2 - T_1)$$

Thus $$C = \frac{350}{5 \times (125 - 25)} = \mathbf{0.7\ kJ/kg°C}$$

2.8 WORK

Work like heat is also a form of *energy in transit*. It is defined as the energy transfer associated with force acting through a distance. It is an interaction between a system and its surroundings.

Energy can cross the boundary of the system as heat or work. Therefore, if the energy crossing the boundary is not heat, then it must be work. A moving piston, a rotating shaft, a rising weight are all associated with work interaction.

Work is also measured in kJ. Work done during a process from the state 1 to the state 2 is denoted by W_{1-2} or W. The work done per unit mass (w) is defined as

$$w = \frac{W}{m} \text{ (kJ/kg)} \qquad ...(2.17)$$

An insulated chamber containing a system of gas, and exchanging energy as work transfer only is shown in Fig. 2.7. The heat energy does not cross the system boundary as the insulated wall and the moving blades add internal energy to the system.

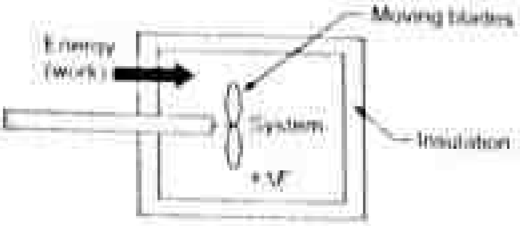


Fig. 2.7 *An energy interaction as work transfer to a insulated system*

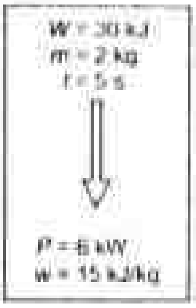


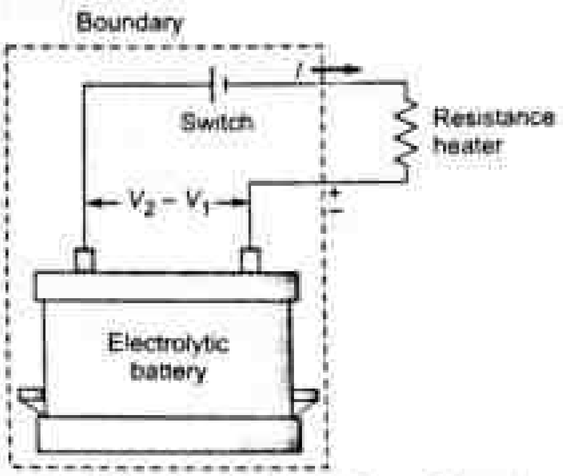
Fig. 2.8 *Relation between W, P and w*

2.8.1 Thermodynamic Definition of Work

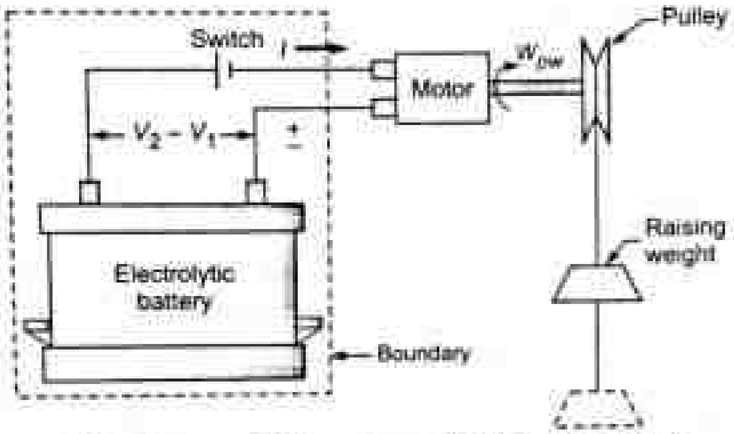
In thermodynamics, force and distance are not easily recognized in some energy interactions. According to the thermodynamic definition of work, *an energy interaction between a system and its surroundings during a process can be considered as work transfer, if its sole effect on every thing external to the system could have been to raise a weight.*

Thermodynamic work refers to transfer of energy due to potential difference other than temperature difference, without transfer of mass across the system boundary. It is an extension of the concept of work in mechanics.

Consider a system consisting of an electrical battery, switch, and a resistance coil outside the system as shown in Fig. 2.9(a). When the switch is closed, the current flows through the resistance coil. Thus, electrical energy crossing the boundary of the system is converted into heat energy. At the boundary of the system, force and motion are not evident; and thus according to mechanics, this energy interaction cannot be regarded as work transfer.



(a) Battery work through a resistance



(b) Battery works through an electric motor-pulley and weight

Fig. 2.9 *Concept of thermodynamic work*

However, an electric current is driven by an electrical potential difference external to the system. Thus, the work is done by the battery according to thermodynamic definition. This concept can be illustrated by replacing the external resistance by an *imaginary* motor-pulley and weight as shown in Fig. 2.9(b). When the switch is closed, the battery drives the motor. The pulley rotates and in turn raises the suspended weight. Thus, the sole effect external to the system becomes to raise a weight.

2.8.2 Power

The quantity of work transfer per unit time is called *power.* It is actually the rate of work transfer. It is denoted by P and measured in kW (= kJ/s).

$$P = \frac{\delta W}{dt} \text{ (kW)} \qquad \ldots(2.18)$$

Sometimes the power is also expressed in horse power (hp). The relation between hp and kW is

$$1 \text{ hp} = 0.746 \text{ kW}$$

2.8.3 Sign Convention for Work Transfer

The complete specification of work transfer also requires magnitude and direction. The universally accepted sign conventions for work transfer are shown in Fig. 2.10.

1. The production of work is desirable, therefore, the work done by a system is considered *positive.*
2. The consumption of work is always undesirable, therefore, work done on a system is considered as *negative.*

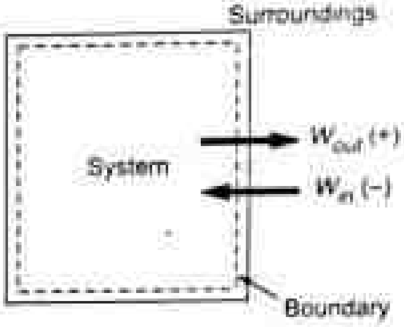


Fig. 2.10 *Sign convention for work transfer*

By the sign convention, work produced by a car engine, hydraulic motor, steam, and gas turbines is positive and work consumed in operation of a compressor, a pump, a refrigerator, a fan, etc., is negative.

2.8.4 Salient Features of Work Transfer

The features of work transfer are given below:

(i) Work is recognized at the system boundary; thus it is a *boundary phenomenon.*

(ii) Work is transferred in specific direction in a process; thus it is *a path function.*

(iii) If the *nature of the process* changes between two given states, the magnitude of work may change.

(iv) Magnitude of work transfer can also be obtained by calculating the area under the path of the process.

2.8.5 Similarities between Heat and Work Transfer

Heat and work both are the interaction of energy between a system and its surroundings and they have some similarities between them.

1. Both are recognized at the boundary of the system as they cross it, thus, both heat and work are boundary phenomena.
2. A system may have energy, but not heat or work, because, heat and work are transient phenomena.
3. Both are associated with a process, not a state. Therefore, unlike properties heat or work has no meaning at a state.
4. Both are path functions. They are represented by a path followed during the process.
5. The equations for heat and work transfer cannot be differentiated exactly. The differential quantities of heat and work are represented as δQ and δW, respectively.

2.8.6 Dissimilarities between Heat and Work Transfer

1. Heat is a *low-grade energy*, whereas the work is a *high-grade energy*.
2. Heat transfer takes place due to *temperature difference* only, while work transfer may take place due to any *potential difference* in pressure, voltage, height, velocity, temperature, etc.
3. A stationary system cannot do work, while such a restriction is not imposed on heat transfer.
4. The entire quantity of work can be converted into heat or any other form of energy, while conversion of the entire quantity of heat into work is not possible.
5. Conversion of work into heat or another form of energy is possible with a single process, while conversion of heat into work requires a complete cyclic process, like a steam power plant.

2.9 FORMS OF WORK TRANSFER

1. Electrical work
2. Mechanical work
3. Moving boundary work
4. Flow work
5. Gravitational work
6. Acceleration work
7. Shaft work
8. Spring work

2.9.1 Electrical Work

Electrical work is the energy interaction due to crossing of electrons at the system boundary. In an electric field, the electrons in a wire move under the effect of electromotive forces for doing work (driving a motor, fan, etc.). The resistance heating as an electrical work is shown in Fig. 2.11.

Fig. 2.11 *Resistance heating as electrical work*

Rate of electrical work transfer can be expressed as

$$W_E = VI \text{ (watts)} \quad \ldots(2.19)$$

The work done W_E in time Δt is

$$W_E = VI\Delta t \text{ (joules)} \quad \ldots(2.20)$$

2.9.2 Mechanical Work

In mechanics, the work done by a system is expressed as a product of force (F) and displacement (s)

$$W = Fs \quad \ldots(2.21)$$

If the force is not constant, the work done is obtained by adding the differential amounts of work,

$$W = \int_1^2 F\,ds \quad \ldots(2.22)$$

2.9.3 Moving Boundary Work

In many thermodynamic problems, mechanical work is the form of moving boundary work. The moving boundary work is associated with real engines and compressors. The pressure difference is the driving force for mechanical work.

Consider the gas enclosed in a frictionless piston cylinder arrangement as shown in Fig. 2.12. Let the gas pressure is p, volume V and piston cross-sectional area is A. If the piston is allowed to move through a distance ds in a quasi-equilibrium manner, the force applied on piston is

$$F = \text{pressure} \times \text{cross-sectional area of piston} = pA$$

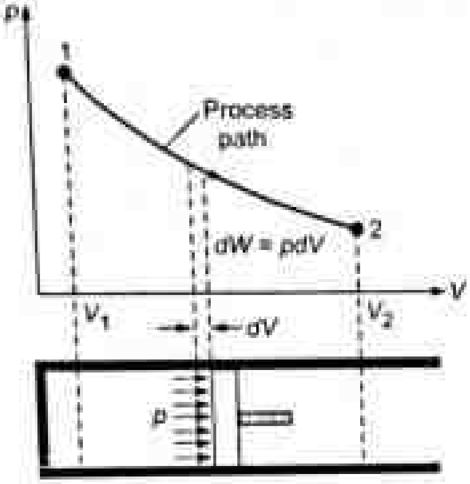


Fig. 2.12 *Schematic and p-V diagram of mechanical work*

Then differential work transfer through a displacement of ds during this process

$$\delta W = pA\,ds = pdV \qquad ...(2.23)$$

Thus, the moving boundary work of a system in differential form is equal to the product of absolute pressure and differential change in its volume dV $(= A\,ds)$.

The total boundary work can be obtained by adding all differential works from the initial state 1 to the final state 2 as

$$W = \int_1^2 pdV \text{ (kJ)} \qquad ...(2.24)$$

This work transfer during a process is equal to the area under the curve on a p–V diagram and the work done by each kg of system is

$$w = \int_1^2 pdv \text{ (kJ/kg)} \qquad ...(2.25)$$

2.9.4 Gravitational Work

The work done against the gravitational force is called *gravitational work* or change in potential energy. The gravitation force F_g acting on a body of mass is

$$F_g = mg \qquad ...(2.26)$$

where g is the acceleration due to gravity. The gravitational work done to raise the body from the elevation z_1 to z_2 is

$$W_g = \int_1^2 F_g\,dz = mg\int_{z_1}^{z_2} dz$$

$$= mg(z_2 - z_1) \text{ (joules)} \qquad ...(2.27)$$

It is an increase in potential energy of the body due to gravitation work done on it.

2.9.5 Acceleration Work

The work associated with change in velocity of a system is defined as the *acceleration work*. Acceleration force, F_a according to Newton's second law of motion is

$$F_a = ma \qquad ...(2.28)$$

where a is the acceleration, which is defined in terms of the velocity $\mathcal{V}$ as

$$a = \frac{d\mathcal{V}}{dt} \qquad ...(2.29)$$

and the velocity $\mathcal{V}$ in terms of the displacement s is defined as

$$\mathcal{V} = \frac{ds}{dt} \qquad ...(2.30)$$

the $\qquad ds = \mathcal{V}dt$

Thus, the acceleration work

$$W_a = \int_1^2 F_a\,ds = \int_1^2 m\left(\frac{d\mathcal{V}}{dt}\right)(\mathcal{V}dt) = m\int_{\mathcal{V}_1}^{\mathcal{V}_2} \mathcal{V}d\mathcal{V}$$

$$= (1/2)\,m(\mathcal{V}_2^2 - \mathcal{V}_1^2) \text{ (joules)} \qquad ...(2.31)$$

where $\mathcal{V}_1$ and $\mathcal{V}_2$ are the initial and final velocities of the moving mass m. The acceleration work is recognised as the *change in kinetic energy*.

2.9.6 Shaft Work

The shaft work is the work associated with energy transmission with a rotating shaft. It is the product of torque (product of force and radius of shaft) and angular displacement.

Consider a shaft of radius r, rotating with N revolutions per minute as shown in Fig. 2.13. If the

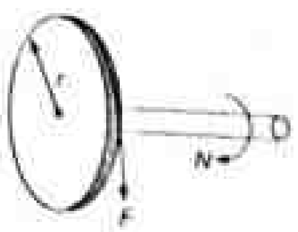


Fig. 2.13 *Work of a moving shaft*

force F is acting through an arm radius r then the *torque* is

$$T = Fr \quad \text{or} \quad F = \frac{T}{r}$$

This force acts through a displacement per unit time,

$$s = (2\pi r) \times \frac{N}{60}$$

Then the shaft work per unit time (shaft power) can be expressed as

$$W_{sh} = Fs = 2\pi r \times \left(\frac{N}{60}\right) \times \frac{T}{r}$$

$$= \frac{2\pi NT}{60} \text{ (watts)} \qquad \ldots(2.32)$$

2.9.7 Spring Work

When the force is applied on a spring, its length changes as shown in Fig. 2.14. If dx is the change in the length of a spring under the influence of a force F then the work done by the spring is

$$\delta W_{spring} = F dx$$

where the force F exerted can be defined in terms of the spring constant k (N/m) as

$$F = kx \text{ (N)}$$

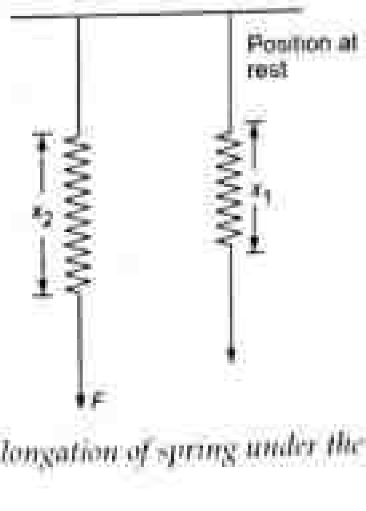


Fig. 2.14 *Elongation of spring under the effect of force*

Then the spring work

$$\delta W_{spring} = kx\,dx$$

If the spring length changes from x_1 (undisturbed position) to x_2 under the action of force, the spring work is

$$W_{spring} = k\int_{x_1}^{x_2} x\,dx$$

$$= (1/2)k(x_2^2 - x_1^2) \qquad \ldots(2.33)$$

Example 2.5 *A gas is compressed from an initial volume of 0.38 m³ to a final volume of 0.1 m³. During the quasi-equilibrium process, the pressure changes with volume according to the relation, $p = aV + b$, where, $a = -1200$ kPa/m³ and $b = 600$ kPa. Calculate the work done during this process.*

Solution

Given Compression of gas in quasi-static manner
$V_1 = 0.38$ m³, $V_2 = 0.1$ m³,
$a = -1200$ kPa/m³, $b = 600$ kPa
and relation $p = aV + b$

To find The work done by the system.

Analysis The work done by a system can be calculated as

$$W = \int_1^2 p dV = \int_{0.38}^{0.1} (aV + b)\, dV$$

$$= \left[\frac{1}{2}aV^2 + bV\right]_{0.38}^{0.1}$$

Using the numerical values

$$W = -1200 \times \frac{0.1^2 - 0.38^2}{2} + 600 \times (0.1 - 0.38)$$

$$W = 80.64 - 168 = \mathbf{-87.36\ kJ}$$

Example 2.6 *In a reversible non-flow process, the work is done by a substance in accordance with $V = \frac{2.80}{p}$ m³, where p is the pressure in bar. Find the work done on or by system as pressure increases from 0.7 bar to 7 bar.*

Solution

Given A reversible non-flow process with
$p_1 = 0.7$ bar $= 70$ kPa, $p_2 = 7$ bar $= 700$ kPa
and relation $V = \frac{2.80}{p}$ m³

INSTITUTE OF TEXTILE TECHNOLOGY
CHOUDWAR

Thermal Engineering-I

Chapter-2
Laws of Thermodynamics

1.13 TEMPERATURE AND ZEROTH LAW OF THERMODYNAMICS

1.13.1 Temperature

Temperature can be defined as a measure of hotness or coldness, but it is not the exact definition. Temperature is a basic property, such as mass, length and time thus cannot be defined precisely. Based on our sensation, we express the level of temperature qualitatively with words like 'cold', 'freezing cold', 'warm', 'hot' and 'red hot'. However, a numerical value cannot be assigned to these feelings, because our sensations may be misleading. For example, a metal chair will feel much colder than a wooden one, even when both are at the same temperature.

1.13.2 Equality of Temperature

If a hot system and cold system are brought into contact with each other, isolated from their surroundings, the hot system gives its heat energy to the cold system till they reach a common temperature, which is the requirement for thermal equilibrium. Two systems attain equal temperature if no changes occur in any property when they remain in contact.

1.13.3 Zeroth Law of Thermodynamics

It states that *when two systems are in thermal equilibrium with a third system, they in turn have thermal equilibrium with each other.*

Consider two systems S_1 and S_2 which are separated by an adiabatic wall, and a third system S_3 is in communication with both the systems as shown in Fig. 1.29.

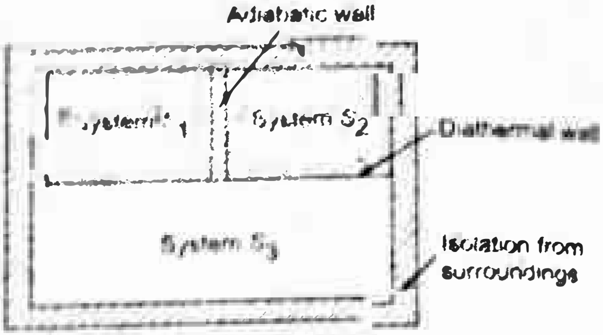


Fig. 1.29 *Three systems in thermal eqilibrium*

If systems S_1 and S_2 are individually in thermal equilibrium with a third system S_3, then the systems S_1 and S_2 will also be in thermal equilibrium with each other, even though they are not in contact.

The zeroth law serves a basis for the validity of temperature measurement, by replacing the third system by a thermometer. The zeroth law can be restated as *two systems are in thermal equilibrium if both have the same temperature reading even if they are not in contact.*

First Law of Thermodynamics

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. 4.1. 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. 4.2 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

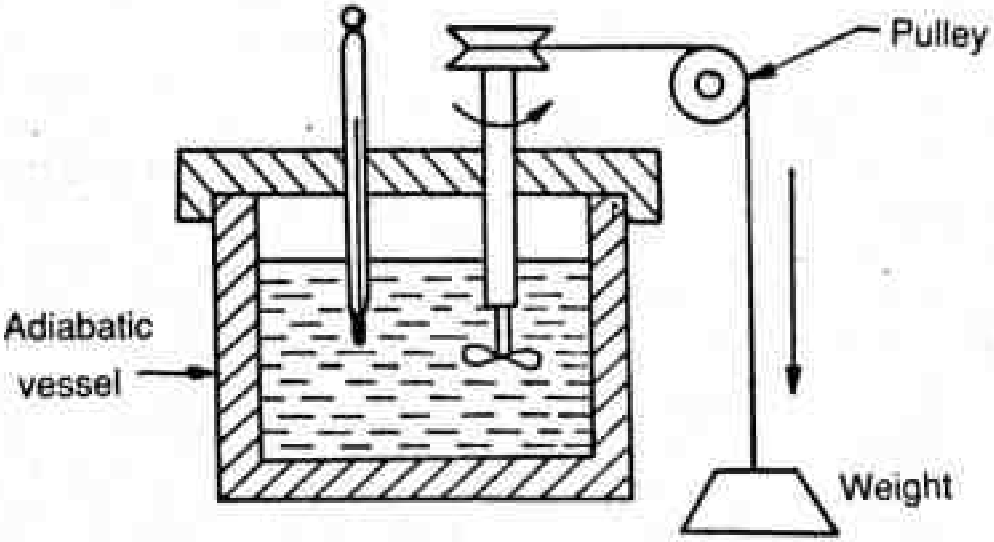


FIG. 4.1 *Adiabatic work*

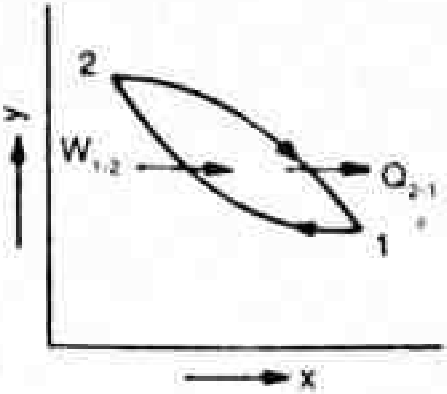


FIG. 4.2 *Cycle completed by a system with two energy interactions: adiabatic work transfer W_{1-2} followed by heat transfer Q_{2-1}.*

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. 4.2, can be estimated. The system thus executes a cycle, which consists of a 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*. In the simple example given here, there are only two energy transfer quantities as the system performs a thermodynamic cycle. If the cycle involves many more heat and work quantities, the same result will be found. Expressed algebraically.

$$(\Sigma W)_{\text{cycle}} = J\,(\Sigma Q)_{\text{cycle}} \tag{4.1}$$

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

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

where the symbol $\oint$ denotes the cyclic integral for the closed path. This is the *first law for a closed system undergoing a cycle*. It is accepted as a *general law of nature*, since no violation of it has ever been demonstrated.

In the S.I. system of units, both heat and work are measured in the derived unit of energy, the Joule. The constant of proportionality, J, is therefore unity (J = 1 Nm/J).

The first law of thermodynamics owes much to J.P. Joule who, during the period 1840–1849, carried out a series of experiments to investigate the equivalence of work and heat. In one of these experiments, Joule used an apparatus similar to the one shown in Fig. 4.1. Work was transferred to the measured mass of water by means of a paddle wheel driven by the falling weight. The rise in the temperature of water was recorded. Joule also used mercury as the fluid system, and later a solid system of metal blocks which absorbed work by friction when rubbed against each other. Other experiments involved the supplying of work in an electric current. In every case, he found the same ratio (J) between the amount of work and the quantity of heat that would produce identical effects in the system.

Prior to Joule, heat was considered to be an invisible fluid flowing from a body of higher calorie to a body of lower calorie, and this was known as the *caloric theory of heat*. It was Joule who first established that heat is a form of energy, and thus laid the foundation of the first law of thermodynamics.

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 (Fig. 4.3), 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 $$Q = \Delta E + W \tag{4.2}$$

Here Q, W, and ΔE are all expressed in the same units (in joules). Energy may be stored by a system in different modes, as explained in Article 4.4.

If there are more energy transfer quantities involved in the process, as shown in Fig. 4.4, the first law gives

$$(Q_2 + Q_3 - Q_1) = \Delta E + (W_2 + W_3 - W_1 - W_4)$$

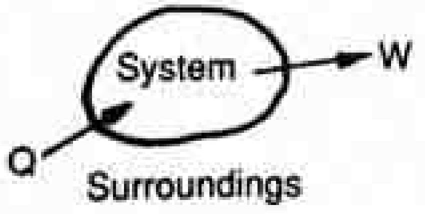


FIG. 4.3 *Heat and work interactions of a system with its surroundings in a process*

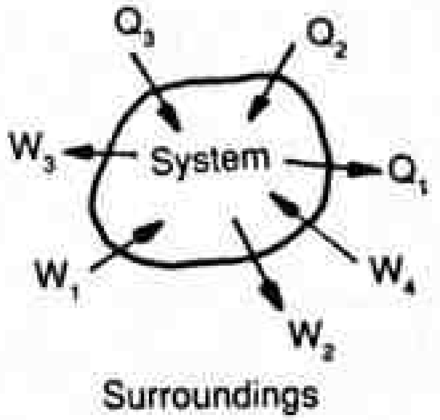


FIG. 4.4 *System-surroundings interaction in a process involving many energy fluxes*

Energy is thus conserved in the operation. The first law is a particular formulation of the principle of the conservation of energy. Equation (4.2) may also be considered as the definition of energy. This definition does not give an absolute value of energy E, but only the change of energy ΔE for the process. It can, however, be shown that the energy has a definite value at every state of a system and is, therefore, a property of the system.

4.3 ENERGY—A PROPERTY OF THE SYSTEM

Consider a system which changes its state from state 1 to state 2 by following the path A, and returns from state 2 to state 1 by following the path B (Fig. 4.5). So the system undergoes a cycle. Writing the first law for path A

$$Q_A = \Delta E_A + W_A \tag{4.3}$$

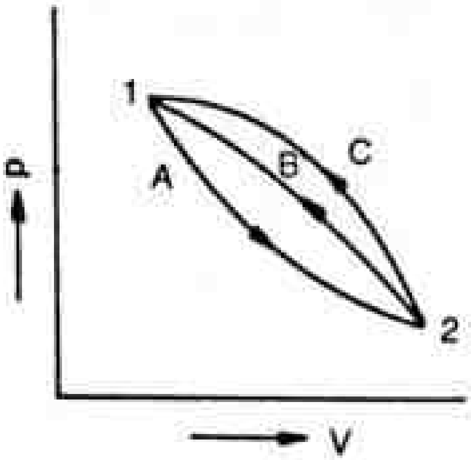


FIG. 4.5 *Energy—a property of a system*

and for path B

$$Q_B = \Delta E_B + W_B \tag{4.4}$$

The processes A and B together constitute a cycle, for which

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

or

$$W_A + W_B = Q_A + Q_B$$

or

$$Q_A - W_A = W_B - Q_B \tag{4.5}$$

From equations (4.3), (4.4), and (4.5), it yields

$$\Delta E_A = -\Delta E_B \tag{4.6}$$

Similarly, had the system returned from state 2 to state 1 by following the path C instead of path B

$$\Delta E_A = -\Delta E_C \tag{4.7}$$

From equations (4.6) and (4.7)

$$\Delta E_B = \Delta E_C \tag{4.8}$$

Therefore, it is seen that the change in energy between two states of a system is the same, whatever path the system may follow in undergoing that change of state. If some arbitrary value of energy is assigned to state 2, the value of energy at state 1 is fixed independent of the path the system follows. Therefore, energy has a definite value for every state of the system. Hence, it is a *point function and a property of the system.*

The energy E is an extensive property. The *specific energy,* $e = E/m$ (J/kg), is an intensive property.

The cyclic integral of any property is zero, because the final state is identical with the initial state. $\oint dE = 0$, $\oint dV = 0$, etc. So for a cycle, the equation (4.2) reduces to equation (4.1).

4.4 DIFFERENT FORMS OF STORED ENERGY

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 $\bar{V}$ (Fig. 4.6). The macroscopic kinetic energy E_K of the fluid element by virtue of its motion is given by

$$E_K = \frac{m\bar{V}^2}{2}$$

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. Matter is composed of molecules. Molecules are in random thermal motion (for a gas) with an average velocity $\bar{v}$, constantly colliding with one another and with the walls (Fig. 4.6). Due to a collision, the molecules may be subjected to rotation as well as vibration. They can have translational kinetic energy, rotational kinetic energy, vibrational energy, electronic energy, chemical energy and nuclear energy (Fig. 4.7). If ε represents the energy of one molecule, then

$$\varepsilon = \varepsilon_{\text{trans}} + \varepsilon_{\text{rot}} + \varepsilon_{\text{vib}} + \varepsilon_{\text{chem}} + \varepsilon_{\text{electronic}} + \varepsilon_{\text{nuclear}} \tag{4.9}$$

If N is the total number of molecules in the system, then the total internal energy

$$U = N\varepsilon \tag{4.10}$$

In an ideal gas there are no intermolecular forces of attraction and repulsion, and the internal energy depends only on temperature. Thus

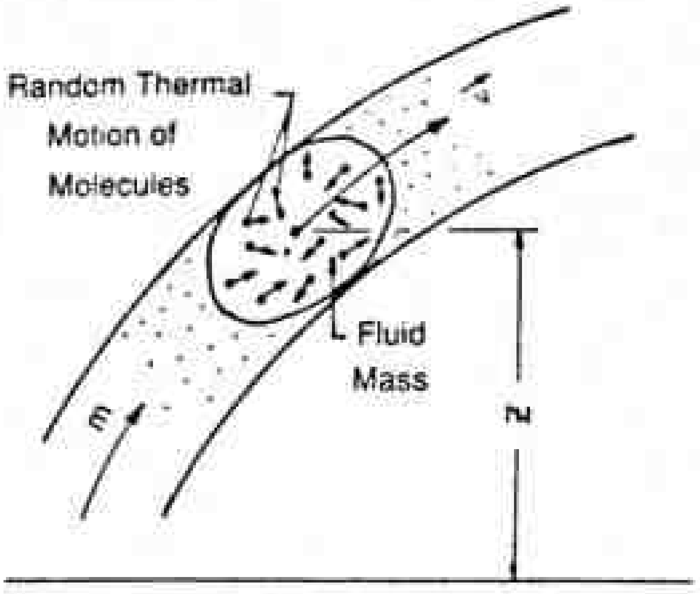


FIG. 4.6 *Macroscopic and microscopic energy*

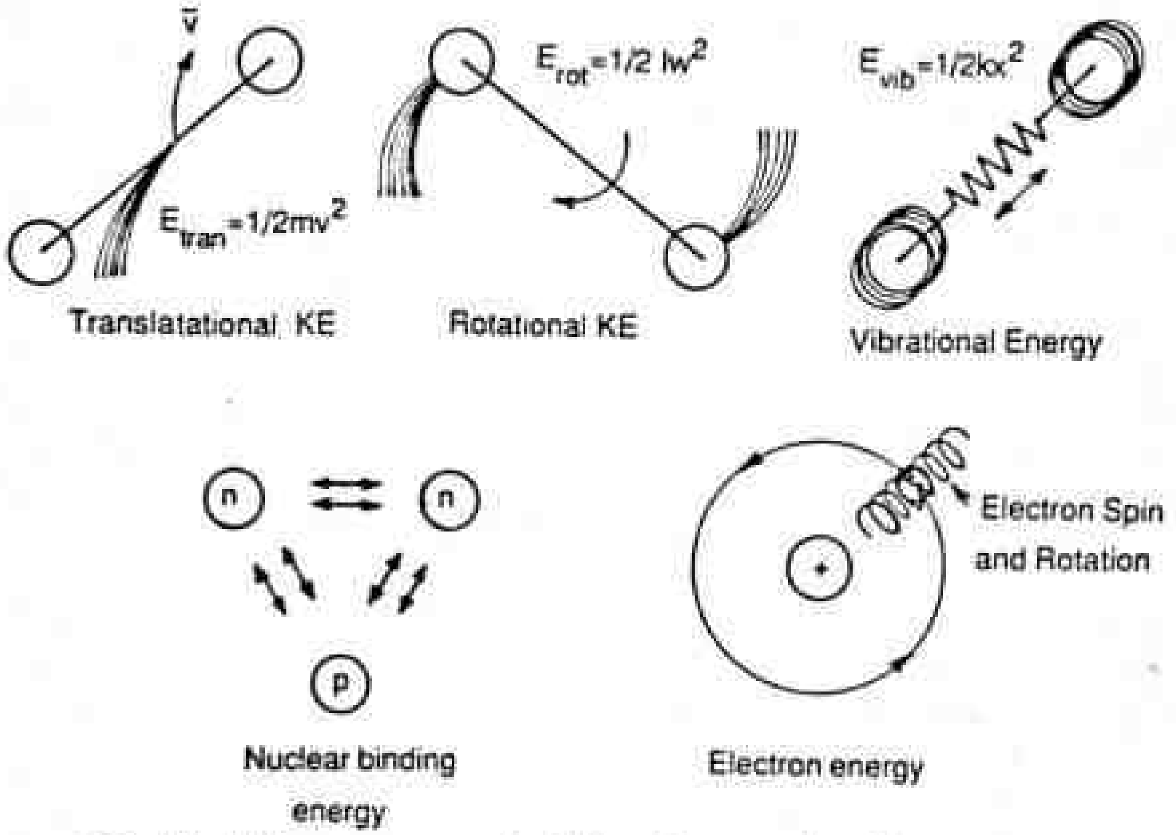


FIG. 4.7 *Various components of internal energy stored in a molecule*

$$U = f(T) \text{ only} \tag{4.11}$$

for an ideal gas

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

$$E = \underbrace{E_K + E_P}_{\text{macro}} + \underbrace{U}_{\text{micro}} \tag{4.12}$$

where E_K, E_P, and U refer to the kinetic, potential and internal energy, respectively. In the absence of motion and gravity

$$E_K = 0,\ E_P = 0$$
$$E = U$$

and equation (4.2) becomes

$$Q = \Delta U + W \tag{4.13}$$

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, equations (4.2) and (4.13) become

$$đQ = dE + đW \tag{4.14}$$

$$đQ = dU + đW \tag{4.15}$$

where $$đW = đW_{pdV} + đW_{\text{shaft}} + đW_{\text{electrical}} + \ldots,$$

considering the different forms of work transfer which may be present. When only pdV work is present, the equations become

$$đQ = dE + p\,dV \tag{4.16}$$

$$đQ = dU + p\,dV \tag{4.17}$$

or, in the integral form

$$Q = \Delta E + \int p dV \tag{4.18}$$

$$Q = \Delta U + \int p dV \tag{4.19}$$

4.5 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.

$$c_v = \left(\frac{\partial u}{\partial T}\right)_v \tag{4.20}$$

For a constant-volume process

$$(\Delta u)_v = \int_{T_1}^{T_2} c_v \cdot dT \tag{4.21}$$

The first law may be written for a closed stationary system composed of a unit mass of a pure substance

$$Q = \Delta u + W$$

or $$đQ = du + đW$$

For a process in the absence of work other than pdV work

$$đW = p\,dV$$

$\therefore$

$$\text{đ}Q = du + p\,dV \tag{4.22}$$

When the volume is held constant

$$(Q)_v = (\Delta u)_v$$

$\therefore$

$$(Q)_v = \int_{T_1}^{T_2} c_v\,dT \tag{4.23}$$

Heat transferred at constant volume increases the internal energy of the system.

If the specific heat of a substance is defined in terms of heat transfer, then

$$c_v = \left(\frac{\partial Q}{\partial T}\right)_v$$

Since Q is not a property, this definition does not imply that c_v is a property of a substance. Therefore, this is not the appropriate method of defining the specific heat, although $(\text{đ}Q)_v = du$.

Since u, T, and v are properties, c_v is a property of the system. The product $mc_v = C_v$ is called the *heat capacity at constant volume* (J/K).

4.6 ENTHALPY

The enthalpy of a substance, h, is defined as

$$h = u + pv \tag{4.24}$$

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 equation (4.22), it is possible to derive 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

$$\text{đ}Q = du + pdV$$

At constant pressure

$$pdV = d(pv)$$

$\therefore$

$$(\text{đ}Q)_p = du + d(pv)$$

or

$$(\text{đ}Q)_p = d(u + pv)$$

or

$$(\text{đ}Q)_p = dh \tag{4.25}$$

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

$$h = u + RT \tag{4.26}$$

Since the internal energy of an ideal gas depends only on the temperature

(Eq. 4.11), the enthalpy of an ideal gas also depends on the temperature only, i.e.

$$h = f(T) \text{ only} \tag{4.27}$$

Total enthalpy $H = mh$

Also
$$H = U + pV$$

and
$$h = H/m \text{ (J/kg)}$$

4.7 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

$$c_p = \left(\frac{\partial h}{\partial T}\right)_p \tag{4.28}$$

Since h, T and p are properties, so c_p is a property of the system. Like c_v, c_p should not be defined in terms of heat transfer at constant pressure, although $(\text{đ}Q)_p = dh$.

For a constant pressure process

$$(\Delta h)_p = \int_{T_1}^{T_2} c_p\, dT \tag{4.29}$$

The first law for a closed stationary system of unit mass

$$\text{đ}Q = du + p\, dV$$

Again
$$h = u + pv$$

$\therefore$
$$dh = du + p\, dV + v\, dp$$
$$= \text{đ}Q + v dp$$

$\therefore$
$$\text{đ}Q = dh - v dp \tag{4.30}$$

$\therefore$
$$(\text{đ}Q)_p = dh$$

or
$$(Q)_p = (\Delta h)_p$$

$\therefore$ From equations (4.19) and (4.20)

$$(Q)_p = \int_{T_1}^{T_2} c_p\, dT$$

c_p is a property of the system, just like c_v. The *heat capacity at constant pressure* C_p is equal to mc_p (J/K).

4.8 ENERGY OF AN ISOLATED SYSTEM

An isolated system is one in which there is no interaction of the system with the surroundings. For an isolated system, $\text{đ}Q = 0$, $\text{đ}W = 0$.

$$dE = 0$$

or

$$E = \text{constant}$$

The energy of an isolated system is always constant.

4.9 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. 4.8). 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. 4.9).

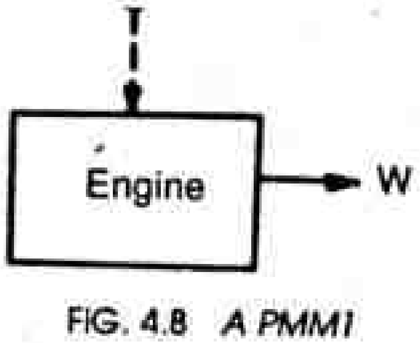


FIG. 4.8 *A PMM1*

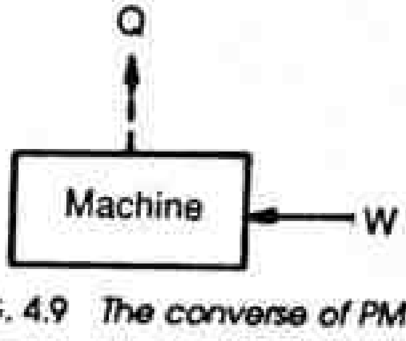


FIG. 4.9 *The converse of PMM1*

3.2.2 pdV-Work in Various Quasi-Static Processes

(a) Constant pressure process (Fig. 3.7) (isobaric or isopiestic process)

$$W_{1-2} = \int_{V_1}^{V_2} p\,dV = p(V_2 - V_1) \tag{3.4}$$

(b) Constant volume process (Fig. 3.8) (isochoric process)

$$W_{1-2} = \int p\,dV = 0 \tag{3.5}$$

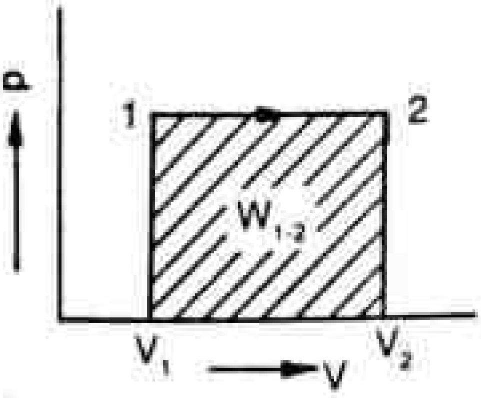


FIG. 3.7 *Constant pressure process*

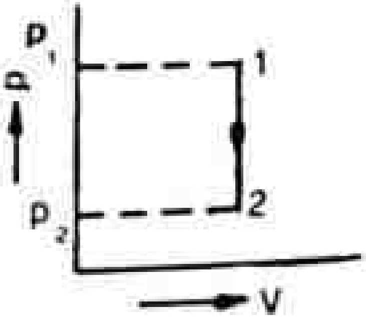


FIG. 3.8 *Constant volume process*

(c) Process in which $pV = C$ (Fig. 3.9)

$$pV = p_1V_1 = C$$

$$\therefore \quad W_{1-2} = \int_{V_1}^{V_2} p\,dV \qquad p = \frac{(p_1V_1)}{V}$$

$$W_{1-2} = p_1V_1 \int_{V_1}^{V_2} \frac{dV}{V} = p_1V_1 \ln \frac{V_2}{V_1}$$

$$= p_1V_1 \ln \frac{p_1}{p_2} \qquad (3.6)$$

(d) Process in which $pV^n = C$, where n is a constant (Fig. 3.10).

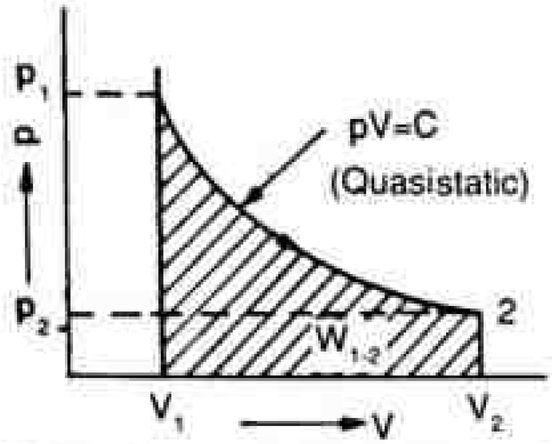


FIG. 3.9 *Process in which pV = constant*

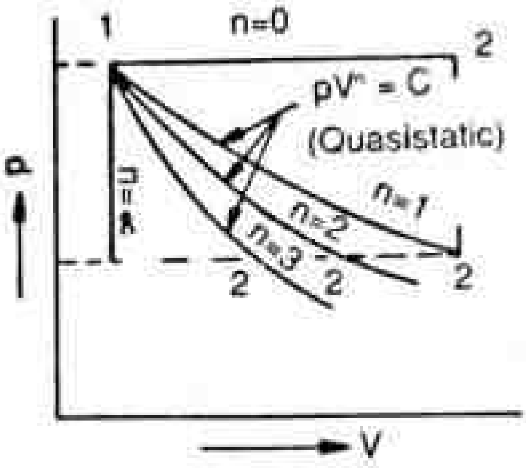


FIG. 3.10 *Process in which pVⁿ = constant*

$$pV^n = p_1V_1^n = p_2V_2^n = C$$

$$\therefore \qquad p = \frac{(p_1V_1^n)}{V^n}$$

$$\therefore \qquad W_{1-2} = \int_{V_1}^{V_2} p\,dV$$

$$= \int_{V_1}^{V_2} \frac{p_1V_1^n}{V^n} \cdot dV$$

$$= (p_1V_1^n)\left[\frac{V^{-n+1}}{-n+1}\right]_{V_1}^{V_2}$$

$$= \frac{p_1V_1^n}{1-n}(V_2^{1-n} - V_1^{1-n})$$

$$= \frac{p_2V_2^n \times V_2^{1-n} - p_1V_1^n \times V_1^{1-n}}{1-n}$$

$$= \frac{p_1V_1 - p_2V_2}{n-1} = \frac{p_1V_1}{n-1}\left[1 - \left(\frac{p_2}{p_1}\right)^{n-1/n}\right] \qquad (3.7)$$

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

$$W_{1-2} = \int_{V_1}^{V_2} p\,dV = p(V_2 - V_1)$$

$$= 0.105\ (0.15 - 0.30)\ \text{MJ}$$

$$= -\ 15.75\ \text{kJ}$$

$$Q_{1-2} = -37.6\ \text{kJ}$$

∴ Substituting in equation (1)

$$-37.6 \text{ kJ} = U_2 - U_1 - 15.75 \text{ kJ}$$

∴ $$U_2 - U_1 = -21.85 \text{ kJ}$$ Ans.

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. Ex. 4.2, 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*.

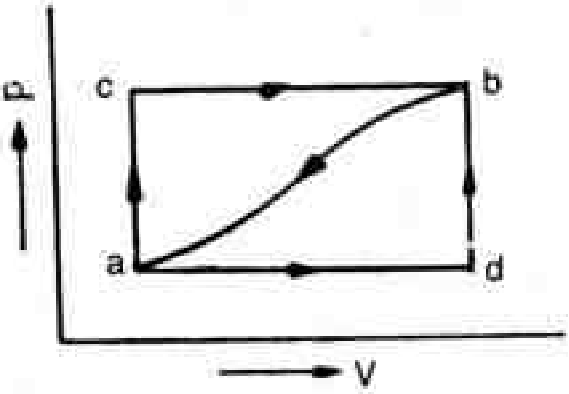


FIG. EX. 4.2

Solution

$$Q_{acb} = 84 \text{ kJ}$$
$$W_{acb} = 32 \text{ kJ}$$

We have

$$Q_{acb} = U_b - U_a + W_{acb}$$

∴ $$U_b - U_a = 84 - 32 = 52 \text{ kJ}$$ Ans.

(a) $$Q_{adb} = U_b - U_a + W_{adb}$$
$$= 52 + 10.5$$
$$= 62.5 \text{ kJ}$$ Ans.

(b) $$Q_{b-a} = U_a - U_b + W_{b-a}$$
$$= -52 - 21$$
$$= -73 \text{ kJ}$$ Ans.

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 $$Q_{adb} = 62.5 \text{ kJ} = Q_{ad} + Q_{db}$$

$$\therefore \quad Q_{db} = 62.5 - 52.5 = 10 \text{ kJ}$$

Ans.

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.

$$\because \quad Q_{ab} + Q_{bc} + Q_{cd} + Q_{da} = -17000 \text{ kJ/min}$$

$$0 + 21{,}000 - 2100 + Q_{da} = -17{,}000$$

$$\therefore \quad Q_{da} = -35{,}900 \text{ kJ/min}$$

Now $\oint dE = 0$, since cyclic integral of any property is zero.

$$\therefore \quad \Delta E_{a-b} + \Delta E_{b-c} + \Delta E_{c-d} + \Delta E_{d-a} = 0$$

$$-2170 + 21{,}000 - 36{,}600 + \Delta E_{d-a} = 0$$

$$\therefore \quad \Delta E_{d-a} = 17{,}770 \text{ kJ/min}$$

$$\therefore \quad W_{d-a} = Q_{d-a} - \Delta E_{d-a}$$

$$= -35{,}900 - 17{,}770$$

$$= -53{,}670 \text{ kJ/min}$$

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

$$= -17{,}000 \text{ kJ/min}$$

$$= -283.3 \text{ kW}$$

Ans.

6.1 LIMITATIONS OF THE FIRST LAW OF THERMODYNAMICS

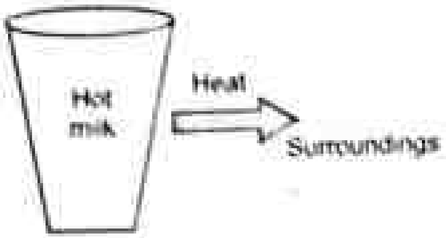
The first law of thermodynamics states that during any cyclic process, the net work transfer is always directly proportional to heat transfer and therefore, work and heat are mutually convertible one into another. A certain energy balance must be held when a system undergoes a process.

But the first law of thermodynamics does not impose any restriction on the direction in which the process is feasible. As far as the first law is concerned, all heat transferred to a heat engine could be converted to useful work. But we all know it is not possible to convert net heat into work.

Further, it is our experience that if a glass of hot milk is left in the room, it eventually cools off after a certain period. The amount of heat rejected by the milk is gained by the room air and the quantity of heat is balanced. Now let us consider the reverse of the process, i.e., getting cold milk hotter as a result of heat transfer from the room air. But such a process is impossible in nature.

Another common example is that an electrical work can be converted into heat energy through an electric heating element, but its reverse process—supplying an amount of heat to this heating element—will not generate any amount of electric work.

Other common example is when a cycle rider



(a) *Hot milk losing heat to surroundings*

(b) *Transferring heat to heating element will not generate electricity*

Fig. 6.1

stops his cycle by applying friction brakes. The kinetic energy of the moving wheel is absorbed by brake blocks, whose temperature rises, and hence the kinetic energy lost by the moving wheel is converted into heat energy. The first law should be equally satisfied, if the brake blocks are to cool off and they give their energy back to the cycle wheel, causing it to rotate. However, it is never seen in practice.

Other common experiences are the following:

(i) Heat always flow in the direction of decreasing temperature.

(ii) Water always flows downwards.

(iii) A paddle wheel is operated by falling weight. As it rotates, it stirs a fluid within an insulated container. The decrease in potential energy of weight is equal to increase of internal energy of the fluid mass. However, the reverse of the process—raising the weight by decreasing internal energy of the fluid—does not occur in nature.

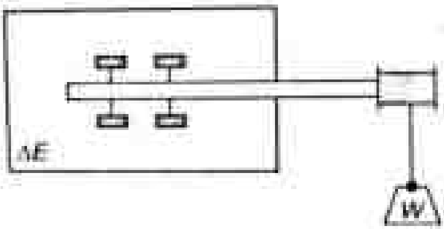


Fig. 6.2 *Supplying heat to a paddle wheel will not cause it to rotate*

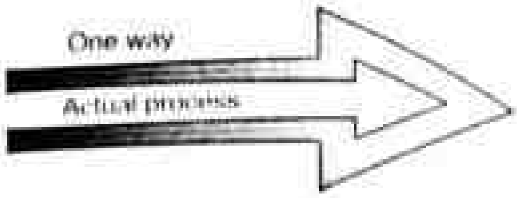


Fig. 6.3 *Process occurs in a certain direction and not in reverse direction*

It is clear from the above discussion that the processes proceed in a certain direction only and not in the reverse direction. The first law of thermodynamics does not place any restriction on the direction of process. Satisfying the first law does not ensure that the process will actually occur, because it only keeps the account of energy in quantity during any process. The second law of thermodynamics is introduced to overcome the remedies of the first law of thermodynamics. The *second law* of thermodynamics takes into account the direction of process as well as quality of energy, and it states that *in any process, high-grade energy can only be converted to low-grade energy*. The energy cannot be upgraded by its own. According to the second law of thermodynamics, heat and work can be classified as low and high-grade energy, respectively. *Therefore, net quantity of work can be converted in any form of energy, but net quantity of heat cannot.*

6.2 THERMAL RESERVOIR

It is a hypothetical body with an infinite heat capacity. A *thermal reservoir* can supply or absorb any amount of heat without affecting its temperature. For example, large bodies of water such as oceans, rivers as well as the atmosphere can be considered as thermal reservoirs.

A two-phase system of fluids can also be treated as a thermal reservoir as long as it does not return to single phase, since the two-phase system can absorb or release any amount of heat while maintaining a constant temperature. Similarly, large industrial furnaces can also be treated as thermal reservoirs. They are maintained almost at constant temperatures and are capable of transferring a large quantity of heat energy in an isothermal manner.

Second Law of Thermodynamics

6.1 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. The spontaneity of the process is due to a finite driving potential, sometimes called the 'force' or the 'cause', and what happens is called the 'flux', the 'current' or the 'effect'. The typical forces like temperature gradient, concentration gradient, and electric potential gradient, have their respective conjugate fluxes of heat transfer, mass transfer, and flow of electric current. These transfer processes can never spontaneously occur from a lower to a higher potential. This directional law puts a limitation on energy transformation other than that imposed by the first law.

Joule's experiments (Article 4.1) amply demonstrate that energy, when supplied to a system in the form of work, can be completely converted into heat (work transfer → internal energy increase → 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.*

$$Q \underset{\rightarrow}{\gtrsim} W$$

The arrow indicates the direction of energy transformation. This is illustrated in Fig. 6.1. As shown in Fig. 6.1(a), a system is taken from state 1 to state 2 by work transfer W_{1-2}, and then by heat transfer Q_{2-1} the system is brought back from state 2 to state 1 to complete a cycle. It is always found that $W_{1-2} = Q_{2-1}$. But if the system is taken from state 1 to state 2 by heat transfer Q_{1-2}, as shown in Fig. 6.1(b), then the system cannot be brought back from state 2 to state 1 by work transfer W_{2-1}. Hence, heat cannot be converted completely and continuously into work in a cycle. Some heat has to be rejected. In Fig. 6.1(b), W_{2-3} is the work done and Q_{3-1} is the heat rejected to complete the cycle. This underlies the work of Sadi Carnot, a French military engineer, who first studied this aspect of energy transformation (1824). 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.*

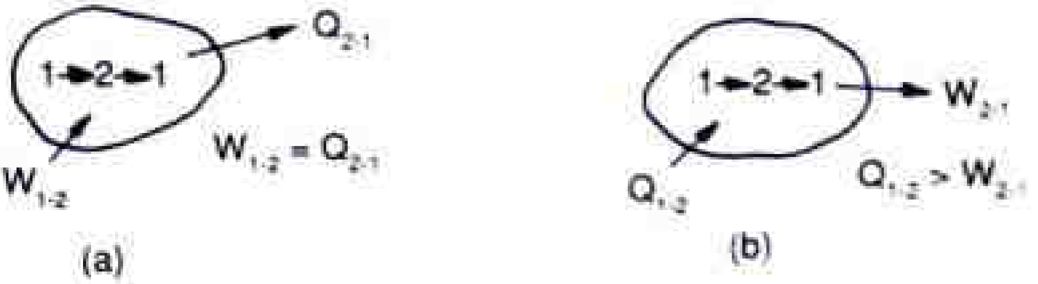


Fig. 6.1 *Qualitative distinction between heat and work*

6.2 CYCLIC HEAT ENGINE

For engineering purposes, the second law is best expressed in terms of the conditions which govern the production of work by a thermodynamic system operating in a cycle.

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*.

A heat engine may be in the form of a mass of gas confined in a cylinder and piston machine (Fig. 6.2a) or a mass of water moving in a steady flow through a steam power plant (Fig. 6.2b).

In the cyclic heat engine, as represented in Fig. 6.2(a), 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

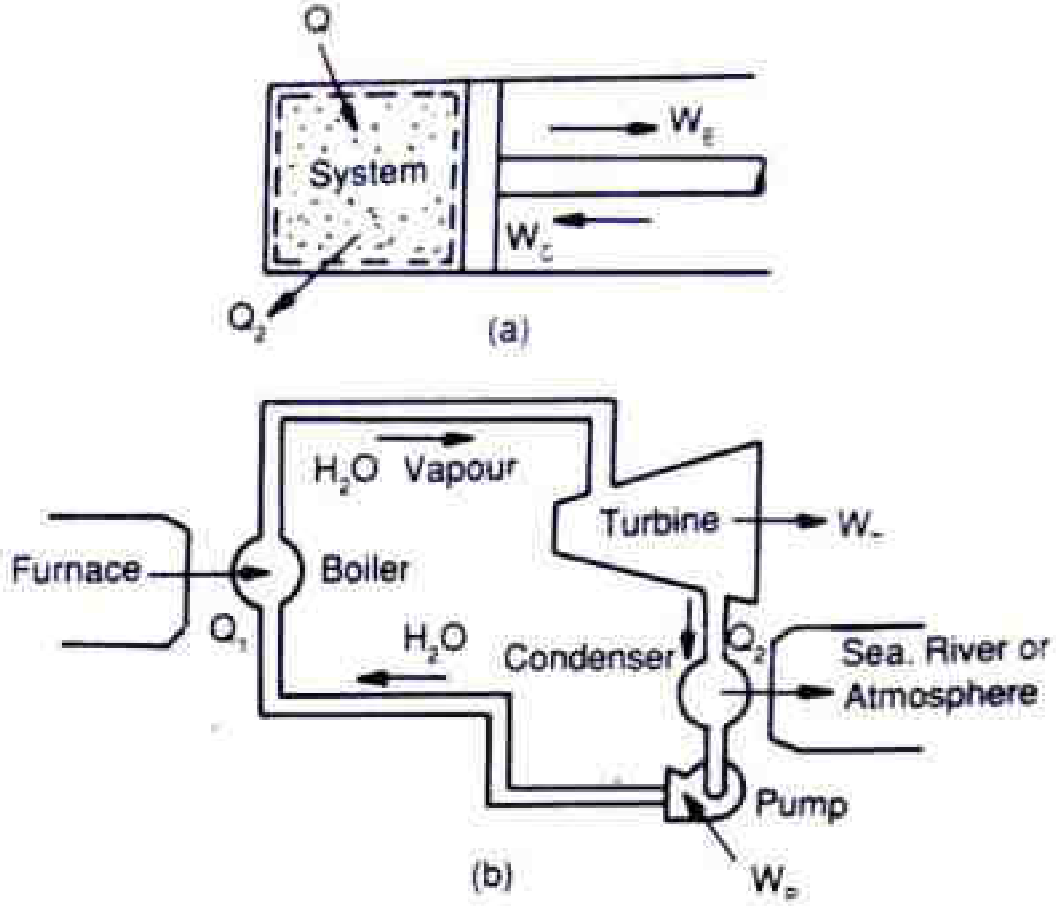


FIG. 6.2 *Cyclic heat engine*
(a) Heat engine cycle performed by a closed system udergoing four successive energy interactions with the surroundings
(b) Heat engine cycle performed by a steady flow system interacting with the surroundings as shown

constitute a heat engine cycle. In Fig. 6.2(b) heat Q_1 is transferred from the furnace to the water in the boiler to form steam which then works on the turbine rotor to produce work W_T, then the steam is condensed to water in the condenser in which an amount Q_2 is rejected from the system, and finally work W_p is done on the system (water) to pump it to the boiler. The system repeats the cycle.

The net heat transfer in a cycle to either of the heat engines

$$Q_{net} = Q_1 - Q_2 \tag{6.1}$$

and the net work transfer in a cycle

$$W_{net} = W_T - W_p \tag{6.2}$$

$$(\text{or} \quad W_{net} = W_E - W_C)$$

By the first law of thermodynamics, we have

$$\sum_{cycle} Q = \sum_{cycle} W$$

$$\therefore \qquad Q_{net} = W_{net}$$

or

$$Q_1 - Q_2 = W_T - W_P \tag{6.3}$$

Figure 6.3 represents a cyclic heat engine in the form of a block diagram

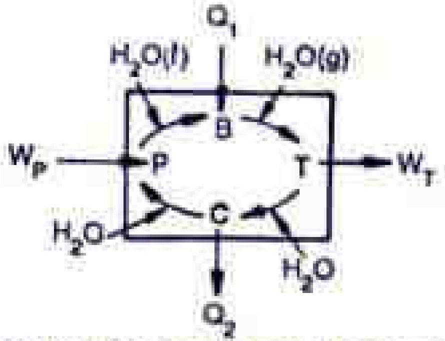


FIG. 6.3 *Cyclic heat engine with energy interactions represented in a block diagram*

indicating the various energy interactions during a cycle. Boiler (*B*), turbine (*T*), condenser (*C*), and pump (*P*), all four together constitute a heat engine. A heat engine is here a certain quantity of water undergoing the energy interactions, as shown, in cyclic operations to produce net work from a certain heat input.

The function of a heat engine cycle is to produce work continuously at the expense of heat input to the system. So the net work W_{net} and heat input Q_1 referred to the cycle are of primary interest. The efficiency of a heat engine or a heat engine cycle is defined as

$$\eta = \frac{\text{Net work output of the cycle}}{\text{Total heat input to the cycle}}$$

$$= \frac{W_{net}}{Q_1} \tag{6.4}$$

From equations (6.1), (6.2), (6.3), and (6.4)

$$\eta = \frac{W_{net}}{Q_1} = \frac{W_T - W_P}{Q_1} = \frac{Q_1 - Q_2}{Q_1}$$

$$\eta = 1 - \frac{Q_2}{Q_1} \tag{6.5}$$

This is also known as the *thermal efficiency* of a heat engine cycle. A heat engine is very often called upon to extract as much work (net) as possible from a certain heat input, i.e., to maximize the cycle efficiency

6.3 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 source where fuel is continuously burnt, and a typical sink is a river or sea or the atmosphere itself.

A mechanical energy reservoir (MER) is a large body enclosed by an adiabatic impermeable wall capable of storing work as potential energy (such as a raised weight or wound spring) or kinetic energy (such as a rotating flywheel). All processes of interest within an MER are essentially quasi-static. An MER receives and delivers mechanical energy quasi-statically.

Figure 6.4 shows a cyclic heat engine exchanging heat with a source and a sink and delivering W_{net} in a cycle to an MER.

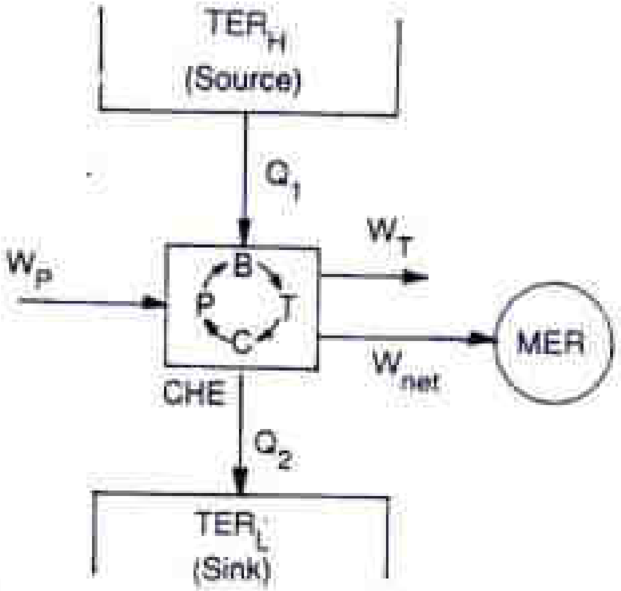


FIG. 6.4 *Cyclic heat engine (CHE) with source and sink*

6.4 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 $W_{net} < Q_1$, since heat Q_1 transferred to a system cannot be completely converted to work in a cycle (Article 6.1). 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. 6.5). 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 (Fig. 6.6). 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.

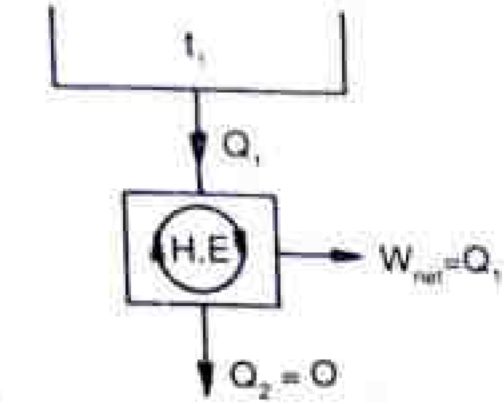


FIG. 6.5 *A PMM2*

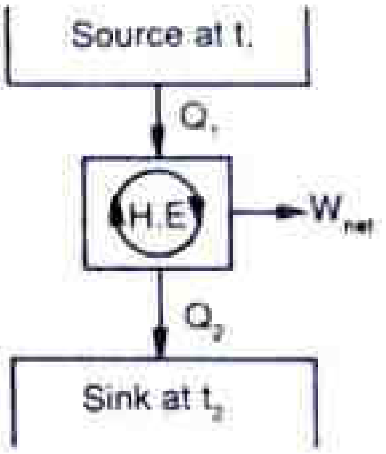


FIG. 6.6 *Heat engine producing net work in a cycle by exchanging heat at two different temperatures*

6.5 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.

6.6 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. 6.7) be maintained at t_2, which is lower than the ambient temperature t_1. Even though *A* is insulated, there will always be heat leakage Q_2 into the body from the surroundings by virtue of the temperature difference. 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. This heat (Q_2) is absorbed by a working fluid, called the refrigerant, which evaporates in the evaporator E_1 at a temperature lower than t_2 absorbing the latent heat of vaporization from the body *A* which is cooled or refrigerated (Process 4–1). The vapour is first compressed in the compressor C_1 driven by a motor which absorbs work W_C (Process 1–2), and is then condensed in the condenser C_2 rejecting the latent heat of condensation Q_1 at a temperature higher than that of the atmosphere (at t_1) for heat transfer to take place (Process 2–3). The condensate then expands adiabatically through an expander (an engine or turbine) producing work

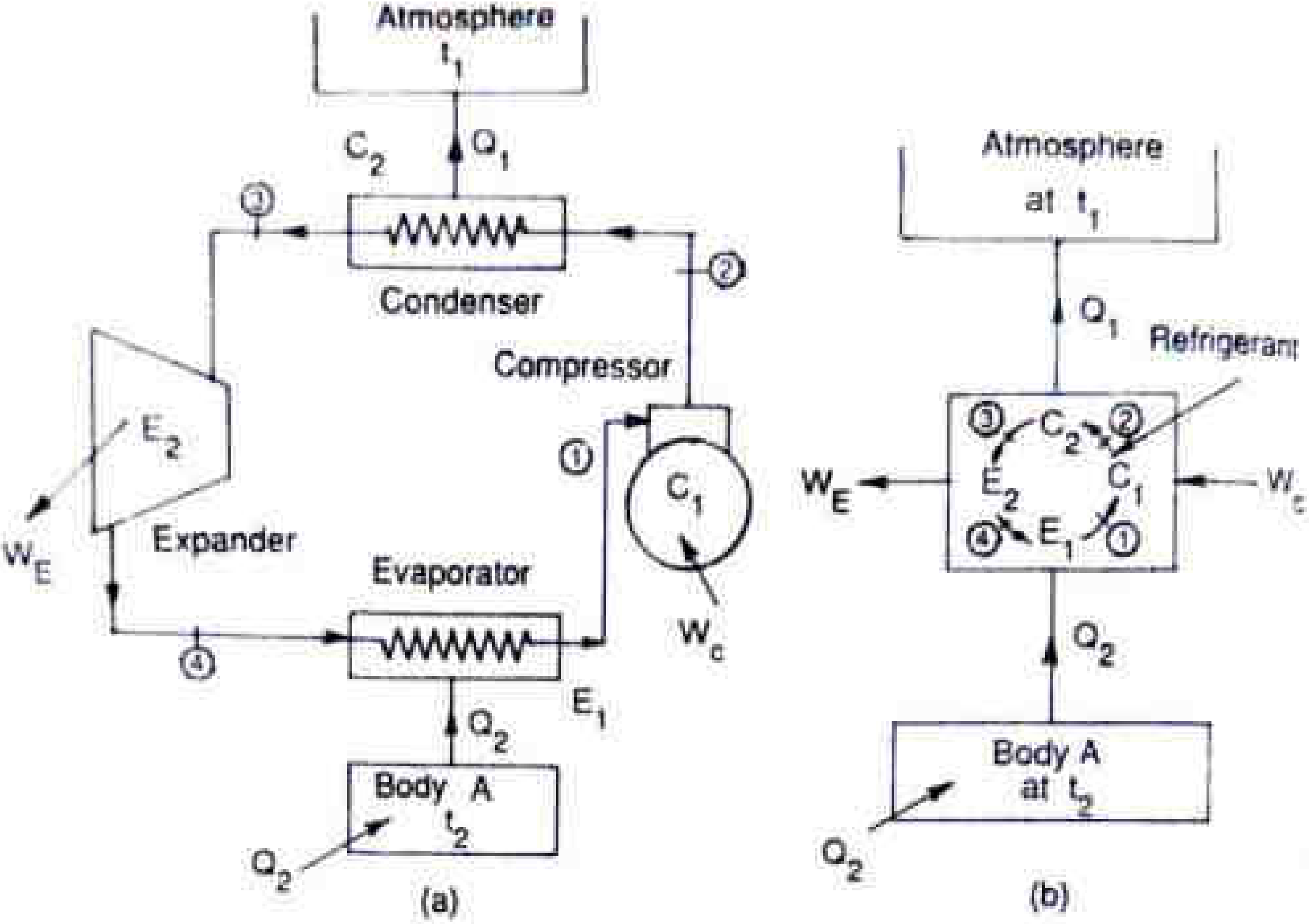


FIG. 6.7 *A cyclic refrigeration plant*

W_E, when the temperature drops to a value lower than t_2 such that heat Q_2 flows from the body *A* to make the refrigerant evaporate (Process 3–4). Such a cyclic device of flow through E_1–C_1–C_2–E_2 is called a *refrigerator*. 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

$$\text{COP} = \frac{\text{Desired effect}}{\text{Work input}} = \frac{Q_2}{W}$$

$$\therefore \qquad [\text{COP}]_{\text{ref}} = \frac{Q_2}{Q_1 - Q_2} \qquad (6.6)$$

A *heat pump* is a device which, operating in a cycle, maintains a body, say *B* (Fig. 6.8), at a temperature higher than the temperature of the surroundings. By virtue of the temperature difference, there will be heat leakage Q_1 from the body to the surroundings. The body will be maintained at the constant temperature t_1, if heat is discharged into the body at the same rate at which heat leaks out of the body. The heat is extracted from the low temperature reservoir, which is nothing but the atmosphere, and discharged into the high temperature body *B*, with the expenditure of work *W* in a cyclic device called a heat pump. The working fluid operates in a cycle flowing through the evaporator E_1, compressor C_1, condenser C_2 and expander E_2, similar to a refrigerator, but the attention is here focussed on

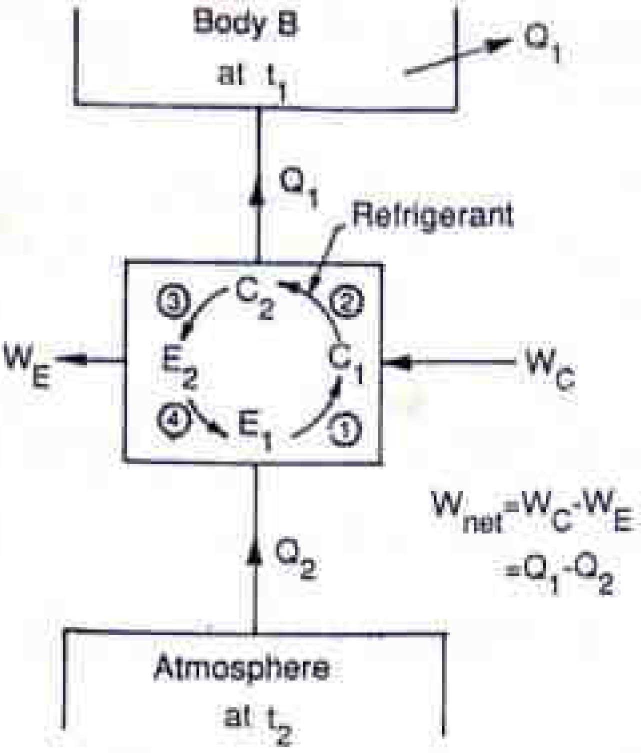


FIG. 6.8 *A cyclic heat pump*

the high temperature body *B*. Here Q_1 and W are of primary interest, and the COP is defined as

$$\text{COP} = \frac{Q_1}{W}$$

$$\therefore \qquad [\text{COP}]_{H.P.} = \frac{Q_1}{Q_1 - Q_2} = \frac{Q_1 - Q_2 + Q_2}{Q_1 - Q_2} \tag{6.7}$$

From equations (6.6) and (6.7), it is found that $= 1 + \frac{Q_2}{Q_1 - Q_2} = 1 + [\text{COP}]_{Ref}$

$$[\text{COP}]_{H.P.} = [\text{COP}]_{ref} + 1 \tag{6.8}$$

The COP of a heat pump is greater than the COP of a refrigerator by unity. Equation (6.8) expresses a very interesting feature of a heat pump. Since

$$\begin{aligned} Q_1 &= [\text{COP}]_{H.P.}\, W \\ &= [\text{COP}_{ref} + 1]\, W \end{aligned} \tag{6.9}$$

Q_1 is always greater than W.

For an electrical resistance heater, if W is the electrical energy consumption, then the heat transferred to the space at steady state is W only, i.e., $Q_1 = W$.

A 1 kW electric heater can give 1 kW of heat at steady state and nothing more. In other words, 1 kW of work (high grade energy) dissipates to give 1 kW of heat (low grade energy), which is thermodynamically inefficient.

However, if this electrical energy W is used to drive the compressor of a heat pump, the heat supplied Q_1 will always be more than W, or $Q_1 > W$. Thus, a heat pump provides a thermodynamic advantage over direct heating.

For heat to flow from a cooler to a hotter body, W cannot be zero, and hence, the COP (both for refrigerator and heat pump) cannot be infinity. Therefore, $W > 0$, and $\text{COP} < \infty$.

6.7 EQUIVALENCE OF KELVIN-PLANCK AND CLAUSIUS STATEMENTS

At first sight, Kelvin-Planck's and Clausius' statements may appear to be unconnected, but it can easily be shown that they are virtually two parallel statements of the second law and are equivalent in all respects.

The equivalence of the two statements will be proved if it can be shown that the violation of one statement implies the violation of the second, and vice versa.

(a) Let us first consider a cyclic heat pump *P* which transfers heat from a low temperature reservoir (t_2) to a high temperature reservoir (t_1) with no other effect, i.e., with no expenditure of work, violating Clausius statement (Fig. 6.9).

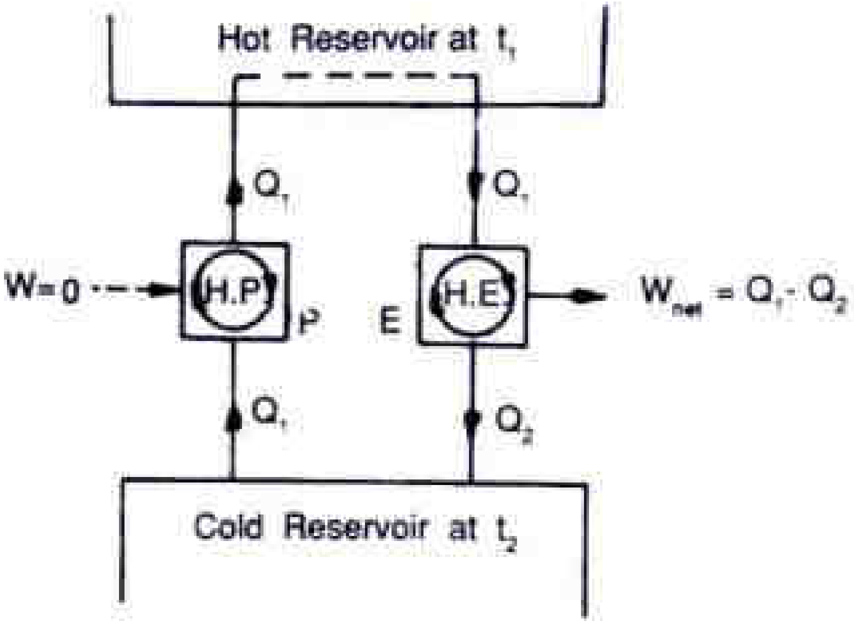


FIG. 6.9 *Violation of the Clausius statement*

Let us assume a cyclic heat engine *E* operating between the same thermal energy reservoirs, producing W_{net} in one cycle. The rate of working of the heat engine is such that it draws an amount of heat Q_1 from the hot reservoir equal to that discharged by the heat pump. Then the hot reservoir may be eliminated and the heat Q_1 discharged by the heat pump is fed to the heat engine. So we see that the heat pump *P* and the heat engine *E* acting together constitute a heat engine operating in cycles and producing net work while exchanging heat only with one body at a single fixed temperature. This violates the Kelvin-Planck statement.

(b) Let us now consider a perpetual motion machine of the second kind (*E*) which produces net work in a cycle by exchanging heat with only one thermal energy reservoir (at t_1) and thus violates the Kelvin-Planck statement (Fig. 6.10).

Let us assume a cyclic heat pump (*P*) extracting heat Q_2 from a low temperature reservoir at t_2 and discharging heat to the high temperature

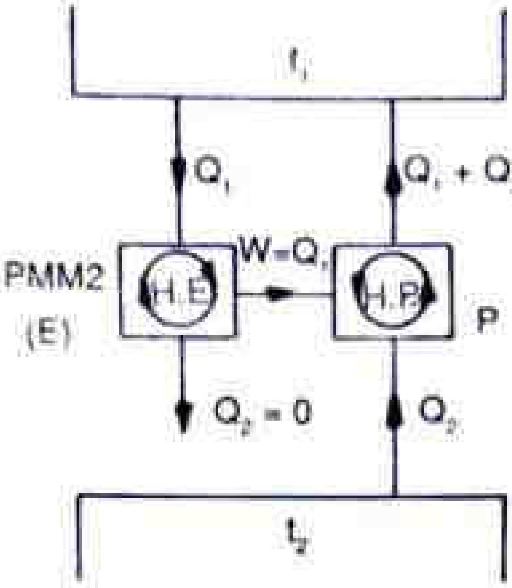


FIG. 6.10 *Violation of the Kelvin-Planck statement*

reservoir at t_1 with the expenditure of work W equal to what the PMM2 delivers in a complete cycle. So *E* and *P* together constitute a heat pump working in cycles and producing the sole effect of transferring heat from a lower to a higher temperature body, thus violating the Clausius statement.

6.8 REVERSIBILITY AND IRREVERSIBILITY

The second law of thermodynamics enables us to divide all processes into two classes:

(a) Reversible or ideal process.
(b) Irreversible or natural process.

A *reversible* process is one which is performed in such a way that at the conclusion of the process, both the system and the surroundings may be restored to their initial states, without producing any changes in the rest of the universe. Let the state of a system be represented by *A* (Fig. 6.11), and

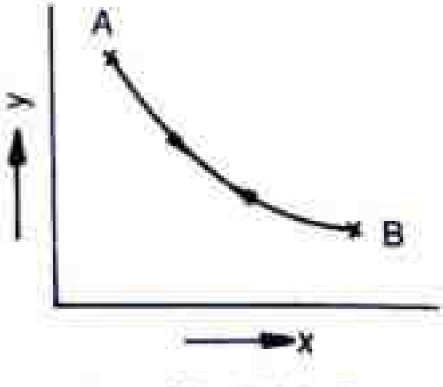


FIG. 6.11 *Violation of the Kelvin-Planck statement*

let the system be taken to state *B* by following the path *A-B*. If the system and also the surroundings are restored to their initial states and no change in the universe is produced, then the process *A-B* will be a reversible process. In the reverse process, the system has to be taken from state *B* to *A* by

If enough engines are placed in series to make the total work output equal to Q_1, then by the first law the heat rejected from the last engine will be zero. By the second law, however, the operation of a cyclic heat engine with zero heat rejection cannot be achieved, although it may be approached as a limit. When the heat rejected approaches zero, the temperature of heat rejection also approaches zero as a limit. *Thus it appears that a definite zero point exists on the absolute temperature scale but this point cannot be reached without a violation of the second law.*

Thus any attainable value of absolute temperature is always greater than zero. This is also known as the *Third Law of Thermodynamics* which may be stated as follows: *It is impossible by any procedure, no matter how idealized, to reduce any system to the absolute zero of temperature in a finite number of operations.*

This is what is called the Fowler-Guggenheim statement of the third law. The third law itself is an independent law of nature, and not an extension of the second law. The concept of heat engine is not necessary to prove the non-attainability of absolute zero of temperature by any system in a finite number of operations.

6.16 EFFICIENCY OF THE REVERSIBLE HEAT ENGINE

The efficiency of a reversible heat engine in which heat is received solely at T_1 is found to be

$$\eta_{rev} = \eta_{max} = 1 - \left(\frac{Q_2}{Q_1}\right)_{rev} = 1 - \frac{T_2}{T_1}$$

or

$$\eta_{rev} = \frac{T_1 - T_2}{T_1}$$

It is observed here that as T_2 decreases, and T_1 increases, the efficiency of the reversible cycle increases.

Since η is always less than unity, T_2 is always greater than zero and positive.

The COP of a refrigerator is given by

$$(\text{COP})_{refr} = \frac{Q_2}{Q_1 - Q_2} = \frac{1}{\dfrac{Q_1}{Q_2} - 1}$$

For a reversible refrigerator, using

$$\frac{Q_1}{Q_2} = \frac{T_1}{T_2}$$

$$[\text{COP}_{refr}]_{rev} = \frac{T_2}{T_1 - T_2} \tag{6.24}$$

Similarly, for a reversible heat pump

$$[\text{COP}_{H.P.}]_{rev} = \frac{T_1}{T_1 - T_2} \tag{6.25}$$

SOLVED EXAMPLES

EXAMPLE 6.1

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. Ex. 6.1).

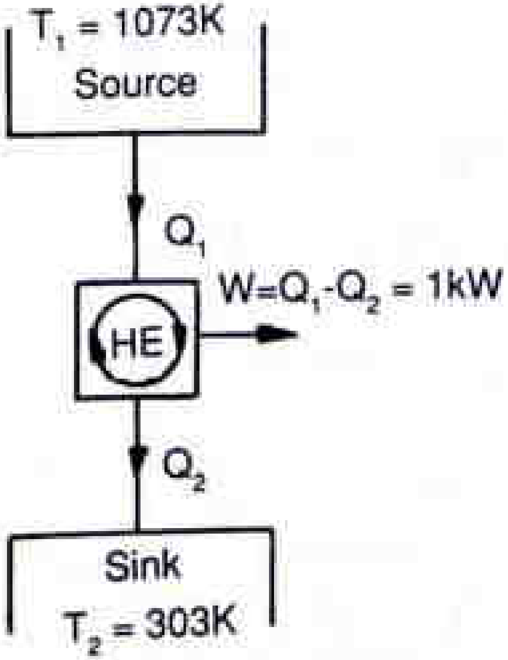


FIG. EX. 6.1

$$\eta_{max} = \eta_{rev} = 1 - \frac{T_2}{T_1}$$

$$= 1 - \frac{30 + 273}{800 + 273}$$

$$= 1 - 0.282 = 0.718$$

Now $$\frac{W_{net}}{Q_1} = \eta_{max} = 0.718$$

∴ $$Q_1 = \frac{1}{0.718} = 1.392 \text{ kW}$$

Now $$Q_2 = Q_1 - W_{net} = 1.392 - 1$$

$$= 0.392 \text{ kW}$$

This is the least rate of heat rejection.

EXAMPLE 6.2

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. Ex. 6.2).

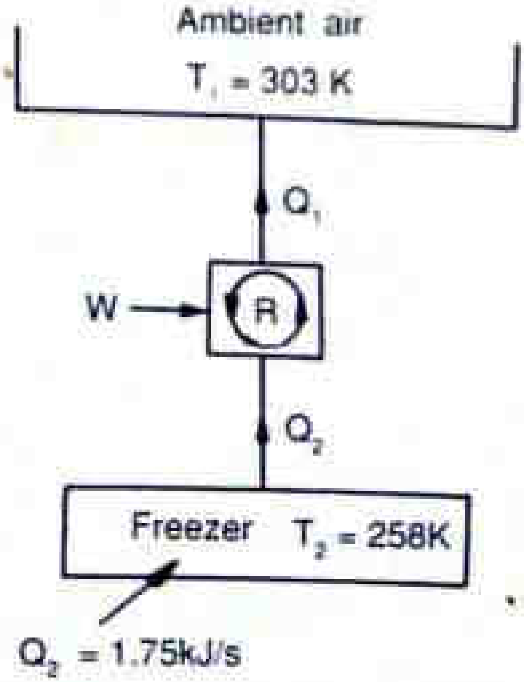


FIG. EX. 6.2

ALTERNATE METHOD

$$C.O.P. = \frac{Q_2}{W} = \frac{T_2}{T_1 - T_2}$$

$$\Rightarrow \frac{1.75}{W} = \frac{258}{303-258}$$

$$\Rightarrow W = 0.31 \text{ kW}$$

For minimum power requirement

$$\frac{Q_2}{T_2} = \frac{Q_1}{T_1}$$

$$\therefore \quad Q_1 = \frac{1.75}{258} \times 303 = 2.05 \text{ kJ/s}$$

$$\therefore \quad W = Q_1 - Q_2$$

$$= 2.05 - 1.75 = 0.31 \text{ kJ/s}$$

$$= 0.31 \text{ kW}$$

EXAMPLE 6.3

A reversible heat engine operates between two reservoirs at temperatures of 600°C and 40°C. The engine drives a reversible refrigerator which operates between reservoirs at temperatures of 40°C and – 20°C. The heat transfer to the heat engine is 2000 kJ and the net work output of the combined engine refrigerator plant is 360 kJ.

(a) Evaluate the heat transfer to the refrigerant and the net heat transfer to the reservoir at 40°C.

(b) Reconsider (a) given that the efficiency of the heat engine and the COP of the refrigerator are each 40% of their maximum possible values.

Solution

(a) Maximum efficiency of the heat engine cycle (Fig. Ex. 6.3) is given by

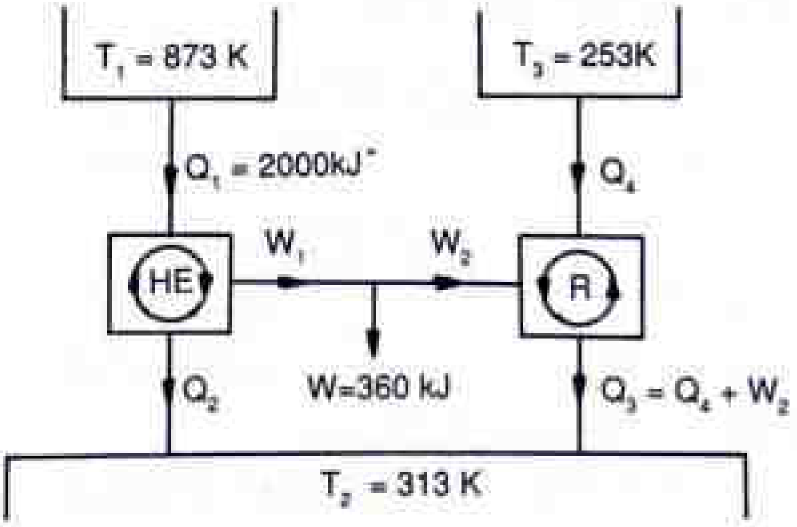


FIG. EX. 6.3

$$\eta_{\max} = 1 - \frac{T_2}{T_1} = 1 - \frac{313}{873} = 1 - 0.358 = 0.642$$

Again $\quad \frac{W_1}{Q_1} = 0.642$

$$\therefore \quad W_1 = 0.642 \times 2000 = 1284 \text{ kJ}$$

Maximum COP of the refrigerator cycle

$$(\mathrm{COP})_{\max} = \frac{T_3}{T_2 - T_3} = \frac{253}{313 - 253} = 4.22$$

Also $$\mathrm{COP} = \frac{Q_4}{W_2} = 4.22$$

Since $$W_1 - W_2 = W = 360 \text{ kJ}$$

$$\therefore \quad W_2 = W_1 - W = 1284 - 360 = 924 \text{ kJ}$$

$$\therefore \quad Q_4 = 4.22 \times 924 = 3899 \text{ kJ}$$

$$\therefore \quad Q_3 = Q_4 + W_2 = 924 + 3899 = 4823 \text{ kJ}$$

$$Q_2 = Q_1 - W_1 = 2000 - 1284 = 716 \text{ kJ}$$

Heat rejection to the 40°C reservoir

$$= Q_2 + Q_3 = 716 + 4823 = 5539 \text{ kJ}$$ Ans. (a)

(b) Efficiency of the actual heat engine cycle

$$\eta = 0.4 \ \ \eta_{\max} = 0.4 \times 0.642$$

$$\therefore \quad W_1 = 0.4 \times 0.642 \times 2000$$

$$= 513.6 \text{ kJ}$$

$$\therefore \quad W_2 = 513.6 - 360 = 153.6 \text{ kJ}$$

COP of the actual refrigerator cycle

$$\mathrm{COP} = \frac{Q_4}{W_2} = 0.4 \times 4.22 = 1.69$$

Therefore

$$Q_4 = 153.6 \times 1.69 = 259.6 \text{ kJ}$$ Ans. (b)

$$Q_3 = 259.6 + 153.6 = 413.2 \text{ kJ}$$

$$Q_2 = Q_1 - W_1 = 2000 - 513.6 = 1486.4 \text{ kJ}$$

Heat rejected to the 40°C reservoir

$$= Q_2 + Q_3 = 413.2 + 1486.4 = 1899.6 \text{ kJ}$$ Ans. (b)

Example 1.5. *An engine works between the temperature limits of 1775 K and 375 K. What can be the maximum thermal efficiency of this engine ?*

Solution. Given : $T_1 = 1775$ K ; $T_2 = 375$ K

We know that maximum thermal efficiency of the engine,

$$\eta_{max} = \frac{T_1 - T_2}{T_1} = \frac{1775 - 375}{1775} = 0.7887 \text{ or } 78.87\% \textbf{ Ans.}$$

Example 1.6. *A reversible engine is supplied with heat from two constant temperature sources at 900 K and 600 K and rejects heat to a constant temperature sink at 300 K. The engine develops work equivalent to 90 kJ/s and rejects heat at the rate of 56 kJ/s. Estimate : 1. Heat supplied by each source, and 2. Thermal efficiency of the engine.*

Solution. Given : $T_1 = 900$ K ; $T_3 = 600$ K ; $T_2 = T_4 = 300$ K ; $W_E = 90$ kJ/s ; $Q_2 + Q_4 = 56$ kJ/s

1. Heat supplied by each source

Let Q_1 = Heat supplied by the first source, and

Q_3 = Heat supplied by the second source.

We know that efficiency of the engine when the heat is supplied from the first source,

$$\eta_1 = \frac{\text{Work obtained}}{\text{Heat supplied}} = \frac{W_1}{Q_1}$$

$$= \frac{Q_1 - Q_2}{Q_1} = \frac{T_1 - T_2}{T_1}$$

$$\ldots \left(\because \text{ For a reversible engine, } \frac{Q_1}{T_1} = \frac{Q_2}{T_2} \right)$$

$$= \frac{900 - 300}{900} = 0.67$$

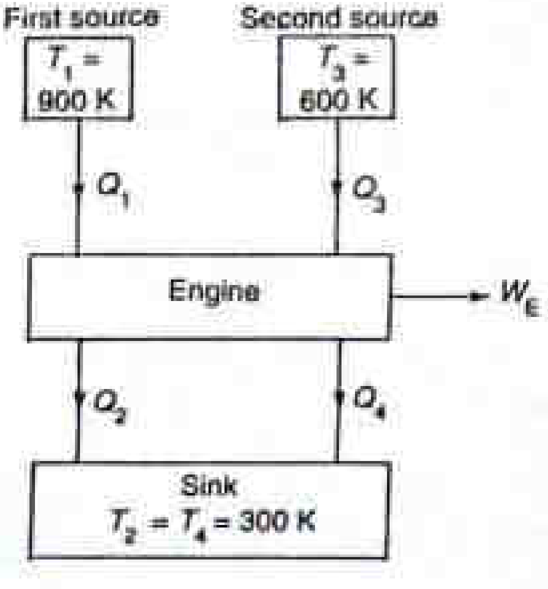


Fig. 1.14

$\therefore$ Work obtained by the engine from the first source,

$$W_1 = Q_1 - Q_2 = 0.67\, Q_1$$

and heat rejected to the sink,

$$Q_2 = Q_1 - W_1 = Q_1 - 0.67\, Q_1 = 0.33\, Q_1$$

Similarly, efficiency of the engine when the heat is supplied from the second source

$$\eta_2 = \frac{W_2}{Q_3} = \frac{Q_3 - Q_4}{Q_3} = \frac{T_3 - T_4}{T_3} = \frac{600 - 300}{600} = 0.5$$

$\therefore$ Work obtained by the engine from the second source,

$$W_2 = Q_3 - Q_4 = 0.5\, Q_3$$

and heat rejected to the sink,

$$Q_4 = Q_3 - W_2 = Q_3 - 0.5\,Q_3 = 0.5\,Q_3$$

We know that total work obtained from the engine (W_E),

$$90 = W_1 + W_2 = 0.67\,Q_1 + 0.5\,Q_3 \qquad \ldots(i)$$

and total heat rejected to the sink,

$$56 = Q_2 + Q_4 = 0.33\,Q_1 + 0.5\,Q_3 \qquad \ldots(ii)$$

From equations (*i*) and (*ii*),

Q_1 = 100 kJ/s and Q_3 = 46 kJ/s **Ans.**

2. Thermal efficiency of the engine

We know that maximum thermal efficiency of the engine,

$$\eta_{max} = \frac{\text{Work obtained}}{\text{Heat supplied}} = \frac{W_E}{Q_1 + Q_3}$$

$$= \frac{90}{100 + 46} = 0.616 \quad \text{or} \quad 61.6\% \ \textbf{Ans.}$$

Example 1.7. *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 C.O.P of the refrigeration plant is one -third of an ideal plant working between the same temperatures. Find the power required to drive the plant.*

Solution. Given : $T_2 = -5°C = -5 + 273 = 268$ K ; $T_1 = 35°C = 35 + 273 = 308$ K

$Q_2 = 29$ kW ; $(C.O.P)_{actual} = \frac{1}{3}\,(C.O.P)_{ideal}$

The refrigerating plant operating between the temperatures T_1 and T_2 is shown in Fig. 1.15.

Let W_R = Work or power required to drive the plant.

We know that the coefficient of performance of an ideal refrigeration plant,

$$(C.O.P)_{ideal} = \frac{T_2}{T_1 - T_2}$$

$$= \frac{268}{308 - 268} = 6.7$$

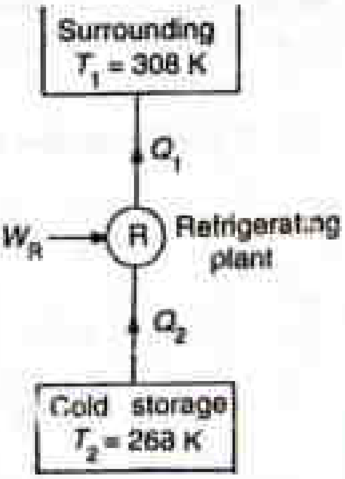


Fig. 1.15

∴ Actual coefficient of performance,

$$(C.O.P)_{actual} = \frac{1}{3} \times (C.O.P)_{ideal} = \frac{1}{3} \times 6.7 = 2.233$$

We also know that $C.O.P. = \dfrac{Q_2}{W_R}$

$$\therefore \quad W_R = \frac{Q_2}{(C.O.P)_{actual}} = \frac{29}{2.233} = 12.987 \text{ kW} \ \textbf{Ans.}$$

5

First Law Applied to Flow Processes

5.1 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.

For a pure substance

$$E = E_K + E_P + U$$

where E_K is the K.E., E_P the P.E., and U the residual energy stored in the molecular structure of the substance.

$$\therefore \qquad Q = \Delta E_K + \Delta E_P + \Delta U + W \tag{5.1}$$

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.

Equation (5.1) refers to a system having a particular mass of substance, and it is free to move from place to place.

Consider a steam turbine (Fig. 5.1) in which steam enters at a high pressure, does work upon the turbine rotor, and then leaves the turbine at low pressure through the exhaust pipe.

If a certain mass of steam is considered as the thermodynamic system, then the energy equation becomes

$$Q = \Delta E_K + \Delta E_P + \Delta U + W$$

and in order to analyze the expansion process in turbine the moving system is to be followed as it travels through the turbine, taking into account the work and heat interactions all the way through. This method of analysis is similar to that of Lagrange in fluid mechanics.

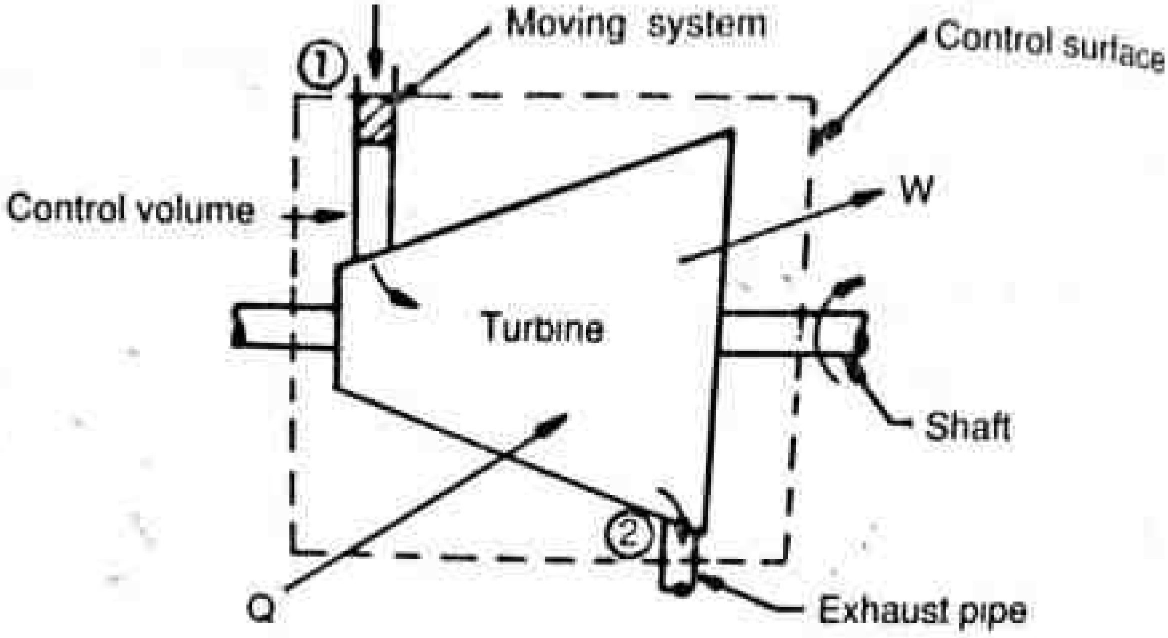


FIG. 5.1 *Flow process involving work and heat interactions*

Although the system approach is quite valid, there is another approach which is found to be highly convenient. Instead of concentrating attention upon a certain quantity of fluid, which constitutes a moving system in flow processes, attention is focussed upon a certain fixed region in space called a *control volume* through which the moving substance flows. This is similar to the analysis of Euler in fluid mechanics.

To distinguish the two concepts, it may be noted that while the system (closed) boundary usually changes shape, position and orientation relative to the observer, the control volume boundary remains fixed and unaltered. Again, while matter usually crosses the control volume boundary, no such flow occurs across the system boundary.

The broken line in Fig. 5.1 represents the surface of the control volume which is known as the *control surface*. This is the same as the system boundary of the open system. The method of analysis is to inspect the control surface and account for all energy quantities transferred through this surface. Since there is mass transfer across the control surface, a mass balance also has to be made. Sections 1 and 2 allow mass transfer to take place, and Q and W are the heat and work interactions respectively.

5.2 STEADY FLOW PROCESS

As a fluid flows through a certain control volume, its thermodynamic properties may vary along the space coordinates as well as with time. If the rates of flow of mass and energy through the control surface change with time, the mass and energy within the control volume also would change with time.

'Steady flow' means that the rates of flow of mass and energy across the control surface are constant.

In most engineering devices, there is a constant rate of flow of mass and energy through the control surface, and the control volume in course of time attains a steady state. *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.

5.3 MASS BALANCE AND ENERGY BALANCE IN A SIMPLE STEADY FLOW PROCESS

In Fig. 5.2, a steady flow system has been shown in which one stream of fluid enters and one 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. 5.2

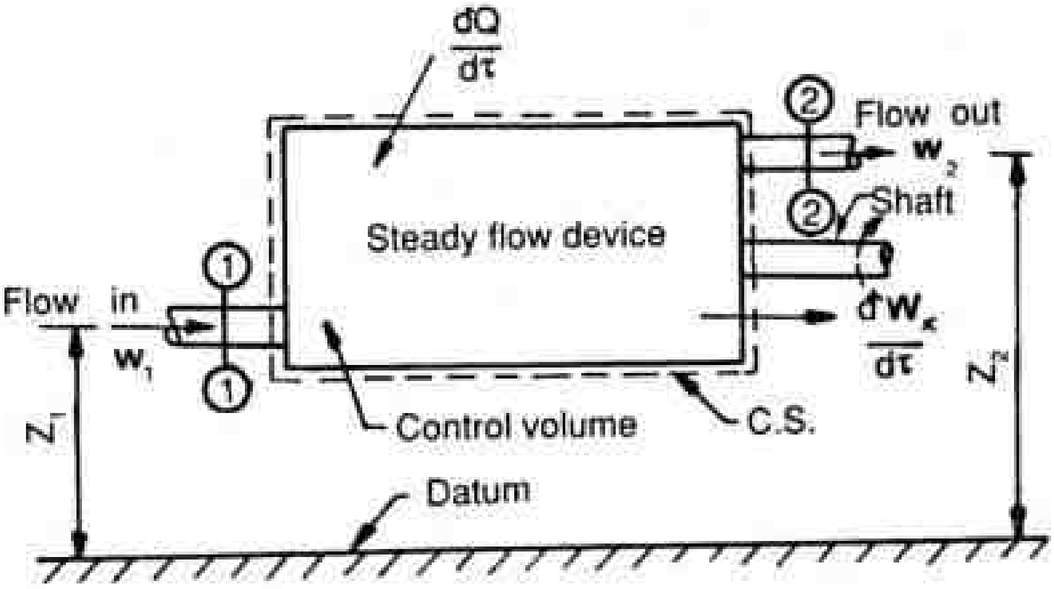


FIG. 5.2 *Steady flow process*

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
V_1, V_2—velocity, m/s
Z_1, Z_2—elevation above an arbitrary datum, m

$\omega_1 = \frac{dm_1}{dt}$, $\omega_2 = \frac{dm_2}{dt}$

$\frac{dQ}{d\tau}$—net rate of heat transfer through the control surface, J/s

$\frac{dW_x}{d\tau}$—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.

5.3.1 Mass Balance

By the conservation of mass, if there is no accumulation of mass within th control volume, the mass flow rate entering must equal the mass flow rat leaving, or

$$w_1 = w_2 \Rightarrow \rho_1 A_1 V_1 = \rho_2 A_2 V_2$$

or

$$\frac{A_1 \mathbf{V}_1}{v_1} = \frac{A_2 \mathbf{V}_2}{v_2} \tag{5.2}$$

This equation is known as the *equation of continuity.*

5.3.2 Energy Balance

In a flow process, the work transfer may be of two types: the *external work* and the *flow work.* The external work refers to all the work transfer across the control surface other than that due to normal fluid forces. In engineering thermodynamics the only kinds of external work of importance are *shear* (shaft or stirring) *work* and *electrical work.* In Fig. 5.2 the only external work occurs in the form of shaft work, W_x. The flow work, as discussed in Sec. 3.4, 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 $(-p_1 v_1\, dm_1)$ and $(+ p_2 v_2\, dm_2)$ respectively. Therefore, the total work transfer is given by

$$W = W_x - p_1 v_1\, dm_1 + p_2 v_2\, dm_2 \tag{5.3}$$

In the rate form,

$$\frac{\text{đ}W}{d\tau} = \frac{\text{đ}W_x}{d\tau} - p_1 v_1 \frac{dm_1}{d\tau} + p_2 v_2 \frac{dm_2}{d\tau}$$

or

$$\frac{\text{đ}W}{d\tau} = \frac{\text{đ}W_x}{d\tau} - w_1 p_1 v_1 + w_2 p_2 v_2 \tag{5.4}$$

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

$$w_1 e_1 + \frac{\text{đ}Q}{d\tau} = w_2 e_2 + \frac{\text{đ}W}{d\tau}$$

Substituting for $\frac{\text{đ}W}{d\tau}$ from Eq. (5.4)

$$w_1 e_1 + \frac{\text{đ}Q}{d\tau} = w_2 e_2 + \frac{\text{đ}W_x}{d\tau} - w_1 p_1 v_1 + w_2 p_2 v_2$$

$$\therefore \quad w_1 e_1 + w_1 p_1 v_1 + \frac{\text{đ}Q}{d\tau} = w_2 e_2 + w_2 p_2 v_2 + \frac{\text{đ}W_x}{d\tau} \tag{5.5}$$

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

$$e = e_k + e_p + u$$

$$= \frac{\mathbf{V}^2}{2} + Zg + u \tag{5.6}$$

Substituting the expression for e in equation (5.5)

$$w_1\left(\frac{\mathbf{V}_1^2}{2} + Z_1 g + u_1\right) + w_1 p_1 v_1 + \frac{dQ}{d\tau}$$

$$= w_2\left(\frac{\mathbf{V}_2^2}{2} + Z_2 g + u_2\right) + w_2 p_2 v_2 + \frac{dW_x}{d\tau}$$

or

$$w_1\left(h_1 + \frac{\mathbf{V}_1^2}{2} + Z_1 g\right) + \frac{dQ}{d\tau}$$

$$= w_2\left(h_2 + \frac{\mathbf{V}_2^2}{2} + Z_2 g\right) + \frac{dW_x}{d\tau} \tag{5.7}$$

where $h = u + pv$.

And, since $w_1 = w_2$, let $w = w_1 = w_2 = \frac{dm}{d\tau}$

Dividing equation (5.7) by $\frac{dm}{d\tau}$

$$h_1 + \frac{V_1^2}{2} + Z_1 g + \frac{dQ}{dm}$$

$$= h_2 + \frac{V_2^2}{2} + Z_2 g + \frac{dW_x}{dm} \tag{5.8}$$

Equations (5.7) and (5.8) 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. All the terms in equation (5.8) represent energy flow per unit mass of fluid (J/kg), whereas all the terms in equation (5.7) represent energy flow per unit time (J/s). The basis of energy flow per unit mass is usually more convenient when only a single stream of fluid enters and leaves a control volume. When more than one fluid stream is involved the basis of energy flow per unit time is more convenient.

Equation (5.8) can be written in the following form,

$$Q - W_x = (h_2 - h_1) + \frac{\overline{\mathbf{V}}_2^2 - \overline{\mathbf{V}}_1^2}{2} + g(Z_2 - Z_1) \tag{5.9}$$

where Q and W_x refer to energy transfer per unit mass. In the differential form, the SFEE becomes

$$\text{đ}Q - \text{đ}W_x = dh + \overline{\mathbf{V}}d\overline{\mathbf{V}} + gdZ \tag{5.10}$$

When more than one stream of fluid enters or leaves the control volume (Fig. 5.3), the mass balance and energy balance for steady flow are given below.

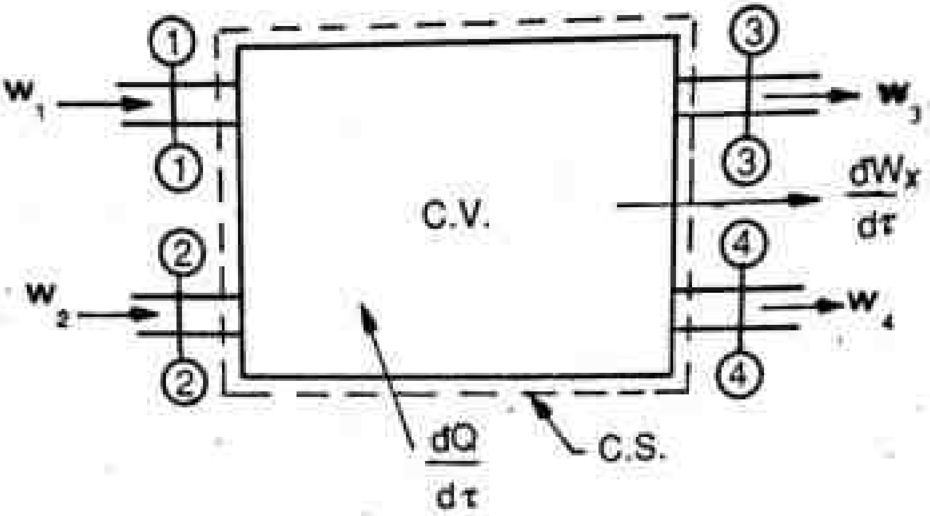


FIG. 5.3 *Steady flow process involving two fluid streams at the inlet and exit of the control volume*

Mass balance

$$w_1 + w_2 = w_3 + w_4 \tag{5.11}$$

$$\frac{A_1\mathbf{V}_1}{v_1} + \frac{A_2\mathbf{V}_2}{v_2} = \frac{A_3\mathbf{V}_3}{v_3} + \frac{A_4\mathbf{V}_4}{v_4} \tag{5.12}$$

Energy balance

$$w_1\left(h_1 + \frac{\mathbf{V}_1^2}{2} + Z_1g\right) + w_2\left(h_2 + \frac{\mathbf{V}_2^2}{2} + Z_2g\right) + \frac{\text{đ}Q}{d\tau}$$

$$= w_3\left(h_3 + \frac{\mathbf{V}_3^2}{2} + Z_3g\right) + w_4\left(h_4 + \frac{\mathbf{V}_4^2}{2} + Z_4g\right) + \frac{\text{đ}W_x}{d\tau} \tag{5.13}$$

The steady flow energy equation applies to a wide variety of processes like pipe line flows, heat transfer processes, mechanical power generation in engines and turbines, combustion processes, and flows through nozzles and diffusors. In certain problems, some of the terms in steady flow energy equation may be negligible or zero. But it is best to write the full equation first, and then eliminate the terms which are unnecessary.

5.4 SOME EXAMPLES OF STEADY FLOW PROCESSES

The following examples illustrate the applications of the steady flow energy equation in some of the engineering systems.

5.4.1 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 5.4 shows a nozzle which is insulated. The steady flow energy equation of the control surface gives

$$h_1 + \frac{V_1^2}{2} + Z_1 g + \frac{đQ}{dm} = h_2 + \frac{V_2^2}{2} + Z_2 g + \frac{đW_x}{dm}$$

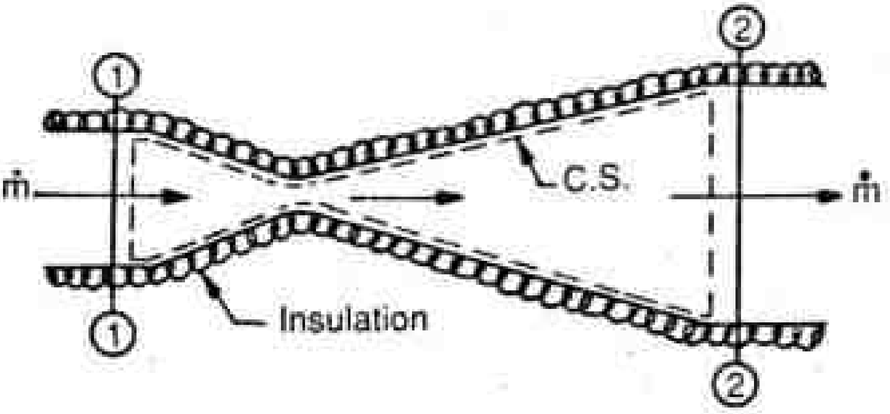


FIG. 5.4 *Steady flow process involving two fluid streams at the inlet and exit of the control volume*

Here $\frac{đQ}{dm} = 0, \frac{đW_x}{dm} = 0$, and the change in potential energy is zero.

The equation reduces to

$$h_1 + \frac{V_1^2}{2} = h_2 + \frac{V_2^2}{2} \tag{5.14}$$

The continuity equation gives

$$w = \frac{A_1 V_1}{v_1} = \frac{A_2 V_2}{v_2} \tag{5.15}$$

When the inlet velocity or the 'velocity of approach' V_1 is small compared to the exit velocity V_2, equation (5.14) becomes

$$h_1 = h_2 + \frac{V_2^2}{2}$$

or

$$V_2 = \sqrt{2(h_1 - h_2)} \text{ m/s}$$

where $(h_1 - h_2)$ is in J/kg.
Equations (5.14) and (5.15) hold good for a diffusor as well.

5.4.2 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 5.5 shows the process of throttling by a partially opened valve on a fluid flowing in an insulated pipe. In the steady-flow energy equation (5.8),

$$\frac{đQ}{dm} = 0, \frac{đW_x}{dm} = 0$$

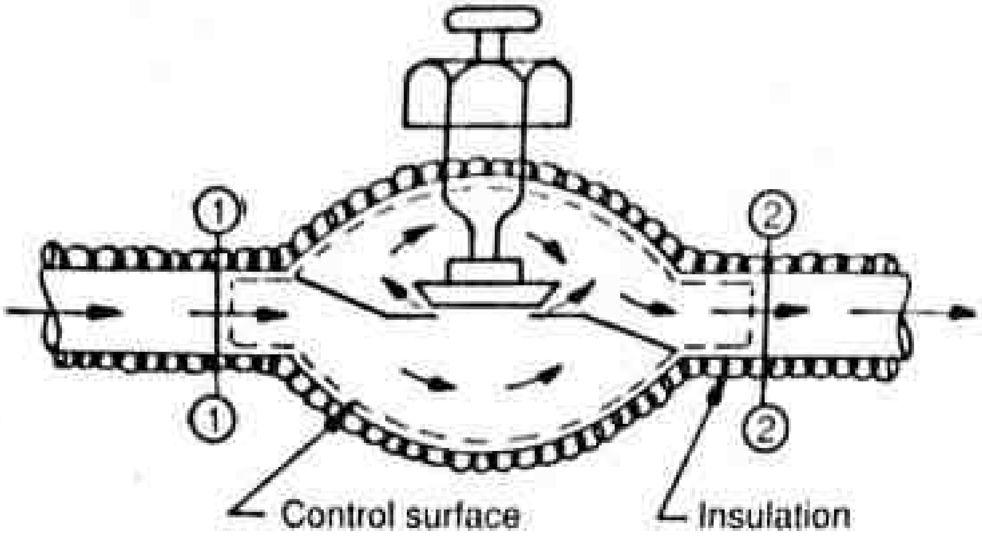


FIG. 5.5 *Flow through a valve*

and the changes in P.E. are very small and ignored. Thus the S.F.E.E. reduces to

$$h_1 + \frac{V_1^2}{2} = h_2 + \frac{V_2^2}{2}$$

Often the pipe velocities in throttling are so low that the K.E. terms are also negligible. So

$$h_1 = h_2 \tag{5.16}$$

or *the enthalpy of the fluid before throttling is equal to the enthalpy of the fluid after throttling.*

5.4.3 Turbine and Compressor

Turbines and engines give positive power output, whereas compressors and pumps require power input.

For a turbine (Fig. 5.6) which is well insulated, the flow velocities are often small, and the K.E. terms can be neglected. The S.F.E.E. then becomes

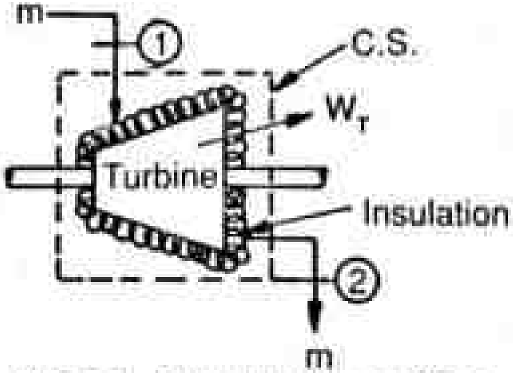


FIG. 5.6 *Flow through a turbine*

$$h_1 = h_2 + \frac{dW_x}{dm}$$

or

$$\frac{W_x}{m} = (h_1 - h_2)$$

It is seen that work is done by the fluid at the expense of its enthalpy.

Similarly, for an adiabatic pump or compressor, work is done upon the fluid and W is negative. So the S.F.E.E. becomes

$$h_1 = h_2 - \frac{W_x}{m}$$

or

$$\frac{W_x}{m} = h_2 - h_1$$

The enthalpy of the fluid increases by the amount of work input.

5.4.4 Heat Exchanger

A heat exchanger is a device in which heat is transferred from one fluid to another. Figure 5.7 shows a steam condenser, where steam condensers outside the tubes and cooling water flows through the tubes. The S.F.E.E. for the C.S. gives

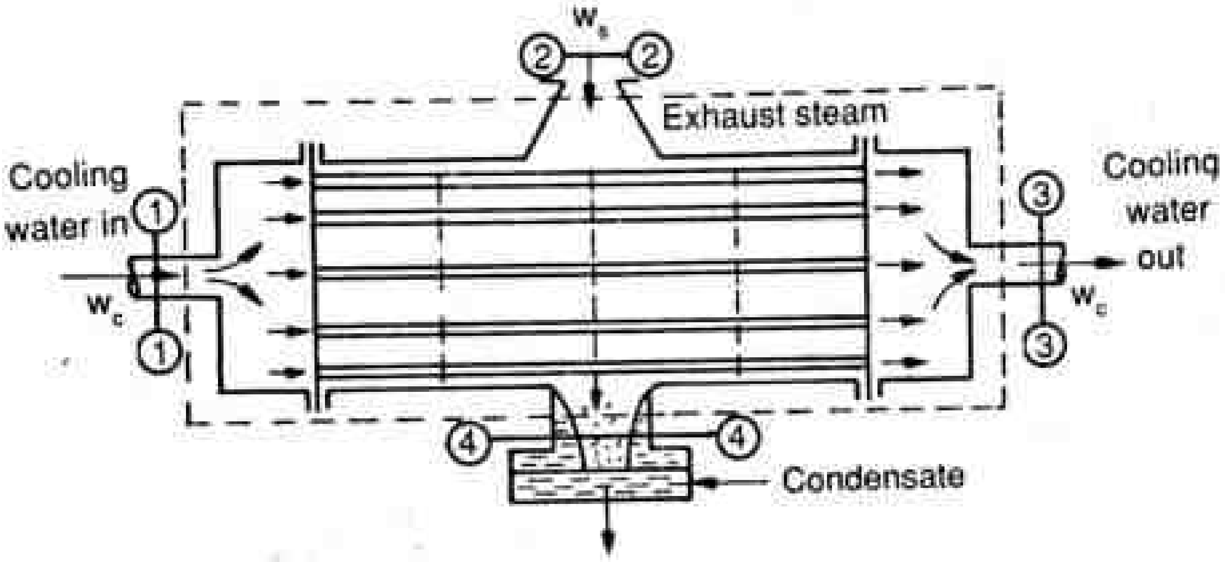


FIG. 5.7 *Steam condenser*

$$w_c h_1 + w_s h_2 = w_c h_3 + w_s h_4$$

or

$$w_s(h_2 - h_4) = w_c(h_3 - h_1)$$

Here the K.E. and P.E. terms are considered small, there is no external work done, and energy exchange in the form of heat is confined only between the two fluids, i.e., there is no external heat interaction or heat loss.

Figure 5.8 shows a steam desuperheater where the temperature of the superheated steam is reduced by spraying water. If w_1, w_2, and w_3 are the mass flow rates of the injected water, of the steam entering, and of the steam leaving, respectively, and h_1, h_2, and h_3 are the corresponding enthalpies, and if K.E. and P.E. terms are neglected as before, the S.F.E.E. becomes

$$w_1 h_1 + w_2 h_2 = w_3 h_3$$

and the mass balance gives

$$w_1 + w_2 = w_3$$

where the subscript p refers to the constant state of the fluid in the pipeline. If the tank is initially empty, $m_1 = 0$.

$$m_p h_p = m_2 u_2$$

Since

$$m_p = m_2$$

$$h_p = u_2$$

If the fluid is an ideal gas, the temperature of the gas in the tank after it is charged is given by

$$c_p T_p = c_v T_2$$

or

$$T_2 = \gamma T_p \tag{5.35}$$

SOLVED EXAMPLES

EXAMPLE 5.1

Air flows steadily at the rate of 0.5 kg/s through an air compressor, entering at 7 m/s velocity, 100 kPa pressure, and 0.95 m^3/kg volume, and leaving at 5 m/s, 700 kPa, and 0.19 m^3/kg. The internal energy of the air leaving is 90 kJ/kg greater than that of the air entering. Cooling water in the compressor jackets absorbs heat from the air at the rate of 58 kW. (a) Compute the rate of shaft work input to the air in kW. (b) Find the ratio of the inlet pipe diameter to outlet pipe diameter.

Solution Figure Ex. 5.1 shows the details of the problem.

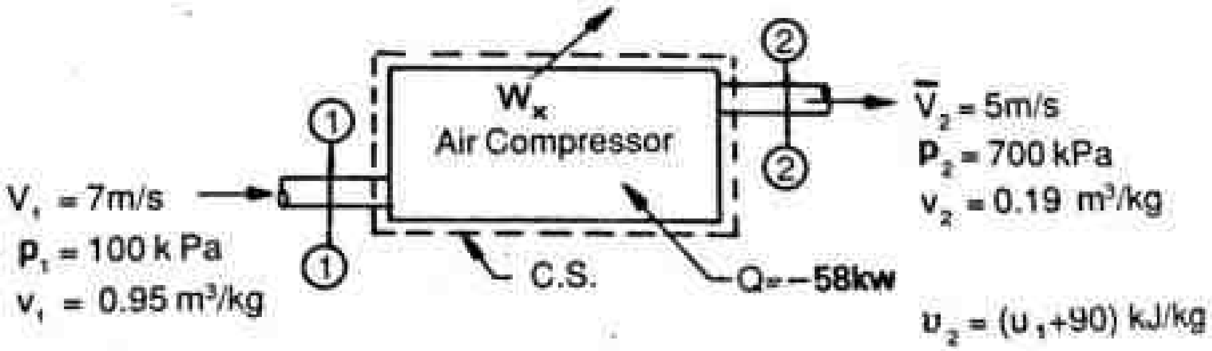


FIG. EX. 5.1

(a) Writing the steady flow energy equation, we have

$$w\left(u_1 + p_1 v_1 + \frac{\mathbf{V}_1^2}{2} + Z_1 g\right) + \frac{dQ}{d\tau}$$

$$= w\left(u_2 + p_2 v_2 + \frac{\mathbf{V}_2^2}{2} + Z_2 g\right) + \frac{dW_x}{d\tau}$$

$$\therefore\ \frac{dW_x}{d\tau} = -w\left[(u_2 - u_1) + (p_2 v_2 - p_1 v_1) + \frac{\mathbf{V}_2^2 - \mathbf{V}_1^2}{2} + (Z_2 - Z_1) g\right] + \frac{dQ}{d\tau}$$

$$\therefore \qquad \frac{dW_x}{d\tau} = -0.5\,\frac{\text{kg}}{\text{s}}\left[90\,\frac{\text{kJ}}{\text{kg}} + (7\times 0.19 - 1\times 0.95)\,100\,\frac{\text{kJ}}{\text{kg}} + \frac{(5^2-7^2)\times 10^{-3}}{2}\,\frac{\text{kJ}}{\text{kg}} + 0\right] - 58\text{ kW}$$

$$= -0.5\,[90 + 38 - 0.012]\text{ kJ/s} - 58\text{ kW}$$

$$= -122\text{ kW}$$

Ans. (a)

Rate of work input is 122 kW.

(b) From mass balance, we have

$$w = \frac{A_1 \mathbf{V}_1}{v_1} = \frac{A_2 \mathbf{V}_2}{v_2}$$

$$\therefore \qquad \frac{A_1}{A_2} = \frac{v_1}{v_2}\cdot\frac{\mathbf{V}_2}{\mathbf{V}_1} = \frac{0.95}{0.19}\times\frac{5}{7} = 3.57$$

$$\therefore \qquad \frac{d_1}{d_2} = \sqrt{3.57} = 1.89$$

Ans. (b)

EXAMPLE 5.2

In a steady flow apparatus, 135 kJ of work is done by each kg of fluid. The specific volume of the fluid, pressure, and velocity at the inlet are 0.37 m^3/kg, 600 kPa, and 16 m/s. The inlet is 32 m above the floor, and the discharge pipe is at floor level. The discharge conditions are 0.62 m^3/kg, 100 kPa, and 270 m/s. The total heat loss between the inlet and discharge is 9 kJ/kg of fluid. In flowing through this apparatus, does the specific internal energy increase or decrease, and by how much?

Solution Writing the steady flow energy equation for the control volume, as shown in Fig. Ex. 5.2.

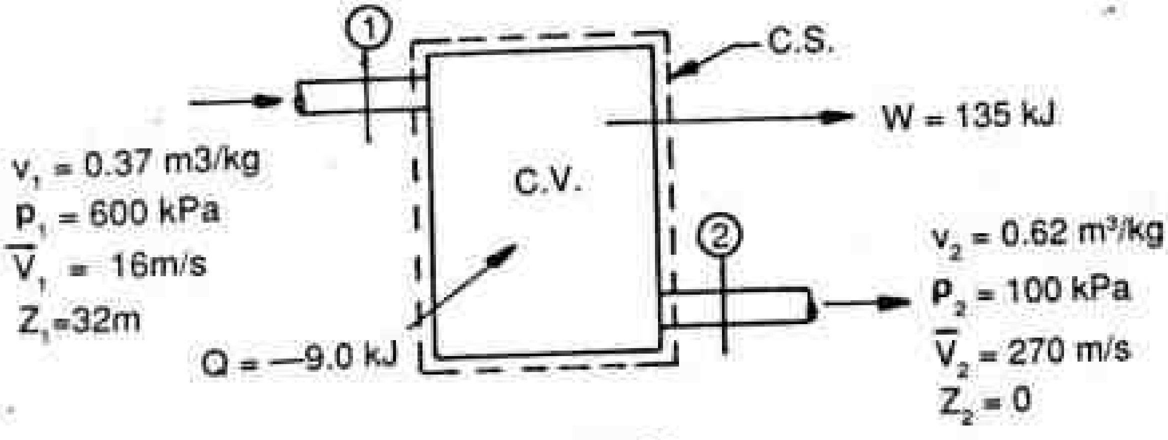


FIG. EX. 5.2

$$u_1 + p_1 v_1 + \frac{\mathbf{V}_1^2}{2} + Z_1 g + \frac{dQ}{dm} = u_2 + p_2 v_2 + \frac{\mathbf{V}_2^2}{2} + Z_2 g + \frac{dW_x}{dm}$$

$$\therefore \qquad u_1 - u_2 = (p_2 v_2 - p_1 v_1) + \frac{\mathbf{V}_2^2 - \mathbf{V}_1^2}{2} + (Z_2 - Z_1)g + \frac{dW_x}{dm} - \frac{dQ}{dm}$$

$$= (1 \times 0.62 - 6 \times 0.37) \times 10^2 + \frac{(270^2 - 16^2) \times 10^{-3}}{2}$$

$$+ (-32 \times 9.81 \times 10^{-3}) + 135 - (-9.0)$$

$$= -160 + 36.45 - 0.314 + 135 + 9$$

$$= 20.136 \text{ kJ/kg}$$

Specific internal energy decreases by 20.136 kJ.

EXAMPLE 5.4

A certain water heater operates under steady flow conditions receiving 4.2 kg/s of water at 75°C temperature, enthalpy 313.93 kJ/kg. The water is heated by mixing with steam which is supplied to the heater at temperature 100.2°C and enthalpy 2676 kJ/kg. The mixture leaves the heater as liquid water at temperature 100°C and enthalpy 419 kJ/kg. How much steam must be supplied to the heater per hour?

Solution By mass balance across the control surface (Fig. Ex. 5.4)

$$w_1 + w_2 = w_3$$

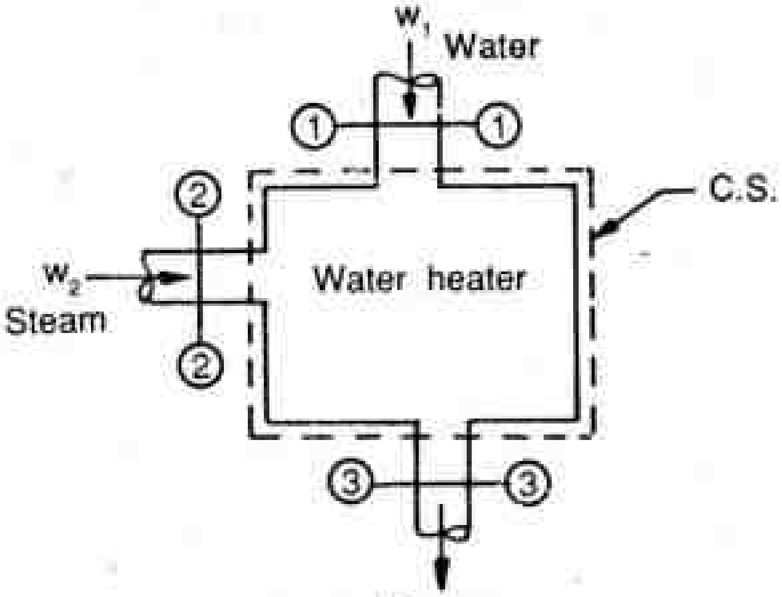


FIG. EX. 5.4

By energy balance

$$w_1\left(h_1 + \frac{V_1^2}{2} + Z_1 g\right) + \frac{dQ}{d\tau} + w_2\left(h_2 + \frac{V_2^2}{2} + Z_2 g\right)$$

$$= w_3\left(h_3 + \frac{V_3^2}{2} + Z_3 g\right) + \frac{dW_x}{d\tau}$$

By the nature of the process, there is no shaft work. Potential and kinetic energy terms are assumed to balance zero. The heater is assumed to be insulated. So the steady flow energy equation reduces to

$$w_1 h_1 + w_2 h_2 = w_3 h_3$$

$$4.2 \times 313.93 + w_2 \times 2676 = (4.2 + w_2)\ 419$$

$$\therefore \qquad w_2 = 0.196 \text{ kg/s}$$

$$= 705 \text{ kg/h}$$

INSTITUTE OF TEXTILE TECHNOLOGY
CHOUDWAR

Thermal Engineering-I

Chapter-3
Properties of Perfect Gases

Properties of Perfect Gases

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1. Introduction. 2. Laws of Perfect Gases. 3. Boyle's Law. 4. Charles' Law. 5. Gay-Lussac Law 6. General Gas Equation. 7. Joule's Law. 8. Characteristic Equation of Gas. 9. Avogadro's Law. 10. Universal Gas Constant or Molar Constant. 11. Specific Heat of a Gas. 12. Specific Heat at Constan Volume. 13. Specific Heat at Constant Pressure. 14. Enthalpy of a Gas. 15. Molar Specific Heats of a Gas. 16. Regnaults' Law. 17. Relation between Specific Heats. 18. Ratio of Specific Heats.

2.1. Introduction

A perfect gas (or an ideal gas) may be defined as a state of a substance, whose evaporatio from its liquid state is complete*, and strictly obeys all the gas laws under all conditions of temperatur and pressure. In actual practice, there is no real or actual gas which strictly obeys the gas laws ove the entire range of temperature and pressure. But, the real gases which are ordinarily difficult t liquify, such as oxygen, nitrogen, hydrogen and air, within certain temperature and pressure limits, may be regarded as perfect gases.

2.2. Laws of Perfect Gases

The physical properties of a gas are controlled by the following three variables :

1. Pressure exerted by the gas, 2. Volume occupied by the gas, and 3. Temperature of the gas.

The behaviour of a perfect gas, undergoing any change in the above mentioned variables, i governed by the following laws which have been established from experimental results.

1. Boyle's law, 2. Charles' law, and 3. Gay-Lussac law.

These laws are discussed, in detail, in the following pages.

2.3. Boyle's Law

This law was formulated by Robert Boyle in 1662. It states, "*The absolute pressure of a give mass of a perfect gas varies inversely as its volume, when the temperature remains constant*. Mathematically,

$$p \propto \frac{1}{v} \quad \text{or} \quad p\,v = \text{Constant}$$

The more useful form of the above equation is :

$$p_1 v_1 = p_2 v_2 = p_3 v_3 = \ldots\ldots = \text{Constant}$$

where suffixes $_{1},_{2}$ and $_{3}$ .... refer to different sets of conditions.

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* If its evaporation is partial, the substance is called vapour. A vapour, therefore, contains some particles liquid in suspension. It is thus obvious, that steam, carbon dioxide, sulphur dioxide and ammonia a regarded as vapours. It may be noted that a vapour becomes dry, when it is completely evaporated. If th dry vapour is further heated, the process is called *super heating* and the vapour is called *superheated vapo* The behaviour of superheated vapour is similar to that of a perfect gas.

2.4. Charles' Law

This law was formulated by a Frenchman Jacques A.C. Charles in about 1787. It may be stated in the following two different forms :

(*i*) *"The volume of a given mass of a perfect gas varies directly as its absolute temperature, when the absolute pressure remains constant."* Mathematically,

$$v \propto T \quad \text{or} \quad \frac{v}{T} = \text{Constant}$$

or
$$\frac{v_1}{T_1} = \frac{v_2}{T_2} = \frac{v_3}{T_3} = \ldots = \text{Constant}$$

where suffixes $_{1, 2}$ and $_{3}$ ..... refer to different sets of conditions.

(*ii*) *"All perfect gases change in volume by 1/273th of its original volume at 0° C for every 1° C change in temperature, when the pressure remains constant."*

Let v_0 = Volume of a given mass of gas at 0° C, and

v_t = Volume of the same mass of gas at t° C.

Then, according to the above statement,

$$v_t = v_0 + \frac{1}{273} v_0 t = v_0 \left(\frac{273 + t}{273} \right) = v_0 \times \frac{T}{T_0}$$

or
$$\frac{v_t}{T} = \frac{v_0}{T_0}$$

where T = Absolute temperature corresponding to t° C.

T_0 = Absolute temperature corresponding to 0° C.

A little consideration will show, that the volume of a gas goes on decreasing by 1/273th of its original volume for every 1° C decrease in temperature. It is thus obvious, that at a temperature of – 273° C, the volume of the gas would become *zero. The temperature at which the volume of a gas becomes zero is called *absolute zero temperature*.

Note. In all calculations of a perfect gas, the pressure and temperature values are expressed in absolute units.

2.5. Gay-Lussac Law

This law states, *"The absolute pressure of a given mass of a perfect gas varies directly as its absolute temperature, when the volume remains constant."* Mathematically

$$p \propto T \quad \text{or} \quad \frac{p}{T} = \text{Constant}$$

or
$$\frac{p_1}{T_1} = \frac{p_2}{T_2} = \frac{p_3}{T_3} = \ldots = \text{Constant}$$

where suffixes $_{1, 2}$ and $_{3}$ ... refer to different sets of conditions.

2.6. General Gas Equation

In the previous section we have discussed the gas laws which give us the relation between the two variables when the third variable is constant. But in actual practice, all the three variables *i.e.*, pressure, volume and temperature, change simultaneously. In order to deal with all practical cases, the Boyle's law and Charles' law are combined together, which give us a *general gas equation*.

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* It is only theoretical. Its exact value is – 273.16 °C. But for all practical purposes, this value is taken as – 273 °C.

According to Boyle's law

$$p \propto \frac{1}{v} \quad \text{or} \quad v \propto \frac{1}{p} \qquad \text{. . . (Keeping } T \text{ constan}$$

and according to Charles' law

$$v \propto T \qquad \text{. . . (Keeping } p \text{ constan}$$

It is thus obvious that

$$v \propto \frac{1}{p} \text{ and } T \text{ both} \quad \text{or} \quad v \propto \frac{T}{p}$$

$$\therefore \qquad pv \propto T \quad \text{or} \quad pv = CT$$

where C is a constant, whose value depends upon the mass and properties of the gas concerned.

The more useful form of the general gas equation is :

$$\frac{p_1 v_1}{T_1} = \frac{p_2 v_2}{T_2} = \frac{p_3 v_3}{T_3} = \ldots = \text{Constant}$$

where suffixes $_{1}$, $_{2}$ and $_{3}$ refer to different sets of conditions.

Example 2.1. *A gas occupies a volume of 0.1 m^3 at a temperature of 20° C and a pressure of 1.5 bar. Find the final temperature of the gas, if it is compressed to a pressure of 7.5 bar and occupies a volume of 0.04 m^3.*

Solution. Given : $v_1 = 0.1 \text{ m}^3$; $T_1 = 20° \text{C} = 20 + 273 = 293 \text{ K}$; $p_1 = 1.5$ ba $= {}^*0.15 \times 10^6 \text{ N/m}^2$; $p_2 = 7.5 \text{ bar} = 0.75 \times 10^6 \text{ N/m}^2$; $v_2 = 0.04 \text{ m}^3$

Let T_2 = Final temperature of the gas.

We know that $\dfrac{p_1 v_1}{T_1} = \dfrac{p_2 v_2}{T_2}$

$$\therefore \qquad T_2 = \frac{p_2 v_2 T_1}{p_1 v_1} = \frac{0.75 \times 10^6 \times 0.04 \times 293}{0.15 \times 10^6 \times 0.1} = 586 \text{ K}$$

$$= 586 - 273 = 313° \text{C} \quad \textbf{Ans.}$$

2.8. Characteristic Equation of a Gas

It is a modified form of general gas equation. If the volume (v) in the general gas equation is taken as that of 1 kg of gas (known as its specific volume, and denoted by v_s), then the constant C (in the general gas equation) is represented by another constant R (in the characteristic equation of gas). Thus the general gas equation may be rewritten as :

$$p v_s = RT$$

where R is known as *characteristic gas constant* or simply *gas constant*.

For any mass m kg of a gas, the characteristic gas equation becomes :

$$m\,p\,v_s = m\,R\,T$$

or

$$p\,v = m\,R\,T \qquad \ldots(\because\ m\,v_s = v)$$

Notes : 1. The units of gas constant (R) may be obtained as discussed below:

$$R = \frac{p\,v}{m\,T} = \frac{\text{N/m}^2 \times \text{m}^3}{\text{kg} \times \text{K}} = \frac{\text{N-m}}{\text{kg} \times \text{K}} = \text{N-m/kg K} = \text{J/kg K}$$

$$\ldots(\because\ 1\ \text{N-m} = 1\ \text{J})$$

2. The value of gas constant (R) is different for different gases. In S.I. units, its value for atmospheric air is taken 287 J/kg K or 0.287 kJ/kg K.

3. The equation $pv = m\,R\,T$ may also be expressed in another form *i.e.*,

$$p = \frac{m}{v}\,R\,T = \rho\,R\,T \qquad \ldots\left(\because\ \frac{m}{v} = \rho\right)$$

where ρ (rho) is the density of the given gas.

Example 2.2. *A vessel of capacity 3 m³ contains air at a pressure of 1.5 bar and a temperature of 25° C. Additional air is now pumped into the system until the pressure rises to 30 bar and temperature rises to 60° C. Determine the mass of air pumped in and express the quantity as a volume at a pressure of 1.02 bar and a temperature of 20° C.*

If the vessel is allowed to cool until the temperature is again 25° C, calculate the pressure in the vessel.

Solution. Given : $v_1 = 3\ \text{m}^3$; $p_1 = 1.5\ \text{bar} = 0.15 \times 10^6\ \text{N/m}^2$; $T_1 = 25°\text{C} = 25 + 273 = 298\ \text{K}$; $p_2 = 30\ \text{bar} = 3 \times 10^6\ \text{N/m}^2$; $T_2 = 60°\text{C} = 60 + 273 = 333\ \text{K}$; $p_3 = 1.02\ \text{bar} = 0.102 \times 10^6\ \text{N/m}^2$; $T_3 = 20°\text{C} = 20 + 273 = 293\ \text{K}$

Mass of air pumped in

Let m_1 = Mass of air initially filled in the vessel, and

m_2 = Mass of air in the vessel after pumping.

We know that $p_1\,v_1 = m_1\,R\,T_1$

$$\therefore \quad m_1 = \frac{p_1\,v_1}{R\,T_1} = \frac{0.15 \times 10^6 \times 3}{287 \times 298} = 5.26\ \text{kg}$$

...(Taking R for air = 287 J/kg K)

Similarly, $p_2\,v_2 = m_2\,R\,T_2$

$$\therefore \quad m_2 = \frac{p_2\,v_2}{R\,T_2} = \frac{3 \times 10^6 \times 3}{287 \times 333} = 94.17\ \text{kg} \qquad \ldots(\because\ v_2 = v_1)$$

∴ Mass of air pumped in,

$$m = m_2 - m_1 = 94.17 - 5.26 = 88.91 \text{ kg} \quad \textbf{Ans.}$$

Volume of air pumped in at a pressure of 1.02 bar and temperature of 20° C

Let v_3 = Volume of air pumped in.

We know that

$$p_3 v_3 = m R T_3$$

$$\therefore \quad v_3 = \frac{m R T_3}{p_3} = \frac{88.91 \times 287 \times 293}{0.102 \times 10^6} = 73.3 \text{ m}^3 \quad \textbf{Ans.}$$

Pressure in the vessel after cooling

Let p_4 = Pressure in the vessel after cooling.

We know that the temperature after cooling,

$$T_4 = T_1 = 25° \text{C} = 298 \text{ K}$$

Since the cooling is at constant volume, therefore

$$\frac{p_4}{p_2} = \frac{T_4}{T_2}$$

$$\therefore \quad p_4 = \frac{T_4 p_2}{T_2} = \frac{298 \times 3 \times 10^6}{333} = 2.68 \times 10^6 \text{ N/m}^2 = 26.8 \text{ bar} \quad \textbf{Ans.}$$

Example 2.3. *A spherical vessel of 1.5 m diameter, containing air at 40° C is evacuated till the vacuum inside the vessel becomes 735 mm of Hg. Calculate the mass of air pumped out. If the tank is then cooled to 3° C, what will be the final pressure in the tank ? Take atmospheric pressure as 760 mm of Hg.*

Solution. Given : $d = 1.5$ m ; $T_1 = 40° \text{C} = 40 + 273 = 313$ K ; $p_v = 735$ mm of Hg; $T_3 = 3° \text{C} = 3 + 273 = 276$ K; $p_1 = 760$ mm of Hg

Mass of air pumped out

Let m = Mass of air pumped out.

First of all, let us find out the initial mass of air (m_1) in a vessel. We know that volume of a spherical vessel,

$$v_1 = \frac{\pi d^3}{6} = \frac{\pi (1.5)^3}{6} = 1.767 \text{ m}^3$$

We know that $p_1 v_1 = m_1 R T_1$

$$\therefore \quad m_1 = \frac{p_1 v_1}{R T_1} = \frac{(760 \times 133.3)\, 1.767}{287 \times 313} = 1.993 \text{ kg}$$

... ($\because$ 1 mm of Hg = 133.3 N/m^2 ; and R for air = 287 J/kg K)

Let m_2 = Mass of air left in the vessel after evacuation.

We know that pressure after evacuation,

$$p_2 = \text{Atmospheric pressure} - \text{Vacuum pressure}$$

$$= 760 - 735 = 25 \text{ mm of Hg} = 25 \times 133.3 = 3332.5 \text{ N/m}^2$$

$$\therefore \quad m_2 = \frac{p_2 v_2}{R T_2} = \frac{3332.5 \times 1.767}{287 \times 313} = 0.066 \text{ kg}$$

$$\ldots (\because v_2 = v_1 \text{ and } T_2 = T_1)$$

∴ Mass of air pumped out,

$$m = m_1 - m_2 = 1.993 - 0.066 = 1.927 \text{ kg} \quad \textbf{Ans.}$$

Final pressure in the tank

Let p_3 = Final pressure in the tank.

Since the cooling is at constant volume, therefore

$$\frac{p_3}{T_3} = \frac{p_2}{T_2}$$

or

$$p_3 = \frac{p_2 T_3}{T_2} = \frac{3332.5 \times 276}{313} = 2938 \text{ N/m}^2 = 22 \text{ mm of Hg} \quad \textbf{Ans.}$$

2.9. Avogadro's Law

It states, "*Equal volumes of all gases, at the same temperature and pressure, contain equal number of molecules.*"

Thus, according to Avogadro's law, 1 m^3 of oxygen (O_2) will contain the same number of molecules as 1 m^3 of hydrogen (H_2) when the temperature and pressure is the same. Since the molecular mass of hydrogen is 2 and that of oxygen is 16, therefore a molecule of oxygen has a mass which is 32/2 = 16 times the mass of hydrogen molecules. Moreover, as 1 m^3 of these two gases contain the same number of molecules, and a molecule of oxygen has a mass 16 times than that of hydrogen molecule, therefore it is evident that density of oxygen is 16 times the density of hydrogen. Hence, the Avogadro's law indicates that the density of any two gases is directly proportional to their molecular masses, if the gases are at the same temperature and pressure.

The density of oxygen at Normal Temperature and Pressure (briefly written as N.T.P.) *i.e.* at 0° C and 1.013 bar is 1.429 kg/m^3.

∴ Specific volume (of 1 kg) of oxygen at N.T.P.,

$$v_s = \frac{1}{1.429} \text{ m}^3/\text{kg} \qquad \ldots \left[\because \text{ Specific volume} = \frac{1}{\text{Density}} \right]$$

and volume of 32 kg (or 1 kg molecule briefly written as 1 kg-mol)

$$= \frac{1}{1.429} \times 32 = 22.4 \text{ m}^3$$

Similarly, it can be proved that the volume of 1 kg mol of any gas at N.T.P. is 22.4 m^3.

Note : 1 g-mole (molecular mass expressed in gram) of all gases occupies a volume of 22.4 litres at N.T.P.

The values of molecular mass for some common gases are given in the following table :

Table 2.1. Molecular mass for some common gases.

S.No.	*Gas*	*Molecular mass*	*S.No.*	*Gas*	*Molecular mass*
1.	Hydrogen (H_2)	2	5.	Carbon dioxide (CO_2)	44
2.	Oxygen (O_2)	32	6.	Methane (CH_4)	16
3.	Nitrogen (N_2)	28	7.	Acetylene (C_2H_2)	26
4.	Carbon monoxide (CO)	28	8.	Sulphur dioxide (SO_2)	64

The *universal gas constant* or *molar constant* (generally denoted by R_u) of a gas is the produ of the gas constant and the molecular mass of the gas. Mathematically,

$$R_u = MR$$

where M = Molecular mass of the gas expressed in kg-mole, and

R = Gas constant.

In general, if M_1, M_2, M_3, etc. are the molecular masses of different gases and R_1, R_2, R_3, etc are their gas constants respectively, then

$$M_1 R_1 = M_2 R_2 = M_3 R_3 = ... = R_u$$

Notes : 1. The value of R_u is same for all gases.

2. In S.I. units, the value of R_u is taken as 8314 J/kg-mol K or 8.314 kJ/kg-mol K.

3. The characteristic gas equation (*i.e.* $p\,v = R\,T$) may be written in terms of molecular mass as :

$$p\,v = M\,R\,T \qquad PV = n R_u T \qquad n = \frac{m}{M} \qquad R_u = mR$$

Example 2.4. *A mass of 2.25 kg of nitrogen occupying 1.5 m³ is heated from 25° C to 200° at a constant volume. Calculate the initial and final pressures of the gas. Take universal gas constan as 8314 J/kg mol K. The molecular mass of nitrogen is 28.*

Solution. Given : $m = 2.25$ kg ; $v_1 = 1.5$ m³ ; $T_1 = 25°\text{ C} = 25 + 273 = 298$ K ; $T_2 = 200°\text{ C} = 200 + 273 = 473$ K ; $R_u = 8314$ J/kg mol K ; $M = 28$

We know that gas constant,

$$R = \frac{R_u}{M} = \frac{8314}{28} = 297 \text{ J/kg K}$$

Initial pressure of the gas

Let p_1 = Initial pressure of the gas.

We know that

$$p_1 v_1 = m\,R\,T_1$$

$$\therefore \quad p_1 = \frac{m\,R\,T_1}{v_1} = \frac{2.25 \times 297 \times 298}{1.5} = 0.133 \times 10^6 \text{ N/m}^2 = 1.33 \text{ bar} \quad \textbf{Ans.}$$

Final pressure of the gas

Let p_2 = Final pressure of the gas.

Since the volume is constant, therefore

$$\frac{p_1}{T_1} = \frac{p_2}{T_2} \quad \text{or} \quad p_2 = \frac{p_1 T_2}{T_1} = \frac{1.33 \times 473}{298} = 2.11 \text{ bar} \quad \textbf{Ans.}$$

Example 2.5. *Nitrogen is to be stored at pressure 140 bar, temperature 27° C in a steel fla of 0.05 m³ volume. The flask is to be protected against excessive pressure by a fusible plug which wi melt and allow the gas to escape if the temperature rises too high. Find :*

1. How many kg of nitrogen will the flask hold at the designed conditions ? Take molecul mass of nitrogen as 28 ; and

2. At what temperature must the fusible plug melt in order to limit the pressure of the full fla to a maximum of 168 bar ?

Solution. Given : $p_1 = 140$ bar $= 14 \times 10^6$ N/m^2 ; $T_1 = 27°$C $= 27 + 273 = 300$ K ; $v_1 = 0.05$ m^3 ; $M = 28$

1. Mass of nitrogen

Let m = Mass of nitrogen in kg which the flask will hold

We know that gas constant,

$$R = \frac{\text{Universal gas constant}}{\text{Molecular mass}} = \frac{R_u}{M} = \frac{8314}{28} = 297 \text{ J/kg K}$$

... (R_u for all gases = 8314 J/kg K)

We also know that

$$p_1 v_1 = m R T_1$$

$$\therefore \quad m = \frac{p_1 v_1}{R T_1} = \frac{14 \times 10^6 \times 0.05}{297 \times 300} = 7.86 \text{ kg} \quad \textbf{Ans.}$$

2. Melting temperature of fusible plug

Let T_2 = Melting temperature of fusible plug, and

p_2 = Maximum pressure = 168 bar = 16.8×10^6 N/m^2 ... (Given)

Since the gas is heated at constant volume, therefore

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

$$\therefore \quad T_2 = \frac{p_2 T_1}{p_1} = \frac{16.8 \times 10^6 \times 300}{14 \times 10^6} = 360 \text{ K} = 87° \text{C} \quad \textbf{Ans.}$$

2.11. Specific Heats of a Gas

The specific heat of a substance may be broadly defined as the amount of heat required to raise the temperature of its unit mass through one degree. All the liquids and solids have one specific heat only. But a gas can have any number of specific heats (lying between zero and infinity) depending upon the conditions, under which it is heated. The following two types of specific heats of a gas are important from the subject point of view :

1. Specific heat at constant volume, and 2. Specific heat at constant pressure.

These specific heats are discussed, in detail, as follows :

$Q = m \cdot C \cdot \Delta T$

$C = \frac{Q}{m \cdot \Delta T}$

2.12. Specific Heat at Constant Volume

if $m=1$, $\Delta T=1$, $C=Q$

It is the amount of heat required to raise the temperature of a unit mass of gas through one degree when it is heated at a constant volume. It is generally denoted by c_v .

Consider a gas contained in a container with a fixed lid as shown in Fig. 2.1. Now, if this gas is heated, it will increase the temperature and pressure of the gas in the container. Since the lid of the container is fixed, therefore the volume of gas remains unchanged.

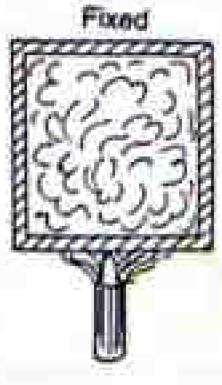


Fig. 2.1. Heat being supplied at constant volume.

Let m = Mass of the gas,

T_1 = Initial temperature of the gas, and

T_2 = Final temperature of the gas.

∴ Total heat supplied to the gas at constant volume,

$$Q_{1-2} = \text{Mass} \times \text{Sp. heat at constant volume} \times \text{Rise in temperature}$$

$$= mc_v (T_2 - T_1)$$

It may be noted that whenever a gas is heated at constant volume, no work is done by the gas. The whole heat energy is utilised in increasing the temperature and pressure of the gas. In other words, all the amount of heat supplied remains within the body of the gas, and represents the *increase in internal energy of the gas.*

2.13. Specific Heat at Constant Pressure

It is the amount of heat required to raise the temperature of a unit mass of a gas through on degree, when it is heated at constant pressure. It is generally denoted by c_p.

Consider a gas contained in a container with a movable lid as shown in Fig. 2.2. Now if this gas is heated, it will increase the temperature and pressure of the gas in the container. Since the lid of the container is movable, therefore it will move upwards, in order to counterbalance the tendency for pressure to rise.

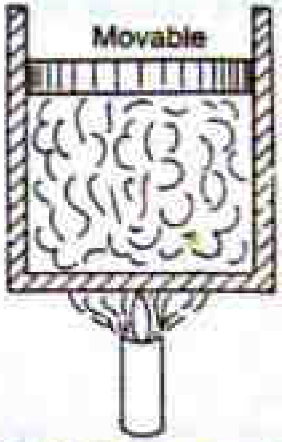


Fig. 2.2. Heat being supplied at constant pressure.

Let m = Mass of the gas,

T_1 = Initial temperature of the gas,

v_1 = Initial volume of the gas, and

T_2, v_2 = Corresponding values for the final condition of the gas.

∴ Total heat supplied to the gas, at constant pressure,

$$Q_{1-2} = \text{Mass} \times \text{Sp. heat at constant pressure} \times \text{Rise in temperature}$$

$$= mc_p (T_2 - T_1)$$

Whenever a gas is heated at a constant pressure, the heat supplied to the gas is utilised for th following two purposes :

1. To raise the temperature of the gas. This heat remains within the body of the gas, an represents the increase in internal energy Mathematically, increase in internal energy,

$$dU = mc_v \ (T_2 - T_1)$$

2. To do some external work during expansion. Mathematically, workdone by the gas,

$$W_{1-2} = p(v_2 - v_1) = mR(T_2 - T_1)$$

It is thus obvious, that the specific heat at constant pressure is higher than the specific heat a constant volume.

From above, we may write as

$$Q_{1-2} = dU + W_{1-2} \quad \text{or} \quad {}^{**}Q_{1-2} - W_{1-2} = dU \quad \text{... (First Law of Thermodynamic}$$

2.14. Enthalpy of a Gas

In thermodynamics, one of the basic quantities most frequently recurring is the *sum* of the internal energy (U) and the product of pressure and volume ($p\,v$). This sum ($U + p\,v$) is termed as *enthalpy* and is written as H. Mathematically,

Enthalpy, $\quad H = U + p\,v$

Since ($U + p\,v$) is made up entirely of properties, therefore enthalpy (H) is also a property.

For a unit mass, specific enthalpy,

$$h = u + p\,v_s$$

where $\quad u$ = Specific internal energy, and

v_s = Specific volume.

Note. We know that $\quad Q_{1-2} = dU + W_{1-2} = dU + p\,dv$

When gas is heated at constant pressure from an initial condition 1 to a final condition 2, then change in internal energy,

$$dU = U_2 - U_1$$

and workdone by the gas,

$$W_{1-2} = p\,dv = p\,(v_2 - v_1)$$

$$\therefore \quad Q_{1-2} = (U_2 - U_1) + p\,(v_2 - v_1)$$

$$= (U_2 + p\,v_2) - (U_1 + p\,v_1) = H_2 - H_1$$

and for a unit mass, $\quad q_{1-2} = h_2 - h_1$

Thus, for a constant pressure process, the heat supplied to the gas is equal to the change of enthalpy.

2.15. Molar Specific Heats of a Gas

The molar or volumetric specific heat of a gas may be defined as the amount of heat required to raise the temperature of unit mole of gas through one degree. Mathematically, molar specific heat,

$$\boxed{c_m = Mc}$$

where $\quad M$ = Molecular mass of the gas.

In the similar way as discussed in Art. 2.11, the molar specific heat at constant volume,

$$c_{vm} = M\,c_v$$

and molar specific heat at constant pressure,

$$c_{pm} = M\,c_p$$

Example 2.6. *A closed vessel contains 2 kg of carbon dioxide at temperature 20° C and pressure 0.7 bar. Heat is supplied to the vessel till the gas acquires a pressure of 1.4 bar. Calculate : 1. Final temperature ; 2. Work done on or by the gas ; 3. Heat added ; and 4. Change in internal energy. Take specific heat of the gas at constant volume as 0.657 kJ/kg K.*

Solution. Given : $m = 2$ kg ; $T_1 = 20°\text{ C} = 20 + 273 = 293$ K ; $p_1 = 0.7$ bar ; $p_2 = 1.4$ bar

1. Final temperature

Let $\quad T_2$ = Final temperature.

Since the gas is heated in a closed vessel, therefore the volume of gas will remain constant.

We know that $\quad \dfrac{p_1}{T_1} = \dfrac{p_2}{T_2}$

$$\therefore \qquad T_2 = \frac{p_2 T_1}{p_1} = \frac{1.4 \times 293}{0.7} = 586 \text{ K} = 586 - 273 = 313^\circ \text{C} \ \textbf{Ans.}$$

2. Workdone on or by the gas

Since there is no change in volume, therefore workdone on or by the gas (W_{1-2}) is *zero*. **An**

3. Heat added

We know that heat added at constant volume,

$$Q_{1-2} = m\, c_v (T_2 - T_1) = 2 \times 0.657\,(586 - 293) = 385 \text{ kJ} \ \textbf{Ans.}$$

4. Change in internal energy

Let dU = Change in internal energy.

We know that $Q_{1-2} = W_{1-2} + dU$

$$\therefore \qquad dU = Q_{1-2} = 385 \text{ kJ} \ \textbf{Ans.} \qquad \ldots (\because W_{1-2} =$$

Example 2.7. *A mass of 0.25 kg of air in a closed system expands from 2 bar, 60° C to 1 ba and 40° C while receiving 1.005 kJ of heat from a reservoir at 100° C. The surrounding atmospher is at 0.95 bar and 27° C. Determine the maximum work. How much of this work would be done o the atmosphere ?*

Solution. Given : $m = 0.25$ kg ; $p_1 = 2 \text{ bar} = 0.2 \times 10^6 \text{ N/m}^2$; $T_1 = 60^\circ \text{C} = 60 + 27$ $= 333$ K ; $p_2 = 1 \text{ bar} = 0.1 \times 10^6 \text{ N/m}^2$; $T_2 = 40^\circ \text{C} = 40 + 273 = 313$ K ; $Q = 1.005$ kJ ; *$T_R = 100^\circ$ C ; $p = 0.95 \text{ bar} = 0.095 \times 10^6 \text{ N/m}^2$; *$T = 27^\circ$ C

Maximum Workdone

First of all, let us find the values of initial volume (v_1) and final volume (v_2) of air. We kno that

$$v_1 = \frac{m R T_1}{p_1} \qquad \ldots (\because pv = mRT$$

$$= \frac{0.25 \times 287 \times 333}{0.2 \times 10^6} = 0.119 \text{ m}^3 \qquad \ldots (\text{Taking } R = 287 \text{ J/kg K}$$

Similarly $$v_2 = \frac{m R T_2}{p_2} = \frac{0.25 \times 287 \times 313}{0.1 \times 10^6} = 0.224 \text{ m}^3$$

∴ Workdone on the atmosphere,

$$W_1 = p\,(v_2 - v_1) = 0.095 \times 10^6\,(0.224 - 0.119) = 9975 \text{ J} = 9.975 \text{ kJ}$$

We know that change of internal energy,

$$dU = m\, c_v (T_2 - T_1) = 0.25 \times 0.712\,(313 - 333) = -3.56 \text{ kJ}$$

$$\ldots (\text{Taking } c_v = 0.712 \text{ kJ/kg K}$$

The –ve sign shows that there is a *decrease* of internal energy.

Net workdone, $W_2 = Q - dU = 1.005 - (-3.56) = 4.565$ kJ

∴ Maximum workdone,

$$W = W_1 + W_2 = 9.975 + 4.565 = 14.54 \text{ kJ} \ \textbf{Ans.}$$

2.17. Relation between Specific Heats

Consider a gas enclosed in a container and being heated, at a constant pressure, from the initial state 1 to the final state 2.

Let m = Mass of the gas,

T_1 = Initial temperature of the gas,

T_2 = Final temperature of the gas,

v_1 = Initial volume of the gas,

v_2 = Final volume of the gas,

c_p = Specific heat at constant pressure,

c_v = Specific heat at constant volume, and

p = Constant pressure.

We know that the heat supplied to the gas at constant pressure,

$$Q_{1-2} = m\,c_p\,(T_2 - T_1)$$

As already discussed, a part of this heat is utilised in doing the external work, and the rest remains within the gas, and is used in increasing the internal energy of the gas.

∴ Heat utilised for external work,

$$W_{1-2} = p\,(v_2 - v_1) \qquad \ldots (i)$$

and increase in internal energy, $dU = m\,c_v\,(T_2 - T_1)$ ... (ii)

We know that $Q_{1-2} = W_{1-2} + dU$ ... (iii)

$$\therefore \quad m\,c_p\,(T_2 - T_1) = p\,(v_2 - v_1) + m\,c_v\,(T_2 - T_1) \qquad \ldots (iv)$$

Using characteristic gas equation (*i.e.* $p\,v = m\,R\,T$), we have

$$p\,v_1 = m\,R\,T_1 \qquad \ldots \text{(for initial condition)}$$

and

$$p\,v_2 = m\,R\,T_2 \qquad \ldots \text{(for final condition)}$$

$$\therefore \quad p\,(v_2 - v_1) = m\,R\,(T_2 - T_1)$$

Now substituting the value of $p\,(v_2 - v_1)$ in equation (*iv*),

$$m\,c_p\,(T_2 - T_1) = m\,R\,(T_2 - T_1) + m\,c_v\,(T_2 - T_1)$$

$$\therefore \quad c_p = R + c_v \quad \text{or} \quad c_p - c_v = R \qquad \ldots (v)$$

The above equation may be rewritten as :

$$c_p - c_v = R \quad \text{or} \quad c_v(\gamma - 1) = R \qquad \ldots \left(\text{where } \gamma = \frac{c_p}{c_v} \right)$$

$$\therefore \qquad c_v = \frac{R}{(\gamma - 1)} \qquad \ldots (vi)$$

Notes. 1. The equation (*v*) gives an important result, as it proves that characteristic constant of a gas (R) is equal to the difference of its two specific heats (*i.e.* $c_p - c_v$).

2. The value of R is taken as 287 J/kg K or 0.287 kJ/kg K.

3. In terms of molar specific heats, the equation (*v*) may be written as

$$c_{pm} - c_{vm} = R_u$$

where R_u is the universal gas constant and its value is taken 8314 J/kg K or 8.314 kJ/kg K.

2.18. Ratio of Specific Heats

The ratio of two specific heats (*i.e.* c_p/c_v) of a gas is an important constant in the field of Thermodynamics and is represented by a Greek letter gamma (γ). It is also known as *adiabatic index*. Since c_p is always greater than c_v, the value of γ is always greater than unity.

We have seen in Art. 2.17 that

$$c_p - c_v = R \quad \text{or} \quad c_p = c_v + R$$

Dividing both sides by c_v,

$$\frac{c_p}{c_v} = 1 + \frac{R}{c_v} \quad \text{or} \quad \gamma = 1 + \frac{R}{c_v}$$

The values of c_p, c_v and γ for some common gases are given below :

Table 2.2. Values of c_p and c_v for some common gases.

S.No.	*Name of gas*	c_p (kJ/kg K)	c_v (kJ/kg K)	$\gamma = \frac{c_p}{c_v}$
1.	Air	1.000	0.720	1.40
2.	Carbon dioxide (CO_2)	0.846	0.657	1.29
3.	Oxygen (O_2)	0.913	0.653	1.39
4.	Nitrogen (N_2)	1.043	0.745	1.40
5.	Ammonia (NH_3)	2.177	1.692	1.29
6.	Carbon monoxide (CO)	1.047	0.749	1.40
7.	Hydrogen (H_2)	14.257	10.133	1.40
8.	Argon (A)	0.523	0.314	1.67
9.	Helium (He)	5.234	3.153	1.66
10.	Methane (CH_4)	2.169	1.650	1.31

Example 2.9. *One kg of a perfect gas occupies a volume of 0.85 m^3 at 15° C and at a constant pressure of 1 bar. The gas is first heated at a constant volume, and then at a constant pressure. Find the specific heat at constant volume and constant pressure of the gas. Take γ = 1.4.*

Solution. Given : $m = 1$ kg ; $v = 0.85$ m^3 ; $T = 15°$ C $= 15 + 273 = 288$ K ; $p = 1$ bar $= 0.1 \times 10^6$ N/m^2 ; $\gamma = c_p/c_v = 1.4$

Specific heat of gas at constant volume

Let c_v = Specific heat of gas at constant volume, and

R = Characteristic gas constant.

We know that

$$p\,v = m\,R\,T$$

$$\therefore \quad R = \frac{p\,v}{m\,T} = \frac{0.1 \times 10^6 \times 0.85}{1 \times 288} = 295 \text{ J/kg K} = 0.295 \text{ kJ/kg K}$$

We also know that

$$c_v = \frac{R}{\gamma - 1} = \frac{0.295}{1.4 - 1} = 0.7375 \text{ kJ/kg K} \quad \textbf{Ans.}$$

Specific heat of gas at constant pressure

We know that specific heat of gas at constant pressure,

$$c_p = 1.4\,c_v = 1.4 \times 0.7375 = 1.0325 \text{ kJ/kg K} \quad \textbf{Ans.} \quad \ldots (\because c_p/c_v = 1.4$$

Example 2.10. *A gas mixture obeying perfect gas law has a molecular mass of 26.7. Assuming a mean molar specific heat at constant volume of 21.1 kJ/kg K, determine the values of characteristic gas constant, molar specific heat at constant pressure and the ratio of specific heats.*

Solution. Given : $M = 26.7$; $c_{vm} = 21.1$ kJ/kg K

Characteristic gas constant

We know that characteristic gas constant,

$$R = \frac{\text{Universal gas constant}}{\text{Molecular mass}} = \frac{R_u}{M} = \frac{8.314}{26.7} = 0.3114 \text{ kJ/kg K} \quad \textbf{Ans.}$$

$$\ldots (\because R_u \text{ for all gases} = 8.314 \text{ kJ / kg K})$$

Molar specific heat at constant pressure

Let c_{pm} = Molar specific heat at constant pressure.

We know that

$$c_{pm} - c_{vm} = R_u \quad \text{or} \quad c_{pm} = R_u + c_{vm} = 8.314 + 21.1 = 29.414 \text{ kJ/kg K} \quad \textbf{Ans.}$$

Ratio of specific heats

We know that ratio of specific heats,

$$\gamma = \frac{c_{pm}}{c_{vm}} = \frac{29.414}{21.1} = 1.394 \quad \textbf{Ans.}$$

Example 2.11. *One kg of ideal gas is heated from 18.3° C to 93.4° C. Assuming $R = 0.264$ kJ/kg K and $\gamma = 1.18$ for the gas, find : 1. Specific heats ; 2. Change in internal energy ; and 3. Change in enthalpy.*

Solution. Given : $m = 1$ kg ; $T_1 = 18.3°\text{C} = 18.3 + 273 = 291.3$ K ; $T_2 = 93.4°\text{C} = 93.4 + 273 = 366.4$ K ; $R = 0.264$ kJ/kg K ; $\gamma = c_p/c_v = 1.18$

Specific heats

Let c_p = Specific heat at constant pressure, and

c_v = Specific heat at constant volume.

We know that $$c_v = \frac{R}{\gamma - 1} = \frac{0.264}{1.18 - 1} = 1.47 \text{ kJ/kg K} \quad \textbf{Ans.}$$

$$\therefore \quad c_p = \gamma\, c_v = 1.18 \times 1.47 = 1.73 \text{ kJ/kg K} \quad \textbf{Ans.}$$

Change in internal energy

We know that change in internal energy,

$$dU = m\, c_v (T_2 - T_1) = 1 \times 1.47\,(366.4 - 291.3) = 110.4 \text{ kJ} \quad \textbf{Ans.}$$

Change in enthalpy

We know that change in enthalpy,

$$dH = m\, c_p (T_2 - T_1) = 1 \times 1.73\,(366.4 - 291.3) = 130 \text{ kJ} \quad \textbf{Ans.}$$

Example 2.12. *A gas, having initial pressure, volume and temperature as 275 kN/m², 0.09 m³ and 185° C respectively, is compressed at constant pressure until its temperature is 15° C. Calculate the amount of heat transferred and work done during the process. Take R = 290 J/kg K and c_p = 1.005 kJ/kg K.*

Solution. Given : p_1 = 275 kN/m² = 275 × 10³ N/m² ; v_1 = 0.09 m³ ; T_1 = 185° C = 185 + 273 = 458 K ; T_2 = 15° C = 15 + 273 = 288 K ; R = 290 J/kg K ; c_p = 1.005 kJ/kg K

Amount of heat transferred

First of all, let us find the mass of the gas (m). We know that

$$p_1 v_1 = m\, R\, T_1$$

$$\therefore \quad m = \frac{p_1 v_1}{R\, T_1} = \frac{275 \times 10^3 \times 0.09}{290 \times 458} = 0.186 \text{ kg}$$

We know that the amount of heat transferred,

$$Q_{1\text{-}2} = m\, c_p (T_2 - T_1) = 0.186 \times 1.005\,(288 - 458) \text{ kJ}$$

$$= -\,31.78 \text{ kJ} \quad \textbf{Ans.}$$

The –ve sign indicates that the heat has been extracted from the gas during the process. In other words, the gas is compressed.

Workdone during the process

First of all, let us find the final volume of the gas (v_2). Since the process takes place at constant pressure, therefore

$$\frac{v_1}{T_1} = \frac{v_2}{T_2} \quad \text{or} \quad v_2 = \frac{v_1\, T_2}{T_1} = \frac{0.09 \times 288}{458} = 0.056 \text{ m}^3$$

We know that the workdone during the process,

$$W_{1\text{-}2} = p\,(v_2 - v_1) = 275 \times 10^3\,(0.056 - 0.09) = -\,9350 \text{ J}$$

$$= -\,9.35 \text{ kJ} \quad \textbf{Ans.}$$

The –ve sign indicates the work is done on the gas. In other words, the gas is compressed.

Example 2.13. *A certain gas has c_p = 1.96 kJ/kg K and c_v = 1.5 kJ/kg K. Find its molecular mass and gas constant. A constant volume chamber of 0.3 m³ capacity contains 2 kg of this gas at 5° C. The heat is transferred to the gas until the temperature is 100° C. Find the workdone, heat transferred and change in internal energy.*

Solution. Given : $c_p = 1.96$ kJ/kg K ; $c_v = 1.5$ kJ/kg K ; $v = 0.3$ m^3 ; $m = 2$ kg ; $T_1 = 5°$ C $= 5 + 273 = 278$ K ; $T_2 = 100°$ C $= 100 + 273 = 373$ K

Molecular mass and gas constant

Let M = Molecular mass, and

R = Gas constant.

We know that gas constant,

$$R = c_p - c_v = 1.96 - 1.5 = 0.46 \text{ kJ/kg K}$$

and molecular mass,

$$M = \frac{\text{Universal gas constant}}{\text{Gas constant}} = \frac{R_u}{R} = \frac{8.314}{0.46} = 18 \text{ kg} \quad \textbf{Ans.}$$

. . . ($\because$ R_u for all gases = 8.314 kJ/kg K)

Workdone

Since the volume is constant, therefore workdone ($W_{1\text{-}2}$) is zero. **Ans.**

Heat transferred

We know that heat transferred,

$$Q_{1-2} = m\, c_v (T_2 - T_1) = 2 \times 1.5\,(373 - 278) = 285 \text{ kJ} \quad \textbf{Ans.}$$

Change in internal energy

Let dU = Change in internal energy.

We know that $Q_{1-2} = W_{1-2} + dU = 0 + dU = dU$

$\therefore$ $dU = Q_{1-2} = 285$ kJ **Ans.**

3.5. Heating and Expansion of Gases in Non-flow Processes

The heating and expanding of a gas may be performed in many ways. But the following are the different non-flow processes (reversible and irreversible) as applied to perfect gas :

1. *Reversible non-flow processes.* These processes are as follows :

(*a*) Constant volume process (or Isochoric process),

(*b*) Constant pressure process (or Isobaric process),

(*c*) Hyperbolic process,

(*d*) Constant temperature process (or Isothermal process)

(*e*) Adiabatic process (or Isentropic process), and

(*f*) Polytropic process

2. *Irreversible non-flow processes.* The free expansion process is an irreversible non-flow process.

These above mentioned processes are discussed, in detail, in the following pages.

Note: The above mentioned processes are also applicable to the cooling and compression of gases. Cooling is regarded as negative heating, and compression as negative expansion.

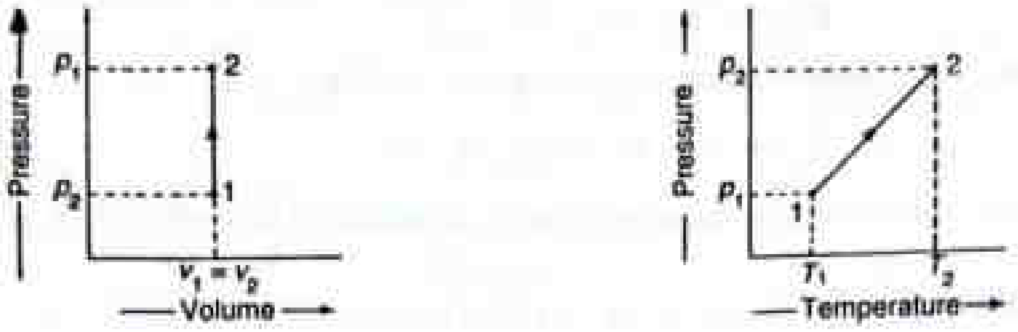
3.6. Constant Volume Process (or Isochoric Process)

We have already discussed that when a gas is heated at a constant volume, its temperature and pressure will increase. Since there is no change in its volume, therefore no work is done by the gas. All the heat supplied to the gas is stored within the gas in the form of internal energy. It may be noted that this process is governed by Gay-Lussac law. Now consider m kg of a certain gas being heated at constant volume from initial state 1 to a final state 2.

Let p_1, v_1 and T_1 = Pressure, volume and temperature at the initial state 1, and

p_2, v_2 and T_2 = Pressure, volume and temperature at the final state 2.

The process is shown on the pressure-volume (p-v) and pressure-temperature (p-T) diagrams in Fig. 3.4 (*a*) and (*b*) respectively.



(*a*) p-v diagram. (*b*) p-T diagram.

Fig. 3.4. Constant volume process.

Now let us derive the following relations for the reversible constant volume process.

1. *Pressure-volume-temperature (p-v-T) relationship*

We know that the general gas equation is

$$\frac{p_1 v_1}{T_1} = \frac{p_2 v_2}{T_2} \qquad \ldots (i)$$

Since the gas is heated at constant volume, therefore $v_1 = v_2$.

$$\therefore \qquad \frac{p_1}{T_1} = \frac{p_2}{T_2} \quad \text{or} \quad \frac{p}{T} = \text{Constant} \qquad \ldots \text{[From equation } (i)]$$

Thus the constant volume process is governed by Gay-Lussac law.

2. *Workdone by the gas*

We know that $\delta W = p\, dv$

On integrating from state 1 to state 2,

$$\int_1^2 \delta W = \int_1^2 p\, dv = p \int_1^2 dv$$

or

$$W_{1\text{-}2} = p\,(v_2 - v_1) = 0 \qquad \ldots (\because v_1 = v_2)$$

3. *Change in internal energy*

We know that change in internal energy,

$$dU = m\, c_v\, dT \qquad \ldots \text{(Joule's law)}$$

On integrating from state 1 to state 2,

$$\int_1^2 dU = m\, c_v \int_1^2 dT$$

or

$$U_2 - U_1 = m\, c_v\, (T_2 - T_1)$$

4. *Heat supplied or heat transfer*

We know that $\delta Q = dU + \delta W$

On integrating from state 1 to state 2,

$$\int_1^2 \delta Q = \int_1^2 dU + \int_1^2 \delta W$$

or $$Q_{1-2} = (U_2 - U_1) + W_{1-2}$$

Since $W_{1-2} = 0$, therefore heat supplied or heat transfer,

$$Q_{1-2} = U_2 - U_1 = m\, c_v (T_2 - T_1)$$

This shows that all the heat supplied to the gas is utilised in increasing the internal energy of the gas.

5. *Change in enthalpy*

We know that the change in enthalpy,

$$dH = dU + d(pv)$$

On integrating from state 1 to state 2,

$$\int_1^2 dH = \int_1^2 dU + \int_1^2 d(p\,v)$$

or
$$H_2 - H_1 = (U_2 - U_1) + (p_2 v_2 - p_1 v_1)$$
$$= m\, c_v (T_2 - T_1) + m\, R\, (T_2 - T_1)$$
$$\ldots (\because p_1 v_1 = m\,R\,T_1 \text{ ; and } p_2 v_2 = m\,R\,T_2)$$
$$= m\,(T_2 - T_1)(c_v + R) = m\, c_p (T_2 - T_1) \qquad \ldots (\because c_p - c_v = R)$$

Note : The change in internal energy (dU) and the change in enthalpy (dH) have the same expression for each process.

Example 3.3. *A certain gas occupies a space of 0.3 m^3 at a pressure of 2 bar and a temperature of 77° C. It is heated at a constant volume, until the pressure is 7 bar. Determine : 1. temperature at the end of the process ; 2. mass of the gas ; 3. change in internal energy ; and 4. change in enthalpy during the process.*

Assume c_p = 1.005 kJ/kg K ; c_v = 0.712 kJ/kg K ; and R = 287 J/kg K.

Solution. Given : $v_1 = 0.3$ m^3 ; $p_1 = 2$ bar $= 0.2 \times 10^6$ N/m^2 ; $T_1 = 77°$ C $= 77 + 273 = 350$ K ; $p_2 = 7$ bar $= 0.7 \times 10^6$ N/m^2 ; $c_p = 1.005$ kJ/kg K ; $c_v = 0.712$ kJ/kg K ; $R = 287$ J/kg K

1. *Temperature at the end of the process*

Let T_2 = Temperature at the end of the process.

We know that $$\frac{p_1}{T_1} = \frac{p_2}{T_2}$$

$$\therefore \quad T_2 = \frac{p_2 T_1}{p_1} = \frac{0.7 \times 10^6 \times 350}{0.2 \times 10^6} = 1225 \text{ K} = 1225 - 273 = 952° \text{ C} \quad \textbf{Ans.}$$

2. *Mass of the gas*

Let m = Mass of the gas.

We know that $p_1 v_1 = m\,R\,T_1$

$$\therefore \qquad m = \frac{p_1 v_1}{R T_1} = \frac{0.2 \times 10^6 \times 0.3}{287 \times 350} = 0.597 \text{ kg} \quad \textbf{Ans.}$$

3. Change in internal energy

We know that change in internal energy,

$$dU = U_2 - U_1 = m\, c_v (T_2 - T_1)$$
$$= 0.597 \times 0.712\,(1225 - 350) = 372 \text{ kJ} \quad \textbf{Ans.}$$

4. Change in enthalpy

We know that change in enthalpy,

$$dH = H_2 - H_1 = m\, c_p (T_2 - T_1)$$
$$= 0.597 \times 1.005\,(1225 - 350) = 525 \text{ kJ} \quad \textbf{Ans.}$$

3.7. Constant Pressure Process (or Isobaric Process)

We have already discussed that when a gas is heated at a constant pressure, its temperature and volume will increase. Since there is a change in its volume, therefore the heat supplied to the gas is utilised to increase the internal energy of the gas and for doing some external work. It may be noted that this process is governed by Charles' law.

Now consider *m* kg of a certain gas being heated at a constant pressure from an initial state 1 to a final state 2.

Let p_1, v_1 and T_1 = Pressure, volume and temperature at the initial state 1, and

p_2, v_2 and T_2 = Pressure, volume and temperature at the final state 2.

The process is shown on the *p-v* and *p-T* diagrams in Fig. 3.5 (*a*) and (*b*) respectively.

(*a*) *p-v* diagram. (*b*) *p-T* diagram.

Fig. 3.5. Constant pressure process.

Now let us derive the following relations for the reversible constant pressure process.

1. Pressure-volume-temperature (p-v-T relationship)

We know that the general gas equation is

$$\frac{p_1 v_1}{T_1} = \frac{p_2 v_2}{T_2} \qquad \ldots (i)$$

Since the gas is heated at constant pressure, therefore $p_1 = p_2$.

$$\therefore \qquad \frac{v_1}{T_1} = \frac{v_2}{T_2} \quad \text{or} \quad \frac{v}{T} = \text{Constant} \qquad \ldots \text{[From equation } (i)]$$

Thus, the constant pressure process is governed by Charles' law.

2. Workdone by the gas

We know that $\delta W = p\, dv$

On integrating from state 1 to state 2,

$$\int_1^2 \delta W = \int_1^2 p\,dv = p\int_1^2 dv$$

or $$W_{1-2} = p\,(v_2 - v_1) = m\,R\,(T_2 - T_1)$$

$$\ldots \left(\because\ p\,v_1 = m\,R\,T_1 \text{ and } p\,v_2 = m\,R\,T_2\right.$$

3. Change in internal energy

We have discussed in the previous article that the change in internal energy (dU) is same fo all the processes. Therefore, change in internal energy,

$$dU = U_2 - U_1 = m\,c_v\,(T_2 - T_1)$$

4. Heat supplied or heat transferred

We know that $\delta Q = dU + \delta W$

On integrating from state 1 to state 2,

$$\int_1^2 \delta Q = \int_1^2 dU + \int_1^2 \delta W$$

$$\therefore \quad Q_{1-2} = (U_2 - U_1) + W_{1-2} \qquad \ldots (ii)$$

$$= m\,c_v\,(T_2 - T_1) + m\,R\,(T_2 - T_1)$$

$$= m\,(T_2 - T_1)\,(c_v + R)$$

$$= m\,c_p\,(T_2 - T_1) \qquad \ldots (\because c_p - c_v = R)$$

The equation (*ii*) shows that the heat supplied to the gas is utilised in increasing the internal energy of the gas and for doing some external work.

5. Change in enthalpy

We have discussed in the previous article that the change in enthalpy (dH) is same for all the processes. Therefore, change in enthalpy,

$$dH = H_2 - H_1 = m\,c_p\,(T_2 - T_1)$$

We see that change in enthalpy is equal to the heat supplied or heat transferred.

Notes. 1. If the gas is cooled at a constant pressure, then there will be a compression. It is thus obvious that during cooling, the temperature and volume will decrease and work is said to be done on the gas. In this case,

Workdone on the gas, $W_{1-2} = p\,(v_1 - v_2) = m\,R\,(T_1 - T_2)$

Decrease in internal energy, $dU = U_1 - U_2 = m\,c_v\,(T_1 - T_2)$

and heat rejected by the gas, $Q_{1-2} = m\,c_p\,(T_1 - T_2)$

2. During expansion or heating process, work is done by the gas (*i.e.* W_{1-2} is + ve) ; internal energy of the gas increases (*i.e.* dU is +ve) and heat is supplied to the gas (*i.e.* Q_{1-2} is +ve).

3. During compression or cooling process, work is done on the gas (*i.e.* W_{1-2} is −ve) ; internal energy of the gas decreases (*i.e.* dU is −ve) and heat is rejected by the gas (*i.e.* Q_{1-2} is −ve).

Example 3.4. *The values of specific heats at constant pressure and at constant volume for an ideal gas are 0.984 kJ/kg K and 0.728 kJ/kg K. Find the values of characteristic gas constant (R) and ratio of specific heats (γ) for the gas. If one kg of this gas is heated at constant pressure from 25° C to 200° C, estimate the heat added, ideal workdone and change in internal energy. Also calculate the pressure and final volume, if the initial volume was 2 m³.*

Solution. Given : $c_p = 0.984$ kJ/kg K ; $c_v = 0.728$ kJ/kg K ; $m = 1$ kg ; $T_1 = 25°\text{ C} = 25 + 273 = 298$ K ; $T_2 = 200°\text{ C} = 200 + 273 = 473$ K ; $v_1 = 2\text{ m}^3$

The heating of gas at constant pressure is shown in Fig. 3.6.

Characteristic gas constant

We know that characteristic gas constant,

$$R = c_p - c_v = 0.984 - 0.728$$

$$= 0.256 \text{ kJ/kg K} \quad \textbf{Ans.}$$

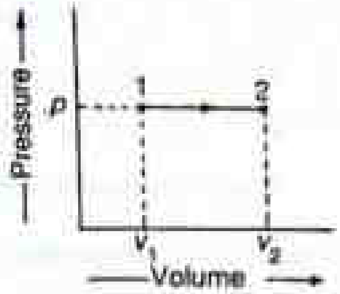


Fig. 3.6

Ratio of specific heats

We know that ratio of specific heats,

$$\gamma = c_p / c_v = 0.984 / 0.728 = 1.35 \quad \textbf{Ans.}$$

Heat added

We know that heat added during constant pressure operation,

$$Q_{1-2} = m\, c_p (T_2 - T_1) = 1 \times 0.984\,(473 - 298) = 172.2 \text{ kJ} \quad \textbf{Ans.}$$

Workdone

We know that workdone during constant pressure operation,

$$W_{1-2} = p\,(v_2 - v_1) = m\,R\,(T_2 - T_1) \qquad \ldots (\because p\,v = m\,R\,T)$$

$$= 1 \times 0.256\,(473 - 298) = 44.8 \text{ kJ} \quad \textbf{Ans.}$$

Change in internal energy

*We know that change in internal energy,

$$dU = U_2 - U_1 = m\, c_v (T_2 - T_1) = 1 \times 0.728\,(473 - 298) \text{ kJ}$$

$$= 127.4 \text{ kJ} \quad \textbf{Ans.}$$

Pressure and final volume of the gas if the initial volume, $v_1 = 2 \text{ m}^3$

Let $p_1 = p_2$ = Pressure of the gas, and

v_2 = Final volume of the gas.

We know that $$\frac{p_1\, v_1}{T_1} = \frac{p_2\, v_2}{T_2} \quad \text{or} \quad \frac{v_1}{T_1} = \frac{v_2}{T_2} \qquad \ldots (\because \text{Pressure is constant})$$

$$\therefore \quad v_2 = \frac{v_1\, T_2}{T_1} = \frac{2 \times 473}{298} = 3.17 \text{ m}^3 \quad \textbf{Ans.}$$

We also know that

$$p_1\, v_1 = m\,R\,T_1$$

$$\therefore \quad p_1 = \frac{m\,R\,T_1}{v_1} = \frac{1 \times 256 \times 298}{2} = 38\,140 \text{ N/m}^2 \qquad \ldots (R \text{ is taken in J/kg K})$$

$$= 0.3814 \text{ bar} \quad \textbf{Ans.} \qquad \ldots (\because 1 \text{ bar} = 10^5 \text{ N/m}^2)$$

Example 3.5. *A quantity of gas has a volume of 0.14 m^3, pressure 1.5 bar and a temperature 100° C. If the gas is compressed at a constant pressure, until its volume becomes 0.112 m^3, determine :*

[illegible]

1. the temperature at the end of compression ; 2. work done in compressing the gas ; 3 decrease in internal energy ; and 4. heat given out by the gas.

Assume $c_p = 1.005$ *kJ/kg K ;* $c_v = 0.712$ *kJ/kg K ; and* $R = 285$ *J/kg K*

Solution. Given : $v_1 = 0.14\ \text{m}^3$; $p = 1.5\ \text{bar} = 0.15 \times 10^6\ \text{N/m}^2$; $T_1 = 100°\text{C} = 100 + 273 = 373\ \text{K}$; $v_2 = 0.112\ \text{m}^3$; $c_p = 1.005$ kJ/kg K ; $c_v = 0.712$ kJ/kg K ; $R = 285$ J/kg K

The compression of gas at constant pressure is shown in Fig. 3.7.

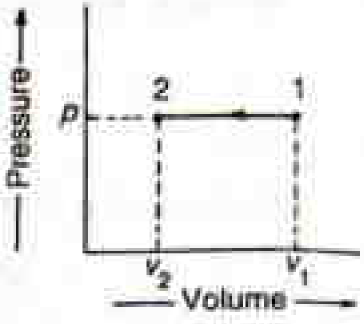


Fig. 3.7

1. Temperature at the end of compression

Let T_2 = Temperature at the end of compression.

We know that
$$\frac{v_1}{T_1} = \frac{v_2}{T_2}$$

$$\therefore \quad T_2 = \frac{v_2 T_1}{v_2} = \frac{0.112 \times 373}{0.14} = 298.4\ \text{K}$$

$$= 298.4 - 273 = 25.4°\text{C} \quad \textbf{Ans.}$$

2. Workdone is compressing the gas

We know that workdone in compressing the gas,

$$W_{1-2} = p\,(v_1 - v_2) = 0.15 \times 10^6\,(0.14 - 0.112) = 4200\ \text{J} = 4.2\ \text{kJ} \quad \textbf{Ans.}$$

3. Decrease in internal energy

First of all, let us find the mass of gas (m) admitted for compression. We know that

$$p_1 v_1 = m R T_1$$

$$\therefore \quad m = \frac{p_1 v_1}{R T_1} = \frac{0.15 \times 10^6 \times 0.14}{285 \times 373} = 0.197\ \text{kg} \qquad \ldots (\because p_1 = p)$$

We know that decrease in internal energy,

$$dU = U_1 - U_2 = m\,c_v\,(T_1 - T_2)$$

$$= 0.197 \times 0.712\,(373 - 298.4) = 10.46\ \text{kJ} \quad \textbf{Ans.}$$

4. Heat given out by the gas

We know that heat given out by the gas,

$$Q_{1-2} = m\,c_p\,(T_1 - T_2)$$

$$= 0.197 \times 1.005\,(373 - 298.4) = 14.77\ \text{kJ} \quad \textbf{Ans.}$$

3.9. Constant Temperature Process (or Isothermal Process)

A process, in which the temperature of the working substance remains constant during its expansion or compression, is called *constant temperature process* or *isothermal process*. This will happen when the working substance remains in a perfect thermal contact with the surroundings, so that the heat 'sucked in' or 'squeezed out' is compensated exactly for the work done by the gas or on the gas respectively. It is thus obvious that in an isothermal process :

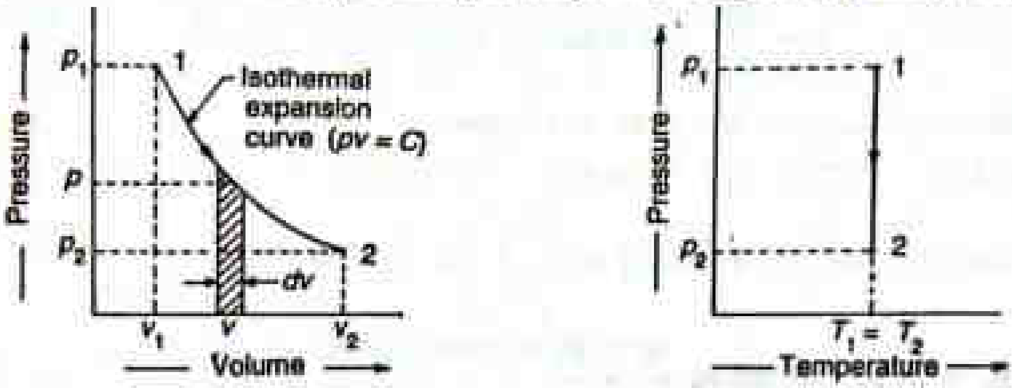
1. there is no change in temperature,
2. there is no change in internal energy, and
3. there is no change in enthalpy.

Now consider m kg of a certain gas being heated at constant temperature from an initial state 1 to final state 2.

Let p_1, v_1 and T_1 = Pressure, volume and temperature at the initial state 1, and

p_2, v_2 and T_2 = Pressure, volume and temperature at the final state 2.

The process is shown on the *p-v* and *p-T* diagrams in Fig. 3.9 (*a*) and (*b*) respectively.



(*a*) *p-v* diagram. (*b*) *p-T* diagram.

Fig. 3.9. Constant temperature (Isothermal) process.

Now let us derive the following relations for the reversible constant temperature process or isothermal process.

1. *Pressure-volume-temperature (p-v-T) relationship*

We know that the general gas equation is

$$\frac{p_1 v_1}{T_1} = \frac{p_2 v_2}{T_2} \qquad \ldots (i)$$

Since the gas is heated at constant temperature, therefore $T_1 = T_2$.

$$\therefore \quad p_1 v_1 = p_2 v_2 \quad \text{or} \quad p\,v = \text{Constant} \qquad \ldots \text{[From equation } (i)]$$

Thus, the constant temperature process or isothermal process is governed by Boyle's law.

2. *Workdone by the gas*

We know that $\delta W = p\,dv$

On integrating from state 1 to state 2,

$$\int_1^2 \delta W = \int_1^2 p\,dv$$

or

$$W_{1-2} = \int_1^2 p\,dv \qquad \ldots (ii)$$

Since the expansion of the gas is isothermal, *i.e.* $p\,v = C$, therefore

$$p\,v = p_1\,v_1 \quad \text{or} \quad p = \frac{p_1\,v_1}{v}$$

$$P_1V_1 = P_2V_2$$

$$\Rightarrow \frac{V_2}{V_1} = \frac{P_1}{P_2}$$

Substituting this value of p in equation (*ii*), we have

$$W_{1-2} = \int_{v_1}^{v_2} \frac{p_1\,v_1}{v}\,dv = p_1\,v_1 \int_{v_1}^{v_2} \frac{dv}{v}$$

$$= P_1V_1 \ln\left(\frac{P_1}{P_2}\right)$$

$$= p_1\,v_1\Big[\log_e v\Big]_{v_1}^{v_2} = p_1\,v_1\,\log_e\left(\frac{v_2}{v_1}\right) = P_1V_1 \ln\left(\frac{V_2}{V_1}\right) \quad \dots(iii$$

The above equation may be expressed in terms of corresponding logarithm to the base 10, *i.e*

$$W_{1-2} = 2.3\,p_1\,v_1\log\left(\frac{v_2}{v_1}\right) = 2.3\,p_1\,v_1\log r \quad \dots(iv$$

where $\quad r = \dfrac{v_2}{v_1}$, and is known as *expansion ratio.*

The equation (*iv*) may also be written as follows :

We know that $\quad p_1\,v_1 = p_2\,v_2 = m\,R\,T$

$\therefore$ Work done, $\quad W_{1-2} = 2.3\,m\,R\,T\log\left(\dfrac{v_2}{v_1}\right) = 2.3\,m\,R\,T\log r$

Since $p_1\,v_2 = p_2\,v_2$, therefore $\dfrac{v_2}{v_1} = \dfrac{p_1}{p_2}$

$\therefore$ Work done, $\quad W_{1-2} = 2.3\,p_1\,v_1\log\left(\dfrac{p_1}{p_2}\right)$

Notes : (*a*) Expansion ratio, $r = \dfrac{\text{Volume at the end of expansion}}{\text{Volume at the beginning of expansion}}$

(*b*) Compression ratio, $r = \dfrac{\text{Volume at the beginning of compression}}{\text{Volume at the end of compression}}$

3. *Change in internal energy*

We know that change in internal energy,

$$dU = U_2 - U_1 = m\,c_v\,(T_2 - T_1)$$

Since it is a constant temperature process, *i.e.* $T_1 = T_2$, therefore

$$dU = U_2 - U_1 = 0 \quad \text{or} \quad U_1 = U_2$$

4. *Heat supplied or heat transferred*

We know that heat supplied or heat transferred from state 1 to state 2,

$$Q_{1-2} = dU + W_{1-2} = W_{1-2} \quad \dots(\because dU = 0$$

This shows that all the heat supplied to the gas is equal to the workdone by the gas.

5. *Change in enthalpy*

We know that change in enthalpy,

$$dH = H_2 - H_1 = m\,c_p\,(T_2 - T_1)$$

Since it is a constant temperature process, *i.e.* $T_1 = T_2$, therefore

$$dH = H_2 - H_1 = 0 \quad \text{or} \quad H_1 = H_2$$

Example 3.6. *A quantity of air has a volume of 0.4 m³ at a pressure of 5 bar and a temperature of 80° C. It is expanded in a cylinder at a constant temperature to a pressure of 1 bar. Determine the amount of work done by the air during expansion.*

Solution. Given : $v_1 = 0.4\ \text{m}^3$; $p_1 = 5\ \text{bar} = 0.5 \times 10^6\ \text{N/m}^2$; *$T = 80°\ \text{C}$; $p_2 = 1\ \text{bar} = 0.1 \times 10^6\ \text{N/m}^2$

First of all, let us find the volume of air at the end of expansion (*i.e.* v_2). We know that

$$p_1 v_1 = p_2 v_2 \quad \text{or} \quad v_2 = \frac{p_1 v_1}{p_2} = \frac{0.5 \times 10^6 \times 0.4}{0.1 \times 10^6} = 2\ \text{m}^3$$

and expansion ratio, $\quad r = v_2 / v_1 = 2 / 0.4 = 5$

We know that workdone by the air during expansion,

$$W_{1-2} = 2.3\, p_1 v_1 \log r = 2.3 \times 0.5 \times 10^6 \times 0.4 \log 5\ \text{J}$$

$$= 0.46 \times 10^6 \times 0.699 = 321\ 540\ \text{J} = \mathbf{321.54\ kJ\ \ Ans.}$$

Example 3.7. *0.1 m³ of air at a pressure of 1.5 bar is expanded isothermally* [illegible] *m³. Calculate the final pressure of the gas and heat supplied during the process.*

Solution. Given : $v_1 = 0.1\ \text{m}^3$; $p_1 = 1.5\ \text{bar} = 0.15 \times 10^6\ \text{N/m}^2$; $v_2 = 0.5\ \text{m}^3$

Final pressure of the gas

Let $\quad p_2 =$ Final pressure of the gas.

We know that $\quad p_1 v_1 = p_2 v_2$

$$\therefore \quad p_2 = \frac{p_1 v_1}{v_2} = \frac{0.15 \times 10^6 \times 0.1}{0.5} = 0.03 \times 10^6\ \text{N/m}^2 = \mathbf{0.3\ bar\ \ Ans.}$$

Heat supplied during the process

We know that expansion ratio,

$$r = v_2 / v_1 = 0.5 / 0.1 = 5$$

$\therefore$ Workdone during the process,

$$W_{1-2} = 2.3\, p_1 v_1 \log r = 2.3 \times 0.15 \times 10^6 \times 0.1 \log 5\ \text{J}$$

$$= 0.0345 \times 10^6 \times 0.699 = 24\ 115\ \text{J} = 24.115\ \text{kJ}$$

We know that in an isothermal process, heat supplied (Q_{1-2}) is equal to the workdone during the process.

$$\therefore \quad Q_{1-2} = W_{1-2} = \mathbf{24.115\ kJ\ \ Ans.}$$

3.10. Adiabatic Process (or Isentropic Process)

A process, in which the working substance neither receives nor gives out heat to its surroundings, during its expansion or compression, is called an ***adiabatic process*. This will happen when the working substance remains thermally insulated, so that no heat enters or leaves it during th process. It is thus obvious, that in an adiabatic or isentropic process :

1. No heat leaves or enters the gas,
2. The temperature of the gas changes, as the work is done at the cost of internal energy, an
3. The change in internal energy is equal to the work done.

Now consider m kg of a certain gas being heated adiabatically from an initial state 1 to a fin state 2.

Let p_1, v_1 and T_1 = Pressure, volume and temperature at the initial state 1, and

p_2, v_2 and T_2 = Pressure, volume and temperature at the final state 2.

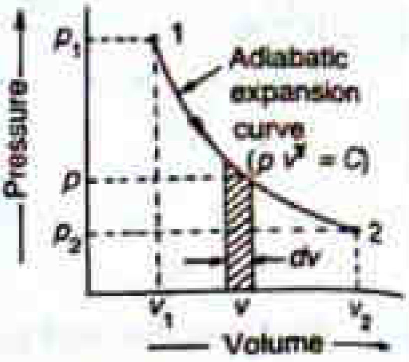


Fig. 3.10. Adiabatic process

The process is shown on the p-v diagram in Fig. 3.10.

Now let us derive the following relations for a reversible adiabatic process.

1. Pressure-volume-temperature (p-v-T) relationship

We know that $\delta Q = \delta W + dU$ (First law of thermodynamics) ... (i)

Since in an adiabatic process, no heat transfer takes places, therefore

$$\delta Q = 0$$

$$\therefore \quad \delta W + dU = 0$$

or

$$p\,dv + m\,c_v\,dT = 0$$

$$\therefore \quad dT = \frac{-p\,dv}{m\,c_v} \qquad \ldots (ii)$$

We know that $pv = mRT$

Differentiating this expression, we get

$$p\,dv + v\,dp = mR\,dT$$

$$\therefore \quad dT = \frac{p\,dv + v\,dp}{mR} = \frac{p\,dv + v\,dp}{m(c_p - c_v)} \qquad \ldots (iii)$$

$$\ldots (\because R = c_p - c_v)$$

Equating equations (ii) and (iii),

$$\frac{-p\,dv}{m\,c_v} = \frac{p\,dv + v\,dp}{m(c_p - c_v)}$$

$$\frac{c_p - c_v}{c_v} = \frac{p\,dv + v\,dp}{-p\,dv} = -1 - \frac{v\,dp}{p\,dv}$$

$$\frac{c_p}{c_v} - 1 = -1 - \left(\frac{v}{dv} \times \frac{dp}{p}\right)$$

$$\gamma = -\left(\frac{v}{dv} \times \frac{dp}{p}\right) \qquad \ldots \left(\because \frac{c_p}{c_v} = \gamma\right)$$

$$\therefore \qquad \gamma \times \frac{dv}{v} = -\frac{dp}{p}$$

$$\gamma \times \frac{dv}{v} + \frac{dp}{p} = 0$$

Integrating both sides,

$$\gamma \log_e v + \log_e p = \text{Constant} \quad \text{or} \quad \log_e pv^\gamma = \log_e C$$

$$\therefore \qquad pv^\gamma = C \quad \text{or} \quad p_1 v_1^\gamma = p_2 v_2^\gamma = \ldots = C \qquad \ldots (iv)$$

The equation (*iv*) may also be expressed in the following forms ;

$$\frac{p_1}{p_2} = \left(\frac{v_2}{v_1}\right)^\gamma \qquad \ldots (v)$$

From the general gas equation, we know that

$$\frac{p_1 v_1}{T_1} = \frac{p_2 v_2}{T_2} \quad \text{or} \quad \frac{p_1}{p_2} = \frac{T_1}{T_2} \times \frac{v_2}{v_1} \qquad \ldots (vi)$$

Equating equations (*v*) and (*vi*),

$$\left(\frac{v_2}{v_1}\right)^\gamma = \frac{T_1}{T_2} \times \frac{v_2}{v_1} \quad \text{or} \quad \frac{T_1}{T_2} = \left(\frac{v_2}{v_1}\right)^\gamma \times \frac{v_1}{v_2} = \left(\frac{v_2}{v_1}\right)^\gamma \left(\frac{v_2}{v_1}\right)^{-1}$$

$$\therefore \qquad \frac{T_1}{T_2} = \left(\frac{v_2}{v_1}\right)^{\gamma - 1} \qquad \ldots (vii)$$

From equation (*iv*), we also know that

$$\frac{v_1}{v_2} = \left(\frac{p_2}{p_1}\right)^{\frac{1}{\gamma}} \qquad \ldots (viii)$$

From the general gas equation, we know that

$$\frac{p_1 v_1}{T_1} = \frac{p_2 v_2}{T_2} \quad \text{or} \quad \frac{v_1}{v_2} = \frac{T_1}{T_2} \times \frac{p_2}{p_1} \qquad \ldots (ix)$$

Equating equations (*viii*) and (*ix*),

$$\left(\frac{p_2}{p_1}\right)^{\frac{1}{\gamma}} = \frac{T_1}{T_2} \times \frac{p_2}{p_1} \quad \text{or} \quad \frac{T_1}{T_2} = \left(\frac{p_2}{p_1}\right)^{\frac{1}{\gamma}} \times \frac{p_1}{p_2} = \left(\frac{p_1}{p_2}\right)^{-\frac{1}{\gamma} + 1}$$

$$\therefore \qquad \frac{T_1}{T_2} = \left(\frac{p_1}{p_2}\right)^{\frac{\gamma - 1}{\gamma}} \qquad \ldots (x)$$

2. *Workdone during adiabatic expansion*

We have already discussed that workdone,

$$\delta W = p\, dv$$

On integrating from state 1 to state 2,

$$\int_1^2 \delta W = \int_1^2 p\, dv \quad \text{or} \quad W_{1-2} = \int_1^2 p\, dv \qquad \ldots (xi)$$

Since adiabatic expansion of the gas follows the law,

$$pv^\gamma = p_1 v_1^\gamma \quad \text{or} \quad p = \frac{p_1 v_1^\gamma}{v^\gamma}$$

Substituting this value of p in equation (xi),

$$W_{1-2} = \int_1^2 \frac{p_1 v_1^\gamma}{v^\gamma} dv = p_1 v_1^\gamma \int_1^2 v^{-\gamma} dv = p_1 v_1^\gamma \left[\frac{v^{-\gamma+1}}{-\gamma+1} \right]_1^2$$

$$= \frac{p_1 v_1^\gamma}{1-\gamma} \left[v_2^{1-\gamma} - v_1^{1-\gamma} \right]$$

$$= \frac{p_1 v_1^\gamma v_2^{1-\gamma} - p_1 v_1^\gamma v_1^{1-\gamma}}{1-\gamma}$$

$$= \frac{p_2 (v_2^\gamma v_2^{1-\gamma}) - p_1 (v_1^\gamma v_1^{1-\gamma})}{1-\gamma} \qquad \ldots (\because p_1 v_1^\gamma = p_2 v_2$$

$$= \frac{p_2 v_2 - p_1 v_1}{1-\gamma}$$

$$= \frac{p_1 v_1 - p_2 v_2}{\gamma - 1} \qquad \ldots \text{(For expansio}$$

$$= \frac{p_2 v_2 - p_1 v_1}{\gamma - 1} \qquad \ldots \text{(For compressio}$$

Note : The above equation for work done may also be expressed as :

(*a*) We know that $p_1 v_1 = m R T_1$ and $p_2 v_2 = m R T_2$. Substituting these values in the equation f expansion,

$$W_{1-2} = \frac{m R T_1 - m R T_2}{\gamma - 1} = \frac{m R (T_1 - T_2)}{\gamma - 1} \qquad \ldots \text{(For expansio}$$

$$= \frac{m R (T_2 - T_1)}{\gamma - 1} \qquad \ldots \text{(For compressio}$$

(*b*) We also know that work done during expansion,

$$W_{1-2} = \frac{p_1 v_1 - p_2 v_2}{\gamma - 1} = \frac{p_1 v_1}{\gamma - 1} \left[1 - \frac{p_2 v_2}{p_1 v_1} \right]$$

$$= \frac{m R T_1}{\gamma - 1} \left[1 - \frac{p_2 v_2}{p_1 v_1} \right] \qquad \ldots (\because p v = m R$$

3. *Change in internal energy*

We know that change in internal energy,

$$dU = U_2 - U_1 = m c_v (T_2 - T_1)$$

4. *Heat supplied or heat transferred*

We know that head supplied or heat transferred in case of adiabatic process is zero, therefo

$$Q_{1-2} = 0$$

5. *Change in enthalpy*

We know that change in enthalpy,

$$dH = H_2 - H_1 = m c_p (T_2 - T_1)$$

Example 3.8. *One litre of hydrogen at 0° C is suddenly compressed to one-half of its volume. Find the change in temperature of the gas, if the ratio of two specific heats for hydrogen is 1.4.*

Solution Given : $v_1 = 1$ litre ; $T_1 = 0° \text{ C} = 0 + 273 = 273 \text{ K}$; $v_2 = v_1/2 = 1/2 = 0.5$ litre ; $\gamma = 1.4$

Let T_2 = Final temperature of the gas.

We know that
$$\frac{T_1}{T_2} = \left(\frac{v_2}{v_1}\right)^{\gamma-1} = \left(\frac{0.5}{1}\right)^{1.4-1} = (0.5)^{0.4} = 0.758$$

$$\therefore \quad T_2 = T_1 / 0.758 = 273 / 0.758 = 360.16 \text{ K}$$

$$= 360.16 - 273 = 87.16° \text{ C} \quad \textbf{Ans.}$$

Example 3.9. *The initial volume of 0.18 kg of a certain gas was 0.15 m³ at a temperature of 15° C and a pressure of 1 bar. After adiabatic compression to 0.056 m³, the pressure was found to be 4 bar. Find ;*

1. Gas constant ; 2. Molecular mass of the gas ; 3. Ratio of specific heats ; 4. Two specific heats, one at a constant pressure and the other at a constant volume ; and 5. Change of internal energy.

Solution. Given : $m = 0.18$ kg ; $v_1 = 0.15 \text{ m}^3$; $T_1 = 15° \text{ C} = 15 + 273 = 288$ K ; $p_1 = 1$ bar $= 0.1 \times 10^6 \text{ N/m}^2$; $v_2 = 0.056 \text{ m}^3$; $p_2 = 4 \text{ bar} = 0.4 \times 10^6 \text{ N/m}^2$

The *p-v* diagram is shown in Fig. 3.11.

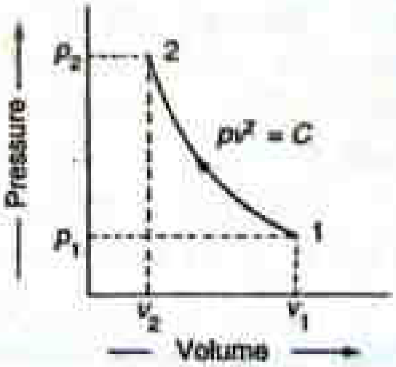


Fig. 3.11

1. Gas constant

Let R = Gas constant.

We know that

$$p_1 v_1 = m R T_1$$

$$\therefore \quad R = \frac{p_1 v_1}{m T_1} = \frac{0.1 \times 10^6 \times 0.15}{0.18 \times 288}$$

$$= 289.4 \text{ J/kg K} = 0.2894 \text{ kJ/kg K} \quad \textbf{Ans.}$$

2. Molecular mass of the gas

We know that molecular mass of the gas,

$$M = \frac{\text{Universal gas constant } (R_u)}{\text{Characteristic gas constant } (R)} = \frac{8314}{289.4} = 28.73 \text{ kg} \quad \textbf{Ans.}$$

$$\ldots (\because R_u = 8314 \text{ J/kg K, for all gases})$$

3. Ratio of specific heats

We know that ratio of specific heats,

$$\gamma = \frac{\log\left(\frac{p_2}{p_1}\right)}{\log\left(\frac{v_1}{v_2}\right)} = \frac{\log\left(\frac{0.4 \times 10^6}{0.1 \times 10^6}\right)}{\log\left(\frac{0.15}{0.056}\right)} = \frac{\log 4}{\log 2.678} = \frac{0.6020}{0.4278}$$

$$= 1.407 \quad \textbf{Ans.}$$

4. Specific heat at a constant volume and constant pressure

Let c_v = Specific heat at a constant volume, and

c_p = Specific heat at a constant pressure.

We know that $c_p - c_v = R$ or $1.407\,c_v - c_v = 0.2894$ $\quad \ldots (\because \gamma = c_p / c_v = 1.4$

$$\therefore \quad c_v = 0.2894 / 0.407 = \textbf{0.711 kJ/kg K Ans.}$$

and $$c_p = 1.407\ c_v = 1.407 \times 0.711 = \textbf{1 kJ/kg K Ans.}$$

5. Change in internal energy

First of all, let us find the final temperature (T_2). We know that

$$\frac{T_1}{T_2} = \left(\frac{p_1}{p_2}\right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{1}{4}\right)^{\frac{1.407-1}{1.407}} = (0.25)^{0.289} = 0.67$$

$$\therefore \quad T_2 = T_1 / 0.67 = 288 / 0.67 = 430 \text{ K}$$

We know that change in internal energy,

$$dU = U_2 - U_1 = m\,c_v (T_2 - T_1) = 0.18 \times 0.711\,(430 - 288) \text{ kJ}$$

$$= \textbf{18.17 kJ Ans.}$$

Example 3.10. *A system contains 0.15 m³ of a gas at a pressure of 3.8 bar and 150° C. I expanded adiabatically till the pressure falls to 1 bar. The gas is then heated at a constant press till its enthalpy increases by 70 kJ. Determine the total work done. Take c_p = 1 kJ/kg K and c_v = 0.7 kJ/kg K.*

Solution. Given : $v_1 = 0.15 \text{ m}^3$; $p_1 = 3.8 \text{ bar} = 0.38 \times 10^6 \text{ N/m}^2$; $T_1 = 150° \text{ C} = 150 + 2$ $= 423$ K ; $p_2 = 1 \text{ bar} = 0.1 \times 10^6 \text{ N/m}^2$; $dH = 70$ kJ ; $c_p = 1$ kJ/kg K ; $c_v = 0.714$ kJ/kg K

In Fig. 3.12, process 1-2 represents adiabatic expansion of the gas and the process 2-3 represents heating at constant pressure.

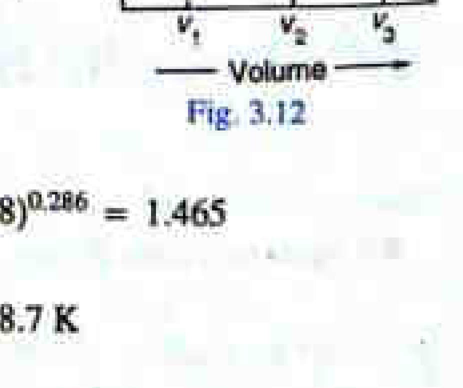


Fig. 3.12

First of all, let us find the temperature (T_2) and volume (v_2) after the adiabatic expansion.

We know that adiabatic index,

$$\gamma = c_p / c_v = 1 / 0.714 = 1.4$$

$$\therefore \quad \frac{T_1}{T_2} = \left(\frac{p_1}{p_2}\right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{3.8}{1}\right)^{\frac{1.4-1}{1.4}} = (3.8)^{0.286} = 1.465$$

or $$T_2 = T_1 / 1.465 = 423 / 1.465 = 288.7 \text{ K}$$

and $$\frac{v_1}{v_2} = \left(\frac{p_2}{p_1}\right)^{\frac{1}{\gamma}} = \left(\frac{1}{3.8}\right)^{\frac{1}{1.4}} = (0.263)^{0.714} = 0.385$$

$$\therefore \quad v_2 = v_1 / 0.385 = 0.15 / 0.385 = 0.39 \text{ m}^3$$

Now let us find the temperature (T_3) and volume (v_3) after constant pressure heating.

Let m = Mass of gas contained in the system.

We know that gas constant,

$$R = c_p - c_v = 1 - 0.714 = 0.286 \text{ kJ/kg K} = 286 \text{ J/kg K}$$

and

$$p_1 v_1 = m R T_1$$

$$\therefore \quad m = \frac{p_1 v_1}{R T_1} = \frac{0.38 \times 10^6 \times 0.15}{286 \times 423} = 0.47 \text{ kg}$$

We also know that increase in enthalpy (dH),

$$70 = m\, c_p (T_3 - T_2) = 0.47 \times 1\, (T_3 - 288.7) \text{ kJ}$$

$$\therefore \quad T_3 = \frac{70}{0.47} + 288.7 = 437.6 \text{ K}$$

Since the heating is at constant pressure, therefore

$$\frac{v_2}{T_2} = \frac{v_3}{T_3} \quad \text{or} \quad v_3 = \frac{v_2 T_3}{T_2} = \frac{0.39 \times 437.6}{288.7} = 0.59 \text{ m}^3$$

We know that work done during adiabatic expansion,

$$W_{1-2} = \frac{p_1 v_1 - p_2 v_2}{\gamma - 1} = \frac{0.38 \times 10^6 \times 0.15 - 0.1 \times 10^6 \times 0.39}{1.4 - 1} \text{ J}$$

$$= \frac{57 \times 10^3 - 39 \times 10^3}{0.4} = 45\,000 \text{ J} = 45 \text{ kJ}$$

and workdone during constant pressure heating,

$$W_{2-3} = p_2 (v_3 - v_2) = 0.1 \times 10^6\, (0.59 - 0.39) = 20\,000 \text{ J} = 20 \text{ kJ}$$

$\therefore$ Total work done, $W = W_{1-2} + W_{2-3} = 45 + 20 =$ 65 kJ **Ans.**

Example 3.11. *0.336 m³ of gas at 10 bar and 150° C expands adiabatically, until its pressure is 4 bar. It is then compressed, isothermally, to its original volume. Find the final temperature and pressure of the gas. Also determine the change in internal energy. Take c_p = 0.996 kJ/kg K ; and c_v = 0.703 kJ/kg K.*

Solution. Given : $v_1 = 0.336 \text{ m}^3$; $p_1 = 10 \text{ bar} = 1 \times 10^6 \text{ N/m}^2$; $T_1 = 150° \text{ C} = 150 + 273 = 423 \text{ K}$; $p_2 = 4 \text{ bar} = 0.4 \times 10^6 \text{ N/m}^2$; $v_3 = v_1 = 0.336 \text{ m}^3$; $c_p = 0.996 \text{ kJ/kg K}$; $c_v = 0.703 \text{ kJ/kg K}$

In Fig. 3.13, process 1-2 represents the adiabatic expansion of the gas and the process 2-3 represents the isothermal compression to its original volume.

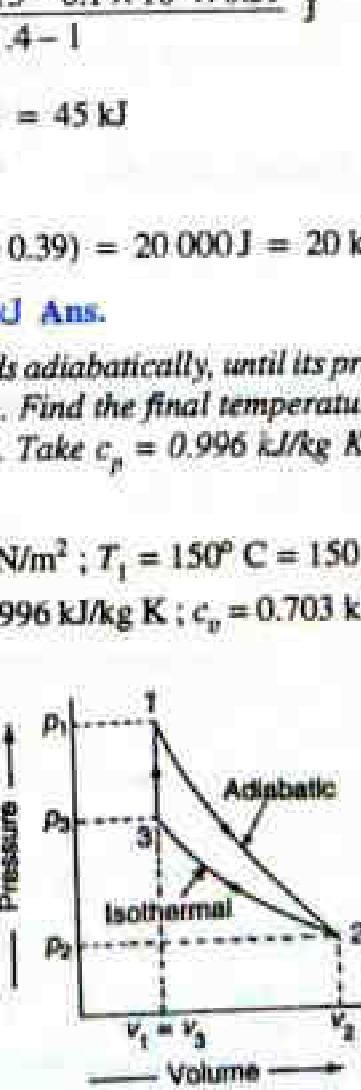


Fig. 3.13

We know that adiabatic index,

$$\gamma = c_p / c_v = 0.996/0.703 = 1.417$$

Final temperature of the gas

Let T_3 = Final temperature of the gas, and

T_2 = Temperature of the gas after adiabatic expansion.

We know that

$$\frac{T_1}{T_2} = \left(\frac{p_1}{p_2}\right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{10}{4}\right)^{\frac{1.417-1}{1.417}} = (2.5)^{0.294} = 1.31$$

$$T_2 = T_1/1.31 = 423/1.31 = 323\text{ K}$$

Since the compression is isothermal from 2 to 3, therefore

$$T_3 = T_2 = 323\text{ K} = 50°\text{C}\ \textbf{Ans.}$$

Final pressure of the gas

Let p_3 = Final pressure of the gas.

We know that for a constant volume process 3-1,

$$\frac{p_3}{T_3} = \frac{p_1}{T_1}$$

$$\therefore \quad p_3 = \frac{T_3 p_1}{T_1} = \frac{323 \times 1 \times 10^6}{423} = 0.76 \times 10^6\text{ N/m}^2 = 7.6\text{ bar}\ \textbf{Ans.}$$

Change in internal energy

First of all, let us find the mass of the gas (m).

We know that gas constant,

$$R = c_p - c_v = 0.996 - 0.703 = 0.293\text{ kJ/kg K} = 293\text{ J/kg K}$$

We also know that

$$p_1 v_1 = m R T_1$$

or

$$m = \frac{p_1 v_1}{R T_1} = \frac{1 \times 10^6 \times 0.336}{293 \times 423} = 2.7\text{ kg}$$

$\therefore$ Change in internal energy,

$$dU = U_3 - U_1 = m c_v (T_3 - T_1) = 2.7 \times 0.703\,(323 - 423)\text{ kJ}$$

$$= -189.8\text{ kJ}\ \textbf{Ans.}$$

The *negative* sign indicates that there is a decrease in internal energy.

3.11. Polytropic Process

The polytropic process is also known as the general law for the expansion and compre of gases, and is given by the relation :

$$pv^n = \text{Constant}$$

where n is a polytropic index, which may have any value from zero to infinity, depending upon manner, in which the expansion or compression has taken place.

The various equations for polytropic process may be expressed by changing the index γ in the adiabatic process.

Now consider m kg of a certain gas being heated polytropically from an initial state 1 to a fi state 2.

Let p_1, v_1 and T_1 = Pressure, volume and temperature at the initial state 1, and

p_2, v_2 and T_2 = Pressure, volume and temperature at the final state 2.

The process is shown on the p-v diagram in Fig. 3.15. Now let us derive the following relati for the polytropic process.

1. Pressure-volume-temperature (p-v-T) relationship

The following relations for the polytropic process are derived in the similar way as discuss for adiabatic process.

(a) $p_1 v_1^n = p_2 v_2^n = \ldots = C$

(b) $\dfrac{T_1}{T_2} = \left(\dfrac{v_2}{v_1}\right)^{n-1}$

(c) $\dfrac{v_1}{v_2} = \left(\dfrac{p_2}{p_1}\right)^{\frac{1}{n}}$

(d) $\dfrac{T_1}{T_2} = \left(\dfrac{p_1}{p_2}\right)^{\frac{n-1}{n}}$

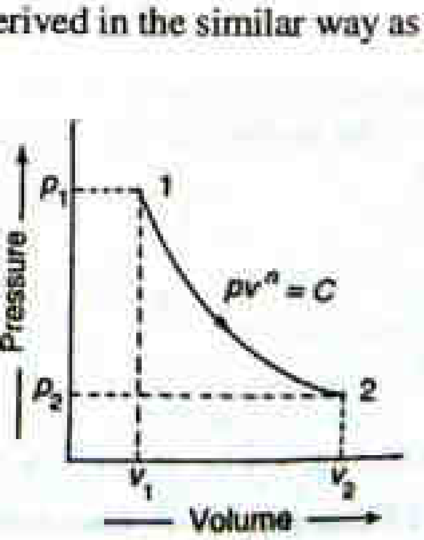


Fig. 3.15. Polytropic process.

2. Workdone during polytropic expansion

The equations for the work done during a polytropic process may also be expressed changing the index n for γ in the adiabatic process.

∴ Workdone during a polytropic process from state 1 to state 2,

$$W_{1-2} = \frac{p_1 v_1 - p_2 v_2}{n-1} = \frac{m\,R\,(T_1 - T_2)}{n-1} \qquad \text{. . . (For expansion)}$$

$$= \frac{p_2 v_2 - p_1 v_1}{n-1} = \frac{m\,R\,(T_2 - T_1)}{n-1} \qquad \text{. . . (For compression)}$$

3. Change in internal energy

We know that change in internal energy,

$$dU = U_2 - U_1 = m\,c_v\,(T_2 - T_1)$$

4. Heat supplied or heat transfer

We know that the heat supplied or heat transferred,

$$Q_{1-2} = W_{1-2} + dU$$

$$= \frac{p_1 v_1 - p_2 v_2}{n-1} + m\,c_v\,(T_2 - T_1)$$

$$= \frac{m\,R\,(T_1 - T_2)}{n-1} + m \times \frac{R}{\gamma - 1}(T_2 - T_1) \qquad \text{. . .}\left(\because\ {}^{*}c_v = \frac{R}{\gamma - 1}\right)$$

$$= m\,R\,(T_1 - T_2)\left[\frac{1}{n-1} - \frac{1}{\gamma - 1}\right]$$

$$= m\,R\,(T_1 - T_2)\left[\frac{(\gamma - 1) - (n-1)}{(n-1)(\gamma - 1)}\right]$$

$$= m\,R\,(T_1 - T_2)\left[\frac{\gamma - n}{(n-1)(\gamma - 1)}\right]$$

$$= \frac{\gamma - n}{\gamma - 1} \times \frac{m\,R\,(T_1 - T_2)}{n-1}$$

5. Change in enthalpy

We know that change in enthalpy,

$$dH = H_2 - H_1 = m\,c_p\,(T_2 - T_1)$$

Notes : 1. The equations for heat transfer may also be expressed as :

(*a*)
$$Q_{1-2} = \frac{\gamma - n}{\gamma - 1} \times \text{Workdone} = \frac{\gamma - n}{\gamma - 1} \times \frac{p_1 v_1 - p_2 v_2}{(n-1)}$$

(*b*) We know that

$$Q_{1-2} = \frac{\gamma - n}{\gamma - 1} \times \frac{m\,R\,(T_1 - T_2)}{n-1} = \frac{\gamma - n}{n-1} \times m\,c_v\,(T_1 - T_2) \qquad \text{. . .}\left(\because \frac{R}{\gamma - 1} = c_v\right)$$

$$= \frac{\gamma - n}{n-1} \times \text{Change in internal energy}$$

---

* We know that $c_p - c_v = R$

Dividing throughout by c_v, we have

$$\frac{c_p}{c_v} - 1 = \frac{R}{c_v} \quad \text{or} \quad \gamma - 1 = \frac{R}{c_v}, \qquad \therefore c_v = \frac{R}{\gamma - 1}$$

2. The above equations give the amount of heat, which has passed into the gas through the cylind walls as the gas expands. It may be noted that this will happen only when n is less than γ. If however, n is grea than γ, then heat is rejected by the gas.

3. Similarly, during compression, work done will be negative, *i.e.* work will be done on the ga Moreover, heat will be rejected by the gas. This will happen only when n is less than γ.

4. The relation for work done may also be expressed as :

$$W_{1-2} = \frac{p_1 v_1 - p_2 v_2}{(n-1)} = \frac{p_1 v_1 \left(1 - \dfrac{p_2 v_2}{p_1 v_1}\right)}{(n-1)}$$

$$= \frac{p_1 v_1 (1 - r^{n-1})}{(n-1)} \qquad \left[\because \frac{p_2}{p_1} = \left(\frac{v_1}{v_2}\right)^n = r^n \text{ and } \frac{p_2 v_2}{p_1 v_1} = r^n \times \frac{1}{r} = r^{n-}\right.$$

Example 3.13. *A certain quantity of air has a volume of 0.028 m³ at a pressure of 1.25 ba and 25° C. It is compressed to a volume of 0.0042 m³ according to the law $pv^{1.3}$ = Constant. Find th final temperature and work done during compression. Also determine the reduction in pressure at constant volume required to bring the air back to its original temperature.*

Solution. Given : $v_1 = 0.028$ m³ ; $p_1 = 1.25$ bar $= 0.125 \times 10^6$ N/m² ; $T_1 = 25°$ C $= 25 + 27$ $= 298$ K ; $v_2 = 0.0042$ m³ ; $n = 1.3$

The p-v diagram is shown in Fig. 3.16.

Final temperature

Let T_2 = Final temperature.

We know that

$$\frac{T_1}{T_2} = \left(\frac{v_2}{v_1}\right)^{n-1} = \left(\frac{0.0042}{0.028}\right)^{1.3-1}$$

$$= (0.15)^{0.3} = 0.566$$

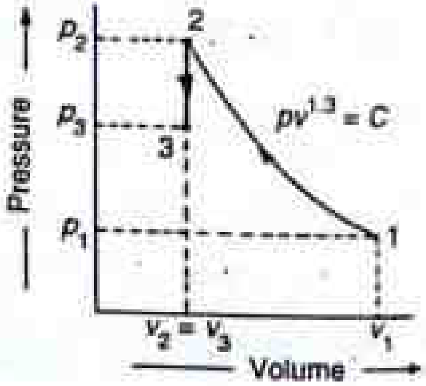


Fig. 3.16

$$\therefore \qquad T_2 = T_1 / 0.566 = 298 / 0.566 = 526.5 \text{ K} = 526.5 - 273 = 253.5° \text{ C} \textbf{ Ans.}$$

Workdone during compression

First of all, let us find the final pressure (p_2) at the end of compression. We know that

$$p_1 v_1^n = p_2 v_2^n \text{ or } \frac{p_1}{p_2} = \left(\frac{v_2}{v_1}\right)^n = \left(\frac{0.0042}{0.028}\right)^{1.3} = 0.085$$

$$\therefore \qquad p_2 = p_1 / 0.085 = 1.25 / 0.085 = 14.7 \text{ bar} = 1.47 \times 10^6 \text{ N/m}^2$$

We know that workdone during compression,

$$W_{1-2} = \frac{p_2 v_2 - p_1 v_1}{n-1} = \frac{1.47 \times 10^6 \times 0.0042 - 0.125 \times 10^6 \times 0.028}{1.3 - 1}$$

$$= \frac{6174 - 3500}{0.3} = 8913 \text{ J} = 8.913 \text{ kJ} \textbf{ Ans.}$$

Pressure at a constant volume

Let p_3 = Pressure at a constant volume required to bring the air back to its initial temperature, $T_1 = 298$ K.

We know that for a constant volume process 2-3,

$$\frac{p_2}{T_2} = \frac{p_3}{T_3} \quad \text{or} \quad p_3 = \frac{p_2 T_3}{T_2} = \frac{14.7 \times 298}{526.5} = 8.32 \text{ bar Ans.}$$

$$\ldots (\because v_2 = v_3 \text{ and } T_3 = T_1)$$

Example 3.14. *A gas mixture obeying perfect gas law has a molecular mass of 26.7. The gas mixture is compressed through a compression ratio of 12 according to the law $pv^{1.25}$ = Constant, from initial conditions of 0.9 bar and 333 K. Assuming a mean molar specific heat at constant volume of 21.1 kJ/kg K, find, per kg of mass, the workdone and heat flow across the cylinder walls.*

For the above gas, determine the value of characteristic gas constant, molar specific heat at a constant pressure and ratio of specific heats.

Solution. Given : $M = 26.7$; $r = v_1/v_2 = 12$; $n = 1.25$; $p_1 = 0.9$ bar $= 0.09 \times 10^6$ N/m^2 ; $T_1 = 333$ K ; $c_{vm} = 21.1$ kJ/kg K ; $m = 1$ kg

The p-v diagram is shown in Fig. 3.17.

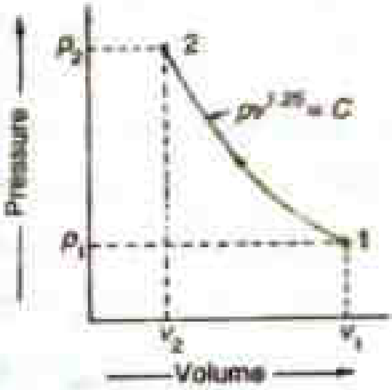


Fig. 3.17

Workdone per kg of gas

First of all, let us find the initial volume (v_1), final volume (v_2) and final pressure (p_2).

We know that $\quad p_1 v_1^n = p_2 v_2^n$.

$$\therefore \quad p_2 = p_1 \left(\frac{v_1}{v_2} \right)^n = 0.9\,(12)^{1.25}$$

$$= 20.1 \text{ bar} = 2.01 \times 10^6 \text{ N/m}^2$$

We also know that gas constant,

$$R = \frac{R_u}{M} = \frac{8314}{26.7} = 311.4 \text{ J/kg K}$$

and

$$p_1 v_1 = m\,R\,T_1 \quad \text{or} \quad v_1 = \frac{m\,R\,T_1}{p_1} = \frac{1 \times 311.4 \times 333}{0.09 \times 10^6} = 1.15 \text{ m}^3$$

$$\therefore \quad v_2 = v_1/12 = 1.15/12 = 0.096 \text{ m}^3 \qquad \ldots (\because v_1/v_2 = 12)$$

We know that workdone

$$W_{1\text{-}2} = \frac{p_1 v_1 - p_2 v_2}{n - 1} = \frac{0.09 \times 10^6 \times 1.15 - 2.01 \times 10^6 \times 0.096}{1.25 - 1}$$

$$= \frac{103\,500 - 192\,960}{0.25} = -357\,840 \text{ J} = -357.84 \text{ kJ Ans.}$$

The *negative* sign indicates that the work is done on the gas.

Heat flow across the cylinder walls

Let $\quad T_2$ = Final temperature.

We know that $\quad \dfrac{T_1}{T_2} = \left(\dfrac{v_2}{v_1} \right)^{n-1} = \left(\dfrac{1}{12} \right)^{1.25-1} = 0.537$

$$\therefore \quad T_2 = T_1 / 0.537 = 333 / 0.537 = 620 \text{ K}$$

and specific heat at constant volume,

$$c_v = c_{vm} / M = 21.1 / 26.7 = 0.79 \text{ kJ/kg K}$$

∴ Change in internal energy,

$$dU = U_2 - U_1 = m\, c_v (T_2 - T_1) = 1 \times 0.79\,(620 - 333) = 226.7 \text{ kJ}$$

We know that heat flow across the cylinder walls,

$$Q_{1-2} = W_{1-2} + dU = -357.84 + 226.7 = -131.1 \text{ kJ} \quad \textbf{Ans.}$$

The *negative* sign indicates that the heat is rejected through the cylinder walls.

Characteristic gas constant

We know that characteristic gas constant,

$$R = \frac{\text{Universal gas constant}}{\text{Molecular mass}} = \frac{R_u}{M} = \frac{8314}{26.7}$$

$$\ldots (\because R_u = 8314 \text{ J/kg K, for all gase}$$

$$= 311.4 \text{ J/kg K} = 0.3114 \text{ kJ/kg K} \quad \textbf{Ans.}$$

Molar specific heat at a constant pressure

Let c_{pm} = Molar specific heat at a constant pressure.

We know that $c_p - c_v = R$ or $c_p - 0.79 = 0.3114$

$$\therefore \quad c_p = 0.3114 + 0.79 = 1.1014 \text{ kJ/kg K}$$

and $$c_{pm} = M\, c_p = 26.7 \times 1.1014 = 29.4 \text{ kJ/kg K} \quad \textbf{Ans.}$$

Ratio of specific heats

We know that ratio of specific heats,

$$\gamma = c_p / c_v = 1.1014 / 0.79 = 1.394 \quad \textbf{Ans.}$$

Example 3.15. *An internal combustion engine has the following dimensions :*

Diameter of cylinder = 550 mm ; Stroke = 750 mm ; Compression ratio = 13.5. At the end of the suction stroke, the pressure is 1 bar and temperature is 316 K. The compression follows the law $pv^{1.37} = C$. Determine :

1. the pressure and temperature at the end of compression ; 2. the mass of the charge ; 3. the work done during compression ; and 4. the heat rejected during compression.

Take $c_p = 0.996$ kJ/kg K and $c_v = 0.707$ kJ/kg K.

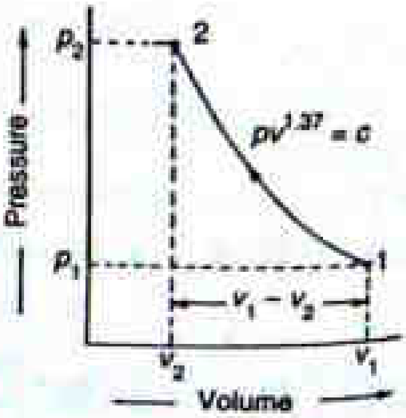


Fig. 3.18

Solution. Given : $D = 550$ mm $= 0.55$ m ; $L = 750$ mm $= 0.75$ m ; $v_1/v_2 = 13.5$; $p_1 = 1$ bar $= 0.1 \times 10^6$ N/m² ; $T_1 = 316$ K ; $n = 1.37$; $c_p = 0.996$ kJ/kg K ; $c_v = 0.707$ kJ/kg K

In the *p-v* diagram, as shown in Fig. 3.18, point 1 refers to the end of suction stroke and point 2 refers to the end of compression stroke.

1. Pressure and temperature at the end of compression

Let p_2 and T_2 = Pressure and temperature at the end of compression respectively.

We know that

$$p_1 v_1^n = p_2 v_2^n$$

$$\therefore \qquad p_2 = p_1\left(\frac{v_1}{v_2}\right)^n = 0.1 \times 10^6\,(13.5)^{1.37}\ \text{N/m}^2$$

$$= 3.536 \times 10^6\ \text{N/m}^2 = 3.536\ \text{bar} \quad \textbf{Ans.}$$

We also know that

$$\frac{T_1}{T_2} = \left(\frac{v_2}{v_1}\right)^{n-1} = \left(\frac{1}{13.5}\right)^{1.37-1} = (0.074)^{0.37} = 0.3816$$

$$\therefore \qquad T_2 = T_1 / 0.3816 = 316 / 0.3816 = 828\ \text{K} \quad \textbf{Ans.}$$

2. Mass of the charge

Let $\qquad m$ = Mass of the charge.

We know that swept volume,

$$v_1 - v_2 = \frac{\pi}{4} \times D^2 \times L = \frac{\pi}{4}(0.55)^2\,0.75 = 0.178\ \text{m}^3$$

or

$$v_1 - \frac{v_1}{13.5} = 0.178 \qquad \ldots\left(\because \frac{v_1}{v_2} = 13.5\right)$$

$$\therefore \qquad v_1 = 0.178 \times 13.5 / 12.5 = 0.192\ \text{m}^3$$

and gas constant,

$$R = c_p - c_v = 0.996 - 0.707 = 0.289\ \text{kJ/kg K} = 289\ \text{J/kg K}$$

We know that $\quad p_1 v_1 = m R T_1$

$$\therefore \qquad m = \frac{p_1 v_1}{R T_1} = \frac{0.1 \times 10^6 \times 0.192}{289 \times 316} = 0.21\ \text{kg} \quad \textbf{Ans.}$$

3. Workdone during compression

We know that workdone during compression,

$$W_{1-2} = \frac{m R\,(T_2 - T_1)}{n-1} = \frac{0.21 \times 0.289\,(828 - 316)}{1.37 - 1} = 84\ \text{kJ} \quad \textbf{Ans.}$$

4. Heat rejected during compression

We know that adiabatic index,

$$\gamma = c_p / c_v = 0.996 / 0.707 = 1.41$$

∴ Heat rejected during compression,

$$Q_{1-2} = \frac{\gamma - n}{\gamma - 1} \times \text{Workdone during compression}$$

$$= \frac{1.41 - 1.37}{1.41 - 1} \times 84 = 8.195\ \text{kJ} \quad \textbf{Ans.}$$

3.14. Free Expansion (or Unresisted Expansion) Process

The free expansion (or unresisted expansion) process is an irreversible non-flow process. A free expansion occurs when a fluid is allowed to expand suddenly into a vacuum chamber through an orifice of large dimensions.

Consider two chambers *A* and *B* separated by a partition as shown in Fig. 3.23 (*a*). Let the chamber *A* contains a perfect gas having volume v_1, pressure p_1, and temperature T_1 and the chamber *B* is completely evacuated. These chambers are perfectly insulated so that no heat transfer takes place from or to its surroundings. Now, if the partition is removed, the gas will expand freely and occupy the whole space as shown in Fig. 3.23 (*b*). By this, the volume of the gas increases to v_2, pressure decreases to p_2 and the temperature may also decrease to T_2.

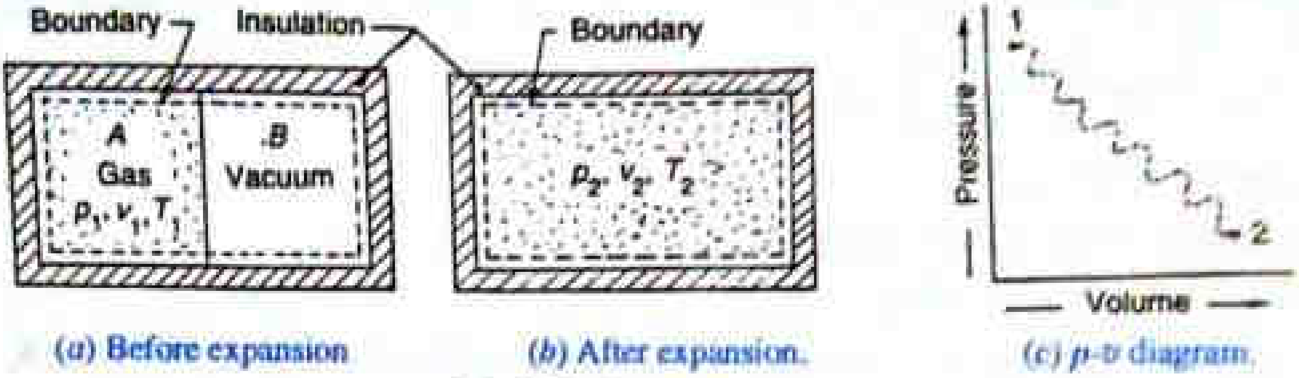
Since there is no expansion of the boundary of the system, because it is rigid, therefore no work is done. Thus, for a free expansion process,

$$Q_{1-2} = 0 \; ; \; W_{1-2} = 0 \text{ and } dU = 0$$

The following points may be noted regarding the free expansion of a gas :

1. Since the system is perfectly insulated so that no heat transfer takes place (*i.e.* $Q_{1-2} = 0$), therefore the expansion of gas may be called as an adiabatic expansion.

2. Since the free expansion of the gas from the equilibrium state 1 to the equilibrium state 2 takes place suddenly, therefore the intermediate states will not be in equilibrium states, as shown on the *p-v* diagram in Fig. 3.23 (*c*). Thus the process is irreversible and the expansion is, therefore, known as irreversible adiabatic expansion.



(*a*) Before expansion (*b*) After expansion. (*c*) *p-v* diagram.

Fig. 3.23. Free expansion.

3. Since there is no resistance to overcome during free expansion process, therefore no work is done by the system (*i.e.* $W_{1-2} = 0$). Thus, the free expansion process is also known as * *unresisted expansion process.*

4. According to the first law of thermodynamics,

$$Q_{1-2} = W_{1-2} + dU$$

Since for the free expansion, $Q_{1-2} = 0$ and $W_{1-2} = 0$, therefore the change in internal energy,

$$dU = U_2 - U_1 = 0 \quad \text{or} \quad U_2 = U_1$$

In other words, the internal energy of the system, in a free expansion process remains constant. Thus, the free expansion process is also known as *constant internal energy process*.

5. We know that change in internal energy,

$$dU = m\,c_v\,dT = m\,c_v\,(T_2 - T_1)$$

Since $dU = 0$, therefore $dT = 0$ or $T_2 = T_1$, *i.e.* there is no change in temperature of the system. In other words, the temperature of the system, in a free expansion process remains constant.

Note : It can not be called an isothermal process because in an actual isothermal process, work is done by the gas during expansion.

6. We know that change in enthalpy,

$$dH = H_2 - H_1 = m\,c_p\,dT$$

Since $dT = 0$, therefore $dH = 0$ or $H_2 = H_1$. In other words, the enthalpy of the system in a free expansion process remains constant. Thus the free expansion process may also be called *constant enthalpy process*.

INSTITUTE OF TEXTILE TECHNOLOGY
CHOUDWAR

Thermal Engineering-I

Chapter-4
Internal Combustion Engine

INTERNAL COMBUSTION ENGINE

INTRODUCTION

Heat engine:

A heat engine is a device which transforms the chemical energy of a fuel into thermal energy and uses this energy to produce mechanical work. It is classified into two types-

(a) External combustion engine
(b) Internal combustion engine

External combustion engine:

In this engine, the products of combustion of air and fuel transfer heat to a second fluid which is the working fluid of the cycle.

Examples:

*In the steam engine or a steam turbine plant, the heat of combustion is employed to generate steam which is used in a piston engine (reciprocating type engine) or a turbine (rotary type engine) for useful work.

*In a closed cycle gas turbine, the heat of combustion in an external furnace is transferred to gas, usually air which the working fluid of the cycle.

Internal combustion engine:

In this engine, the combustion of air and fuels take place inside the cylinder and are used as the direct motive force. It can be classified into the following types:

1. According to the basic engine design- (a) Reciprocating engine (Use of cylinder piston arrangement), (b) Rotary engine (Use of turbine)

2. According to the type of fuel used- (a) Petrol engine, (b) diesel engine, (c) gas engine (CNG, LPG), (d) Alcohol engine (ethanol, methanol etc)

3. According to the number of strokes per cycle- (a) Four stroke and (b) Two stroke engine

4. According to the method of igniting the fuel- (a) Spark ignition engine, (b) compression ignition engine and (c) hot spot ignition engine

5. According to the working cycle- (a) Otto cycle (constant volume cycle) engine, (b) diesel cycle (constant pressure cycle) engine, (c) dual combustion cycle (semi diesel cycle) engine.

6. According to the fuel supply and mixture preparation- (a) Carburetted type (fuel supplied through the carburettor), (b) Injection type (fuel injected into inlet ports or inlet manifold, fuel injected into the cylinder just before ignition).

7. According to the number of cylinder- (a) Single cylinder and (b) multi-cylinder engine

8. Method of cooling- water cooled or air cooled

9. Speed of the engine- Slow speed, medium speed and high speed engine

10. Cylinder arrangement-Vertical, horizontal, inline, V-type, radial, opposed cylinder or piston engines.

11. Valve or port design and location- Overhead (I head), side valve (L head); in two stroke engines: cross scavenging, loop scavenging, uniflow scavenging.

12. Method governing- Hit and miss governed engines, quantitatively governed engines and qualitatively governed engine

14. Application- Automotive engines for land transport, marine engines for propulsion of ships, aircraft engines for aircraft propulsion, industrial engines, prime movers for electrical generators.

Comparison between external combustion engine and internal combustion engine:

External combustion engine	Internal combustion engine
*Combustion of air-fuel is outside the engine cylinder (in a boiler)	* Combustion of air-fuel is inside the engine cylinder (in a boiler)
*The engines are running smoothly and silently due to outside combustion	* Very noisy operated engine
*Higher ratio of weight and bulk to output due to presence of auxiliary apparatus like boiler and condenser. Hence it is heavy and cumbersome.	* It is light and compact due to lower ratio of weight and bulk to output.
*Working pressure and temperature inside the engine cylinder is low; hence ordinary alloys are used for the manufacture of engine cylinder and its parts.	* Working pressure and temperature inside the engine cylinder is very much high; hence special alloys are used
*It can use cheaper fuels including solid fuels	*High grade fuels are used with proper filtration
*Lower efficiency about 15-20%	*Higher efficiency about 35-40%
* Higher requirement of water for dissipation of energy through cooling system	*Lesser requirement of water
*High starting torque	*IC engines are not self-starting

Main components of reciprocating IC engines:

Cylinder: It is the main part of the engine inside which piston reciprocates to and fro. It should have high strength to withstand high pressure above 50 bar and temperature above

2000 °C. The ordinary engine is made of cast iron and heavy duty engines are made of steel alloys or aluminum alloys. In the multi-cylinder engine, the cylinders are cast in one block known as cylinder block.

Cylinder head: The top end of the cylinder is covered by cylinder head over which inlet and exhaust valve, spark plug or injectors are mounted. A copper or asbestos gasket is provided between the engine cylinder and cylinder head to make an air tight joint.

Piston: Transmit the force exerted by the burning of charge to the connecting rod. Usually made of aluminium alloy which has good heat conducting property and greater strength at higher temperature.

Figure 1 shows the different components of IC engine.

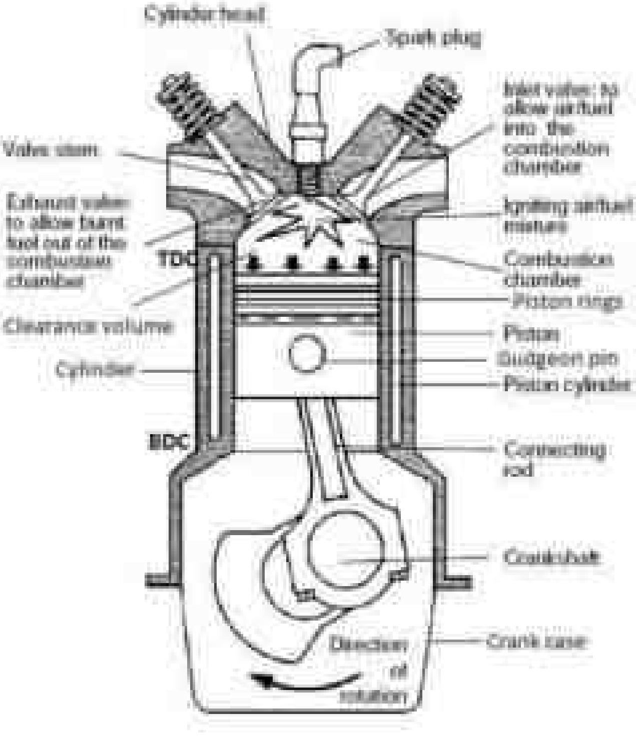


Fig. 1. Different parts of IC engine

Piston rings: These are housed in the circumferential grooves provided on the outer surface of the piston and made of steel alloys which retain elastic properties even at high temperature. 2 types of rings- compression and oil rings. Compression ring is upper ring of the piston which provides air tight seal to prevent leakage of the burnt gases into the lower portion. Oil ring is lower ring which provides effective seal to prevent leakage of the oil into the engine cylinder.

Connecting rod: It converts reciprocating motion of the piston into circular motion of the crank shaft, in the working stroke. The smaller end of the connecting rod is connected with the piston by gudgeon pin and bigger end of the connecting rod is connected with the crank with crank pin. The special steel alloys or aluminium alloys are used for the manufacture of connecting rod.

Crankshaft: It converts the reciprocating motion of the piston into the rotary motion with the help of connecting rod. The special steel alloys are used for the manufacturing of the crankshaft. It consists of eccentric portion called crank.

Crank case: It houses cylinder and crankshaft of the IC engine and also serves as sump for the lubricating oil.

Flywheel: It is big wheel mounted on the crankshaft, whose function is to maintain its speed constant. It is done by storing excess energy during the power stroke, which is returned during other stroke.

Terminology used in IC engine:

1. Cylinder bore (D): The nominal inner diameter of the working cylinder.

2. Piston area (A): The area of circle of diameter equal to the cylinder bore.

3. Stroke (L): The nominal distance through which a working piston moves between two successive reversals of its direction of motion.

4. Dead centre: The position of the working piston and the moving parts which are mechanically connected to it at the moment when the direction of the piston motion is reversed (at either end point of the stroke).

(a) Bottom dead centre (BDC): Dead centre when the piston is nearest to the crankshaft.

(b) Top dead centre (TDC): Dead centre when the position is farthest from the crankshaft.

5. Displacement volume or swept volume (V_s): The nominal volume generated by the working piston when travelling from the one dead centre to next one and given as,

$$V_s = A \times L.$$

6. Clearance volume (V_c): the nominal volume of the space on the combustion side of the piston at the top dead centre.

7. Cylinder volume (V): Total volume of the cylinder.

$$V = V_c + V_s$$

8. Compression ratio (r): $r = \frac{v}{vc}$

26.5. Sequence of Operations in a Cycle

Strictly speaking, when an engine is working continuously, we may consider a cycle starting from any stroke. We know that when the engine returns back to the stroke where it started we say that one cycle has been completed.

The readers will find different sequence of operations in different books. But in this chapter, we shall consider the following sequence of operation in a cycle, which is widely used.

1. *Suction stroke.* In this stroke, the fuel vapour in correct proportion, is supplied to the engine cylinder.
2. *Compression stroke.* In this stroke, the fuel vapour is compressed in the engine cylinder.
3. *Expansion or working stroke.* In this stroke, the fuel vapour is fired just before the compression is complete. It results in the sudden rise of pressure, due to expansion of the combustion products in the engine cylinder. This sudden rise of the pressure pushes the piston with a great force, and rotates the crankshaft. The crankshaft, in turn, drives the machine connected to it.
4. *Exhaust stroke.* In this stroke, the burnt gases (or combustion products) are exhausted from the engine cylinder, so as to make space available for the fresh fuel vapour.

26.6. Two-stroke and Four-stroke Cycle Engines

In a two-stroke engine, the working cycle is completed in two strokes of the piston or one revolution of the crankshaft. This is achieved by carrying out the suction and compression processes in one stroke (or more precisely in inward stroke), expansion and exhaust processes in the second stroke (or more precisely in outward stroke). In a four-stroke engine, the working cycle is completed in four-strokes of the piston or two-revolutions of the crankshaft. This is achieved by carrying out suction, compression, expansion and exhaust processes in each stroke.

It will be interesting to know that from the thermodynamic point of view, there is no difference between two-stroke and four-stroke cycle engines. The difference is purely mechanical.

26.7. Advantages and Disadvantage of Two-stroke over Four-stroke Cycle Engines

Following are the advantages and disadvantages of two-stroke cycle engines over four-stroke cycle engines :

Advantages

1. A two stroke cycle engine gives twice the number of power strokes than the four stroke cycle engine at the same engine speed. Theoretically, a two-stroke cycle engine should develop twice the power as that of a four-stroke cycle engine. But in actual practice, a two-stroke cycle engine develops 1.7 to 1.8 times (greater value for slow speed engines) the power developed by four-stroke cycle engine of the same dimensions and speed. This is due to lower compression ratio and effective stroke being less than the theoretical stroke.

2. For the same power developed, a two-stroke cycle engine is lighter, less bulky and occupies less floor area. Thus it makes, a two-stroke cycle engine suitable for marine engines and other light vehicles.

3. As the number of working strokes in a two-stroke cycle engine are twice than the four-stroke cycle engine, so the turning moment of a two-stroke cycle engine is more uniform. Thus it makes a two-stroke cycle engine to have a lighter flywheel and foundations. This also leads to a higher mechanical efficiency of a two-stroke cycle engine.

4. The initial cost of a two-stroke cycle engine is considerably less than a four-stroke cycle engine.

5. The mechanism of a two-stroke cycle engine is much simpler than a four-stroke cycle engine.

6. The two-stroke cycle engines are much easier to start.

Disadvantages

1. Thermal efficiency of a two-stroke cycle engine is less than that a four-stroke cycle engine, because a two-stroke cycle engine has less compression ratio than that of a four-stroke cycle engine.

2. Overall efficiency of a two-stroke cycle engine is also less than that of a four-stroke cycle engine because in a two-stroke cycle, inlet and exhaust ports remain open simultaneously for some time. Inspite of careful design, a small quantity of charge is lost from the engine cylinder.

3. In case of a two-stroke cycle engine, the number of power strokes are twice as those of a four-stroke cycle engine. Thus the capacity of the cooling system must be higher. Beyond a certain limit, the cooling capacity offers a considerable difficulty. Moreover, there is a greater wear and tear in a two-stroke cycle engine.

4. The consumption of lubricating oil is large in a two-stroke cycle engine because of high operating temperature.

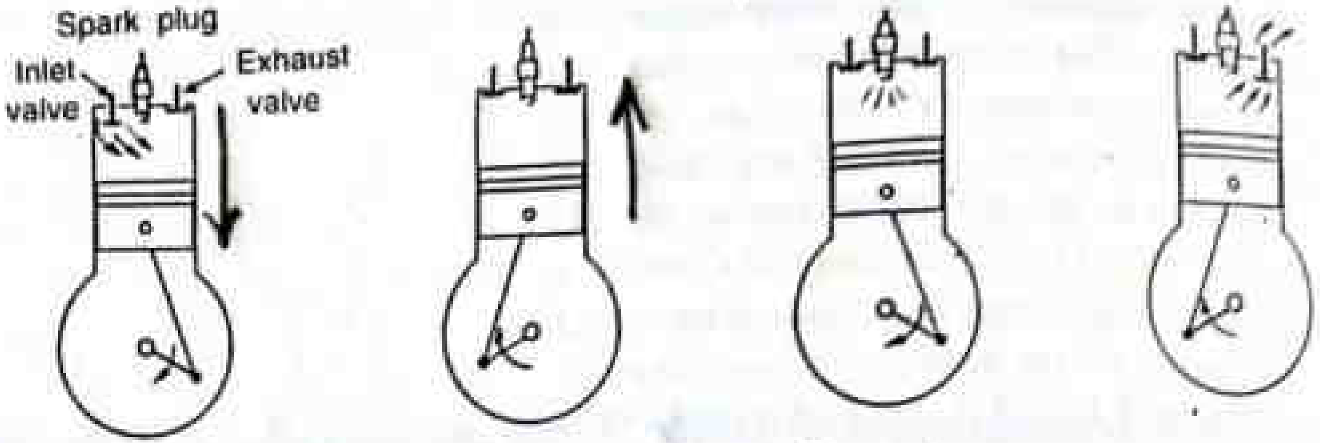
5. The exhaust gases in a two-stroke cycle engine creates noise, because of short time available for their exhaust.

26.9. Four-stroke Cycle Petrol Engine

It is also known as Otto cycle*. It requires four strokes of the piston to complete one cycle of operation in the engine cylinder. The four strokes of a petrol engine sucking fuel-air mixture (petrol mixed with proportionate quantity of air in the carburettor known as charge) are described below :

1. *Suction or charging stroke.* In this stroke, the inlet valve opens and charge is sucked into the cylinder as the piston moves downward from top dead centre (*T.D.C.*). It continues till the piston reaches its bottom dead centre (*B.D.C.*) as shown in Fig. 26.4 (*a*).

2. *Compression stroke.* In this stroke, both the inlet and exhaust valves are closed and the charge is compressed as the piston moves upwards from *B.D.C.* to *T.D.C.* As a result of compression, the pressure and temperature of the charge increases considerably (the actual values depend upon the compression ratio). This completes one revolution of the crankshaft. The compression stroke is shown in Fig. 26.4 (*b*).



(*a*) Suction or charging stroke.

(*b*) Compression stroke.

(*c*) Expansion or working stroke.

(*d*) Exhaust stroke.

Fig. 26.4. Four-stroke cycle petrol engine.

3. *Expansion or working stroke.* Shortly before the piston reaches *T.D.C.* (during compression stroke), the charge is ignited with the help of a spark plug. It suddenly increases the pressure and temperature of the products of combustion but the volume, practically, remains constant. Due to the rise in pressure, the piston is pushed down with a great force. The hot burnt gases expand due to high speed of the piston. During this expansion, some of the heat energy produced is transformed into mechanical work. It may be noted that during this working stroke, as shown in Fig. 26.4 (*c*), both the valves are closed and piston moves from *T.D.C.* to *B.D.C.*

4. *Exhaust stroke.* In this stroke, the exhaust valve is open as piston moves from *B.D.C.* to *T.D.C.* This movement of the piston pushes out the products of combustion, from the engine cylinder and are exhausted through the exhaust valve into the atmosphere, as shown in Fig. 26.4 (*d*). This completes the cycle, and the engine cylinder is ready to suck the charge again.

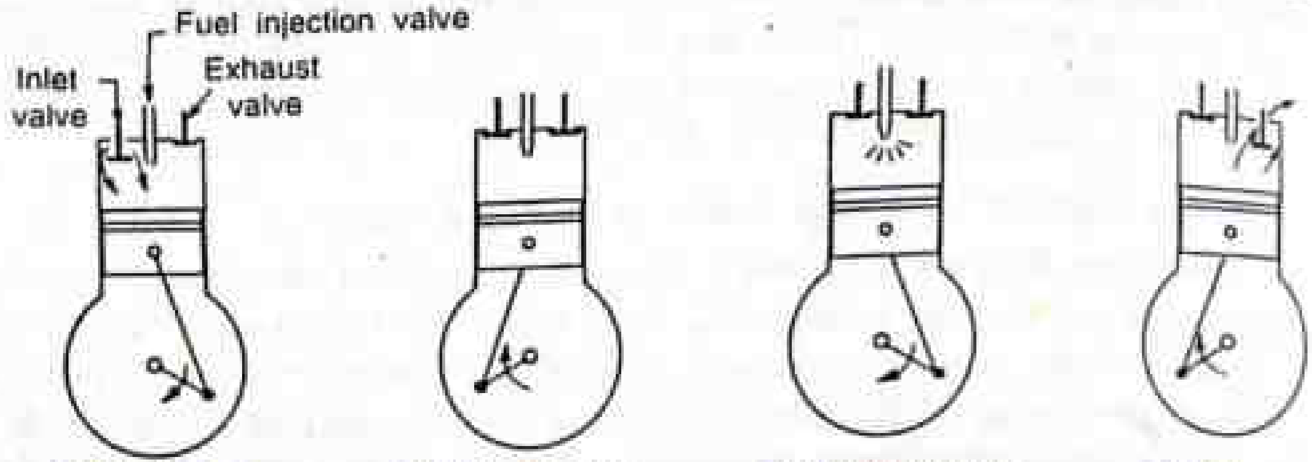
Note : The four stroke cycle petrol engine are usually employed in light vehicles such as cars, jeeps and aeroplanes.

26.12. Four-stroke Cycle Diesel Engine

It is also known as *compression ignition engine* because the ignition takes place due to the heat produced in the engine cylinder at the end of compression stroke. The four strokes of a diesel engine sucking pure air are described below :

1. *Suction or charging stroke.* In this stroke, the inlet valve opens and pure air is sucked into the cylinder as the piston moves downwards from the top dead centre (*TDC*). It continues till the piston reaches its bottom dead centre (*BDC*) as shown in Fig. 26.7 (*a*).

2. *Compression stroke.* In this stroke, both the valves are closed and the air is compressed as the piston moves upwards from *BDC* to *TDC*. As a result of compression, pressure and temperature of the air increases considerably (the actual value depends upon the compression ratio). This completes one revolution of the crank shaft. The compression stroke is shown in Fig. 26.7 (*b*).



(*a*) Suction or charging stroke. (*b*) Compression stroke. (*c*) Expansion or working stroke. (*d*) Exhaust stroke.

Fig. 26.7. Four stroke cycle diesel engine.

3. *Expansion or working stroke.* Shortly before the piston reaches the *TDC* (during the compression stroke), fuel oil is injected in the form of very fine spray into the engine cylinder, through the nozzle, known as fuel injection valve. At this moment, temperature of the compressed air is sufficiently high to ignite the fuel. It suddenly increases the pressure and temperature of the products of combustion. The fuel oil is continuously injected for a fraction of the revolution. The fuel oil is assumed to be burnt at constant pressure. Due to increased pressure, the piston is pushed down with a great force. The hot burnt gases expand due to high speed of the piston. During this expansion, some of the heat energy is transformed into mechanical work. It may be noted that during this working stroke, both the valves are closed and the piston moves from *TDC* to *BDC*.

4. *Exhaust stroke.* In this stroke, the exhaust valve is open as the piston moves from *BDC* to *TDC*. This movement of the piston pushes out the products of combustion from the engine cylinder through the exhaust valve into the atmosphere. This completes the cycle and the engine cylinder is ready to suck the fresh air again.

Note : The four stroke cycle diesel engines are generally employed in heavy vehicles such as buses, trucks, tractors, pumping sets, diesel locomotives and in earth moving machinery.

26.16. Comparison of Petrol and Diesel Engines

Following points are important for the comparison of petrol engines and diesel engines :

S. No	Petrol Engines	*Diesel Engines*
1.	A petrol engine draws a mixture of petrol and air during suction stroke.	A diesel engine draws only air during suction stroke.
2.	The carburettor is employed to mix air and petrol in the required proportion and to supply it to the engine during suction stroke.	The injector or atomiser is employed to inject the fuel at the end of compression stroke.
3.	Pressure at the end of compression is about 10 bar.	Pressure at the end of compression is about 35 bar.
4.	The charge (*i.e.* petrol and air mixture) is ignited with the help of spark plug.	The fuel is injected in the form of fine spray. The temperature of the compressed air (about 600°C at a pressure of about 35 bar) is sufficiently high to ignite the fuel.
5.	The combustion of fuel takes place approximately at constant volume. In other words, it works on Otto cycle.	The combustion of fuel takes place approximately at constant pressure. In other words, it works on Diesel cycle.
6.	A petrol engine has compression ratio approximately from 6 to 10.	A diesel engine has compression ratio approximately from 15 to 25.
7.	The starting is easy due to low compression ratio.	The starting is little difficult due to high compression ratio.
8.	As the compression ratio is low, the petrol engines are lighter and cheaper.	As the compression ratio is high, the diesel engines are heavier and costlier.
9.	The running cost of a petrol engine is high because of the higher cost of petrol.	The running cost of diesel engine is low because of the lower cost of diesel.
10.	The maintenance cost is less.	The maintenance cost is more.
11.	The thermal efficiency is upto about 26%.	The thermal efficiency is upto about 40%.
12.	Oveheating trouble is more due to low thermal efficiency.	Oveheating trouble is less due to high thermal efficiency.
13.	These are high speed engines.	These are relatively low speed engines.
14.	The petrol engines are generally employed in light duty vehicles such as scooters, motorcycles, cars. These are also used in aeroplanes.	The diesel engines are generally employed in heavy duty vehicles like buses, trucks, and earth moving machines etc.

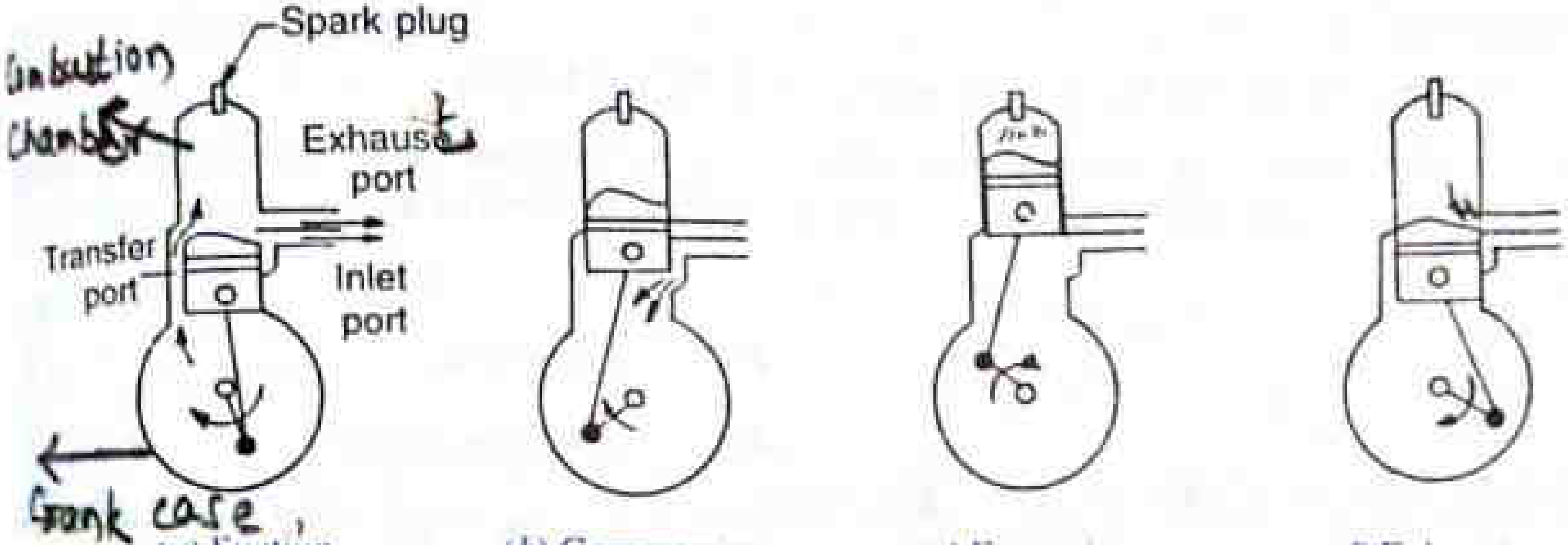
26.17. Two-stroke Cycle Petrol Engine

A two-stroke cycle petrol engine was devised by Duglad Clerk in 1880. In this cycle, the suction, compression, expansion and exhaust takes place during two strokes of the piston. It means that there is one working stroke after every revolution of the crank shaft. A two stroke engine has ports instead of valves. All the four stages of a two stroke petrol engine are described below :

1. *Suction stage*. In this stage, the piston, while going down towards *BDC*, uncovers both the transfer port and the exhaust port. The fresh fuel-air mixture flows into the engine cylinder from the crank case, as shown in Fig. 26.10 (*a*).

2. *Compression stage.* In this stage, the piston, while moving up, first covers the transfer port and then exhaust port. After that the fuel is compressed as the piston moves upwards as shown in Fig. 26.10 (*b*). In this stage, the inlet port opens and fresh fuel-air mixture enters into the crank case.

3. *Expansion stage.* Shortly before this piston reaches the *TDC* (during compression stroke), the charge is ignited with the help of a spark plug. It suddenly increases the pressure and temperature of the products of combustion. But the volume, practically, remains constant. Due to rise in the pressure, the piston is pushed downwards with a great force as shown in Fig. 26.10 (*c*). The hot burnt gases expand due to high speed of the piston. During this expansion, some of the heat energy produced is transformed into mechanical work.



(*a*) Suction. (*b*) Compression. (*c*) Expansion. (*d*) Exhaust.

Fig. 26.10. Two-stroke cycle petrol engine.

4. *Exhaust stage.* In this stage, the exhaust port is opened as the piston moves downwards. The products of combustion, from the engine cylinder are exhausted through the exhaust port into the atmosphere, as shown in Fig. 26.10 (*d*). This completes the cycle and the engine cylinder is ready to suck the charge again.

Note : The two stroke petrol engines are generally employed in very light vehicles such as scooters, motor cycles, three wheelers and sprayers.

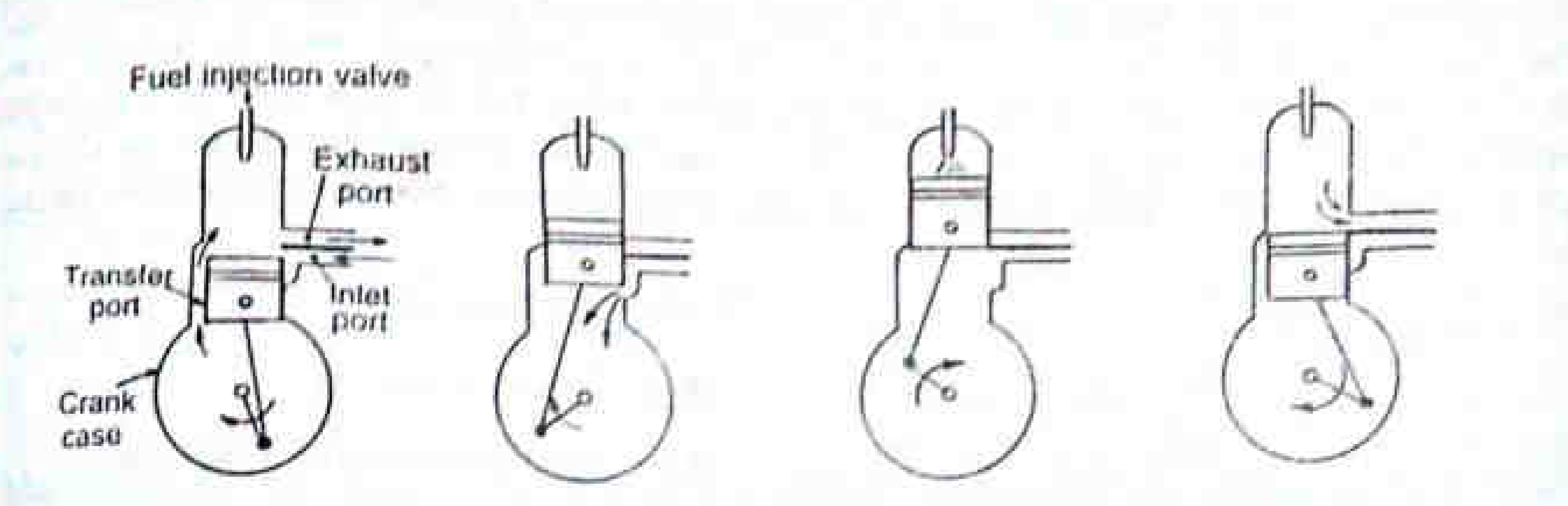
26.20. Two-stroke Cycle Diesel Engine

A two-stroke cycle diesel engine also has one working stroke after every revolution of the crank shaft. All the four stages of a two stroke cycle diesel engine are described below :

1. *Suction stage.* In this stage, the piston while going down towards *BDC* uncovers the transfer port and the exhaust port. The fresh air flows into the engine cylinder from the crank case, as shown in Fig. 26.13 (*a*).

2. *Compression stage.* In this stage, the piston while moving up, first covers the transfer port and then exhaust port. After that the air is compressed as the piston moves upwards as shown in Fig. 26.13 (*b*). In this stage, the inlet port opens and the fresh air enters into the crank case.

3. *Expansion stage.* Shortly before the piston reaches the *TDC* (during compression stroke), the fuel oil is injected in the form of very fine spray into the engine cylinder through the nozzle known as fuel injection valve, as shown in fig. 26.13 (*c*). At this moment, temperature of the compressed air is sufficiently high to ignite the fuel. It suddenly increases the pressure and temperature of the products of combustion. The fuel oil is continuously injected for a fraction of the crank revolution. The fuel oil is assumed to be burnt at constant pressure. Due to increased pressure, the piston is pushed with a great force. The hot burnt gases expand due to high speed of the piston. During the expansion, some of the heat energy produced is transformed into mechanical work.



(*a*) Suction. (*b*) Compression. (*c*) Expansion. (*d*) Exhaust.

Fig. 26.13. Two-stroke cycle diesel engine.

4. *Exhaust stage.* In this stage, the exhaust port is opened and the piston moves downwards. The products of combustion from the engine cylinder are exhausted through the exhaust port into the atmosphere as shown in Fig. 26.13 (*d*). This completes the cycle, and the engine cylinder is ready to suck the air again.

Note : The two stroke diesel engines are mainly used in marine propulsion where space and lightness are the main considerations.

24.5 COMPARISON BETWEEN PETROL AND DIESEL ENGINES

According to	*Petrol Engine*	*Diesel Engine*
1. Basic cycle	It operates on constant-volume cycle.	It operates on constant-pressure cycle.
2. Fuel used	It uses gasolene or petrol as fuel.	It uses diesel and oils as a fuel.
3. Fuel induction	The air–fuel mixture is prepared in the carburettor and inducted into the engine cylinder during the suction stroke.	The Diesel engine takes in only air during the suction stroke, and it is compressed. At the end of the compression stroke the fuel is injected under the high pressure by a fuel injector.
4. Ignition of charge	The charge (air–fuel mixture) is ignited by a high-intensity spark produced at the spark plug.	Fuel is injected in very hot air, therefore, it is self-ignited.
5. Compression ratio	It uses less compression ratio, usually range of 4 to 10.	It uses high compression ratio, range of 14 to 21.
6. Pressure rise	Lower and controlled rate of pressure rise; therefore, operation is salient and smooth.	High rate of pressure variation, so engine operation is rough, and noisier.
7. Efficiency	For the same compression ratio, the efficiency of petrol engine is better.	It has lower efficiency for same compression ratio.
8. Pollution	Comparatively lower pollution for same power output.	Higher pollution for same power output.
9. Weight	It has comparatively less number of parts, thus is less in weight.	It uses large number of sturdier parts, thus engine is heavy.
10. Cost	Engines are cheaper.	Costlier engine due to complicated parts.
11. Maintenance	It requires less and cheaper maintenance.	It requires costlier and large maintainance.
12. Starting	Very easy to start due to lower compression ratio.	Very difficult to start due to higher compression ratio.

24.6 COMPARISON BETWEEN TWO-STROKE AND FOUR-STROKE ENGINES

According to	*Two-Stroke Engine*	*Four-Stroke Engine*
1. Working stroke	There is one working stroke in each revolution. Hence engine has more even torque and reduced vibration.	There is one working stroke in two revolutions. Hence engine has uneven torque and large vibration.
2. Engine design	It uses ports and hence engine design is simple.	It uses valves, therefore, mechanism involved is complex.
3. Mechanical efficiency	The working cycle completes in one revolution and hence it has high mechanical efficiency.	Working cycle completes in two revolution, hence, it has more friction, thus less mechanical efficiency.
4. Scavenging	The burnt gases are not completely driven out. It results in dilution of fresh charge.	It has separate stroke for explusion of burnt gases, thus ideally no dilution of fresh charge.

Contd.

Contd.

5. Thermal efficiency	Poor thermal efficiency due to poor scavenging and escaping of charge with exhaust gases.	Very good thermal efficiency.
6. Cost	Less cost due to less parts in engine.	More cost due to large number of parts.
7. Maintenance	Cheaper and simple.	Costlier and slightly complex.
8. Weight	Lighter engine body.	Heavier engine body.

INSTITUTE OF TEXTILE TECHNOLOGY
CHOUDWAR

Thermal Engineering-I

Chapter-5
Gas Power Cycle

Thermodynamic Air Cycles

1. Introduction. 2. Assumptions in Thermodynamic Cycles. 3. Classifications of Thermodynamic Cycles. 4. Reversible Cycle. 5. Irreversible Cycle. 6. Reversibility and Irreversibility of Thermodynamic Processes. 7. Relation between Cycle and Engine. 8. Working of an Ideal Engine. 9. Important Terms used in Thermodynamic Cycles. 10. Efficiency of a Cycle. 11. Types of Thermodynamic Cycles. 12. Carnot Cycle. 13. Stirling Cycle. 14. Ericsson Cycle. 15. Joule's Cycle. 16. Otto Cycle. 17. Diesel Cycle. 18. Dual Combustion Cycle.

6.1. Introduction

A thermodynamic cycle or a cyclic process consists of a series of thermodynamic operations (processes), which take place in a certain order, and the initial conditions are restored at the end of the processes. When the operations or processes of cycle are plotted on *p-v* diagram, they form a closed figure, each operation being represented by its own curve. Since the area under each curve gives the work done to some scale, during each operation, it therefore follows that the net work done during one cycle will be given by the enclosed area of the diagram as shown, shaded in Fig. 6.1.

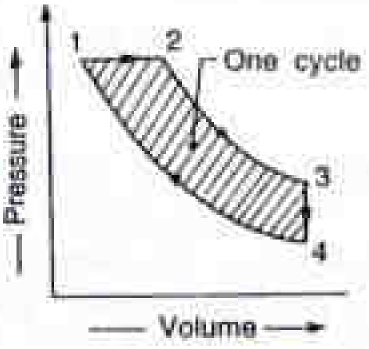


Fig. 6.1. A thermodynamic cycle

The study of various thermodynamic cycles is very essential for the power developing systems (such as petrol engine diesel engine, gas turbine etc.). These engines use a mixture of fuel and air for their operations. Since the mass of fuel used, as compared to the mass of air is very small, therefore the mixture may be assumed to obey the properties of a perfect gas.

Notes : 1. A cycle, which requires four piston strokes and two complete revolutions of the crank is known as *four stroke cycle*. But a cycle, which requires only two piston strokes and one revolution of the crank, is known as *two stroke cycle*.

2. When air is assumed to be the working substance inside the engine cylinder, the cycle is called as an *air cycle*.

6.2. Assumptions in Thermodynamic Cycles

The analysis of all thermodynamic cycles (or air cycles) is based on the following assumptions :

1. The gas in the engine cylinder is a perfect gas, *i.e.* it obeys the gas laws and constant specific heats.
2. The physical constants of the gas in the engine cylinder are same as those of air at moderate temperatures.
3. All the compression and expansion processes are adiabatic and they take place without any internal friction.

4. Heat is supplied by bringing a hot body in contact with the cylinder at appropriate points during the process. Similarly heat is rejected by bringing a cold body in contact with the cylinder at these points.
5. The cycle is considered to be a closed one and the same air is used again and again to repeat the cycle.
6. No chemical reaction, whatsoever, takes place in the engine cylinder.

6.9. Important Terms used in Thermodynamic Cycles

Though there are many terms used in thermodynamic cycles, yet the following are importan from the subject point of view :

1. *Cylinder bore.* The inner diameter of the cylinder, in which the piston moves, is known a cylinder bore.

2. *Stroke length.* The piston moves in the cylinder due to rotation of the crank. Its extreme positions are known as top dead centre (TDC) and bottom dead centre (BDC) respectively as show in Fig. 6.3. The distance between these two extreme positions is known as stroke length or stroke

3. *Clearance volume.* The volume occupied by the working fluid, when piston reaches the to dead centre, is known as clearance volume. It is generally denoted by (v_c).

4. *Swept volume.* The volume swept by the piston, when it moves between the two extrem positions is known as swept volume or displacement volume or stroke volume. Mathematically, swep volume,

$$v_s = \text{Piston area} \times \text{Stroke length} = \frac{\pi}{4} \times d^2 \times l$$

where d = Cylinder bore or diameter of the piston.

5. *Total cylinder volume.* The volume occupied by the working fluid, when the piston is at th bottom dead centre, is known as total cylinder volume. Mathematically, total cylinder volume is equa to the sum of clearance volume (v_c) and swept volume (v_s).

6. *Compression ratio.* The ratio of total cylinder volume to the clearance volume is known a compression ratio. It is an important term used in an engine. Mathematically, compression ratio,

$$r = \frac{v_c + v_s}{v_c} = 1 + \frac{v_s}{v_c}$$

7. *Mean effective pressure.* As a matter of fact, pressure in the cylinder keeps on changin with the position of the piston. For all sorts of calculations, we need the mean effective pressur which may be defined as the constant pressure acting on the piston during the working stroke. It wi be able to do the same amount of work, as done by the actual varying pressure, produced during th cycle. It is ratio of work done to the stroke volume or piston displacement volume. Mathematicall mean effective pressure,

$$p_m = \frac{\text{Work done}}{\text{Stroke volume}}$$

6.10. Efficiency of a Cycle

It may be defined as the ratio of work done to the heat supplied during a cycle. Mathematically, efficiency of a cycle,

$$\eta = \frac{\text{Work done}}{\text{Heat supplied}}$$

Since the work done during a cycle is equal to heat supplied *minus* the heat rejected, the efficiency of a cycle, therefore, may also be expressed as

$$\eta = \frac{\text{Heat supplied} - \text{Heat rejected}}{\text{Heat supplied}}$$

Notes : 1. The efficiency, as given above, is the theoretical efficiency of the cycle. Therefore it is known as *theoretical thermal efficiency.*

2. It does not take into account the practical losses, which occur in the running of the engine.

3. In order to compare the efficiency of the thermodynamic cycles, air is assumed to be the working substance inside the engine cylinder. Moreover, air is assumed to behave as a perfect gas. The efficiency, thus, obtained is known as *air standard efficiency*. It is also called *ideal efficiency*.

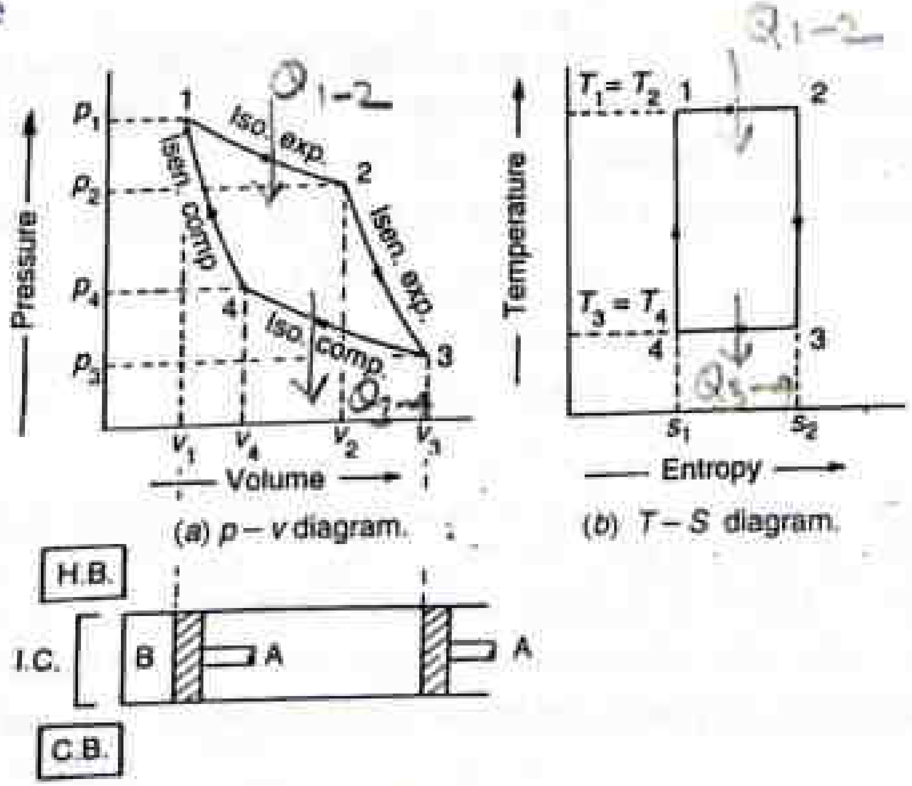
6.11. Types of Thermodynamic Cycles

Though there are many types of thermodynamic cycles, yet the following are important from the subject point of view :

1. Carnot cycle, 2. Stirling cycle, 3. Ericsson cycle, 4. Joule cycle, 5. Otto cycle, 6. Diesel cycle, and 7. Dual combustion cycle.

The above mentioned cycles will be discussed, in detail, in the following pages.

6.12. Carnot Cycle



(a) p – v diagram. (b) T – S diagram.

Fig. 6.4. Carnot cycle.

This cycle was devised by *Carnot, who was the first scientist to analyse the problem of the efficiency of a heat engine, disregarding its mechanical details. He focussed his attention on the basic features of a heat engine. In a Carnot cycle, the working substance is subjected to a cyclic operation consisting of two isothermal and two reversible adiabatic or isentropic operations. The p-v and T-S diagrams of this cycle are shown in Fig. 6.4 (*a*) and (*b*).

The engine imagined by Carnot has air (which is supposed to behave like a perfect gas) as its working substance enclosed in a cylinder, in which a frictionless piston *A* moves. The walls of the cylinder and piston are perfect non-conductor of heat. However, the bottom *B* of the cylinder can be covered, at will, by an insulating cap (I.C.). The engine is assumed to work between two sources of infinite heat capacity, one at a higher temperature and the other at a lower temperature.

Now, let us consider the four stages of the Carnot's cycle. Let the engine cylinder contain *m* kg of air at its original condition represented by point 1 on the *p-v* and *T-S* diagrams. At this point, let p_1, T_1 and v_1 be the pressure, temperature and volume of the air, respectively.

1. *First stage (Isothermal expansion).* The source (hot body, H.B.) at a higher temperature is brought in contact with the bottom *B* of the cylinder. The air expands, practically at constant temperature T_1, from v_1 to v_2. It means that the temperature T_2 at point 2 is equal to the temperature T_1. This isothermal expansion is represented by curve 1-2 on *p-v* and *T-S* diagrams in Fig. 6.4 (*a*) and (*b*). It may be noted that the heat supplied by the hot body is fully absorbed by the air, and is utilised in doing external work.

∴ Heat supplied = *Work done by the air during isothermal expansion

or
$$Q_{1-2} = p_1 v_1 \log_e\left(\frac{v_2}{v_1}\right) = m\,R\,T_1 \log_e\left(\frac{v_2}{v_1}\right) \qquad \ldots(\because p_1 v_1 = mRT_1)$$
$$= 2.3\, m\,R\,T_1 \log r$$

where r = Expansion ratio = v_2/v_1.

2. *Second stage (Reversible adiabatic or isentropic expansion).* The hot body is removed from the bottom of the cylinder *B* and the insulating cap I.C. is brought in contact. The air is now allowed to expand reversibly and adiabatically. Thus the reversible adiabatic expansion is represented by the curve 2-3 on *p-v* and *T-S* diagrams. The temperature of the air falls from T_2 to T_3. Since no heat is absorbed or rejected by the air, therefore

Decrease in internal energy = Workdone by the air during adiabatic expansion
$$= \frac{p_2 v_2 - p_3 v_3}{\gamma - 1} = \frac{m\,R\,T_2 - m\,R\,T_3}{\gamma - 1} \qquad \ldots(\because pv = mRT)$$
$$= \frac{m\,R\,(T_1 - T_3)}{\gamma - 1} \qquad \ldots(\because T_1 = T_2)$$

3. *Third stage (Isothermal compression).* Now remove the insulating cap I.C. from the bottom of the cylinder and bring the cold body C.B. in its contact. The air is compressed practically at constant temperature T_3 from v_3 to v_4. It means that the temperature T_4 (at point 4) is equal to the temperature T_3. This isothermal compression is represented by the curve 3-4 on *p-v* and *T-S* diagrams. It would be seen that during this process, the heat is rejected to the cold body and is equal to the work done on the air.

∴ Heat rejected = Work done on the air during isothermal compression
$$Q_{3-4} = p_3 v_3 \log_e\left(\frac{v_3}{v_4}\right) = m\,R\,T_3 \log_e\left(\frac{v_3}{v_4}\right) \qquad \ldots(\because pv = mRT)$$
$$= 2.3\, m\,R\,T_3 \log r$$

---

[*] Since the temperature is constant, therefore there is no change in internal energy of the air, i.e. $dU = 0$. According to the first law of thermodynamics,
$$Q_{1-2} = dU + W_{1-2} \text{ or } Q_{1-2} = W_{1-2}$$

where $r = {}^*\text{Compression ratio} = v_3/v_4$

4. Fourth stage (Reversible adiabatic or isentropic compression). Now again the insulated cap I.C. is brought in contact with the bottom of the cylinder B, and the air is allowed to be compressed reversibly and adiabatically. The reversible adiabatic compression is represented by the curve 4-1 on p-v and T-S diagrams. The temperature of the air increases from T_4 to T_1. Since no heat is absorbed or rejected by the air, therefore

Increase in internal energy = Work done on the air during adiabatic compression

$$= \frac{p_1 v_1 - p_4 v_4}{\gamma - 1} = \frac{m R T_1 - m R T_4}{\gamma - 1} \qquad \ldots (\because p v = m R T)$$

$$= \frac{m R (T_1 - T_3)}{\gamma - 1} \qquad \ldots (\because T_3 = T_4)$$

We see from the above discussion that the decrease in internal energy during reversible adiabatic expansion 2-3 is equal to the increase in internal energy during reversible adiabatic compression 4-1. Hence their net effect during the whole cycle is zero. We know that

Work done, W = Heat supplied – Heat rejected

$$= 2.3\, m R T_1 \log r - 2.3\, m R T_3 \log r = 2.3\, m R \log r\, (T_1 - T_3)$$

and efficiency

$$^{**}\eta = \frac{\text{Work done}}{\text{Heat supplied}} = \frac{2.3\, m R \log r\, (T_1 - T_3)}{2.3\, m R T_1 \log r}$$

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

The expression for the efficiency of a Carnot cycle may also be written as discussed below.

We know that for reversible adiabatic or isentropic expansion 2-3,

$$\frac{T_2}{T_3} = \left(\frac{v_3}{v_2}\right)^{\gamma-1} \text{ or } \frac{T_1}{T_3} = \left(\frac{v_3}{v_2}\right)^{\gamma-1} \quad \ldots(i) \quad (\because T_2 = T_1)$$

Similarly, for reversible adiabatic or isentropic compression process 4-1,

$$\frac{T_1}{T_4} = \left(\frac{v_4}{v_1}\right)^{\gamma-1} \text{ or } \frac{T_1}{T_3} = \left(\frac{v_4}{v_1}\right)^{\gamma-1} \quad \ldots(ii) \quad (\because T_4 = T_3)$$

From equations (*i*) and (*ii*),

$$\frac{v_3}{v_2} = \frac{v_4}{v_1} \text{ or } \frac{v_2}{v_1} = \frac{v_3}{v_4} = r$$

where r = Ratio of expansion or compression.

$$\therefore \qquad \frac{T_1}{T_3} = (r)^{\gamma-1}$$

We know that efficiency,

$$\eta = 1 - \frac{T_3}{T_1} = 1 - \left(\frac{1}{r}\right)^{\gamma-1} = 1 - \frac{1}{r^{\gamma-1}}$$

Notes : 1. From the above equation, we see that the efficiency of Carnot's cycle increases as T_1 is increase T_3 is decreased. In other words, the heat should be taken in at as high a temperature as possible, and rejecte as low a temperature as possible. It may be noted that 100% efficiency can be achieved, only, if T_3 reac absolute zero, though it is impossible to achieve in practice.

2. In the above theory, we have taken temperature at points 1, 2, 3 and 4 as T_1, T_2, T_3 and T_4 respecti in order to keep similarity between Carnot cycle and other cycles. But some authors take it T_1 (for points 1 a 2) and T_2 (for points 3 and 4). In that case, they obtain the relation for efficiency as,

$$\eta = \frac{T_1 - T_2}{T_1} = 1 - \frac{T_2}{T_1}$$

3. It may be noted that it is impossible to make an engine working on Carnot's cycle. The simple rea for the same is that the isothermal expansion 1-2 will have to be carried out extremely slow to ensure that the is always at temperature T_1. Similarly, the isothermal compression 3-4 will have to be carried out extremely sl But reversible adiabatic expansion 2-3 and reversible adiabatic compression 4-1 should be carried out as quick as possible, in order to approach ideal adiabatic conditions. We know that sudden changes in the speed of a engine are not possible in actual practice. Moreover, it is impossible to completely eliminate friction betwe the various moving parts of the engine, and also heat losses due to conduction, radiation, etc. It is thus obvio that it is impossible to realise Carnot's engine in actual practice. However, such an imaginary engine is used the ultimate standard of comparison of all heat engines.

Example 6.1. *A Carnot engine, working between 650 K and 310 K, produces 150 kJ of work. Find thermal efficiency and heat added during the process.*

Solution. $T_1 = 650$ K ; $T_3 = 310$ K ; $W = 150$ kJ

Thermal efficiency

We know that thermal efficiency,

$$\eta = \frac{T_1 - T_3}{T_1} = \frac{650 - 310}{650} = 0.523 \text{ or } 52.3\% \text{ Ans.}$$

Heat added during the process

We know that heat added during the process,

$$Q_{1-2} = \frac{W}{\eta} = \frac{150}{0.523} = 286.8 \text{ kJ} \quad \textbf{Ans.}$$

Example 6.2. *A Carnot engine operates between two reservoirs at temperatures T_1 and T_3. The work output of the engine is 0.6 times the heat rejected. The difference in temperatures between the source and the sink is 200° C. Calculate the thermal efficiency, source temperature and the sink temperature.*

Solution. Given : $W = 0.6 \times$ Heat rejected $= 0.6\, Q_{3-4}$; $T_1 - T_3 = 200°$ C

Thermal efficiency

We know that the thermal efficiency,

$$\eta = \frac{\text{Work done}}{\text{Heat supplied}} = \frac{\text{Work done}}{\text{Work done + Heat rejected}}$$

$$= \frac{0.6\, Q_{3-4}}{0.6\, Q_{3-4} + Q_{3-4}} = \frac{0.6}{1.6} = 0.375 \quad \text{or} \quad 37.5\% \quad \textbf{Ans.}$$

Source and sink temperatures

Let T_1 = Source temperature, and

T_3 = Sink temperature.

We know that thermal efficiency (η),

$$0.375 = \frac{T_1 - T_3}{T_1} = \frac{200}{T_1}$$

$$\therefore \quad T_1 = 200/0.375 = 533.3 \text{ K} = 260.3° \text{ C} \quad \textbf{Ans.}$$

and

$$T_3 = T_1 - 200 = 260.3 - 200 = 60.3° \text{ C} \quad \textbf{Ans.}$$

Example 6.3. *An engineer claims his engine to develop 3.75 kW. On testing, the engine consumes 0.44 kg of fuel per hour having a calorific value of 42 000 kJ/kg. The maximum temperature recorded in the cycle is 1400° C and minimum is 350° C. Find whether the engineer is justified in his claim.*

Solution. Give : $P = 3.75$ kW; Fuel consumed = 0.44 kg/h; Calorific value = 42 000 kJ/kg $T_1 = 1400°\text{C} = 1400 + 273 = 1673$ K ; $T_3 = 350°\text{ C} = 350 + 273 = 623$ K

We know that the maximum efficiency, between two specified temperatures, is that of Carnot cycle.

$$\therefore \quad \eta_{carnot} = \frac{T_1 - T_3}{T_1} = \frac{1673 - 623}{1673} = 0.627 \quad \text{or} \quad 62.7\%$$

We also know that the heat supplied to the engine by the fuel

= Fuel consumed × Calorific value of fuel

= 0.44 × 42 000 = 18 480 kJ/h = 5.13 kJ/s

and workdone by the engine = 3.75 kW = 3.75 kJ/s

$$\therefore \text{ Efficiency claimed} = \frac{\text{Workdone}}{\text{Heat supplied}} = \frac{3.75}{5.13} = 0.731 \quad \text{or} \quad 73.1\ \%$$

Since efficiency of the engine claimed (73.1%) is more than the maximum possible efficiency (62.7%), therefore the engineer is not justified in his claim. **Ans.**

6.16. Otto Cycle

The first successful engine working on this *cycle was built by A. Otto. These days, many gas, petrol and many of the oil engines run on this cycle. It is the also known as *constant volume cycle*, as the heat is received and rejected at a constant volume.

This cycle is taken as a standard of comparison for internal combustion engines. For the purpose of comparison with other cycles, the air is assumed to be the working substance.

The engine conceived by Otto has air enclosed in a cylinder, whose walls are perfectly non-conductor of heat, but the bottom is a perfect conductor of heat. There is also a hot body and cold

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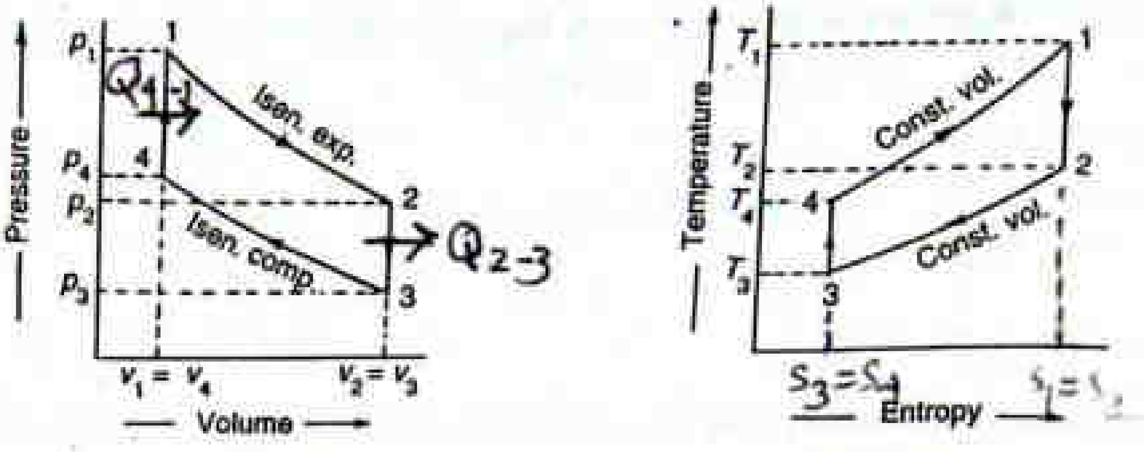
* This cycle was originally devised by a Frenchman Beau-de-Rochas in 1862. The first successful engine, working on this cycle, was built by a German engineer Nicholas A. Otto in 1876.

body and an insulating cap, which are alternately brought in contact with the bottom of the cylind (*i.e.* a cylinder similar to that of Carnot).

The ideal Otto cycle consists of two constant volume and two reversible adiabatic or isentrop processes as shown on p-v and T-S diagrams in Fig. 6.9 (*a*) and (*b*).



(*a*) p-v diagram.

(*b*) T-S diagram.

Fig. 6.9. Otto cycle.

Let the engine cylinder contain m kg of air at point 1. At this point, let p_1, T_1 and v_1 be the pressure, temperature and volume of the air. Following are the four stages of the ideal cycle :

1. *First stage (Reversible adiabatic or isentropic expansion).* The air is expanded reversibly and adiabatically from initial temperature T_1 to a temperature T_2 as shown by the curve 1-2 in Fig. 6.9 (*a*) and (*b*). In this process, no heat is absorbed or rejected by the air.

2. *Second stage (Constant volume cooling).* The air is cooled at constant volume from temperature T_2 to a temperature T_3 as shown by the curve 2-3 in Fig. 6.9 (*a*) and (*b*). We know that heat rejected by the air during this process.

$$Q_{2-3} = m\,c_v\,(T_2 - T_3)$$

3. *Third stage (Reversible adiabatic or isentropic compression).* The air is compressed reversibly and adiabatically from temperature T_3 to a temperature T_4 as shown in by the curve 3-4 in Fig. 6.9 (*a*) and (*b*). In this process, no heat is absorbed or rejected by the air.

4. *Fourth stage (Constant volume heating).* The air is now heated at constant volume from temperature T_4 to a temperature T_1 as shown by the curve 4-1 in Fig. 6.9 (*a*) and (*b*). We know that heat absorbed by the air during this process,

$$Q_{4-1} = m\,c_v\,(T_1 - T_4)$$

We see that the air has been brought back to its original conditions of pressure, volume and temperature, thus completing the cycle.

We know that work done = Heat absorbed – Heat rejected

$$= m\,c_v\,(T_1 - T_4) - m\,c_v\,(T_2 - T_3)$$

$\therefore$ Ideal efficiency or air standard efficiency,

$$\eta = \frac{\text{Work done}}{\text{Heat absorbed}}$$

$$= \frac{m\,c_v\,(T_1 - T_4) - m\,c_v\,(T_2 - T_3)}{m\,c_v\,(T_1 - T_4)}$$

$$= 1 - \frac{T_2 - T_3}{T_1 - T_4} = 1 - \frac{T_3\left(\frac{T_2}{T_3} - 1\right)}{T_4\left(\frac{T_1}{T_4} - 1\right)} \qquad \ldots (i)$$

We know that for reversible adiabatic or isentropic expansion process 1-2,

$$\frac{T_2}{T_1} = \left(\frac{v_1}{v_2}\right)^{\gamma-1} = \left(\frac{1}{r}\right)^{\gamma-1} \qquad \left[TV^{r-1} = C\right] \ldots (ii)$$

where r = Expansion ratio = v_2 / v_1

Similarly, for reversible adiabatic or isentropic compression process 3-4,

$$\frac{T_3}{T_4} = \left(\frac{v_4}{v_3}\right)^{\gamma-1} = \left(\frac{1}{r}\right)^{\gamma-1} \qquad \ldots (iii)$$

where r = Compression ratio = $v_3 / v_4 = v_2 / v_1$

From equations (*ii*) and (*iii*), we find that

$$\frac{T_2}{T_1} = \frac{T_3}{T_4} = \left(\frac{1}{r}\right)^{\gamma-1} = \frac{1}{(r)^{\gamma-1}} \quad \text{or} \quad \underline{\frac{T_1}{T_4} = \frac{T_2}{T_3}}$$

Substituting the value of T_1 / T_4 in equation (*i*),

$$\therefore \quad \boxed{\eta = 1 - \frac{T_3}{T_4} = 1 - \frac{T_2}{T_1} = 1 - \frac{1}{(r)^{\gamma-1}}} \qquad \ldots\left(\because \frac{T_3}{T_4} = \frac{T_2}{T_1}\right) \ldots (iv)$$

Notes : 1. We see from equation (*iv*) that the efficiency of Otto cycle depends on compression ratio (r) only.

2. The efficiency increases with the increase in compression ratio (r). In actual practice, r can not be increased beyond a value of 7 or so.

3. Compression ratio, $r = \dfrac{\text{Total cylinder volume}}{\text{Clearance volume}}$

$$= \frac{\text{Clearance volume + Stroke volume}}{\text{Clearance volume}} = \frac{v_c + v_s}{v_c}$$

$$\therefore \text{ Clearance volume, } v_c = \frac{\text{Stroke volume}}{r-1} = \frac{v_s}{r-1}$$

4. The relations between pressure and temperature or pressure and volume may be obtained from the usual reversible adiabatic or isentropic processes, *i.e.*

$$\frac{T_1}{T_2} = \left(\frac{p_1}{p_2}\right)^{\frac{\gamma-1}{\gamma}} \quad \text{and} \quad \frac{p_1}{p_2} = \left(\frac{v_2}{v_1}\right)^{\gamma} \quad \text{or} \quad \frac{v_1}{v_2} = \left(\frac{p_2}{p_1}\right)^{\frac{1}{\gamma}}$$

Example 6.10. *In an Otto cycle, the temperature at the beginning and end of the isentropic compression are 316 K and 596 K respectively. Determine the air standard efficiency and the compression ratio. Take* $\gamma = 1.4$.

Solution. Given : $T_3 = 316$ K ; $T_4 = 596$ K ; $\gamma = 1.4$

Compression ratio

Let r = Compression ratio = v_3 / v_4

$$\eta = 1 - \frac{T_3}{T_4} = 1 - \frac{316}{596} = 46.98\% \Rightarrow 0.4698 = 1 - \frac{1}{r^{r-1}}$$

$$\Rightarrow r = 4.885$$

We know that for isentropic compression 3-4 (Refer Fig. 6.9),

$$\frac{T_3}{T_4} = \left(\frac{v_4}{v_3}\right)^{\gamma-1} = \left(\frac{1}{r}\right)^{1.4-1} = \frac{1}{(r)^{0.4}}$$

$$\therefore \qquad (r)^{0.4} = \frac{T_4}{T_3} \text{ or } r = \left(\frac{T_4}{T_3}\right)^{\frac{1}{0.4}} = \left(\frac{596}{316}\right)^{2.5} = 4.885 \textbf{ Ans.}$$

Air standard efficiency

We know that air standard efficiency,

$$\eta = 1 - \frac{1}{(r)^{\gamma-1}} = 1 - \frac{1}{(4.885)^{1.4-1}} = 1 - \frac{1}{1.886}$$

$$= 1 - 0.53 = 0.47 \text{ or } 47\% \textbf{ Ans.}$$

Example 6.11. *An engine, working on the Otto cycle, has a cylinder diameter of 150 m and a stroke of 225 mm. The clearance volume is 1.25 × 10^{-3} m^3. Find the air standard efficienc this engine. Take γ = 1.4.*

Solution. Given : $d = 150$ mm $= 0.15$ m ; $l = 225$ mm $= 0.225$ m ; $v_c = 1.25 \times 10^{-3}$ m
$\gamma = 1.4$

We know that swept volume

$$v_s = \frac{\pi}{4} \times d^2 \times l = \frac{\pi}{4}(0.15)^2(0.225) = 3.976 \times 10^{-3} \text{ m}^3$$

$$\therefore \text{ Compression ratio, } r = \frac{v_c + v_s}{v_c} = \frac{1.25 \times 10^{-3} + 3.976 \times 10^{-3}}{1.25 \times 10^{-3}} = 4.18$$

We know that air standard efficiency

$$\eta = 1 - \frac{1}{(r)^{\gamma-1}} = 1 - \frac{1}{(4.18)^{1.4-1}} = 1 - \frac{1}{1.772}$$

$$= 1 - 0.564 = 0.436 \text{ or } 43.6\% \textbf{ Ans.}$$

Example 6.12. *A certain quantity of air at a pressure of 1 bar and temperature 70° C compressed reversibly and adiabatically until the pressure is 7 bar in an Otto cycle engine. 460 of heat per kg of air is now added at constant volume. Determine : 1. compression ratio of the eng 2. temperature at the end of compression, and 3. temperature at the end of heat addition.*

Take for air, $c_p = 1$ kJ/kg K and $c_v = 0.707$ kJ/kg K.

Solution. Given : $p_3 = 1$ bar ; $T_3 = 70°\text{ C} = 70 + 273 = 343$ K ; $p_4 = 7$ bar ; $Q_{4-1} = 460$ k
$m = 1$ kg ; $c_p = 1$ kJ/kg K ; $c_v = 0.707$ kJ/kg K

We know that ratio of specific heats,

$$\gamma = c_p / c_v = 1/0.707 = 1.41$$

1. Compression ratio of the engine

Let r = Compression ratio of the engine $= v_3 / v_4$.

We know that $p_3 v_3^{\gamma} = p_4 v_4^{\gamma}$

$$\therefore \qquad \frac{v_3}{v_4} = \left(\frac{p_4}{p_3}\right)^{\frac{1}{\gamma}} \text{ or } r = \left(\frac{7}{1}\right)^{\frac{1}{1.41}} = (7)^{0.709} = 3.97 \textbf{ Ans.}$$

$$\frac{T_4}{T_3} = \left(\frac{P_4}{P_3}\right)^{\frac{r-1}{r}} \Rightarrow T_4 = 343 \times \left(\frac{7}{1}\right)^{\frac{0.4}{1.4}} = 598\text{K}$$

$$\frac{T_3}{T_4} = \frac{1}{r^{\gamma-1}} \rightarrow \frac{343}{598} = \frac{1}{r^{0.4}}$$
$$\rightarrow r = 4.01$$

2. Temperature at the end of compression

Let T_4 = Temperature at the end of compression.

We know that
$$\frac{T_3}{T_4} = \left(\frac{v_4}{v_3}\right)^{\gamma-1} = \left(\frac{1}{r}\right)^{\gamma-1} = \left(\frac{1}{3.97}\right)^{1.41-1} = (0.252)^{0.41} = 0.568$$

$\therefore$
$$T_4 = T_3 / 0.568 = 343 / 0.568 = 604 \text{ K} = 331°\text{C} \textbf{ Ans.}$$

3. Temperature at the end of heat addition

Let T_1 = Temperature at the end of heat addition.

We know that heat added at constant volume (Q_{4-1}),

$$460 = m\,c_v\,(T_1 - T_4) = 1 \times 0.707\,(T_1 - 604) \text{ kJ}$$

$\therefore$
$$T_1 - 604 = 460 / 0.707 = 651 \quad \text{or} \quad T_1 = 1255 \text{ K} = 982°\text{C} \textbf{ Ans.}$$

Example 6.13. *In an Otto cycle, air at 1 bar and 290 K is compressed isentropically until the pressure is 15 bar. The heat is added at constant volume until the pressure rises to 40 bar. Calculate the air standard efficiency and the mean effective pressure for the cycle. Take c_v = 0.717 kJ/kg K and R_u = 8.314 kJ/kg mole K.*

Solution. Given : p_3 = 1 bar ; T_3 = 290 K ; p_4 = 15 bar ; p_1 = 40 bar ; c_v = 0.717 kJ/kg K ; R_u = 8.314 kJ/kg mole K

R of air = 0.287 kJ/kg K

We know that characteristic gas constant,

$$R = \frac{\text{Universal gas constant } (R_u)}{\text{Molecular mass } (M)} = \frac{8.314}{28.97} = 0.287 \text{ kJ/kg K}$$

$$c_p - c_v = R$$

...($\because$ M for air = 28.97 kg)

and
$$c_p = R + c_v = 0.287 + 0.717 = 1.004 \text{ kJ/kg K}$$

$\therefore$
$$\gamma = c_p / c_v = 1.004 / 0.717 = 1.4$$

Air standard efficiency

We know that for isentropic compression process 3-4 (Refer Fig. 6.9).

$$p_3 v_3^{\gamma} = p_4 v_4^{\gamma} \quad \text{or} \quad \frac{v_3}{v_4} = \left(\frac{p_4}{p_3}\right)^{\frac{1}{\gamma}}$$

$\therefore$ Compression ratio,
$$r = \frac{v_3}{v_4} = \left(\frac{p_4}{p_3}\right)^{\frac{1}{\gamma}} = \left(\frac{15}{1}\right)^{\frac{1}{1.4}} = (15)^{0.714} = 6.914$$

We know that air standard efficiency,

$$\eta = 1 - \frac{1}{(r)^{\gamma-1}} = 1 - \frac{1}{(6.914)^{1.4-1}} = 1 - \frac{1}{2.167}$$
$$= 1 - 0.4615 = 0.5385 \quad \text{or} \quad 53.85\% \textbf{ Ans.}$$

Mean effective pressure

First of all, let us find the workdone during the cycle per kg of air.

Let T_4 = Temperature at the end of isentropic compression, and

T_1 = Temperature at the end of constant volume heating.

We know that $$\frac{T_3}{T_4} = \left(\frac{v_4}{v_3}\right)^{\gamma-1} = \left(\frac{1}{r}\right)^{\gamma-1} = \left(\frac{1}{6.914}\right)^{1.4-1} = \frac{1}{2.167}$$

$$\therefore \quad T_4 = T_3 \times 2.167 = 290 \times 2.167 = 628.5 \text{ K}$$

Now for constant volume heating process 4-1,

$$\frac{p_4}{T_4} = \frac{p_1}{T_1} \quad \text{or} \quad T_1 = T_4 \times \frac{p_1}{p_4} = 628.5 \times \frac{40}{15} = 1676 \text{ K}$$

We know that heat supplied,

$$Q_{4-1} = m\,c_v\,(T_1 - T_4) = 1 \times 0.717\,(1676 - 628.5) = 751 \text{ kJ}$$

∴ Workdone during the cycle

$$= \eta \times \text{Heat supplied} = 0.5385 \times 751 = 404.4 \text{ kJ}$$

Now let us find the stroke volume (*i.e.* $v_3 - v_4$ or $v_2 - v_1$). We know that

$$p_3 v_3 = m\,R\,T_3 \quad \text{or} \quad v_3 = \frac{m\,R\,T_3}{p_3} = \frac{1 \times 287 \times 290}{0.1 \times 10^6} = 0.8323 \text{ m}^3$$

. . . (R is taken in J/kg K and p_3 in N/m

$$\therefore \quad v_4 = v_3 / 6.914 = 0.8323 / 6.914 = 0.1204 \text{ m}^3$$

. . . ($\because r = v_3/v_4 = 6.9$

and stroke volume $$= v_3 - v_4 = 0.8323 - 0.1204 = 0.7119 \text{ m}^3$$

We know that mean effective pressure

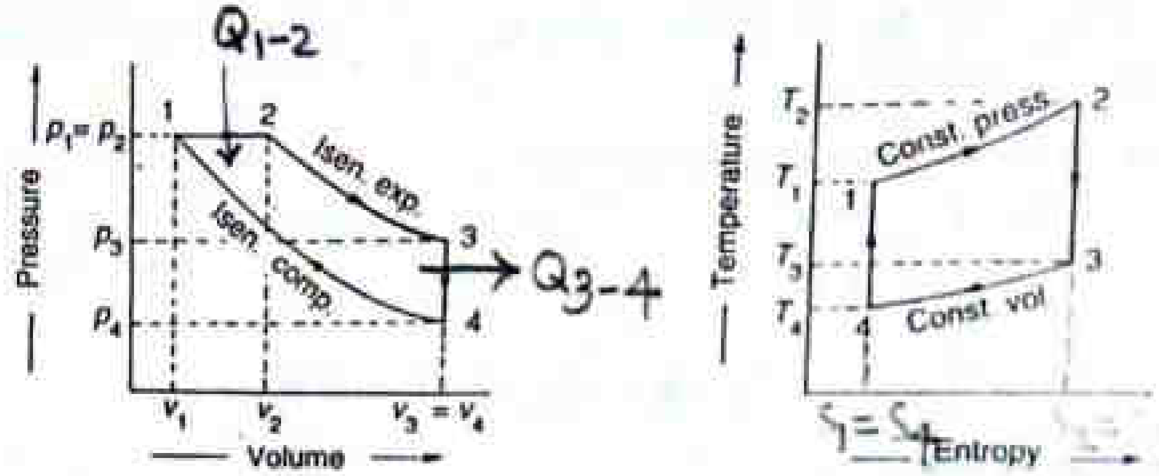
$$= \frac{\text{Work done}}{\text{Stroke volume}} = \frac{404.4}{0.7119} = 568 \text{ kN/m}^2 = 5.68 \text{ bar}$$ **Ans.**

6.17. Diesel Cycle

This cycle was devised by Dr. Rudolph Diesel in 1893, with an idea to attain a higher ther efficiency, with a high compression ratio. This is an important cycle on which all the diesel eng work. It is also known as *constant pressure cycle* as heat is received at a constant pressure.

The engine imagined by Diesel has air enclosed in the cylinder, whose walls are perfec non-conductor of heat, but bottom is a perfect conductor of *heat. Again, there is a hot body, co body and an insulating cap, which are alternately brought in contact with the cylinder.

The ideal diesel cycle consists of two reversible adiabatic or isentropic, a constant pres and a constant volume processes. These processes are represented on p-v and T-S diagrams as show in Fig. 6.10 (*a*) and (*b*).



(*a*) p-v diagram.

(*b*) T-S diagram

Fig. 6.10 Diesel cycle

Let the engine cylinder contain m kg of air at point 1. At this point let, p_1, T_1 and v_1 be the pressure, temperature and volume of the air. Following are four stages of an ideal diesel cycle.

1. *First stage (Constant pressure heating).* The air is heated at constant pressure from initia temperature T_1 to a temperature T_2 represented by the curve 1-2 in Fig. 6.10 (*a*) and (*b*).

∴ Heat supplied to the air,

$$Q_{1-2} = m\, c_p\, (T_2 - T_1)$$

Note : Since the supply of heat is cut off at point 2, therefore it is known as cut-off point.

2. *Second stage (Reversible adiabatic or isentropic expansion).* The air is expanded reversibl and adiabatically from temperature T_2 to a temperature T_3 as shown by the curve 2-3 in Fig. 6.10 (a and (*b*). In this process, no heat is absorbed or rejected by the air.

3. *Third stage (Constant volume cooling).* The air is now cooled at constant volume fro temperature T_3 to a temperature T_4 as shown by the curve 3-4 in Fig. 6.10 (*a*) and (*b*).

∴ Heat rejected by the air,

$$Q_{3-4} = m\, c_v\, (T_3 - T_4)$$

4. *Fourth stage (Reversible adiabatic or isentropic compression).* The air is compressed reversibly and adiabatically from temperature T_4 to a temperature T_1 represented by the curve 4-1 i Fig. 6.10 (*a*) and (*b*). In this process, no heat is absorbed or rejected by the air.

We see that the air has been brought back to its original conditions of pressure, volume a temperature, thus completing the cycle. We know that.

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rk done = Heat absorbed − Heat rejected

$$= m\,c_p\,(T_2 - T_1) - m\,c_v\,(T_3 - T_4)$$

∴ Air standard efficiency,

$$\eta = \frac{\text{Work done}}{\text{Heat absorbed}} = \frac{m\,c_p\,(T_2 - T_1) - m\,c_v\,(T_3 - T_4)}{m\,c_p\,(T_2 - T_1)}$$

$$= 1 - \frac{c_v}{c_p}\left(\frac{T_3 - T_4}{T_2 - T_1}\right) = 1 - \frac{1}{\gamma}\left(\frac{T_3 - T_4}{T_2 - T_1}\right) \qquad \ldots (i)$$

Now let compression ratio,

$$r = \frac{v_4}{v_1}$$

Cut-off ratio, $\rho = \dfrac{v_2}{v_1}$

Expansion ratio, $r_1 = \dfrac{v_3}{v_2} = \dfrac{v_4}{v_2} \qquad \ldots (\because v_3 = v_4)$

$$= \frac{v_4}{v_1} \times \frac{v_1}{v_2} = r \times \frac{1}{\rho} = \frac{r}{\rho} \quad \Rightarrow r_1 = \frac{r}{\rho}$$

We know for constant pressure heating process 1-2,

$$\frac{v_1}{T_1} = \frac{v_2}{T_2} \qquad \ldots \text{(Charles's law)}$$

$$\therefore \quad T_2 = T_1 \times \frac{v_2}{v_1} = T_1 \times \rho \quad \Rightarrow T_2 = T_1 \rho \qquad \ldots (ii)$$

Similarly, for reversible adiabatic or isentropic expansion process 2-3,

$$\frac{T_3}{T_2} = \left(\frac{v_2}{v_3}\right)^{\gamma-1} = \left(\frac{1}{r_1}\right)^{\gamma-1} = \left(\frac{\rho}{r}\right)^{\gamma-1}$$

$$\therefore \quad T_3 = T_2\left(\frac{\rho}{r}\right)^{\gamma-1} = T_1 \times \rho\left(\frac{\rho}{r}\right)^{\gamma-1} \Rightarrow T_3 = T_1 \times \frac{\rho^{\gamma}}{r^{\gamma-1}} \qquad \ldots (iii)$$

and for reversible adiabatic or isentropic compression process 4-1,

$$\frac{T_1}{T_4} = \left(\frac{v_4}{v_1}\right)^{\gamma-1} = (r)^{\gamma-1} \quad \text{or} \quad T_1 = T_4\,(r)^{\gamma-1} \qquad \ldots (iv)$$

Substituting the value of T_1 in equations (*ii*) and (*iii*),

$$T_2 = T_4\,(r)^{\gamma-1} \times \rho \qquad \ldots (v)$$

and

$$T_3 = T_4\,(r)^{\gamma-1} \times \rho\left(\frac{\rho}{r}\right)^{\gamma-1} = T_4\,\rho^{\gamma} \qquad \ldots (vi)$$

Now substituting the values of T_1, T_2 and T_3 in equation (*i*),

$$\eta = 1 - \frac{1}{\gamma}\left[\frac{(T_4\,\rho^{\gamma}) - T_4}{T_4\,(r)^{\gamma-1}\,\rho - T_4\,(r)^{\gamma-1}}\right]$$

$$= 1 - \frac{1}{(r)^{\gamma-1}}\left[\frac{\rho^{\gamma}-1}{\gamma\,(\rho-1)}\right] \qquad \ldots(vii)$$

Notes : 1. The efficiency of the ideal Diesel cycle is lower than that of Otto cycle, for the same compress ratio. This is due to the fact that the cut-off ratio (ρ) is always greater than unity and hence the term within the bracket of equation (*vii*) increases with the increase of cut-off ratio. Thus the negative term increases and th efficiency is reduced.

2. The Diesel cycle efficiency increases with decrease in cut-off ratio and approaches maximum (equa to Otto cycle efficiency) when the term within the bracket is unity.

Example 6.15. *In a diesel engine, the compression ratio is 13 : 1 and the fuel is cut-off a 8% of the stroke. Find the air standard efficiency of the engine. Take γ for air as 1.4.*

Solution. Given : $r = v_4 / v_1 = 13$; $\gamma = 1.4$

Since the cut-off takes place at 8% of the stroke, therefore volume at cut-off,

$$v_2 = v_1 + 8\% \text{ of stroke volume} = v_1 + 0.08\,(v_4 - v_1)$$

Let us assume that the clearance volume $(v_1) = 1\ \text{m}^3$.

$$\therefore \qquad v_4 = 13\ \text{m}^3 \qquad \ldots(\because\ v_4 / v_1 = 13)$$

and stroke volume, $\quad v_4 - v_1 = 13 - 1 = 12\ \text{m}^3$

∴ Volume at cut-off

$$v_2 = v_1 + 0.08\,(v_4 - v_1) = 1 + 0.08 \times 12 = 1.96\ \text{m}^3$$

We know that cut-off ratio,

$$\rho = v_2 / v_1 = 1.96 / 1 = 1.96$$

∴ Air standard efficiency,

$$\eta = 1 - \frac{1}{(r)^{\gamma-1}}\left[\frac{\rho^{\gamma-1}}{\gamma\,(\rho-1)}\right] = 1 - \frac{1}{(13)^{1.4-1}}\left[\frac{(1.96)^{1.4}-1}{1.4\,(1.96-1)}\right]$$

$$= 1 - 0.417 = 0.583 \quad \text{or} \quad 58.3\%\ \textbf{Ans.}$$

Example 6.16. *In an ideal Diesel cycle, the temperatures at the beginning and end o compression are 57° C and 603° C respectively. The temperatures at the beginning and end o expansion are 1950° C and 870° C respectively. Determine the ideal efficiency of the cycle. γ = 1.4*

If the compression ratio is 14 and the pressure at the beginning of the compression is 1 ba calculate the maximum pressure in the cycle.

Solution. Given : $T_4 = 57°\,\text{C} = 57 + 273 = 330\ \text{K}$; $T_1 = 603°\,\text{C} = 603 + 273 = 876\ \text{K}$; $T_2 = 1950°\,\text{C} = 1950 + 273 = 2223\ \text{K}$; $T_3 = 870°\,\text{C} = 870 + 273 = 1143\ \text{K}$; $\gamma = 1.4$; $r = v_4/v_1 = 14$; $p_4 = 1$ bar

Ideal efficiency of the cycle

We know that ideal efficiency of the cycle,

$$\eta = 1 - \frac{1}{\gamma}\left(\frac{T_3 - T_4}{T_2 - T_1}\right) = 1 - \frac{1}{1.4}\left(\frac{1143 - 330}{2223 - 876}\right)$$

$$= 1 - 0.431 = 0.569 \quad \text{or} \quad 56.9\%\ \textbf{Ans.}$$

Maximum pressure in the cycle

Let p_1 = Maximum pressure in the cycle.

We know that for reversible adiabatic compression,

$$p_1 v_1^\gamma = p_4 v_4^\gamma \text{ or } p_1 = p_4 \left(\frac{v_4}{v_1}\right)^\gamma = 1\,(14)^{1.4} = 40.23 \text{ bar} \textbf{ Ans.}$$

Example 6.17. *An ideal Diesel engine has a diameter 150 mm and stroke 200 mm. The clearance volume is 10 per cent of the swept volume. Determine the compression ratio and the air standard efficiency of the engine if the cut-off takes place at 6 per cent of the stroke.*

Solution. Given : d = 150 mm = 0.15 m ; l = 200 mm = 0.2 m ; v_c = 10% of v_s = 0.1 v_s

Compression ratio

We know that stroke volume,

$$v_s = \frac{\pi}{4} \times d^2 \times l = \frac{\pi}{4}(0.15)^2\, 0.2 = 3.53 \times 10^{-3} \text{ m}^3$$

$$\therefore \quad v_c = 0.1\, v_s = 0.1 \times 3.53 \times 10^{-3} = 0.353 \times 10^{-3} \text{ m}^3$$

We know that compression ratio,

$$r = \frac{\text{Total volume}}{\text{Clearance volume}} = \frac{v_c + v_s}{v_c} = \frac{0.353 \times 10^{-3} + 3.53 \times 10^{-3}}{0.353 \times 10^{-3}}$$

$$= 11 \textbf{ Ans.}$$

Air standard efficiency

Since the cut-off takes place at 6% of the stroke, therefore volume at cut-off,

$$v_2 = v_1 + 0.06\, v_s = v_c + 0.06\, v_s \qquad \ldots (\because v_1 = v_c)$$

$$= 0.353 \times 10^{-3} + 0.06 \times 3.53 \times 10^{-3} = 0.565 \times 10^{-3} \text{ m}^3$$

$$\therefore \text{ Cut-off ratio,} \quad \rho = \frac{v_2}{v_1} = \frac{v_2}{v_c} = \frac{0.565 \times 10^{-3}}{0.353 \times 10^{-3}} = 1.6$$

We know that air standard efficiency,

$$\eta = 1 - \frac{1}{(r)^{\gamma-1}}\left[\frac{\rho^\gamma - 1}{\gamma(\rho - 1)}\right] = 1 - \frac{1}{(11)^{1.4-1}}\left[\frac{(1.6)^{1.4} - 1}{1.4\,(1.6 - 1)}\right]$$

$$= 1 - \frac{1}{2.61} \times 1.11 = 1 - 0.4246 = 0.5753 \text{ or } 57.53\% \textbf{ Ans.}$$

Example 6.18. *The compression ratio of an ideal air standard Diesel cycle is 15. The heat transfer is 1465 kJ/kg of air. Find the pressure and temperature at the end of each process and determine the cycle efficiency.*

What is the mean effective pressure of the cycle, if the inlet conditions are 300 K and 1 bar.

Solution. Given : $r = v_4 / v_1 = 15$; Q_{1-2} = 1465 kJ/kg ; T_4 = 300 K ; p_4 = 1 bar = 0.1×10^6 N/m^2

Pressure and temperature at the end of each process

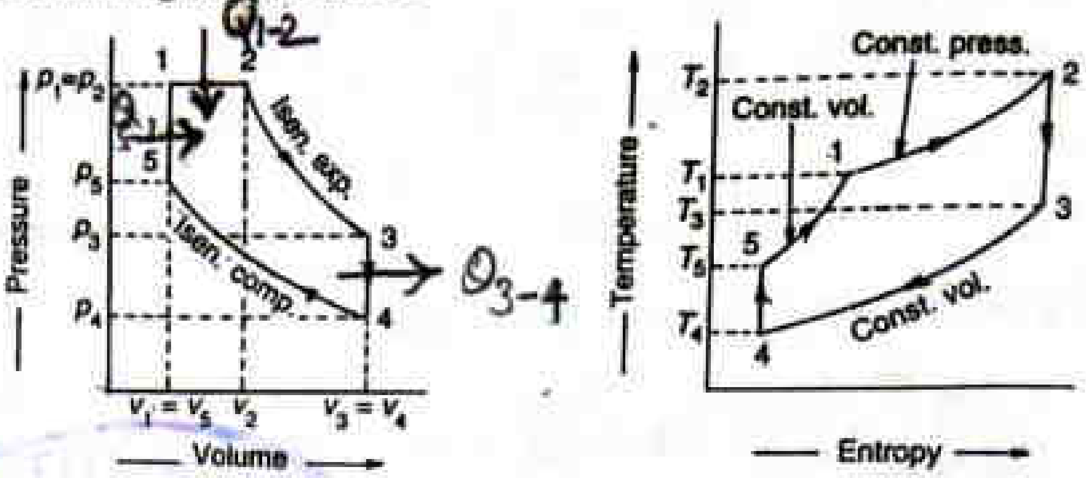
The p-v and T-S diagram for the Diesel cycle is shown in Fig. 6.11.

Let p_1, p_2 and p_3 = Pressures at points 1, 2 and 3 respectively.

6.18. Dual Combustion Cycle

This cycle is a combination of Otto and Diesel cycles. It is sometimes called *semi-diesel cycle*, because semi-diesel engines work on this cycle. In this cycle, heat is absorbed partly at a consta volume and partly at a constant pressure.

The ideal dual combustion cycle consists of *two reversible adiabatic or isentropic*, *two constant volume* and *a constant pressure processes*. These processes are represented on *p-v* and *T-s* diagram as shown in Fig. 6.15 (*a*) and (*b*).



(*a*) *p-v* diagram.

(*b*) *T-S* diagram.

Fig. 6.15. Dual combustion cycle.

Let the engine cylinder* contain *m* kg of air at point 1. At this point, let p_1, T_1 and v_1 be the pressure, temperature and volume of the air. Following are the five stages of an ideal dual combustion cycle.

1. *First stage (Constant pressure heating).* The air is heated at constant pressure from initial temperature T_1 to a temperature T_2 represented by the curve 1-2 in Fig. 6.15 (*a*) and (*b*).

$\therefore$ Heat absorbed by the air, $\quad Q_{1-2} = m\,c_p\,(T_2 - T_1)$

2. *Second stage (Reversible adiabatic or isentropic expansion).* The air is expanded reversibly and adiabatically from temperature T_2 to a temperature T_3 as shown by the curve 2-3 in Fig. 6.15 (*a*) and (*b*). In this process, no heat is absorbed or rejected by the air .

3. *Third stage (Constant volume cooling).* The air is now cooled at constant volume from temperature T_3 to temperature T_4 as shown by the curve 3-4 in Fig. 6.15 (*a*) and (*b*).

$\therefore$ Heat rejected by the air, $\quad Q_{3-4} = m\,c_v\,(T_3 - T_4)$

4. *Fourth stage (Reversible adiabatic or isentropic compression).* The air is compressed reversibly and adiabatically from temperature T_4 to a temperature T_5 as shown by the curve 4-5 in Fig. 6.15 (*a*) and (*b*). In this process, no heat is absorbed or rejected by the air.

5. *Fifth stage (Constant volume heating).* The air is finally heated at constant volume from temperature T_5 to a temperature T_1 as shown by the curve 5-1 in Fig. 6.15 (*a*) and (*b*).

$\therefore$ Heat absorbed by the air, $\quad Q_{5-1} = m\,c_v\,(T_1 - T_5)$

We see that the air has been brought back to its original conditions of pressure, volume and temperature, thus completing the cycle. We know that

$$\text{Work done} = \text{Heat absorbed} - \text{Heat rejected}$$

$$= [m\,c_p\,(T_2 - T_1) + m\,c_v\,(T_1 - T_5)] - m\,c_v\,(T_3 - T_4)$$

---

* The cylinder is of similar type as discussed in Otto and Diesel cycles.

and air standard efficiency, $\eta = \dfrac{\text{Workdone}}{\text{Heat absorbed}}$

$$= \frac{m\,c_p\,(T_2 - T_1) + m\,c_v\,(T_1 - T_5) - m\,c_v\,(T_3 - T_4)}{m\,c_p\,(T_2 - T_1) + m\,c_v\,(T_1 - T_5)}$$

$$= 1 - \frac{c_v\,(T_3 - T_4)}{c_p\,(T_2 - T_1) + c_v\,(T_1 - T_5)}$$

$$= 1 - \frac{T_3 - T_4}{\gamma\,(T_2 - T_1) + (T_1 - T_5)} \qquad \ldots (i)$$

Now, let compression ratio,

$$r = \frac{v_4}{v_5} = \frac{v_3}{v_1} \qquad \ldots (\because v_3 = v_4 \text{ and } v_5 = v_1)$$

Cut-off ratio, $\rho = \dfrac{v_2}{v_1} = \dfrac{v_2}{v_5}$ $\qquad \ldots (\because v_1 = v_5)$

and pressure ratio,

$$\alpha = \frac{p_1}{p_5}$$

We know that in constant pressure heating process 1-2,

$$\frac{v_1}{T_1} = \frac{v_2}{T_2} \qquad \ldots \text{(Charles' law)}$$

$$\therefore \quad T_2 = T_1 \times \frac{v_2}{v_1} = T_1\,\rho \;\Rightarrow T_2 = T_1\,\rho \qquad \ldots (ii)$$

Similarly, in reversible adiabatic or isentropic expansion process 2-3,

$$\frac{T_3}{T_2} = \left(\frac{v_2}{v_3}\right)^{\gamma - 1} = \left(\frac{v_2}{v_1} \times \frac{v_1}{v_3}\right)^{\gamma - 1} = \left(\frac{\rho}{r}\right)^{\gamma - 1}$$

$$\therefore \quad T_3 = T_2\left(\frac{\rho}{r}\right)^{\gamma - 1} = T_1\,\rho\left(\frac{\rho}{r}\right)^{\gamma - 1} \Rightarrow T_3 = T_1\,\rho\left(\frac{\rho}{r}\right)^{\gamma - 1} \qquad \ldots (iii)$$

and in reversible adiabatic or isentropic compression process 4-5,

$$\frac{T_5}{T_4} = \left(\frac{v_4}{v_5}\right)^{\gamma - 1} = (r)^{\gamma - 1}$$

$$\therefore \quad T_5 = T_4\,(r)^{\gamma - 1} \Rightarrow T_5 = T_4\,r^{\gamma - 1} \qquad \ldots (iv)$$

Now in constant volume heating process 5-1,

$$\frac{p_5}{T_5} = \frac{p_1}{T_1} \qquad \ldots \text{(Gay-Lussac law)}$$

$$\therefore \quad T_1 = T_5 \times \frac{p_1}{p_5} = T_5\,\alpha = T_4\,(r)^{\gamma - 1}\,\alpha \Rightarrow T_1 = T_4\,r^{\gamma - 1}\,\alpha \qquad \ldots (v)$$

Substituting the value of T_1 in equations (*ii*) and (*iii*),

$$T_2 = T_4 (r)^{\gamma-1} \alpha \rho$$

and
$$T_3 = T_4 (r)^{\gamma-1} \alpha \rho \left(\frac{\rho}{r}\right)^{\gamma-1} = T_4 \alpha \rho^{\gamma}$$

Now substituting the values of T_1, T_2, T_3 and T_5 in equation (*i*),

$$\eta = 1 - \frac{T_4 \alpha \rho^{\gamma} - T_4}{\gamma [T_4 (r)^{\gamma-1} \alpha \rho) - T_4 (r)^{\gamma-1} \alpha] + [T_4 (r)^{\gamma-1} \alpha - T_4 (r)^{\gamma-1}]}$$

$$= 1 - \frac{T_4 (\alpha \rho^{\gamma} - 1)}{T_4 (r)^{\gamma-1} [\gamma (\alpha \rho - \alpha) + (\alpha - 1)]}$$

$$= 1 - \frac{(\alpha \rho^{\gamma} - 1)}{(r)^{\gamma-1} [\gamma \alpha (\rho - 1) + (\alpha - 1)]}$$

$$= 1 - \frac{1}{(r)^{\gamma-1}} \left[\frac{\alpha \rho^{\gamma} - 1}{(\alpha - 1) + \gamma \alpha (\rho - 1)}\right] \qquad \dots (vi$$

tes : 1. For Otto cycle, $\rho = 1$. Substituting this value in equation (*vi*),

$$\eta_{otto} = 1 - \frac{1}{(r)^{\gamma-1}} \qquad \dots \text{(Same as befor}$$

2. For Diesel cycle, $\alpha = 1$. Substituting this value in equation (*vi*),

$$\eta_{diesel} = 1 - \frac{1}{(r)^{\gamma-1}} \left(\frac{\rho^{\gamma} - 1}{\gamma (\rho - 1)}\right) \qquad \dots \text{(Same as befor}$$

3. The efficiency of dual combustion cycle is greater than Diesel cycle and less than Otto cycle, for th same compression ratio.

Example 6.21. *An oil engine, working on the dual combustion cycle, has a compressio ratio 10 and cut-off takes place at 1/10 of the stroke. If the pressure at the beginning of compressio is 1 bar and maximum pressure 40 bar, determine the air standard efficiency of the cycle. Take* $\gamma = 1.4$

Solution. Given : $r = v_4 / v_5 = 10$; Cut-off = 1/10 of stroke ; $p_4 = 1$ bar ; $p_1 = p_2 = 40$ bar ; $\gamma = 1.4$

Since the cut-off takes place at 1/10 of the stroke, therefore volume at cut-off,

$$v_2 = v_1 + 1/10 \text{ of stroke volume} = v_1 + \frac{1}{10}(v_4 - v_1)$$

$$= v_5 + 0.1 (v_4 - v_5) \qquad \dots (\because v_1 = v$$

$$\therefore \text{ Cut-off ratio,} \quad \rho = \frac{v_2}{v_5} = 1 + 0.1 \left(\frac{v_4}{v_5} - 1\right) \qquad \dots \text{(Dividing both sides by } v$$

$$= 1 + 0.1 (10 - 1) = 1.9$$

We know that for isentropic compression process 4-5 (Refer Fig. 6.15),

$$p_4 v_4^{\gamma} = p_5 v_5^{\gamma} \text{ or } p_5 = p_4 \left(\frac{v_4}{v_5}\right)^{\gamma} = 1 (10)^{1.4} = 25.12 \text{ bar}$$

$$\text{Pressure ratio,} \quad \alpha = p_1 / p_5 = 40 / 25.12 = 1.59$$

We know that air standard efficiency,

$$\eta = 1 - \frac{1}{(r)^{\gamma-1}}\left[\frac{\alpha\rho^{\gamma}-1}{(\alpha-1)+\gamma\alpha(\rho-1)}\right]$$

$$= 1 - \frac{1}{(10)^{1.4-1}}\left[\frac{1.59\,(1.9)^{1.4}-1}{(1.59-1)+1.4\times1.59\,(1.9-1)}\right]$$

$$= 1 - \frac{1}{2.512}\left[\frac{3.9-1}{0.59+2}\right] = 1 - 0.446 = 0.554 \text{ or } 55.4\,\% \textbf{ Ans.}$$

Example 6.22. *In a *compression ignition engine, working on a dual combustion cycle, pressure and temperature at the start of compression are 1 bar and 300 K respectively. At the end of compression, pressure reaches a value of 25 bar. 420 kJ of heat is supplied per kg of air during constant volume heating and pressure becomes 2.8 bar at the end of isentropic expansion. Estimate the ideal thermal efficiency. Take* c_p *= 1.005 kJ/kg K and* c_v *= 0.712 kJ/kg K.*

Solution. Given : $p_4 = 1$ bar ; $T_4 = 300$ K ; $p_5 = 25$ bar ; $Q_{5-1} = 420$ kJ/kg ; $p_3 = 2.8$ bar ; $c_p = 1.005$ kJ/kg K ; $c_v = 0.712$ kJ/kg K

We know that ratio of specific heats or isentropic index,

$$\gamma = c_p / c_v = 1.005 / 0.712 = 1.4$$

First of all, consider the isentropic compression process 4-5 (Refer Fig. 6.15).

We know that

$$p_4 v_4^{\gamma} = p_5 v_5^{\gamma}$$

∴ Compression ratio,

$$r = \frac{v_4}{v_5} = \left(\frac{p_5}{p_4}\right)^{\frac{1}{\gamma}} = \left(\frac{25}{1}\right)^{\frac{1}{1.4}} = (25)^{0.714} = 9.96$$

We also know that $\quad \dfrac{T_5}{T_4} = \left(\dfrac{v_4}{v_5}\right)^{\gamma-1} = (9.96)^{1.4-1} = 2.5$

$$\therefore \qquad T_5 = T_4 \times 2.5 = 300 \times 2.5 = 750 \text{ K}$$

Now consider the constant volume heating process 5-1. We know that heat supplied per kg of air (Q_{5-1}),

$$420 = m\,c_v\,(T_1 - T_5) = 1 \times 0.712\,(T_1 - 750)$$

$$\therefore \qquad T_1 - 750 = 420 / 0.712 = 590 \quad \text{or} \quad T_1 = 590 + 750 = 1340 \text{ K}$$

and pressure ratio, $\qquad \alpha = p_1 / p_5 = T_1 / T_5 = 1340 / 750 = 1.787 \quad \ldots\left(\because\ p_1 / T_1 = p_5 / T_5\right)$

$$\therefore \qquad p_1 = p_5 \times 1.787 = 25 \times 1.787 = 44.7 \text{ bar}$$

Now consider the isentropic expansion 2-3. We know that

$$p_2 v_2^{\gamma} = p_3 v_3^{\gamma} \quad \text{or} \quad \frac{v_2}{v_3} = \left(\frac{p_3}{p_2}\right)^{\frac{1}{\gamma}} = \left(\frac{2.8}{44.7}\right)^{\frac{1}{1.4}} = 0.138 \quad \ldots(\because\ p_2 = p_1)$$

and cut-off ratio, $$\rho = \frac{v_2}{v_1} = \frac{v_2}{v_5} = \frac{v_2}{v_3} \times \frac{v_3}{v_5} = \frac{v_2}{v_3} \times \frac{v_4}{v_5} \qquad \ldots (\because v_1 = v_5 \text{ and } v_3 = v_4$$

$$= 0.138 \times 9.96 = 1.37$$

We know that ideal thermal efficiency,

$$\eta = 1 - \frac{1}{(r)^{\gamma - 1}} \left[\frac{\alpha \rho^{\gamma} - 1}{(\alpha - 1) + \gamma \alpha (\rho - 1)} \right]$$

$$= 1 - \frac{1}{(9.96)^{1.4 - 1}} \left[\frac{1.787 (1.37)^{1.4} - 1}{(1.787 - 1) + 1.4 \times 1.787 (1.37 - 1)} \right]$$

$$= 1 - \frac{1}{2.51} \left[\frac{2.78 - 1}{0.787 + 0.926} \right] = 1 - 0.414 = 0.586 \text{ or } 58.6\,\% \text{ An}$$

INSTITUTE OF TEXTILE TECHNOLOGY
CHOUDWAR

Thermal Engineering-I

Chapter-6
Fuels and Combustion

Fuels

1. Introduction. 2. Classification of Fuels. 3. Solid Fuels. 4. Liquid Fuels. 5. Merits and Demerits of Liquid Fuels over Solid Fuels. 6. Gaseous Fuels. 7. Merits and Demerits of Gaseous Fuels. 8. Requirements of a Good Fuel. 9. Calorific Value of Fuels. 10. Gross or Higher Calorific Value. 11. Net or Lower Calorific Value. 12. Experimental Determination of Higher Calorific Value. 13. Bomb Calorimeter. 14. Boy's Gas Calorimeter.

11.1. Introduction

A fuel, in general terms, may be defined as a substance (containing mostly carbon and hydrogen) which, on burning with oxygen in the atmospheric air, produces a large amount of heat. The amount of heat generated is known as calorific value of the fuel.

As the principal constituents of a fuel are carbon and hydrogen, therefore, it is also known as hydrocarbon fuel. Sometimes, a few traces of sulphur are also present in it.

11.2. Classification of Fuels

The fuels may be classified into the following three general forms :

1. Solid fuels,
2. Liquid fuels, and
3. Gaseous fuels.

Each of these fuels may be further subdivided into the following two types :

(*a*) Natural fuels, and

(*b*) Prepared fuels.

11.3. Solid Fuels

The natural solid fuels are wood, peat, lignite or brown coal, bituminous coal and anthracite coal. The prepared solid fuels are wood charcoal, coke, briquetted coal and pulverised coal.

The following solid fuels are important from the subject point of view :

1. *Wood.* At one time it was extensively used as a fuel. It consists of mainly carbon and hydrogen. The wood is converted into coal when burnt in the absence of air. It is not considered as a commercial fuel, except in industries, where a large amount of waste wood is available. The calorific value of wood varies with its kind and moisture content. The average calorific value of the wood is 19 700 kJ/kg.

2. *Peat.* It is a spongy humid substance found in boggy land. It may be regarded as the first stage in the formation of coal. It has a large amount of water contents (upto 30%) and therefore has to be dried before use. It has a characteristic odour at the time of burning, and has a smoky flame. Its average calorific value is 23 000 kJ/kg.

3. *Lignite or brown coal.* It represents the next stage of peat in the coal formation, and is an intermediate variety between bituminous coal and peat. It contains nearly 40% moisture and 60% of carbon. When dried, it crumbles and hence does not store well. Due to its brittleness, it is conve into briquettes, which can be handled easily. Its average calorific value is 25 000 kJ/kg.

4. *Bituminous coal.* It represents the next stage of lignite in the coal formation and contains very little moisture (4 to 6%) and 75 to 90% of carbon. It is weather-resistant and burns with a yellow flame. The average calorific value of bituminous coal is 33 500 kJ/kg. The bituminous coal is of the following two types :

(*a*) Caking bituminous coal, and (*b*) Non-caking bituminous coal.

(*a*) *Caking bituminous coal* : It softens and swells on heating and its pieces adhere together forming a pasty mass which makes firing difficult. It burns with a fairly long flame. Its specific grav is 1.26 to 1.36. The caking variety is very useful for manufacturing gas. It is also known as soft coal. Its average calorific value is 35 000 kJ/kg.

(*b*) *Non-caking bituminous coal* : It burns with a shorter flame than the caking coal, and gives off little or no smoke. Its specific gravity is 1.22 to 1.42. The non-caking variety is mostly used as fuel for steam boilers, hence it is known as steam coal. Its average calorific value is 33 000 kJ/kg.

Note : The bituminous coal is non-caking, if its carbon content is 78 to 81%. If the percentage of carbon is to 82.5%, it is slightly caking. In medium caking bituminous coal, the carbon content is 82.5 to 84%. But if the carbon content is 84 to 89%, it makes the coal strongly caking.

5. *Anthracite coal.* It represents the final stage in the coal formation, and contains 90% or more carbon with a very little volatile matter. It is thus obvious, that the anthracite coal is comparatively smokeless, and has very little flame. It possesses a high calorific value of about 36 000 kJ/kg and is therefore, very valuable for steam raising and general power purposes.

6. *Wood charcoal.* It is made by heating wood with a limited supply of air to a temperature not less than 280° C. It is a good prepared solid fuel, and is used for various metallurgical processes.

7. *Coke.* It is produced when coal is strongly heated continuously for 42 to 48 hours in the absence of air in a closed vessel. This process is known as *carbonisation of coal.* Coke is dull black in colour, porous and smokeless. It has a high carbon content (85 to 90%) and has a higher calorific value than coal.

If the carbonisation of coal is carried out at 500 to 700° C, the resulting coke is called *low temperature coke* or *soft coke*. It is used as a domestic fuel. The coke produced by carbonisation of coal at 900 to 1100° C, is known as *hard coke*. The hard coke is mostly used as a blast furnace fuel for extracting pig iron from iron ores, and to some extent as a fuel in cupola furnace for producing cast iron.

8. *Briquetted coal.* It is produced from the finely ground coal by moulding under pressure with or without a binding material. The binding materials usually used are pitch, coal tar, crude oil and clay etc. The briquetted coal has the advantage of having, practically, no loss of fuel through grate openings and thus it increases the heating value of the fuel.

9. *Pulverised coal.* The low grade coal with a high ash content, is powdered to produce pulverised coal. The coal is first dried and then crushed into a fine powder by pulverising machines. The pulverised coal is widely used in the cement industry and also in metallurgical processes.

Note : Out of all the above mentioned types of solid fuels, anthracite coal is commonly used in all types of heat engines.

11.4. Liquid Fuels

Almost all the commercial liquid fuels are derived from natural petroleum (or crude oil). The crude oil is obtained from bore-holes in the earth's crust in certain parts of the world. The liquid fuels consist of hydrocarbons. The natural petroleum may be separated into petrol or gasoline, paraffin oil or kerosene, fuel oils and lubricating oils by boiling the crude oil at different temperatures and subsequent fractional distillation* or by a process such as cracking.** The solid products like vaseline and paraffin wax are recovered from the residue in the still.

The following liquid fuels are important from the subject point of view :

1. *Petrol or gasoline.* It is the lightest and most volatile liquid fuel, mainly used for light petrol engines. It is distilled at a temperature from 65° to 220° C.

2. *Kerosene or paraffin oil.* It is heavier and less volatile fuel than the petrol, and is used as heating and lighting fuel. It is distilled at a temperature from 220° to 345° C.

3. *Heavy fuel oils.* The liquid fuels distilled after petrol and kerosene are known as heavy fuel oils. These oils are used in diesel engines and in oil-fired boilers. These are distilled at a temperature from 345° to 470° C.

11.5. Merits and Demerits of Liquid Fuels over Solid Fuels

Following are the merits and demerits of liquid fuels over solid fuels :

Merits

1. Higher calorific value.
2. Lower storage capacity required.
3. Better economy in handling.
4. Better control of consumption by using valves.
5. Better cleanliness and freedom from dust.
6. Practically no ashes.
7. Non-deterioration in storage.
8. Non-corrosion of boiler plates.
9. Higher efficiency.

Demerits

1. Higher cost.
2. Greater risk of fire.
3. Costly containers are required for storage and transport.

11.6. Gaseous Fuels

The natural gas is, usually, found in or near the petroleum fields, under the earth's surface. It, essentially, consists of marsh gas or methane (CH_4) together with small amounts of other gases such as ethane (C_2H_6), carbon dioxide (CO_2) and carbon monoxide (CO).

The following prepared gases, which are used as fuels, are important from the subject point of view :

1. *Coal gas.* It is also known as a *town gas*. It is obtained by the carbonisation of coal and consists mainly of hydrogen, carbon monoxide and various hydrocarbons. The quality of coal gas depends upon the quality of the coal used, temperature of the carbonisaiton and the type of plant. It is very rich among combustible gases, and is largely used in towns for street and domestic lighting and heating. It is also used in furnaces and for running gas engines. Its calorific value is about 21 000 to 25 000 kJ/m^3.

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* It is the distillation by stages, *i.e.* distillation carried out in such a way so that the liquid with the lowest boiling point is first evaporated and recondensed. The liquid with the next higher boiling point is then evaporated and recondensed, and so on until all the available liquid fuels are separately recovered in the sequence of their boiling points.

** Cracking is a special process of heating crude oil to a high temperature under a very high pressure (exceeding 50 atmospheres) to increase the yield of lighter distillates, particularly petrol. The residue left after distillation by cracking is called cracked residue pressure tar and is used in road construction.

2. *Producer gas.* It is obtained by the partial combustion of coal, coke, anthracite coal or charcoal in a mixed air-steam blast. It is, mostly, used for furnaces particularly for glass melting and also for power generation. Its manufacturing cost is low, and has a calorific value of about 5000 to 6700 kJ/m^3.

3. *Water gas.* It is a mixture of hydrogen and carbon monoxide and is made by passing steam over incandescent coke. As it burns with a blue flame, it is also known as *blue water gas.*

The water gas is usually converted into carburetted (enriched) water gas by passing it through a carburetter into which a gas oil is sprayed. It is, usually, mixed with coal gas to form town gas. The water gas is used in furnaces and for welding.

4. *Mond gas.* It is produced by passing air and a large amount of steam over waste coal at about 650° C, It is used for power generation and heating. It is also suitable for use in gas engines. Its calorific value is about 5850 kJ/m^3.

5. *Blast furnace gas.* It is a by-product in the production of pig iron in the blast furnace. This gas serves as a fuel in steel works, for power generation in gas engines, for steam raising in boilers and for preheating the blast for furnace. It is extensively used as fuel for metallurgical furnaces. The gas, leaving the blast furnace, has a high dust content the proportion of which varies with the operation of the furnace. It has a low heating value of about 3750 kJ/m^3.

6. *Coke oven gas.* It is a by-product from coke oven, and is obtained by the carbonisation of bituminous coal. Its calorific value varies from 14 500 to 18 500 kJ/m^3. It is used for industrial heating and power generation.

11.7. Merits and Demerits of Gaseous Fuels

Following are the merits and demerits of the gaseous fuels :

Merits

1. The supply of fuel gas, and hence the temperature of furnace is easily and accurately controlled.
2. The high temperature is obtained at a moderate cost by pre-heating gas and air with heat of waste gases of combustion.
3. They are directly used in internal combustion engines.
4. They are free from solid and liquid impurities.
5. They do not produce ash or smoke.
6. They undergo complete combustion with minimum air supply.

Demerits

1. They are readily inflammable.
2. They require large storage capacity.

11.8. Requirements of a Good Fuel

Though there are many requirements of a good fuel, yet the following are important from the subject point of view :

1. A good fuel should have a low ignition point.
2. It should have a high calorific value.
3. It should freely burn with a high efficiency, once it is ignited.
4. It should not produce harmful gases.
5. It should produce least quantity of smoke and gases.
6. It should be economical, easy to store and convenient for transportation.

11.9. Calorific Value of Fuels

The calorific value (briefly written as C.V.) or heat value of a solid or liquid fuel may be defined as the amount of heat given out by the complete combustion of 1 kg of fuel. It is expressed in terms of kJ/kg of fuel. The calorific value of gaseous fuels is, however, expressed in terms of kJ/m^3 at a specified temperature and pressure.

Following are the two types of the calorific value of fuels :

1. Gross or higher calorific value, and 2. Net or lower calorific value.

These calorific values are discussed, in detail, in the following articles.

11.10. Gross or Higher Calorific Value

All fuels, usually, contain some percentage of hydrogen. When a given quantity of a fuel is burnt, some heat is produced. Moreover, some hot flue gases are also produced. The water, which takes up some of the heat evolved, is converted into steam. If the heat, taken away by the hot flue gases and the steam is taken into consideration, *i.e.* if the heat is recovered from flue gases and steam is condensed back to water at room temperature (15° C), then the amount of total heat produced per kg is known as *gross* or *higher calorific value of fuel*. In other words, the amount of heat obtained by the complete combustion of 1 kg of a fuel, when the products of its combustion are cooled down to the temperature of supplied air (usually taken as 15° C), is called the gross or higher calorific value of fuel. It is briefly written as H.C.V.

If the chemical analysis of a fuel is available, then the higher calorific value of the fuel is determined by the following formula, known as Dulong's formula :

$$\text{H.C.V.} = 33\,800\, C + 144\,000\, H_2 + 9270\, S \text{ kJ/kg} \qquad \ldots (i)$$

where C, H_2 and S represent the mass of carbon, hydrogen and sulphur in 1 kg of fuel, and the numerical values indicate their respective calorific values.

If the fuel contains oxygen (O_2), then it is assumed that the whole amount is combined with hydrogen having mass equal to 1/8th of that of oxygen. Therefore, while finding the calorific value of fuel, this amount of hydrogen should be subtracted.

$$\therefore \qquad \text{H.C.V.} = 33\,800\, C + 144\,000 \left(H_2 - \frac{O_2}{8} \right) + 9270\, S \text{ kJ/kg} \qquad \ldots (ii)$$

11.11. Net or Lower Calorific Value

When the heat absorbed or carried away by the products of combustion is not recovered (which is the case in actual practice), and the steam formed during combustion is not condensed, then the amount of heat obtained per kg of the fuel is known as *net* or *lower calorific value*. It is briefly written as L.C.V.

If the higher calorific value is known, then the lower calorific value may be obtained by subtracting the amount of heat carried away by products of combustion (especially steam) from H.C.V.

$$\therefore \qquad \text{L.C.V.} = \text{H.C.V.} - \text{Heat of steam formed during combustion}$$

Let $\qquad m_s$ = Mass of steam formed in kg per kg of fuel = $9\, H_2$

Since the amount of heat per kg of steam is the latent heat of vaporisation of water corresponding to a standard temperature of 15° C, is 2466 kJ/kg, therefore

$$\text{L.C.V} = \text{H.C.V.} - m_s \times 2466 \text{ kJ/kg}$$

$$= \text{H.C.V.} - 9\, H_2 \times 2466 \text{ kJ/kg} \qquad \ldots (\because m_s = 9\, H_2)$$

26.26. Rating of S.I. Engine Fuels--Octane Number

The hydrocarbon fuels used in spark ignition (S.I.) engine have a tendency to cause engine knock when the engine operating conditions become severe. The knocking tendency of a fuel in S.I. engines is generally expressed by its *octane number*. The percentage, by volume, of iso-octane in a mixture of iso-octane and normal heptane, which exactly matches the knocking intensity of a given fuel, in a standard engine, under given standard operating conditions, is termed as the *octane number rating* of that fuel. Thus, if a mixture of 50 percent iso-octane and 50 percent normal heptane matches the fuel under test, then this fuel is assigned an octane number rating of 50. If a fuel matches in knocking intensity a mixture of 75 percent iso-octane and 25 percent normal heptane, then this fuel would be assigned an octane number rating of 75. This octane number rating is an expression which indicates the ability of a fuel to resist knock in a S.I. engine.

Since iso-octane is a very good anti-knock fuel, therefore it is assigned a rating of 100 octane number. On the other hand, normal heptane has a very poor anti-knock qualities, therefore it is given a rating of 0 (zero) octane number. These two fuels, *i.e.* iso-octane and normal heptane are known as primary reference fuels. It may be noted that higher the octane number rating of a fuel, the greater will be its resistance to knock and the higher will be the compression ratio. Since the power output and specific fuel consumption are functions of compression ratio, therefore we may say that these are also functions of octane number rating. This fact indicates the extreme importance of the octane number rating in fuels for S.I. engines.

26.27. Rating of C.I. Engine Fuels--Cetane Number

The knocking tendency is also found in compression ignition (C.I.) engines with an effect similar to that of S.I. engines, but it is due to a different phenomenon. The knock in C.I. engines is due to sudden ignition and abnormally rapid combustion of accumulated fuel in the combustion chamber. Such a situation occurs because of an ignition lag in the combustion of the fuel between the time of injection and the actual burning.

The property of ignition lag is generally measured in terms of *cetane number*. It is defined as the percentage, by volume, of cetane in a mixture of cetane and alpha-methyl-naphthalene that produces the same ignition lag as the fuel being tested, in the same engine and under the same operating conditions. For example, a fuel of cetane number 50 has the same ignition quality as a mixture of 50 percent cetane and 50 percent alpha-methyl-naphthalene.

The cetane which is a straight chain paraffin with good ignition quality is assigned a cetane number of 100 and alpha-methyl-naphthalene which is a hydrocarbon with poor ignition quality, is assigned a 0 (zero) cetane number.

Note : The knocking in C.I. engines may be controlled by decreasing ignition lag. The shorter the ignition lag, the less is the tendency to knock.