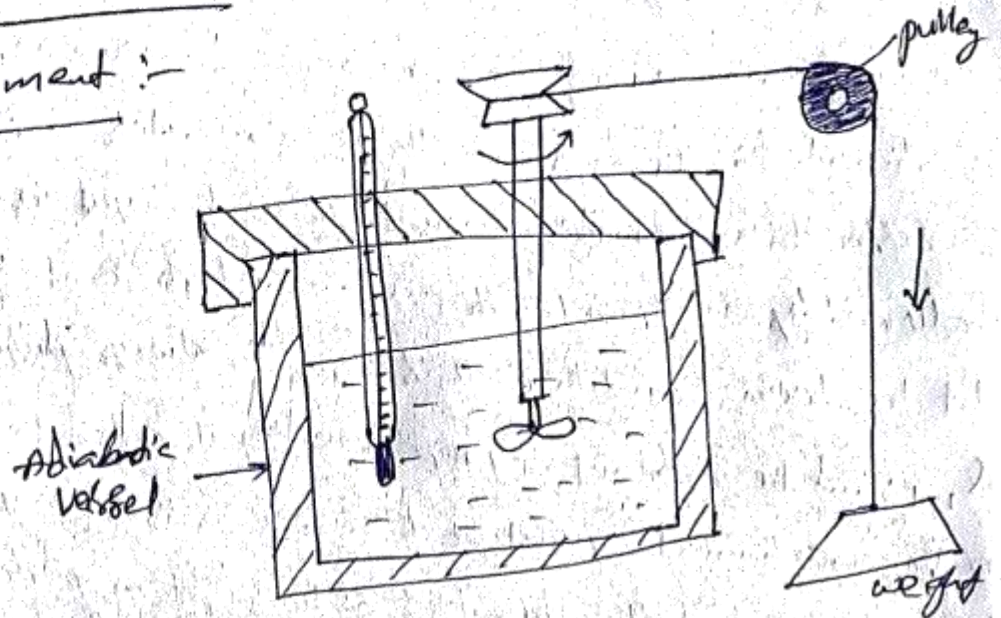


Unit - II

Joule's Experiment :-



Let us consider a closed system which contains a known mass of water contained in an adiabatic vessel having a thermometer and a paddle wheel also shown in fig. Let a certain amount of work w_{1-2} be done upon the system by the paddle wheel. The quantity of work can be measured by the fall of weight which drives the paddle wheel through a pulley.

The system was initially at temperature t_1 , the same as that of atmosphere, and after work transfer let the temperature rise to t_2 . The pressure is always 1 atm. The process 1-2 undergone by the system shown in fig (2) in generalized thermodynamic coordinates X, Y .

Let the insulation now be removed. The system and the surroundings

interacted by heat transfer till the system returns to the original temperature t_1 , attaining the condition of thermal equilibrium

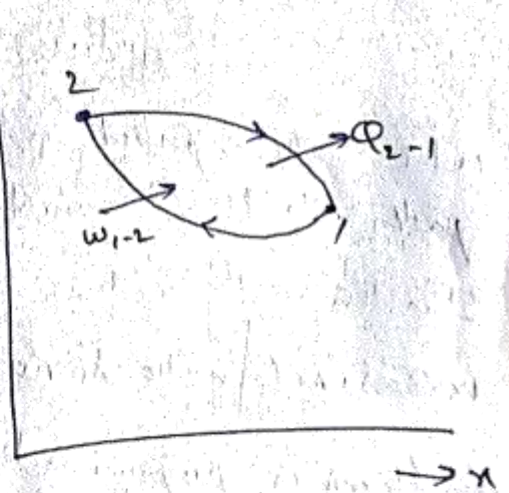


Fig. Cycle completed by a system with two energy interactions, adiabatic work transfer w_{1-2} followed by heat transfer Q_{2-1} .

with the atmosphere. The amount of heat transfer Q_{2-1} from the system during this process, 2-1 shown in fig 2, can be estimated. The system thus executes a cycle, which exhibits a definite amount of work input w_{1-2} to the system followed by the transfer of an amount of heat Q_{2-1} from the system. It has been found that this w_{1-2} is always proportional to the heat Q_{2-1} and the constant of proportionality is called the Joule's equivalent or the mechanical equivalent of heat. In this example, there are only two energy transfer quantities as the system performs a thermodynamic cycle. If the cycle involves many more heat and work quantities, the same result will be found. Expressed algebraically

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

$w \propto Q$ $w = JQ$

where J is the Joule's equivalent. The above equation is also expressed in the form

$\oint dw = J \oint dQ$

where the symbol \oint denotes the cyclic integral for the closed path. This is the first law for a closed system undergoing a cycle. In the S.I. system of units, both heat and work are measured in the derived unit of energy, the Joule. The constant of proportionality, J , is therefore unity ($J = 1 \text{ Nm/J}$).

First law of thermodynamics:-

3

1). Work and energy are mutually convertible.

$$\oint dw = \int \delta Q$$

for the same units of heat and work

$$\oint dw = \int \delta Q$$

$$\boxed{\oint dw = \int \delta Q}$$

2). Energy can neither be created nor destroyed but it can be transformed from one form to another. It is the law of conservation of energy.

Its Q is the amount of heat transferred to the system and w is the amount of work transferred from the system during the process.

The net energy transfer ($Q - w$) will be stored in the system. Energy in storage is neither heat nor work, and is given the name internal energy or simply, the energy of the system.

$$Q - w = \Delta E$$

where ΔE is the increase in the energy of the system.

$$Q = \Delta E + w$$

Here $Q, w, \Delta E$ are all expressed in the same units (in Joules)

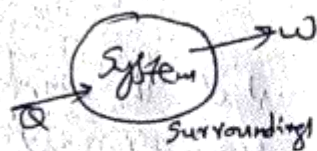
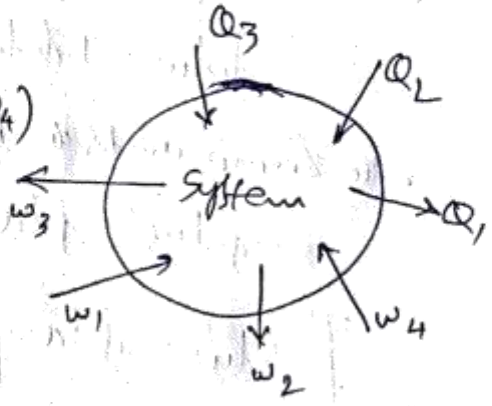


Fig: Heat and work interactions of a system with its surroundings in a process.

First law applied to a process :- It is there are more energy transfer quantities involved in the process as shown in fig. the first law gives

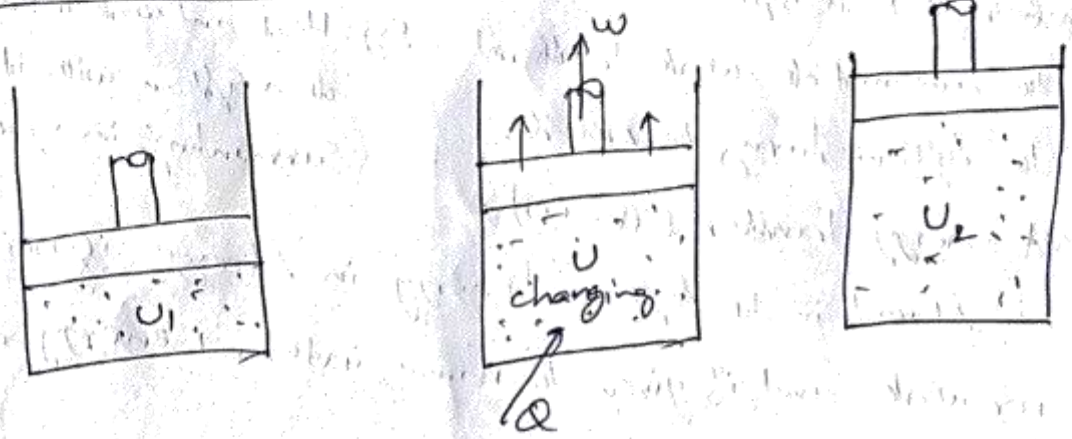
$$Q_2 + Q_3 - Q_1 = \Delta E + (w_2 + w_3 - w_1 - w_4)$$



- heat out from system is -ve (out)
- heat add to system is +ve (in)
- work done on system is -ve (in)
- work done by the system is +ve (out)

Fig: System-surroundings interaction in a process involving many energy fluxes

First law of Thermodynamics applied to closed system :- (non-flow process)



As the system follows a process which is not cyclic, the final state differs from the initial state, and the difference between energy input (heat transfer) and output (work transfer) results in a change in the energy content (internal energy) of the system.

Energy input - Energy output = change in internal energy

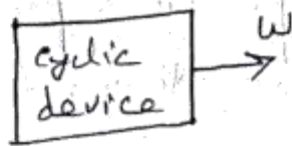
$$Q - w = U_2 - U_1$$

$$\Rightarrow Q = (U_2 - U_1) + w$$

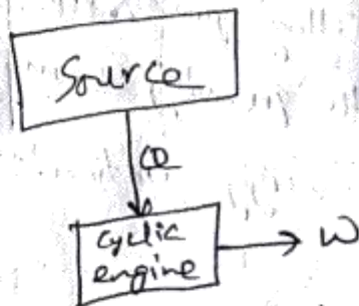
The above formula is called the non-flow energy Equations. This comprises the first Corollary or the first law of Thermodynamics. (5)

Corollaries of First law:-

- 1) For isolated systems, Q and w are zero, and therefore $(U_2 - U_1) = 0$. Thus the internal energy of an isolated system is constant.
- 2) The difference between heat supplied and work done during a non-flow process results in change in the property of the closed system, and is referred as internal energy.
- 3) A perpetual motion machine of first kind is impossible. A device that will deliver work continuously without input (i.e., without receiving energy) is called perpetual motion machine of the first kind (PMM I).



a). PMM-I



b). possible engine.

First law applied to a flow system:- In an open system,

The energy as well as matter cross the boundary. Any process undergone by an open system is called a flow process.

These processes may be sub-divided into two types.

- 1). Steady flow processes, and
- 2). Unsteady flow processes.

Steady flow processes! - Steady flow means that "the rates of flow of mass and energy across the control surface are constant". i.e., the mass of fluid entering the system is equal to the mass of fluid leaving the system in a given time, and the transfer of energy must take place at a uniform rate.

Ex! - flow of steam through a nozzle and a steam boiler operating under a constant load. In order to maintain water level in boiler, the feed pump supplies water at exactly the same rate at which the steam is drawn off from the boiler.

unsteady flow process! - unsteady flow process is one in which the quantity of fluid (matter) in the system is not constant i.e., the mass of fluid entering the system is not the same as the mass of fluid (matter) leaving the system in a given time. Two simple cases of unsteady flow process are tank filling process and tank emptying process. In both the cases the quantity of matter in the tank is not constant.

Steady flow energy equation! -

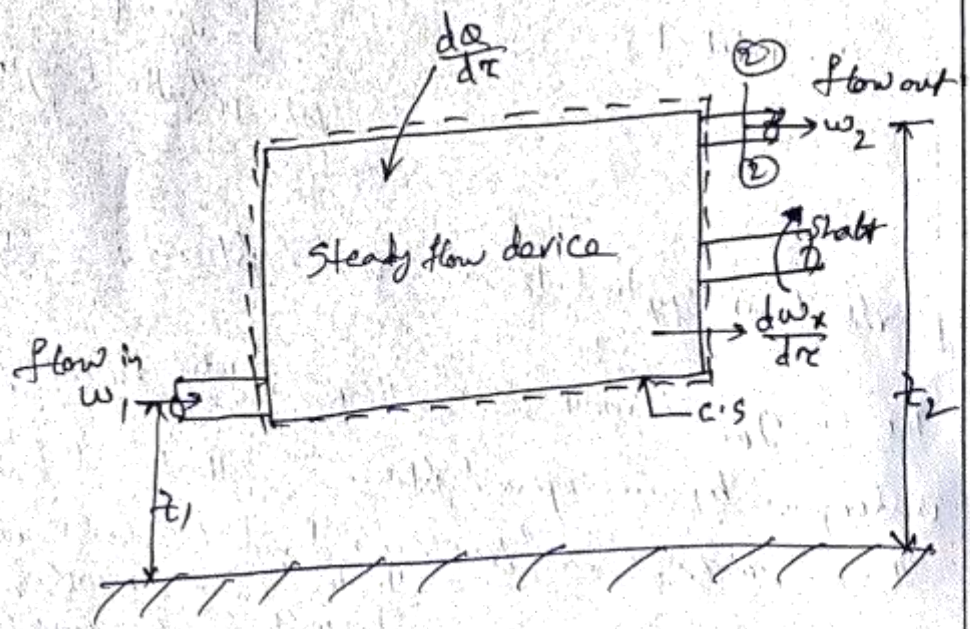


Fig. shows a steady flow system, in which one stream (1) of fluid enters and another stream leaves the control volume. There is no accumulation of mass or energy within the control volume, and the properties at any location within the control volume are steady with time. Sections (1)-(1) and (2)-(2) indicate respectively the entrance and exit of the fluid across the control surface. The following quantities are

A_1, A_2 - cross-section of stream, m^2

w_1, w_2 - mass flow rate, kg/s

p_1, p_2 - pressure, absolute, N/m^2

v_1, v_2 - specific volume, m^3/kg

u_1, u_2 - specific internal energy, J/kg

V_1, V_2 - velocity, m/s

z_1, z_2 - elevation above an arbitrary datum, m

$\frac{dq}{dt}$ - net rate of heat transfer through the control surface, J/s

$\frac{dw_s}{dt}$ - net rate of work transfer through the control surface, J/s

t - time, s

Subscripts 1 and 2 refer to the inlet and exit sections.

Mass balance - By the conservation of mass, if there is no accumulation of mass within the control volume, the mass flow rate entering must equal the mass flow rate leaving

$$w_1 = w_2$$

$$\frac{A_1 V_1}{v_1} = \frac{A_2 V_2}{v_2} \quad \text{--- (1)}$$

This equation is known as the Equation of Continuity.

Energy balance - In a flow process, the work transfer may be of two types: the external work and the flow work.

External work is the shaft work (w_x).
The flow work is the displacement work done by the fluid of mass dm_1 at the inlet section 1 and that at the exit section, which are $(-P_1 \omega_1 dm_1)$ and $(+P_2 \omega_2 dm_2)$ respectively.

∴ Total work transfer

$$W = W_x - P_1 \omega_1 dm_1 + P_2 \omega_2 dm_2 \quad \text{--- (2)}$$

in the rate form

$$\begin{aligned} \frac{dW}{dt} &= \frac{dW_x}{dt} - P_1 \omega_1 \frac{dm_1}{dt} + P_2 \omega_2 \frac{dm_2}{dt} \\ &= \frac{dW_x}{dt} - P_1 \omega_1 w_1 + P_2 \omega_2 w_2 \quad \text{--- (3)} \end{aligned}$$

Since there is no accumulation of energy, by the conservation of energy, the total rate of flow of all energy streams entering the control volume must be equal to the total rate of flow of all energy streams leaving the control volume. This may be expressed in the following equation

$$w_1 e_1 + \frac{dQ}{dt} = w_2 e_2 + \frac{dW}{dt}$$

Substitute equation (3)

$$w_1 e_1 + \frac{dQ}{dt} = w_2 e_2 + \frac{dW_x}{dt} - w_1 P_1 \omega_1 + w_2 P_2 \omega_2$$

$$w_1 e_1 + \frac{dQ}{dt} + w_1 P_1 \omega_1 = w_2 e_2 + \frac{dW_x}{dt} + w_2 P_2 \omega_2 \quad \text{--- (4)}$$

where e_1, e_2 refer to the energy carried into or out of the control volume with unit mass of fluid. (9)

The specific energy e is given by

$$e = e_k + e_p + u$$

$$= \frac{v^2}{2} + z g + u$$

$$e_1 = \frac{v_1^2}{2} + z_1 g + u_1$$

$$e_2 = \frac{v_2^2}{2} + z_2 g + u_2$$

$e_k \rightarrow$ kinetic energy
 $e_p \rightarrow$ potential energy
 $u \rightarrow$ internal energy

Substitute e_1 and e_2 in equation (4)

$$w_1 \left(\frac{v_1^2}{2} + z_1 g + u_1 \right) + w_1 p_1 \omega_1 + \frac{dQ}{dz}$$

$$= w_2 \left(\frac{v_2^2}{2} + z_2 g + u_2 \right) + w_2 p_2 \omega_2 + \frac{dw_1}{dz}$$

$$w_1 \left[u_1 + p_1 \omega_1 + \frac{v_1^2}{2} + z_1 g \right] + \frac{dQ}{dz}$$

$$h = u + p \omega$$

$$h_1 = u_1 + p_1 \omega_1$$

$$h_2 = u_2 + p_2 \omega_2$$

$$= w_2 \left[u_2 + p_2 \omega_2 + \frac{v_2^2}{2} + z_2 g \right] + \frac{dw_2}{dz}$$

$$w_1 \left[h_1 + \frac{v_1^2}{2} + z_1 g \right] + \frac{dQ}{dz} = w_2 \left[h_2 + \frac{v_2^2}{2} + z_2 g \right] + \frac{dw_2}{dz}$$

let $w_1 = w_2$

$$w = w_1 = w_2 = \frac{dm}{dz}$$

$$h_1 + \frac{v_1^2}{2} + z_1 g + \frac{dQ}{dm}$$

$$= h_2 + \frac{v_2^2}{2} + z_2 g + \frac{dw_2}{dm}$$

$$\frac{dQ}{dz} \times \frac{dz}{dm} = \frac{dQ}{dm}$$

(5)

Equations (5) and (6) are known as steady flow energy equations (S.F.E.E) for a single stream of fluid entering and a single stream of fluid leaving the control volume. All the terms in equation (6) represents energy flow per unit mass of fluid (J/kg), whereas the terms in equation (5) represent energy flow per unit time (J/s).

Equation (6) can be written in the following form,

$$Q - w_x = (h_2 - h_1) + \frac{v_2^2 - v_1^2}{2} + g(z_2 - z_1) \quad \text{--- (7)}$$

where Q and w_x refer to energy transfer per unit mass, in the differential form, the SFEE becomes

$$dq - dw_x = dh + v dv + g dz \quad \text{--- (8)}$$

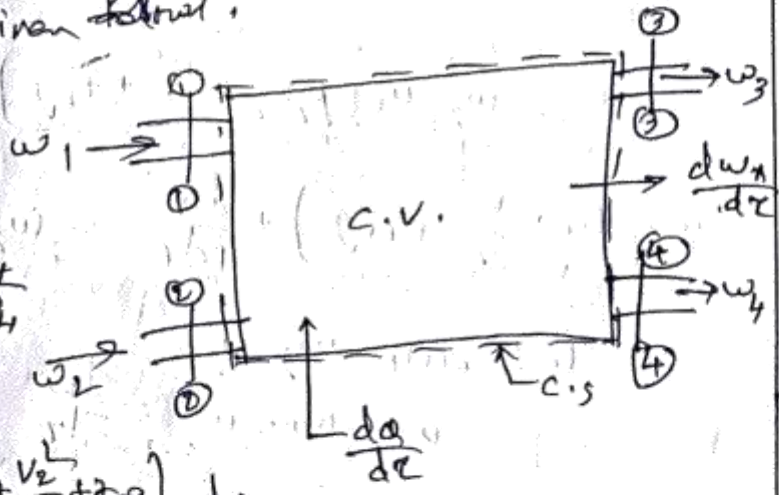
when more than one stream of fluid enters and leaves the control volume (fig below), the mass balance and energy balance for steady flow are given below.

mass balance
 $w_1 + w_2 = w_3 + w_4$

$$\frac{A_1 v_1}{\rho_1} + \frac{A_2 v_2}{\rho_2} = \frac{A_3 v_3}{\rho_3} + \frac{A_4 v_4}{\rho_4}$$

Energy Balance

$$w_1 \left(h_1 + \frac{v_1^2}{2} + gz_1 \right) + w_2 \left(h_2 + \frac{v_2^2}{2} + gz_2 \right) + \frac{dq}{dx} = w_3 \left(h_3 + \frac{v_3^2}{2} + gz_3 \right) + w_4 \left(h_4 + \frac{v_4^2}{2} + gz_4 \right) + \frac{dw_x}{dx}$$

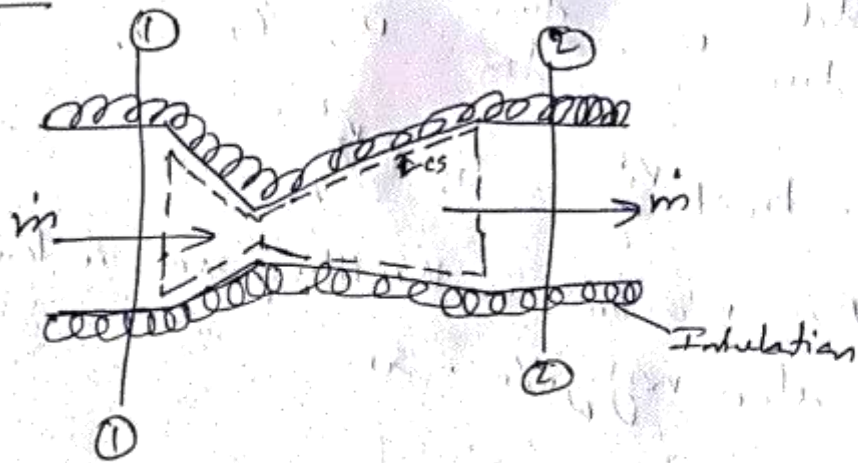


Applications of SFEE :-

(11)

Nozzle :-

A nozzle is a device which increases the velocity or K.E.



of a fluid at the expense of its pressure drop. Fig. shows a nozzle which is insulated. The steady flow energy equation for the control surface gives

$$\frac{dq}{dm} = 0$$

$$\frac{dw_s}{dm} = 0$$

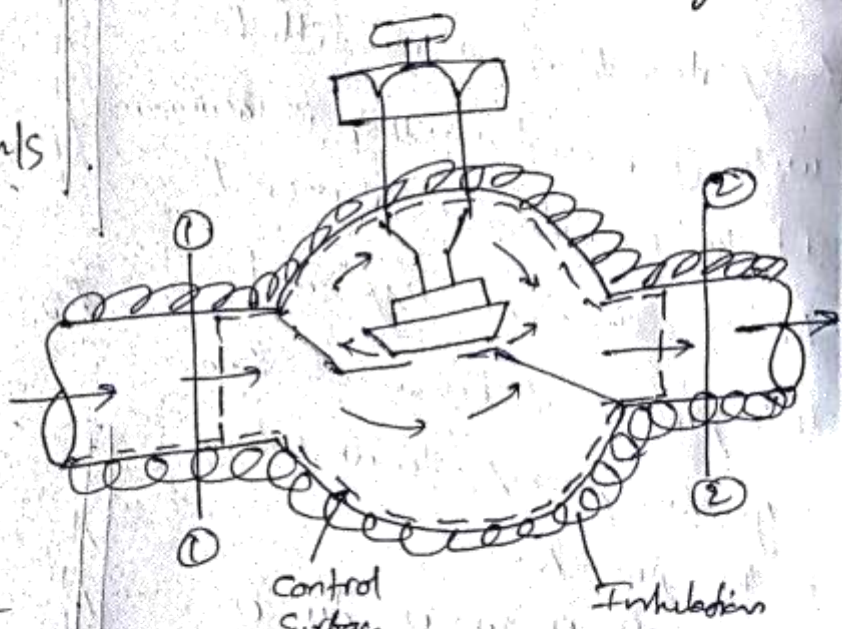
$$z_1 = z_2$$

$$v_1 = \text{neglected}$$

$$h_1 + \frac{v_1^2}{2} + z_1 g + \frac{dq}{dm} = h_2 + \frac{v_2^2}{2} + z_2 g + \frac{dw_s}{dm}$$

$$h_1 = h_2 + \frac{v_2^2}{2}$$

$$\Rightarrow \boxed{v_2 = \sqrt{2(h_1 - h_2)}} \text{ m/s}$$



Throttling device :-

When a fluid flows through a constricted passage, like a partially opened valve, an orifice, or a porous plug, there is an appreciable drop in pressure, and the flow is said to be throttled.

Fig. shows the process of throttling by a partially opened valve on a fluid flowing in an insulated pipe. In the steady flow energy equation

$$\frac{da}{dm} = 0, \quad \frac{dw_m}{dm} = 0, \quad z_1 = z_2$$

(12)

$$\therefore h_1 + \frac{v_1^2}{2} = h_2 + \frac{v_2^2}{2}$$

The pipe velocities in throttling are so low that the k.E. term are also negligible. So

$$h_1 = h_2$$

The enthalpy of the fluid before throttling is equal to the enthalpy of the fluid after throttling.

Free expansion process :-

A Tank is divided into two compartments. one is filled with gas and another is vacuum. If the partition is removed the gas is free expanded. This process is known as free expansion process. no work done in this process.

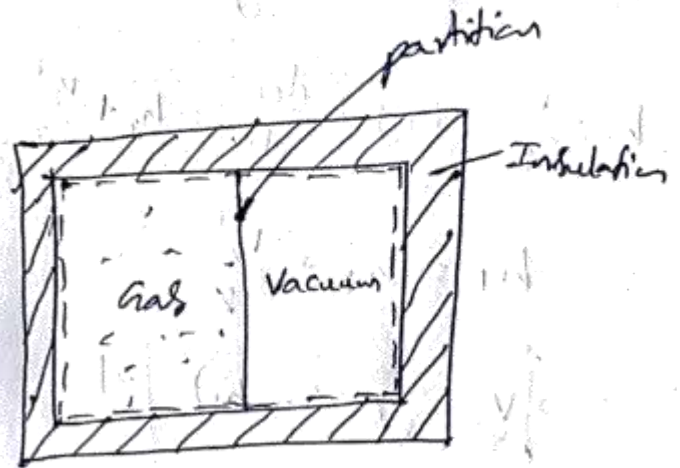


Fig: Before expansion

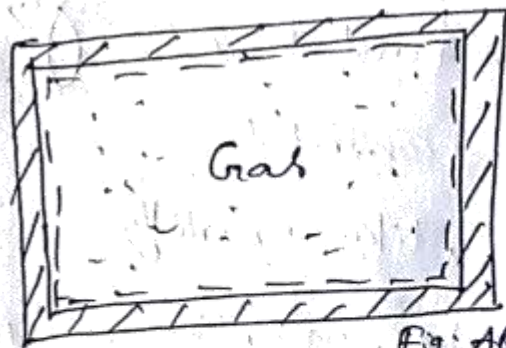


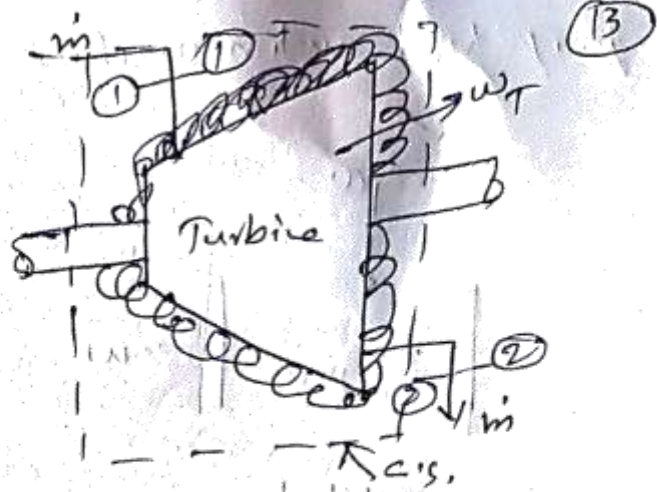
Fig: After expansion

$$Q = 0, \quad w = 0, \quad du = 0$$

$$dv = 0, \quad T_1 = T_2$$

no change in temperature and hence $dh = 0, (H_2 = H_1)$

Turbine :- For a turbine which is well insulated, the flow velocities are often small, and the K.E. terms can be neglected. The SFEE becomes



$$\frac{dQ}{dm} = 0, z_1 = z_2, \text{K.E. neglected}$$

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

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

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

Compressor :- For an adiabatic pump or compressor, work is done upon the fluid and w is negative. So the SFEE becomes

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

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

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

Heat exchanger :-

K.E, P.E terms neglected,
no external work done,
no external heat interaction or heat loss

∴ SFEE becomes

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

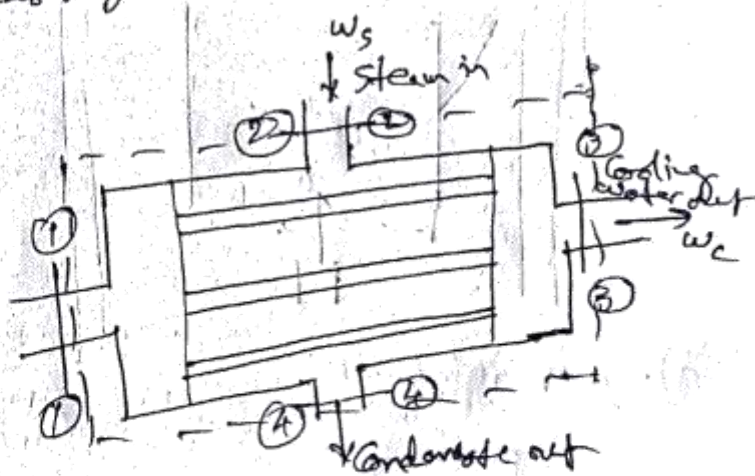


Fig: Steam Condenser

Perpetual motion machine of the first kind (PMM-I) :-

(14)

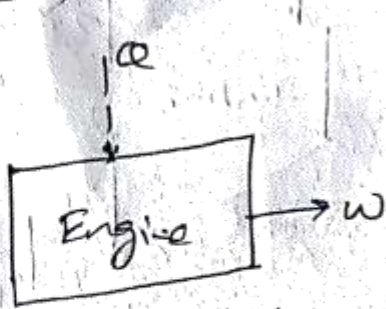


Fig 1 PMM-1

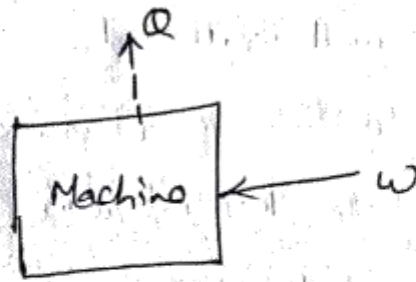


Fig 2 The construction of PMM-1

no machine supply work without energy input. The first law states the principle of conservation of energy. Energy is neither created nor destroyed, but only gets transformed from one form to another.

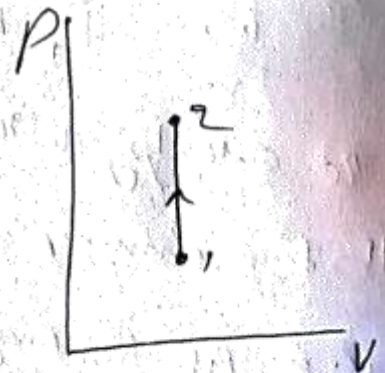
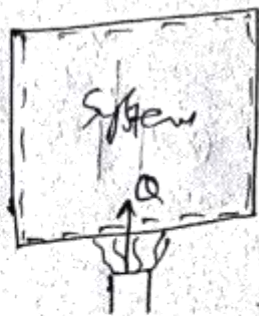
Fig 1 shows, without input, engine develop work, it will impossible.

Fig 2: machine take work but no production of heat, it will impossible.

These two are PMM-I.

First law applied to closed system :-

1). Reversible constant volume process (V constant) :-



a). p-v relationship

$$\frac{P_1}{T_1} = \frac{P_2}{T_2}$$

(for constant volume process)

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2} \text{ (general equation)}$$

(b) work done $\int p \cdot dv = \int p \cdot 0 = 0$

$w = 0$

First law of thermodynamics

$Q = \Delta E + w$

$\therefore Q = \Delta E = \Delta U$

(c) change of internal energy

$u_2 - u_1 = m c_v (T_2 - T_1)$

(d) Heat supplied $Q = \Delta U = m c_v (T_2 - T_1)$

(e) change of enthalpy

$h_2 - h_1 = (u_2 - u_1) + (p_2 v_2 - p_1 v_1)$

$= m c_v (T_2 - T_1) + m R (T_2 - T_1)$

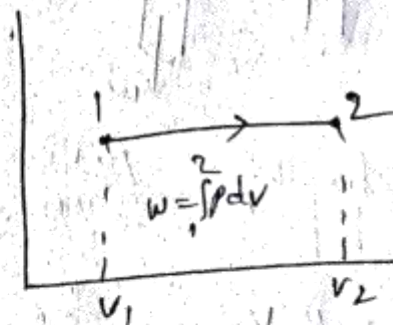
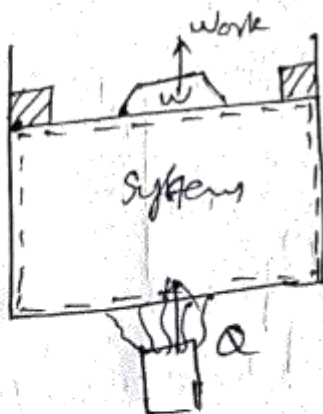
$= m (T_2 - T_1) (c_v + R)$

$= m c_p (T_2 - T_1)$

$c_p - c_v = R$

$c_p = R + c_v$

2) Reversible constant pressure process (p = constant) :-



a) p, v, T relation ship $\frac{p_1 v_1}{T_1} = \frac{p_2 v_2}{T_2}$ (general equation)

$\frac{v_1}{T_1} = \frac{v_2}{T_2}$ (for p = constant)

⑥. work done $W = p(V_2 - V_1)$
 $= mR(T_2 - T_1)$

$pV = RT$
 $p_1V_1 = RT_1$
 $p_2V_2 = RT_2$
 $p_2V_2 - p_1V_1$

⑩

⑦. change in internal energy

$Q = \Delta E + w$
 $\Delta U = U_2 - U_1 = mC_v(T_2 - T_1)$

$= R(T_2 - T_1)$

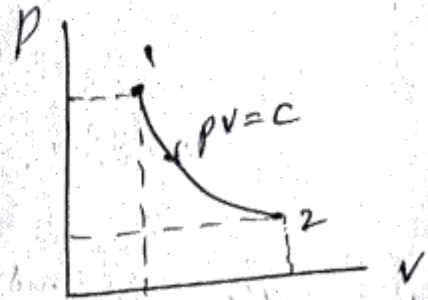
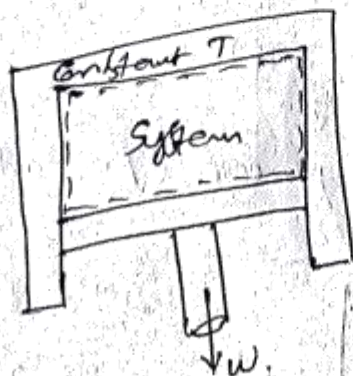
⑧. Heat Supplied or transferred

$Q = \Delta U + w$
 $= mC_p(T_2 - T_1)$

⑨. change in enthalpy

$\Delta H = H_2 - H_1 = mC_p(T_2 - T_1)$

3). Reversible constant temperature process:-



a). p, v, T relationship $\frac{p_1V_1}{T_1} = \frac{p_2V_2}{T_2}$

$p_1V_1 = p_2V_2$ (for $T = \text{constant}$)

b). work done $w = p_1V_1 \ln \frac{V_2}{V_1}$

c). change internal energy

$\Delta U = U_2 - U_1 = 0$

d). Heat supplied $Q_{1-2} = \Delta U + w = w = p_1V_1 \ln \frac{V_2}{V_1}$

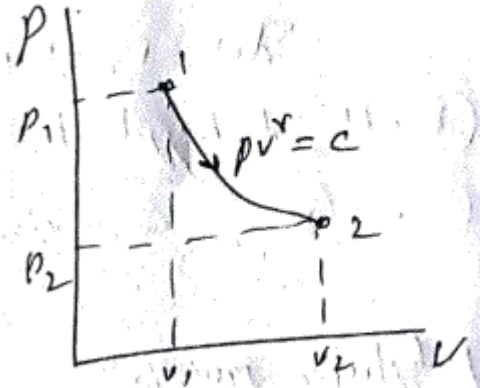
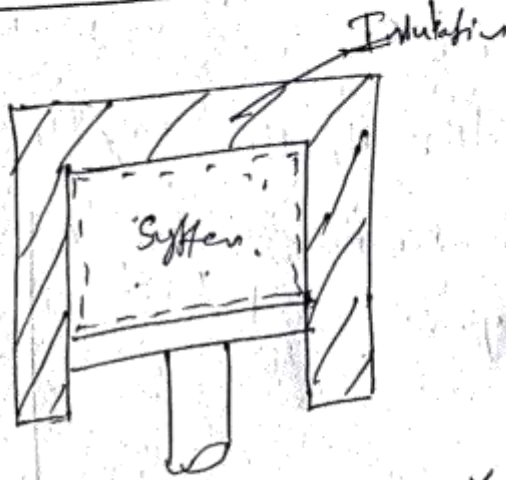
②. change of enthalpy $dH = H_2 - H_1 = 0$

(17)

i.e.; $H_2 = H_1$, because temperature is constant.

4) Adiabatic process:-

It is a process in which neither receives nor gives heat to its surroundings during its expansion or compression process.



③. P, V, T relationship

$$PV^\gamma = c$$

$$P_1 V_1^\gamma = P_2 V_2^\gamma$$

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}$$

$$\frac{P_1}{P_2} = \frac{T_1}{T_2} \times \frac{V_2}{V_1}$$

$$\boxed{\frac{P_1}{P_2} = \left(\frac{V_2}{V_1}\right)^\gamma}$$

$$\frac{T_1}{T_2} \times \frac{V_2}{V_1} = \left(\frac{V_2}{V_1}\right)^\gamma \Rightarrow \frac{T_1}{T_2} = \left(\frac{V_2}{V_1}\right)^{\gamma-1}$$

$$\boxed{\frac{T_1}{T_2} = \left(\frac{V_2}{V_1}\right)^{\gamma-1}}$$

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}$$

$$\frac{V_1}{V_2} = \frac{T_1}{T_2} \times \frac{P_2}{P_1} = \frac{T_1}{T_2} \times \frac{P_2}{P_1}$$

$$\frac{T_1}{T_2} = \frac{V_1}{V_2} \times \frac{P_1}{P_2} = \left(\frac{P_1}{P_2}\right)^{1/\gamma} \times \frac{P_1}{P_2}$$

$$\boxed{\frac{T_1}{T_2} = \left(\frac{P_1}{P_2}\right)^{\frac{\gamma}{\gamma-1}}}$$

(b) work done $w = \frac{P_1 V_1 - P_2 V_2}{\gamma - 1}$

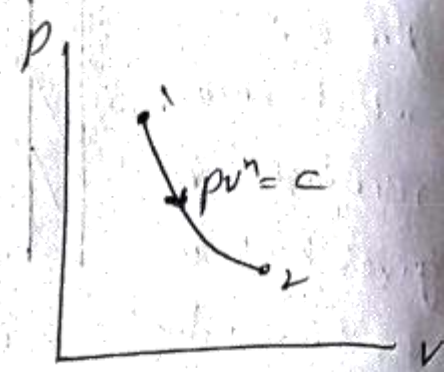
(c) change in internal energy

$$du = u_2 - u_1 = m c_v (T_2 - T_1)$$

(d) Heat supplied $Q_{1-2} = 0$

(e) change in enthalpy, $dh = H_2 - H_1 = m c_p (T_2 - T_1)$

polytropic process! — It is also known as the general law for the expansion and compression of gases.



$$pV^n = \text{constant}$$

(a) p, v, T relationship

$$P_1 V_1^n = P_2 V_2^n$$

$$\frac{T_1}{T_2} = \left(\frac{V_2}{V_1}\right)^{n-1}$$

$$\frac{T_1}{T_2} = \left(\frac{P_1}{P_2}\right)^{\frac{n-1}{n}}$$

$$\frac{V_1}{V_2} = \left(\frac{P_2}{P_1}\right)^{\frac{1}{n}}$$

(b) work done $w_{1-2} = \frac{P_1 V_1 - P_2 V_2}{n - 1}$

(c) Heat supplied or transferred

$$Q_{1-2} = w_{1-2} + du$$

$$= \frac{P_1 V_1 - P_2 V_2}{n - 1} + m c_v (T_2 - T_1)$$

$$= \frac{m R (T_2 - T_1)}{n - 1} + \frac{m R}{\gamma - 1} (T_2 - T_1)$$

$$\left(\because c_v = \frac{R}{\gamma - 1} \right)$$

$$= mR (T_1 - T_2) \left[\frac{1}{n-1} - \frac{1}{r-1} \right]$$

$$= mR (T_2 - T_1) \left[\frac{(r-1) - (n-1)}{(n-1)(r-1)} \right]$$

$$= mR (T_1 - T_2) \left[\frac{r-n}{(n-1)(r-1)} \right]$$

$$= \frac{r-n}{r-1} \times \frac{mR (T_1 - T_2)}{n-1}$$

①. change in internal energy

$$dU = U_2 - U_1 = mC_v (T_2 - T_1)$$

②. change in enthalpy

$$dH = H_2 - H_1 = mC_p (T_2 - T_1)$$

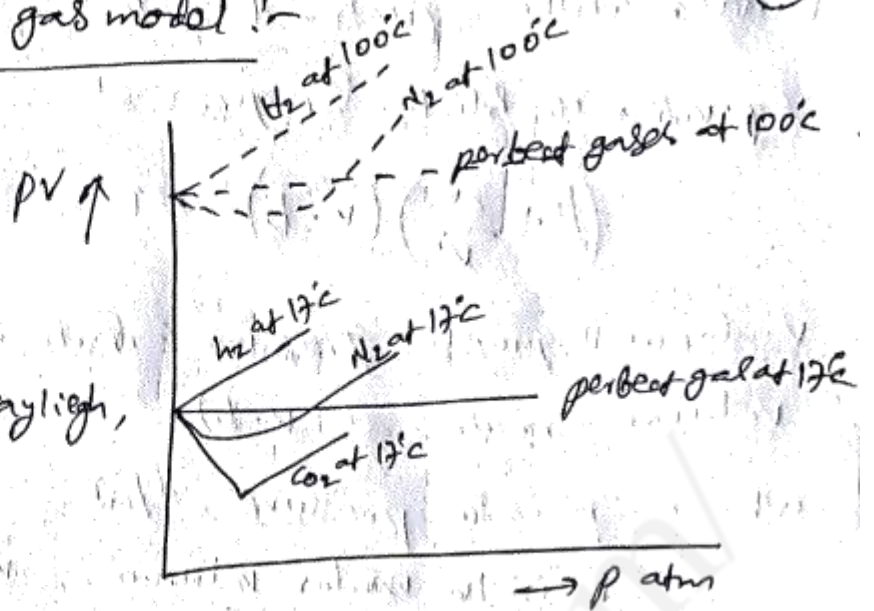
Summary of processes for perfect gas (unit mass) :-

process	Index	Heat supplied	work done	P, V, T, relationship	change in internal energy	change in enthalpy	Specific heat
1). Constant pressure process	$n = 0$	$C_p (T_2 - T_1)$	$P (V_2 - V_1)$	$\frac{T_2}{T_1} = \frac{V_2}{V_1}$	$m C_v (T_2 - T_1)$	$m C_p (T_2 - T_1)$	C_p
2). Constant Volume process	$n = \infty$	$C_v (T_2 - T_1)$	0	$\frac{T_1}{T_2} = \frac{P_1}{P_2}$	$m C_v (T_2 - T_1)$	$m C_p (T_2 - T_1)$	C_v
3). Constant temperature process	$n = \infty$	$P_1 V_1 \ln \left(\frac{V_2}{V_1} \right)$	$P_1 V_1 \ln \left(\frac{V_2}{V_1} \right)$	$P_1 V_1 = P_2 V_2$	$m C_v (T_2 - T_1)$	$m C_p (T_2 - T_1)$	∞
4). Adiabatic process	$n = \gamma$	0	$\frac{P_1 V_1 - P_2 V_2}{\gamma - 1} = \frac{R}{\gamma - 1} (T_2 - T_1)$	$P_1 V_1^\gamma = P_2 V_2^\gamma$	$m C_v (T_2 - T_1)$	$m C_p (T_2 - T_1)$	0
5). Polytropic process	$n = n$	$\frac{(C_p - n) m R (T_2 - T_1)}{(n - 1)(C_p - 1)}$	$\frac{P_1 V_1 - P_2 V_2}{n - 1}$ or $\frac{R}{n - 1} (T_2 - T_1)$	$P_1 V_1^n = P_2 V_2^n$	$m C_v (T_2 - T_1)$	$m C_p (T_2 - T_1)$	$C_n = C_v \left(\frac{\gamma - n}{1 - n} \right)$

Deviations from perfect gas model :-

(21)

Figure shows the deviations of real gases from perfect gases by the experimental results Lord Rayleigh, those curves are called isotherms.



According to Boyle's law

$PV = \text{constant}$ at all pressure and variation of pressure with PV is a straight line. But this is only for perfect gas and real gases are not showing straight lines.

At low pressures for H_2 PV increases as P increases.

for N_2 PV decreases as P increases.

For perfect gas PV remain constant as P increase, for CO_2 , and N_2 , PV first decreases and then increases as P increases, for perfect gas PV remains constant as P increases.

all real gases have higher values of PV than that of a perfect gas.

Vander wall's Equation of State - Vanderwall proposed a

Equation of States for gas as

$$(p + \frac{a}{v^2})(v-b) = RT$$

Vander wall proposed pressure correction as $(p + \frac{a}{v^2})$ and volume correction as $(v-b)$.

where p is the pressure, N/m^2

v is the molar volume, $m^3/kg\text{mole}$

T is the temperature, K

R is the gas constant = 8.314 kJ/kg mole

a is the constant, $N \cdot m^4 / (kg\text{mole})^2$

b is the constant, $m^3/kg\text{mole}$

Compressibility chart:-

The Compressibility factor (z) of any gas is a function of only two properties, usually temperature and pressure, so that

$$z = \frac{pv}{RT}$$

$z = f(T_r, P_r)$ except near

the critical point. The

value of z for any real gas may be less or more than unity, depending on pressure and temperature conditions of the gas.

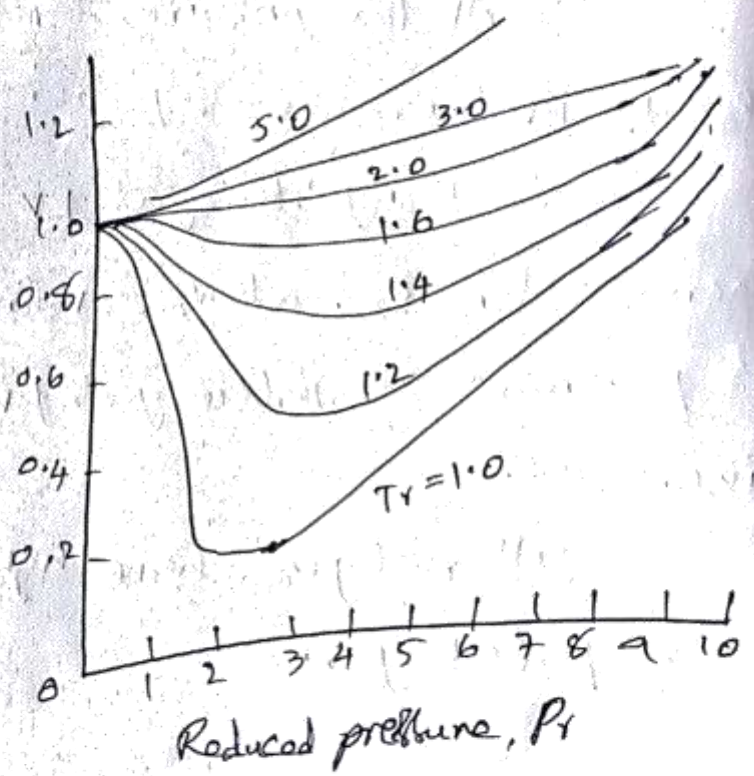


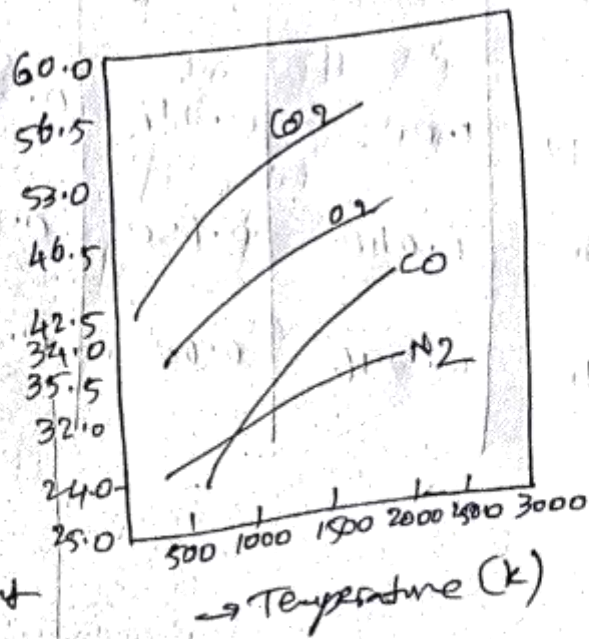
Fig: Generalized Compressibility chart

The general compressibility chart is plotted (23)

with Z versus P_r for various values of T_r . This is constructed by plotting the known data of one or more gases and can be used for any gas. Such chart is shown in fig. This chart gives best results for the regions well removed from the critical state for all gases.

Variation of specific heat with temperature:

Specific heat of any gas increases with increasing temperature because increase of vibration of molecules at high temperature. The vibrations are caused because of collisions among molecules which are significant at high temperatures.



The temperature range of 300 K to 1500 K the specific heat is a linear function of temperature and may be expressed as $C_p = a + kT$, $C_v = b + kT$ where a, b, k are constants.

characteristic gas constant $R = C_p - C_v$
 $= (a + kT) - (b + kT)$
 $= a - b$

above 1500 k

$$C_p = a + k_1 T^2$$

$$C_v = b + k_1 T + k_2 T^2$$

Gas Tables:- By using gas tables we read the properties of gases.

Gas	molecular weight	C_p (kJ/kgk)	C_v (kJ/kgk)	$R = C_p - C_v$	$\gamma = \frac{C_p}{C_v}$	$Z_c = \frac{P_c V_c}{R_o T_c}$
Air	28.97	1.005	0.718	0.287	1.4	0.204
CO ₂	44	0.845	0.650	0.190	1.3	0.274
SO ₂	64	0.796	0.67	0.126	1.19	0.268

1) A stationary mass of gas is compressed without friction ⁽²⁵⁾ from an initial state of 0.3 m^3 and 0.105 MPa to a final state of 0.15 m^3 and 0.105 MPa , the pressure remaining constant during the process. There is a transfer of 37.6 kJ of heat from the gas during the process. How much does the internal energy of the gas change?

Soln: First law for a stationary system in a process gives

$$Q = \Delta U + W$$

$$Q_{1-2} = U_2 - U_1 + W_{1-2} \quad \text{--- (1)}$$

$$\begin{aligned} \text{Here } W_{1-2} &= \int_{v_1}^{v_2} p \, dv = p(v_2 - v_1) \\ &= 0.105(0.15 - 0.30) \text{ MJ} \\ &= -15.75 \text{ kJ} \end{aligned}$$

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

\therefore from equation (1)

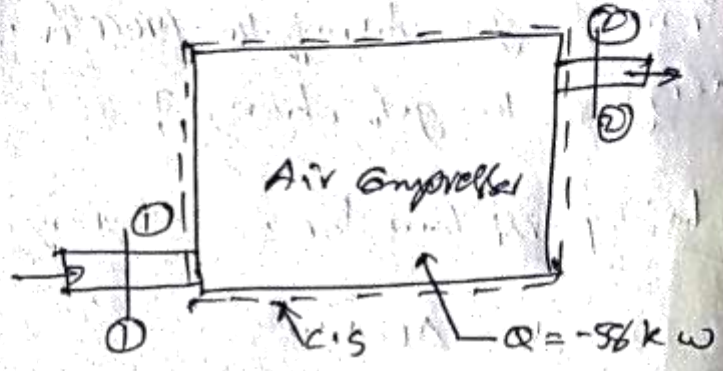
$$\begin{aligned} -37.6 &= U_2 - U_1 + (-15.75) \\ &= (U_2 - U_1) - 15.75 \end{aligned}$$

$$\therefore (U_2 - U_1) = -21.85 \text{ kJ}$$

The internal energy of the gas decreases by 21.85 kJ in the process.

2) Air flows steadily at the rate of 0.5 kg/s through an air compressor, entering at 7 m/s velocity, 100 kPa pressure, and $0.95 \text{ m}^3/\text{kg}$ volume, and leaving at 5 m/s , 700 kPa and $0.19 \text{ m}^3/\text{kg}$. 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.



Soln: $v_1 = 7 \text{ m/s}$
 $P_1 = 100 \text{ kPa}$
 $\rho_1 = 0.95 \text{ m}^3/\text{kg}$

$v_2 = 5 \text{ m/s}$
 $P_2 = 700 \text{ kPa}$
 $\rho_2 = 0.19 \text{ m}^3/\text{kg}$
 $u_2 = (u + 90) \text{ kJ/kg}$
 $Q = -58 \text{ kW}$

(a). writing the steady flow energy equation

$$w \left(u_1 + P_1 v_1 + \frac{v_1^2}{2} + z_1 g \right) + \frac{dq}{dx} = w \left(u_2 + P_2 v_2 + \frac{v_2^2}{2} + z_2 g \right) + \frac{dw_x}{dx}$$

$$= \frac{dw_x}{dx} = -w \left[(u_2 - u_1) + (P_2 v_2 - P_1 v_1) + \frac{v_2^2 - v_1^2}{2} + (z_2 - z_1)g \right] + \frac{dq}{dx}$$

$$= -0.5 \left[90 + (7 \times 0.19 - 1 \times 0.95) 100 + \frac{(5^2 - 7^2) \times 10^{-3}}{2} + 0 \right] - 58$$

$$= -0.5 [90 - 38 - 0.012] - 58$$

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

Rate of work input is 122 kW

(b). From mass balance, we have

$$w = \frac{A_1 v_1}{\rho_1} = \frac{A_2 v_2}{\rho_2}$$

$$\frac{A_1}{A_2} = \frac{\rho_2 v_2}{\rho_1 v_1} = \frac{0.19 \times 5}{0.95 \times 7} = 3.57$$

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