Module 4.

The first law of Thermodynamics deals with the quantity of energy and asserts that energy cannot be created and destroyed

The second law of Thermodynamics deals with the quality of energy. More specifically it is concerned with degradation of energy during a process, the entropy generation and lost opportunit to do work and it offers plenty of room for improvement.

The objective of exergy analysis/Availability Analysi is to design and analyse thermal systems whi uses conservation of mass, energy together with sec law of thermodynamics.

Classification of Energy

1. High Grade Energy 2. Low Grade Energy.

High Grade Energy	Low Grade Energy.
a) Mechanical work	a) Heat or thermal energy
b) Electrical energy	b) Heat derived from nuclea fission /fusion
c) Water power	c) Heat derived from Combustion of fossil f (chemical energy from
d) wind power	d) Solar Energy
e) kinetic energy of jet	e) Geothermal Energy
f) Tidal power	

The objective of Thermodynamics is to conve Low Grade Energy into High Grade Energy.

The complete conversion of Low Grade Energy to High Grade Energy (shaft work) is impossible by virtue of second law of Thermodynamics.

Q (low grade energy) → (cycle) → W + Q rejected

W (High grade energy) → (cycle) → Q (W = Q)

LOW GRADE ENERGY

↓ continuous conversion through a cyclic device

Max Amount Obtained as Useful Work.

↓

Availability / Available Energy

or

Exergy of low grade energy with reference to prescribed surrounding

Min. Amount left as low grade energy

↓

Non Availability / Non-available Energy / Anergy of low grade energy with reference to prescribed surrounding.

Exergy :- Work potential of low grade energy.

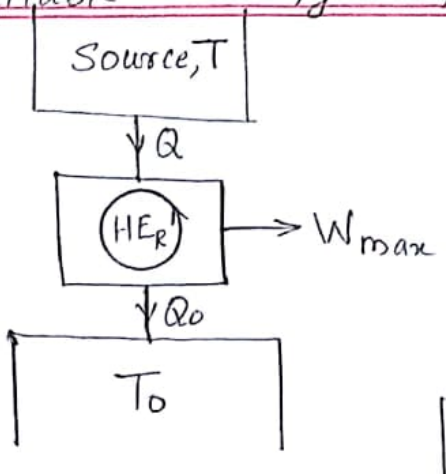
Available Energy : The part of the low grade energy which can be converted into high grade energy by a reversible cyclic heat engine.

or

The maximum work output obtainable from a certain heat input in a cyclic heat engine is called available energy or the available part of energy supplied.

Unavailable Energy : The minimum energy that has to be rejected to the sink by the second law in a cyclic heat engine is called the unavailable energy or the unavailable part of the energy supplied.

Available Energy Referred to a Cycle



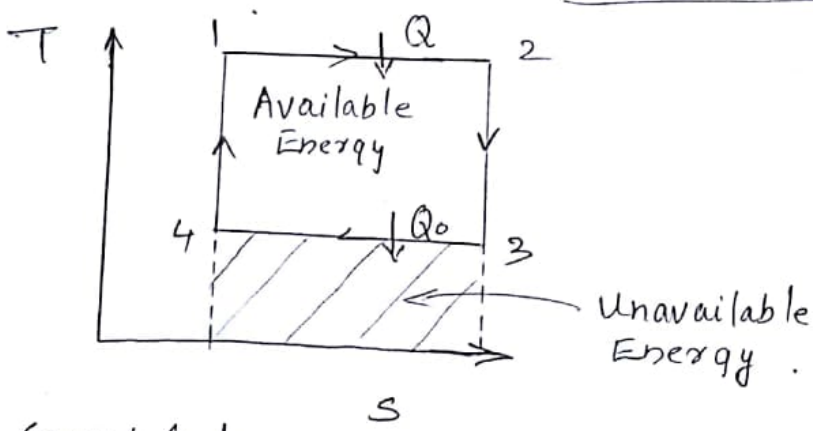
$$\eta = \frac{W_{max}}{Q} = \frac{Q - Q_0}{Q} = 1 - \frac{Q_0}{Q}$$

$$\frac{W_{max}}{Q} = 1 - \frac{T_0}{T}$$

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

$$W_{max} = Q - \frac{Q}{T} \cdot T_0 = Q - Q_0$$

$$\boxed{W_{max} = Q - T_0 \cdot \Delta S}$$



$Q_0 = T_0 \Delta S$ (heat rejected)

Carnot Cycle

Dead state : A system is said to be in dead state when it is in thermodynamic equilibrium with environment or surroundings. ie At the dead state, a system is at the temperature and pressure of its surroundings.

It has no kinetic energy and potential energy relative to the surroundings.

The system doesn't interact with surroundings (chemically inert).

Also there are no unbalanced magnetic, electrical

and surface tension effects between system & surroundings.
A system has zero exergy or available energy at dead state.

LAW OF DEGRADATION OF ENERGY

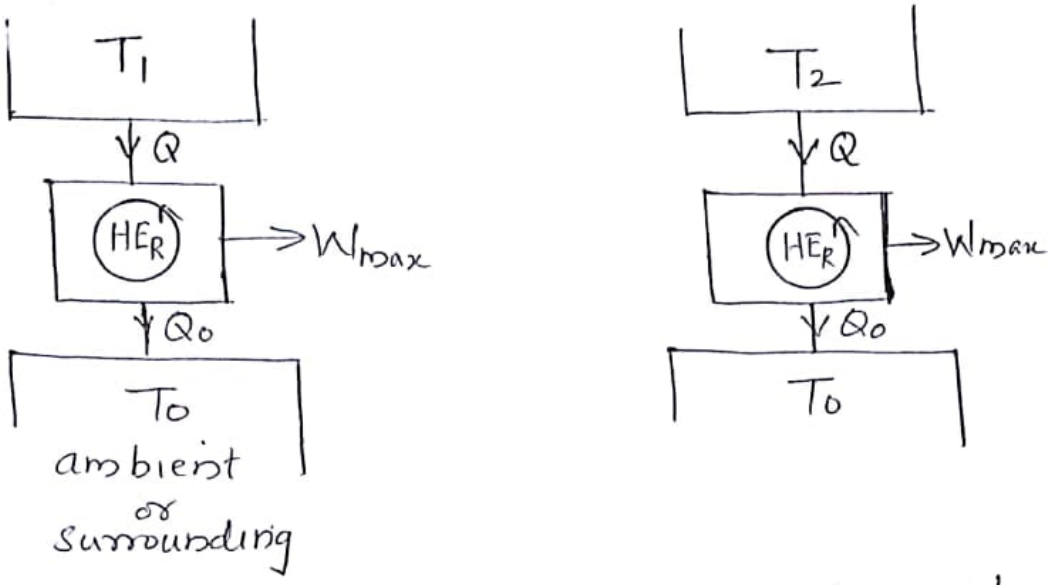
The available energy of a system decreases as its temperature or pressure decreases and approaches that of the surroundings. When heat is transferred from a system, its temperature decreases and hence the quality of its energy deteriorates.

The first law states that energy is always conserved quantity wise, but the second law emphasizes that energy always degrades quality wise.

- The first law — law of conservation of energy
  The second law of TD – law of degradation of energy.

eg. When a gas is throttled adiabatically from a high to a low pressure, the enthalpy (energy per unit mass) remains same, but there is a degradation of energy or available work.

✡ Energy Degradation due to Thermal Irreversibility



Available Energy of Q at T_1 with reference to surrounding temperature of T_0, IAE $= Q\left(1-\frac{T_0}{T_1}\right)$ —— (1)

Unavailable Energy of Q at T_1 with reference to surrounding temperature of $T_0 = Q\cdot\frac{T_0}{T_1}$ —— (2).

Available Energy of Q at T_2 with reference to surrounding temperature of T_0, FAE $= Q\left(1-\frac{T_0}{T_2}\right)$ —— (3)

Unavailable Energy of Q at T_2 with reference to surrounding temperature of $T_0 = Q\cdot\frac{T_0}{T_2}$ —— (4)

Loss in available energy = IAE − FAE
or
Increase in unavailable energy

$$= Q\left(1-\frac{T_0}{T_1}\right) - Q\left(1-\frac{T_0}{T_2}\right)$$

$$= Q\left(1-\frac{T_0}{T_1} - \left(1-\frac{T_0}{T_2}\right)\right)$$

$$= Q\left(\frac{T_0}{T_2} - \frac{T_0}{T_1}\right)$$

loss in available energy $= Q\left[\frac{T_0}{T_2} - \frac{T_0}{T_1}\right]$

$= T_0 Q\left[\frac{1}{T_2} - \frac{1}{T_1}\right]$

$\Delta S = Q\left[\frac{1}{T_2} - \frac{1}{T_1}\right] > 0$, since $T_1 > T_2$

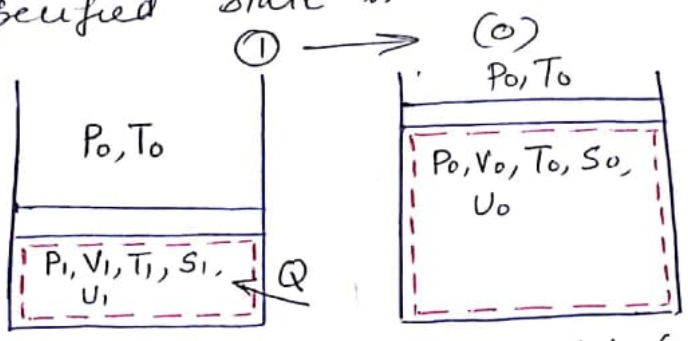
$\therefore$ loss in available energy $= T_0 \Delta S$.

The energy has degraded to the extent that the useful work has been decreased by $T_0 \Delta S$.

The increase in entropy is a measure of the extent to which energy becomes degraded.

✡ Availability / Exergy of Control mass system (closed system)

It is defined as the maximum possible useful work that is obtainable from a system as it undergoes a reversible process in which system comes into equilibrium with its surroundings ie dead state. This maximum useful work potential of the system at the specified state is called exergy.



Initial State (1) Dead state (0)

From 1st Law of Thermodynamics, $Q = \Delta U + W$

ie $Q = U_0 - U_1 + W$ —①

From 2nd law of Thermodynamics.

$(\Delta S)_{isolated\ system} \geq 0$

For reversible process, $(\Delta S)_{isolated\ system} = 0$ (no irreversibility)

$$\Delta S_{system} + \Delta S_{surrounding} = 0$$

$$(S_0 - S_1) + \frac{-Q}{T_0} = 0$$

$$Q = T_0 (S_0 - S_1) \quad \text{—— ②}$$

Sub equation ② in ①.

$$Q = U_0 - U_1 + W = \Delta U + W$$

$$W = Q - \Delta U = T_0 (S_0 - S_1) - (U_0 - U_1)$$

$$W_{max} = T_0 (S_0 - S_1) + (U_1 - U_0)$$

$$W_{max} = (U_1 - U_0) + T_0(S_0 - S_1)$$

$$\boxed{W_{max} = (U_1 - T_0 S_1) - (U_0 - T_0 S_0)}$$

$$\boxed{W_{max_{1\to 0}} = (U_1 - U_0) - T_0(S_1 - S_0)}$$

(Exergy of closed system at state 1)

∴ Exergy of closed system at state 2 (intermediate b/w initial & dead state)

$$\boxed{W_{max_{2\to 0}} = (U_2 - U_0) - T_0(S_2 - S_0)}$$

$$W_{max_{1-2}} = W_{max_{1\to 0}} - W_{max_{2\to 0}}$$

$$\therefore \boxed{W_{max_{1-2}} = W_{Rev} = (U_1 - U_2) - T_0(S_1 - S_2)}$$

Reversible work W_{Rev} is defined as the maximum amount of useful work that can be produced as system undergoes a reversible process b/w initial and final state.

When final state is the dead state, the reversible work equals exergy.

<u>Note</u> : The work done by work producing devices is not always entirely in a usable form.

eg. When a gas in a piston cylinder device expands, part of the work done by the gas is used to push the atmospheric air out of the way of the piston.

$W_{surrounding}$ is not significant for cyclic devices and systems whose boundaries remains fixed during the process such as rigid tanks and steady flow devices like turbines, compressors, nozzles, heat exchangers etc

Useful work (W_u)

$$W_{u_{1\to 0}} = W_{max} - W_{surroundings}$$

Availability at state 1

$$W_{u_{1\to 0}} = W_{max} - P_0(V_0 - V_1)$$

$$W_{u_{1\to 0}} = (U_1 - T_0 S_1) - (U_0 - T_0 S_0) - P_0(V_0 - V_1)$$

$$W_{useful_{1\to 0}} = (U_1 + P_0 V_1 - T_0 S_1) - (U_0 + P_0 V_0 - T_0 S_0)$$

$$W_{useful_{1\to 0}} = \phi_1 - \phi_0$$

where $\phi = U + P_0 V - T_0 S$ — Availability function.

$U, V, S \longrightarrow$ system property.

$P_0, T_0 \longrightarrow$ surrounding property.

Availability at state 2

$$\text{|||ly } W_{useful_{2\to 0}} = \phi_2 - \phi_0$$

$$\therefore W_{useful\ 1\to 2} = W_{useful_{1\to 0}} - W_{useful\ 2\to 0}$$

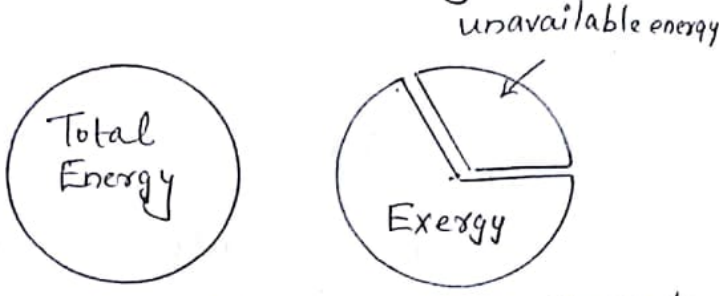
$$= \phi_1 - \phi_2$$

$$\therefore W_{useful\ 1\to 2} = (U_1 + P_0 V_1 - T_0 S_1) - (U_2 + P_0 V_2 - T_0 S_2)$$

(Decrease in Availability)

Availability / Exergy of a system : It is defined as the maximum possible useful work that is obtained from a system as it undergoes a reversible process in which system comes into equilibrium with its surroundings ie dead state. This maximum work potential of the system at the specified state is called Availability.

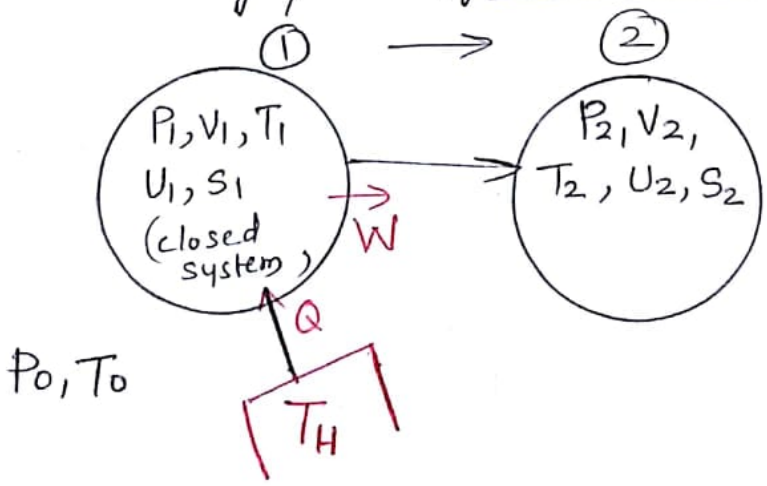
Availability is a composite property which depends on state of both system & surrounding :



Exergy represents the upper limit on the amount of work a device can deliver without violating any thermodynamic laws.

There will be always a difference between exergy and actual work delivered by a device which represents the scope of improvement

Availability / Exergy Balance in a Closed system:



Energy Balance, $Q = U_2 - U_1 + W$

Exergy Balance.

Availability of system at state 1, $A_1 = (U_1 + P_0V_1 - T_0S_1) - (U_0 + P_0V_0 - T_0S_0)$

Availability of system at state 2, $A_2 = (U_2 + P_0V_2 - T_0S_2) - (U_0 + P_0V_0 - T_0S_0)$

Net available energy within the system, $A_{in} = A_1 - A_2$

$$= (U_1 - U_2) + P_0(V_1 - V_2) - T_0(S_1 - S_2)$$

Availability coming out of the system $= W_{max} - P_0(V_2 - V_1)$

Availability coming into the system $= Q\left(1 - \frac{T_0}{T_H}\right)$

Net available Energy transfered out of the system, $A_{out} = W - P_0(V_2 - V_1) - Q\left(1 - \frac{T_0}{T_H}\right)$

$$\therefore A_{out} = Q + (U_1 - U_2) + P_0(V_1 - V_2) - Q + Q \cdot \frac{T_0}{T_H}$$

$$A_{in} - A_{out} = T_0\left((S_2 - S_1) + -\frac{Q}{T_H}\right)$$

$$= T_0\left(\Delta S_{sys} + \Delta S_{surrounding}\right)$$

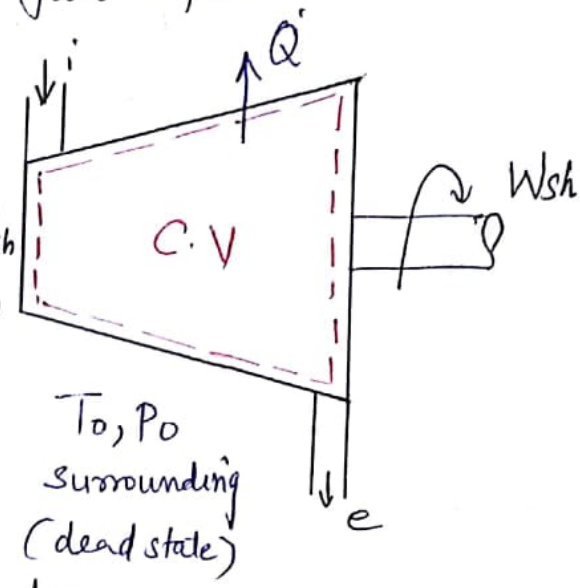
$A_{in} - A_{out} = T_0 (\Delta S)_{universe} = T_0 \cdot S_G =$ Irreversibility

$A_{in} - A_{out} > 0$ $\qquad$ $\Delta S_{universe} > 0$.

Availability of Steady flow systems

From 1st Law of Thermodynamics

$$\dot{m}_e\left(h_e+\frac{V_e^2}{2}+gZ_e\right)-\dot{m}_i\left(h_i+\frac{V_i^2}{2}+gZ_i\right)=\dot{Q}-\dot{W}_{sh} \quad \text{— (1)}$$



From 2nd law of Thermodynamics.

$$\Delta S_{universe} = \dot{S}_G = (\Delta S)_{system} + (\Delta S)_{surrounding}$$

$$\dot{S}_G = \dot{m}_e S_e - \dot{m}_i S_i - \frac{\dot{Q}}{T_0}$$

$$T_0 \dot{S}_G = \dot{m}_e S_e T_0 - \dot{m}_i S_i T_0 - \dot{Q}$$

$$\dot{Q} = \dot{m}_e S_e T_0 - \dot{m}_i S_i T_0 - T_0 \dot{S}_G \quad \text{— (2)}$$

Combining (1) & (2), we get.

$$\dot{m}_e\left(h_e+\frac{V_e^2}{2}+gZ_e\right)-\dot{m}_i\left(h_i+\frac{V_i^2}{2}+gZ_i\right) = \dot{m}_e S_e T_0 - \dot{m}_i S_i T_0 - T_0 \dot{S}_G - W_{sh}.$$

$$W_{useful} = W_{shaft} = \dot{m}_i\left(h_i+\frac{V_i^2}{2}+gZ_i - T_0 S_i\right) - \dot{m}_e\left(h_e+\frac{V_e^2}{2}+gZ_e - T_0 S_e\right) - T_0 \dot{S}_G.$$

For reversible process, $\dot{S}_G = 0$

$$W_{rev} = \dot{m}_i\left(h_i+\frac{V_i^2}{2}+gZ_i - T_0 S_i\right) - \dot{m}_e\left(h_e+\frac{V_e^2}{2}+gZ_e - T_0 S_e\right)$$

Irreversibility, $I = W_{rev} - W_{useful} = T_0 \dot{S}_G$

we have.

flow exergy at inlet, $\psi_i = \psi_i - \psi_0$ $\quad V_0 = 0$, $Z_0 = 0$

$$= \dot{m}_i\left(h_i + \frac{V_i^2}{2} + gz_i - T_0 s_i\right) - \dot{m}\left(h_0 + \frac{V_0^2}{2} + gz_0 - T_0 s_0\right)$$

$$= \dot{m}_i\left((h_i - h_0) + \frac{V_i^2}{2} + gz_i - T_0(s_i - s_0)\right) \text{ — (1)}$$

Similarly flow exergy at exit, $\psi_e = \psi_e - \psi_0$

$$= \dot{m}_e\left((h_e - h_0) + \frac{V_e^2}{2} + gz_e - T_0(s_e - s_0)\right) \text{ — (2)}$$

The exergy change of fluid stream as it undergoes a process from state (2) -

$$\Delta\psi = (\psi_i - \psi_0) - (\psi_e - \psi_0)$$

$$= \psi_i - \psi_e$$

$$\Delta\psi = \dot{m}_i\left((h_i - h_e) + \frac{V_i^2 - V_e^2}{2} + g(z_i - z_e) - T_0(s_i - s_e)\right)$$

Reversible work (Availability / Exergy) ;

$$\boxed{\dot{W}_{rev} = \Delta\psi = \psi_i - \psi_e}$$

✡ Irreversibility & Gouy - Stodola Theorem

The actual work done by a system is always less than the idealized reversible work and the difference between the two is called the Irreversibility of the process.

$$I = W_{max,Rev_{out}} - W_{actual_{out}} \quad \text{or} \quad I = W_{actual_{in}} - W_{max,Rev_{in}}$$

Irreversibility ⇒ wasted work potential or the lost opportunity to do work

Irreversibility is equivalent to the exergy destroyed.

The smaller the Irreversibility associated with a process, greater the work that is produced.

The performance of a thermal system can be improved by minimising the irreversibility associated with it.

Irreversibility for nonflow process.

For a non flow process, when the system exchanges heat only with environment or surrounding

$$I = (U_1 - U_2) - T_0(S_1 - S_2) - W_{actual\ out}$$

$$= (U_1 - U_2) + T_0(S_2 - S_1) - ((U_1 - U_2) + Q)$$

$$= T_0(S_2 - S_1) - Q$$

$$= T_0\left((S_2 - S_1) - \frac{Q}{T_0}\right)$$

$$I = T_0 \left(\Delta S_{system} + \Delta S_{surrounding} \right)$$

$$I = T_0 \, \Delta S_{universe} = \underline{T_0 S_G}.$$

$$\Delta S_{universe} = S_G \geq 0$$

$$I \geq 0$$

Similarly for steady flow process.

$$I = T_0 S_G$$

The quantity $T_0 \Delta S_{universe}$ ($T_0 S_G$) represents an increase in unavailable energy (anergy) or exergy destroyed.

The Gouy Stodola Theorem states that the rate of loss of available energy or exergy in a process is proportional to the rate of entropy generation (S_{gen}).

$$I_{irreversibility} = W_{lost} = T_0 S_G.$$

Note: A thermodynamically efficient process would involve minimum exergy loss with minimum rate of entropy generation.