

Thermodynamics

THERMODYNAMIC SYSTEM & SURROUNDINGS

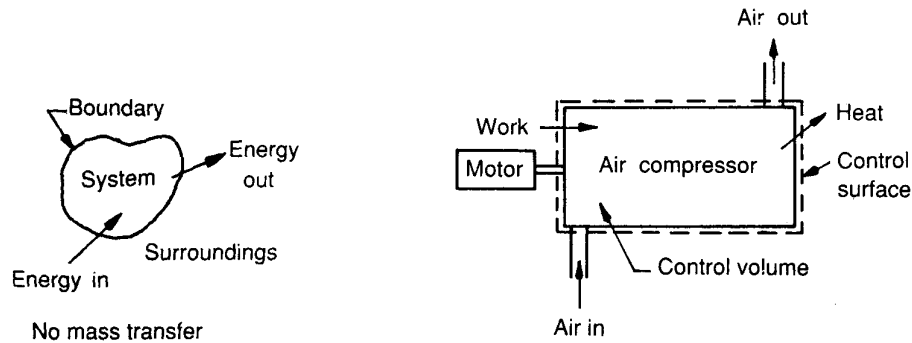
A thermodynamic system may be considered as a quantity of working substance with which heat and work interactions are studied. The envelope enclosing the system, which may be real or hypothetical is known as boundary of the system. The region outside the system is known as surroundings. The transfer of mass and energy take place between the system and surroundings.

Thermodynamic system are classified as

- (a) closed (b) open (c) isolated

Closed System (Non Flow System)

A good example of closed system is a piston and cylinder as shown in figure given below:

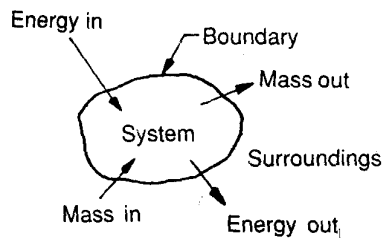


Closed systems

No mass can flow in or out, only heat or work or both may flow into and out of the closed system. If heat is supplied to the cylinder from external source, the volume of the gas increases and the piston moves up. Work transfer occurs due to the movement of the boundary of the system.

Open System (Flow System)

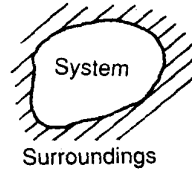
In open system, the working substances used crosses the boundary of the system. Heat and work may also cross the boundary. (see fig.)



The system turbine, gas turbine and rotary compressor are good examples of open system.

Isolated System

An isolated system has no mass or energy interactions with the surroundings. Though such a system has no practical interest, it is a useful concept in the study and analysis of thermodynamics principles.

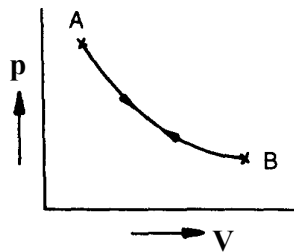


No mass or energy
transfer

An isolated system

REVERSIBLE OR IRREVERSIBLE PROCESSES

A process is said to be *reversible* if the reversal of the process does not leave any trace on the system or the surroundings. For example, if during a process from state A to B as shown in figure given below, the work and heat transfers are W and Q and if by supplying back W and Q to the system, the state of the system can be brought back from B to A, the process is said to be reversible.



If there is any change in the requirement of work and heat to bring back the system from state B to A, the process becomes *irreversible*. The processes used in practice are mostly *irreversible* due to friction, heat transfer and mixing, but in many cases idealization is used for analysis.

PRESSURE

The standard atmospheric pressure is defined as the pressure produced by a column of mercury 769 mm high. The standard atmospheric pressure is 1.0332 kgf/cm² and is denoted by atm. In S.I. units, it is expressed in N/m² or Pascal abbreviated as Pa. Various pressure units are

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

$$1 \text{ bar} = 10^5 \text{ Pa} = 100 \text{ kPa} = 0.1 \text{ MPa}$$

$$1 \text{ atm} = 101.325 \text{ kPa} = 1.01325 \text{ bar}$$

$$1 \text{ metre mercury head} = 1.3366 \text{ bar}$$

The pressure relative to a perfect vacuum is called *absolute pressure*.

$$\text{Abs. pressure} = \text{gauge pressure} + \text{atmospheric pressure}$$

When the pressure in a system is less than atmospheric pressure, the gauge pressure becomes negative, but is frequently designated by a positive number and called *vacuum*. For example, 16 mm vacuum will be

$$\frac{76-16}{76} \times 1.013 = 0.80 \text{ bar}$$

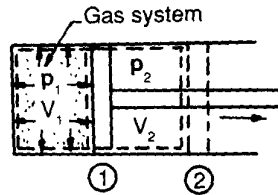
WORK, POWER & ENERGY

Work is said to be done when a force acts upon a body causing that body to move along the direction of the force. The work done given by the product of force and distance travelled by the body along the direction of the force.

$$W = \text{Force (F)} \times \text{Distance (S)}$$

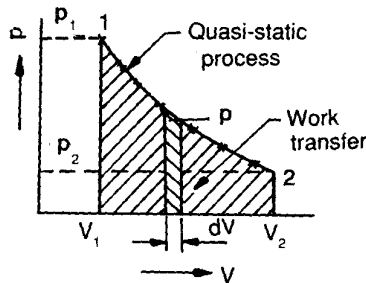
If a force of 1 N acts on a body causing 1 m displacement, the work done on the body is given by

$$W = 1 \text{ N} \times 1 \text{ m} = 1 \text{ N-m}$$



Consider a closed system of a piston and cylinder as shown in Fig. given above. The net pressure of the gas in the system causes the piston to move in the forward direction. The force acting on the piston is $p.A$, where A is the area of the piston, if the piston moves through a small distance dx , the work done by the gas on the piston = $p.A \, dx = p.dv$ as $A.dx$ is the change in the volume of the gas. If the gas expands from state 1 to 2 as shown in the figure, the work done is given by,

$$W = \int_{v_1}^{v_2} p.dv$$



Hence we see that work done is equal to $\int p \, dv$ under following conditions:

- System is closed and process takes place in non flow system
- Process is quasi static (reversible)
- Boundary of the system should move in order that work may be transferred

Power is the rate at which work is done. The common unit of power is watt (W), kilowatt (kW) or megawatt (MW).

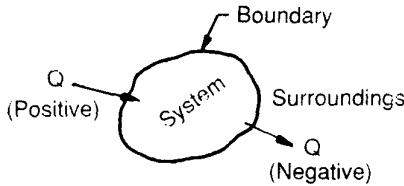
$$1 \text{ W} = 1 \text{ J/s} = 1 \text{ Nm/s}$$

$$1 \text{ kW} = 1000 \text{ W}$$

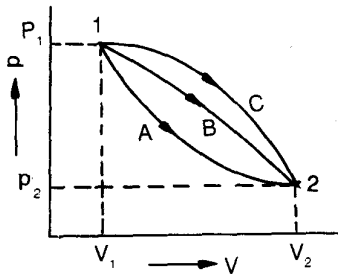
Energy may exist in the form of potential energy, mechanical work or heat. The unit of energy is N-m or J in S.I. units.

Heat is defined as the energy transferred without transfer of mass across the boundary of a system due to a temperature difference between the system and surroundings.

The direction of heat transfer is taken from the high temperature system to the low temperature system. *Heat flow into a system is taken to be positive, and heat flow out of a system is taken as negative.*



The amount of heat transferred during a process or work done by the system during the same process is dependent on the path followed during the process. Though the end conditions are same. as shown in figure below.



The heat exchange and work done during the processes will be different for the two different paths. Thus heat and work are said to be *path functions* and *not* point functions (or properties).

The unit of heat in MKS system is *kcal* which is defined as the quantity of heat required to raise the temperature of 1 kg water through 1°C. The unit of heat in S.I. system is *Joule* which is equivalent to 1 N-m.

Heat energy is generally transferred in three ways:

- **Conduction** (propagation of heat by molecular activity without actual transfer of molecules).
- **Convection** (heat transfer in fluids only by molecular collisions between hotter and cooler molecules, which lead to development of convection currents).
- **Radiation** (no medium is required for heat transfer, e.g. heating of earth surface by solar radiation).

INTERNAL ENERGY

Matter is composed of molecules which move continuously and randomly. In gases, movement of the molecules is more pronounced than in solids and liquids. Matter possesses internal kinetic energy due to the motion of its molecules. In addition to this internal K.E., matter has internal potential energy due to relative position of their molecules. The sum of these two energies is known as *specific internal energy (or simply internal energy)* and it is denoted by *u*, the unit commonly used being *J/kg* or *kJ/kg*. If the temperature of a gas is increases by adding heat, the molecular activity increases. Therefore the internal energy of a

gas is a function of its temperature and its value can be increased or decreased by adding or removing heat from the gases which are commonly used as working fluids.

Total internal energy is denoted by U , its unit is J or kJ.

ENTHALPY

Enthalpy (H) of a substance at any point is quantification of energy content in it, which could be given by summation of internal energy and flow energy. Enthalpy is very useful thermodynamic property for the analysis of engineering systems.

Mathematically, it is given as,

$$H = U + PV$$

On unit mass basis, the specific enthalpy could be given as,

$$h = u + pv$$

FIRST LAW OF THERMODYNAMICS

The law of conservation of energy states that the energy can neither be created nor destroyed. However, energy can be converted from one form to another form. The first law of thermodynamics is a particular and a more rigorous statement of this general principle with reference to energy in the form of heat and mechanical work.

The first law of thermodynamics states that heat and work are mutually convertible. It does not say anything about the possibility and method of conversion of heat into work or work into heat. It simply states that “Q” J of heat is equivalent to “W” N-m of work. This establishes a relation between work energy and heat energy. This relation was first established by Joule and the conversion factor is denoted by J and its value is 1 Newton/Joule. This simply indicates that 1 N-m mechanical work is equivalent to 1 joule of heat.

The first law of thermodynamics can be stated:

When a system undergoes a thermodynamics cycle, the net heat supplied to the system from its surroundings is equal to the net work done by the system on its surroundings.

Symbolically, the above statement is represented as $dQ = dW$

Energy Equation for Non-Flow System (Closed System)

Now, consider a process, during which, the internal energy of the fluid in a closed system is increased, the conservation of energy equation can be written as

$$\text{Net heat supplied} = \text{gain in internal energy} + \text{Net work output}$$

This can also be stated as

$$Q = \Delta E + W = m(u_2 - u_1) + W$$

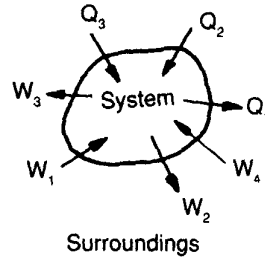
where $J = 1 \text{ N-m/Joule}$ and $u_1, u_2 = \text{internal energies in J/kg}$

This is applicable for non-flow reversible or irreversible process

$$Q = m(u_2 - u_1) + \int_1^2 p \cdot dv$$

This is applicable only for non-flow reversible processes.

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



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

First Law Of Thermodynamics Applied To Open Systems

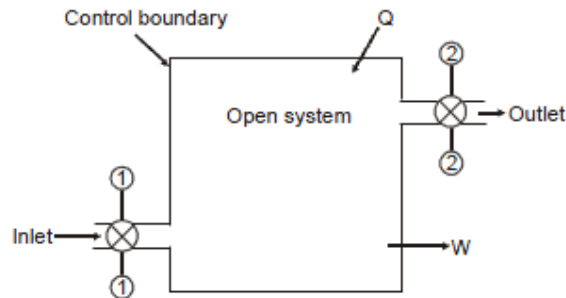
Let us consider an open system as shown in figure having inlet at section 1-1 and outlet at section 2-2.

The cross-section area, pressure, specific volume, mass flow rate, energy at section 1-1 and 2-2 are

Section 1-1 = A_1, p_1, v_1, m_1, e_1

Section 2-2 = A_2, p_2, v_2, m_2, e_2

Open system is also having heat and work interactions Q, W as shown in figure.



Applying the energy balance at the two sections, it can be given as,

Energy added to the system + Stored energy of the fluid at inlet

= Stored energy of the fluid at outlet

Quantifying the various energies;

Energy of fluid at inlet shall comprise of stored energy and flow energy as given here.

$$= m_1(e_1 + p_1 v_1)$$

Similarly, energy of fluid at outlet shall comprise of stored energy and flow energy,

= Stored energy + Flow energy

$$= m_2 (e_2 + p_2 v_2)$$

The energy added to the system shall be the net energy interaction due to heat and work interactions.

$$= Q - W$$

Writing energy balance, mathematically;

$$Q - W + m_1 (e_1 + p_1 v_1) = m_2 (e_2 + p_2 v_2)$$

or
$$Q + m_1(e_1 + p_1 v_1) = W + m_2(e_2 + p_2 v_2)$$

A PREPARATORY COURSE FOR J.E. LEVEL EXAMS

THERMODYNAMICS

A FOCUSED APPROACH

If the mass flow rates at inlet and exit are same, then

$$Q + m(e_1 + p_1 v_1) = W + m(e_2 + p_2 v_2)$$

On unit mass basis

$$q + e_1 + p_1 v_1 = w + e_2 + p_2 v_2$$

Thus,

$$\text{Heat} + (\text{Stored energy} + \text{Flow energy})_1 = \text{Work} + (\text{Stored energy} + \text{Flow energy})_2$$

Stored energy at inlet and outlet can be mathematically given as,

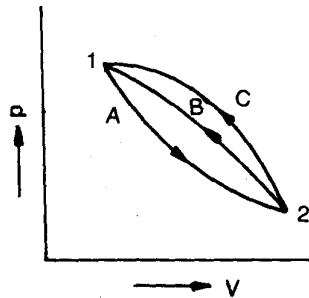
$$e_1 = u_1 + \frac{C_1^2}{2} + gz_1$$

and
$$e_2 = u_2 + \frac{C_2^2}{2} + gz_2$$

where C_1 and C_2 are velocities at inlet and exit, u_1 and u_2 are internal energy at inlet and outlet, z_1 and z_2 are elevations of inlet and exit.

Energy - A property of the system

Consider following diagram



For path A

$$Q_A = \Delta E_A + W_A$$

For path B

$$Q_B = \Delta E_B + W_B$$

Combining two cycles

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

or
$$W_A + W_B = Q_A + Q_B$$

i.e.
$$Q_A - W_A = W_B - Q_B$$

i.e.
$$\Delta E_A = -\Delta E_B$$

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

$$\Delta E_A = -\Delta E_C$$

Also
$$\Delta E_B = \Delta E_C$$

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. Further, energy has a definite value for every state of the system.

Example

- (i) *Is the first law of thermodynamics applicable to irreversible processes ?*
(ii) *State the important consequences of the first law of thermodynamics.*

Solution

- (i) The first law of thermodynamics is applicable to all types of processes-reversible as well as irreversible.
(ii) The first law of thermodynamics leads to the following important consequences.
1. Heat interaction is a path function.
 2. Energy is a property of a thermodynamic system.
 3. The energy of an isolated system is conserved.
 4. A perpetual motion machine of the first kind is impossible.

Example

Show that the first law of thermodynamics implies that a Perpetual Motion Machine of the First Kind (PMMFK) is impossible

Solution

We know that the macroscopic modes of energy can be converted from one form to the other and work can be obtained. However, the microscopic modes of energy cannot be readily converted into macroscopic modes of energy. An important application of thermodynamics is to devise means of converting the microscopic modes of energy into the macroscopic modes of energy. For this purpose heat engines which work cyclically are devised. The first law of thermodynamics when applied to a cyclic process gives

$$\oint (dQ - dW) = 0$$

or $\oint dQ = \oint dW$

or $Q = W$

where Q is the net heat interaction and W is the net work delivered.

An imaginary device which would deliver work continuously without absorbing energy as heat is called a **Perpetual Motion Machine** of the First Kind (PMMFK). A perpetual motion machine of the first kind has to operate on a cycle to deliver work continuously. If the device does not absorb any energy as heat in a cycle, then $\int dQ = Q = 0$. Then the first law of thermodynamics tells that for such a device $\int dW = W = 0$. Thus, the first law of thermodynamics implies that it is impossible to devise a PMMFK. A PMMFK violates the first law of thermodynamics.

State the limitations of the first law of thermodynamics with the help of examples involving heat and work interactions.

Solution

We know that kinetic energy and potential energy are interconvertible and the macroscopic modes of energy (KE and PE) can be readily converted into work. The conversion of microscopic modes of energy (that is energy associated with the random molecular motion of the matter) or internal energy into work requires a device called heat engine. Is it possible for the complete conversion of internal energy into work in a heat engine? Or is it possible to devise a heat engine, the efficiency (defined as the ratio of the net work done to the energy absorbed) of which is equal to one? Is it possible to transfer energy as heat spontaneously from a body at a lower temperature to a body at a higher temperature? All the above questions which deal with work and heat interactions cannot be answered by the application of the first law of thermodynamics and hence they reflect the limitations of the first law thermodynamics.

Example

A stationary mass of gas is compressed without friction from an initial state of 0.3 m³ and 0.105 MPa to a final state of 0.15 m³ 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 $Q_{1-2} = U_2 - U_1 + W_{1-2}$

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

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

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

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

\therefore 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

In a closed system

(a) *17 kJ of heat is added to the system whilst 8 kN-m of work is performed by the system, determine the change in internal energy of the system.*

(b) *16 kN-m work is performed by the system and no heat transfer occurs, determine the change in internal energy.*

- (c) 105 kJ of heat is transferred to the system and 20 kN-m of work is performed on the system, determine the change in internal energy,
- (d) 21 kJ of heat is added and no change in internal energy occurs, determine the work done by the system.

Solution

We can apply the energy equation as obtained from the first law of thermodynamics applied to a closed system, i.e.

$$Q = W + \Delta U$$

Heat Q should be taken positive if it is supplied to the system, and negative if rejected by the system. Work W should be taken positive if it is developed by the system and negative if supplied to the system.

(a) $Q = W + \Delta U$

$$\Rightarrow 17000 = 8000 + \Delta U \quad (J = 1 \text{ N-m/J})$$

$$\therefore \Delta U = \frac{17000 - 8000}{1000} = 9 \text{ kJ} \quad (\text{increase})$$

(b) $Q = W + \Delta U$

$$\Rightarrow 0 = 16000 + \Delta U \Rightarrow \Delta U = -16 \text{ kJ} (\text{decrease})$$

(b) $Q = W + \Delta U$

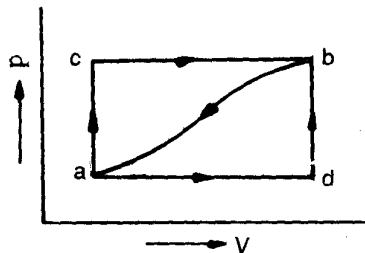
$$\Rightarrow 105 = -20 + \Delta U \quad \Delta U = 105 + 20 = 125 \text{ kJ} \quad (\text{increase})$$

(d) $Q = W + \Delta U$

$$\Rightarrow 21 = \frac{W}{J} + 0 \quad W = 21 \text{ kN-m (work developed by the system)}$$

Example

When a system is taken from state a to state b , in figure, 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? 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 $U_b = 42$ kJ, find the heat absorbed in the processes ad and db .



Solution

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

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

We have

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

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

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

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

The system liberates 73 kJ of heat.

$$\text{(c)} \quad W_{adb} = W_{ad} + W_{db} = W_{ad} = 10.5 \text{ kJ}$$

$$Q_{ad} = U_d - U_a + W_{ad}$$

$$42 - 0 + 10.5 = 52.5 \text{ kJ}$$

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

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

Problem

A gas undergoes a thermodynamic cycle consisting of three processes beginning at an initial state where $p_1 = 1 \text{ bar}$, $V_1 = 1.5 \text{ m}^3$ and $U_1 = 512 \text{ kJ}$. The processes are as follows:

- (i) Process 1-2: compression with $pV = \text{constant}$ to $p_2 = 2 \text{ bar}$, $U_2 = 690 \text{ kJ}$
- (ii) Processes 2-3: $W_{23} = 0$, $Q_{23} = -150 \text{ kJ}$, and
- (iii) Process 3-1: $W_{31} = +50 \text{ kJ}$. Neglecting KE and PE change, determine the heat interaction Q_{12} and Q_{31} .

Answer: 74 kJ, 22 kJ

Problem

A mass of 8 kg gas expands within a flexible container so that the p - v relationship is of the form $pv^{1.2} = \text{const}$. The initial pressure is 1000 kPa and the initial volume is 1 m³. The final pressure is 5 kPa. If specific internal energy of the gas decreases by 40 kJ/kg, find the heat transfer in magnitude and direction.

Answer: +2615 kJ

SPECIFIC HEAT

Specific heat of a substance is the amount of heat that must be added to unit mass of the substance to raise the temperature through 1°C. The symbol “c” will be used for specific heat.

$$c(\text{or } C) = \frac{Q}{m \cdot \Delta t} \text{ J/kgK}$$

Gases have two specific heats, namely, specific heat at constant volume and specific heat at constant pressure.

Specific heat at constant volume (C_v): The amount heat required in kJ to raise the temperature of 1 kg of the gas through 1 K at constant volume is known as specific heat at constant volume. There is no work of expansion as the gas volume remains constant, and , therefore, all the heat supplied is used to increase its internal energy.

Specific heat at constant pressure (C_p): The amount of heat required in kJ to raise the temperature of 1 kg of the gas through 1 K at constant pressure is known as specific heat at constant pressure.

When the gas is heated at constant pressure, it gets expanded and moves the piston through a distance L , therefore in addition to the heat required to increase the kinetic energy of the molecule, further heat must be added to perform the work of moving the piston through a distance L . Therefore, the specific heat of a gas at constant pressure is always greater than the specific heat at constant volume by an amount equivalent to expansion work.

The ratio of two specific heats, C_p and C_v of any gas is assumed to a constant and this is expressed by the symbol γ (gamma),

$$\gamma = \frac{C_p}{C_v} = \frac{1.004}{0.715} = 1.4 \text{ for all}$$

The relation between two specific heats is given by

$$C_p - C_v = R$$

Where, R is known as characteristic gas constant.

Example

The specific heat of a gas at constant volume is 3.15 kJ/kg-°C and the ratio of specific heats $\gamma = 1.66$ for the same gas. If 1.5 kg of this gas is heated from 50°C to 350°C at constant pressure, determine heat supplied to the gas in kJ.

Solution

We know that

$$\gamma = \frac{C_p}{C_v}$$

$$\therefore C_p = \gamma \times C_v = 1.66 \times 3.15 = 5.23 \text{ kJ/kg-°C}$$

Heat supplied to the gas at constant pressure

$$= m \cdot C_p \cdot (T_2 - T_1) = 1.5 \times 5.23 \times (350 - 50) = 2353 \text{ kJ} \quad \text{Ans.}$$

SECOND LAW OF THERMODYNAMICS

According to the first law of thermodynamics, from 1 N-m of work, one joule of heat can be obtained and 1 N-m of work can be obtained from 1 Joule of heat if so converted. But the general observation is that while work can be completely converted to heat, but it is not possible to convert heat completely into work. It becomes necessary for any heat engine to reject some of the heat it receives during the cycle to the surroundings even if an ideal engine is considered. The limitation of the first law is that it does not simply unidirectional phenomenon concerned with energy conversion.

It is observed in the nature that heat by itself never flows from an object at a lower temperature to one at a higher temperature, in the same way that a river never flows by itself uphill. These observations are the basis of the second law of thermodynamics. The second law of thermodynamics states the possibility and extent of transformation of heat into work. The different statements of second law of thermodynamics are given below.

Kelvin Plank Statement

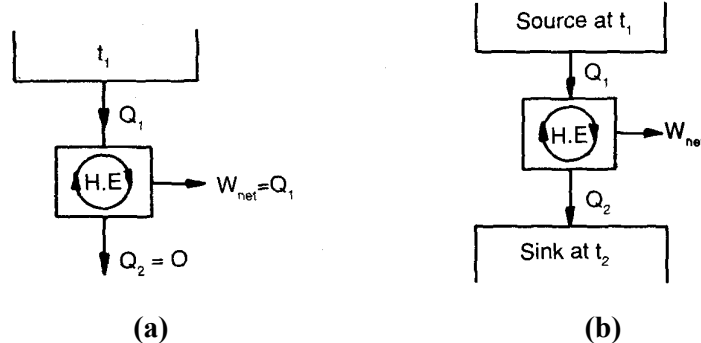
It states that it is impossible to construct an engine working in a cyclic process, whose sole effect is the conversion of all the heat supplied to it into an equivalent amount of work.

$$\eta = \frac{W_{\text{net}}}{Q_1} = 1 - \frac{Q_2}{Q_1}$$

Practically $W_{\text{net}} < Q_1$. Hence *an engine can not be 100% efficient.*

If $Q_2 > 0$, there will always be *heat rejection*.

If $Q_2 = 0$, then $\eta = 1$ (100%), then *we get perpetual motion machine (PMM). PMM is impossible.* Figure (a) shows a PMM.



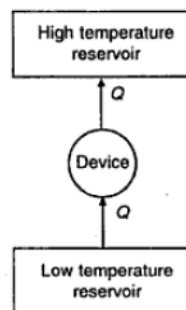
A heat engine has, therefore, to exchange heat with two thermal energy reservoirs at two different temperatures to produce net work in a complete cycle (figure b). Motive power can be produced till there is *no* difference of temperature.

Clausius' Statement

It is impossible to construct a device working in cyclic process whose sole effect is transfer of heat from a body at a lower temperature to a body of higher temperature.

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.

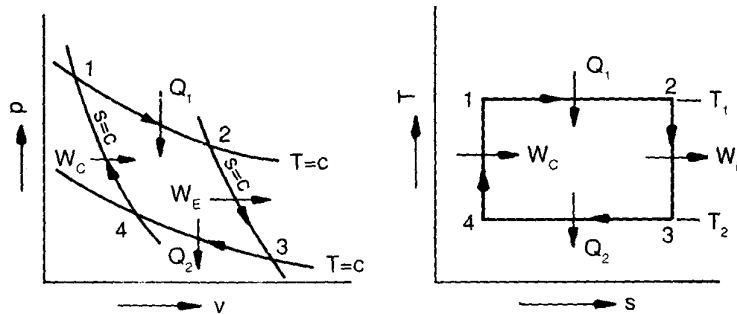
A schematic of the device which is impossible to devise according to the Clausius statement of the second law of thermodynamics is shown in figure.



We know that the transfer of energy as heat from a high temperature body to a low temperature body occurs spontaneously. The Clausius statement of the second law of thermodynamics denies the possibility of self reversal of such a spontaneous process. In other words the second law of thermodynamics dictates the direction of a spontaneous process. The coefficient of performance of the device shown in given figure is given by $COP = Q/W = Q/0 = \infty$. Thus the second law of thermodynamics implies that the COP of a heat pump or refrigerator cannot be infinity.

Carnot Cycle

The second law of thermodynamics states that *only a part of the heat supplied to the heat engine can be converted into work*. Naturally the next step is to examine the practical means for doing so and analyse their effectiveness. Carnot postulated that the most efficient engine is a *reversible* engine and he devised such an engine working on a cycle known as *Carnot cycle*. All the constituent processes of the cycle are reversible processes as shown in figure given below on p-v and T-s diagram.



Carnot cycle

1. The process 1-2 represents isothermal expansion of the working fluid in the cylinder.
2. The process 2-3 represents isentropic expansion of the working fluid.
3. The process 3-4 represents isothermal compression, and
4. The process 4-1 represents isentropic compression till the fluid reaches its original condition completing the cycle.

The efficiency of the cycle is given by

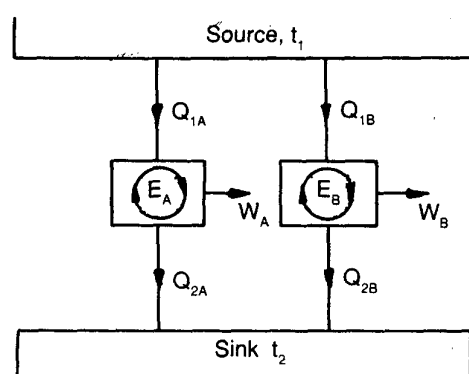
$$\eta = \frac{W_{\text{net}}}{Q_1} = \frac{T_1 - T_2}{T_1}$$

Carnot efficiency is the highest possible efficiency of a heat engine. The efficiency is also independent of the type of the fluid used. Therefore it is considered as a standard of comparison for heat engine performance.

Carnot Theorem

It states that of all heat engines operating between a given constant temperature source and a given constant temperature sink, none has a higher efficiency than a reversible engine.

Proof. Let two heat engines E_A and E_B operate between the given source at temperature t_1 and the given sink at temperature t_2 as shown in figure (a).



Let E_A be any heat engine and E_B be any reversible heat engine. We have to prove that the efficiency of E_B is more than that of E_A . Let us assume that this is not true and $\eta_A > \eta_B$. Let the rates of working of the engines be such that

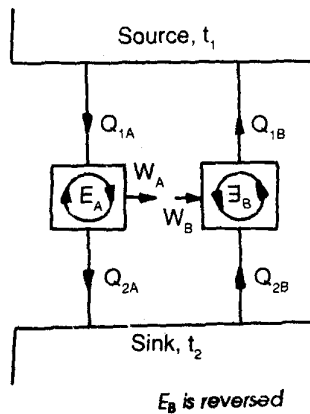
$$Q_{1A} = Q_{1B} = Q_1$$

Since $\eta_A > \eta_B$

$$\frac{W_A}{Q_{1A}} > \frac{W_B}{Q_{1B}}$$

$\therefore W_A > W_B$

Now, let E_B be reversed. Since E_B is a reversible heat engine, the magnitudes of heat and work transfer quantities will remain the same, but their directions will be reversed, as shown in figure (b).



Since $W_A > W_B$, some part of W_A (equal to W_B) may be fed to drive the reversed heat engine Ξ_B .

Since $Q_{1A} = Q_{1B} = Q_1$, the heat discharged by Ξ_B may be supplied to E_A . The source may, therefore, be eliminated (figure c). The net result is that E_A and Ξ_B together constitute a heat engine which, operating in a cycle, produces net work $W_A - W_B$, while exchanging heat with a single reservoir at t_2 . This violates the Kelvin-Planck statement of the second law. Hence the assumption that $\eta_A > \eta_B$ is wrong.

Therefore $\eta_B \geq \eta_A$

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

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

or

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

The COP (Coeff. of Performance) of a refrigerator is given by

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

For a reversible refrigerator, using

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

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

Similarly, for a reversible heat pump

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

Example

Distinguish between reversible and irreversible processes and give some examples of irreversible processes.

Solution

A process is said to be reversible if both the system and its surroundings can be restored to their respective initial states by reversing the direction of the process. If a process does not satisfy the above criterion, it is an irreversible process.

Examples of irreversible processes are :

- Expansion or compression with finite pressure difference.
- Energy transfer as heat with finite temperature difference.
- Free expansion of a gas.
- Mixing of non identical gases.
- Mixing of matter at different states.
- Motion with friction.
- Viscous fluid flow.
- Spontaneous chemical reactions.

Example

What is the importance of reversible processes in engineering thermodynamics ?

Solution

A reversible process is an idealization. This is a concept which can be approximated closely at times by actual devices, but never followed.

The presence of friction, inelasticity and electrical resistance makes the processes irreversible. These elements can be reduced but cannot be completely eliminated. The presence of these elements of irreversibility makes a process irreversible. Since the real processes occur when these elements of irreversibility are present, the reversible process is a limiting process toward which all actual processes may approach in performance. The reversible processes deliver maximum work in engines and require minimum work in devices such as refrigerators, compressors etc. A thermodynamic analysis based on idealized reversible processes provides the limiting performance of the devices, against which the actual performance can be compared. This in turn provides an opportunity to improve the performance of the devices by reducing the sources of irreversibility.

Example

Give the criteria of reversibility, irreversibility and impossibility of a thermodynamic cycle.

Solution

Since the second law of thermodynamics distinguishes between reversible and irreversible processes, one can use the following criterion to identify a reversible process. If a process can proceed in either direction without violating the second law of thermodynamics, then it is a reversible process. Suppose a process is proceeding in one direction and the assumption of reversibility of the process leads to a violation of the second law of thermodynamics, then the process can be called irreversible.

Example

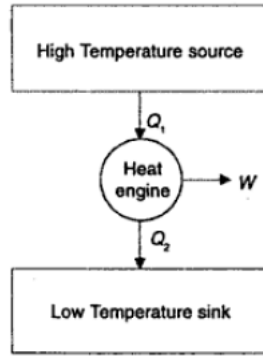
What is meant by a heat engine and what are its characteristics ?

Solution

A heat engine is an energy conversion device. It is a cyclically operating device and its primary objective is to convert the energy received as heat into work. It employs a working fluid which undergoes cyclic change. The working fluid absorbs energy as heat from a source and rejects energy as heat to a sink. The characteristics of a heat engine are :

- It is a cyclically operating device.
- Its primary purpose is to convert energy absorbed as heat into work.
- It absorbs energy as heat from a high temperature source.
- It rejects energy as heat to a low temperature sink.
- It delivers some net work.

A heat engine can be represented as shown in figure.



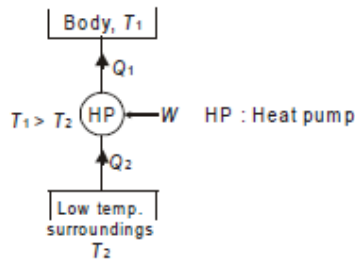
Example

Explain (i) heat pump (ii) refrigerator

Solution

Heat Pump

Heat pump refers to a device used for extracting heat from a low temperature surroundings and sending it to high temperature body, while operating in a cycle. In other words *heat pump maintains a body or system at temperature higher than temperature of surroundings*, while operating in cycle. Block diagram representation for a heat pump is given below:



As heat pump transfers heat from low temperature to high temperature, which is non spontaneous process, so external work is required for realizing such heat transfer. Heat pump shown picks up heat Q_2 at temperature T_2 and rejects heat Q_1 for maintaining high temperature body at temperature T_1 .

For causing this heat transfer heat pump is supplied with work W as shown.

As heat pump is not a work producing machine and also its objective is to maintain a body at higher temperature, so its performance can't be defined using efficiency as in case of heat engine. Performance of heat pump is quantified through a parameter called coefficient of performance (C.O.P). Coefficient of performance is defined by the ratio of desired effect and net work done for getting the desired effect.

$$COP = \text{desired effect/Net work done}$$

For heat pump :

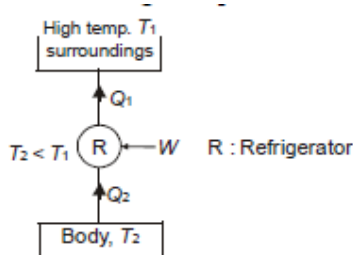
$$\text{Net work} = W$$

Desired effect = heat transferred Q_1 to high temperature body at temperature, T_1 .

$$COP = \frac{Q_1}{W} = \frac{Q_1}{Q_1 - Q_2}$$

Refrigerator

Refrigerator is a device similar to heat pump but with reverse objective. It maintains a body at temperature lower than that of surroundings while operating in a cycle. Block diagram representation of refrigerator is shown in given figure.



Refrigerator also performs a non spontaneous process of extracting heat from low temperature body for maintaining it cool, therefore external work W is to be done for realizing it.

Block diagram shows how refrigerator extracts heat Q₂ for maintaining body at low temperature T₂ at the expense of work W and rejects heat to high temperature surroundings.

Performance of refrigerator is also quantified by coefficient of performance, which could be defined as:

$$COP_{ref} = \frac{\text{desired effect}}{\text{net work}} = \frac{Q_2}{W} = \frac{Q_2}{Q_1 - Q_2}$$

COP values of heat pump and refrigerator can be interrelated as:

$$COP_{hp} = COP_{ref} + 1$$

Example

A reversible engine receives heat from a reservoir at 700°C and rejects the heat at temperature T₂. A second reversible engine receive heat reject by the first engine and reject to the sink at 37°C. Determine the temperature T₂ if (a) both the engines give same thermal efficiency (b) both the engines develop same power.

Solution

(a) For equal efficiency condition

$$\frac{T_1 - T_2}{T_1} = \frac{T_2 - T_3}{T_2}$$

$$\frac{973 - T_2}{973} = \frac{T_2 - 310}{T_2}$$

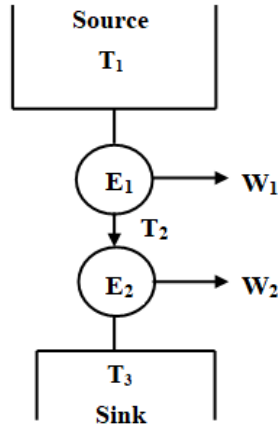
Gives on solving, T = 549.2 K

(b) The work-output of any reversible engine is proportional to the temperature difference between source and sink,

$$W_1 = K \cdot (T_1 - T_2)$$

$$W_2 = K \cdot (T_2 - T_3)$$

For the given condition.



$$W_1 = W_2$$

$$T_1 - T_2 = T_2 - T_3$$

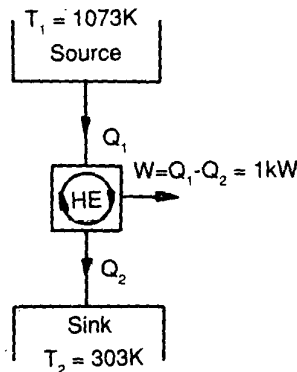
$$\Rightarrow T_2 = \frac{T_1 + T_3}{2} = \frac{973 + 310}{2} = 641.5 \text{ K}$$

Example

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.



We have $\eta_{\max} = \eta_{\text{rev}} = 1 - \frac{T_2}{T_1} = 1 - \frac{30 + 273}{800 + 273} = 0.718$

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

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

Now $Q_2 = Q_1 - W_{\text{net}} = 1.392 - 1 = 0.392 \text{ kW}$

This is the least rate of heat rejection.

Example

A reversible engine is used for only driving a reversible refrigerator. Engine is supplied 2000 kJ/s heat from a source at 1500 K and rejects some energy to a low temperature sink. Refrigerator is desired to maintain the temperature of 15°C while rejecting heat to the same low temperature sink. Determine the temperature of sink if total 3000 kJ/s heat is received by the sink.

Solution

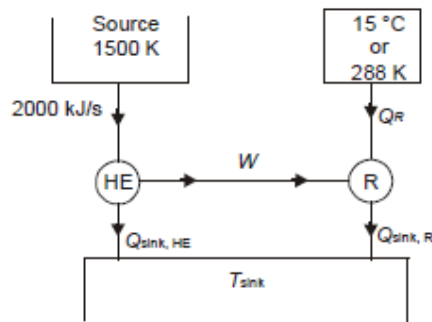
Let temperature of sink be T_{sink} K.

Given: $Q_{\text{sink, HE}} + Q_{\text{sink, R}} = 3000 \text{ kJ/s}$

Since complete work output from engine is used to run refrigerator so,

$$2000 - Q_{\text{sink, HE}} = Q_{\text{sink, R}} - Q_R$$

$$Q_R = 3000 - 2000 = 1000 \text{ kJ/s}$$



Also for engine $\frac{2000}{1500} = \frac{Q_{\text{sink, HE}}}{T_{\text{sink}}} \Rightarrow Q_{\text{sink, HE}} = \frac{4}{3} T_{\text{sink}}$

For refrigerator $\frac{Q_R}{288} = \frac{Q_{\text{sink, R}}}{T_{\text{sink}}} \Rightarrow Q_{\text{sink, R}} = \frac{1000}{288} T_{\text{sink}}$

Substituting $Q_{\text{sink, HE}}$ and $Q_{\text{sink, R}}$ values.

$$\frac{4}{3} T_{\text{sink}} + \frac{1000 T_{\text{sink}}}{288} = 3000$$

$\therefore T_{\text{sink}} = 624.28 \text{ K}$

Temperature of sink = 351.28 °C

Problem

A household refrigerator is maintained at a temperature of 2°C. Every time the door is opened, warm material is placed inside, introducing an average of 420 kJ, but making only a small change in the temperature of the refrigerator. The door is opened 20 times a day, and the refrigerator operates at 15% of the ideal COP. The cost of work is 32 paise per kWh. What is the monthly bill for this refrigerator? The atmosphere is at 30°C.

Answer: Rs. 15.20

Problem

A heat pump working on the Carnot cycle takes in heat from a reservoir at 5°C and delivers heat to a reservoir at 60°C. The heat pump is driven by a reversible heat engine which takes in heat from a reservoir at 840°C and rejects heat to a reservoir at 60°C. The reversible heat engine also drives a machine that absorbs 30 kW. If the heat pump extracts 17 kJ/s from the 5°C reservoir, determine (a) the rate of heat supply from 840°C source (b) the rate of heat rejection to the 60°C sink.

Answer: (a) 47.61 kW (b) 34.61 kW

Problem

Two reversible heat engines A and B are arranged in series. A rejecting heat directly to B. Engine A receives 200 kJ at a temperature of 421°C from a hot source, while engine B is in communication with a cold sink at a temperature of 4.4°C. If the work output of A is twice that of B, find (a) the intermediate temperature between A and B (b) the efficiency of each engine, and (c) the heat rejected to the cold sink.

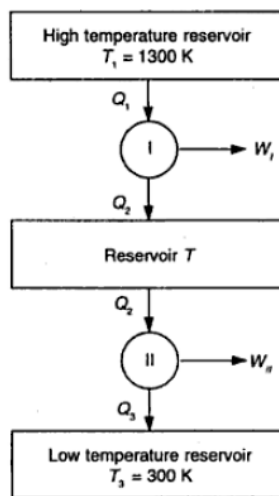
Answer: 143.4°C, 40% & 33.5%, 80 kJ

Example

Two Carnot engines I and II operate in series between a high temperature reservoir at 1027°C and a low temperature reservoir at 27°C. The engine I absorbs energy from the high temperature reservoir and rejects energy to a reservoir at temperature T. The engine II receives energy from the reservoir at T and rejects energy to the low temperature reservoir. The amount of energy absorbed by engine II from the reservoir at T is the same as that rejected by engine I to the reservoir at T. If engines I and II are found to have the same efficiency, determine the temperature T. If engine I receives 100 kJ energy as heat from the high temperature reservoir, calculate the work delivered by engine I and engine II.

Solution

A schematic of engines I and II is shown below.



$$\eta_1 = 1 - \frac{T}{T_1}; \eta_2 = 1 - \frac{T_3}{T}$$

$$\eta_1 = \eta_2$$

$$1 - \frac{T}{T_1} = 1 - \frac{624.5}{1300} = 0.5196$$

$$W_1 = \eta_1 Q_1 = 0.5196 \times 100 = 51.96 \text{ kJ}$$

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

$$Q_2 = \frac{T}{T_1} Q_1 = \frac{624.5}{1300} \times 100 = 48.038 \text{ kJ}$$

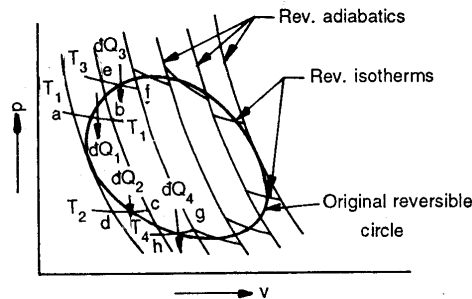
$$W_2 = \eta_2 Q_2 = 0.5196 \times 48.038 = 24.96 \text{ kJ}$$

Entropy

Second law of thermodynamics leads to definition of a new property, known as entropy. If the first law is said to be the law of internal energy, then second law may be the law of entropy.

CLAUSIUS' THEOREM

Let a smooth closed curve representing a reversible cycle (as shown in figure) be considered.



Let the closed cycle be divided into a large number of strips by means of reversible adiabatics. Each strip may be closed at the top and bottom by reversible isotherm. The original closed cycle is thus replaced by a zig zag closed path consisting of alternate adiabatic and isothermal processes, such that the heat transferred during all the isothermal processes is equal to the heat transferred in the original cycle.

For the elemental cycle abcd dQ_1 heat is absorbed reversibly at T_1 , and dQ_2 heat is rejected reversibly at T_2 .

$$\frac{dQ_1}{T_1} = \frac{dQ_2}{T_2}$$

If heat supplied is taken as positive and heat rejected as negative

$$\frac{dQ_1}{T_1} + \frac{dQ_2}{T_2} = 0$$

Similarly, for elemental cycle efgh

$$\frac{dQ_3}{T_3} + \frac{dQ_4}{T_4} = 0$$

If similar equations are written for all the elemental Carnot cycles, then for the whole original cycle

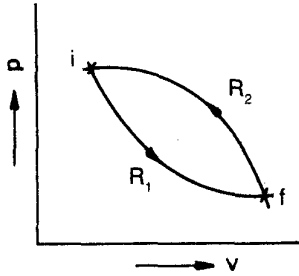
$$\frac{dQ_1}{T_1} + \frac{dQ_2}{T_2} + \frac{dQ_3}{T_3} + \frac{dQ_4}{T_4} + \dots = 0$$

or
$$\oint_R \frac{dQ}{T} = 0 \quad (1)$$

The cyclic integral of dQ/T for a reversible cycle is equal to zero. This is known as Clausius' theorem. The letter R shows that the equation is *valid only* for reversible cycle.

THE PROPERTY OF ENTROPY

Let a system be taken from an initial equilibrium state i to a final equilibrium state f by following the reversible path R_1 (see figure).



The system is brought back from f to i following another reversible path R_2 . Then the two paths R_1 and R_2 together constitute a reversible cycle. From Clausius' theorem

$$\oint_{R_1, R_2} \frac{dQ}{T} = 0$$

The above integral may be replaced as the sum of two integrals, one for path R_1 and the another for path R_2 .

$$\int_{R_1}^f \frac{dQ}{T} + \int_{R_2}^i \frac{dQ}{T} = 0$$

or
$$\int_{R_1}^f \frac{dQ}{T} = - \int_{R_2}^i \frac{dQ}{T}$$

Since R_2 is a reversible path

$$\int_{R_1}^f \frac{dQ}{T} = \int_{R_2}^i \frac{dQ}{T}$$

Since R_1 and R_2 represent any two reversible paths, $\int_R^f \frac{dQ}{T}$ is independent of the reversible path connecting i and f . Therefore, there exists a property of the system whose value at the final state f minus its value at the initial state i is equal to $\int_i^f \frac{dQ}{T}$. This property is called

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entropy, and is denoted by S . If S_i is the entropy at the initial state i , and S_f is the entropy at final state f .

$$\int_i^f \frac{dQ}{T} = S_f - S_i$$

When the two equilibrium states are very near then

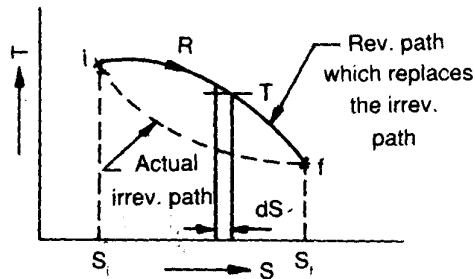
$$\frac{dQ_R}{T} = dS$$

The unit of entropy is J/K.

The specific entropy

$$s = \frac{S}{m} \text{ J/kg.K}$$

If the system is taken from an initial equilibrium state i to a final equilibrium state f by an irreversible path, since entropy is a point or state function, and the entropy change is independent of the path followed, the non-reversible path is to be replaced by a reversible path to integrate for the evaluation of entropy change in the irreversible processes (see following figure).



$$S_f - S_i = \int_i^f \frac{dQ_{rev}}{T} = (\Delta S)_{irrev\ path}$$

Integration can be performed only on a reversible path.

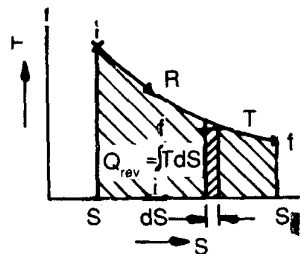
TEMPERATURE ENTROPY PLOT

Reversible Adiabatic Process

$$S = \text{constant}$$

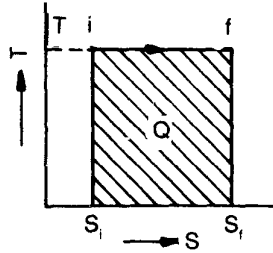
$$Q_{rev} = \int_i^f TdS$$

The system is taken from i to f reversibly(see figure).



The area under the curve $\int_i^f TdS$ is equal to the heat transferred in the process.

Reversible Isothermal Process



$$T = \text{constant}$$

$$Q_{\text{rev}} = T \int_i^f dS = T(S_f - S_i)$$

ENTROPY PRINCIPLE

For an isolated system¹

$$dS_{\text{iso}} \geq 0$$

For a reversible process

$$dS_{\text{iso}} = 0$$

or

$$S = \text{constant}$$

For an irreversible process

$$dS_{\text{iso}} > 0$$

It is thus proved that the entropy of an isolated system can never decrease. It always increase and remains constant only when the process is reversible. This is known as *entropy principle*.

Also
$$dS_{\text{sys}} + dS_{\text{surr}} \geq 0$$

FIRST AND SECOND LAWS COMBINED

By the second law

$$dQ_{\text{rev}} = TdS$$

and by the first law, for a closed non flow system

$$dQ = dU + pdV$$

$$TdS = dU + pdV \quad (1)$$

Again, the enthalpy

$$H = U + pV$$

$$dH = dU + pdV + Vdp = TdS + Vdp$$

$$TdS = dH - Vdp \quad (2)$$

Equations (1) and (2) are the thermodynamic equations relating the properties of the system.

¹ system with single boundary surrounding. For example, universe is, system plus surrounding.

Example

An inventor claims that he has developed a heat engine which absorbs 1200 kJ and 800 kJ of heat from reservoirs at 800 K and 600 K respectively, and rejects 600 kJ and 200 kJ of heat to reservoirs at 400 K and 300 K. The engine is further stated to give an output equivalent to 1200 kJ. Determine whether the engine suggested by the inventor is theoretically possible.

Solution

The entropy change of a system is defined as

$$dS = \frac{\delta Q}{T}$$

Hence entropy change for reservoir A

$$dS_a = \frac{-1200}{800} = -1.5 \text{ kJ} / \text{K}$$

Entropy change for reservoir B

$$dS_b = \frac{-800}{600} = -1.33 \text{ kJ} / \text{K}$$

Entropy change for reservoir C

$$dS_c = \frac{600}{400} = 1.5 \text{ kJ} / \text{K}$$

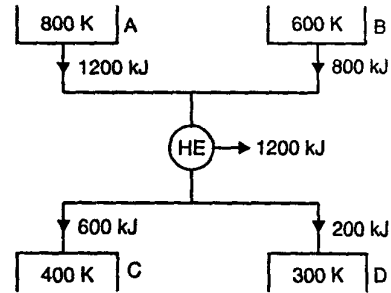
Entropy change for reservoir D

$$dS_d = \frac{200}{300} = 0.667 \text{ kJ} / \text{K}$$

Net entropy change for the arrangement (universe)

$$\begin{aligned} &= dS_a + dS_b + dS_c + dS_d \\ &= -1.5 - 1.333 + 1.5 + 0.667 = -0.666 \text{ kJ} / \text{K} \end{aligned}$$

For any possible cycle $(dS)_{net} \geq 0$. For the proposed engine, the net entropy change is found to be negative and this not possible. Obviously, the engine suggested by the inventor is theoretically not possible.



Example

If water is heated from 273 K to 373 K by first bringing it in contact with a reservoir at 323 K and then with a reservoir at 373 K, what will the entropy change of the universe be?

Solution

Water is being heated in two stages, first from 273 K to 323 K by bringing it in contact with a reservoir at 323 K, and then from 323 K to 373 K by bringing it in contact of a second reservoir at 373 K.

$$(\Delta S)_{\text{water}} = \int_{273\text{K}}^{323\text{K}} mc \frac{dT}{T} + \int_{323\text{K}}^{373\text{K}} mc \frac{dT}{T} = 4.187 \left(\ln \frac{323}{273} + \ln \frac{373}{323} \right) = 1.305 \text{ kJ} / \text{K}$$

$$(\Delta S)_{\text{res I}} = -\frac{1 \times 4.187 \times (323 - 273)}{323} = -0.647 \text{ kJ} / \text{K}$$

$$(\Delta S)_{\text{res II}} = -\frac{1 \times 4.187 \times (373 - 323)}{373} = -0.56 \text{ kJ/K}$$

$$\therefore (\Delta S)_{\text{univ}} = (\Delta S)_{\text{water}} + (\Delta S)_{\text{res I}} + (\Delta S)_{\text{res II}} = 1.305 - 0.647 - 0.56 = 0.098 \text{ kJ/K}$$

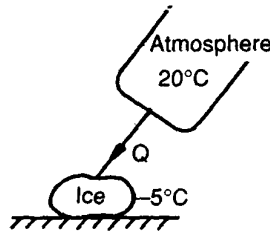
Example

One kg of ice at -5°C is exposed to the atmosphere which is at 20°C . The ice melts and comes into thermal equilibrium with the atmosphere. (a) Determine the entropy increase of the universe

Solution

Heat absorbed by ice Q from the atmosphere (see figure)

$$\begin{aligned} &= \text{Heat absorbed in solid phase} + \text{Latent heat} + \text{Heat absorbed in liquid phase} \\ &= 1 \times 2.093 \times [0 - (-5)] + 1 \times 333.3 + 1 \times 4.187 \times (20 - 0) \\ &= 427.5 \text{ kJ} \end{aligned}$$



Entropy change of the atmosphere

$$(\Delta S)_{\text{atm}} = -\frac{Q}{T} = -\frac{427.5}{293} = -1.46 \text{ kJ/K}$$

Entropy change of the system (ice) as it gets heated from -5°C to 0°C

$$(\Delta S_{\text{I}})_{\text{system}} = \int_{268}^{273} mc_p \frac{dT}{T} = 1 \times 2.093 \ln \frac{273}{268} = 2.093 \times 0.0186 = 0.0389 \text{ kJ/K}$$

Entropy change of the system as ice melts at 0°C to become water at 0°C

$$(\Delta S_{\text{II}})_{\text{system}} = \frac{333.3}{273} = 1.22 \text{ kJ/K}$$

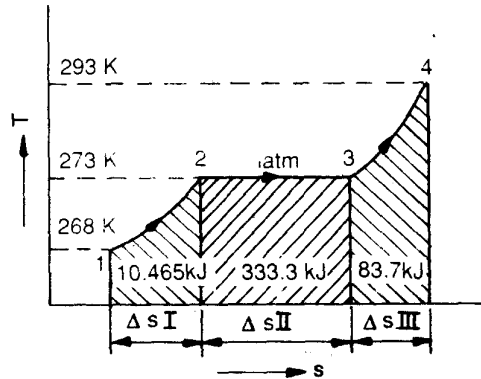
Entropy change of water as it gets heated from 0°C to 20°C

$$(\Delta S_{\text{III}})_{\text{system}} = \int_{273}^{293} mc_p \frac{dT}{T} = 1 \times 4.187 \ln \frac{293}{273} = 0.296 \text{ kJ/K}$$

Total entropy change of ice as it melts into water

$$(\Delta S)_{\text{total}} = \Delta S_{\text{I}} + \Delta S_{\text{II}} + \Delta S_{\text{III}} = 0.0389 + 1.22 + 0.296 = 1.5549 \text{ kJ/K}$$

The entropy-temperature diagram for the system as ice at -5°C converts to water at 20°C is shown in following figure



∴ Entropy increase of the universe

$$(\Delta S)_{\text{univ}} = (\Delta S)_{\text{system}} + (\Delta S)_{\text{atm}} = 1.5549 - 1.46 = 0.0949 \text{ kJ/K}$$

Problem

Water is heated at a constant pressure of 0.7 MPa. The boiling point is 164.97°C . The initial temperature of water is 0°C . The latent heat of evaporation is 2066.3 kJ/kg . Find the increase of entropy of water, if the final state is steam.

Answer: 6.6967 kJ/kg K

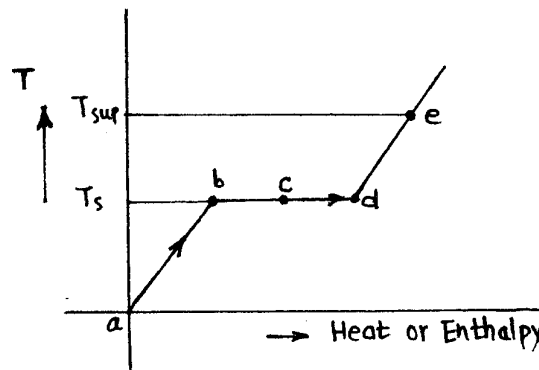
Problem

Two kg of water at 80°C are mixed adiabatically with 3 kg of water at 30°C in a constant pressure process of 1 atmosphere. Find the increase in the entropy of the total mass of water due to the mixing process (c_p of water = 4.187 kJ/kg K).

Answer: 0.0576 kJ/K

Steam

CONDITION OF STEAM



The steam may exist in the wet, dry-saturated or superheated condition. When the steam contains water particles, the steam is known as wet steam. When the steam does not contain water particles and its temperature is equal to saturation temperature at the given pressure, the steam is known as dry steam. When the steam temperature is above the saturation temperature, the steam is known as superheated steam. The wet, dry and superheated steam conditions c, d and e are shown in figure given above.

The quality of the wet steam is measured by a factor known as *dryness fraction*. Dryness fraction of wet steam is the ratio of the mass of actual dry steam to the mass of total steam. Dryness fraction is often spoken as the *quality of steam* and it is expressed by a symbol x .

W = Mass of dry steam in the steam considered

w = Mass of water in suspension in the steam considered.

Then the dryness fraction of steam is given by

$$x = \frac{W}{W + w}$$

If the quality of steam given is 80% dry, it means that one kg of steam contains 0.8 kg of dry steam and 0.2 kg of water particles.

When the steam is completely dry than it is said that steam is 100% dry. The condition of superheated steam is measured by degree of superheated which is equal to $(T_{\text{sup}} - T_s)$.

ADVANTAGES OF SUPERHEATED STEAM

In most of the power developing systems. superheated steam is generally used as it offers the following advantages.

1. The heat content of superheated steam is more than saturated steam, hence its capacity to do work is increased without increasing its pressure.
2. Increase in wetness during expansion of superheated steam is less than saturated or wet steam at the same pressure and so the condensation of steam on cylinder walls of engine or in the last stage of the turbine is reduced considerably.
3. The superheating of the steam is done by using the heat in the hot gases coming out from the boiler.
4. The overall thermal efficiency of the plant increase by the use of superheated steam

THERMODYNAMIC PROPERTIES OF STEAM

Enthalpy or Total Heat

The energy content of the steam above water at 0°C is known as enthalpy or total heat.

Dry Saturated Steam: The heat content of saturated steam per kg at a given pressure is equal to sensible heat and latent heat.

$$h_g = h_f + h_{fg}$$

Wet Steam: The heat content of wet steam per kg at a given pressure is equal to the sum of the sensible heat and latent heat of the wet steam. If the dryness fraction of the steam is x , then the total heat or enthalpy of wet steam is given by

is the specific heat of superheated steam.

$$h = h_f + x h_{fg}$$

Superheated Steam: The heat content of superheated steam per kg at a given pressure is equal to the total heat of dry steam and the superheat. If the temperature of steam at a pressure p is T_{sup} then the total heat of superheated steam is given by

$$h = h_f + h_{fg} + C_{ps} (T_{\text{sup}} - T_s) = h_g + C_{ps} (T_{\text{sup}} - T_s)$$

Where, T_s is the saturation temperature of steam, at the given p pressure and C_{ps} is the specific heat of superheated steam.

Specific Volume and Density

The specific volume of steam is the volume occupied by one kg of steam at the given pressure and temperature.

The density of the steam is the mass of steam per unit volume of steam at the given pressure and temperature. The density is always the reciprocal of the specific volume.

Dry Saturated Steam: The specific volume of dry steam is the volume occupied by 1 kg of steam and it is denoted by v . It decreases with increasing pressure.

The density of dry steam is given by

$$\rho = \frac{1}{v_g}$$

Wet Steam: If the dryness fraction of steam is x then one kg of steam contains x kg of dry steam and $(1 - x)$ kg of saturated liquid. The volume of one kg of wet steam is equal to the volume of x kg dry steam and volume of $(1 - x)$ kg saturated liquid.

Therefore the specific volume of wet steam is given by

$$v = xv_g + (1 - x) v_f$$

Where, v_g and v_f are the specific volume of dry steam and saturated liquid at given pressure.

Superheated Steam: It is always assumed that the steam is generated at constant pressure, the dry and superheated obeys the gas laws as mentioned earlier. Therefore, the specific volume of superheated steam is given by

$$v_{sup} = v_g \frac{T_{sup}}{T_s}$$

Where T_{sup} and T_s are the temperature of superheated steam and saturated steam at the given pressure in absolute unit, v_g is the specific volume of dry steam.

Internal Energy of Steam

The internal energy of wet steam is given by

$$u = (h_f + xh_{fg}) - p(xv_g)$$

The internal energy of superheated steam is given by

$$u = h_g + C_{ps}(T_{sup} - T_s) - pv_{sup}$$

where $v_{sup} = v_g \frac{T_{sup}}{T_s}$

Entropy of Steam

The entropy is denoted by S and it is given by

$$ds = \frac{dQ}{T}$$

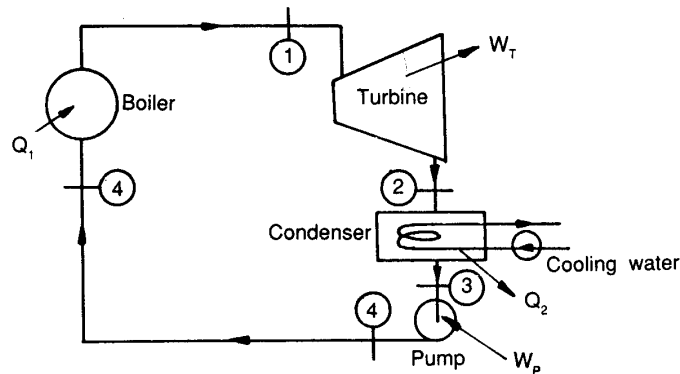
For any constant pressure process, such as generation of steam from water. It is given by

$$s_2 - s_1 = C_p \log_e \left(\frac{T_2}{T_1} \right)$$

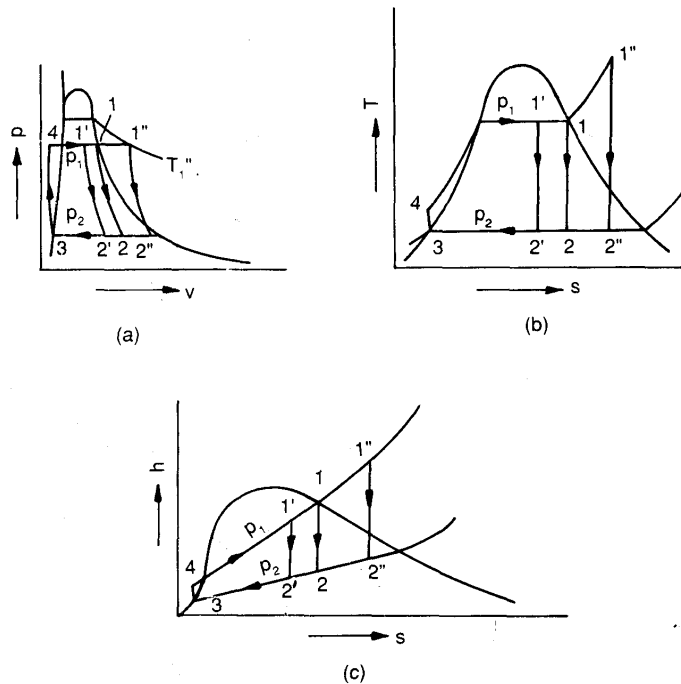
where water is heated at constant pressure from T_1 and T_2 .

RANKINE CYCLE

For each process in the vapour power cycle, it is possible to assume a hypothetical or ideal process which represents the basic intended operation. For the steam boiler, this would be a reversible constant pressure heating process of water to form steam, for the turbine the ideal process would be a reversible adiabatic expansion of steam, for the condenser it would be a reversible constant pressure heat rejection as the steam condenses till it becomes saturated liquid, and for the pump, the ideal process would be the reversible adiabatic compression of this liquid ending at the initial pressure. When all these four processes are ideal, the cycle is an ideal cycle, called a *Rankine cycle*. This is a reversible cycle. Given figure shows the flow diagram of the Rankine cycle.



and in following figure, the cycle has been plotted on the $p-v$, $T-s$, and $h-s$ planes.



Rankine cycle on $p-v$, $T-s$, and $h-s$ diagrams

The numbers on the plots correspond to the numbers on the flow diagram. For any given pressure, the steam approaching the turbine may be dry saturated (state 1) wet (state 1'), or superheated (state 1''), but the fluid approaching the pump is, in each case, saturated liquid (state 3). Steam expands reversibly and adiabatically in the turbine from state 1 to state 2 (or 1' to 2', or 1'' to 2''), the steam leaving the turbine condenses to water in the condenser reversibly at constant pressure from state 2 (or 2', or 2'') to state 3, the water at state 3 is then pumped to the boiler at state 4 reversibly and adiabatically, and the water is heated in the boiler to form steam reversibly at constant pressure from State 4 to state 1 (or 1' or 1'').

For 1 kg fluid

The SFEE for the boiler (control volume) gives

$$h_4 + Q_1 = h_1$$

$$\therefore Q_1 = h_1 - h_4$$

The SFEE for the turbine as the control volume gives

$$h_1 = W_T + h_2$$

$$\therefore W_T = h_1 - h_2$$

Similarly, the SFEE for the condenser is

$$h_2 = Q_2 + h_3$$

$$\therefore Q_2 = h_2 - h_3$$

and the SFEE for the pump gives

$$h_3 + W_p = h_4$$

$$\therefore W_p = h_4 - h_3$$

The efficiency of the Rankine cycle is then given by

$$\eta = \frac{W_{\text{net}}}{Q_1} = \frac{W_T - W_p}{Q_1} = \frac{(h_1 - h_2) - (h_4 - h_3)}{h_1 - h_4}$$

The pump handles liquid water which is incompressible, i.e. its density or specific volume undergoes little change with an increase in pressure. For reversible adiabatic compression, by the use of the general property relation

$$Tds = dh - vdp; ds = 0$$

and $dh = vdp$

Since change in specific volume is negligible

$$\Delta h = v\Delta p$$

or $h_4 - h_3 = v_3(p_1 - p_2)$

If v is in m^3/kg and p is in bar

$$h_4 - h_3 = v_3(p_1 - p_2) \times 10^5 \text{ J/kg}$$

Usually, the pump work is quite small compared to the turbine work and is sometimes neglected. Then $h_4 = h_3$ and the cycle efficiency approximately becomes

$$\eta = \frac{h_1 - h_2}{h_1 - h_4}$$

Example

In a thermal power plant operating on an ideal Rankine cycle, steam at 15 bar and 250°C enters a turbine which generates 40 kW indicated power. If the steam consumption is 300 kg/hr and condenser is maintained at 0.15 bar, determine the final condition of steam, Rankine efficiency and relative efficiency. Neglect pump work. Also determine the fuel to be supplied per hour if its calorific value is 41850 kJ/kg.

Solution

Refer to following figure

From steam table:

At 15 bar, (steam is superheated)

$$h_1 = 2923.5 \text{ kJ/kg}$$

$$s_1 = 6.709 \text{ kJ/kg K}$$

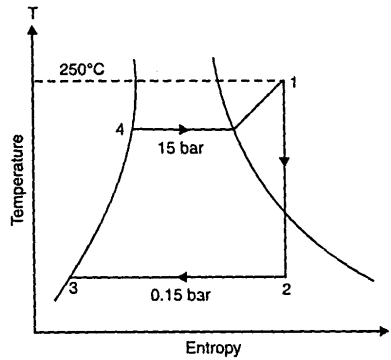
At 0.15 bar

$$h_f = 226 \text{ kJ/kg}$$

$$h_{fg} = 2372.2 \text{ kJ/kg}$$

$$s_f = 0.755 \text{ kJ/kg K}$$

$$s_{fg} = 7.254 \text{ kJ/kg K}$$



- (a) Considering adiabatic expansion from state 1 to state 2

$$s_1 = s_2; s_1 = (s_f + x_2 s_{fg})_{0.15 \text{ bar}}$$

$$6.709 = 0.755 + x_2 \times 7.254$$

$$x_2 = 0.821$$

The dryness fraction of steam at exit from turbine is 0.821.

- (b)
$$h_2 = (h_f + x_2 h_{fg})_{0.15 \text{ bar}} = 226 + 0.821 \times 2372.2 = 2174.4 \text{ kJ / kg}$$

$$h_3 = (h_f)_{0.15 \text{ bar}} = 226 \text{ kJ / kg}$$

$$\text{Rankine efficiency} = \frac{h_1 - h_2}{h_1 - h_3} = \frac{2923.5 - 2174.4}{2923.5 - 226} = 0.278 \text{ or } 27.8\%$$

(c) Industrial power = 40 kW = 40 kJ/s

$$\text{Heat input} = (h_1 - h_3) = (2923.5 - 226) = 224.79 \text{ kJ / s}$$

$$= \frac{300}{3600} (2923.5 - 226) = 224.79 \text{ kJ / s}$$

$$\text{Indicated thermal efficiency} = 40/224.79 = 0.178$$

$$\therefore \text{Relative efficiency} = 0.178/0.278 = 0.64 \text{ or } 64\%$$

STEAM BOILERS

Classification of boilers

Boilers can be classified on various points. Some of the important basis of classifications are as follows:

Content of the Tubes

- Fire Tube In fire-tube boilers, hot flue gases are allowed to flow inside the tubes and water surrounds the tubes, e.g., simple vertical, Cochran, and Lancashire boilers.
- Water Tube In water-tube boilers, water is allowed to flow inside the tubes and the hot flue gases surrounds the tube, e.g., Babcock and Wilcox, Sterling, and Lamont boilers.

Steam Pressure

- Low-pressure Boilers The boilers which produce steam at a pressure lower than 30 bars are called low-pressure boilers, e.g. simple vertical, Cochran, Babcock and Wilcox , and Lancashire boilers etc.
- Medium-pressure Boilers The boilers which produce steam at a pressure in the range of 30 bars to 80 bars are called medium pressure boilers.
- High-pressure Boilers The boilers which produce steam at a pressure higher than 80 bars are called high pressure boilers, e.g. Velox, Lamount, and Benson boilers.

Type of Water Circulation in the Boiler

- Natural Water Circulation In natural water circulation, the circulation of water takes place by the convection currents caused due to temperature difference of water, e.g., simple vertical, Cochran, Babcock and Wilcox , and Lancashire boilers.
- Forced Water Circulation In forced water circulation , water is circulated inside the boiler with the help of a pump. (at high pressure the natural convection becomes ineffective and hence force water circulation is adopted). Examples Lamount, Velox, and Benson boilers.

Furnace Position

- Internally Fired In internally fired boilers, the furnace is located inside the boiler shell, e.g., Cochran, and Lancashire boilers.
- Externally Fired In externally fired boilers, the furnace is located outside the shell of the boiler, e.g., Babcock and Wilcox, and Stirling boilers.

Use

- **Stationary Boilers** These boilers are mounted on a fixed platform and are stationed in only one place. These are generally used in steam power plants and in other industries for producing process steam.
- **Portable Boilers** Portable boilers are small boilers and can be carried from one place to another, e.g., simple vertical boilers.
- **Mobile Boilers** Mobile boilers are mounted on a moving platform like locomotive, marine, etc.

Position of the Boiler Shell

- **Horizontal** If the position of the axis of the boiler shell is horizontal then it is called horizontal boiler, e.g., Lancashire, and Babcock and Wilcox boilers.
- **Vertical** If the axis of the boiler shell is vertical then it is called vertical boiler, e.g., simple vertical, and Cochran boiler.

Type of the Fuel Used

- Coal fired
- Oil fired
- Gas fired

Type of Fuel Firing

- **Hand Fired** In hand fired boilers the fuel is fired manually into the furnace. This is normally employed in small boilers, e.g., simple vertical, and Lancashire boilers.
- **Stoker Fired** In a stoker-fired system, the stoker (conveyor made of chain links on which coal is fed through a hopper) moves at a constant speed into the furnace. Thus, it is a continuous coal-feeding device. These are normally used in Babcock and Wilcox, and Stirling boilers.
- **Pulverized Fuel Fired** In pulverized fuel firing system the coal is ground to a fine powder form and then it is supplied with compressed air through the nozzle into the furnace. These are normally used in thermal power plants. Pulverized fuel fired boilers can meet the fluctuating demand of steam.

BOILER MOUNTINGS

According to the Indian Boiler Regulation Act, the boiler must be fitted with the following mountings for its proper and safe functioning.

- **Safety Valves** Safety valves are placed on the top of the boiler. The function of the safety valve is to blow off the excess quantity of steam if the pressure of the steam exceeds the working pressure limit of the boiler.
- **Water Level Indicator** Generally, two water level indicators are provided along the two sides of the boiler. One end of the water level indicator is connected to the steam space while the other end is connected to the water space. The water-level indicator is mounted in front of a boiler so that it is easily visible to the attendant. The function of the water level indicator is to show the level of water inside the boiler.
- **Pressure Gauge** The pressure gauge is mounted in a place such that the operator can read it conveniently. Its end is connected to the steam space through a U tube (siphon tube) in which water is filled. The purpose of this siphon tube is to avoid the live steam

coming in direct contact with the Bourdon tube used in a Bourdon pressure gauge. The function of the pressure gauge is to indicate the pressure of the steam inside a boiler.

- **Steam Stop Valve** The steam stop valve is mounted on the top part of the steam space of the boiler. The function of the steam stop valve is to stop or to regulate the flow of steam from the boiler to the main steam pipe.
- **Feed Check Valve** The feed check valve is fitted on the boiler just below the working level of the water in the boiler. The function of a feed check valve is to supply the water from the feed pump to the boiler. It also prevents the water escaping from the boiler in case of the failure of the feed pump or when the feed pump is stopped, i.e. it acts as one way valve.
- **Blow-off Cock** A blow-off cock is fitted on the boiler shell at the bottom-most part of the water space. The function of the blow-off cock is to remove the sediments, mud, scale collected at the bottom of the water space periodically by opening the valve, when the boiler is in operation. It is also used to empty the boiler at the time of inspection, cleaning and maintenance.
- **Fusible Plug** The fusible plug is fitted at the top of the crown of furnace or on the top of the combustion chamber. In normal working conditions, the fusible plug is dipped inside the water. The function of the fusible plug is to prevent the boiler from overheating by extinguishing the fire inside the furnace when the water level falls below the unsafe level.

ACCESSORIES

The boiler accessories are used either to increase the efficiency of a boiler or to increase the performance.

Economiser

An economizer is installed or erected in the passage of hot flue waste gases between the boiler and the chimney.

An economizer is used for heating feed water by the hot flue waste gases. It recovers part of the heat being carried away by the flue gases to the chimney.

The advantages gained by the use of an economizer are as follows:

- It improves the fuel economy
- Improves evaporative capacity
- Increases the efficiency of boiler

Air Pre-heater

An air pre-heater is also installed in the passage of the waste hot flue gases between an economizer and the chimney.

An air pre-heater also recovers part of the heat being carried away by the flue gases, leaving the economizer to the chimney. An air pre-heater heats fresh air to be fed to the furnace. The tubular type of air heater consists of number of tubes arranged in bundles. Hot flue gases are allowed to pass through these tubes. The fresh air to be supplied to the combustion chamber of the boiler is allowed to pass over the tubes a number of times by baffles. Thus air gets heated before it is fed to the furnace.

The advantages gained by the use of an air pre heater are as follows

- It improves the fuel economy.
- It accelerates the rate of combustion of fuel.
- It also helps in the combustion of low grade fuel.

COCHRAN BOILER

A Cochran boiler is a vertical, multi-tubular, **fire-tube type** of a boiler.

The hot flue gases pass from the grate to the combustion chamber through a short flue pipe. After the combustion chamber, it passes through the horizontal tubes in to the smoke box and then to the stack as shown. The water surrounding the tubes and the combustion chamber gets heated by the natural circulation. The steam formed from heating water inside the boiler is collected in the steam space.

BABCOCK AND WILCOX BOILER

A Babcock and Wilcox boiler is a horizontal, **water tube boiler**.

The water is supplied to the boiler through a feed-check valve up to the pre specified level. When the combustion of fuel takes place, the hot flue gases rise up. The hot flue gases are compelled to pass in the upward direction between the tubes towards the upper header, then in the downward direction between the tubes and then once again in the upward direction and then finally to the chimney by the baffles provided. The hot gases heat the water flowing through the water tubes. The water flows from the rear boiler shell to the bottom header and then to the upper header through the inclined tubes into the drum. The water then moves from front of the drum to the rear of the drum and then to the bottom header.