Engineering Thermodynamics (BME-12)
UNIT-II

Lecture-1

Lecture contains

First law applied to flow processes

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UNIT-II
Lecture-1

First Law applied to Flow Processes

STEADY FLOW ENERGY EQUATION

For any system and in any process, the first law can be written as

$$Q = \Delta E + W$$

Where E represents all forms of stored energy in the system.

For a pure substance

$$E = E_K + E_P + U$$

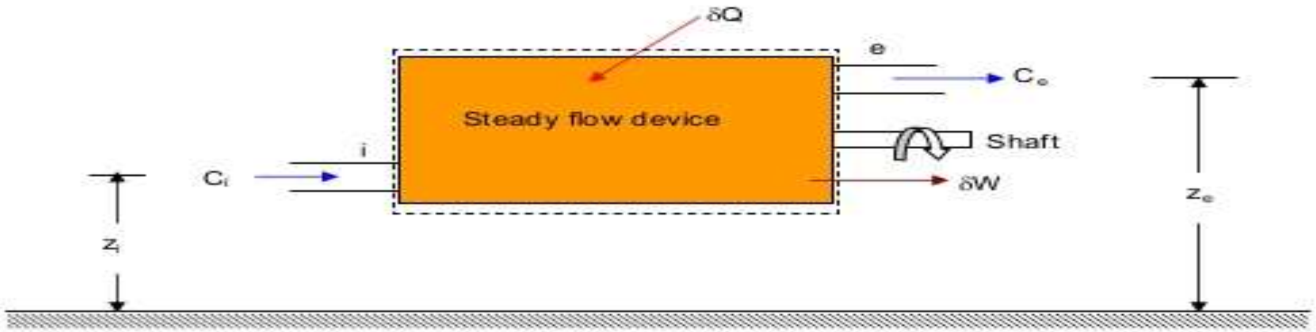
Where

E_K= Kinetic energy = $\frac{mC^2}{2}$; where C is the velocity of fluid.

E_P = Potential energy = mgz

U is the residual energy (internal energy) stored in the molecular structure of the substance. Hence,

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



Steady-flow process

Let

A_i, A_e — Cross sectional area, m^2

w_i, w_e — mass flow rate, kg/s

p_i, p_e — absolute pressure, N/m^2

v_i, v_e — specific volume, m^3/kg

u_i, u_e — specific internal energy, J/kg

C_i, C_e — velocity, m/s

z_i, z_e — elevation from an arbitrary datum level, m

Subscript i and e refers to the inlet and exit sections.

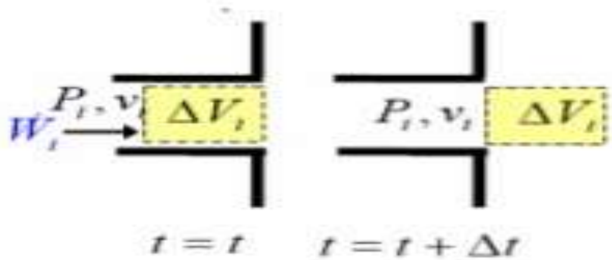
The total energy of mass δm at the inlet is

$$U_i + \frac{1}{2}\delta m\, C_i^2 + \delta m\, g\, z_i \quad \text{or} \quad \delta m\left(u_i + \frac{C_i^2}{2} + gz_i\right)$$

Similarly, the total energy of mass δm at the outlet is

$$\delta m\left(u_e + \frac{C_e^2}{2} + gz_e\right)$$

Lastly we must consider how the system changes its state from i to e. We may assume that δQ units of energy are transferred to the system as heat and that δW units of energy are transferred to the surroundings as work via. a turbine shaft. δW is not only work done so far as the system is concerned because parts of its boundary move at sections i and e. For the element δm to enter the open system, the system must be compressed, its volume decreasing by $\delta m\, v_i$. This is accompanied by a force p_iA moving a distance $l = \delta m\, v_1/A$, where A is the cross-sectional area of the element. The work done by the surroundings on the system is therefore $\delta m\, p_i\, v_i$. Similarly it can be shown that the work done by the system to the surroundings is $\delta m\, p_e\, v_e$. The net work done by the system during the change is therefore



$$\delta W + \delta m\,(p_e\, v_e - p_i\, v_i)$$

We may now write the energy equation for the open system as

$$\delta Q - \{\delta W + \delta m\,(p_e\, v_e - p_i\, v_i)\} = \delta m\left(u_e + \frac{C_e^2}{2} + gz_e\right) - \delta m\left(u_i + \frac{C_i^2}{2} + gz_i\right)$$

By writing h for (u + pv), the equation becomes

$$\delta Q - \delta W = \delta m\left(h_e + \frac{C_e^2}{2} + z_e\right) - \delta m\left(h_i + \frac{C_i^2}{2} + z_i\right)$$

The continuous steady-flow process consists of the sum total of all the elemental mass transfers across sections 1 and 2. It may therefore be represented as

$$\sum \delta Q - \sum \delta W = \sum \delta m\left(h_e + \frac{C_e^2}{2} + z_e\right) - \sum \delta m\left(h_i + \frac{C_i^2}{2} + z_i\right)$$

If we consider the properties to be uniform over the cross-section of flow at inlet and outlet and write m for $\Sigma\delta m$ then the above equation becomes after simplifying

$$Q - W = (h_e - h_i) + \frac{1}{2}(C_e^2 - C_i^2) + g(z_e - z_i)$$

where Q and W are the heat and work transfers per unit mass flowing through the system. The assumptions upon which the equation is based may be summarised as follows:

1. The mass flow at the inlet is constant with respect to time, and equal to mass flow at outlet.
2. The properties at any point within the open system do not vary with time.
3. The properties are constant over the cross-section of the flow at inlet and outlet.
4. Any heat or work crossing the boundary does so at a uniform rate.

Finally we must note an important equation which follows directly from assumptions (1) and (3). It is known as the ***continuity equation*** and expresses the principle of conservation of mass in steady flow. If m is the rate of mass flow, we have

$$m = \frac{A_i C_i}{v_i} = \frac{A_e C_e}{v_e} = \rho_i C_i A_i = \rho_e C_e A_e$$

Lecture-2

Lecture contains

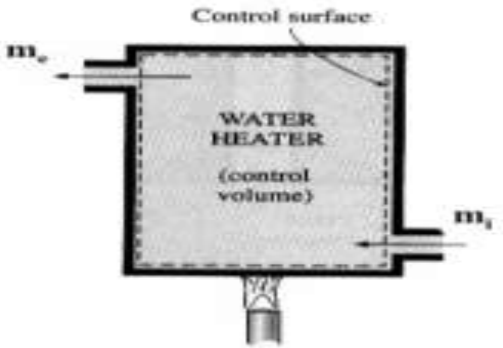
Steady state flow equation

Example of steady state Devices

First law as a rate equation:-

It expresses the instantaneous or average rate at which energy crosses the system boundary as heat and work and the rate at which the energy of the system changes.

Conservation of Mass



Mass flow in – mass flow out = accumulation in the control volume.

i.e. $\delta m_{cv} = m_i - m_e$

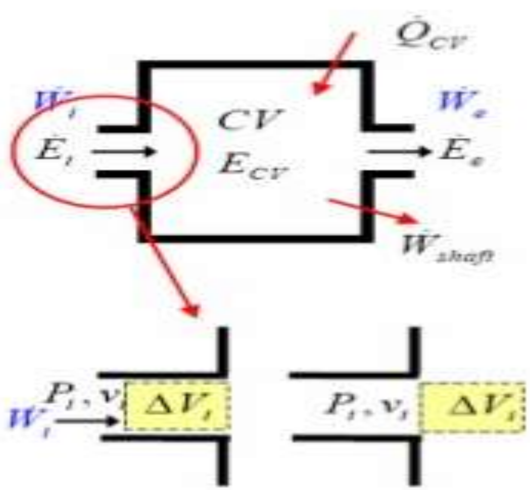
Dividing by δt we get

$$\frac{\delta m_{cv}}{\delta t} = \frac{m_i}{\delta t} - \frac{m_e}{\delta t}$$

or $$\frac{dm_{cv}}{dt} = m_i - m_e$$

where $$\frac{\delta m_i}{\delta t} = m_i \quad \text{and} \quad \frac{\delta m_e}{\delta t} = m_e$$

Conservation of Energy



Consider a time interval δt during which an amount of heat δQ crosses the system boundary, an amount of work δW is done by the system, the internal energy change is ΔU, the kinetic energy change is ΔK and potential energy change is ΔPE. Since the mass flow rates at the inlet m_i and outlet m_e are not same, there will be a change of energy stored in the system. If the change in energy stored in the system is ΔE_{cv}, then

First Law states

$$\delta Q = \Delta U + \Delta KE + \Delta PE + \delta W + \Delta E_{cv}$$

Dividing by δt we get

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$$\frac{\delta Q}{\delta t}=\frac{\Delta U}{\delta t}+\frac{\Delta KE}{\delta t}+\frac{\Delta PE}{\delta t}+\frac{\delta W}{\delta t}+\frac{\Delta E_{cv}}{\delta t}$$

or $$Q=\frac{dU}{dt}+\frac{d(KE)}{dt}+\frac{d(PE)}{dt}+W+\frac{dE_{cv}}{dt}$$

where $\frac{\delta Q}{\delta t}=Q$ and $\frac{\delta W}{\delta t}=W$

Hence, the First Law becomes

$$Q+\sum m_i\left(h_i+\frac{C_i^2}{2}+gz_i\right)=\sum m_e\left(h_e+\frac{C_e^2}{2}+gz_e\right)+W+\frac{dE_{cv}}{dt}$$

i.e. $$\frac{dE_{cv}}{dt}=Q-W+\sum m_i\left(h_i+\frac{C_i^2}{2}+gz_i\right)-\sum m_e\left(h_e+\frac{C_e^2}{2}+gz_e\right)$$

Simplifications

1. Steady State Flow

Fluid properties may vary in space but are constant at each location.

$m_i \neq m_e$; $h_i \neq h_e$

$$\frac{dE_{cv}}{dt}=0$$

Hence,

$$0=Q-W+\sum m_i\left(h_i+\frac{C_i^2}{2}+gz_i\right)-\sum m_e\left(h_e+\frac{C_e^2}{2}+gz_e\right)$$

2. Steady state flow with uniform mass flow rate

Continuity equation becomes

$$m_i=m_e=m$$

$$\therefore \quad Q-W=m(h_e-h_{i1})+\frac{m}{2}(C_e^2-C_i^2)+mg(z_e-z_i)$$

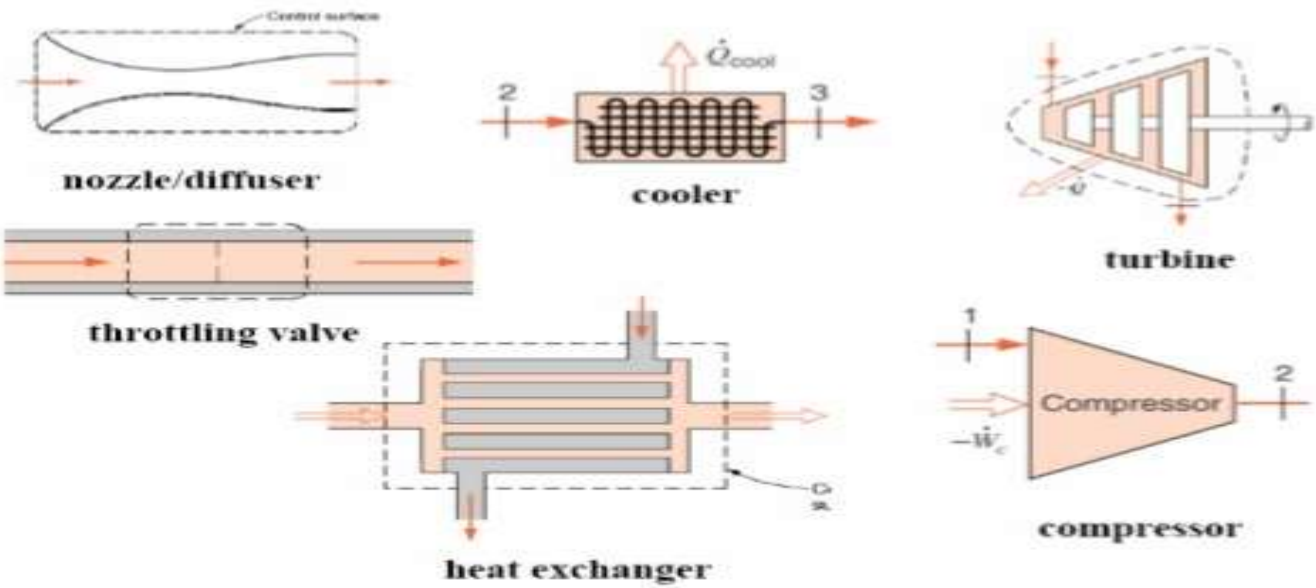
3. Negligible KE and PE

$$\dot{Q}-\dot{W}=\dot{m}(h_e-h_{i1})$$

4. No heat loss, work with negligible KE and PE

$$h_i = h_e$$

Examples of Steady State Devices



OPEN SYSTEM WITH STEADY FLOW

Boiler

In the boiler, the fluid entering as liquid, leaves as a vapour at a constant rate. In this case no work is done on or by the fluid as it passes through the system. The velocities are usually quite low, so that the difference between kinetic energies at the inlet and outlet is negligible compared to the other terms of the equation.

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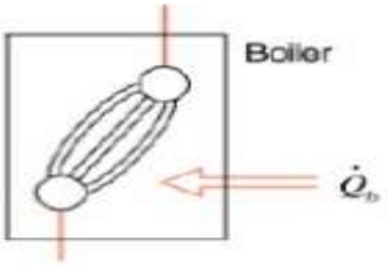
Lecture-3

Lecture contains

Example of steady state Devices

Assumptions

- Steady ($dE_{CV}/dt = 0$)
- Single inlet/exit
- No shaft work
- KE, PE change negligible (usually)



Hence, Steady Flow Energy Equation (SFEE) becomes

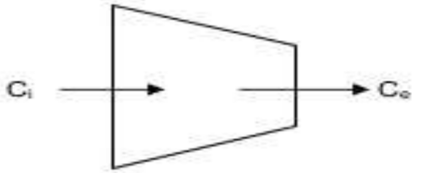
$$Q = h_e - h_i \quad kJ/kg$$

Nozzles and Diffusers

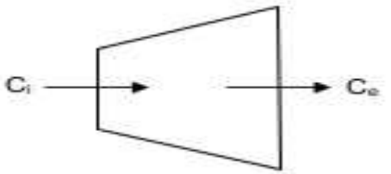
A nozzle is a duct of varying cross-sectional area so designed that a drop in pressure from inlet to outlet accelerates the flow. The flow through a nozzle usually occurs at a very high speed, and there is little time for the fluid to gain or lose energy by a flow of heat through the walls of the nozzle as the fluid passes through it. The process is therefore always assumed to be adiabatic. Also, no work crosses the boundary during the process. The function of diffuser is the reverse of that of nozzle.

Nozzle – A device to increase velocity at the expense of pressure.

Diffuser – A device to increase pressure at the expense of velocity.



Nozzle, $C_i < C_e$



Diffuser, $C_i > C_e$

Assumptions

- Steady ($dE_{CV}/dt = 0$)
- Single inlet/exit
- No heat transfer (assuming adiabatic)
- No shaft work
- PE change negligible

Hence, SFEE becomes

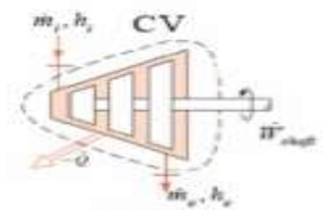
$$h_i + \frac{C_i^2}{2} = h_e + \frac{C_e^2}{2}$$

If $C_e > C_i$ (nozzle) $\Rightarrow$ $h_e < h_i$ (cools down)

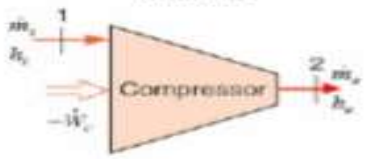
If $C_e < C_i$ (diffuser) $\Rightarrow$ $h_e > h_i$ (warms up)

Turbine/Compressor

A turbine is a means of extracting work from a flow of fluid expanding from a high pressure to a low pressure. The fluid is accelerated in a set of fixed nozzles and the resulting high-speed jets of fluid then change their direction as they pass over a row of curved blades attached to the rotor. As first approximation, the velocity at the inlet and outlet of the turbine can be assumed equal. Since the velocity of flow through the turbine is very high, the process can be assumed to be adiabatic. The rotary compressor can be regarded as a reverse turbine, work being done on the fluid to raise the pressure.



turbine



compressor

Assumptions

- Steady ($dE_{CV}/dt = 0$)
- Single inlet/exit
- No heat transfer (usually, but not always)
- KE, PE change negligible (usually)

Hence, SFFF becomes

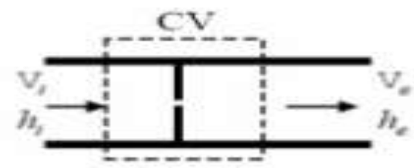
$W = h_i - h_e$ kJ/kg

Throttling Valves

A flow-restricting device that causes a significant pressure drop accompanied by a large drop in Temperature (valves, porous plug, capillary tubes in refrigerators). The term throttling is usually applied to relatively low-speed flow, i.e. low enough for any difference between the kinetic energy at the inlet and outlet to be negligible. Any heat transfer across the boundary can be neglected. Also no work crosses the boundary.

Assumptions

- Steady ($dE_{CV}/dt = 0$)
- Single inlet/exit
- No heat transfer and shaft work
- KE, PE change negligible



Hence, SFFF becomes

$$h_i = h_e \quad kJ/kg$$

$$u_i + p_i v_i = u_e + p_e v_e$$

Hence, pv increases at the expense of u (temperature drops)

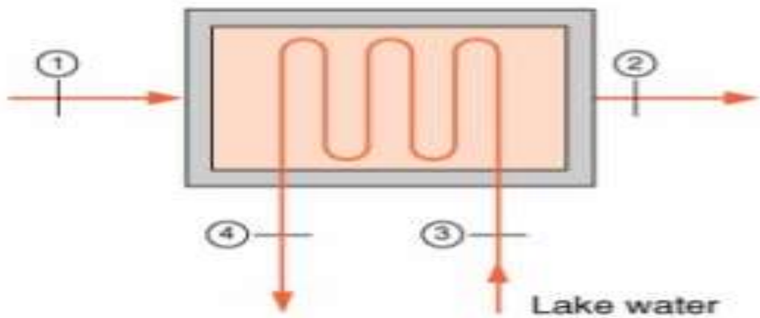
For real gases, h = h (T) only, i.e. $T_i = T_e$

Heat Exchangers

Consider a double-tube type heat exchanger (tube and shell). In heat exchanger, the change in potential energy and kinetic energy terms are very small and can be neglected. Also, there is no external work.

Assumptions

- Steady ($dE_{CV}/dt = 0$)
- Multiple inlets/exits
- No heat transfer and shaft work
- KE, PE change negligible



Hence, SFEE becomes

$$\sum_i m_i h_i = \sum_e m_e h_e$$

or $$m_1 h_1 + m_3 h_3 = m_2 h_2 + m_4 h_4$$

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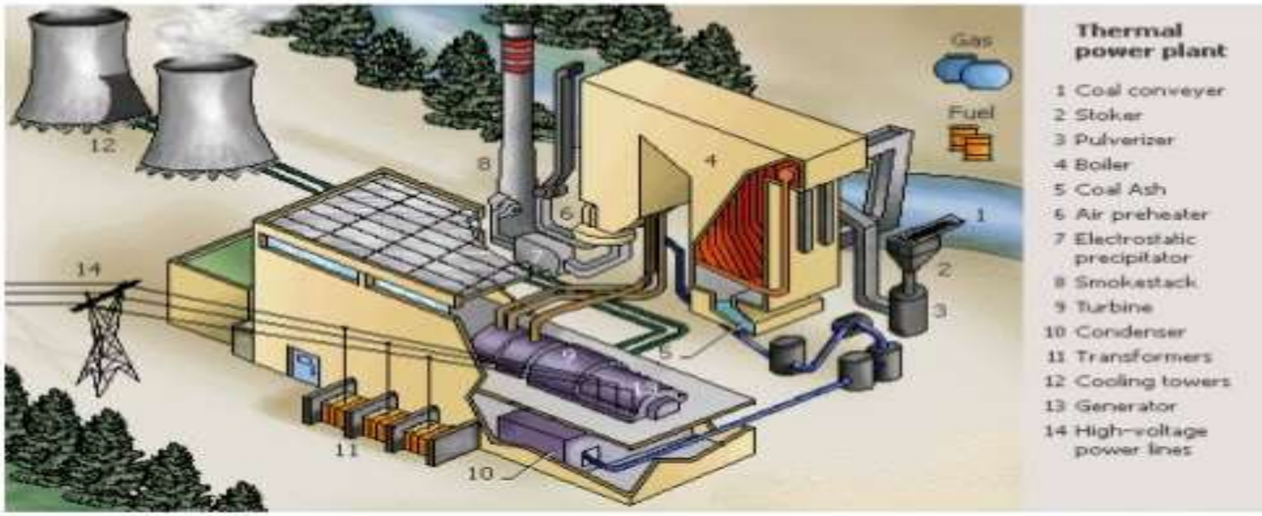
Power Plant



Boiler: $Q_b = {}_1Q_2 = m(h_1 - h_5) = m(h_2 - h_5), \text{since } h_1 = h_2$

Turbine: $W_T = -{}_2W_3 = m(h_3 - h_2)$

Condenser: $-Q_C = {}_3Q_4 = m(h_4 - h_3)$

Pump: $-W_P = -{}_4W_5 = m(h_5 - h_4)$

Adding we have

$${}_1Q_2 + {}_3Q_4 - {}_2W_3 - {}_4W_5 = 0$$

or $$\sum \delta Q - \sum \delta W = 0$$

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Lecture-4

Lecture contains

- Unsteady Flow Processes and their analysis
- Limitations of first law of thermodynamics

Unsteady Flow Processes and their analysis :-

In earlier discussions, for a steady flow system, it has been assumed that the properties do not change with time.

However, there exist a number of systems such as filling up of a bottle or emptying of a vessel etc. in which properties change continuously as the process proceeds. Such systems can not be analysed with the steady state assumptions. Unsteady flow processes are also known as transient flow processes or variable flow processes.

Let us take example of filling up of the bottle.

The bottle is filled up gradually, therefore it is case of an unsteady system. By conservation of mass, the unsteady process over a period of time '*dt*' can be expressed as following in generic form.

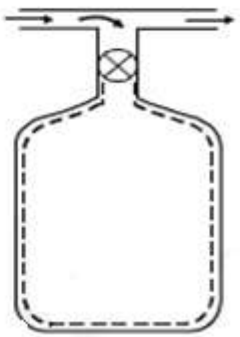


Fig. Filling of bottle

(Mass entering the control volume in time *dt*)

– (Mass leaving the control volume in time *dt*)

= Net change in mass in control volume in time *dt*.

If the mass flow rate at inlet and exit are given as m_i, m_e then

$$\frac{dm_i}{dt} - \frac{dm_e}{dt} = \frac{dm_{cv}}{dt}$$

and also, $\sum m_i - \sum m_e = (m_{\text{final}} - m_{\text{initial}})_{cv}$

By the conservation of energy principle applied on control volume for time '*t*', energy balance yields;

Net energy interaction across the boundary in time *dt*

+ Energy entering into control volume in time *dt*

– Energy leaving out of control volume in time *dt*

= Change in energy in control volume in time *dt*

Mathematically, it can be given as:

$$\boxed{(Q - W) + \sum E_i - \sum E_e = \Delta E_{cv}}$$

where $$E_i = \int_0^t m_i\left(h_i + \frac{C_i^2}{2} + gz_i\right).dt$$

$$E_e = \int_0^t m_e\left(h_e + \frac{C_e^2}{2} + gz_e\right).dt$$

Thus, the above mass balance and energy balance can be used for analysing the unsteady flow systems with suitable assumptions.

It may be assumed that the control volume state is uniform and fluid properties are uniform and steady at inlet and exit.

Simplified form of energy balance written above can be given as;

$$Q - W + \sum m_i\left(h_i + \frac{C_i^2}{2} + gz_i\right) - \sum m_e\left(h_e + \frac{C_e^2}{2} + gz_e\right)$$

$$= (m_{\text{final}} \cdot u_{\text{final}} - m_{\text{initial}} \cdot u_{\text{initial}})_{cV}$$

If the changes in kinetic energy and potential energy are negligible, then energy balance gets modified as;

$$Q - W + \sum m_i \cdot h_i - \sum m_e \cdot h_e = (m_{\text{final}} \cdot u_{\text{final}} - m_{\text{initial}} \cdot u_{\text{initial}})_{cV}$$

Case 1: Let us now use the energy and mass balance to the unsteady flow process of filling up a bottle as shown in Figure Bottle is initially empty and connected to a pipe line through valve for being filled.

Let us denote initial state of system by subscript 1 and final state by 2.

Initially as bottle is empty, so $m_1 = 0$

From mass balance

$$\Sigma m_i - \Sigma m_e = (m_2 - 0)_{cv}$$

Here there is no exit from the bottle so $m_e = 0$

hence, $\Sigma m_i = m_2$

or, $m_i = m_2$

Mass entered into bottle = Final mass inside the bottle

Applying the energy balance assuming change in kinetic and potential energy to be negligible, treating bottle filling process to be occurring in insulated environment, and no work interaction, we get

$Q \approx 0$, $W \approx 0$, $\Delta KE \approx 0$, $\Delta PE \approx 0$,

Initial internal energy in bottle = 0

Mass leaving = 0

$$0 = -\Sigma m_i \cdot h_i + (m_2 \cdot u_2)_{cv}$$

or $m_i \cdot h_i = m_2 u_2$

also $\boxed{h_i = u_2 \text{ as } m_i = m_2}$

Enthalpy of fluid entering bottle = Final internal energy of fluid in bottle.

If fluid is ideal gas, then $c_p \cdot T_i = c_v \cdot T_2$

or $T_2 = \gamma \cdot T_i$

where $\frac{c_p}{c_v} = \gamma$

Case 2: Let us now take a case of emptying of bottle. Arrangement is shown in Fig. 3.28.

Initially bottle has mass m_1 and finally as a result of emptying, say mass left is m_2 after some time.

Applying mass balance, (as mass entering is zero),

or, $0 - \Sigma m_e = (m_2 - m_1)_{cv}$

or $\Sigma m_e = (m_1 - m_2)_{cv}$

or $\boxed{m_e = (m_1 - m_2)_{cv}}$

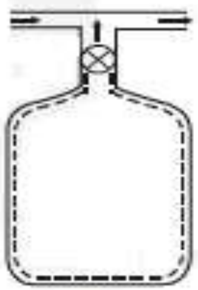


Fig. Emptying of bottle

Total mass leaving the bottle = (Mass reduced in bottle)

Applying energy balance, with the assumptions given below;

(i) No heat interaction i.e. $Q = 0$

(ii) No work interaction i.e. $W = 0$

(iii) No change in kinetic energy i.e. $\Delta KE = 0$

(iv) No change in potential energy i.e. $\Delta PE = 0$

$$-\sum m_e \cdot h_e = (m_2 u_2 - m_1 u_1)_{cv}$$

or, $$(-m_e \cdot h_e) = (m_2 u_2 - m_1 u_1)_{cv}$$

Substituting for 'm_e' we get $(m_2 - m_1)_{cv} \cdot h_e = (m_2 u_2 - m_1 u_1)_{cv}$

In case of complete emptying, $m_2 = 0$

and so, $\boxed{h_e = u_1}$

Limitations of first law of thermodynamics:-

First law of thermodynamics based on law of energy conservation has proved to be a powerful tool for thermodynamic analysis. But over the period of time when it was applied to some real systems, it was observed that theoretically first law stands valid for the processes which are not realizable practically. It was then thought that there exist certain flaws in first law of thermodynamics and it should be used with certain limitations.

Say for example let us take a bicycle wheel and paddle it to rotate. Now apply brake to it. As a result of braking wheel comes to rest upon coming in contact with brake shoe. Stopping of wheel is accompanied by heating of brake shoe. Examining the situation from Ist law of thermodynamics point of view it is quite satisfying that rotational energy in wheel has been transformed into heat energy with shoe, thus causing rise in its temperature.

Now, if we wish to introduce the same quantity of heat into brake shoe and wish to restore wheel motion then it is not possible simply, whereas theoretically first law permits the conversion from heat to work (rotation of wheel in this case) as well.

Therefore, it is obvious that Ist law of thermodynamics has certain limitations as given below:

(*i*) First law of thermodynamics does not differentiate between heat and work and assures full convertibility of one into other whereas full conversion of work into heat is possible but the vice-versa is not possible.

(*ii*) First law of thermodynamics does not explain the direction of a process. Such as theoretically it shall permit even heat transfer from low temperature body to high temperature body which is not practically feasible. Spontaneity of the process is not taken care of by the first law of thermodynamics.

Perpetual motion machine of the first kind (PMM-I) is a hypothetical device conceived, based on violation of First law of thermodynamics. Let us think of a system which can create energy as shown below.

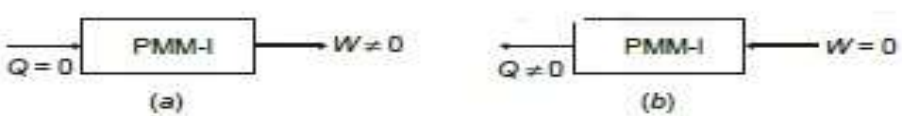


Fig. PMM-I, based on violation of Ist law of thermodynamics

Here a device which is continuously producing work without any other form of energy supplied to it has been shown in (*a*), which is not feasible.

Similarly a device which is continuously emitting heat without any other form of energy supplied to it has been shown in (*b*), which is again not feasible.

Problems:-

Example 1 Air flows steadily at the rate of 0.5 kg/s through an air compressor, entering at 7m/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. 1 shows the details of the problem.

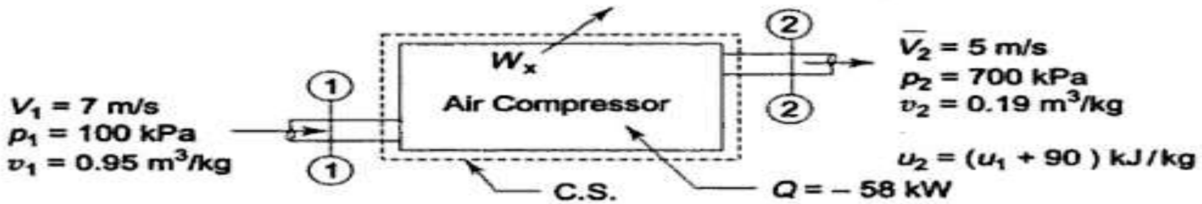


Fig. Ex. 1

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

$$w\left(u_1 + p_1v_1 + \frac{V_1^2}{2} + Z_1g\right) + \frac{dQ}{d\tau}$$

$$= w\left(u_2 + p_2v_2 + \frac{V_2^2}{2} + Z_2g\right) + \frac{dW_x}{d\tau}$$

$$\therefore \frac{dW_x}{d\tau} = -w\left[(u_2 - u_1) + (p_2v_2 - p_1v_1) + \frac{V_2^2 - V_1^2}{2} + (Z_2 - Z_1)g\right] + \frac{dQ}{d\tau}$$

$$\therefore \quad \frac{dW_x}{d\tau} = -0.5\,\frac{kg}{s}\left[90\,\frac{kJ}{kg} + (7 \times 0.19 - 1 \times 0.95)100\,\frac{kJ}{kg}\right.$$

$$\left. + \frac{(5^2 - 7^2) \times 10^{-3}}{2}\,\frac{kJ}{kg} + 0\right] - 58 \text{ kW}$$

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

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

Ans. (a)

Problems:-

Rate of work input is 122 kW.

(b) From mass balance, we have

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

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

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

Ans. (b)

Example 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 m³/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 m³/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. 2.

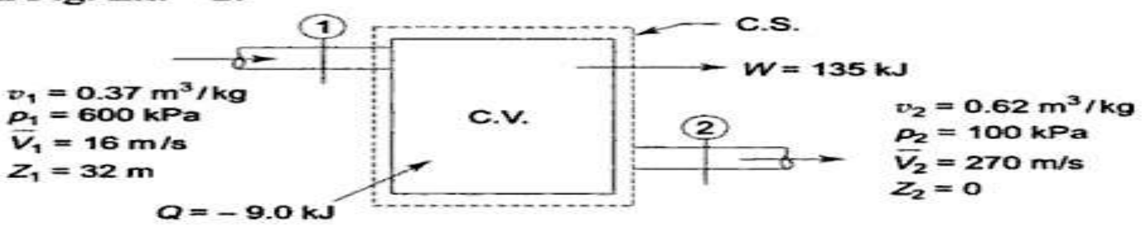


Fig. Ex. 2

$$u_1 + p_1 v_1 + \frac{\mathbf{V}_1^2}{2} + Z_1 g + \frac{\mathrm{d}Q}{\mathrm{d}m} = u_2 + p_2 v_2 + \frac{\mathbf{V}_2^2}{2} + Z_2 g + \frac{\mathrm{d}W_x}{\mathrm{d}m}$$

$$\therefore \quad u_1 - u_2 = (p_2 v_2 - p_1 v_1) + \frac{\mathbf{V}_2^2 - \mathbf{V}_1^2}{2} + (Z_2 - Z_1)g + \frac{\mathrm{d}W_x}{\mathrm{d}m} - \frac{\mathrm{d}Q}{\mathrm{d}m}$$

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

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

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

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

Specific internal energy decreases by 20.136 kJ.

Problems:-

Example-3 In a steam power station, steam flows steadily through a 0.2 m diameter pipeline from the boiler to the turbine. At the boiler end, the steam conditions are found to be; p = 4 MPa, t = 400 ^{0}C , h = 3213.6 kJ/kg and v = 0.073 m^3/kg. At the turbine end, the conditions are found to be; p = 3.5 MPa, t = 392 ^{0}C, h = 3202.6 kJ/kg and v = 0.084 m^3/kg. There is a heat loss of 8.5 kJ/kg from the pipeline. Calculate the steam flow rate.

Example-4 An evacuated bottle of 0.5 m^3 volume is slowly filled from atmospheric air at 1.0135 bars until the pressure inside the bottle also becomes 1.0135 bar. Due to heat transfer, the temperature of air inside the bottle after filling is equal to the atmospheric air temperature. Determine the amount of heat transfer.

(Lecture-5)

Second law of Thermodynamics:-

The lecture contains

- **Limitations of First Law of Thermodynamics**
- **Heat Engine**
- **Heat Pump**
- **Refrigerator**
- **KELVIN PLANCK STATEMENT**

Engineering Thermodynamics (BME-12)

UNIT-II (Lecture-5)

Limitations of First Law of Thermodynamics

The first law of thermodynamics is a law of conservation of energy. It does not specify the direction of the process. All spontaneous processes processed in one direction only. The first law of thermodynamics does not deny the feasibility of a process reversing itself. The first law of thermodynamics does not provide answers to the following questions.

- IS A PARTICULAR PROCESS / REACTION FEASIBLE?
- TO WHAT EXTENT DOES THE PROCESS / REACTION PROCEED?
- IS COMPLETE CONVERSION OF INTERNAL ENERGY INTO WORK POSSIBLE?

There exists a law which determines the direction in which a spontaneous process proceeds. The law, known as the second law of thermodynamics, is a principle of wide generality and provides answer to the above questions.

It is essential to understand the meaning of the following terms in order to discuss the second law of thermodynamics:

➢Thermal reservoir is a large body from which a finite quantity of energy can be extracted or to which a finite quantity of energy can be added as heat without changing its temperature.

➢A source is a thermal reservoir at high temperature from which a heat engine receives the energy as heat.

➢A sink is a low temperature thermal reservoir to which a heat engine rejects energy as heat.

Heat Engine

- A heat engine is a device which converts the energy it receives at heat, into work.
- It is a cyclically operating device.
- It receives energy as heat form a high temperature body, converts part of it into work and rejects the rest to a low temperature body.
- A thermal power plant is an example of a heat engine.

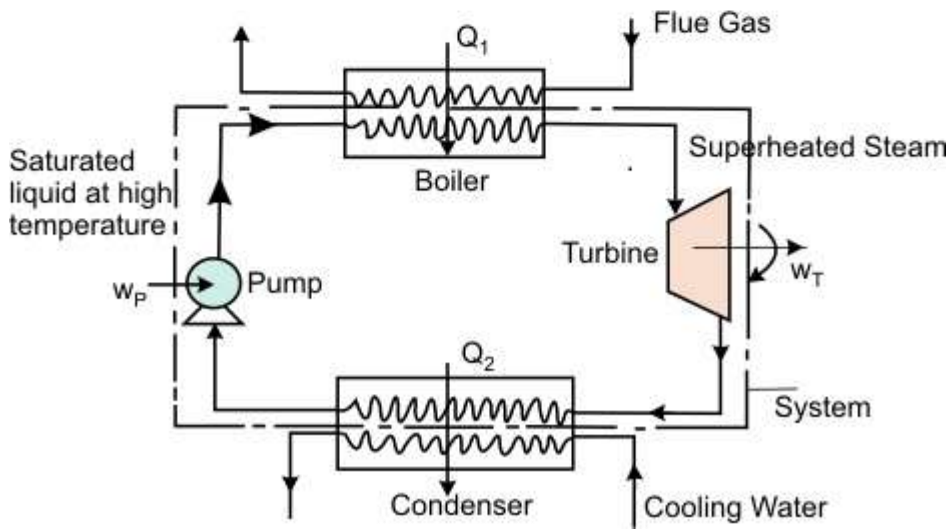


Figure describes a basic arrangement of a thermal power plant

- In the boiler, the working fluid receives a certain amount of heat (Q_1) from the hot combustion products.

- The superheated steam enters a turbine where it undergoes expansion performing the shaft work (W_T).
- The low pressure steam enters a condenser where it exchange energy as heat at constant pressure with the cooling water and emerges as the condensate. The condensate rejects a certain amount of heat (Q_2) to the cooling water.

The low pressure condensate from the condenser enters the pump. Work (W_P). is done on the pump to elevate the condensate to the boiler pressure and return it to the boiler.

In the above example,

Work done by the system = (W_T - W_P)

Energy absorbed as heat by the system = Q_1

Energy rejected as heat by the system = Q_2

According to first law of thermodynamics, the heat and work interaction are related by the equation.

$$\oint dQ = \int dW$$

Finally, the thermal efficiency (η) of a heat engine can be expressed as

$$\eta = \frac{(\text{Energy absorbed as heat} - \text{Energy rejected as heat})}{\text{Energy absorbed as heat}}$$

$$= \frac{\text{Net work done}}{\text{Energy absorbed as heat}}$$

Or,

$$\eta = \frac{Q_1 - Q_2}{Q_1}$$

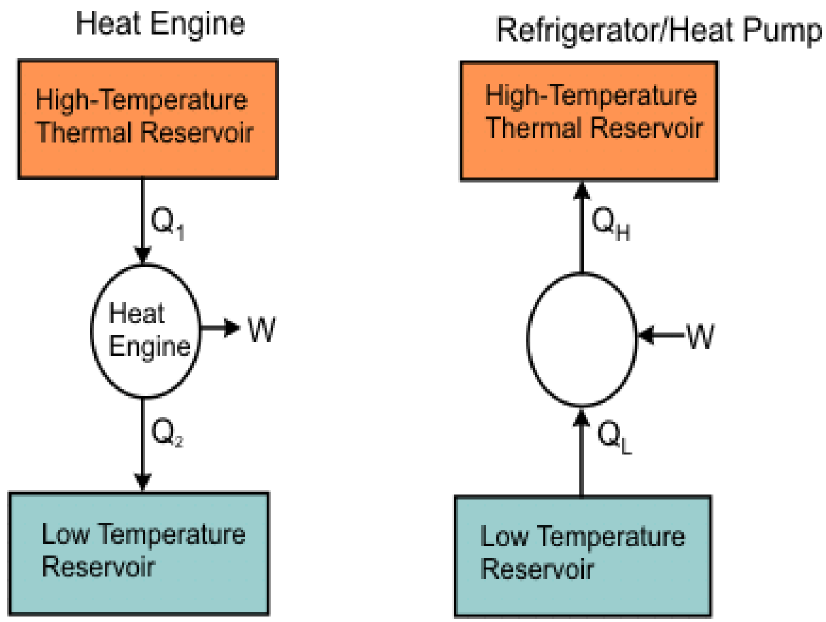
Heat Pump

Heat Pump is cyclically operating device which absorbs energy form a low temperature reservoir and reject energy as heat to a high temperature reservoir when work is performed on the device. Its objective is to reject energy as heat to a high temperature body (space heating in winter). The atmosphere acts as the low temperature reservoir.

Refrigerator

A refrigerator is a cyclically operating device which absorbs energy as heat from a low temperature body and rejects energy as heat to a high temperature body when work is performed on the device. The objective of this device is to refrigerate a body at low temperature. Usually it uses atmosphere as the high temperature reservoir.

Engineering Thermodynamics (BME-12)
UNIT-II (Lecture-5)



Refer to figure. Let Q_L and Q_H represents the amount of energy absorbed as heat from the low temperature reservoir and the energy rejected as heat to the high temperature reservoir respectively, Let W be the work done on the device to accomplish the task.

$$Q_H - Q_L = W$$

Therefore,

$$(COP)_R = \frac{Q_L}{W} = \frac{Q_L}{(Q_H - Q_L)}$$

$$(COP)_{HP} = \frac{Q_H}{W} = \frac{Q_H}{(Q_H - Q_L)}$$

Heat engine and the refrigerator (/heat pump) can be represented as shown in Figure.

The efficiency of a heat engine is given by

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

$W_{net} < Q_1$ since Q_1 (heat) transferred to the system cannot be completely converted to work in a cycle. Therefore η is less than unity. A heat engine can never be 100 efficient. Therefore $Q_2 > 0$ i.e., there has always to be a heat rejection. Thus a heat engine has to exchange heat with two reservoirs, the source and the sink. This experience leads to the proposition of the second law of thermodynamics which has been stated in several different ways.

Engineering Thermodynamics (BME-12)
UNIT-II

Lecture-6

The lecture contains

- Kelvin - Planck Statement
- Clausius Statement of the Second Law

KELVIN PLANCK STATEMENT

It is impossible to construct a cyclically operating device such that it produces no other effect than the absorption of energy as heat from a single thermal reservoir and performs an equivalent amount of work.

The only option then is that the engine converts part of the energy it receives as heat into work and rejects the rest to another thermal reservoir the temperature of which is less than the temperature of the source.

Two thermal reservoirs, one of high temperature (source), from which the working fluid receives energy as heat, and the other of low temperature (sink), to which the working fluid rejects energy as heat, are needed for a heat engine. Once the heat engine rejects a part of the energy it receives, its efficiency becomes less than one.

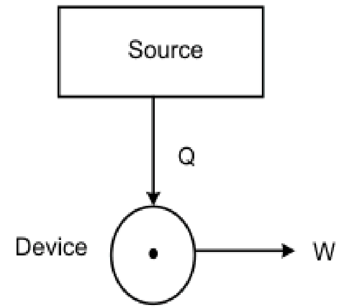
Thus the Kelvin Planck statement further implies that no heat engine can have a thermal efficiency of one (hundred percent). This does not violate the first law of thermodynamics either.

Engineering Thermodynamics (BME-12)
UNIT-II (Lecture-6)

Kelvin - Planck Statement (continued)

Second law restricts the thermal efficiency of a heat engine to less than one. It stipulates that some portion of the energy absorbed as heat from a source must always be rejected to a low temperature sink.

Wilhelm Ostwald introduced the concept of perpetual motion machine of the second kind (PMMSK or PMM2), that is, of a device which would perform work solely by absorbing energy as heat from a body. Such a device does not violate the first law of thermodynamics.

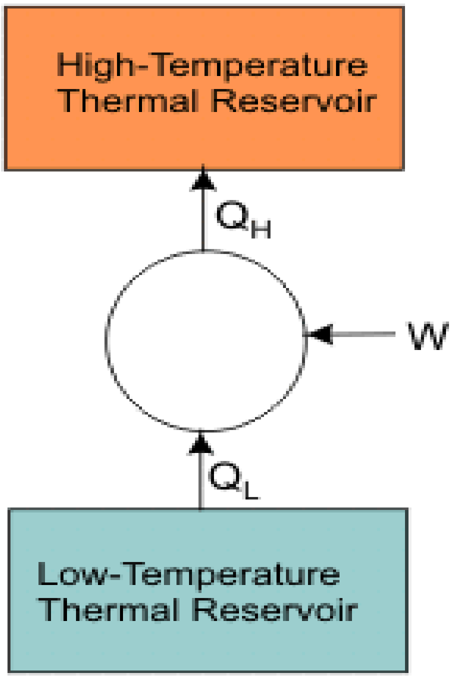


A PMMSK is a hypothetical device (Figure) which working cyclically, receives energy as heat from a single thermal reservoir, and delivers as equivalent amount of work. **The Kelvin-Planck statement of the second law** tells us that it is impossible to constructs a perpetual motion machine of the second kind.

Clausius Statement of the Second Law

Heat always flows from a body at 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 low-temperature body to a high temperature body.

This statement tells us that it is impossible for any device, unaided by an external agency, to transfer energy as heat from a cooler body to a hotter body. Consider the case of a refrigerator or a heat pump (Figure).



Clausius Statement of the Second Law (cont…)

When W = 0

$$(COP)_R \rightarrow \infty$$

$$(COP)_{HP} \rightarrow \infty$$

It is impossible to construct a refrigerator or a heat pump whose COP is infinity. Consider a domestic refrigerator, this device extracts energy as heat from the substance to be coded and transfers it to the surroundings. The refrigerator is supplied with electric power. Energy transfer as heat from a high temperature body to a low temperature body is a spontaneous process.

The Clausius statement of the second law of thermodynamics tells that this spontaneous process cannot proceed in the reverse direction.

Apparently, the Kelvin Planck statement and the Clausius statement of the second law of thermodynamics are altogether different. They are not ! Instead, they are equivalent. A violation of Kelvin Planck statement leads to a violation of the Clausis statement too and vice-versa.

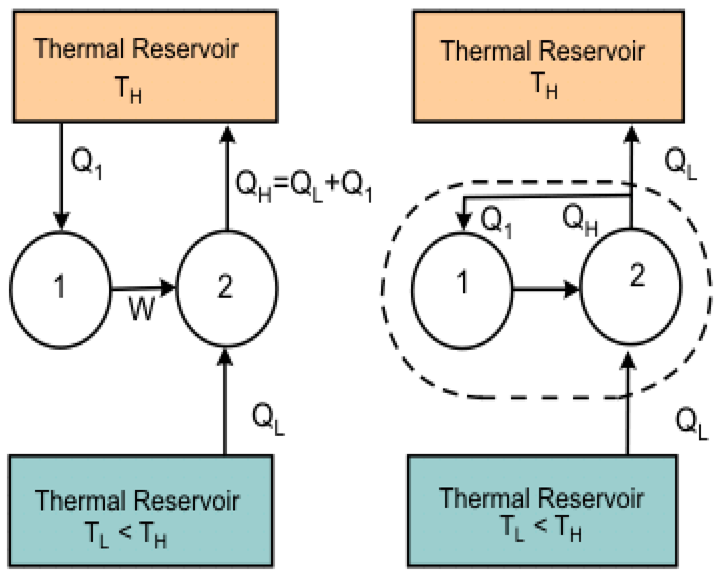
Engineering Thermodynamics (BME-12)
UNIT-II

Lecture-7

The lecture contains

- Clausius Statement of the Second Law
- **Reversibility, Irreversibility and Carnot cycle**

Clausius Statement of the Second Law (cont…)



Refer to Figure that is, it is possible to construct a device I which, working cyclically, absorbs energy a heat (Q_1) from a source at temperature T_H and performs an equivalent amount of work ($W = Q_1$)

Next consider a device II which absorbs Q_L amount of energy from a low temperature body T_L at and delivers energy as heat Q_H to a high temperature reservoir at T_H

To accomplish this, work W is done on the device. The device II does not violate the Clausius statement. For device II, we can write $Q_H = Q_L + W$. Now combine I and II. The work delivered by device I is used by device, II.

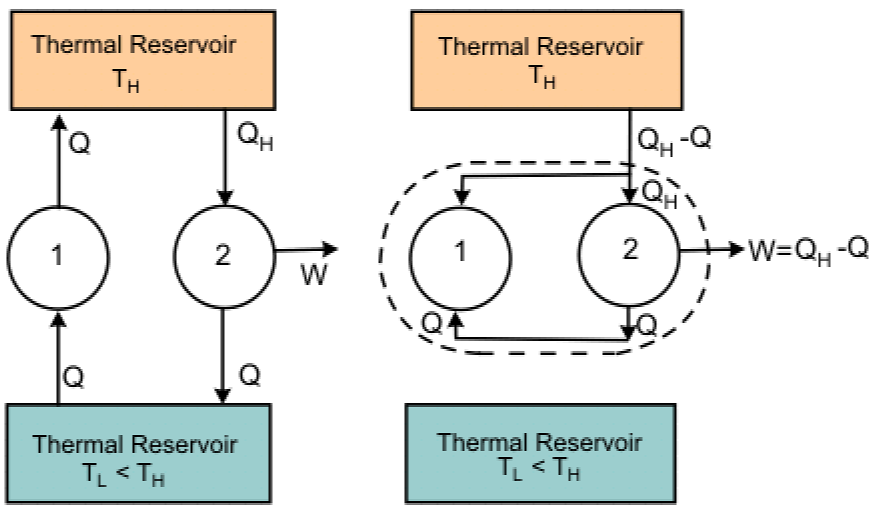
Clausius Statement of the Second Law (cont…)

Then

$W = Q_1$

$Q_H = Q_L + W = Q_L + Q_1$

This combined device (which is no more aided by any external agency) working cyclically, is not producing any effect other than the transfer of energy as heat Q_L from the low temperature reservoir to the high temperature reservoir. This is in violation of the Clausius statement.



I **II**

To prove that violation of the Clausius' statement leads to violation of Kelvin Planck statement, let us assume that the Clausius' statement is incorrect.

Clausius Statement of the Second Law (cont…)

That is, it is possible to constructs a device I (refer to Figure) such that it transfers energy as heat Q from a body at lower temperature to a body at higher temperature unaided by any external agency.

Consider another device II which receives energy as heat Q_H from a body at higher temperature, delivers work W and rejects energy as heat Q to the body at a low temperature. Device II does not violate Kelvin Planck statement. Application of the first law of thermodynamics to device II gives,

$$Q_H = Q_L + W$$

Now consider the combination of devices I and II as a single device. This combined device, working cyclically, absorbs $(Q_H – Q)$ amount of energy as heat from the thermal reservoir at temperature T_H and delivers work $(W = Q_H – Q)$, leaving the thermal reservoir at temperature T_L unaffected. That is, the resulting device is a PMMSK, which is in violation of the Kelvin Planck statement. Thus the Kelvin Planck statement and the Clausius' statement are equivalent.

Engineering Thermodynamics (BME-12)
UNIT-II (Lecture-7)

Reversibility, Irreversibility and Carnot cycle

The second law of thermodynamics distinguishes between reversible and irreversible processes.

A process is reversible with respect to the system and surroundings if the system and the surroundings can be restored to their respective initial states by reversing the direction of the process, that is, by reversing the heat transfer and work transfer. The process is irreversible if it cannot fulfill this criterion.

- If a process can proceed in either direction without violating the second law of thermodynamics, it is reversible process. A reversible process is carried out infinitely slowly with an infinitesimal gradient, so that every state passed through by the system is an equilibrium state. So, a reversible process is a quasi-static process which can proceed in either direction.

- Given a process, if the attempt to reverse its direction leads to a violation of the second law of thermodynamics, then the given process is irreversible.

Any natural process carried out with a finite gradient is an **irreversible process** . A reversible process which consists of a succession of equilibrium states, is an idealized hypothetical process, approached only as a limit. **It is said to be an asymptote to reality**, All spontaneous processes are irreversible.

Engineering Thermodynamics (BME-12)

UNIT-II (Lecture-7)

Irreversible Processes

The example of irreversible processes are: Motion with friction, free expansion, Expansion/ compression with finite pressure difference, Energy transfer as heat with finite , Mixing of matter at different states, Mixing of non-identical gases.

Reversible Processes

The processes which can be idealized as reversible are: Motion without friction, Expansion/compression with infinitesimal pressure difference, Energy transfer as heat with infinitesimal temperature difference.

Carnot Cycle

A French engineer Sadi Carnot was the first to introduce the idea of reversible cycle. From the second law, it has been observed that the efficiency of a heat engine is less than unity. If the efficiency of heat engine is less than unity, what is the maximum efficiency of a heat engine? This can be answered by considering the Carnot cycle. The concept of carnot cycle is executed via Carnot engine.

Engineering Thermodynamics (BME-12)
UNIT-II

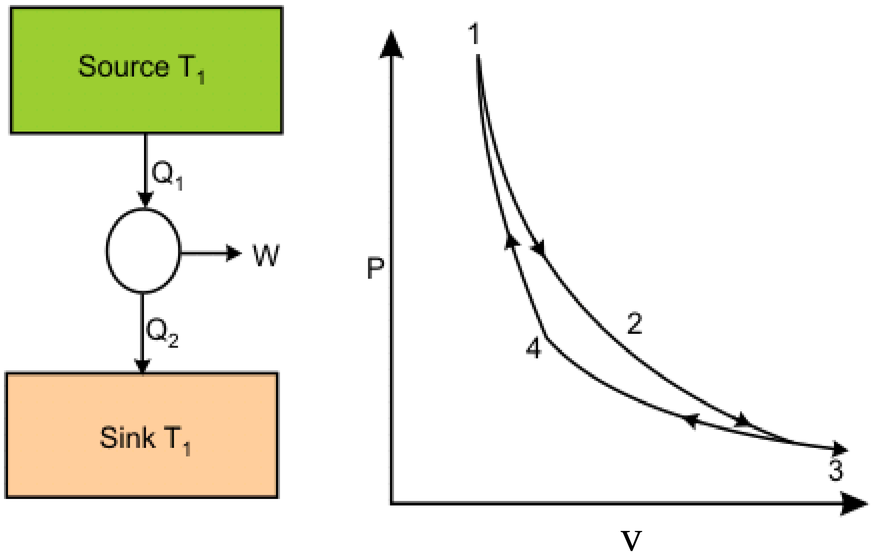
Lecture-8

The lecture contains

- **Carnot Engine**

Carnot Engine:-

- Let us consider the operation of a hypothetical engine which employs the Carnot cycle. The Carnot engine consists of a **cylinder-piston assembly** in which a certain amount of gas(working fluid) is enclosed. Refer to Figure representing the Carnot cycle.



Reversible Isothermal Heat Addition

In the first process, the cylinder head is brought into contact with a source at temperature T_1 The gas inside the cylinder is also at temperature T_1. The gas expands **reversibly and isothermally** . During this process, the system absorbs energy as heat Q_1 from the source. The system changes its state from 1 to 2 on the p-v diagram.

$$Q_1 = (U_2 - U_1) + W_{1-2}$$

where, for an ideal gas, $U_2 – U_1$

Reversible Adiabatic Expansion

In the second process, the cylinder head is insulated and the gas is allowed to expand till its temperature is equal to the sink temperature . The system thus reaches state 3. **This is a reversible adiabatic process.**

$$0 = (U_3 - U_2) + W_{2-3}$$

Reversible Isothermal Heat Rejection

In the next process, the system is brought into contact with the sink which is at a temperature T_2.

The heat Q_2 leaves the system and the internal energy further decreases

$$-Q_2 = (U_4 - U_3) - W_{3-4}$$

where, only for an ideal gas, $U_4 = U_3$

Through a reversible isothermal process the system reaches state 4.

Reversible Adiabatic Compression

- In the next process, the gas is compressed reversibly and adiabatically till it reaches the initial state 1, thus, completing the cycle.

$$0 = U_1 - U_4 - W_{4-1}$$

Summing up all the processes, one can write

$$Q_1 - Q_2 = (W_{1-2} + W_{2-3}) - (W_{3-4} + W_{4-1})$$

Or,

$$\sum_{cycle} Q_{net} = \sum_{cycle} W_{net}$$

The thermal efficiency,

$$\eta = \frac{W}{Q_1} = \frac{Q_1 - Q_2}{Q_1} = 1 - \frac{Q_2}{Q_1}$$

Efficiency of Carnot Engine Using Ideal Gas

- 1-2: A reversible isothermal expansion with heat addition

$$Q_1 = \int_1^2 P dv = RT_1 \ ln\left(\frac{v_2}{v_1}\right)$$

2-3: A reversible adiabatic expansion

$$W = c_v (T_1 - T_2)$$

- 3-4: A reversible isothermal compression with heat rejection

$$Q_2 = \int_3^4 P dv = RT_2 \; In\left(\frac{v_4}{v_3}\right)$$

- 4-1: A reversible adiabatic compression

$$W = \int_4^1 du = c_v\left(T_2 = -T_1\right)$$

$$\sum W = RT_1 \; In\left(\frac{\hat{v}_2}{\hat{v}_1}\right) + c_v\left(T_1 - T_2\right) + RT_2 \; In\left(\frac{v_4}{v_3}\right) + c_v\left(T_2 - T_1\right)$$

$$= RT_1 \; In\left(\frac{v_2}{v_1}\right) + RT_2 \; In\left(\frac{v_4}{v_3}\right)$$

Energy absorbed as heat

$$Q_1 = RT_1 \; In\left(v_2 / v_1\right)$$

Thermal efficiency,

$$\eta = 1 + \frac{RT_2 \ \text{ln}(v_4 / v_3)}{RT_1 \ \text{ln}(v_2 / v_1)}$$

Here, for the ideal gases we can write

$$\frac{T_2}{T_1} = \left(\frac{v_2}{v_3} \right)^{\gamma - 1}$$

$$\frac{T_2}{T_1} = \left(\frac{v_1}{v_4} \right)^{\gamma - 1}$$

Also,

$$\frac{v_2}{v_3} = \frac{v_1}{v_4}$$

Or,

$$\frac{v_2}{v_1} = \frac{v_3}{v_4}$$

So,

$$\eta = 1 - \frac{T_2 \; In(v_2 / v_1)}{T_1 \; In(v_2 / v_1)} = 1 - \frac{T_2}{T_1}$$

Engineering Thermodynamics (BME-12)
UNIT-II

(Lecture-9)

The lecture contains

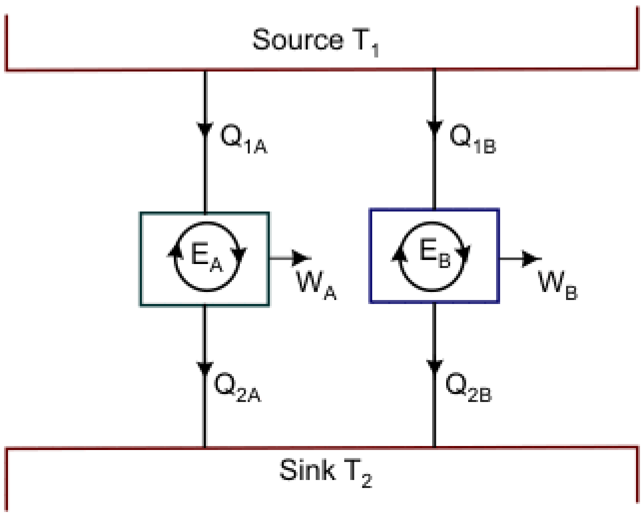
- Carnot's Principle I
- Carnot's Principle II

Engineering Thermodynamics (BME-12)
UNIT-II (Lecture-9)

Two consequences of the second law of thermodynamics are will known as Carnot's principles.

Principle I:

No heat engine operating between the two given thermal reservoirs, each of which is maintained at a constant temperature, can be more efficient than a reversible engine operating between the same two thermal reservoirs. Refer to Figure



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.

Engineering Thermodynamics (BME-12)
UNIT-II (Lecture-9)

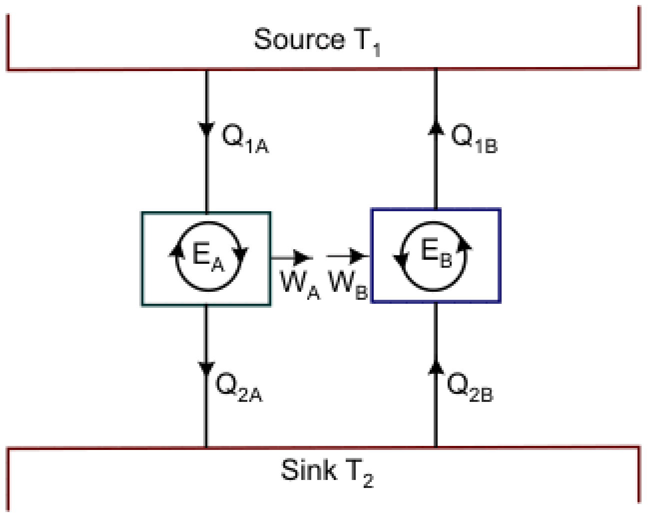
Let E_A be any heat engine and E_B any reversible heat engine. We are to prove that the efficiency of E_B is more than that of E_A . Let us assume that it is not true $\eta_A > \eta_B$.

Let the rates of working of the engines be such that

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

Since,

$$\eta_A > \eta_B \Rightarrow \frac{W_A}{Q_{1A}} > \frac{W_B}{Q_{1B}}; \ or, \ W_A > W_B$$



Now let the direction of be reversed.

Refer to Figure , Since E_B is a reversible heat engine, the magnitudes of heat and work quantities will remain the same, but their directions will be reversed as shown.

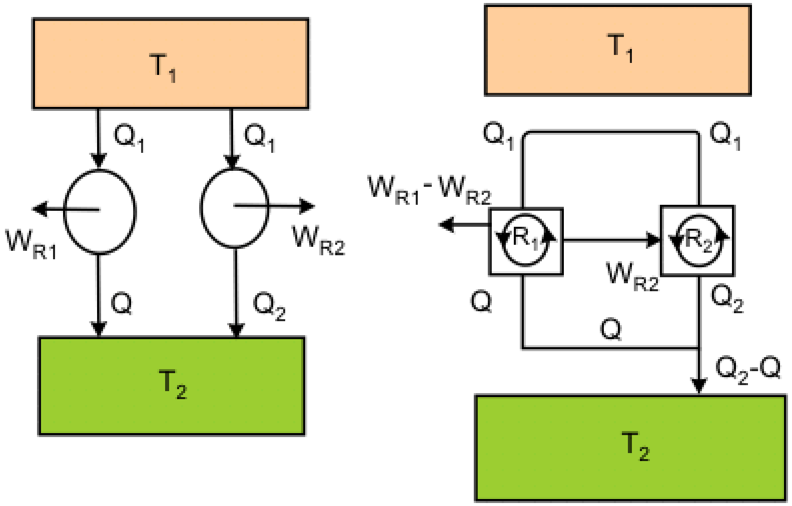
Since $W_A > W_B$ some part of W_A (equal to W_B) may be fed to drive the reversed heat engine E_B. Since, $Q_{1A} = Q_{1B} = Q_1$, the heat discharged by the reversed E_B may be supplied to E_A.

The source may, therefore, be eliminated. The net result is that E_A and reversed E_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 $\eta_A > \eta_B$ is wrong.

Therefore, $\eta_B \geq \eta_A$

- **Principle II:**
- All reversible heat engines operating between the two given thermal reservoirs have the same efficiency. The efficiency of reversible heat engine does not depend on the working fluid, it depends only on the temperature of the reservoirs between which it operates.
- To prove the proposition, let us assume that the efficiency of the reversible engine R_1 is greater than the efficiency of the reversible engine R_2 .



Engineering Thermodynamics (BME-12)
UNIT-II (Lecture-9)

Refer to Figure . The engine R_1 absorbs energy as heat Q_1 from the constant temperature thermal reservoir at T_1, does work W_{R1} and rejects energy as heat Q to the reservoir at T_2. The engine R_2 absorbs energy as heat Q_1 from the reservoir at T_1, does work W_{R2} and rejects energy as heat Q_2 to the reservoir at T_2. Then $W_{R1} = Q_1 - Q$, $W_{R2} = Q_1 - Q_2$

$$\eta_{R1} = W_{R1} / Q_1 = 1 - \frac{Q}{Q_1}$$

and,

$$\eta_{R2} = W_{R2} / Q_1 = 1 - \frac{Q_2}{Q_1}$$

By assumption,

$$\eta_{R1} > \eta_{R2}$$

Then,

$$\left(1-\frac{Q}{Q_1}\right) > \left(1-\frac{Q_2}{Q_1}\right) \quad or \quad Q < Q_2$$

Therefore, $W_{R1} > W_{R2}$

Since R_2 is a reversible engine, it can be made to execute the cycle in the reversed order. That is, when work W_{R2} is performed on the device, it absorbs energy as heat, Q_2 from the reservoir at T_2 and rejects energy as heat Q_1 to the reservoir at T_1. Since, $W_{R1} > W_{R2}$, R_2 can be run as a heat pump utilizing **part of the work done by** R_1. The combination of the two devices is also shown in the figure.

The net work done by the device is given by

$$W_{R1} - W_{R2} = (Q_1 - Q) - (Q_1 - Q_2) = Q_2 - Q$$

The resulting device absorbs energy as heat $(Q_2 – Q)$ from the reservoir at T_2 .

- Does not require any interaction with the second reservoir.
- Delivers an equivalent amount of work.
- This is in violation of the Kelvin-Planck statement of the second law of thermodynamics. Hence the assumption that $\eta_{R1} > \eta_{R2}$, is incorrect. Therefore,

$$\eta_{R2} \geq \eta_{R1}$$

Nov let us assume that the reversible engine R_2 is more efficient then the reversible engine R_1. Then the reversible engine R_1 can be run as a heat pump, utilizing the part of the work done by R_2. By following the similar argument as the earlier case, we can arrive at the result that,

$$\eta_{R1} \geq \eta_{R2}$$

Hence, it can be concluded that $\eta_{R1} = \eta_{R2}$

Stated in works: All reversible engines operating between the two given thermal reservoirs have the same efficiency.

Problems:-

Example 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.

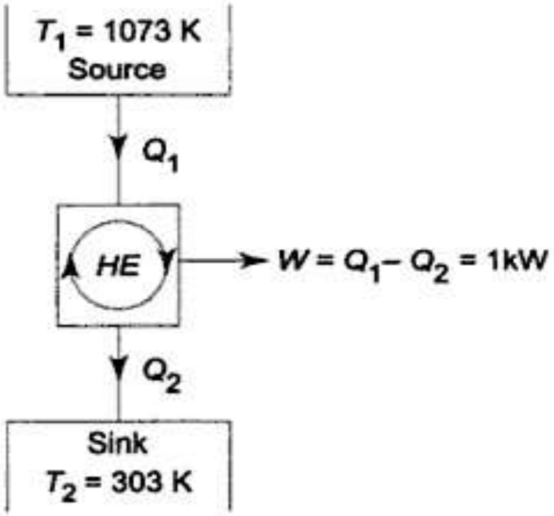


Fig.

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

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

$$= 1 - 0.282 = 0.718$$

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 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?

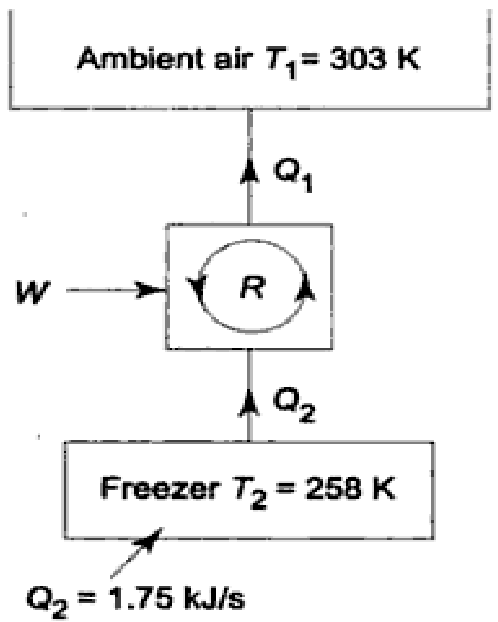
Solution Freezer temperature,

$$T_2 = -15 + 273 = 258 \text{ K}$$

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.



For minimum power requirement

$Q_2/T_2 = Q_1/T_1$

$$\therefore \qquad Q_1 = \frac{1.75}{258} \times 303 = 2.06 \text{ kJ/s}$$

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

$$= 2.06 - 1.75 = 0.31 \text{ kJ/s}$$

$$= 0.31 \text{ kW}$$

Example 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. is given by

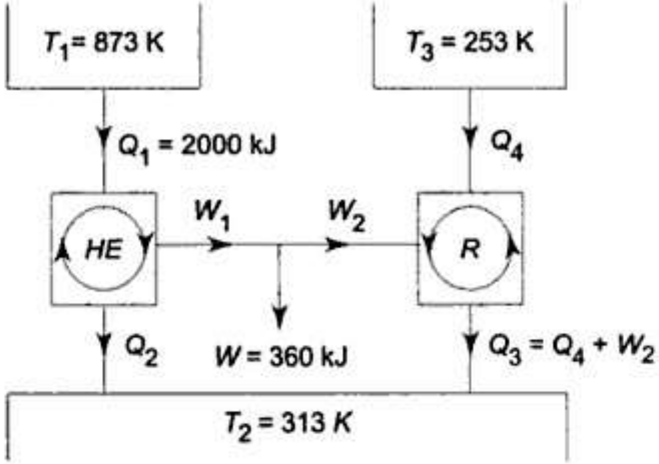


Fig.

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

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

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

Maximum COP of the refrigerator cycle

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

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

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

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

$\therefore \quad Q_4 = 4.22 \times 924 = 3899$ kJ

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

$Q_2 = Q_1 - W_1 = 2000 - 1284 = 716$ kJ

Heat rejection to the 40°C reservoir

$= Q_2 + Q_3 = 716 + 4823 = 5539$ kJ *Ans.* (a)

(b) Efficiency of the actual heat engine cycle

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

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

$= 513.6$ kJ

$\therefore \quad W_2 = 513.6 - 360 = 153.6$ kJ

COP of the actual refrigerator cycle

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

Therefore

$Q_4 = 153.6 \times 1.69 = 259.6$ kJ *Ans.* (b)

$Q_3 = 259.6 + 153.6 = 413.2$ kJ

$Q_2 = Q_1 - W_1 = 2000 - 513.6 = 1486.4$ kJ

Heat rejected to the 40°C reservoir

$= Q_2 + Q_3 = 413.2 + 1486.4 = 1899.6$ kJ *Ans.* (b)