

Second law of Thermodynamics

- Second law gives the ^{concept of} degradation of energy by the concept of entropy. AKA dissipative law @ law of degradation of energy.
- First law tells about quantity of heat called quantitative law. 2nd law tells about quality of energy. AKA qualitative law.

Why 2nd law:

- * Complete conversion of heat into work isn't possible whereas a complete conversion of work into heat is possible.
- * Direction of natural process.
- Universal law (2nd law of TD) based on observation made in the universe (observational law).

Thermal Energy Reservoir (TER):

It is defined as a large body of infinite heat capacity, which is capable of absorbing @ rejecting heat an unlimited quantity of heat without suffering appreciable change in its thermodynamic ~~and~~ coordinates.

Source: Source is a TER which can provide large amount of heat without undergoing any temp change.

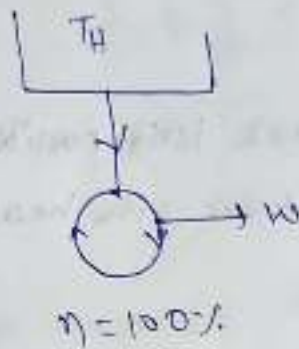
Sink: It is TER which can absorb large amount of heat without undergoing any temp change.

Kelvin-Planck statement of second law:

It is impossible to develop a cyclic device which produces net work by exchanging energy with a single reservoir. The concept of such a device will have 100% thermal efficiency and is called PMM-II and is impossible.

Clausius' statement of second law:

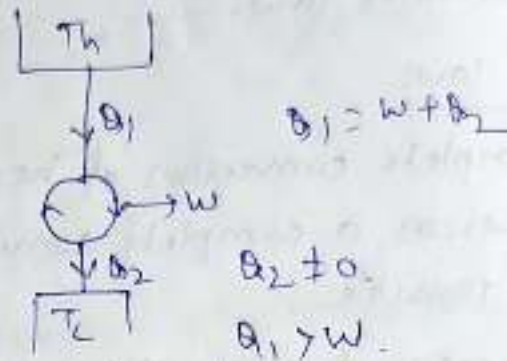
It is impossible to develop a device which transfers heat from lower temp to higher temp without any external energy input. Such a device will have infinite COP and is impossible.



Impossible A/C

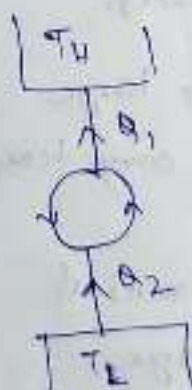
2nd law (K.P. statement)

For a process: $T = C$
 $dQ = dW$ } that's why K.P. statement is for a cycle.



Complete conversion of heat into work is not possible. Only a partial conversion is possible. Remaining heat is rejected to sink.

→ Although HR is a loss but still it is necessary for a continuous work output from the cycle.

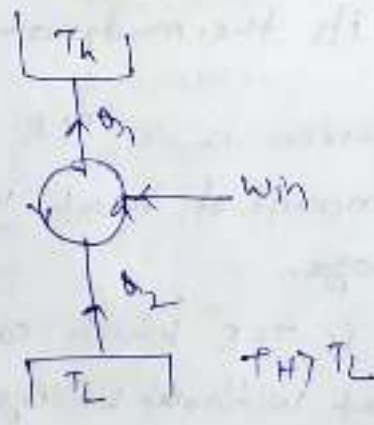


$T_H > T_L$

Impossible A/C

to 2nd law

[Clausius statement]



possible.

1st law of TD:

$$Q_2 + W = Q_1$$

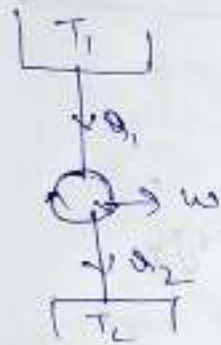
$$W_{in} = Q_1 - Q_2$$

Ex: Refrigerator.

Note: K.P statement gave the concept of heat engine whereas clausius statement gave the concept of heat pump and refrigerator.

Heat Engine / Thermal Engine:

The work producing device that converts thermal energy (heat) into some useful mechanical work.



$$\text{Efficiency} = \frac{\text{Net work o/p}}{\text{Heat supplied}}$$

1st law:
 $W = Q_1 - Q_2$

$$= \left(\frac{W_{out}}{Q_1} \right)$$

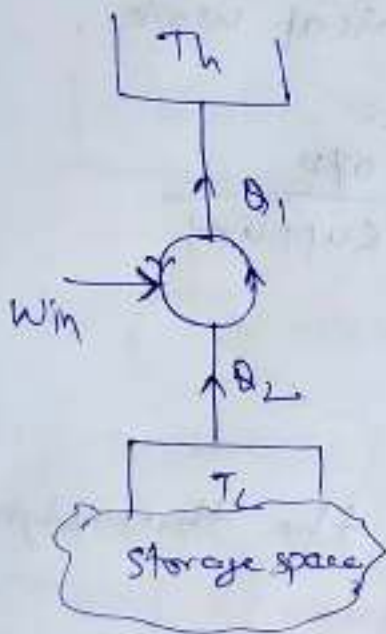
- η is given an order to measure the thermodynamic performance of an engine.
- fraction of heat supplied that is available for work o/p.

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

- Valid for both reversible as well as irreversible engine
- A/c to K.P statement: $Q_2 \neq 0$. Hence $\eta \neq 100\%$
- No engine can have 100% efficiency, no matter it is highly reversible @ ideal, it violates 2nd law of T.D (K.P statement)

Refrigerators: It is work consuming device based on clausius' statement.

It is used to maintain a space at a temp lower than the surroundings temp. and the process is known as refrigeration.



from 1st law:

$$Q_2 + W_{in} = Q_1$$

$$W_{in} = Q_1 - Q_2$$

Coefficient of Performance / Energy performance Ratio:

COP @ EPR = Ratio of desired effect from a work consuming device with W_{in} to it.

$$(COP)_R = \left(\frac{Q_2}{W_{in}} \right) = \left(\frac{Q_2}{Q_1 - Q_2} \right)$$

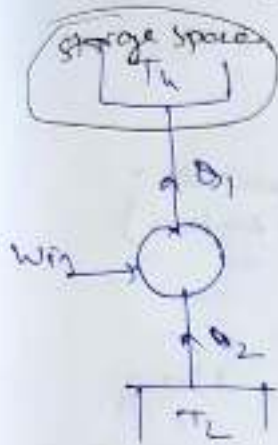
$$(COP)_R \propto \left(\frac{1}{W_{in}} \right)$$

Higher COP \Rightarrow less work input \Rightarrow less electricity supply \Rightarrow More economical.

$$1 \text{ unit} = 1 \text{ kWh} = 3600 \text{ kJ}$$

maintains \rightarrow continuously cyclic process.

Heat Pump: It is a device which, operating in a cycle maintains a space at a temp higher than the temp of surroundings.



from 1st law of T.D.

$$Q_2 + W_m = Q_1$$

$$W_m = Q_1 - Q_2$$

Desired Effect = Q_1

$$\text{COP/EPR} = \left(\frac{Q_1}{W_m} \right) = \left(\frac{Q_1}{Q_1 - Q_2} \right)$$

Qn) How heater is different from heat pump.



$$Q_1 = W_{EH}$$

$$\text{COP} = 1$$

$$(\text{COP})_{HP} = \left(\frac{Q_1}{Q_1 - Q_2} \right) > 1$$

$$(\text{COP})_{HP} > (\text{COP})_{EH}$$

Operating cost of heat pump is very less as compare to ~~heat pump~~ heater.

Comparison:

$$(\text{COP})_{HP} = \left(\frac{Q_1}{Q_1 - Q_2} \right) = \left(\frac{1}{1 - Q_2/Q_1} \right) = \left(\frac{1}{\eta} \right)$$

$$(\text{COP})_{HP} - (\text{COP})_R = 1$$

$$(\text{COP})_{HP} = (1 + \text{COP})_R$$

$$(\text{COP})_{HP} = 1 + (\text{COP})_R = \frac{1}{\eta_{HE}}$$

Valid only when the temp limits of operation are same.

→ Act of HP are obtained by reversing the dirⁿ of a heat engine. AKA reversed heat engine.

76)

A heat engine with 30% efficiency is reversed in operation. Then COP of reversed engine will be

(a) 0.33

(b) 1.33

(c) 2.33

(d) 4.33

$$(COP)_{HP} = \left(\frac{1}{\eta}\right) = \left(\frac{1}{0.3}\right) = 3.33 \quad (\text{Not available, option match})$$

$$(COP)_R = (COP)_{HP} - 1 = 2.33$$

If in question ^{both} 2.33 & 3.33 ^{are} ~~both~~ mentioned then choose 3.33.

#

$$\eta_{HE} \in (0, 1)$$

$$(COP)_R \in (0, \infty)$$

$$(COP)_{HP} \in [1, \infty)$$



CLAUSIUS INEQUALITY

↳ Valid only for a cycle.

$$\oint \frac{dq}{T} \leq 0$$

$$\oint \frac{dq}{T} < 0 \quad [\text{Irreversible cycle}]$$

$$\oint \frac{dq}{T} = 0 \quad [\text{Reversible cycle}]$$

$$\oint \frac{dq}{T} > 0 \quad [\text{Impossible cycle}]$$

For a reversible process

$$q = f(T) \text{ only}$$

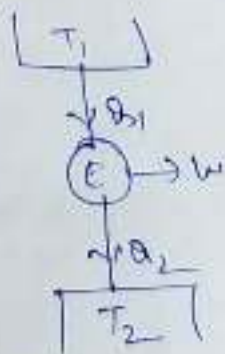
$$q \propto T$$

In terms of temp measurement:

→ $x = q$.

Thermometric property $T = \frac{273.16}{q_{tr}} \cdot q$

Reversible cycle: All the processes must be reversible then cycle will be a reversible cycle. i.e. even a single process in the cycle is irreversible then the whole cycle will be irreversible cycle. Proof $\oint \frac{dq}{T} |_{\text{rev}} = 0$.



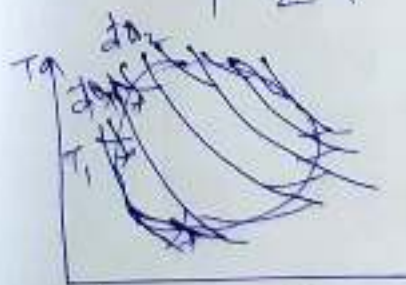
$$\oint \frac{dq}{T} = \frac{Q_1}{T_1} + \left(-\frac{Q_2}{T_2} \right)$$

$$\oint \frac{dq}{T} = \frac{Q_1}{T_1} - \frac{Q_2}{T_2}$$

for a reversible process

$q \propto T$ (From T. D temp scale)

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

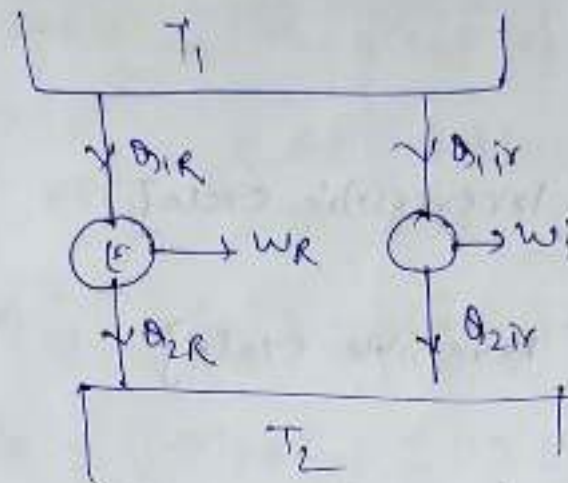


$$\sum_{\text{cycle}} \frac{dq_1}{T_1} = \sum_{\text{cycle}} \frac{dq_2}{T_2}$$

Now:

$$\oint \left(\frac{dq}{T} \right)_{\text{rev}} = 0$$

For an irreversible cycle:



Obviously

$\eta_R > \eta_{irr}$. (~~due to losses~~ (Carnot Principle))

$$1 - \left(\frac{Q_2}{Q_1}\right)_{irr} < 1 - \left(\frac{Q_2}{Q_1}\right)_{rev}$$

$$-\left(\frac{Q_2}{Q_1}\right)_{irr} < -\left(\frac{Q_2}{Q_1}\right)_{rev}$$

$$\left(\frac{Q_2}{Q_1}\right)_{irr} > \left(\frac{Q_2}{Q_1}\right)_{rev}$$

But for reversible:

$$\left(\frac{Q_2}{Q_1}\right)_{rev} = \left(\frac{T_2}{T_1}\right)$$

$$\frac{Q_{2,ir}}{Q_{1,ir}} > \frac{T_2}{T_1}$$

$$\Rightarrow \frac{Q_{2,ir}}{T_2} > \frac{Q_{1,ir}}{T_1}$$

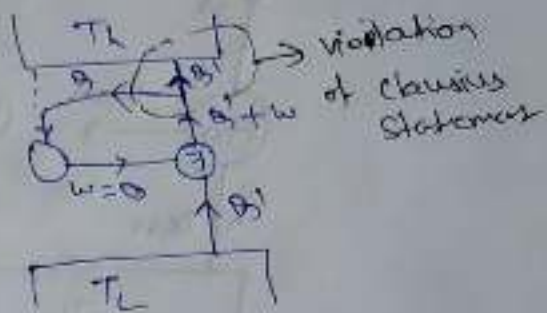
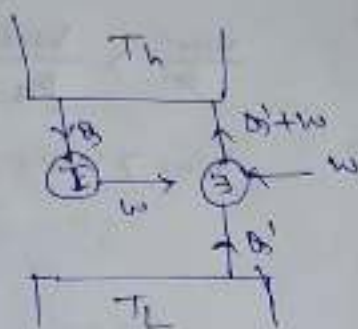
$$0 > \frac{Q_{2,ir}}{T_1} - \frac{Q_{2,ir}}{T_2}$$

$$\oint \left(\frac{dQ}{T}\right)_{irr} < 0$$

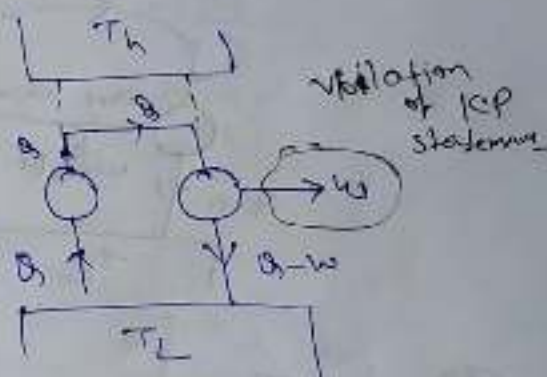
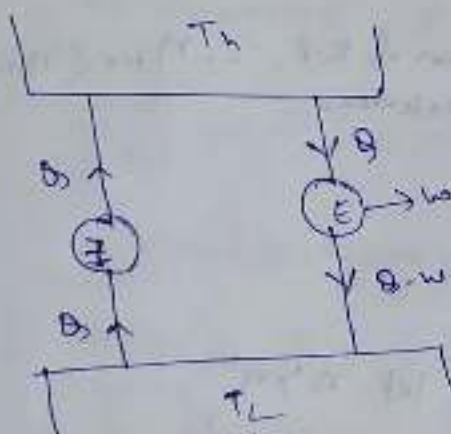
Proves

Equivalence of Kelvin-Planck & Clausius statement:

Violation of Kelvin Planck statement:



Violation of Clausius statement:

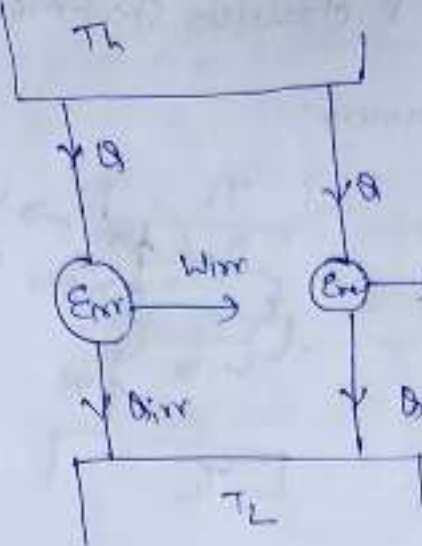


→ Violation of K.P statement leads to ~~no~~ violation of Clausius statement and vice-versa. Hence two statements are called as parallel statement of T.D.

Carnot Principal:

- (i) The efficiency of an irreversible heat engine is always less than the reversible engine operating b/w same temp limits.
- (ii) Efficiency of all reversible engine operating b/w same temp limits is same.
 \Downarrow
 η of reversible engine is independent of working fluids. (depends on only temp limits).

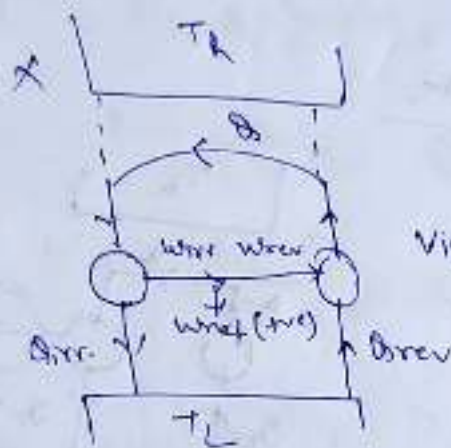
①



let $\eta_{1ir} > \eta_{2ev}$

$$\frac{W_{1ir}}{Q_1} > \frac{W_{2ev}}{Q_2}$$

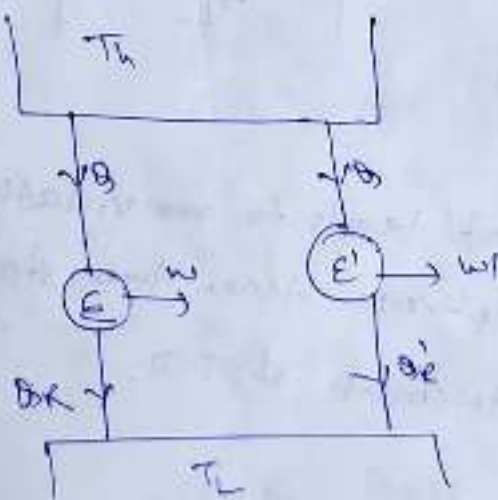
$$W_{1ir} > W_{2ev}$$



$\eta_{1ir} > \eta_{2ev}$

Violation of K-P statement $\therefore \eta_{1ir} < \eta_{2ev}$

②

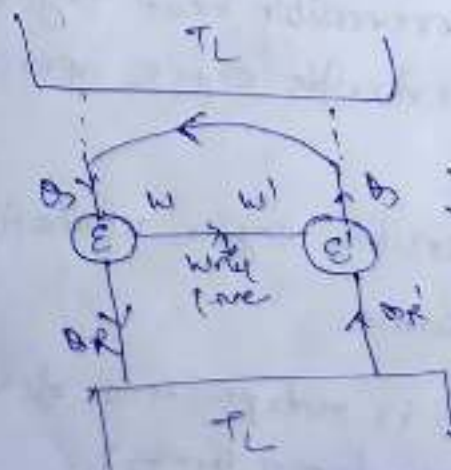


let $\eta > \eta'$

$$\frac{W}{Q} > \frac{W'}{Q'}$$

$$W > W'$$

E, E' = Rev engine.



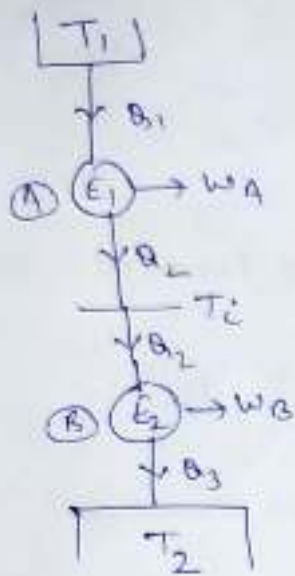
$\eta > \eta'$

$$\Delta \eta \neq \eta \neq \eta'$$

$$\eta = \eta'$$

Violation of K-P

Engine in Series:



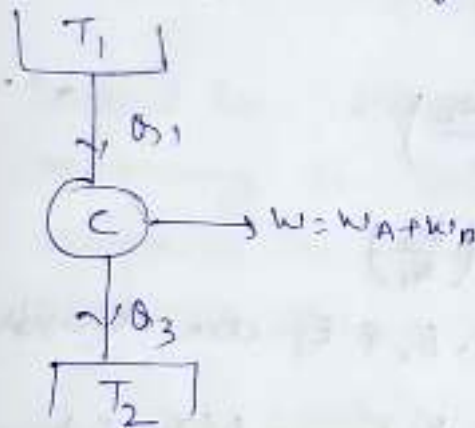
$$\eta_A = 1 - \left(\frac{Q_2}{Q_1}\right)$$

$$\left(\frac{Q_2}{Q_1}\right) = (1 - \eta_A)$$

$$\eta_B = 1 - \left(\frac{Q_3}{Q_2}\right)$$

$$\frac{Q_3}{Q_2} = (1 - \eta_B)$$

Equivalent Engine.



$$\eta_C = 1 - \left(\frac{Q_3}{Q_1}\right)$$

$$\frac{Q_3}{Q_1} = (1 - \eta_C)$$

Now

$$\frac{Q_3}{Q_1} = \frac{Q_3}{Q_2} \times \left(\frac{Q_2}{Q_1}\right)$$

$$(1 - \eta_C) = (1 - \eta_A)(1 - \eta_B)$$

Valid for both reversible as well as irreversible cycle.

Engine in Series (Reversible)

Find out Intermediate temp (T_i)



(a) Work of both the engines are equal

(b) $\eta_A = \eta_B$

(a) $W_A = W_B$

$$Q_1 - Q_2 = Q_2 - Q_3$$

$$Q_2 = \frac{Q_3 + Q_1}{2}$$

for reversible cycle

$$Q = kT$$

$$\therefore T_i = \frac{T_3 + T_1}{2}$$

$$(b) \quad \eta_A = \eta_B$$

$$1 - \frac{Q_2}{Q_1} = 1 - \frac{Q_3}{Q_2}$$

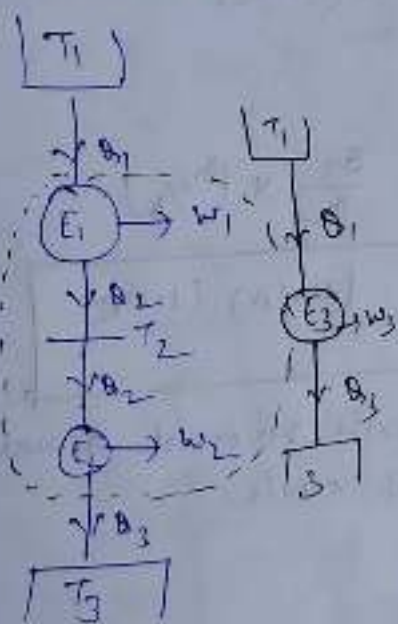
$$\frac{Q_2}{Q_1} = \frac{Q_3}{Q_2} \Rightarrow Q_2 = \sqrt{Q_1 \cdot Q_3}$$

for reversible cycle $Q = kT$

$$\therefore kT_2 = k\sqrt{T_1 \cdot T_3}$$

$$T_2 = \sqrt{T_1 \cdot T_3}$$

Thermodynamic Temp scale:



$$\eta_3 = \left(\frac{W_1 + W_2}{Q_1} \right)$$

$$\eta_3 = 1 - \left(\frac{Q_3}{Q_1} \right)$$

As E_1, E_2 & E_3 are reversible

$$\eta_1 = 1 - \frac{Q_2}{Q_1} = f(T_1, T_2)$$

$$\frac{Q_2}{Q_1} = F(T_1, T_2) \quad \text{--- (i)}$$

$$\text{Similarly} \quad \frac{Q_3}{Q_2} = F(T_2, T_3) \quad \text{--- (ii)}$$

(i) & (ii)

$$\frac{Q_3}{Q_1} = F(T_1, T_2) \cdot F(T_2, T_3)$$

$E_3 = \text{Reversible}$

$$\frac{Q_3}{Q_1} = F(T_1, T_3)$$

$$\text{From (i)} \quad \frac{Q_2}{Q_1} = F(T_1, T_2) = \frac{\phi(T_2)}{\phi(T_1)}$$

$$\frac{Q_3}{Q_2} = F(T_2, T_3) = \frac{\phi(T_3)}{\phi(T_2)}$$

Second law Efficiency:

$$\eta_{II} = \frac{n_{actual}}{n_{max}} = \frac{W_{act}/Q_1}{W_{max}/Q_1} = \left(\frac{W_{act}}{W_{max}} \right)$$

for work consuming device.

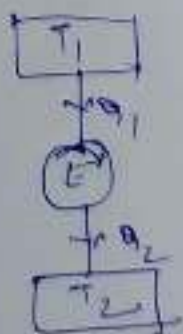
$$\eta_{II} = \frac{(COP)_{act}}{(COP)_{max}} = \frac{DE/w_{act}}{DE/w_{in}} = \left(\frac{w_{in}}{w_{act}} \right)$$

Second law efficiency is a better criterion for measuring the performance of a device because it compares the performance with best possible in given situation.

Internal Reversibility & External Reversibility:

A process is said to be externally reversible if no entropy generation takes place outside the system. It is called internally reversible if no entropy generation takes place inside the system.

→ A cycle is totally reversible if it is both internally as well as externally reversible.



Source temp = cycle temp @ H.A. } External
Sink temp = cycle temp @ H.R. } Reversible

Internal irreversibility: dissipative effect.

Entropy

Ans) Prove that entropy is a property of the system.

$$\oint \left(\frac{dq}{T} \right)_{\text{rev}} = 0$$

side (1-a-2-b-1)

$$\left(\frac{dq}{T} \right)_{1a2} + \left(\frac{dq}{T} \right)_{2b1} = 0 \quad \text{--- (i)}$$

for side (1-a-2-c-1):

$$\left(\frac{dq}{T} \right)_{1a2} + \left(\frac{dq}{T} \right)_{2c1} = 0 \quad \text{--- (ii)}$$

Subtracting from (i) to (ii)

$$\left(\frac{dq}{T} \right)_{2c1} = \left(\frac{dq}{T} \right)_{2b1}$$

$$\left(\frac{dq}{T} \right)_{\text{rev}} = (ds)$$

The quantity $\left(\frac{dq}{T} \right)$ when evaluated for a reversible path comes out to be same b/w same initial and final points irrespective of path. Hence it must represent the change in property b/w two points joined by the path. This property is called ~~path~~ entropy.

Entropy: Measurement of degree of randomness of the system.

$$\left(\frac{dq}{T} \right)_{\text{rev}} = (ds)$$

$$\text{I.F} = \frac{1}{T}$$

Reversible heat transfer process:

$$\Delta S = \int \frac{\delta Q_R}{T}$$

$\Delta S = 0$ (Reversible adiabatic process)

$\Delta S = -ve$ (Heat rejection)

$\Delta S = +ve$ (Heat addition)

Irreversible heat transfer process

$$\Delta S = \int \frac{dQ}{T} + S_{gen}$$

Adiabatic process $\int \frac{dQ}{T} = 0$

$$\Delta S = S_{gen}$$

$$S_{gen} > 0 \Rightarrow \boxed{\Delta S > 0}$$

At a certain point: $\int \frac{dQ}{T} = -S_{gen}$ (At heat rejection in irreversible way)

$\Delta S = 0$ (Isentropic but not adiabatic)

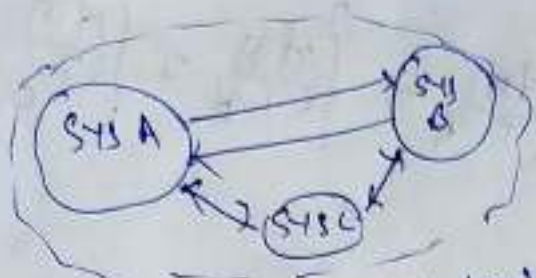
Isolated system:



$(\Delta S)_{isolated} > 0$

$(\Delta S)_{Per\ changes} = 0$

$(\Delta S)_{isolated} > 0$

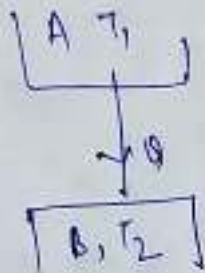


Universe (Isolated system)

$$(DS)_{universe} > 0$$

$$(DS)_{universe} = (DS)_A + (DS)_B + (DS)_C > 0$$

Ex:

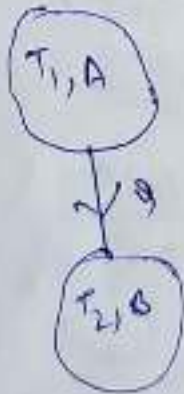


$$(DS)_A = -\frac{Q}{T_1}$$

$$(DS)_B = \left(\frac{+Q}{T_2}\right)$$

$$(DS)_{universe} = Q \left[-\frac{1}{T_1} + \frac{1}{T_2} \right] > 0$$

Ex:



$$T_f = \frac{T_1 + T_2}{2}$$

$$(DS)_{universe} = (DS)_A + (DS)_B$$

$$(DS)_A = \int \frac{\delta Q}{T} = \int_{T_1}^{T_f} \frac{c_p dT}{T} = c_p \ln\left(\frac{T_f}{T_1}\right)$$

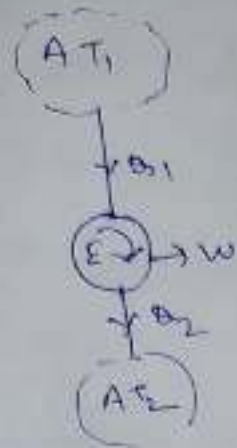
$$(DS)_B = \int \frac{\delta Q}{T} = \int_{T_2}^{T_f} \frac{c_p dT}{T} = c_p \ln\left(\frac{T_f}{T_2}\right)$$

$$(DS)_A + (DS)_B = c_p \ln \frac{T_f^2}{T_1 T_2} = c_p \ln \frac{\left(\frac{T_1 + T_2}{2}\right)^2}{T_1 T_2}$$

AM > GM

$$(DS)_{universe} > 0$$

Ex:-



In this case T_f will not be AM of T_1 & T_2 . If heat rejected by system 1 are totally received by system 2. Then it will be AM. Here some heat is expanded in the form of work.

$$T_f = ?$$

$$(\Delta S)_{universe} = ?$$

If all process are reversible then

$$(\Delta S)_{universe} = 0$$

$$\Rightarrow (\Delta S)_A + (\Delta S)_{HE} + (\Delta S)_C = 0$$

Heat engine works on cycle.

$$C_p \ln \frac{T_f}{T_1} + 0 + C_p \ln \frac{T_1}{T_2} = 0$$

$$\int \frac{dQ}{T} = 0$$

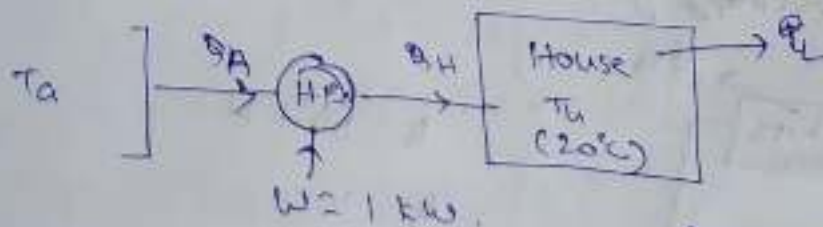
$$T_f^2 = T_1 \cdot T_2$$

$$T_f = \sqrt{T_1 \cdot T_2}$$

$$W_{max} = Q_1 - Q_2$$

Qm A heat pump as a cop that is 50% of the theoretical maximum. It maintains a house at 20°C , which leaks energy of 0.6 kW per degree difference to the ambient. For a maximum of 1.0 kW power input, find the max^m outside temp for which the heat pump is a sufficient heat source.

Solⁿ:



$$0^\circ\text{C} = 273.15 \text{ K}$$

$$20^\circ\text{C} = 293.15 \text{ K}$$

$$\approx 293 \text{ K}$$

$$Q_H = Q_L$$

$$Q_H = Q_L = 0.6(T_h - T_a) \text{ kW} \quad \text{--- (1) For maintaining at } T = 0^\circ\text{C}$$

$$Q_H = (\text{COP})_{HP} \times W \leq (\text{COP})_{HP} \times 1 = (\text{COP})_{HP} \text{ kW}$$

$$(\text{COP})_{\text{ideal}} = \left(\frac{T_h}{T_h - T_c} \right)$$

$$(\text{COP})_{\text{HP}} = 0.5 \left(\frac{T_h}{T_h - T_c} \right)$$

$$Q_H = 0.5 \left(\frac{T_h}{T_h - T_c} \right)$$

from (1)

$$0.5 \left(\frac{T_h}{T_h - T_c} \right) = 0.6 (T_h - T_c)$$

$$0.5 T_h = 0.6 (T_h - T_c)^2$$

$$T_h = 293 \text{ K}$$

$$T_c = 277.4 \text{ K} \quad \underline{\text{Ans}}$$

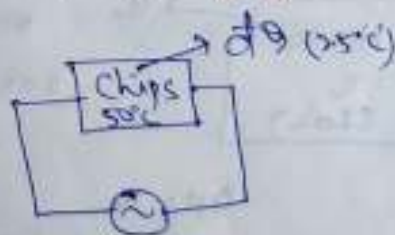
$$t_c = 4^\circ\text{C}$$

Q2) A computer chip dissipated 2 kJ of electric work over time and rejects that as heat transfer from its surface at a steady state temp of 50°C to ambient air at 25°C.

Determine

- Entropy change of chip
- Entropy change of universe
- Entropy generation within the chip
- Entropy generated outside the chip
- Total entropy generated

Soln:



$$Q = Q_H + W$$

$$Q = W$$

$$dS = \int \frac{dQ}{T} + (dS)_i$$

$$(dS)_{\text{chip}} = 0$$

$$(\Delta S)_i = \frac{Q}{T_{chip}} = 0$$

$$(\Delta S)_i = \frac{Q}{T_{chip}} = \frac{2}{(273+50)} = \left(\frac{2}{323}\right) (10^3 \text{ J/K}) = 6.19 \text{ J/K}$$

Entropy generated within the chip (internally irreversibility)

$$(\Delta S)_e = -\frac{Q}{T_{chip}} + \left(\frac{Q}{T_a}\right)$$

(entropy generated due to externally irreversibility)

$$\textcircled{a} \quad (\Delta S)_{\text{generated}} = (\Delta S)_i + (\Delta S)_e$$

$$= \frac{Q}{T_{chip}} - \frac{Q}{T_{chip}} + \left(\frac{Q}{T_a}\right)$$

$$= \left(\frac{2000}{298}\right) = 6.7114 \text{ J/K}$$

$$\textcircled{b} \quad (\Delta S)_{\text{universe}} = (\Delta S)_{\text{chip}} + (\Delta S)_{\text{surroundings}}$$

$$= 0 + \left(\frac{Q}{T_a}\right)$$

$$(\Delta S)_{\text{universe}} = 6.7114 \text{ J/K}$$

#

$$dS_{\text{sys}} \geq \frac{dQ}{T}$$

$$ds = \frac{dQ}{T} + \dot{S}_{\text{gen}} \geq 0$$

$$\delta Q = dU + \delta W \quad (\Delta KE = 0, \Delta PE = 0)$$

for a reversible process

$$T \cdot ds = dU + p \cdot dv$$

$$\downarrow$$

$$\delta W + \delta(LW)$$

$$T \cdot ds = dU + \delta W + \delta(LW)$$

$$T \cdot ds = \delta Q + \delta(LW)$$

$$ds = \frac{\delta Q}{T} + \frac{\delta(LW)}{T}$$

$$\delta Q = \delta(LW) \leftarrow S_{\text{gen}}$$

Ex: $P = P_0, T = T_0$

$$ds \geq \frac{dq}{T}$$

$$ds \leq T ds$$

$$du + \delta w \leq T ds$$

✓ quasiequilibrium process

$$du + p dv \leq T ds$$

$$d(u + p_0 v) \leq T_0 ds$$

$$d(u + p_0 v - T_0 s) \leq 0$$

$$d(H - T_0 s) \leq 0$$

$$dG \leq 0$$

Any spontaneous process takes place if Gibbs free energy decreases.

Reversible adiabatic process of an ideal gas.

1st law: $\delta Q = du + \delta w$

$$0 = du + \delta w(p dv)$$

$$0 = c_v du + p dv$$

$$p v = R T$$

$$= c_v p dT + p dv$$

$$p dv + v dp = R dT$$

$$= c_v R dT + p dv$$

$$dT = \frac{p dv + v dp}{R}$$

~~$$= \frac{R(T_0 - T)}{T} + p dv$$~~

$$= \frac{c_v (p dv + v dp)}{R} + p dv$$

$$= (c_v + R) p dv + c_v v dp$$

$$= c_p p dv + c_v v dp$$

$$= \gamma p dv + v dp$$

$$\Rightarrow 0 = \gamma \frac{dV}{V} + \frac{dP}{P}$$

$$\boxed{PV^\gamma = c}$$

Adiabatic process of an ideal gas:

$$\delta Q = dU + \delta W$$

0 (adiabatic)

$$dU = -\delta W$$

$$-(U_2 - U_1) = \int \delta W$$

$$\int_1^2 \delta W = -(U_2 - U_1)$$

$$C_v = \text{const}$$

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

$$= -\frac{mR (T_2 - T_1)}{\gamma - 1}$$

$$= \frac{P_1 V_1 - P_2 V_2}{\gamma - 1}$$

Note: Workdone in adiabatic process is equal but difference is that in reversible process it will always be true even if C_p and C_v are function of temp. In irreversible process only when C_p & $C_v = \text{constant}$.

C_p & $C_v = c$ ~~constant~~ calorically perfect gas.

Combined 1st & 2nd law of T.D:

$$dQ = dU + dW$$

for a reversible process

$$T \cdot ds = dU + P dV \quad \text{--- (i)}$$

$$H = U + PV$$

$$dH = dU + P dV + V dP$$

$$dH = dQ + V dP$$

$$dH = T \cdot ds + V dP$$

$$T \cdot ds = dH - V dP \quad \text{--- (ii)}$$

Each term of eqⁿ (i) & (ii) represents change in prop & that is same for either reversible or irreversible process. Hence valid for both process.

Slope on T-s diagram:

(i) $P = C$

$$T \cdot ds = dU + P dV$$

$$T \cdot ds = dH - V dP$$

$$T \cdot ds = dH$$

$$T \cdot ds = C_p dT$$

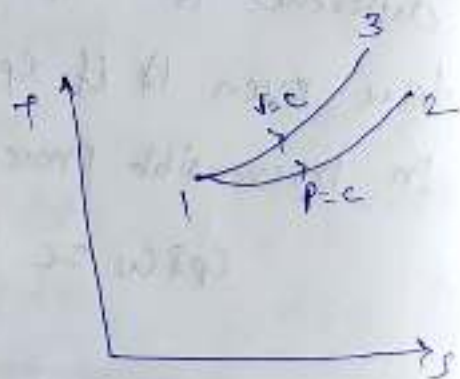
$$\left(\frac{dT}{ds}\right)_{P=C} = \left(\frac{T}{C_p}\right)$$

(ii) $V = C$

$$T \cdot ds = dU + P dV$$

$$T \cdot ds = C_v dT$$

$$\frac{dT}{ds} = \left(\frac{T}{C_v}\right)$$



Reversible work in a steady flow process:

$$w = -vdp$$

Assumptions:

(i) Steady flow

(ii) $\Delta KE = 0$ $\Delta PE = 0$

$$h_1 + q = h_2 + w_{cv}$$

$$q = (h_2 - h_1) + w_{cv}$$

$$dq = dh + \delta w_{cv}$$

If reversible $dq = T ds$

$$T ds = dh + \delta w_{cv} \quad \text{--- (i)}$$

$$T ds = dh + -vdp \quad \text{--- (ii)}$$

from (i) + (ii)

$$\delta w_{cv} = -vdp$$

$$w_{cv} = - \int v dp$$



If process is polytropic:

$$pv^n = C$$

$$w_{cv} = - \int v dp = - \int \left(\frac{C}{p}\right)^{1/n} dp$$

$$= - C^{1/n} \int p^{-1/n} dp$$

$$w_{cv} = \frac{n}{n-1} (P_1 v_1 - P_2 v_2)$$

Entropy change for an ideal gas:

$$T \cdot ds = du + p dv$$

$$ds = \frac{du}{T} + \frac{p}{T} dv$$

for an ideal gas $du = mc_v dT$

$$ds = \frac{mc_v dT}{T} + mR \frac{dv}{v}$$

$$ds = mc_v \ln \frac{T_2}{T_1} + mR \ln \frac{v_2}{v_1}$$

→ Ideal gas
Any process

$$T \cdot ds = dh - v dp$$

$$ds = \frac{dh}{T} - \frac{v}{T} dp$$

$$ds = \frac{mc_p dT}{T} - \frac{mR}{p} dp$$

$$ds = mc_p \ln \frac{T_2}{T_1} - mR \ln \frac{p_2}{p_1}$$

→ Ideal gas
Any process

Entropy change for reservoir & phase change:

$$S = \frac{Q}{T}$$

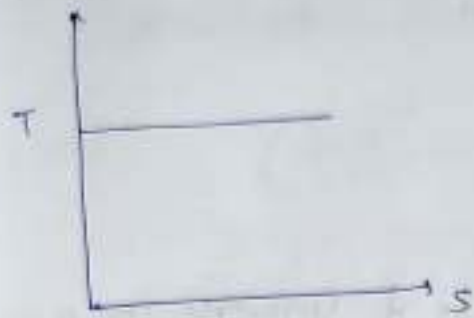
Entropy change for solid/liquid:

$$ds = \int \frac{mc dt}{T}$$

$c = \text{const}$

$$(ds) = mc \ln \frac{T_2}{T_1}$$

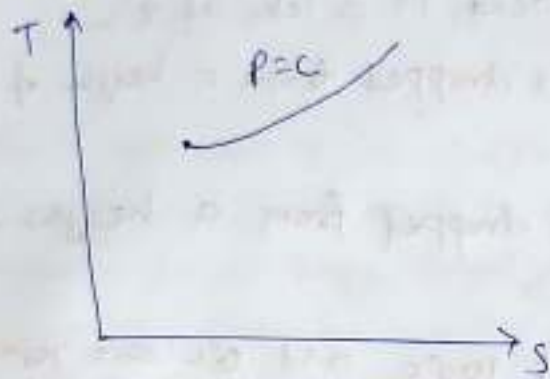
Representation of various process on T-s diagram:



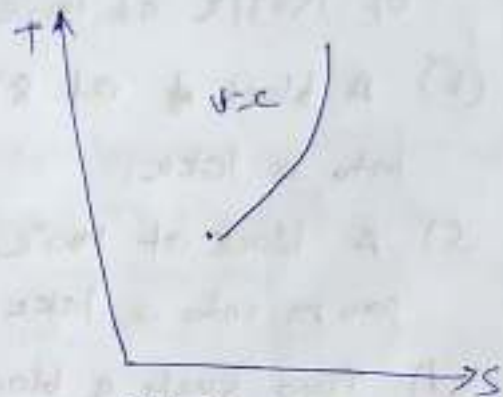
(a) Isothermal



(b) Isentropic process.



Isobaric process



(1) Isochoric process.

Note: For isothermal H.A process

$$dQ = +ve$$

$$dQ = T \cdot ds = +ve \quad (s_2 > s_1)$$

$$dQ = dW + dU$$

$$dQ = dW \quad (+ve)$$

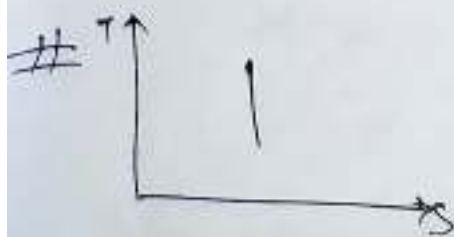
Hence expansion process.

My: Isothermal H.R @ Isothermal compression.

For isentropic process (Rev + adiabatic)

$$dQ = 0 = dU + dW$$

$$0 = dU + dW \Rightarrow dU = -dW$$



$\delta W = +ve$ (Expansion)

$dU = -ve$ (T↓)



Qn) Calculate the entropy change of universe as a result of the following processes

(a) A copper block of 600g mass and heat capacity of 150 J/K at 100°C placed in a lake at 8°C.

(b) A block at 8°C is dropped from a height of 100 m into a lake.

(c) A block at 100°C is dropped from a height of 100 m into a lake.

(d) Two such a block at 100°C and 0°C are joined together.

$$(a) \quad (\Delta S)_{\text{lake}} = \frac{mc_p \ln \frac{T_2}{T_1}}{c} = \frac{150 \ln \frac{281}{373}}{1} = -42.18$$

$$Q_{\text{rej}} = mc \Delta T = 150 \times (100 - 8) = 13800 \text{ J}$$

$$(\Delta S)_{\text{lake}} = \frac{13800}{281} = 49.11 \text{ J/K}$$

$$(\Delta S)_{\text{univ}} = 49.11 - 42.18 = 6.92 \text{ J/K}$$

$$(b) \quad (\Delta S)_b = 0$$

$$mgh = 0.6 \times 9.81 \times 100 = 588.6 \text{ J}$$

$$(\Delta S) = \frac{588.6}{281} = 2.09 \text{ J/K}$$

$$(c) \quad PE = 588.6 \text{ J}$$

$$Q_{\text{rej}} = 13800 \text{ J}$$

$$(\Delta S)_{\text{lake}} = \frac{588.6 + 13800}{281} = 51.20 \text{ J/K}$$

$$(DS)_b = 150 \ln \left(\frac{281}{373} \right) = -42.48 \text{ J/K}$$

$$(DS)_{\text{universe}} = 51.20 - 42.48 = 8.72 \text{ J/K}$$



$$T = \frac{100 + 0}{2} = 50^\circ\text{C}$$

$$(DS)_A = 150 \ln \frac{T_2}{T_1} = 150 \ln \frac{323}{373} = -21.59$$

$$(DS)_b = 150 \ln \frac{323}{273} = 25.23 \text{ J/K}$$

$$(DS)_{\text{universe}} = 2.63 \text{ J/K}$$

Qn) A resistor of $30\ \Omega$ is maintained at 27°C while a current of $10\ \text{Amp}$ is allowed to flow for $1\ \text{sec}$. Determine entropy change of the resistor and the universe. Assume water at 27°C used for cooling of electric resistor.

If the resistor initially at 27°C is now insulated and same current is passed for the same time, determine the entropy change of the resistor and universe. The specific heat of resistor is $0.9\ \text{kJ/kg}\cdot\text{K}$ and mass of resistor is $10\ \text{gm}$.

(a) $(DS)_{\text{resistor}} = \frac{\Delta Q}{T} = 0$

$$Q = i^2 R t = (10)^2 \times 30 \times 1 = 3000 \text{ J}$$

$$(DS)_{H_2O} = \frac{Q}{T} = \left(\frac{3000}{300} \right) = 10$$

$$(DS)_{\text{universe}} = (DS)_{\text{resistor}} + (DS)_{H_2O} = 10 \text{ J/K}$$



(b) resistor = 0

At steady state its thermodynamic coordinates ~~does~~ don't change. Entropy is a point f² hence entropy will also not change.

(for entropy change of state must change)

(b)

$$\delta_{\text{tot}} = dU + \delta W$$

$$dU = -\delta W$$

$$10 \times 0.9 (T_f - 300) = -(-3000)$$

$$T_f = 633.33 \text{ K}$$

$$(\Delta S)_{\text{res}} = 10 \times 0.9 \ln \frac{633.3}{300}$$

$$= 6.725 \text{ kJ/K}$$

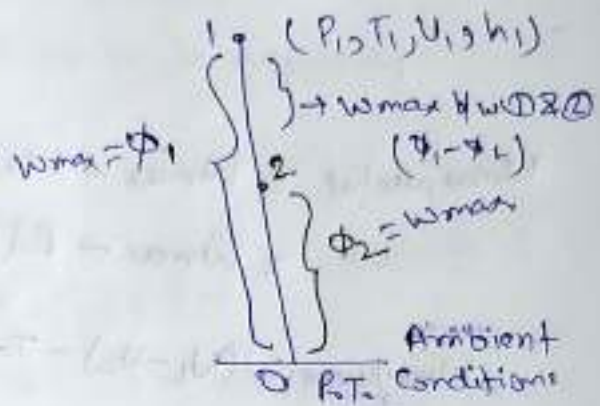
$$(\Delta S)_{\text{H}_2\text{O}} = 0$$

$$(\Delta S)_{\text{univ}} = 6.725 \text{ kJ/K}$$

Available Energy

Availability: The maximum useful work that can be obtained in a process when the system comes into eqm with atmospheric conditions.

→ Decrease in Availability represent maximum work b/w two points.



Maximum work in a closed system:

$$d\theta = dU + dw$$

$$(dw)_{system} = d\theta - dU$$

Maximum Work

↓
Rev

$$(ds)_{surr} = 0$$

$$(ds)_{system} + (ds)_{surr} = 0$$

$$(ds)_{system} = -(ds)_{surr} \quad \text{--- (i)}$$

$$(d\theta)_{system} = -(d\theta)_{surr} \quad \text{--- (ii)}$$

$$(ds)_{surr} = \frac{d\theta}{T_0}$$

$$d\theta = T_0 ds_{surr}$$

$$d\theta_{surr} = T_0 (ds)_{surr} \quad \text{--- (iii)}$$

$$(dw)_{system} = -T_0 (ds)_{surr} - dU$$

Since $(d\theta)_{system} = -(d\theta)_{surr}$

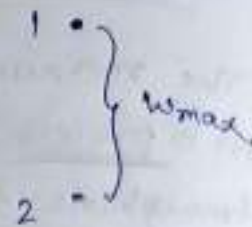
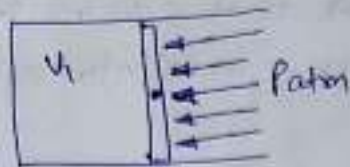
$$= -T_0 (ds)_{surr}$$

$$(dw)_{system} = T_0 [+(ds)_{sys}] - (dU)_{sys}$$

$$= T_0 (s_2 - s_1) - (U_2 - U_1)$$

$$(dw)_{system} = (U_1 - T_0 s_1) - (U_2 - T_0 s_2)$$

$$(dw)_{system} = (U_1 - T_0 s_1) - (U_2 - T_0 s_2) \quad \text{closed system.}$$



$$W_{max, useful} = W_{max} - W_{atm}$$

$$= W_{max} - P_0(V_2 - V_1)$$

$$W_{max, useful} = (U_1 - U_2) - T_0(S_1 - S_2) - P_0(V_2 - V_1)$$

$$W_{max, useful} = \underbrace{(U_1 - T_0 S_1 + P_0 V_1)}_{\phi_1} - \underbrace{(U_2 - T_0 S_2 + P_0 V_2)}_{\phi_2}$$

$$W_{max, useful} = (\phi_1 - \phi_2)$$

$$\boxed{\phi = U - T_0 S + P_0 V} \rightarrow \text{Availability function for closed system}$$

≠ Maximum work in open systems:

↓
 $(W_{max} = W_{max, useful})$ because there is no boundary movement against atm.

$$h_1 + \frac{c_1^2}{2} + z_1 \rho + q = h_2 + \frac{c_2^2}{2} + z_2 \rho + w \rightarrow \text{(Steady flow open system)}$$

Neglect $\Delta KE, \Delta PE$

$$h_1 + q = h_2 + w$$

$$w = q - dh$$

$$W_{max} = h_1 - h_2 - T_0(S_1 - S_2)$$

$$W_{max} = (h_1 - h_2) - T_0(S_1 - S_2)$$

(open)

$$W_{max, useful} = (h_1 - T_0 S_1) - (h_2 - T_0 S_2)$$

for closed system

$$dw = d\phi - dU$$

$$W_{max, useful} = \psi_1 - \psi_2$$

$\psi = h - T_0 s$ Availability for open system.

Irreversibility:

$$I = W_{max} - W_{act} \quad [I \text{ can never be negative}]$$

closed system

$$W_{max} = (U_1 - U_2) - T_0 (S_1 - S_2)$$

$$W_{max} = \underbrace{(U_1 - U_2)}_{sys} - T_0 \underbrace{(S_1 - S_2)}_{sys}$$

$$I = [(U_1 - U_2) - T_0 (S_1 - S_2)] - [T_0 (-ds)_{sur} - (U_2 - U_1)]$$

$$I = T_0 [(ds)_{sys} + (ds)_{sur}]$$

$$I = T_0 [ds]_{univ}$$

$$I = T_0 (SS)_{gen}$$

\downarrow \downarrow
 +ve +ve

$$d\psi = du + dw$$

$$dw = d\psi - du$$

$$(dw)_{syst} = (d\psi)_{syst} - (du)_{syst}$$

$$= -(d\psi)_{sur} - (du)_{syst}$$

$$(dw)_{syst} = -T_0 (ds)_{sur} - (du)_{syst}$$

$$W_{act} = T_0 (-ds)_{sur} - (U_2 - U_1)$$

Valid for both closed system as well as open system.

Gouy-Stodola Theorem:

→ Irreversibility is directly proportional to entropy generation.

$$I \propto (SS)_{gen}$$

$$I = T_0 (SS)_{gen}$$

\downarrow
Atm temp = constant.

$$W_{\max} = (U_1 - U_2) - T_0(S_1 - S_2)$$

$$= [U - T_0 S_1] - [U_2 - T_0 S_2]$$

$$F_1 - F_2$$

$$\text{Helmholtz function (F)} = U - TS$$

$$\text{Gibbs function (G)} = H - TS$$

$$W_{\max, \text{open}} = (h_1 - T_0 s_1) - (h_2 - T_0 s_2)$$

$$G_1 - G_2$$

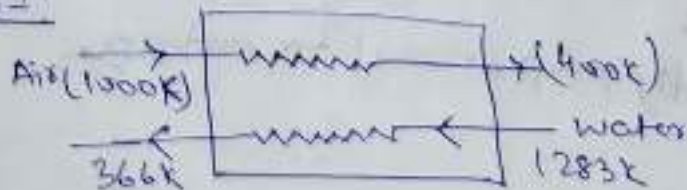
At phase change $\Delta h = 0$.

→ Difference in Helmholtz function gives maximum work in closed system.

→ Difference in Gibbs function gives maximum work for open system.

Q. In a counter flow Hx 12 kg/s of air at 1000K is cooled to 400K using water which enters at 283K and leaves at 366K. If the ambient condition are 300K and 0.1 MPa. Determine (a) water flow rate (b) change in availability of air (c) change in availability of water, (d) loss in availability.

Soln.



Heat lost by air = Heat gained by H_2O .

$$(m c \Delta T)_{H_2O} = (m c \Delta T)_{\text{air}}$$

$$12 \times 1005 \times (1000 - 400) = m_w \times 4.18 \times (366 - 283)$$

$$m_w = 20.82 \text{ kg/s.}$$

Air:
 $m_a = 12 \text{ kg/s}$
 $T_1 = 1000 \text{ K}$
 $T_2 = 400 \text{ K}$
 $T_0 = 300 \text{ K}$

change in availability of air

$$\begin{aligned} W_{\max} &= \phi_1 - \phi_2 = (h_1 - h_2) - T_0 (S_1 - S_2) \\ &= c_p (T_1 - T_2) - T_0 (S_1 - S_2) \end{aligned}$$

$$S_2 - S_1 = c_p \ln \frac{T_2}{T_1} - R \ln \left(\frac{P_2}{P_1} \right)$$

In heat exchanger we assume pressure remain same over the flow.

$$S_2 - S_1 = 1.005 \ln \left(\frac{400}{1000} \right)$$

$$\ln \frac{P_2}{P_1} = 0$$

$$S_2 - S_1 = -0.921 \text{ kJ/kgK}$$

$$S_1 - S_2 = 0.921$$

$$W_{\max} = 1.005(1000 - 400) - 300(0.921)$$

$$(\phi_1 - \phi_2)_{\text{air}} = 326.7 \text{ kJ/kg}$$

Total change in availability of air

$$= 12 \left(\frac{\text{kg}}{\text{s}} \right) \times 326.7 \times \frac{\text{kJ}}{\text{kg}}$$

$$\phi_1 - \phi_2 = 3920.4 \text{ kJ/s}$$

Water
 $m_w = 20.82 \text{ kg/s}$
 $T_1 = 283 \text{ K}$
 $T_2 = 366$
 $c_w = 4.187$

$$\phi_1 - \phi_2 = (h_1 - h_2) - T_0 (S_1 - S_2)$$

$$h_1 = u_1 + P v_1$$

$$h_2 = u_2 + P v_2$$

for Heat exchanger $P_1 = P_2 = \text{const}$ (Assumption)

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

negligible

$$h_1 - h_2 = u_1 - u_2$$

v.v.v

$$h_1 - h_2 = c (T_1 - T_2)$$

$$\phi_1 - \phi_2 = c(T_1 - T_2) - T_0(S_1 - S_2)$$

$$\Delta S = mc \ln \frac{T_f}{T_i} =$$

$$\Delta S = c \ln \frac{T_1}{T_2} = 4.187 \ln \left(\frac{300}{283} \right)$$

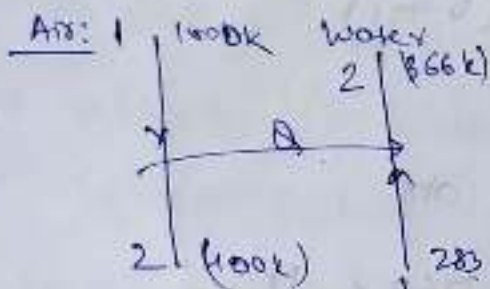
$$= 1.07687$$

$$-\Delta S = -1.07684$$

$$\phi - \phi_2 = 4.187(283.366) - 300(-1.07684)$$

$$= -24.47 \text{ kJ/s}$$

Total change in availability of water = -509 kJ/s



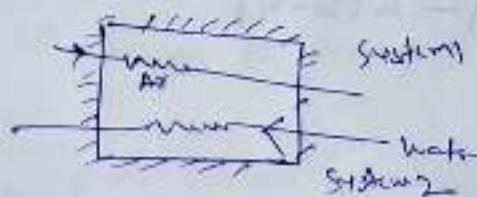
loss of availability of

$$= 3920 - 509$$

$$= 3411 \text{ kJ/s}$$

2nd method:

$$I = T_0 [\Delta S]_{univ} = T_0 [(\Delta S)_{sys} + (\Delta S)_{surr}]$$



$$(\Delta S)_{air} = (\Delta S)_{system 1}$$

$$(\Delta S)_{water} = (\Delta S)_{sys 2}$$

$$\Delta (\Delta S)_{sys} = (\Delta S)_1 + (\Delta S)_2$$

$$(\Delta S)_{surr} = 0 \text{ no Heat interaction}$$

$$(\Delta S)_{system} = (\Delta S)_a + (\Delta S)_w$$

$$= -0.921 \times 12 = -11.052 \frac{\text{kJ}}{\text{K}}$$

$$(\Delta S)_2 = 1.07684 \times 2052 = 22.082 \frac{\text{kJ}}{\text{K}}$$

$$(\Delta S)_{sys} = -11.052 + 22.4$$

$$= 11.36$$

$$I = T_0 (\Delta S) = 300 \times 11.36 = 3410 \text{ kJ/s}$$

39/ Air at 6 bar and 77°C flows through a turbine adiabatically with a velocity of 90 m/s and leave the turbine at 1.2 bar and 7°C with a velocity of 150 m/s. Determine per kg of air (a) w_{max} , (b) irreversibility (c) Actual work. Assume surroundings at 25°C and 1 bar.

30/ Air Ideal Gas: $h = c_p T$

$$w_{max} = (h_1 - h_2) - T_0 (s_1 - s_2) + \frac{c_1^2 - c_2^2}{2000}$$

$$w_{max} = c_p (T_1 - T_2) - T_0 (s_1 - s_2) + \frac{c_1^2 - c_2^2}{2000}$$

$$P_1 = 6 \text{ bar}$$

$$T_1 = 350 \text{ K}$$

$$c_1 = 90 \text{ m/s}$$

$$P_2 = 1.2 \text{ bar}$$

$$T_2 = 280 \text{ K}$$

$$c_2 = 150 \text{ m/s}$$

$$s_2 - s_1 = c_p \ln \frac{T_2}{T_1} - R \ln \left(\frac{P_2}{P_1} \right)$$

$$= 1.005 \ln \left(\frac{280}{350} \right) - 0.287 \ln \left(\frac{1.2}{6} \right)$$

$$(ds) = 0.2376 \text{ kJ/kgK}$$

$$w_{max} = 1.005(350 - 280) - 298(-0.2376)$$

$$w_{max} = 133.95 \text{ kJ/kg}$$

$$+ \frac{90^2 - 150^2}{2000}$$

$$I = T_0 [ds_{mix}] = T_0 [ds]_{sys} + [ds]_{univ}$$

$$I = 298 \times 0.2376 \quad \downarrow \text{Adiabatic}$$

$$I = 70.8 \text{ kJ/kg}$$

$$ds = 0$$

$$ds = 0$$

$$h_1 + \frac{c_1^2}{2000} + \frac{218}{1000} + \frac{q}{1} = h_2 + \frac{c_2^2}{2000} + \frac{225}{1000} + w$$

adiabatic APE = 0

$$c_p (T_1 - T_2) + \frac{c_1^2 - c_2^2}{2000} = w$$

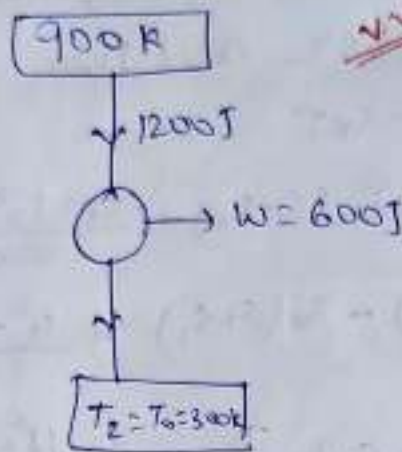
$$w_{act} = 63.15$$

$$I = w_{max} - w_{act} = 133.95 - 63.15$$

$$I = 70.8 \text{ kJ/kg}$$

VVI

Qn) An engine reversibly receive 1200J at 900K. After rejecting heat to the ambient at 300K, it develops 600J of work. The irreversibility of engine is — .



VVI Reversibly: Only one process is reversible.

$$AE = W_{max} = Q \left(1 - \frac{T_0}{T} \right)$$

$$= 1200 \left(1 - \frac{300}{900} \right)$$

$$= 1200 \times \left(1 - \frac{1}{3} \right) = 1200 \times \frac{2}{3}$$

$$= \frac{2}{3} \times 1200 = 800 \text{ J}$$

$$W_{max} = 800 \text{ J}$$

$$W_{act} = 600 \text{ J}$$

$$I = W_{max} - W_{act} = 800 - 600 = 200 \text{ J} \quad \underline{\text{Ans}}$$

Qn) A solid aluminium sphere of 0.1 meters in diameter and initially at 200°C is allowed to cool to the ambient temp of 25°C. The irreversibility of this process in kJ/s — .

$$(\rho_{Al} = 2700 \text{ kg/m}^3, C = 0.9 \text{ kJ/kg}^\circ\text{C})$$

$$m = \rho V = 2700 \times \frac{4}{3} \pi r^3$$

$$= 900 \times 4 \times \pi (0.05)^3$$

$$= 3600 \times \pi \times 125 \times 10^{-6}$$

$$m = 1.414 \text{ kg}$$

$$T_1 = 473 \text{ K}$$

$$T_2 = 298 \text{ K}$$



$$I = T_0 (\Delta S)_{univ}$$

$$= T_0 [(\Delta S)_{sys} + (\Delta S)_{sur}]$$

$$(\Delta S)_{sys} = mc \ln \frac{T_2}{T_1} = 1.414 \times 0.9 \ln \left(\frac{298}{473} \right)$$

$$= -0.5875 \text{ kJ/K}$$

$$Q = mc(\Delta T)_{sys}$$

$$= 1.414 \times 0.9 \times (473 - 298)$$

$$= 222.7 \text{ kJ}$$

$$(\Delta S)_{sur} = + \left(\frac{Q}{T_2} \right) = \left(\frac{222.7}{298} \right) = 0.747 \text{ kJ/K}$$

$$J = T_0 [-0.5875 + 0.747] \text{ kJ}$$

$$J = 47.5 \text{ kJ}$$

Ex) Air at state 1 at 5 bar and 1000 K having 0.1 kg mass is expanded in reciprocating cylinder to state 2 at a pressure of 1 bar and temp of 600 K. If $T_0 = 300$, $P_0 = 1$ bar. Determine \downarrow in availability of air during this process in kJ. ($S_1 = 836 \text{ J/kg}$, $S_2 = 787 \text{ J/kg}$).

Reciprocating cylinder \rightarrow closed system



Reciprocating compressor \rightarrow valves will be there \rightarrow open system.

Decrease in Availability = Maximum useful work.

$$= \phi_1 - \phi_2$$

$$= (u_1 - u_2) - T_0(S_1 - S_2) + P_0(V_1 - V_2)$$

$$s_1 = 836 \frac{\text{J}}{\text{kg}} \quad , \quad S_1 = 836 \times 0.01 = 8.36 \text{ J/K}$$

$$s_2 = 787 \frac{\text{J}}{\text{kg}} \quad , \quad S_2 = 787 \times 0.01 = 7.87 \text{ J/K}$$

$$\phi_1 - \phi_2 = \underbrace{(u_1 - u_2) - T_0(s_1 - s_2)}_{\text{kJ/kg}} - \underbrace{P_0(v_2 - v_1)}_{\text{kJ}}$$

Take care of unit

$$\begin{aligned} (\phi_1 - \phi_2) &= m \left[(u_1 - u_2) - T_0(s_1 - s_2) \right] - P_0(v_2 - v_1) \\ &= mcvT_1 - mcvT_2 - T_0(s_1 - s_2) - P_0(v_2 - v_1) \\ &= 0.01 \times 0.718 (1000 - 600) - 300 (8.36 - 7.87) \\ &\quad - P_0(v_2 - v_1) \end{aligned}$$

$$P_1 v_1 = mRT_1$$

$$5 \times 10^5 v_1 = 0.01 \times 287 \times 1000$$

$$v_1 = \frac{0.01 \times 287 \times 1000}{5 \times 10^5}$$

$$v_1 = 5.74 \times 10^{-3} \text{ m}^3$$

$$v_2 = \frac{mRT_2}{P_2}$$

$$v_2 = \frac{0.01 \times 287 \times 600}{10^5}$$

$$v_2 = 0.01722 \text{ m}^3$$

$$\phi_1 - \phi_2 = 1.57 \text{ kJ}$$

Qn Availability per unit mass associated with air flowing from a reservoir at 10 atm and 25°C when atm is at 1 atm and 25°C (Neglect AKE & DPE).

flowing \rightarrow open system



$$m = 1 \text{ kg}$$

$$P_1 = 10 \text{ atm}$$

$$T_1 = 25^\circ\text{C} = 298 \text{ K}$$

$$P_0 = 1 \text{ atm}$$

$$T_0 = 298 \text{ K}$$

$$\text{Availability} = (\psi_1 - \psi_0)$$

$$= (h_1 - h_0) - T_0(s_1 - s_0)$$

$$= c_p(T_1 - T_0) - T_0(s_1 - s_0)$$

$$\text{Availability} = 1.005(298 - 298) - 298(s_1 - s_0)$$

$$ds = c_p \ln \frac{T_2}{T_1} - R \ln \frac{P_2}{P_1}$$

$$= 0 - R \ln \left(\frac{1}{10} \right) = R \ln 10$$

$$s_2 - s_1 = 0.66084$$

$$(s_1 - s_0) = -0.66084$$

$$\text{Availability} = +298 \times 0.66084 = 196.93 \text{ kJ}$$

10) The pressure, temp^r, and velocity of air flowing in a pipe are 5 bar, 500K and 50 m/s respectively. The specific heats of air at constant pressure and at constant volume are 1.005 kJ/kgK and 0.718 kJ/kgK respectively. Neglect APE. If $p_0 = 1 \text{ bar}$ and $T_0 = 300 \text{ K}$. Find the available energy of air in kJ/kg.

6/12/20

$$p_1 = 5 \text{ bar}$$

$$T_1 = 500 \text{ K}$$

$$c_1 = 50 \text{ m/s}$$

$$p_0 = 1 \text{ bar}$$

$$T_0 = 300 \text{ K}$$

flowing = open system



$$\psi_1 - \psi_2 = \psi_1 - \psi_0$$

$$= (h_1 - h_0) - T_0(s_1 - s_0) + \frac{c_1^2}{2}$$

$$\psi_1 - \psi_2 = c_p(T_1 - T_0) - T_0(s_1 - s_0) + \frac{c_1^2}{2000}$$

$$ds = c_p \ln \frac{T_2}{T_1} - R \ln \frac{p_2}{p_1}$$

$$s_2 - s_1 = 1.005 \ln \frac{300}{500} - 0.287 \ln \left(\frac{1}{5}\right) = -0.05147 \left(\frac{\text{kJ}}{\text{kgK}}\right)$$

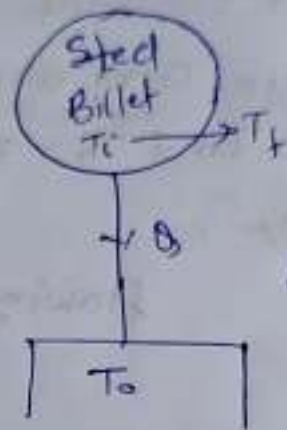
$$s_1 - s_2 = +0.05147 \left(\frac{\text{kJ}}{\text{kgK}}\right)$$

~~$$\psi_1 - \psi_2 = 1.005 \ln \frac{300}{500} = -0.287$$~~

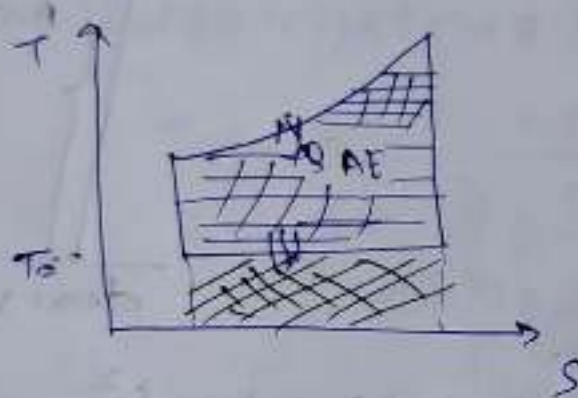
$$\psi_1 - \psi_2 = 1.005(500 - 300) - 300 \times 0.05147 + \frac{(50)^2}{2000}$$

Qm) A steel billet of 2000 kg mass is to be cooled from 1250 K to 450 K. The heat released during this process is to be used as a source of energy. The ambient temp is 303 K and specific heat of steel is 0.5 kJ/kgK. Find the A.E of this billet.

$$\begin{aligned}
 m &= 2000 \text{ kg} \\
 T_i &= 1250 \text{ K} \\
 T_f &= 450 \text{ K} \\
 T_0 &= 303 \text{ K} \\
 c &= 0.5 \frac{\text{kJ}}{\text{kgK}}
 \end{aligned}$$



$$\begin{aligned}
 dQ &= mc dT \\
 dS &= mc dT \left(\frac{T_0}{T} \right) \\
 Q &= \int dQ = mc(T_i - T_f)
 \end{aligned}$$



$$AE = Q \left(1 - \frac{T_0}{T} \right)$$

$$AE = \int mc dT \left(1 - \frac{T_0}{T} \right)$$

$$= mc \int_{T_f}^{T_i} \left(1 - \frac{T_0}{T} \right) dT$$

$$AE = mc \left[(T_f - T_i) - T_0 \ln \frac{T_f}{T_i} \right]$$

$$A.E = 2000 \times 0.5 \left[(1250 - 450) - 303 \ln \frac{1250}{450} \right]$$

$$AE = -490.44 \times 10^3 \text{ kJ}$$