

FIRST LAW OF THERMODYNAMICS

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The First Law of Thermodynamics states that work and heat are mutually convertible. The present tendency is to include all forms of energy. The First Law can be stated in many ways:

1. Energy can neither be created nor destroyed; it is always conserved. However, it can change from one form to another.
2. All energy that goes into a system comes out in some form or the other. Energy does not vanish and has the ability to be converted into any other form of energy.
3. If the system is carried through a cycle, the summation of work delivered to the surroundings is equal to summation of heat taken from the surroundings.
4. No machine can produce energy without corresponding expenditure of energy.
5. Total energy of an isolated system in all its forms, remain constant.

The first law of thermodynamics cannot be proved mathematically.

FIRST LAW FOR A CLOSED SYSTEM UNDERGOING A CYCLE

According to first law, when a closed system undergoes a thermodynamic cycle, the net heat transfer is equal to the net work transfer. The cyclic integral of heat transfer is equal to cyclic integral of work transfer.

$$\oint dQ = \oint dW.$$

where \oint stands for cyclic integral (integral around complete cycle), dQ and dW are small elements of heat and work transfer and have same units.

FIRST LAW FOR A CLOSED SYSTEM UNDERGOING A CHANGE OF STATE

According to first law, when a system undergoes a thermodynamic process (change of state) both heat and work transfer take place. The net energy transfer is stored within the system and is called stored energy or total energy of the system.

When a process is executed by a system the change in stored energy of the system is numerically equal to the net heat interaction minus the net work interaction during the process.

$$dE = dQ - dW \text{ -----(1)}$$

$$E_2 - E_1 = Q_{1-2} - W_{1-2}$$

Where E is an extensive property and represents the total energy of the system at a given state, i.e.,

E = Total energy

$$dE = dPE + dKE + dU$$

If there is no change in PE and KE then, PE = KE = 0

dE = dU, putting in equation (1), we get

$$dU = dQ - dW$$

$$\text{or } dQ = dU + dW$$

This is the first law of thermodynamics for closed system.

Where,

dU = Change in Internal Energy

dW = Work Transfer = PdV

dQ = Heat Transfer = mcdT

{Heat added to the system taken as positive and heat rejected/removal by the system taken as negative}

For a cycle dU = 0; dQ = dW

COROLLARIES OF FIRST LAW OF THERMODYNAMICS

Corollary 1 : (*First Law for a process*).

There exists a property of a closed system, the change in the value of this property during a process is given by the difference between heat supplied and work done.

$$dE = dQ - dW$$

where E is the property of the system and is called total energy which includes internal energy (U), kinetic energy (KE), potential energy (PE), electrical energy, chemical energy, magnetic energy, etc.

Corollary 2: (*Isolated System*).

For an isolated system, both heat and work interactions are absent (d Q = 0, d W = 0) and E = constant.

Energy can neither be created nor destroyed, however, it can be converted from one form to another.

Corollary 3 : (*PMM - 1*).

A perpetual motion machine of the first kind is impossible.

LIMITATIONS OF FIRST LAW OF THERMODYNAMICS

There are some important limitations of First Law of Thermodynamics.

1. When a closed system undergoes a thermodynamic cycle, the net heat transfer is equal to the net work transfer. The law does not specify the direction of flow of heat and work nor gives any condition under which energy transfer can take place.
2. The heat energy and mechanical work are mutually convertible. The mechanical energy can be fully converted into heat energy but only a part of heat energy can be converted into mechanical work. Therefore, there is a limitation on the amount of conversion of one form of energy into another form.

SPECIFIC HEAT

The specific heat of a solid or liquid is usually defined as the heat required by unit mass for raising its temperature through one degree.

i.e., $dQ = mcdT$;

$dQ = mC_p dT$; For a reversible non flow process at constant pressure;

$dQ = mC_v dT$; For a reversible non flow process at constant volume;

C_p = Heat capacity at constant pressure

C_v = Heat capacity at constant volume

JOULE'S LAW

Joules law experiment is based on constant volume process, and it states that the I.E. of a perfect gas is a function of the absolute temperature only.

i.e., $U = f(T)$

$dU = dQ - dW$;

At constant volume $dW = 0$

So $dU = dQ$; but $dQ = mC_v dT$, at constant volume

Hence $dU = mC_v dT$; for a perfect gas

ENTHALPY

It is the sum of I.E. (U) and product of pressure & volume.

$h = u + pv$

For unit mass $pv = RT$

$h = C_v T + RT = (C_v + R)T = C_p T$

$H = mC_p T$

$dH = mC_p dT$

RELATION BETWEEN TWO SPECIFIC HEATS

$dQ = dU + dW$; for a perfect gas

dQ at constant pressure

dU at Constant volume; $= mC_v dT = mC_v(T_2 - T_1)$

dW at constant pressure $= PdV = P(V_2 - V_1) = mR(T_2 - T_1)$

Putting all the values we get

$dQ = mC_v(T_2 - T_1) + mR(T_2 - T_1)$

$dQ = m(C_v + R)(T_2 - T_1)$

but $dQ = mC_p(T_2 - T_1)$

$mC_p(T_2 - T_1) = m(C_v + R)(T_2 - T_1)$

$C_p = C_v + R$; $C_p - C_v = R$ -----(1)

Now dividing by C_v ; we get

$C_p/C_v - 1 = R/C_v$; Since $C_p/C_v = \gamma$ (gamma = 1.41)

$\gamma - 1 = R/C_v$;

or;

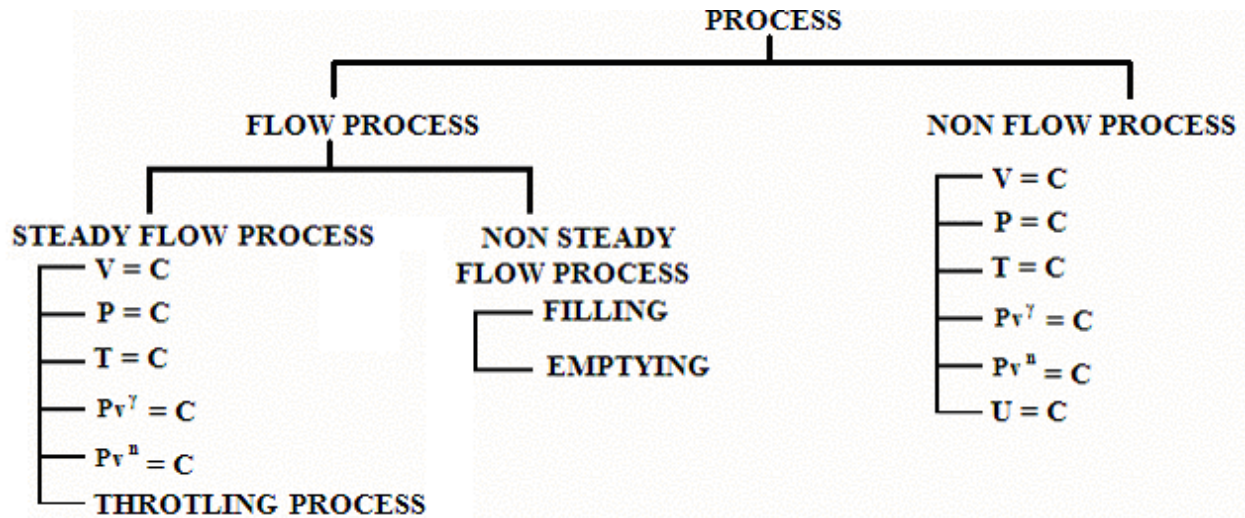
$$C_v = R/(\gamma - 1); C_p = \gamma R/(\gamma - 1); C_p > C_v; \gamma > 1$$

CONCEPT AND CLASSIFICATION OF THE PROCESS

A process is defined as a change in the state or condition of a substance or working medium. For example, heating or cooling of thermodynamic medium, compression or expansion of a gas, flow of a fluid from one location to another. In thermodynamics there are two types of processes; Flow process and Non flow process

Flow Process: The processes in open system permits the transfer of mass to and from the system. Such process is called flow process. The mass enters the system and leaves after exchanging energy. Examples are, I.C. Engines, Boilers.

Non Flow Process: The process occurring in a closed system where there is no transfer of mass across the boundary is called non flow process. In such process the energy in the form of heat and work cross the boundary of the system.



In steady flow, fluid flow at a uniform rate and the flow parameter do not change with time. For example, if the absorption of heat work output, gas flow etc. occur at a uniform rate (Not varying with time), the flow will be known as steady flow. But if these vary throughout the cycle with time, the flow will be known as non-steady flow process.

Examples are- Flow of gas or flow of heat in an engine but if a long interval of time is chosen as criteria for these flows, the engine will be known to be operating under steady – flow condition.

WORK DONE, HEAT TRANSFER AND CHANGE IN INTERNAL ENERGY IN FREE EXPANSION OR CONSTANT INTERNAL ENERGY PROCESS

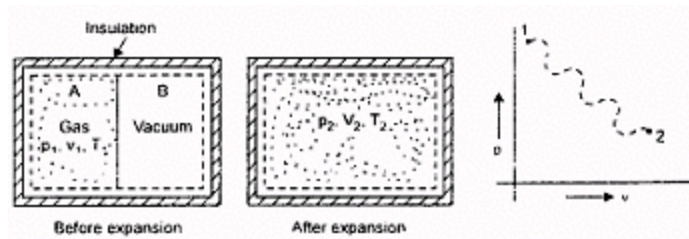


Fig 1

A free expansion process is such a process in which the system expands freely without experience any resistance. I.E. is constant during state change This process is highly irreversible due to eddy flow of fluid during the process and there is no heat transfer.

$$dU = 0; dQ = dW \text{ (For reversible process)}$$

$$dQ = 0; dW = 0; T_1 = T_2; dU = 0$$

MECHANICAL WORK IN DIFFERENT STEADY FLOW PROCESSES

work done by a steady flow process,

$$w_{1-2} = - \int_1^2 v dp$$

and work done in a non - flow process,

$$w_{1-2} = \int_1^2 p dv.$$

1. CONSTANT VOLUME PROCESS; $W_{1-2} = V (P_1 - P_2)$

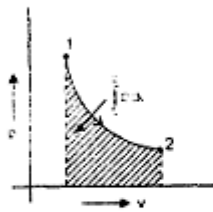
Steady flow equation,

$$dq - dW = dh + d(ke) + d(pe)$$

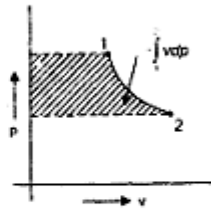
Now $h = u + pv$

Differentiating,

$$dh = du + d(pv) \\ = du + p dv + v dp.$$



Non-flow process



Steady flow process

From First Law of Thermodynamics for a closed system,

$$dq = du + p dv$$

$$dh = dq + v dp$$

$$\therefore dq - du = (dq + v dp) + d(ke) + d(pe)$$

$$\therefore - du = v dp + d(ke) + d(pe)$$

If $d(ke) = 0$ and $d(pe) = 0$,

$$- du = v dp$$

$$\text{or } dW = - v dp$$

Integrating, $\int_1^2 dW = - \int_1^2 v dp$ $w_{1-2} = - \int_1^2 v dp$

2. Constant Pressure process; $W_{1-2} = V (P_1 - P_2) = 0$

$$w_{1-2} = - \int_1^2 v dp = - v \int_1^2 dp = v (p_1 - p_2) = 0 \quad [\because p_1 = p_2]$$

3. Constant temperature process; $W_{1-2} = P_1 V_1 \ln P_1/P_2 = P_1 V_1 \ln V_2/V_1$

$$w_{1-2} = - \int_1^2 v dp = - \int_1^2 \frac{P_1 v_1}{p} dp \quad \left[\because \begin{array}{l} pv = P_1 v_1 \\ v = \frac{P_1 v_1}{p} \end{array} \right]$$

$$= - P_1 v_1 \int_1^2 \frac{dp}{p} = - P_1 v_1 \ln \frac{p_2}{p_1} = P_1 v_1 \ln \frac{p_1}{p_2}$$

$$= P_1 v_1 \ln \frac{v_2}{v_1} \quad \left(\because \frac{P_1}{p_2} = \frac{v_2}{v_1} \right)$$

4. Adiabatic Process; $W_{1-2} = \gamma (P_1 V_1 - P_2 V_2) / (\gamma - 1)$

$$\begin{aligned}
 p v^\gamma &= p_1 v_1^\gamma = p_2 v_2^\gamma = \text{constant} \\
 v &= v_1 \left(\frac{p_1}{p} \right)^{\frac{1}{\gamma}} \\
 w_{1-2} &= - \int_1^2 v dp = - \int_1^2 v_1 \left(\frac{p_1}{p} \right)^{\frac{1}{\gamma}} dp \\
 w_{1-2} &= - v_1 p_1^{\frac{1}{\gamma}} \int_1^2 p^{-\frac{1}{\gamma}} dp = - v_1 p_1^{\frac{1}{\gamma}} \left[\frac{p^{-\frac{1}{\gamma} + 1}}{-\frac{1}{\gamma} + 1} \right]_1^2 \\
 &= \frac{-v_1 p_1^{\frac{1}{\gamma}}}{\gamma} \left[p_2^{\frac{\gamma-1}{\gamma}} - p_1^{\frac{\gamma-1}{\gamma}} \right] \\
 w_{1-2} &= \frac{\gamma}{\gamma-1} (p_1 v_1 - p_2 v_2)
 \end{aligned}$$

5. Polytropic process; $W_{1-2} = n (P_1 V_1 - P_2 V_2) / (n - 1)$

$$w_{1-2} = \frac{n}{n-1} (p_1 v_1 - p_2 v_2) \quad (\text{Substituting } \gamma = n)$$

6. Throttling Process

The expansion of a gas through an orifice or partly opened valve is called throttling.

$$q_{1-2} = 0 \quad \text{and} \quad w_{1-2} = 0$$

$$\text{Now } h_1 + \frac{V_1^2}{2} + gz_1 + q_{1-2} = h_2 + \frac{V_2^2}{2} + gz_2 + w_{1-2}$$

$$\text{If } V_1 = V_2 \quad \text{and} \quad z_1 = z_2, \quad h_1 = h_2$$

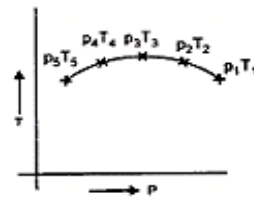
The throttling process is a constant enthalpy process.

If the readings of pressure and temperature of Joule Thompson porous plug experiment are plotted, $h_1 = h_2 = h_3 = h_4 = h_5$.

The slope of this constant enthalpy curve is called Joule Thompson coefficient.

$$\mu = \left[\frac{dT}{dp} \right]_h$$

For a perfect gas, $\mu = 0$.



Constant Enthalpy Process.

CONTROL SURFACE: A control system has control volume which is separated from its surrounding by a real or imaginary control surface which is fixed in shape, position and orientation. Matter can continually flow in and out of control volume, heat and work can cross the control surface. This is also an open system.

STEAM GENERATOR: The volume of generator is fixed. Water is supplied. Heat is supplied. Steam comes out. It is a control system as well as an open system.

The flow process can be analysed as a closed system by applying the concept of control volume. The control surface can be carefully selected and all energies of the system including flow energies can be considered

inside the system. The changes in the state of the working substance (mass) need not be considered during its passage through the system.

$$FE = \text{Force} \times \text{Distance} = (p_1 A_1) x_1$$

$$= p_1 V_1 \text{ (J)} \quad (\because V_1 = A_1 x_1)$$

Now specific volume of working substance is v_1

$$FE = p_1 v_1 \text{ (J/kg)}$$

FLOW WORK: The flow work is the energy required to move the working substance against its pressure. It is also called flow or displacement energy.

If a working substance with pressure p , flows through area A , (m^2) and moves through a distance x , (m), then the work required to move the working substance,

$$\text{Flow work} = \text{force} \times \text{distance} = (P.A).x = PV \text{ Joule}$$

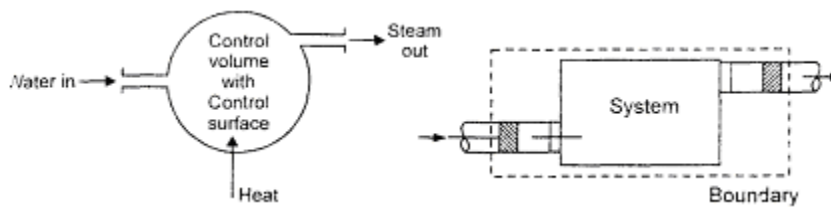


Fig. 2 Control Volume.

FLOW ENERGY: Flow work analysis is based on the consideration that there is no change in KE, PE, U. But if these energies are also considered in a flow process, then flow energy per unit mass will be expressed as

$$E = F.W + KE + PE + I.E.$$

$$E_{\text{flow}} = PV + V^2/2 + gZ + U$$

$$= (PV + U) + V^2/2 + gZ$$

$$E = h + V^2/2 + gZ$$

MASS FLOW RATE (m_f)

In the absence of any mass getting stored in the system we can write;

Mass flow rate at inlet = Mass flow rate at outlet

i.e. $m_{f1} = m_{f2}$

since $m_f = \text{density} \times \text{volume flow rate} = \text{density} \times \text{Area} \times \text{velocity} = \rho.A.V$

$$\rho_1.A_1.V_1 = \rho_2.A_2.V_2$$

or, $m_f = A_1.V_1/v_1 = A_2.V_2/v_2$; Where: $v_1, v_2 = \text{specific volumes}$

STEADY FLOW ENERGY EQUATION

Since the steady flow process is that in which the condition of fluid flow within a control volume do not vary with time, i.e. the mass flow rate, pressure, volume, work and rate of heat transfer are not the function of time.

i.e. for steady flow

$(dm/dt)_{\text{entrance}} = (dm/dt)_{\text{exit}}$; i.e, $dm/dt = \text{constant}$

$dP/dt = dV/dt = d\rho/dt = dE_{\text{chemical}} = 0$

ASSUMPTIONS

The following conditions must hold good in a steady flow process.

- (a) The mass flow rate through the system remains constant.
- (b) The rate of heat transfer is constant.
- (c) The rate of work transfer is constant.
- (d) The state of working substance at any point within the system is same at all times.
- (e) There is no change in the chemical composition of the system.

If any one condition is not satisfied, the process is called unsteady process.

Let;

A_1, A_2 = Cross sectional Areas at inlet and outlet

ρ_1, ρ_2 = Densities of fluids at inlet and outlet

m_1, m_2 = Mass flow rates at inlet and outlet

u_1, u_2 = I.E. of fluids at inlet and outlet

P_1, P_2 = Pressures of mass at inlet and outlet

v_1, v_2 = Specific volumes of fluid at inlet and outlet

V_1, V_2 = Velocities of fluids at inlet and outlet

Z_1, Z_2 = Heights at which the mass enters and leaves

Q = Heat transfer rate

W = Work transfer rate

Consider open system; we have to consider mass balance as well as energy balance.

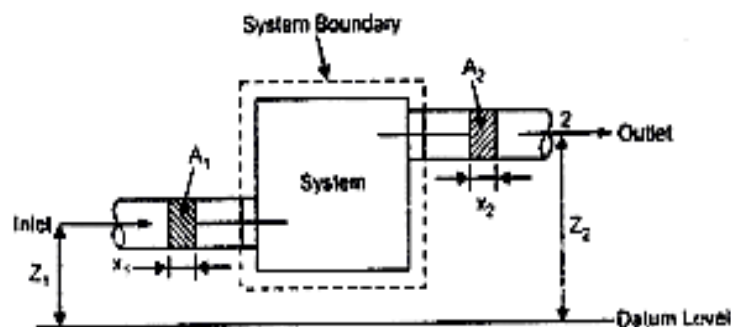


Fig 3

In the absence of any mass getting stored the system we can write;

Mass flow rate at inlet = Mass flow rate at outlet

i.e. $m_{f1} = m_{f2}$

since $m_f = \text{density} \times \text{volume flow rate} = \text{density} \times \text{Area} \times \text{velocity} = \rho \cdot A \cdot V$

$$\rho_1 \cdot A_1 \cdot V_1 = \rho_2 \cdot A_2 \cdot V_2$$

or, $A_1 \cdot V_1 / v_1 = A_2 \cdot V_2 / v_2$; $v_1, v_2 = \text{specific volume}$

Now total energy of a flow system consists of P.E., K.E., I.E., and flow work

Hence, $E = PE + KE + IE + FW$

$$= h + V^2/2 + gZ$$

Now; Total Energy rate cross boundary as heat and work

$$= \text{Total energy rate leaving at (2)} - \text{Total energy rate leaving at (1)}$$

$$Q - W = m_{f2}[h_2 + V_2^2/2 + gZ_2] - m_{f1}[h_1 + V_1^2/2 + gZ_1]$$

For steady flow process $m_f = m_{f1} = m_{f2}$

$$Q - W = m_f [(h_2 - h_1) + \frac{1}{2} (V_2^2 - V_1^2) + g (Z_2 - Z_1)]$$

For unit mass basis

$$Q - W_s = (h_2 - h_1) + \frac{1}{2} (V_2^2 - V_1^2) + g (Z_2 - Z_1) \text{ J/Kg-sec}$$

$W_s = \text{Specific heat work}$

May also be written as

$$dq - dw = dh + dKE + dPE$$

Or;

$$h_1 + V_1^2/2 + gZ_1 + q_{1-2} = h_2 + V_2^2/2 + gZ_2 + W_{1-2}$$

DIFFERENT CASES OF STEADY FLOW ENERGY EQUATION

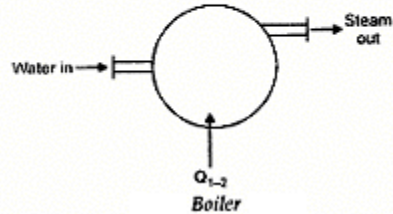
1. Boiler

$$(ke_2 - ke_1) = 0, (pe_2 - pe_1) = 0, w_{1-2} = 0.$$

$$\text{Now, } q_{1-2} - w_{1-2} = (h_2 - h_1) + (ke_2 - ke_1) + (pe_2 - pe_1)$$

$$\therefore q_{1-2} = h_2 - h_1$$

Heat supplied in a boiler increases the enthalpy of the system.



$$q_{1-2} - w_{1-2} = (h_2 - h_1) + (ke_2 - ke_1) + (pe_2 - pe_1)$$

$$\therefore q_{1-2} = h_2 - h_1$$

Heat is lost by the system to the cooling water

$$q_{1-2} = h_1 - h_2$$

2. Condenser. It is used to condense steam into water.

$$(ke_2 - ke_1) = 0, (pe_2 - pe_1) = 0$$

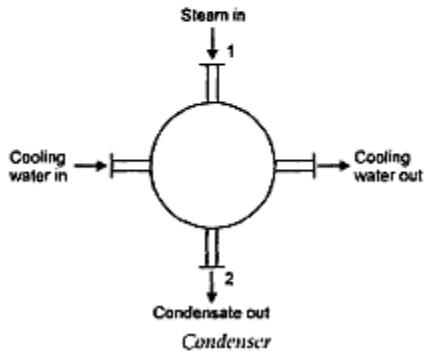
$$w_{1-2} = 0.$$

$$q_{1-2} - w_{1-2} = (h_2 - h_1) + (ke_2 - ke_1) + (pe_2 - pe_1)$$

$$\therefore q_{1-2} = h_2 - h_1$$

Heat is lost by the system to the cooling water

$$q_{1-2} = h_1 - h_2$$

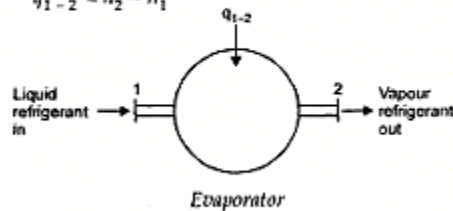


3. Refrigeration Evaporator. It is used to evaporate refrigerant into vapour.

$$(ke_2 - ke_1) = 0, (pe_2 - pe_1) = 0$$

$$w_{1-2} = 0$$

$$q_{1-2} = h_2 - h_1$$



The process is reverse of that of condenser. Heat is supplied by the surrounding to increase the enthalpy of refrigerant.

4. Nozzle

Pressure energy is converted in to kinetic energy

$$q_{1-2} = 0, w_{1-2} = 0$$

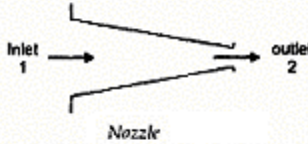
$$(pe_2 - pe_1) = 0.$$

Now, $q_{1-2} - w_{1-2} = (h_2 - h_1) + (ke_2 - ke_1) + (pe_2 - pe_1)$
 $0 - 0 = (h_2 - h_1) + (ke_2 - ke_1) + 0,$

$$\frac{V_2^2}{2} - \frac{V_1^2}{2} = (h_1 - h_2)$$

$$V_2^2 = V_1^2 + 2(h_1 - h_2)$$

$$V_2 = \sqrt{V_1^2 + 2(h_1 - h_2)}$$



If $V_1 \ll V_2$

$$V_2 = \sqrt{2(h_1 - h_2)}$$

Mass flow rate,

$$\dot{m} = \frac{A_1 V_1}{v_1} = \frac{A_2 V_2}{v_2}$$

5. Turbine. It is used to produce work.

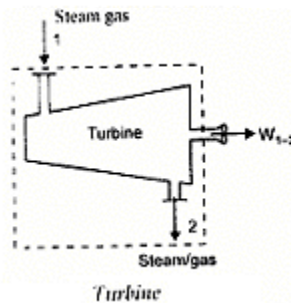
$$q_{1-2} = 0, (ke_2 - ke_1) = 0,$$

$$(pe_2 - pe_1) = 0$$

$$-w_{1-2} = (h_2 - h_1)$$

$$w_{1-2} = (h_1 - h_2)$$

The work is done by the system due to decrease in enthalpy.



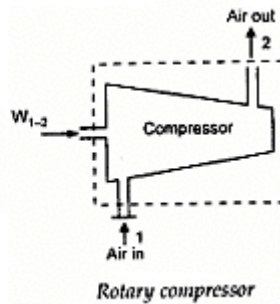
6. Rotary Compressor

$$q_{1-2} = 0, (ke_2 - ke_1) = 0,$$

$$(pe_2 - pe_1) = 0$$

$$w_{1-2} = h_2 - h_1$$

Work is done to increase enthalpy.



7 Reciprocating Compressor. It is used to compressor gases.

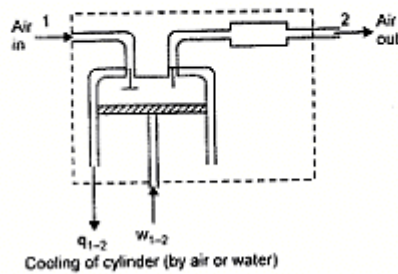
$$(ke_2 - ke_1) = 0, (pe_2 - pe_1) = 0$$

$$q_{1-2} - w_{1-2} = (h_2 - h_1) + 0 + 0$$

$$-q_{1-2} - (-w_{1-2}) = h_2 - h_1$$

$$w_{1-2} = q_{1-2} + (h_2 - h_1)$$

Heat is rejected and work is done on the system.



Reciprocating compressor

DIRRERENT CASES OF SFEE	SFEE
1. Boiler	$q = h_2 - h_1$
2. Condenser	$q = h_1 - h_2$
3. Refrigeration or Evaporator	$q = h_1 - h_2$
4. Nozzle	$V_2^2/2 - V_1^2/2 = h_1 - h_2$
5. Turbine	$W_{1-2} = h_1 - h_2$; WD by the system due to decrease in enthalpy
6. Rotary compressor	$W_{1-2} = h_2 - h_1$; WD by the system due to increase in enthalpy
7. Reciprocating Compressor	$W_{1-2} = q_{1-2} + (h_2 - h_1)$
8. Diffuser	$q - w = (h_2 - h_1) + \frac{1}{2}(V_2^2 - V_1^2)$