

Thermodynamic concept of energy transfer

In thermodynamics energy has been given two states. One is energy in storage i.e. system can store energy. It is property of a state or point function.

Eg:- A gas is stored at high temperature. Energy is stored as internal energy. There are various ways by which a system can store energy such as P.E, K.E of a molecule, chemical energy. Altogether, it is internal energy.

Another is energy in transit. This can be conceived only when some process takes place. This can be classified as heat and work transfer.

Energy

↓
Energy in storage

(Internal energy)

Point function

State variable

i.e. associated with
state of a system.

↓
Energy in transit
Path function.

and takes place when
interaction between system
and surrounding take place

Work Transfer

All other forms of
energy transfer

(say mechanical, electrical, magnetic)

Heat Transfer
Only when there
is temp gradie

→ Different types of work transfer

- * Displacement or pdv work
- * Paddle wheel work.
- * Flow work
- * shaft work.

Mechanical work transfer between system and surroundings.

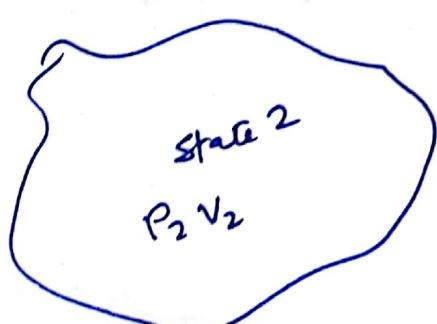
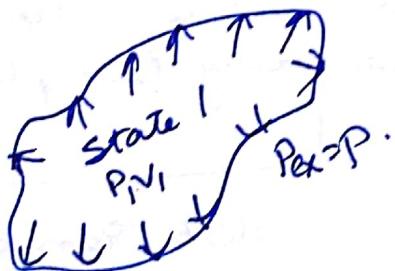
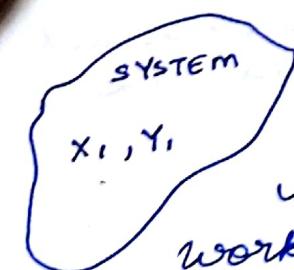
* Displacement or pdv work :- It is associated with a closed system. Work takes place due to displacement of the system boundary. No restriction on system volume i.e. boundary can expand or collapse. So for a specified quantity of mass displacement work takes place due to interaction between system and surroundings. Also the process should be quasi-static.

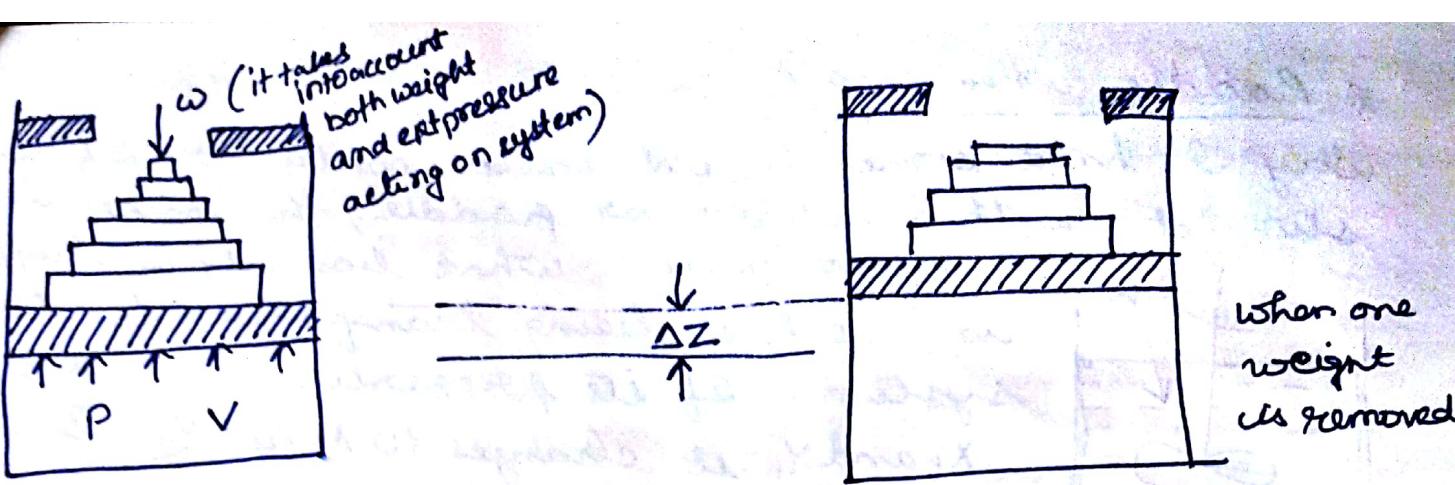
Say I have a system at state 1, P_1 and V_1 .

The system is in equilibrium when internal pressure exerted is equal to the external pressure. Say it reaches state 2 by expansion of the boundary to P_2 and V_2 by a quasi-static process. Then this is called displacement work and is given by

$$W = \int pdv$$

This integral can be evaluated only if P is known as a function of V .





Consider a gas at state 1 in a piston cylinder arrangement. It is a closed system with a movable boundary. Now if infinite number of weight are placed, and one is removed then boundary moves up by a height ΔZ . Friction can be neglected as it is infinitesimally slow process. The system will be in equilibrium when $w = PA$. It can be thus seen, when a weight is removed, work done is,

$$\text{Work done} = P \times A \times \Delta Z = pdV.$$

Thus work takes place due to expansion of boundary and it is called displacement work. The representation of displacement work is hence pdV . This is actually non-dissipative work as it is slow i.e. quasi-static process.

\therefore From state 1 to state 2 via quasi-static process, non-dissipative work is

$$W_{1-2} = \int_1^2 pdV.$$

(Reversible work as this process is reversible)
as no loss in term of friction takes place

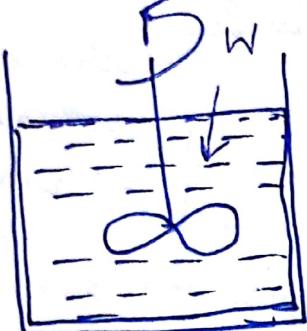
* Paddle wheel work :-

Say I have some liquid in a container. If we stir it with a stirrer or paddle, the temperature will be raised. What basically is happening is work is being transferred to the system. If its properties were say x_1 and y_1 it changes to x_2 and y_2 . Due to work transfer, internal energy increases. This type of work is known as paddle work or stirring work. Here friction is an agent to transfer work to the system. If there was no friction, then work will not be required for stirring. So this is a dissipative work.

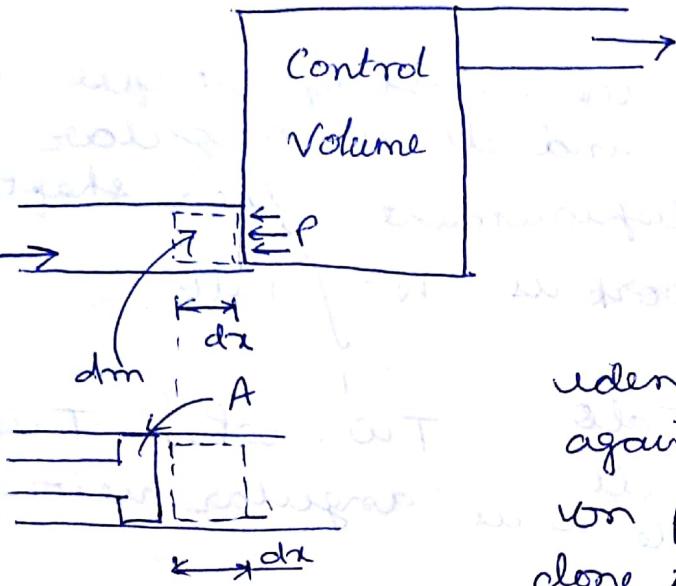
* Flow Work Main difference between pdv is irreversible work. Main difference between pdv is friction is considered as an agent for doing work unlikely in pdv work where it is considered. This work transfer causes a change in system properties and is irreversible.

Flow work is required to maintain a flow and is mainly associated with a control volume. Steady flow of fluid mass or matter coming into the system and going out of the system. So it is an open system, an a control volume system.

Now when fluid flow is taking place, if we consider a layer at any section, the layer has to push its way through to maintain the flow similar to moving in a queue. This means that each and every section does some work in the adjacent neighbouring section downstream to make its way through. So by this some work is done by one section of fluid on its neighbour and this is called flow work. Because of this work,



the adjacent neighbouring section stores some energy. Thus we can say that every adjacent section has some stored energy by the virtue of which it can do work on neighbour to make its way through. Thus, it is again pressure energy. Flow work and pressure energy are both synonymous. In fluid mechanics we call it pressure energy and in thermodynamics it is flow work. Let us consider a control volume say an air compressor. It receives air at low pressure and temp and compresses it because of some turbo machinery and delivers at high pressure and temp. At the inlet consider



a mass dm of width dx which needs to be forced into the system against a pressure ' P '. Hypothetically consider the fluid upstream as a piston pushing the identified mass ' dm ' through CV against pressure ' P '. The force on piston is $F = P \times A$ and work done is $W = P \times A \times dx$. This work

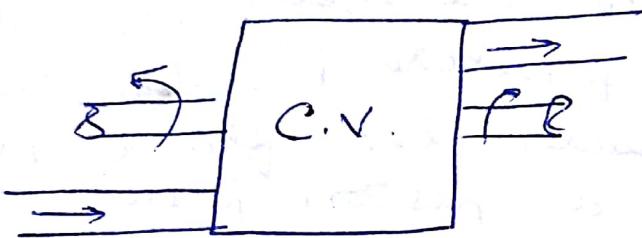
done is represented as energy per unit mass or work done per unit mass i.e.

$$\text{W/mass} = \frac{P A dx}{f A dx} = \frac{P}{f} = \boxed{Pv} \rightarrow \text{specific volume.}$$

In the limiting case, when $dx \rightarrow 0$ we can say that it is the work done by each section per unit mass.

* Shaft Work :-

Say we have a control volume system and a work interacting device. Due to entering or out flow of mass some forework is being done by the system or given to the system. In a compressor work is given to the system in a turbine work is obtained. This work generally obtained as rotation of shaft is known as shaft work against a resisting torque.



If the resisting torque T and $d\theta$ is angular displacement, then shaft work is $W = \int_2^1 T d\theta$.

The shaft power is $\int \frac{T d\theta}{dt} = T \omega$. when ω is considered constant. While ω is angular velocity.

$$\text{Ans} \quad \text{Ans}$$
$$P = T \omega = \frac{F R}{2} \cdot \frac{2 \pi f}{60} = \frac{\pi F R f}{30}$$

pdV work in various quasi-static processes

(a) Constant pressure :-

$$W_{1-2} = \int p dV = P(V_2 - V_1)$$

This is isobaric process.

(b) Constant volume (isochoric) process :-

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

(c) Isothermal process where $T = \text{const}$ and $pV = C$.

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

$$pV = P_1 V_1 = C$$

$$p = \frac{P_1 V_1}{V}$$

$$\therefore W_{1-2} = P_1 V_1 \int_{V_1}^{V_2} \frac{1}{V} dV$$

$$P_1 V_1 = P_2 V_2$$

$$\therefore W_{1-2} = P_1 V_1 \ln \frac{V_2}{V_1}$$

$$W_{1-2} = P_1 V_1 \ln \frac{P_1}{P_2}$$

(d) Process in which $pV^n = C$.

$$W_{1-2} = \int_{V_1}^{V_2} P_1 V_1^n \frac{1}{V^n} dV$$

$$= P_1 V_1^n \left[\frac{V^{-n+1}}{-n+1} \right]_{V_1}^{V_2}$$

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

$$P = \frac{P_1 V_1^n}{V^n}$$

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

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

\rightarrow Path and point function

Consider a thermodynamic coordinate system x and y . A system goes from state 1 to state 2 with any two independent intensive property x_1, y_1 to x_2, y_2 .

Say heat Q is given and work W is being done.

$$W_{1-A-2} \neq W_1 - W_2$$

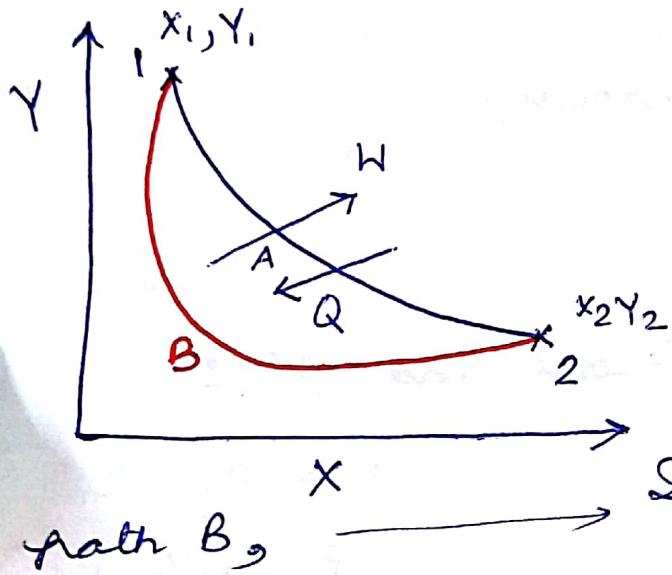
$$Q_{1-A-2} \neq Q_1 - Q_2$$

If we make the system go to state 2 via another

In that case, $W_{1-B-2} \neq W_{1-A-2}$

$$Q_{1-B-2} \neq Q_{1-A-2}$$

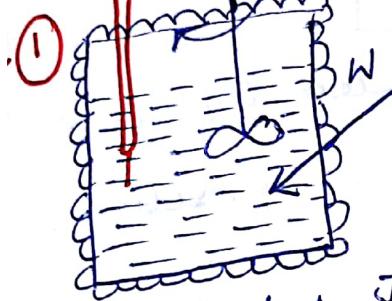
So if two states are undergone by two different path (same change of state), the work and heat interaction will not be same, because they are path functions. But the change in properties are $x_2 - x_1$ and $y_2 - y_1$, because they are point functions.



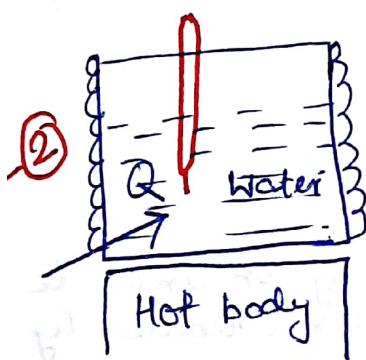
FIRST LAW OF THERMODYNAMICS

Joule's Experiment :-

Consider a container having any liquid say water. The entire system is insulated. A paddle wheel is stirred in the liquid. Let a thermometer be dipped into it. If the stirrer is rotated for some time, some amount of work crosses the system boundary due to which state of system has changed which is again manifested as a change of state.

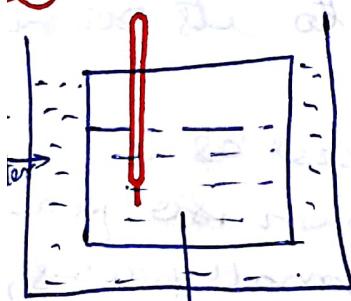


Joule saw that the pressure remains almost the same. Again what Joule did, he took the same container and brought it in contact with a hot body. The other sides were kept insulated.

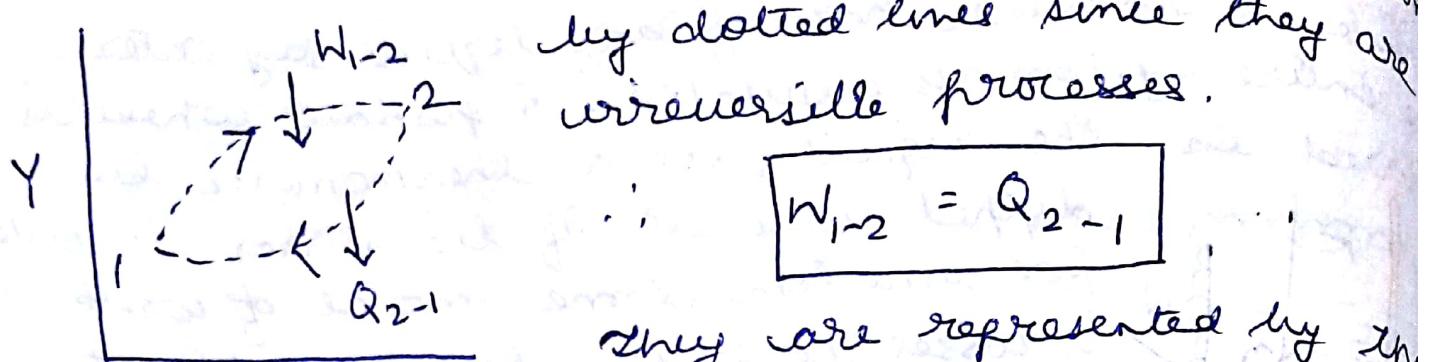


He observed that the same rise in temperature can be achieved by adding a calculated amount of heat to system. Thus, from this experiment Joule proved that work and heat can produce the same effect on a system and same type of energy transfer.

Again Joule, took the container in case 1 in a bigger bath containing cold water and restored the system to initial state 1 i.e. by reading the thermometer heat comes out from the system to the cold water. He found out the amount of heat that is coming out which was found to be exactly equal to the work done.



If the processes are represented on the coordinate system. It can be seen that the system undergoes a cycle. The path is shown



X
they are represented by Σ
saye units. Heat given to a system is positive
and work coming out is positive.

Definition: The algebraic sum of net heat and work interactions between a system and its surrounding in a thermodynamic cycle is zero.

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

$$\oint (Q - W) = 0$$

$$\oint (SQ - SW) = 0 \quad (\text{Considering an infinite slow process executed on a system}) \quad (\text{Infinite amount } SQ \text{ and } SW \text{ is coming out})$$

From knowledge of elementary mathematics, we know that cyclic integral of a point function is zero since the property comes back to its original value.

Thus $SQ - SW = dX$ can be expressed as a point function which was not known so far. But now we know, for an infinite small process $SQ - SW = dX = \text{point function}$.

Thus for a finite process, the difference of heat given and work executed, is a difference / change in point function.

$$\text{Path } \rightarrow Q - W = \Delta X \uparrow_{\text{Path}} \text{Point}$$

This point function $X = \text{internal energy}$.

$$\therefore 8Q - SW = dE : S_Q = SW + dE$$

Finite process $Q - W = \Delta E : Q = W + \Delta E$

$$Q_{1-2} - W_{1-2} = E_2 - E_1 : Q_{1-2} = W_{1-2} + (E_2 - E_1)$$

This is also physically true. We give certain amount of heat to a system and obtain a certain amount of work, the balance has to be stored within the system.

$$E = U + \underbrace{K.E.}_{\text{Intermolecular Energy}} + P.E. + \text{Any other kind of energy}$$

$$\therefore dE = dU + dK.E. + dP.E. + \dots$$

Internal Energy: A property of a system whose change in a process executed by the system equals to the difference between the heat and work interactions by the system with its surroundings.

Note $\left\{ \begin{array}{l} Q_{1-2} = E_2 - E_1 + W_{1-2} \\ S_Q = dE + SW \end{array} \right\}$ This is the first law and is applicable to both closed and open system.

But the version is slightly different for open system. Presently we will concentrate on closed system.

$$E = U + KE + PE.$$

Now

$$dE = dU + d(K.E + P.E)$$

But for a closed system in equilibrium, since the system is at rest at any equilibrium, the matter within the system is at rest.

In practical cases, the change in PE is negligible compared to the intermolecular energy, in a closed system. $\delta d(P.E) = 0$. So for a closed system in equilibrium state, the change in internal energy,

$$dE = dU$$

$$\therefore Q_{1 \rightarrow 2} = U_2 - U_1 + W_{1 \rightarrow 2}$$

$$SQ = dU + SW.$$

If the system does a quasi-state reversible diff work i.e. $p dV = SW$, in that case,

$$Q_{1 \rightarrow 2} = U_2 - U_1 + \int p dV$$

$$\text{or } SQ = dU + pdV$$

$$\frac{Q_{1 \rightarrow 2}}{m} = U_2 - U_1 + \underbrace{\int p dV}_{\text{specific volume}} \rightarrow \text{specific IE} = \text{Int Energy}$$

$$\frac{SQ}{m} = dU + pdV$$

Enthalpy: without going into the significance of enthalpy, the mathematical statement is given as

$$H = U + PV$$

Why this form of expression?? discussed afterwards

Enthalpy is a property like mol, temp, pressure, etc.

$U \rightarrow$ extensive property.

$V \rightarrow$ extensive property.

so $H \rightarrow$ extensive property.

Then intensive property is the specific enthalpy,

$$h = u + Pv$$

With this, let us solve a problem?

Consider a closed system receiving heat and doing PdV work at constant pressure.

So what is the amount of heat added??

$$Q_{1-2} = U_2 - U_1 + \int pdV$$

$$= U_2 - U_1 + P(V_2 - V_1)$$

$$= (U_2 + P_2 V_2) - (U_1 + P_1 V_1)$$
$$= H_2 - H_1$$

Q_{1-2}



So the heat added at constant pressure is given as the difference in enthalpy.

$$\text{Now } \delta Q = dU + pdV$$

$$= d(U + PV) = dH$$

$$Q_{1-2} = H_2 - H_1$$

So a closed system doing PdV work at constant pressure the heat transfer is obtained as difference in enthalpy at the two end states.

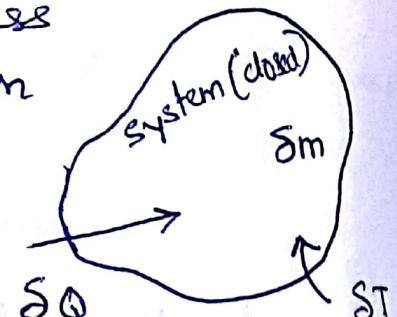
$$\left(\frac{T_2}{T_1}\right) = \frac{(H_2)}{(H_1)}$$

$$= \frac{H_2}{H_1} = \frac{H_2 - H_1}{H_1}$$

But how is this achieved, i.e. work done $p dV$ at constant p ? When the boundary expands, the pressure should decrease. This is counteracted by adding heat to the system. So work is done at p . Again if the boundary collapses, pressure increases. This is again counteracted by heat rejection from the system. And $p dV$ compression work is done at $p = \text{const.}$

Specific Heats: There are two specific heats, specific heat at const volume $\rightarrow C_V$, specific heat at const pressure $\rightarrow C_p$.

Consider a system of very small mass δm , with an infinitely small addition of heat δQ . The "rise" in temp. is δT .



$$C_V = \lim_{\delta T \rightarrow 0} \left(\frac{\delta Q / \delta m}{\delta T} \right)$$

i.e. heat has to be added at constant volume.

Now

$$\delta Q = dU + pdV$$

$$\frac{\delta Q}{\delta m} = dU + pdV$$

$$\left(\frac{\delta Q}{\delta m} \right)_{V=\text{const}} = (dU)_{V=\text{const}} + 0$$

$$\therefore C_V = \lim_{\delta T \rightarrow 0}$$

$$\frac{(dU)_{V=\text{const}}}{\delta T} = \left(\frac{\partial U}{\partial T} \right)_V$$

$$\text{Now } C_p = \left\{ \frac{\left(\frac{\delta Q}{\delta m} \right)_{P=\text{const}}}{\lim_{ST \rightarrow 0} \frac{ST}{S T}} \right\}$$

$$\text{Also, } \lim_{ST \rightarrow 0} \left\{ \frac{(dh)_{P=\text{const}}}{S T} \right\}$$

$$= \left(\frac{\partial h}{\partial T} \right)_P$$

$$\delta Q = dU + PdV$$

$$\frac{\delta Q}{\delta m} = d\bar{u} + Pd\bar{v}$$

$$\left(\frac{\delta Q}{\delta m} \right)_{P=\text{const}} = d(h)_{P=\text{const}}$$

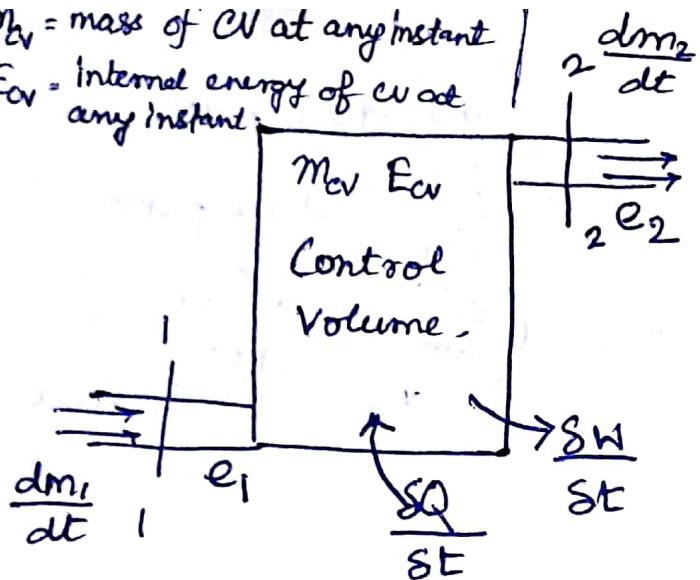
First law applied to an open system or control volume:

Control volume is a ^{fixed} region in space on which attention is concentrated for studying. Continuous flow of matter takes place i.e. coming in and moving out of the CV. During this the property of the matter changes and CV interacts with the surroundings in terms of heat and work.

Eg: Compressor, turbine, heat exchanger.

For a CV, we always describe the energy interactions quantities w.r.t time since a continuous flow of matter takes place. It may be steady or unsteady but continuous flow of matter takes place. This is the principle of a CV. Thus, because of this continuous process with time, things are expressed w.r.t time i.e. energy interactions also.

m_{cv} = mass of CV at any instant
 E_{cv} = internal energy of cv at any instant



Now let us realise a CV.
 flow of matter takes in and out of the CV. There may be multiple inflow and outflow passages, but for simplicity we consider single. From conservation of mass,

$$\frac{dm_1}{dt} - \frac{dm_2}{dt} = \frac{dm_{cv}}{dt}$$

From conservation of energy, the rate of change of energy at any instant within the CV is the rate of change of energy at inlet - rate of change of energy at the outlet. In a closed system, energy interactions take place only in the form of heat and work. But in the present case, since flow of matter is considered, energy quantity associated with this mass is also coming in and going out of the CV. To realise this, one must know what are the forms of energy that can be associated with this flowing mass into the CV.

e (stored energy in a stream of fluid)

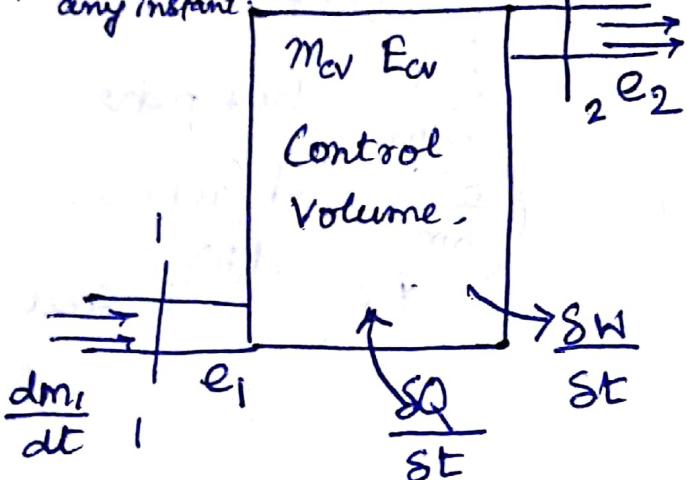
These energies are:

* KE \rightarrow due to velocity
 * PE \rightarrow due to its position in a conservative force field

- * Intermolecular energy \rightarrow due to temperature. A temp above absolute zero always has some intermolecular energy.
- * Pressure energy or flow work.

So a fluid possesses all these energies per unit mass which is flowing continuously.

m_{cv} = mass of CV at any instant
 E_{cv} = Internal energy of cv at any instant



$$2 \frac{dm_2}{dt} \quad 2 e_2$$

Now let us realise a CV. Flow of matter takes in and out of the CV. There may be multiple inflow and out flow passages, but for simplicity we consider single.

From conservation of mass,

$$\frac{dm_1}{dt} - \frac{dm_2}{dt} = \frac{dm_{cv}}{dt}$$

From conservation of energy, the rate of change of energy at any instant within the CV is the rate of change of energy at inlet - rate of change of energy at the outlet. In a closed system, energy interactions take place only in the form of heat and work. But in the present case, since flow of matter is considered, energy quantity associated with this mass is also coming in and going out of the CV. To realise this, one must know what are the forms of energy that can be associated with this flowing mass into the CV.

e (stored energy in a stream of fluid)

These energies are:

- * KE \rightarrow due to velocity

- * PE \rightarrow due to its position in a conservative force field

- * Intermolecular energy \rightarrow due to temperature. A temp above absolute zero always has some intermolecular energy.

- * Pressure energy or flow work.

So a fluid possesses all these energies per unit mass which is flowing continuously.

$e = u + Pv + \frac{V^2}{2} + gz$ These four quantities denote the energy stored per unit mass of a stream of fluid and has been designated as e .

∴ $\frac{dm_1}{dt} q$ and $\frac{dm_2}{dt} e_2$ are the energies entering and leaving the CV respectively. Thus conservation of energy can be written as for the CV:-

$$\underbrace{\frac{dm_1}{dt} q + \frac{SQ}{St}}_{\text{Energy q by coming into the CV.}} - \underbrace{\frac{dm_2}{dt} e_2 - \frac{SW}{St}}_{\text{Energy q by going out of CV}} = \frac{dE_{CV}}{dt} \quad (\text{Rate of change of internal energy of CV}).$$

$$\therefore \frac{dm_1}{dt} \left(u_1 + P_1 v_1 + \frac{V_1^2}{2} + gz_1 \right) + \frac{SQ}{St} - \frac{dm_2}{dt} \left(u_2 + P_2 v_2 + \frac{V_2^2}{2} + gz_2 \right) - \frac{SW}{St} = \frac{dE_{CV}}{dt}$$

This is precisely the first law for a control volume. We have considered that properties at inlet and outlet are invariant with time.

Now at steady state, all the properties of CV, will remain invariant with time i.e. both mass and energy

$$\therefore \frac{dm_{CV}}{dt} = 0 \quad \text{and} \quad \frac{dE_{CV}}{dt} = 0$$

$$\therefore \frac{dm_1}{dt} = \frac{dm_2}{dt} = \frac{dm}{dt} \quad \text{and substitute in the equation,}$$

$$\frac{dm}{dt} \left(u_1 + P_1 v_1 + \frac{V_1^2}{2} + gz_1 \right) + \frac{SQ}{St} - \frac{dm}{dt} \left(u_2 + P_2 v_2 + \frac{V_2^2}{2} + gz_2 \right) - \frac{SW}{St} = 0$$

These quantities are all energy per unit time. It can be expressed as energies per unit mass as follows:

$$\underbrace{\left(u_1 + P_1 v_1 + \frac{V_1^2}{2} + gz_1 \right)}_{\text{Energy/unit mass at inlet}} + \underbrace{\frac{SQ}{Sm}}_{\text{heat/unit mass}} - \underbrace{\left(u_2 + P_2 v_2 + \frac{V_2^2}{2} + gz_2 \right)}_{\text{Energy/unit mass at outlet}} - \underbrace{\frac{SW}{Sm}}_{\text{work/unit mass}} = 0$$

$$\boxed{\frac{\delta Q}{\delta m} - \frac{\delta W}{\delta m} = \left(h_2 + \frac{V_2^2}{2} + gz_2 \right) - \left(h_1 + \frac{V_1^2}{2} + gz_1 \right)} \Rightarrow \text{S.F.E.E.}$$

In all practical appliances, the changes in enthalpy and P.E. are negligible compared to the change in enthalpy. We are not interested here with absolute value of the energies but rather the change in energy. In certain cases such as nozzle and diffuser, the change in K.E. are appreciable. Change in P.E. is always negligible.

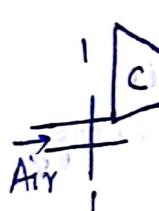
In cases where change in K.E. and P.E. are negligible compared to change in enthalpy, we

$$\frac{\underline{S}Q}{\underline{S}m} - \frac{\underline{S}W}{\underline{S}m} = h_2 - h_1$$

for work interacting devices, $\frac{\underline{S}Q}{\underline{S}m} = 0$,

$$\frac{\underline{S}W}{\underline{S}m} = h_1 - h_2$$

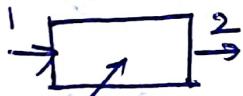
say, I have a compressor having flow of air



On this case, h_2 is more than h_1 denoting work is consumed by compression.

Reverse is the case for a turbine where h_1 is more than h_2 .

For heat interacting devices,



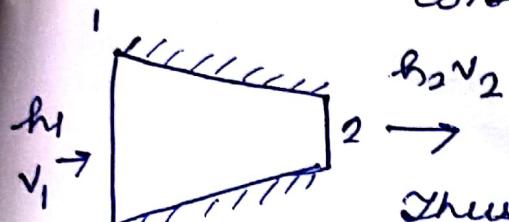
$$\frac{\underline{S}Q}{\underline{S}m} = h_2 - h_1$$

so if heat is added, $h_2 > h_1$

and if heat is rejected, $h_2 < h_1$.

In some cases of CV there are no heat and work interaction but there is conversion of energy from one form to other form. Eg:- Nozzle.

Consider an adiabatic nozzle.



In a nozzle, $v_2 > v_1$,

$$h_2 < h_1$$

Thus at the expense of enthalpy we create the K.E. In that case only PE is neglected.

$$\therefore \frac{30^\circ}{8m} - \frac{8W}{8m} = \left(h_2 + \frac{v_2^2}{2} \right) - \left(h_1 + \frac{v_1^2}{2} \right)$$

Adiabatic No work performed
with surroundings.

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

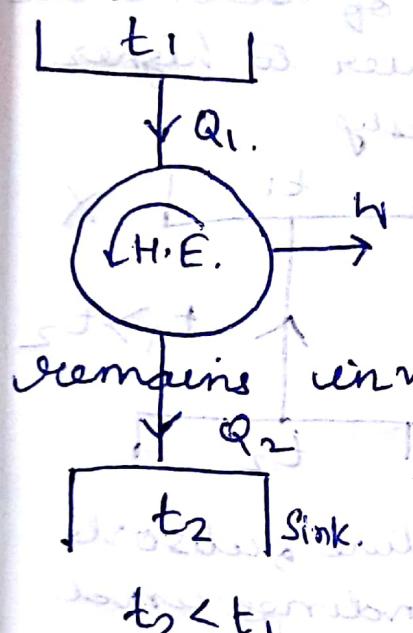
In this way we can apply SFEE to different CV applications.

SECOND LAW OF THERMODYNAMICS

The second law imposes the directional constraint on processes. All process natural and spontaneous occur in a particular direction. But the flow in opposite direction can only take place with the aid of some energy. Eg:- Flow of heat from high temp to low temp or vice versa.

The second law has evolved in many forms but is associated mainly with the directional constraint and interchangeability of heat and work. Let us consider some definitions.

Heat Engine: It is a device where a system operates in a cyclic process so that it develops a work when heat is given to it. To supply this heat, we need to



have a system which is at higher temperature. In this connection we define,

Thermal Reservoir: It is a system of infinite capacity such that when heat transfer takes place, its temperature remains invariant. Const temp infinite heat capacity.

If the reservoir is at a higher temperature from which heat is taken it is known as 'source'.

The reservoir where heat is rejected is at a lower temperature and is known as sink.

$$W = Q_1 \times$$

$$W = Q_1 - Q_2 \checkmark Q_2 \neq 0$$

This is given by

second law that

however ideal process one may achieve, Q_2 cannot be zero.

Thermal efficiency,

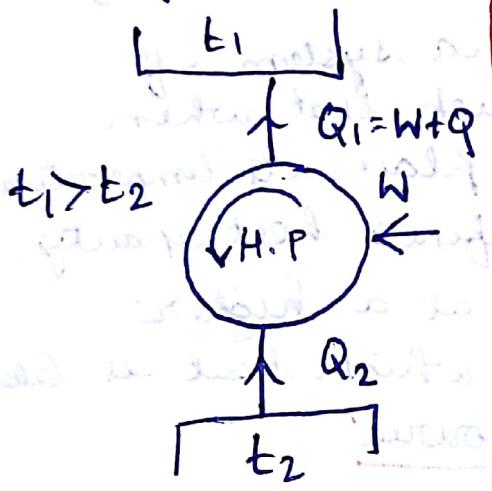
$$\eta_t = \frac{W}{Q_1} = \frac{Q_1 - Q_2}{Q_1}$$

$$\eta_t = 1 - \frac{Q_2}{Q_1} \quad \eta_t \neq 1$$

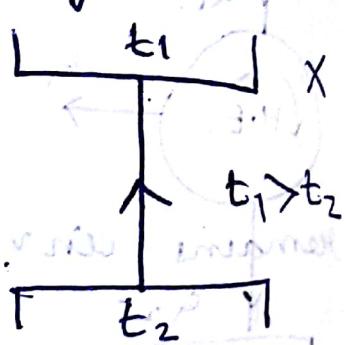
These one cannot convert entire heat to work and there has to be some heat rejection. So the efficiency of heat engine can never be one. This was first told by Kelvin.

Kelvin Planck Statement of second law: It is impossible for a heat engine to produce net work in a complete cycle if it exchanges heat only with bodies at a single fixed temperature.

Now let us realize something called a heat pump. We know that another form of second law says that heat cannot flow from lower to higher temperature spontaneously.



This is law of nature. But we can make a device operating in a cycle which can absorb heat at low temperature, absorb work from surroundings, and can deliver heat to higher temperature.



$$Q \rightarrow W \quad (W < Q)$$

$$W \rightarrow Q \quad (Q = W)$$

Thus work can be totally converted to heat but heat cannot be totally converted to work. Some amount of heat rejection has to be there even in the ideal case and even if we do not consider dissipative effect and practical constraints. Even in ideal case, some amount of heat rejection has to be there and an heat engine cannot have efficiency 1. This forms the base of heat being low grade energy and work being high grade energy.

Clausius Statement of the second law: It is impossible to construct a device which operating in a cycle will produce no effect other than the transfer of heat from a cooler to a hotter body.