

THE HANDBOOK *of* **Mechanical Engineering**

Useful For

ALL competitive examinations especially
UPSC (ESE), GATE, PSUs Central/State AE & JE,
ISRO, DRDO, RRB-JE, SSC-JE etc.



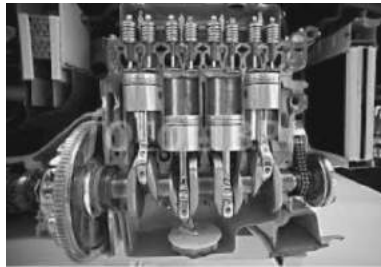
SHISHIR KUMAR PERSAI

Hand Book of

Mechanical Engineering

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Mechanical Engineering



by
Shishir Kumar Persai

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Acknowledgement

The successful completion of this book has been possible with the earnest efforts of several people in my life.

The seed of writing was instilled and nurtured in me by my father, Mr. S.C. Persai, who has always been the guiding torch in my life. I am and will always be thankful for his wisdom and blessings.

I am indebted to Mr. Chaitanya Naik, for without his diligent assistance, perseverance and patience, this book would never have taken shape. Chaitanya has proactively aided me in converting what was an idea into a concrete entity with time-to-time edits and honest feedback.

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My wife, Aditi has been my constant source for motivation. Without her support, I would have never been able to complete this book.

Finally, I would like to thank Team GKP for their dedication and diligent efforts to prepare this book.

Despite our sincere efforts to keep the book void of errors, there is a possibility that some errors might have been left unnoticed while printing. I would sincerely welcome constructive criticism for improving the book for its subsequent edition. The feedback can be shared at shishirpersai@gmail.com.

Shishir Kumar Persai

About the Author

Shishir Kumar Persai is currently running Reva Academy, Chhattisgarh's leading ESE, GATE and PSU preparation academy. Hailing from Bhilai, Mr. Persai completed his post-graduation in 2008 from VJTI, Mumbai with specialization in CAD/CAM and Automation.

With nearly a decade of teaching experience across various leading institutes for several competitive examinations, Mr. Persai is currently mentoring and guiding over 100 students for GATE, ESE, PSUs, IAS & SSC.

Dedicated to his teaching profession sincerely, Mr. Persai believes that good teachers nurture imagination, ignite hope and instill a lifelong love of learning in students. To his credit, several of his taught students are studying in various IIT's and NIT's and have cracked USPC ESE. Many others have made it to illustrious PSUs and BARC.

In his spare time, Mr. Persai loves to explore new places, meet new people and try out new cuisines.

Preface



This book is written with the aim to help and guide ambitious mechanical engineering graduates; preparing for various technical entrance and government job recruitment examinations.

The Handbook inculcates key concepts and well-illustrated formulae required to prepare for GATE, Engineering Services, Civil Services, BARC and all other PSU's recruitments. The author has put in conceptual understanding of the subject in simplest words and his rich experience of qualifying examinations of national repute in the making. The book is especially ideal for last-minute preparation for students.

This book contains all mechanical engineering subjects with special emphasis on exam oriented questions with latest methods & techniques to help students perform better. It also contains engaging tricks and shortcuts for important theories to help save time during the exam.

As per current examination system, the author guarantees more than 90% of any National level Mechanical Engineering exam paper to be covered by studying concepts shared in the book. This book will help readers brush up the most significant areas of Mechanical Engineering.

The endeavour to write this book is a result of excitement and challenge that the author experienced while preparing for competitive examinations.

All the Best
Shishir Kumar Persai

Dedication

*Dedicated to my parents,
Mr. S.C. Persai
and
Lt. Ms. Nutan Persai*



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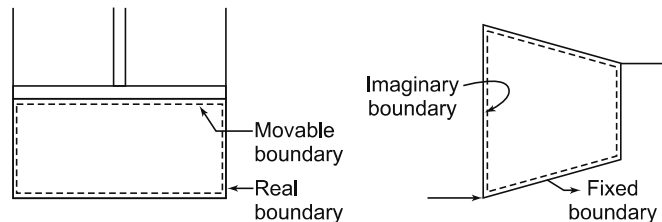
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1. Basic Concepts

- **System:** A fixed mass or region in space on which our analysis is focused.
- **Surrounding:** Everything apart from system forms surrounding. The part of the surrounding which is effected by the system is called immediate surrounding.
- **Boundary:** A real or imaginary surface which separates the system from the surroundings.

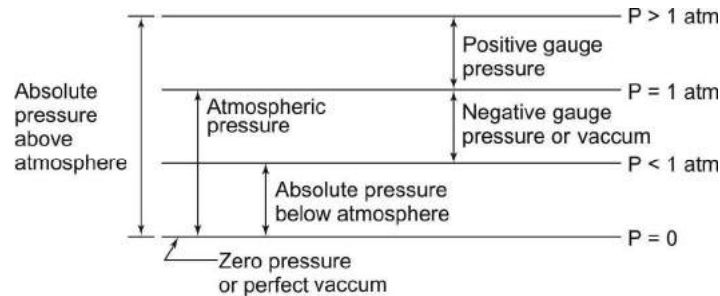
A boundary can be fixed or movable as well as real or imaginary.



Type of System

Types of System	Mass transfer	Energy transfer	Example
Closed	✗	✓	Piston cylinder arrangement without valves
Open	✓	✓	Turbine, pump, Compressor, Piston cylinder arrangement with valves
Isolated	✗	✗	Universe, hot coffee in a perfectly insulated thermos

- **Pressure:** The average normal force per unit area is termed as pressure.



$$P_{abs} = P_{gauge} + P_{atm}$$

$$P_{gauge} = P_{atm} - P_{vac}$$

$$1 \text{ bar} = 10^5 \text{ Pa} = 100 \text{ kPa} = 0.1 \text{ MPa}$$

$$1 \text{ atm} = 101.325 \text{ kPa} = 1.01325 \text{ bar} = 760 \text{ mm of Hg}$$

- Properties of System:** Any characteristic of the system is called property of the system.
 Properties are 'point' function and are 'exact' or 'perfect' differentials
 Ex. internal energy, enthalpy, entropy...
- Intensive Property (Intrinsic):** These properties are 'independent' of size or mass. These are the properties which remains constant (same) at all points of a system.
 Ex. pressure, temperature, density, all specific extensive properties.
- Extensive Property (Extrinsic):** These properties are dependent on size or mass of the system. These are the properties which varies within the system.
 Ex. mass, volume, all forms of energy, entropy.

Note: Ratio of two extensive properties is an intensive property.

Gibbs Phase Rule

$$P + F = C + 2$$

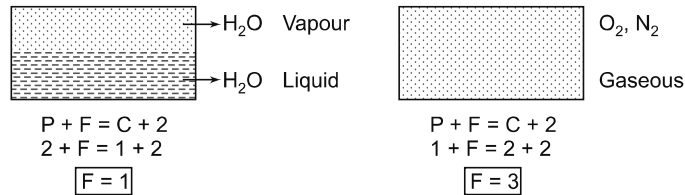
Here,

P = number of phases (Solid, liquid, gas)

F = minimum number of 'independent' intensive variables required to find the state of the system (degree of freedom)

C = number of chemical components

Ex.



Thermodynamic Equilibrium

A body is said to be in thermodynamic equilibrium if it is in

- Thermal equilibrium: equality of 'temperature'
- Mechanical equilibrium: equality of 'forces' and 'couples'
- Chemical equilibrium: equality of chemical potentials.

Point functions	Does not depend on path history (T, P, V)
Path functions	Depend on path history (Work, heat)

- **State:** Any condition of the system is called state of the system. State of the system is specified by properties, if any one of the property changes the state of the system changes.
- **Process:** The change of the state of the system is called process. The infinite states through which the system passes is called process path.

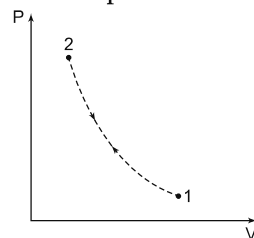
The process can be classified as:

1. Quassi-static (or Quassi-equilibrium) and Non Quassi-static Process:

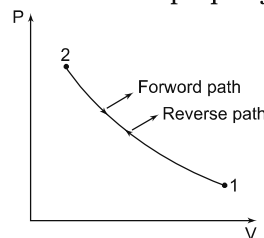
'Quassi = almost'

A process is said to be a quassi-static process if it is carried out in a 'very slow' manner so that the system can be considered to be in 'equilibrium' at any point between initial and final states of the process. It is represented by a joint line on property diagram.

The process which is not quassi-static is called non quassi-static process. It is represented with a dashed line on property diagram.



Non quassi-static process when piston is moving very fast



Quassi-static process when piston is moving very slow

2. Reversible and Irreversible Process: A process is said to be a reversible process when reversed in direction follows the same path as that of the forward path without leaving any change on the system and the surrounding.

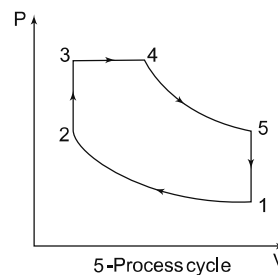
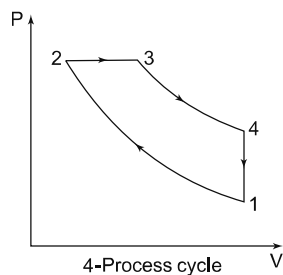
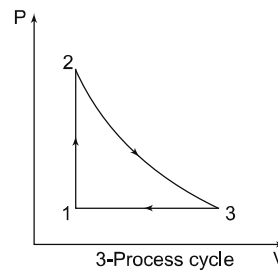
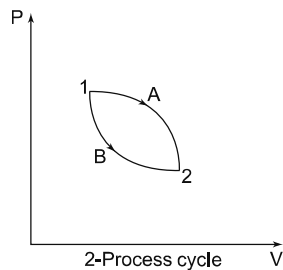
A process which is not reversible is called irreversible process. All 'actual' process are irreversible process.

Note: If a process has to be reversible then it must be quasi-static, but all quasi-static processes need not be reversible.

3. Cyclic Process: A process is said to be a cyclic in which initial state and final state are exactly same.

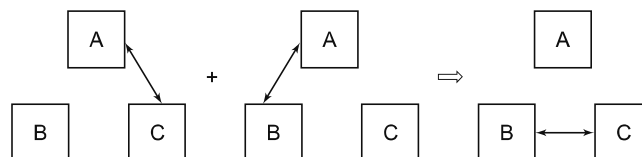
- For a cycle change in property is zero.

Note: Minimum number of process required to make a cyclic process are two.



Zerth Law of Thermodynamics

When a body A is in thermal equilibrium with a body B and also separately with a body C then body B and C will be in thermal equilibrium with each other.



If A $\xrightleftharpoons[\text{equilibrium}]{\text{thermal}}$ B $\xrightleftharpoons[\text{equilibrium}]{\text{thermal}}$ C then A $\xrightleftharpoons[\text{equilibrium}]{\text{thermal}}$ C

Note: Zeroth law of thermodynamics the basis of ‘temperature’ measurement.

Types of Thermometer

Type of thermometer	Principle	Thermometric Property
Resistance	Wheat stone bridge	Resistance
Thermocouple	Seeback effect	E.M.F. (voltage)
Constant volume gas thermometer	Ideal gas equation	Pressure
Constant pressure gas thermometer	Ideal gas equation	Volume

Note: • Ideal gas thermometer is ‘independent’ of material of construction.

- Thermocouple uses copper-constantan, platinum-rhodium combinations.
- **Conversion of temperature unit:**

$$\frac{^{\circ}\text{C}}{5} = \frac{^{\circ}\text{F}-32}{9} = \frac{\text{T}-273.15}{5}$$

Here, $^{\circ}\text{C}$ = temperature in degree celsius
 $^{\circ}\text{F}$ = temperature in degree fahrenheit
 T = temperature in kelvin

- **Triple Point of Water:**
 It is point where all the phases coexist.
 “Degree of freedom at triple point is zero.”

Triple point of Water = $0.01^{\circ}\text{C} = 273.16 \text{ K} = \text{T}_{tp}$
 $P_{tp} = 0.611 \text{ kPa} = 4.6 \text{ mm of Hg}$

Method of Temperature Measurement:

- **Used before 1954:**

$$\text{T} = \frac{100 (P - P_i)}{(P_s - P_i)}$$

Here, T = temperature

P = pressure corresponding to temperature 'T'
 P_i = pressure corresponding to ice point (0°C)
 P_s = pressure corresponding to steam point (100°C)

- **Used after 1954:**

$$T = 273.16 \left[\frac{P}{P_{tp}} \right]$$

Here, T = temperature
 P = property corresponding to temperature 'T'
 P_{tp} = property corresponding to triple point of water (273.16 K)

2. Energy Interaction

Energy = Microscopic + Macroscopic

Microscopic energy = Sensible + latent + Chemical + Nuclear
(Internal energy) energy energy energy energy

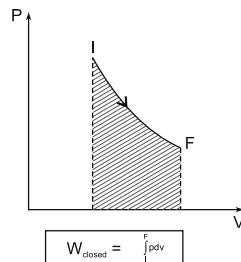
Macroscopic energy : Kinetic Energy, Potential Energy

Methods of Energy Transfer:

- Heat interaction,
- Work interaction
- Mass interaction
- **Work:** Work is said to be done by the system if the sole effect on the things external to the system can be reduced in raising of weight (weight may not actually be raised)

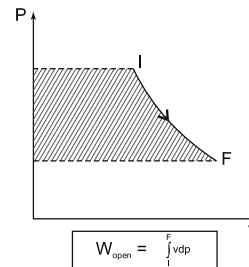
Type of Work

(i) Closed system work or Non flow work



For closed system work is obtain by plotting it on volume axis.
 Conditions for using
 1. Closed system,
 2. Quassi-static process.

(ii) Open system work or Steady work.

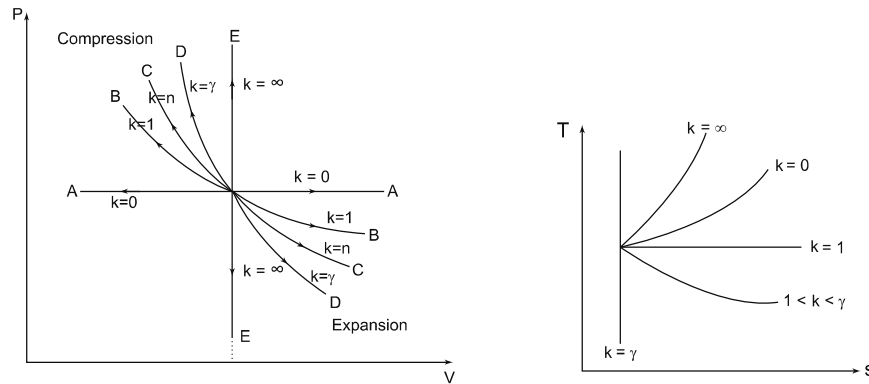


Open system work is obtain by plotting it on 'pressure axis'.
 Conditions for using:
 1. Open system,
 2. Quassi-static process.

Notes:

1. Area enclosed by cycle on P-V diagram is net work done.
 Clockwise cycle= Work done by system (positive)
 anticlockwise cycle= Work done on system (negative)
2. Work is a path function i.e. inexact differential and not a property of system
3. It is a boundary / transient phenomenon.

Representation of various process on P-V and T-s diagram:



Work done

Process	Work done in closed system	Work done in open system
Constant volume/ Isochoric/ Isometric(k = ∞)	$W_{v=c} = 0$	$W_{open} = V(P_I - P_F)$
Constant pressure/ Isobaric/ Isopiestic(k = 0)	$W_{p=c} = P(V_F - V_I)$	$W_{open} = 0$
Constant temperature/ Isothermal (k = 1)	$W = C \ln\left(\frac{V_F}{V_I}\right)$ or $C \ln\left(\frac{P_I}{P_F}\right)$ Here, $C = P_I V_I = P_F V_F = mRT_I = mRT_F$	$W_{open} = W_{closed}$ $= C \ln\left(\frac{V_F}{V_I}\right) = C \ln\left(\frac{P_I}{P_F}\right)$ where, $C = P_I V_I = P_F V_F = mRT_I = mRT_F$

Adiabatic process (k = γ)	$W = \frac{P_I V_I - P_F V_F}{\gamma - 1} = \frac{mR(T_I - T_F)}{\gamma - 1}$	$W_{\text{open}} = \gamma W_{\text{closed}}$
Polytropic process (k = n)	$W = \frac{P_I V_I - P_F V_F}{n - 1} = \frac{mR(T_I - T_F)}{n - 1}$	$W_{\text{open}} = n W_{\text{closed}}$

Note: $P_1 V_1^n = P_2 V_2^n$, $\frac{P_1}{P_2} = \left(\frac{V_2}{V_1}\right)^n$, $\ln\left(\frac{P_1}{P_2}\right) = n \ln\left(\frac{V_2}{V_1}\right)$

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

- **Heat:** It is a form of energy transfer due to the temperature difference. Heat flow 'out' of a system is taken as 'negative' while heat flow 'into' a system is taken as 'positive'.
- Heat like work is also a 'path' function so is 'inexact' or imperfect differential.

It is of two types:

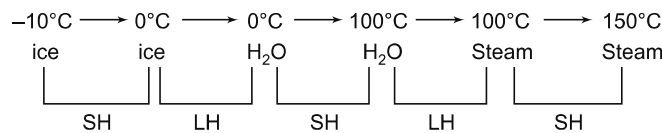
- (a) Sensible heat,
- (b) Latent heat.

Sensible Heat (SH): It is the heat transfer by the virtue of temperature difference.

Latent Heat (LH): The heat required to cause the phase change is known as latent heat.

$$SH = mC\Delta T$$

$$LH = m(LH)$$



Where, C is known as specific heat.

It is the amount of heat which is required to rise the temperature of a unit mass by a unit temperature difference.

$$Q = mC\Delta T \longrightarrow C = \frac{Q}{m\Delta T} = \frac{Q}{1 \times 1} \frac{J}{kg}$$

- Specific heat at constant volume, $C_v = \left(\frac{\partial u}{\partial T}\right)_v$

The heat supplied to a system at constant volume increases its internal energy.

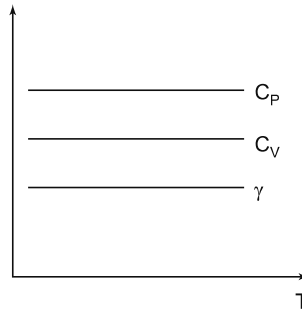
- Specific heat at constant pressure, $C_p = \left(\frac{\partial h}{\partial T}\right)_p$

The heat supplied to a system at constant pressure increases its enthalpy.

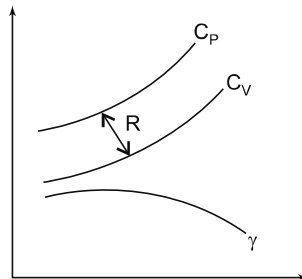
- for solid and liquid i.e. $\rho = \text{Constant}$ $C_p = C_v \xrightarrow{\text{i.e.}} \gamma = 1$
- For gasses i.e. $\rho \neq \text{Constant}$

$$C_p = \frac{\gamma R}{\gamma - 1} \quad C_v = \frac{R}{\gamma - 1} \quad C_p - C_v = R$$

- Ideal gas:** As temperature changes the volume of C_p and C_v do not change for ideal gas.



- Real gas:** For real gas C_p and C_v value increases with temperature whereas value of γ decreases.



- **Air:** Value of C_p and C_v changes with temperature linearly upto 1500 k. Above 1500 k it varies quadratically.

Note :

- The value of isothermal specific heat is infinite ($C_{\text{isothermal}} = \infty$) whereas the value of adiabatic heat is zero. ($C_{\text{adiabatic}} = 0$)
- Heat supplied at constant pressure is more than specific heat supplied at constant volume because C_p includes both internal energy as well as boundary work, C_v includes only internal energy.

$$PV = nR_0T$$

where,

P = pressure (absolute pressure) in kPa

V = volume of tank only in m³

n = number of moles in kilomoles of gas

R_0 = Universal gas constant in kJ/kmol-K

T = Temperature (absolute) in kelvin (K)

$$(R_0)_{\text{oxygen}} = (R_0)_{\text{air}} = (R_0)_{\text{nitrogen}} = (R_0)_{\text{any gas}} = 8.314 \text{ kJ/kmol-K}$$

$$PV = mRT$$

Here,

P = absolute pressure in kPa

V = volume of container in m³

m = mass in kg

R = Characteristic gas constant in (kJ/kg-K)

T = absolute temperature in Kelvin

$$PV = nR_0T = \frac{N}{A} R_0T = N \frac{R_0}{A} T = NkT$$

where, k is Boltzmann's constant

$$R = R_0/M, R_0 = MR, R_{O_2} = \frac{8.314}{32} \frac{\text{kJ}}{\text{kg} - \text{K}}$$

$$\begin{array}{ll} (C_p)_{\text{air}} = 1.008 \text{ kJ/kg-K} & R_{\text{air}} = 0.287 \text{ kJ/kg-K} \\ (C_v)_{\text{air}} = 0.721 \text{ kJ/kg-K} & \gamma_{\text{air}} = 1.4 = 7/5 \\ M_{\text{air}} = 29 & \end{array}$$

- $\gamma = \frac{C_p}{C_v}$: adiabatic index → depends on nature of gases

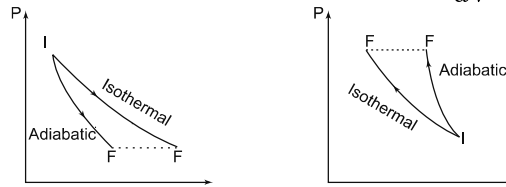
$$T \uparrow \begin{array}{l} C_p \uparrow \\ C_v \uparrow \end{array} \quad \downarrow \gamma = \left(\frac{\uparrow C_p}{\uparrow C_v} \right) \downarrow \quad \begin{array}{l} C_p > C_v \\ \text{always} \end{array}$$

$$\gamma = 1 + \frac{2}{n}$$

where, n = degree of freedom

Monoatomic gas	$\gamma = 1.67$	$\gamma_{\text{water}} = 1$
Diatomic gas	$\gamma = 1.4$	
Polyatomic gas	$\gamma = 1.33$	

- Slope of isothermal curve on P-V diagram = $\left(\frac{dP}{dV}\right) = \frac{-P}{V}$
- Slope of adiabatic curve on P-V diagram = $\frac{dP}{dV} = -\gamma \frac{P}{V}$



adiabatic slope = γ (isothermal slope)
 adiabatic slope > isothermal slope

Ideal Gas Equation For Various Processes

Process	Ideal gas equation
Constant volume (isochoric)	$P \propto T, \frac{P_2}{P_1} = \frac{T_2}{T_1}$
Constant pressure (isobaric)	$V \propto T, \frac{V_2}{V_1} = \frac{T_2}{T_1}$
Polytropic process	$P_1 V_1^n = P_2 V_2^n, T_1 V_1^{n-1} = T_2 V_2^{n-1}$ $\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} = \left(\frac{V_1}{V_2}\right)^{n-1}$
adiabatic	replace n by γ of polyhtropic
constant temperature (isothermal)	$P \propto \frac{1}{V}, \frac{P_1}{P_2} = \frac{V_2}{V_1}$

$$\text{for air } \frac{n-1}{n} = 0.2857 \text{ and } \frac{n}{n-1} = 3.5$$

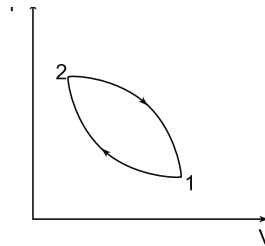
3. First Law of Thermodynamics

According to this law, energy can neither be created nor be destroyed rather it converted from one form of energy to another form.

- For a cycle

Closed system

$$\Sigma Q = \Sigma W$$



$$\delta Q = dE + \delta W$$

$$dE = \text{Total Energy}$$

- First law of thermodynamics,
- Valid only for closed system,
- Undergoing process as well as cycle,
- Both reversible and irreversible

Note : (i) For isolated system energy (E) always constant.

(ii) Energy is a point function and property of the system. Energy is an extensive property while specific energy is an intensive property.

(iii) The internal energy depends only on temperature, for an ideal gas.

Formula	Conditions
$\delta W = PdV$	• Closed system, • Quasi-static (Reversible)
$PV^\gamma = \text{constant}$ $\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}}$ $\frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{\gamma-1}$	• Adiabatic, • Reversible, • Ideal gas.
$\delta Q = dE + \delta W$	Closed system

$\delta Q = du + \delta W$	Closed system and $\Delta K.E. = \Delta P.E. = 0$
$\delta Q = du + PdV$	<ul style="list-style-type: none"> • Closed system, • $\Delta KE = 0 = \Delta PE$, • Quasi-static (reversible)

Heat Transfer In Closed System

Process	Heat transfer
Constant volume (Isochoric)	$\delta Q = du = u_2 - u_1 = \text{change in internal energy}$
Constant pressure (Isobaric)	$\delta Q = dh = h_2 - h_1 = \text{change in enthalpy}$
Constant temperature (Isothermal)	$\delta Q = \delta W$
Adiabatic process	$\delta Q = 0$
Polytropic	$\delta Q = \left(\frac{\gamma - n}{\gamma - 1} \right) \left[\frac{P_1 V_1 - P_2 V_2}{n - 1} \right]$ $\delta Q = \left(\frac{\gamma - n}{\gamma - 1} \right) (\delta W)_{\text{polytropic}}$

Note: • Heat transfer at constant 'Volume' increases the 'internal' energy of the system.

• Heat transfer at constant 'pressure' increases the 'enthalpy' of the system

• In polytropic process, heat transfer is not zero.

Enthalpy and Specific Enthalpy : It is total heat content of the system.

$$H = U + PV$$

Specific enthalpy is the summation of specific internal energy and flow work.

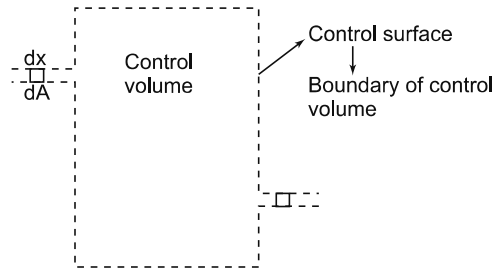
$$\text{Specific enthalpy } \frac{H}{m} = \frac{U}{m} + P \left(\frac{V}{m} \right)$$

$$h = u + Pv$$

Unit of Enthalpy (H) is J or N-m.

Flow Work or Displacement Work: It is the amount of work which is required to displace a small fluid element into or out of the control volume is known as flow work.

The mathematical expression of flow work is the product of pressure and specific volume.



- Control volume is also known as open system and control mass is known as closed system.
- The boundary of the control volume is known as control surface.

	Mass interaction	Energy interaction	
Control volume	✓	✓	Open System
Control mass	✗	✓	Closed System

Expansion process	Compression process
$dW (+ve)$	$dW (-ve)$
$dT (-ve)$	$dT (+ve)$
$T_f - T_i < 0$	$T_f - T_i > 0$
$T_f < T_i$	$T_f > T_i$
Produces cooling effect	produces heating effect

Polytropic Specific Heat

$$C_{poly} = \frac{\gamma - n}{1 - n} \cdot C_V$$

where, $n =$ Polytropic index and $\gamma = \frac{C_p}{C_v}$

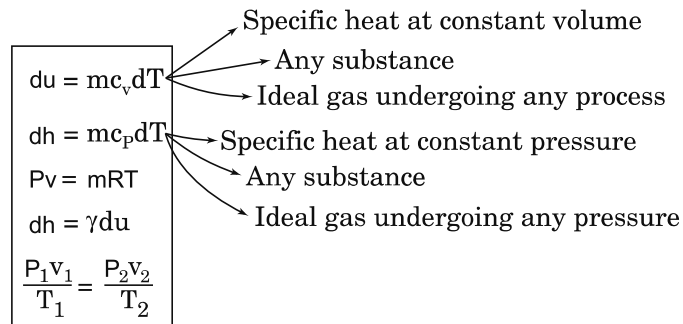
• Polytropic specific heat is always negative for, $1 < n < \gamma$, because even though heat is added to the gas temperature of gas decreases, since the work done by gas is more than the heat supplied.

$$\frac{Q_{\text{poly}}}{m(T_2 - T_1)} = -C_V \left(\frac{\gamma - n}{n - 1} \right)$$

Perpetual Motion Machine of first Kind (PMM1)

There can be no machine which would continuously supply mechanical work without some other form of energy disappearing simultaneously. Such a fictitious machine is called perpetual motion machine of first kind.

Only for Ideal Gas

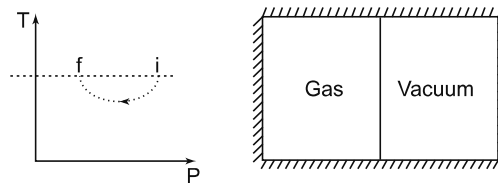


Free Expansion: Expansion against 'vacuum' is called free expansion.

It is an irreversible process. So we cannot apply $\int PdV$.

Free expansion work = 0

Insulated system, $Q = 0$



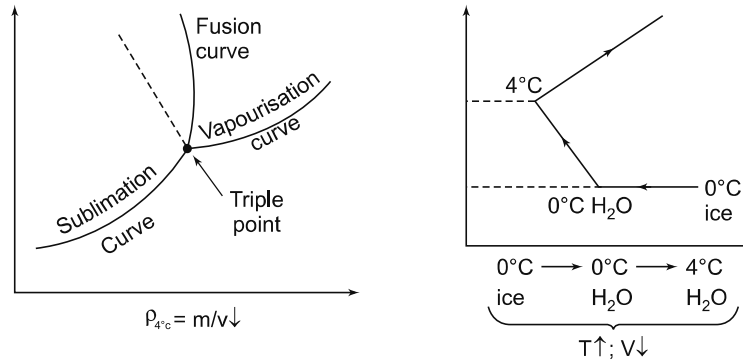
$$W = 0, Q = 0, \Delta U = 0$$

$$U_f = U_i \quad T_f = T_i \quad H_f = H_i \quad \text{Ideal gas undergoing free expansion}$$

Incompressible Substance: A substance whose specific volume (or density) is constant is called an incompressible substance.

The specific volumes of solids and liquids essentially remain constant during a process. Therefore, liquids and solids can be approximated as incompressible substances without sacrificing much in accuracy.

Note:



The density of water is maximum at 4°C and due to this on decreasing its temperature it expands.

- The slope of fusion curve for the water is negative but for all other substances it has positive slope.

Note: 1. Slope of an adiabatic curve on T-V plane = $(1 - \gamma) \frac{T}{V}$

2. Slope of an adiabatic curve on T-P plane = $\left(\frac{\gamma - 1}{\gamma}\right) \frac{T}{P}$

3. Slope of adiabatic curve on lnP - lnV plane = $-\gamma$

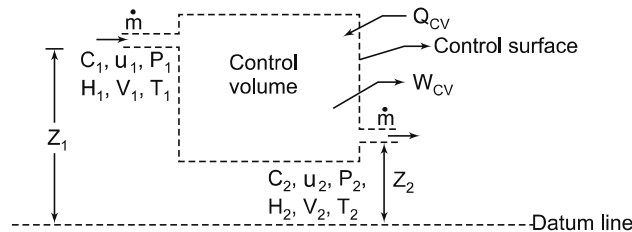
4. Slope of adiabatic curve on lnT - lnV plane = $1 - \gamma$

5. Slope of adiabatic curve on lnT - lnP plane = $\frac{\gamma - 1}{\gamma}$

6. Slope of isothermal curve on lnP - lnV plane = -1

4. First Law Applied To Flow Process

- Steady flow process/Steady flow energy equation (SFEE)



Steady flow means when the properties does not vary with respect to time. Therefore, the mass flow rate at the entry and exit of control volume are exactly same.

Energy Balance:

$$E_{\text{Entering}} = E_{\text{Leaving}}$$

$$H_1 + \frac{1}{2}mC_1^2 + mgz_1 + Q_{CV} = H_2 + \frac{1}{2}mC_2^2 + mgz_2 + W_{CV}$$

for per unit mass,

$$h_1 + \frac{1}{2}C_1^2 + gz_1 + q_{CV} = h_2 + \frac{1}{2}C_2^2 + gz_2 + W_{CV}$$

where, H = Enthalpy C = Velocity Z = Height

Q_{CV} = Heat given W_{CV} = Work done m = Mass flow rate

$$\dot{m} \left(h_1 + \frac{C_1^2}{2000} + \frac{gZ_1}{1000} \right) + Q_{CV} = \dot{m} \left(h_2 + \frac{C_2^2}{2000} + \frac{gZ_2}{1000} \right) + W_{CV}$$

- SFEE can also be written as:**

$$(u_1 + P_1v_1) + gz_1 + q_{CV} + \frac{C_1^2}{2} = (u_2 + P_2v_2) + gz_2 + W_{CV} + \frac{C_2^2}{2}$$

$$u_1 + \frac{C_1^2}{2} + gz_1 + q_{CV} = u_2 + \frac{C_2^2}{2} + gz_2 + W_{\text{total}}$$

where,

W_{total} = (displacement work done on system + displacement work done by system + W_{CV})

$$W_{\text{total}} = -P_1v_1 + P_2v_2 + W_{CV}$$

Mass Balance:

$$\begin{aligned} \dot{m}_1 = \dot{m}_2 \quad \rho_1 A_1 V_1 = \rho_2 A_2 V_2 \\ \text{or} \\ \frac{A_1 C_1}{v_1} = \frac{A_2 C_2}{v_2} \quad \rho_1 A_1 C_1 = \rho_2 A_2 C_2 \end{aligned}$$

where, V and C denotes velocity.

for incompressible fluid flow:

$$\rho = AC = \text{constant}$$

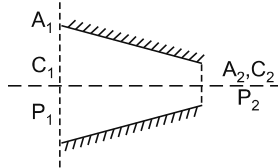
$$\frac{A_1}{A_2} = \frac{C_2}{C_1} = \text{constant}$$

$$A_1 C_1 = A_2 C_2$$

$$A \propto \frac{1}{C}$$

Application of SFEE in Steady Flow Process:

1. Nozzle: It is a mechanical device which is used to increase the kinetic energy at the expense of pressure energy.



$$C_2 = \sqrt{2000 (h_1 - h_2)} = 44.72\sqrt{(h_1 - h_2)} = 44.72\sqrt{C_p(T_1 - T_2)}$$

where, T = Temperature h = Enthalpy C₂ = Velocity at outlet
Condition:

- (i) Nozzle is perfectly insulated,
- (ii) Neglect Potential energy changes.
- (iii) No work is done by Nozzle,
- (iv) Neglecting inlet kinetic energy or inlet velocity

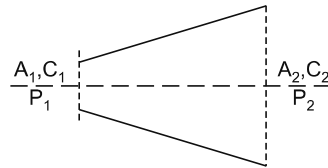
$$C_1 \llll C_2$$

A₁ > A₂ → converging nozzle

A₂ < A₂ → diverging nozzle (converging diverging)

depends upon Mach number

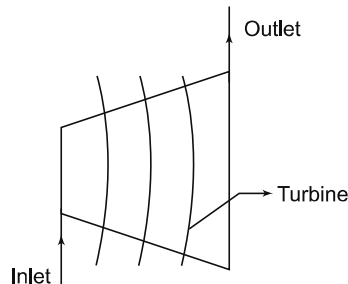
2. Diffuser: It is of diverging shape and used to decrease the velocity.



$$C_1 = 44.72\sqrt{(h_2 - h_1)} = 44.72\sqrt{C_p(T_2 - T_1)}$$

3. Turbine: It is a work producing device. In this the energy is transferred from the working fluid to the rotor.

In the case of turbine pressure reduces i.e. expansion of the steam working fluid takes place.



$$W_T = m(h_1 - h_2)$$

$h_1 > h_2$. So, Work is positive always

Conditions:

- (i) Turbine is perfectly insulated.
- (ii) Neglecting potential and kinetic energy changes.
- (iii) $C_1 \approx C_2$

4. Pump and Compressor: Both are work absorbing devices. In these devices the energy is transferred from rotor to working fluid.

Compressor: used to increase both pressure as well as temperature.

Pump: used to increase pressure

$$W_{C/P} = m(h_2 - h_1)$$

$h_1 > h_2$, So Work is negative

Compressor: deals with compressible fluid, generally vapours

Pump: deals with incompressible fluid, generally liquids.

5. Boiler or Evaporator: Used to convert liquid into vapour. It is a type of heat exchanger in which external heat is supplied due to which enthalpy of the fluid increases.

$$\boxed{Q_{B/E} = m(h_2 - h_1)} \quad W_{1-2} = 0 \text{ and } Q_{1-2} = \text{positive always}$$

$$P_1 = P_2 \quad h_2 > h_1$$

6. Condenser: Used to condense vapour into liquid. It is a type of heat exchanger in which heat is rejected at constant pressure.

$$\boxed{Q_C = m(h_2 - h_1)} \quad h_2 < h_1 \quad \text{i.e. } Q = \text{negative, rejected by fluid}$$

$$W_{1-2} = 0 \text{ (always)}$$

7. Throttling: Flow through a restricted passage, a very small orifice, partially open valve, venturi, porous plug is known as throttling.

Characteristics: 1. No work transfer,

2. No heat transfer,

3. It is an irreversible adiabatic process,

4. It is an isenthalpic process [$h_1 = h_2$],

5. Throttling always results a decrease in pressure (expansion).

$$\boxed{-VdP \text{ work}}$$

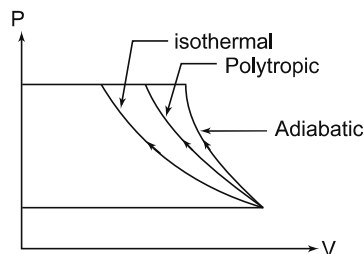
Reversible work in a steady flow process ($-VdP$)

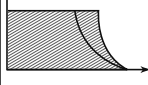
(1) steady state, (2) K.E. = P.E. = 0

$$h_1 + q = h_2 + W_{CV}$$

$$q = (h_2 - h_1) + W_{CV}$$

$$\boxed{\delta q = dh + \delta W_{CV}}$$

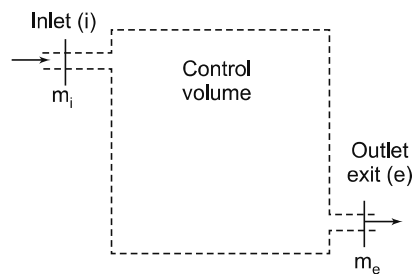


Type of compression process	W_{suction}	$W_{\text{compression}}$ (Closed system work)	$W_{\text{discharge}}$ 	W_{net} compressor work (open system work)
Isothermal	same	maximum	minimum	minimum
Polytropic	same	in between	in between	in between
Adiabatic	same	minimum	maximum	maximum

Unsteady State Flow or Transient Flow:

- Charging or discharging of a tank,
- Bottle filling process.

1. Conservation of Mass:



$$\left(\frac{dm}{dt} \right)_{C.V.} = \frac{dM_i}{dt} - \frac{dM_e}{dt}$$

$$\boxed{\left(\frac{dm}{dt} \right)_{C.V.} = \dot{m}_i - \dot{m}_e}$$

2. Conservation of Energy:

$$\left(\frac{dE}{dt} \right)_{C.V.} = \frac{dE_i}{dt} - \frac{dE_e}{dt}$$

$$E_i = m_i h_i + \frac{1}{2} m_i c_i^2 + m_i g z_i + Q$$

$$E_e = m_e h_e + \frac{1}{2} m_e c_e^2 + m_e g z_e + W_{C.V.}$$

$$\left(\frac{dE}{dt}\right)_{C.V.} = \frac{d}{dt} \left(m_i h_i + \frac{1}{2} m_i c_i^2 + m_i g z_i + Q \right) - \frac{d}{dt} \left(m_e h_e + \frac{1}{2} m_e c_e^2 + m_e g z_e + W_{C.V.} \right)$$

Neglecting K.E. and P.E. changes,

$$\left(\frac{du}{dt}\right)_{C.V.} = \frac{d}{dt} (m_i h_i + Q) - \frac{d}{dt} (m_e h_e + W_{C.V.})$$

If h_i and h_e do not vary with respect to time,

$$\left(\frac{du}{dt}\right)_{C.V.} = h_i \frac{dm_i}{dt} + \dot{Q} - h_e \frac{dm_e}{dt} - W_{C.V.}$$

$$\left(\frac{du}{dt}\right)_{C.V.} = \dot{m}_i h_i + \dot{Q} - \dot{m}_e h_e - \dot{W}_{C.V.}$$

Note: If the fluid flow is an ideal gas.

$$\begin{array}{lll} U = m C_V T & U/m = C_V T & u = C_V T \\ H = m C_P T & H/m = C_P T & h = C_P T \\ u_2 = h_1 & C_V T_2 = C_P T_1 & \end{array}$$

$$T_2 = \gamma T_1$$

5. Second Law of Thermodynamics

It is also known as law of degradation of energy or directional law or qualitative law:

- (i) First law of thermodynamics defines the concept of energy on quantity basis whereas second law of thermodynamics defines the concept of energy on quality basis.
- (ii) It is the second law of thermodynamics which defines the feasibility of the process or the direction of possible energy conversion through the concept of entropy.

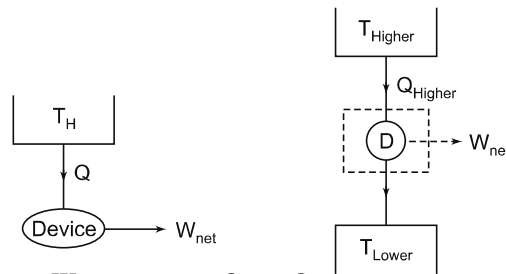
Note: Work is said to be high grade energy and heat is a low grade energy. the complete conversion of 'Low grade energy' into 'high grade energy' in a cycle is impossible while the complete conversion of high grade energy into low grade energy is possible.

Thermal Energy Reservoir (TER): Reservoir of infinite heat capacity. It is of two types:

Source: It is the supplier of heat energy without any change in its temperature.

Sink: It is the absorber of heat energy without affecting its temperature.

1. Kelvin Planck's Statement: It is impossible to construct a device which operates in a cycle producing work continuously while interacting with the single thermal reservoir.



$$\eta = \frac{\text{Output}}{\text{Input}} = \frac{W_{\text{net}}}{Q_S} = \frac{W}{Q_H} = \frac{Q_H - Q_L}{Q_H}$$

$$= 1 - \frac{Q_L}{Q_H} = 1 - \frac{Q_R}{Q_S}$$

$$Q_H = W_{\text{net}} + Q_L$$

$$W_{\text{net}} = Q_H - Q_L$$

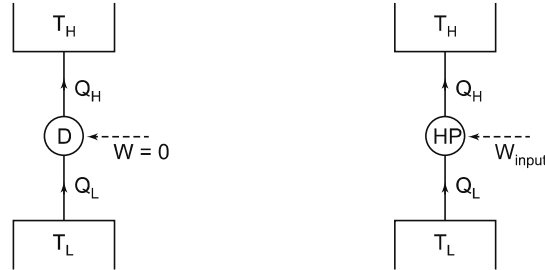
Thermodynamic Temperature Scale or Kelvin Temperature Scale:

$$Q \propto T \quad \eta = 1 - \frac{Q_L}{Q_H} = 1 - \frac{T_L}{T_H}$$

$$\eta_{\text{carnot}} = 1 - \frac{T_L}{T_H}$$

Note: Kelvin Planck statement provides the concept of work produce device.

2. Clausius Statement: It is impossible to construct a device which operates in a cycle transfers heat from low temperature reservoir to high temperature reservoir without consuming any other form of energy. ($W_{\text{input}} = 0$)



Coefficient of performance(COP) or Energy performance ratio(EPR)

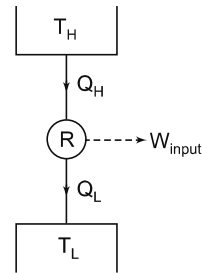
$$\text{COP or EPR} = \frac{\text{desired effect}}{W_{\text{input}}} = \frac{Q_H}{W_{\text{input}}}$$

$$Q_L + W_{\text{in}} = Q_H$$

$$W_{\text{in}} = Q_H - Q_L$$

$$\boxed{(\text{COP})_{HP} = \frac{Q_H}{Q_H - Q_L} = \frac{T_H}{T_H - T_L}}$$

$$(\text{COP})_R = \frac{\text{desired effect}}{W_{\text{input}}} = \frac{Q_L}{Q_{\text{input}}} = \frac{Q_L}{Q_H - Q_L}$$



$$\boxed{(\text{COP})_R = \frac{Q_L}{Q_H - Q_L} = \frac{T_L}{T_H - T_L}}$$

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

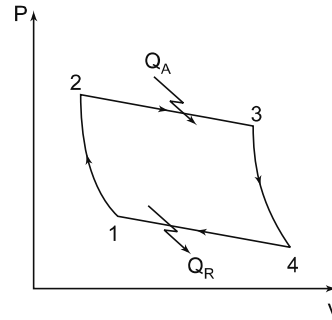
$$\boxed{(\text{COP})_{HP} = 1 + (\text{COP})_R = \frac{1}{\eta_E}}$$

Conditions:

1. The above expression applicable between the same temperature limit.
2. Clausius statement provides the concept of work absorbing device i.e. Heat pump and refrigerator.
3. Both Heat pump and Refrigerator are known as reversed heat engine.

Carnot Cycle:

- 1–2 : Reversible adiabatic compression
- 2–3 : Reversible isothermal heat addition
- 3–4 : Reversible adiabatic expansion
- 4–1 : Reversible isothermal heat rejection.



The Carnot cycle is not a practical cycle because for the process to be reversible the cycle process must be quasi-static and it is not feasible to run a device on a quasi-static process.

Carnot Principles:

- The efficiency of an irreversible heat engine cannot exceed the efficiency of a reversible engine operating between the same reservoirs.

$$\eta_{\text{irrev}} < \eta_{\text{rev}}$$

- The efficiency of all reversible heat engines operating between the same two reservoirs are same.

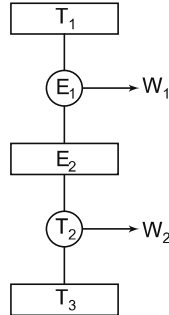
$$(\eta_{\text{rev}})_1 = (\eta_{\text{rev}})_2$$

Note:

1. The Carnot efficiency is a function of temperature limits only.
2. If there are 'n' number of reversible engines operating between the same temperature limits with different working fluids (Petrol, diesel, H₂O, Air) then the value of maximum possible efficiency or Carnot efficiency or ideal efficiency is having the same value.
3. Carnot efficiency is independent of working fluids.

$$\left. \begin{array}{l} \eta > \eta_{\text{rev}} \\ \eta = \eta_{\text{rev}} \\ \eta < \eta_{\text{rev}} \end{array} \right\} \begin{array}{l} \Rightarrow \text{impossible} \\ \Rightarrow \text{Reversible} \\ \Rightarrow \text{Irreversible} \end{array}$$

4. If two reversible engines operating between thermal reservoirs at T_1 , T_2 and T_3 ($T_1 > T_2 > T_3$) as shown in figure:



Case 1: If the efficiency is same for engine

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

Case 2. If work output of both engine same.

$$T_2 = \frac{T_1 + T_3}{2}$$

overall efficiency of arrangement = $\eta = \eta_1 + \eta_2 - \eta_1 \times \eta_2$

Effect of Temperature On The Performance of Reversible

Devices

Engine

$$\eta = 1 - \frac{T_L \downarrow}{T_H \uparrow} = \frac{T_H - T_L}{T_H}$$

(a) $\downarrow T_L$ by ΔT

$$\eta_L = \frac{T_H - (T_L - \Delta T)}{T_H} = \frac{(T_H - T_L) + \Delta T}{T_H}$$

(b) $\uparrow T_H$ by ΔT

$$\eta_H = \frac{(T_H + \Delta T) - T_L}{T_H + \Delta T}$$

$$\eta_H = \frac{(T_H + T_L) - \Delta T}{T_H + \Delta T}$$

$$\boxed{\eta_L > \eta_H > \eta}$$

- Efficiency of engine increases by increasing T_H or by or by decreasing T_L but decreasing T_L is more beneficial for increasing engine efficiency.

- The COP of Refrigerator and Heat pump both increases by decreasing T_H and increasing T_L but increasing T_L is a better option.

Note: Two 'reversible adiabatic' paths cannot intersect each other which violates the Kelvin-Planck's statement. The machine which violate Kelvin-Planck statement is called **PMM2**.

Perpetual Motion Machine of Third Kind (PMM-3)

Continual motion of a movable device in complete absence of friction is known as PMM-3.

Third Law of Thermodynamics:

It is impossible by any procedure, no matter how idealized, to reduce any system to absolute zero of temperature in a finite number of operations.

6. Entropy

Second law of thermodynamics leads to entropy

Clausius Theorem

- The cyclic integral of $\frac{dQ}{T}$ for a reversible cycle is equal to zero.

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

- The cyclic integral of $\frac{dQ}{T}$ for an irreversible cycle is less than zero.

$$\oint_R \frac{dQ}{T} < 0$$

- Entropy Principle

$$dS \geq \frac{\delta Q}{T} \qquad dS = \left(\frac{\delta Q}{T} \right)_{\text{rev}}$$

$$(dS)_{\text{universe}} \geq 0 \qquad [(dS)_{\text{system}} + (dS)_{\text{surrounding}}] \geq 0$$

$$(dS)_{\text{universe}} > 0 \longrightarrow \text{Irreversible process}$$

$$(dS)_{\text{universe}} = 0 \longrightarrow \text{Reversible process}$$

$$(dS)_{\text{universe}} < 0 \longrightarrow \text{Impossible process}$$

Note:

1. Entropy change in reversible process is a point function and exact differential.
2. It is an extensive property.
3. Reversible adiabatic process is an isentropic process but reverse is not always true.
4. When the system is at equilibrium, any conceivable change in entropy would be zero.

Clausius Inequality: It provides the criterion of reversibility or irreversibility of cycle.

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

$$\oint \frac{dQ}{T} = 0, \text{ the cycle is reversible}$$

$$\oint \frac{dQ}{T} < 0, \text{ the cycle is irreversible and possible}$$

$$\oint \frac{dQ}{T} > 0, \text{ the cycle is impossible}$$

Change in entropy of System

Entropy can change by 3 methods

1. Heat interaction
2. Mass interaction [external interaction]
3. Entropy generation [internal interaction]

$$S_2 - S_1 = dS = \int_1^2 \frac{\delta Q}{T} + \delta_{\text{generation}}$$

\downarrow \downarrow
 due to heat due to internal
 transfer irreversibility

- Entropy generation is a path function.
- Entropy generation is always a positive value.

Note: When a device is shown exchanging energy with more than two reservoirs use of Clausius Inequality should be done and any expression developed from heat ratio, temperature ratio should be avoided.

Case 1: Reversible process $[(\delta S)_{\text{gen}} = 0]$

(a) Heat addition $dS = \frac{\delta Q}{T} = \oplus ve$

(b) Heat rejection $dS = \frac{\delta Q}{T} = \ominus ve$

(c) Adiabatic $dS = \frac{\delta Q}{T} = 0$ [isentropic]

Case 2: Irreversible process $[(\delta S)_{\text{gen}} \neq 0]$

$$(a) \text{ Heat added } dS = \frac{\delta Q}{T} + (\delta S)_{\text{gen}} = \oplus \text{ve}$$

$$(b) \text{ Heat rejected } dS = \frac{\delta Q}{T} + (\delta S)_{\text{gen}} = \oplus \text{ve}, \ominus \text{ve}, 0$$

$$(c) \text{ Adiabatic } dS = \frac{\delta Q}{T} + (\delta S)_{\text{gen}} = \oplus \text{ve}$$

Important Points:

1. If we talk about same amount of energy then entropy associated is higher at lower temperature and lower at higher temperature.

2. If mass is same then entropy is higher at higher temperature and lower at lower temperature because total energy is also different.

3. Area under curve on T-s diagram represents heat interaction for a reversible process.

4. Area enclosed by reversible cycle on T-s diagram represents net heat transfer which is equal to net work transfer.

5. All clockwise cycle \Rightarrow power producing device

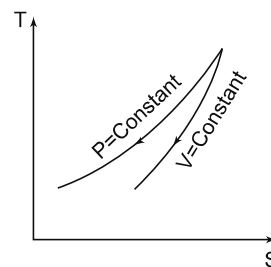
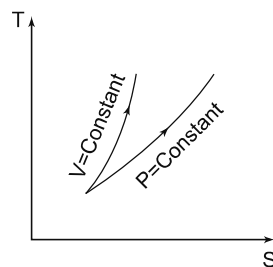
All anticlockwise cycle \Rightarrow power consuming device

• Combined 1st and 2nd law equations or T.ds equation or join equation of entropy:

$$1. T.ds = du + P.dV \quad 2. Tds = dh - v.dp$$

\Rightarrow These equations are valid for all processes and all the systems.

Representation of Constant Volume and Constant Pressure Lines on T-s Diagram:



- Constant volume process is more steeper.

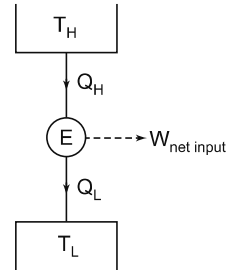
Slope of constant volume line = γ . slope of constant pressure line

$$C_P > C_V$$

$$\frac{1}{C_P} < \frac{1}{C_V}$$

$$\frac{T}{C_P} < \frac{T}{C_V}$$

$$\left(\frac{dT}{dS} \right)_{P=C} = \left(\frac{dT}{dS} \right)_{V=C}$$



$$\eta = \frac{O/P}{I/P} = \frac{W_{net}}{Q_S} \text{ or } \frac{W_{net}}{Q_H}$$

The maximum possible efficiency or η_{carnot}

or

$$\eta_{\text{ideal}} = 1 - \frac{T_L}{T_H}$$

$$\eta_{\text{actual}} = \frac{W}{Q_S} = \frac{Q}{Q_H}$$

the above engine is,

(a) Reversible $\longrightarrow \oint \frac{\delta Q}{T} = 0, (dS)_{\text{universe}} = 0, \eta_{\text{carnot}} = \eta_{\text{actual}}$

(b) Possible Irreversible $\longrightarrow \oint \frac{\delta Q}{T} < 0, (dS)_{\text{universe}} > 0; \eta_{\text{carnot}} > \eta_{\text{actual}}$

(c) Impossible $\longrightarrow \oint \frac{\delta Q}{T} > 0, (dS)_{\text{universe}} < 0; \eta_{\text{carnot}} < \eta_{\text{actual}}$

For a cyclic device

$$\oint dS = 0,$$

[for both reversible and irreversible]

Adiabatic

Reversible

$$ds = \left(\frac{\delta Q}{T} \right)_{\text{rev}} = \frac{0}{T} = 0$$

$$ds = 0$$

$$S_2 = S_1 = \text{Constants}$$

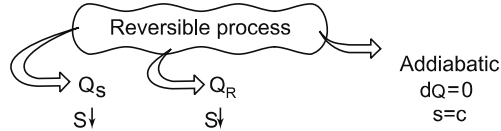
Irreversible

$$ds = \left(\frac{\delta Q}{T} \right)_{\text{irrev}} + (\delta S)_{\text{gen}}$$

$$ds = \frac{0}{T} + (\delta S)_{\text{gen}} = (\delta S)_{\text{gen}}$$

$$S_2 = \text{Positive}$$

$$ds > 0 \text{ (non-isentropic)}$$



Note: In an adiabatic process the system entropy can never decrease.

Entropy Change in Diffusion:

$$\Delta S = -m_1 R_1 \ln\left(\frac{P_1}{P}\right) - m_2 R_2 \ln\left(\frac{P_2}{P}\right)$$

O ₂	N ₂
P ₁	P ₂
T ₁	T ₂

where,

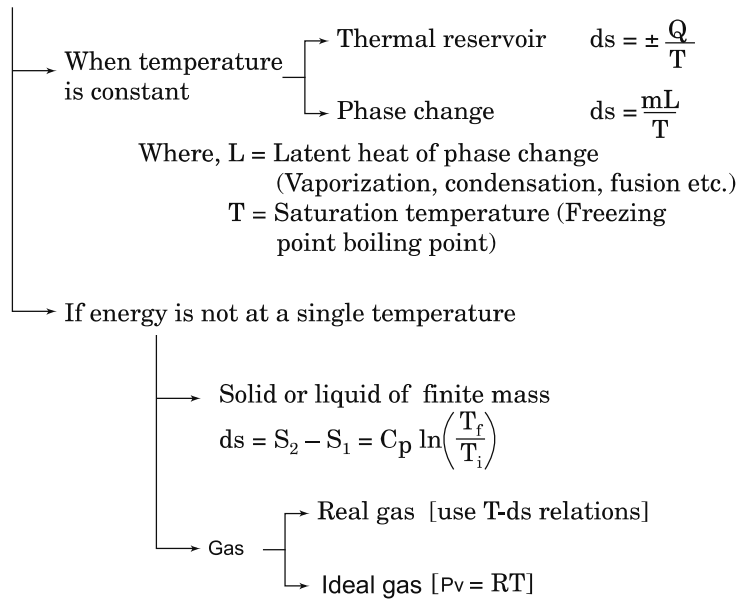
P₁, P₂ = partial pressure of O₂ and N₂

P = final pressure of mixture

R₁, R₂ = Characteristic gas constant for O₂ and N₂

m₁, m₂ = mass of O₂ and N₂

Entropy Calculation



$$\frac{\text{kJ}}{\text{kg-k}} \left\{ \begin{array}{l} 1. \Delta S = S_2 - S_1 = C_P \ln\left(\frac{T_F}{T_I}\right) - R \ln\left(\frac{P_F}{P_I}\right) \\ 2. \Delta S = S_2 - S_1 = C_V \ln\left(\frac{T_F}{T_I}\right) + R \ln\left(\frac{V_F}{V_I}\right) \\ 3. \Delta S = S_2 - S_1 = C_V \ln\left(\frac{P_F}{P_I}\right) + C_P \ln\left(\frac{V_F}{V_I}\right) \end{array} \right.$$

Control Volume Entropy Analysis:

$$(\Delta E)_{C.V} = 0$$

$$(\Delta m)_{C.V} = 0$$

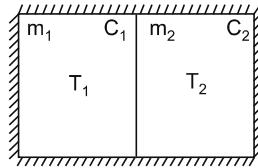
$$(\Delta S)_{C.V} = 0$$

$$(\Delta S) = S_{\text{inlet}} - S_{\text{exit}} + \delta S_{\text{gen}}$$

$$0 = S_{\text{inlet}} - S_{\text{exit}} + \delta S_{\text{gen}}$$

$$\delta S_{\text{gen}} = S_{\text{exit}} - S_{\text{inlet}}$$

Mixing of two incompressible fluids (liquid) or two solids:



$$T_f = \frac{m_1 C_1 T_1 + m_2 C_2 T_2}{m_1 C_1 + m_2 C_2}$$

$$(\Delta S)_{\text{universe}} = m_1 C_1 \ln\left(\frac{T_f}{T_1}\right) + m_2 C_2 \ln\left(\frac{T_f}{T_2}\right)$$

If $m_1 = m_2 = m$ and $C_1 = C_2 = C$

$$T_f = \frac{T_1 + T_2}{2} \quad \text{and} \quad (\Delta S)_{\text{universe}} = 2mC \ln\left(\frac{AM}{GM}\right)$$

AM = Arithmetic Mean, GM = Geometric Mean
for n bodies,

$$(\Delta S)_{\text{universe}} = n \times mC \ln\left(\frac{AM}{GM}\right)$$

Maximum obtainable Work When Two finite body are allowed to exchange heat through Reversible Engine:

$$(\Delta S)_1 + (\Delta S)_E^{\text{cyclic}} + (\Delta S)_2 = 0,$$

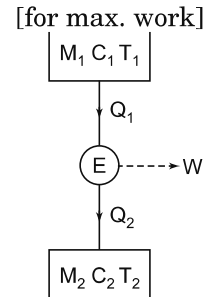
$$m_1 C_1 \ln\left(\frac{T_f}{T_1}\right) + 0 + m_2 C_2 \ln\left(\frac{T_f}{T_2}\right) = 0$$

If $m_1 = m_2 = m$ and $C_1 = C_2 = C$

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

$$W_{\max} = 2m (AM - GM)$$

for n bodies, $W_{\max} = n \times m C (AM - GM)$



If $W = W_{\max} \rightarrow \eta = \eta_{\max} \rightarrow \text{Reversible} \rightarrow S_{\text{gen}} = 0 \rightarrow (\Delta S)_{\text{universe}} = 0$
Note : For the best performance of the device i.e. if it is engine maximum work (or) if it is work consuming device minimum work,

Stirring Process : $(\Delta S)_{\text{universe}} = 0$

$$\Delta S_{\text{universe}} > 0 \text{ (since stirring process is an irreversible process.)}$$

$$du = 0 \text{ but } W_{1-2} = (-)ve$$

Since it is irreversible process, so $W_{1-2} \neq p dv$ (or) change of volume will not decide work transfer.

Here $dv = 0$ But $ W_{1-2} > 0$ Since irreversible process	Insulated, $Q_{1-2} = 0$ (adiabatic) Stirring : adiabatic but Process irreversible
--	--

$$Q_{1-2} = m C_v (T_f - T_i) \Rightarrow \text{only for reversible constant volume process by ideal gas when work done will be zero}$$

Note : If both the components are the same gas, then the entropy change in mixing is zero.
Second Law Efficiency: It is ratio of the actual thermal efficiency to the maximum possible (reversible) thermal efficiency under the same conditions.

For engine,

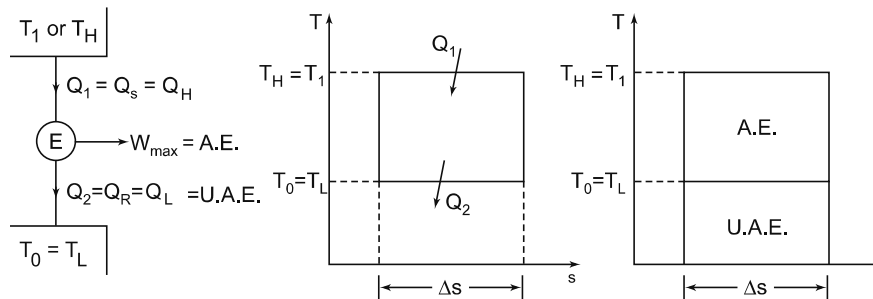
$$\eta_{II} = \frac{\eta_{\text{actual}}}{\eta_{\text{reversible}}} = \frac{W_{\text{actual}}}{W_{\max}}$$

For Refrigerator/Heat pump,

$$\eta_{II} = \frac{(COP)_{\text{actual}}}{(COP)_{\text{rev}}} = \frac{W_{\min}}{W_{\text{actual}}}$$

7. Available Energy, Availability and Irreversibility

The part of low grade energy which is available for conversion to high grade energy is referred to as available energy, which is also known as 'exergy' while the part of low grade energy which, according to second law, must be rejected is called unavailable energy. Unavailable energy is known as 'anergy'.



$$Q_1 = T_1 \Delta S$$

$$\eta = 1 - \frac{T_L}{T_H} = 1 - \frac{T_0}{T_1} = \frac{W_{max}}{Q_1}$$

$$W_{max} = Q_1 - Q_1 \left(\frac{T_0}{T_1} \right) = Q_1 \left(1 - \frac{T_0}{T_1} \right)$$

$$W_{max} = Q_1 - T_0 \Delta S \quad \leftarrow \quad W_{max} = Q_1 - Q_2$$

$$A.E. = Q_s - U.A.E. \quad \leftarrow$$

$U.A.E = T_0 \Delta S$

- The maximum work can be obtained when the lower temperature would be ambient temperature.

Important Points:

- Decrease in available energy takes place due to irreversible process when heat is transferred through a finite temperature difference.
- Same amount of heat has more available energy when it is transferred from a higher temperature body than when it is transferred from a lower temperature body.
- The degradation is more for energy loss at a higher temperature than that at a lower temperature.

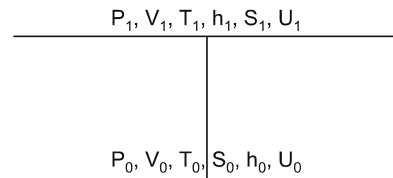
4. The first law states that the energy is always conserved 'quantity wise' while the second law emphasizes that energy always degrades 'quality wise'.

Dead State: A system is said to be in dead state if it is in thermodynamic equilibrium with its surrounding.

Available energy of the system is a function of:

1. Energy of the system,
2. State of the system,
3. State of the surroundings.

Availability: It is the maximum work obtained in which system comes into equilibrium with the surrounding state.



Final state or dead state or surrounding or ambient state or atmospheric state or datum or reference

Availability for a closed System:

$$(AV)_{C.S.} = (u_I - u_F) - T_0(S_I - S_F)$$

useful work

Maximum useful work for closed system:

$$(MUW)_{C.S.} = (U_I - U_F) - T_0(S_I - S_F) + P_0(V_I - V_F)$$

Availability for open System:

$$(AV)_{O.S.} = (h_I - h_F) - T_0(S_I - S_F)$$

useful work

Maximum useful work for open system:

$$(MUW)_{O.S.} = (h_I - h_F) - T_0(S_I - S_F)$$

Availability Function or Flow Availability (ϕ):

Case 1: Closed system

$$\phi_{C.S.} = u + P_0V - T_0S$$

Case 2: Open system

$$\phi_{O.S.} = h - T_0S$$

Gibb's function:

$$G = H - TS$$

Application for open system

$$\text{Change in Gibb's function: } dG = VdP - SdT$$

$$\text{Gibb's Helmholtz function: } F = U - TS$$

Applicable for closed system.

$$\text{Change in GHF: } dF = -PdV - SdT$$

Irreversibility (I): It is defined as the difference between maximum work and actual work.

$$I = W_{\max} - W_{\text{actual}}$$

Gouy Stodula Theorem: According to this theorem the rate of irreversibility is directly proportional to the rate of entropy generation.

$$I \propto (dS)_{\text{gen}} \quad I = T_0 (dS)_{\text{universe}}$$

Note: 1. The change in availability of an open system is equal to change in Gibb's function of system at constant temperature.

2. Gibb's function is useful in evaluating the availability of systems in which chemical reaction occurs.

3. The change in availability of closed system is NOT equal to change in Helmholtz function at given temperature.

Compressibility Factor

It is the factor which represents the deviation of actual gas behaviour from the ideal gas.

$$Z = \frac{PV}{RT}$$

The value of Z is 1 for ideal gas. and for real gas it can be > 1 or < 1 .

Causes of Irreversibility:

- Conversion of high grade energy into low grade energy,
- Friction,
- Viscous force,
- Electric resistance,
- Inelastic collision,
- Heat transfer through finite temperature differences,
- Free expansion,
- Mixing of fluids.