THERMODYNAMICS

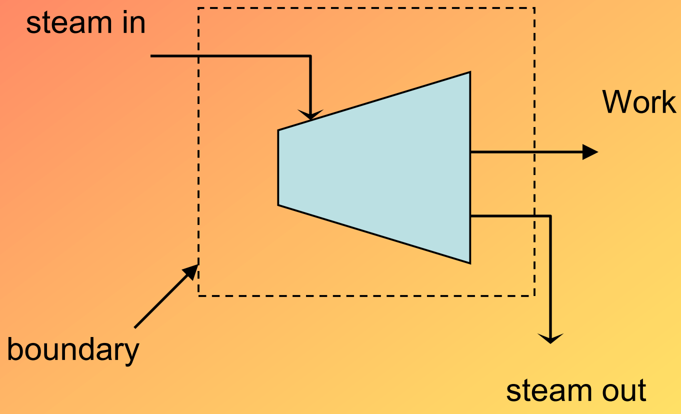
It a science that deals with energy transformation, the transformation of heat into work or vice versa. It was derived from a Greek word “therme” that means Heat and “dynamis” that means Strength.

SYSTEM: Is that portion in the universe, an atom, a galaxy, a certain quantity of matter or a certain volume in space in which one wishes to study. It is a region enclosed by an specified boundary, that may be imaginary, fixed or moving.

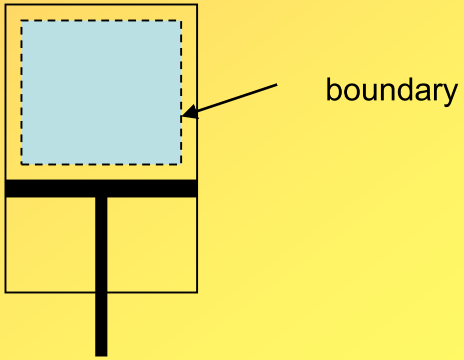
OPEN SYSTEM: A system open to matter flow or a system in which there is an exchange of mass between the system and the surroundings.

CLOSED SYSTEM: A system closed to matter flow or a system in which there’s no exchange of mass between the system and the surroundings.

Open System: Steam turbine



Closed System: Piston in Cylinder



SURROUNDINGS OR ENVIRONMENT: It is the region all about the system.

WORKING SUBSTANCE: A substance responsible for the transformation of energy.

example: steam in a steam turbine, water in a water pump

PURE SUBSTANCE: A substance that is homogeneous in nature and is homogeneous, or a substance that is not a mixture of different specie, or a substance that does not undergo chemical reaction.

PROPERTY: It is a characteristic quality of a certain substance.

INTENSIVE PROPERTY: Property that is independent of the mass of a system.

EXTENSIVE PROPERTY: Property that is dependent upon the mass of the system and are total values such as volume and total internal energy.

PROCESS: It is simply a change of state of a substance. If certain property of a substance is changed, it is said to have undergone a process.

CYCLE: It is a series of two or more processes in which the final and the initial state are the same.

ADIABATIC SYSTEM: A system that is impervious to heat. A system (open or closed) in which heat cannot cross its boundary.

PHASES OF A SUBSTANCE

A. Solid phase
B. Liquid phase
C. Gaseous or Vapor phase

SPECIFIC TERMS TO CHARACTERIZED PHASE TRANSITION:

1. Vaporization: Change from liquid to vapor
2. Condensation: Change from vapor to liquid
3. Freezing: Change from liquid to solid
4. Melting: Change from solid to liquid
5. Sublimation: Change from solid directly to vapor without passing the liquid state.

MASS: It is the absolute quantity of matter in it.

m – mass, kg

VELOCITY: It is the distance per unit time.

$$v = \frac{d}{t} \quad \frac{m}{sec}$$

where:

v – velocity in m/sec
d – distance in meters
t – time in sec

ACCELERATION: It is the rate of change of velocity with respect to time.

$$a = \frac{dv}{dt} \quad \frac{m}{sec^2}$$

FORCE: Force is the mass multiplied by the acceleration.

$$F = ma \frac{kg\text{-}m}{sec^2} \text{ or Newton}$$

$$F = \frac{ma}{1000} \text{ KN}$$

1 Newton = 1 kg-m/sec^2

Newton: Is the force required to accelerate 1 kg mass at the rate of 1 m/sec per second

WEIGHT: It is the force due to gravity.

$$W = mg \text{ N}$$

$$W = \frac{mg}{1000} \text{KN}$$

Where:

g – gravitational acceleration, m/sec^2

At standard condition (sea level condition)

g = 9.81 m/sec^2

FORCE OF ATTRACTION: From Newton’s Law of Gravitation, the force of attraction between two masses is given by the equation

$$Fg = \frac{Gm_1m_2}{r^2} \text{ Newton}$$

Where:

m_1 and m_2 – masses in kg
r – distance apart in meters
G – gravitational constant in $N\text{-}m^2/kg^2$
$G = 6.670 \times 10^{-11}$ $N\text{-}m2/kg^2$

PROPERTIES OF FLUIDS

DENSITY (ρ): It is the mass per unit volume

$$\rho = \frac{m}{V} \; \frac{kg}{m^3}$$

Where;

ρ - density in kg/m^3
m – mass in kg
V – volume in m^3

SPECIFIC VOLUME (υ): It is the volume per unit mass or the reciprocal of its density.

$$\upsilon = \frac{V}{m} = \frac{1}{\rho} \quad \frac{m3}{kg}$$

Where:

υ - specific volume in m^3/kg

SPECIFIC WEIGHT (γ): It is the weight per unit volume.

$$\gamma = \frac{W}{V} = \frac{mg}{1000V} = \frac{\rho g}{1000} \quad \frac{KN}{m^3}$$

Where:

γ - specific weight in KN/m^3

SPECIFIC GRAVITY OR RELATIVE DENSITY

1. For liquids it is the ratio of its density to that of water at standard temperature and pressure.
2. For gases it is the ratio of its density to that of either air or hydrogen at some specified temperature and pressure.

$$\text{For Liquids}: S_L = \frac{\rho_L}{\rho_w}$$

Where:

At standard Condition

$\rho_w = 1000\ kg/m^3$

$\gamma_w = 9.81\ KN/m^3$

$$\text{For Gases}: S_G = \frac{\rho_G}{\rho_{AH}}$$

VISCOSITY: It is a property of a fluid that determines the amount of its resistance to shearing stress.

a. Absolute or Dynamic viscosity

μ - dynamic viscosity in N-sec/m^2

b. Kinematic viscosity

ν - kinematic viscosity in m^2/sec

TEMPERATURE: It is the measure of the intensity of heat.

Fahrenheit Scale

Freezing Point = 32°F

Boiling Point = 212 °F

Centigrade or Celsius Scale

Freezing Point = 0°C

Boiling Point = 100°C

CONVERSION FORMULAS

$$°C = \frac{°F - 32}{1.8}$$

$$°F = 1.8°C + 32$$

ABSOLUTE SCALE

$$°K = °C + 273$$

$$°R = °F + 460$$

PRESSURE: Pressure is defined as the *normal component* of a force per unit *area*.

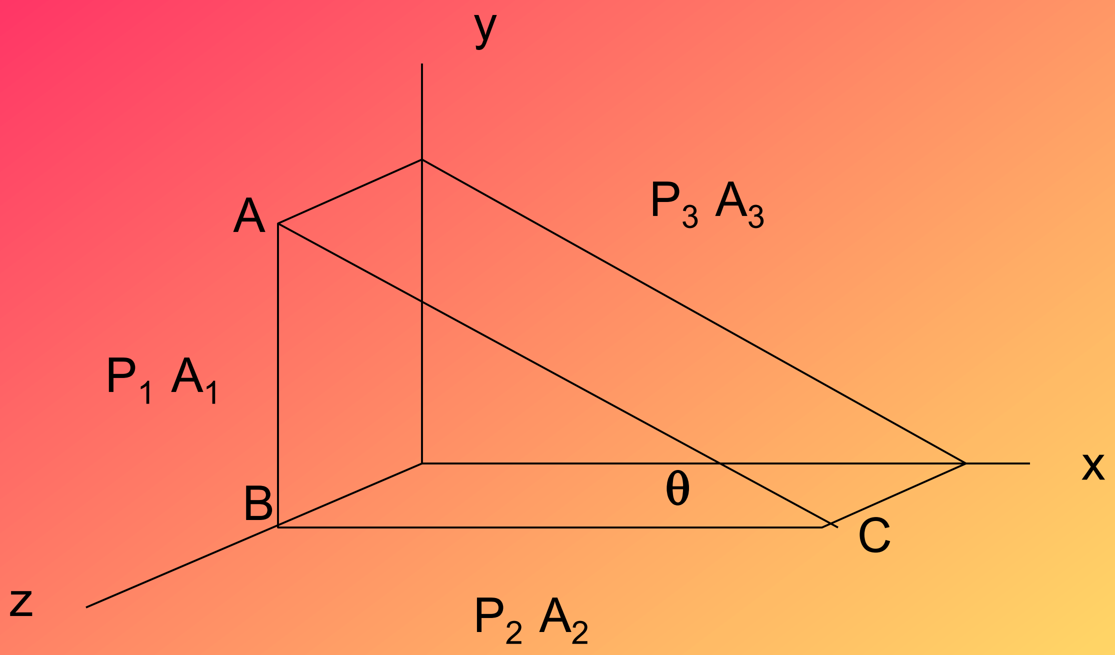
$$P = \frac{F}{A} \quad \frac{KN}{m^2} \text{ or KPa}$$

If a force dF acts normally on an infinitesimal area dA, the intensity of pressure is equal to

$$P = \frac{dF}{dA}$$

where;
P – pressure, KPa
F- force KN
A – area, m^2
1 KPa = 1 KN/m^2
1MPa = 1000 KPa

PASCAL'S LAW: At any point in a homogeneous fluid at rest the pressures are the same in all directions.



$\Sigma Fx = 0$ and $\Sigma Fy = 0$
$P_1A_1 – P_3A_3 \sin \theta = 0 \rightarrow 1$
$P_2A_2 – P_3A_3 \cos \theta = 0 \rightarrow 2$

From Figure:
$A_1 = A3 \sin \theta \rightarrow 3$
$A_2 = A3 \cos \theta \rightarrow 4$

Eq. 3 to Eq. 1
$P_1 = P_3$
Eq. 4 to Eq. 2
$P_2 = P_3$
Therefore:

$\mathbf{P_1 = P_2 = P_3}$

Atmospheric Pressure: It is the absolute pressure exerted by the atmosphere.

At Standard Condition

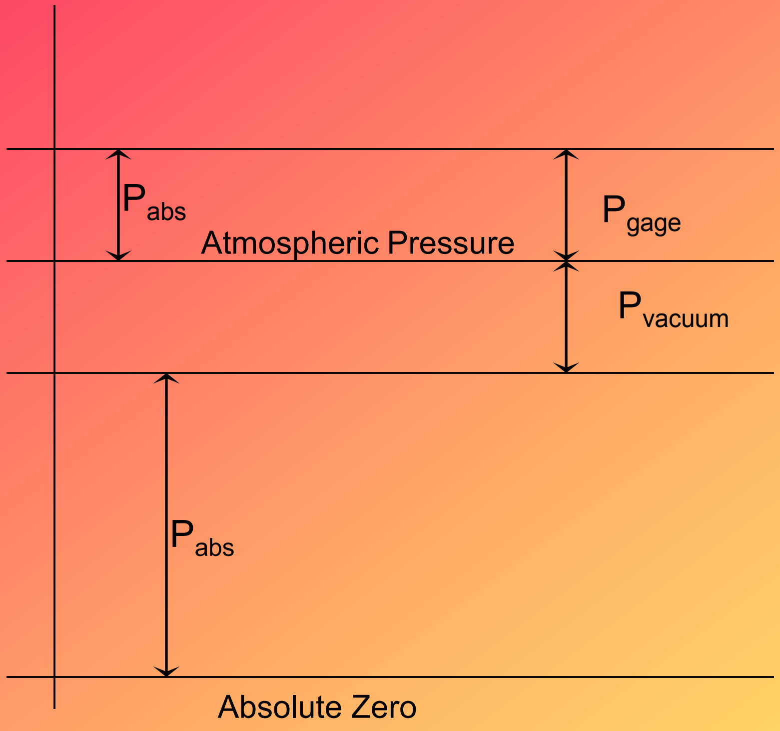
Pa = 101.325 KPa
= 1.033 kg/cm^2
= 0.101325MPa
= 1.01325 Bar
= 760 mm Hg
= 76 cm Hg
= 14.7 lb/in^2
= 10.33 m of H_2O
= 29.921 in of Hg
= 33.88 ft of H_2O

Barometer: an instrument used determine the absolute pressure exerted by the atmosphere.

ABSOLUTE AND GAGE PRESSURE

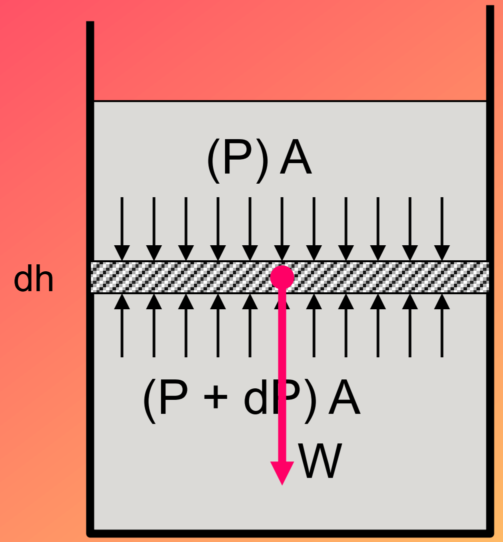
Absolute Pressure is the pressure measured referred to absolute zero and using absolute zero as the base.

Gage Pressure is the pressure measured referred to the existing atmospheric pressure and using atmospheric pressure as the base.



$$P_{abs} = P_a - P_{vacuum}$$
$$P_{abs} = P_a + P_{gage}$$

VARIATION OF PRESSURE WITH ELEVATION



$\Sigma Fx = 0$

$(P + dP)A – PA – W = 0$

$PA + dPA – PA = W$

$dPA = W$

$W = \gamma dV$

$dV = Adh$

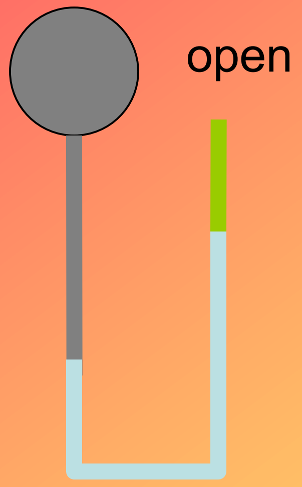
$dPA = - \gamma Adh$

$$dP = - \gamma dh$$

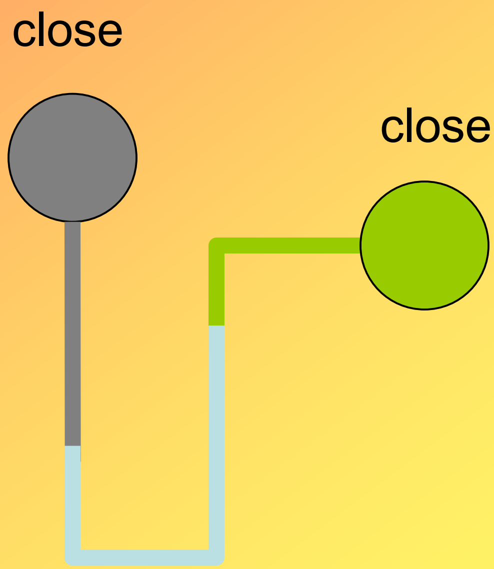
Note: Negative sign is used because Pressure decreases as elevation increases and increases as elevation decreases

Manometer: it is a device used in measuring gage pressure in length of some liquid column.

- Open Type – It has an atmospheric surface and is capable in measuring gage pressure.
- Differential Type – it has no atmospheric surface and is capable in measuring differences of pressure.



Open Type



Differential Type

FORMS OF ENERGY

- Work: It is the force multiplied by the displacement in the direction of the force.

  $W = \int F dx$

  +W – indicates that work is done by the system

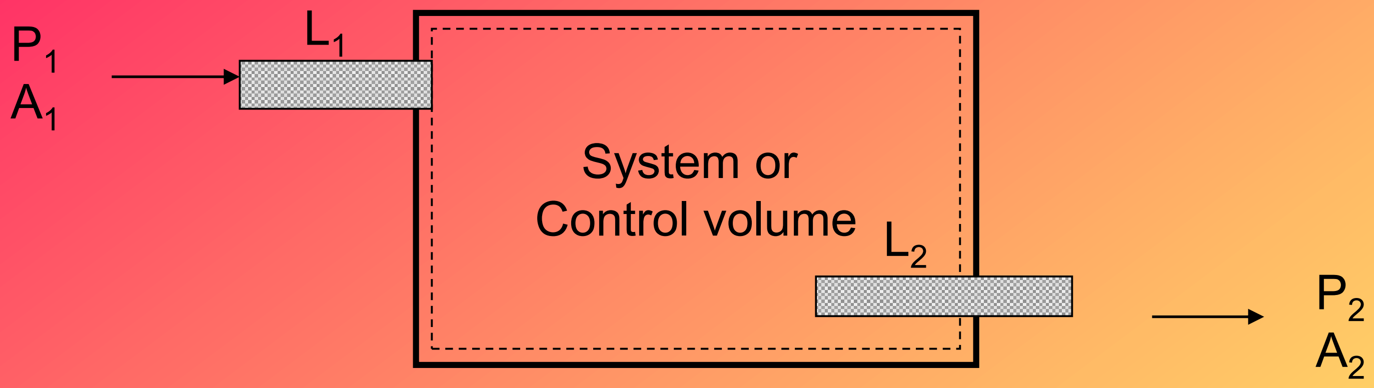
  -W – indicates that work is done on the system
- Heat: It is an energy that crosses a system's boundary because of a temperature difference between the system and the surrounding.

  +Q – indicates that heat is added to the system

  -Q – indicates that heat is rejected from the system
- Internal Energy: It is the energy acquired due to the overall molecular interaction, or it is the total energy that a molecule has.

  U – total internal energy, KJ

  u – specific internal energy, KJ/kg
- Flow Energy or Flow Work: It is the work required in pushing a fluid usually into the system or out from the system.



$E_{f1} = F_1L_1 = P_1A_1L_1$
$A_1L_1 = V_1$
$E_{f1} = P_1V_1$

$E_{f2} = F_2L_2 = P_2A_2L_2$
$A_2L_2 = V_2$
$E_{f2} = P_2V_2$

$\Delta E_f = E_{f2} - E_{f1}$

$\Delta Ef = P_2V_2 - P_1V_1$ KJ

$\Delta E_f = \Delta(PV)$

$\Delta E_f = E_{f2} - E_{f1}$

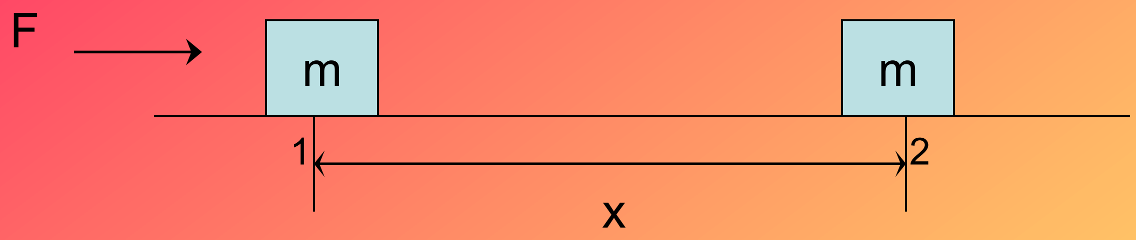
$\Delta E_f = P_2\upsilon_2 - P_1\upsilon_1$ KJ/kg

$\Delta E_f = \Delta(P\,\upsilon)$

Where:

P – pressure in KPa
V – volume in m^3
υ - specific volume in m^3/kg

- Kinetic Energy: It is the energy or the work required due to the motion of a body or a system.



$$\Delta KE = \int_1^2 F\,dx$$

$$\Delta KE = \int_1^2 ma \cdot dx = m\int_1^2 \frac{dv}{dt} \cdot dx = m\int_1^2 \cdot dv \cdot \frac{dx}{dt}$$

$$\Delta KE = m\int_1^2 vdv = m\frac{{v_2}^2 - {v_1}^2}{2} \text{ Joules}$$

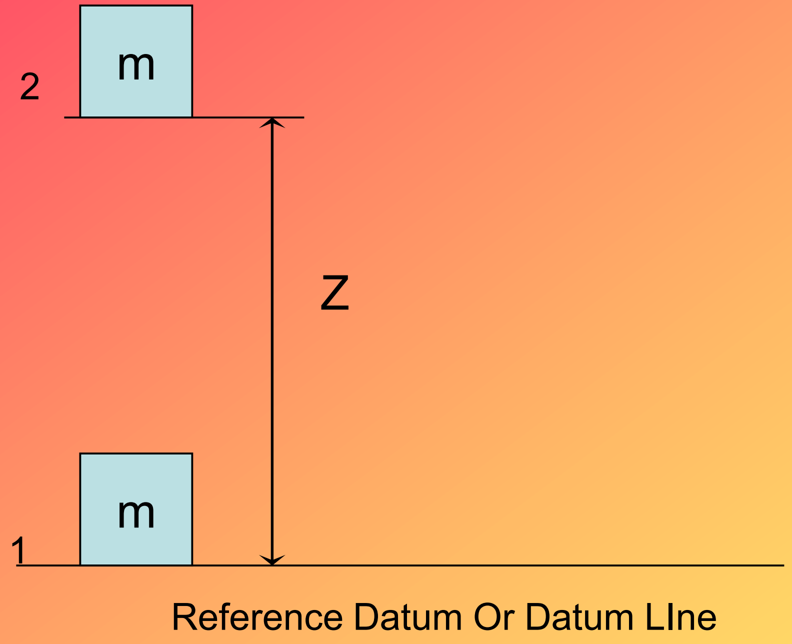
$$\Delta KE = m\frac{{v_2}^2 - {v_1}^2}{2(1000)} \text{ KJ}$$

$$\Delta KE = \frac{{v_2}^2 - {v_1}^2}{2(1000)} \frac{KJ}{kg}$$

Where:

m – mass in kg
v – velocity in m/sec

- Potential Energy: It is the energy or work required by a system by virtue of its configuration or elevation.



$$\Delta PE = \int_1^2 W \cdot dZ = mg\int_1^2 dZ = mg\left(Z_2 - Z_1\right)$$

$$\Delta PE = mg\left(Z_2 - Z_1\right) \text{ Joules}$$

$$\Delta PE = \frac{mg}{1000}\left(Z_2 - Z_1\right) \text{ KJ}$$

$$\Delta PE = \frac{g}{1000}\left(Z_2 - Z_1\right) \ \frac{KJ}{kg}$$

- Enthalpy: It a thermodynamic property that is equal to the sum of the internal energy and the flow energy of a substance.

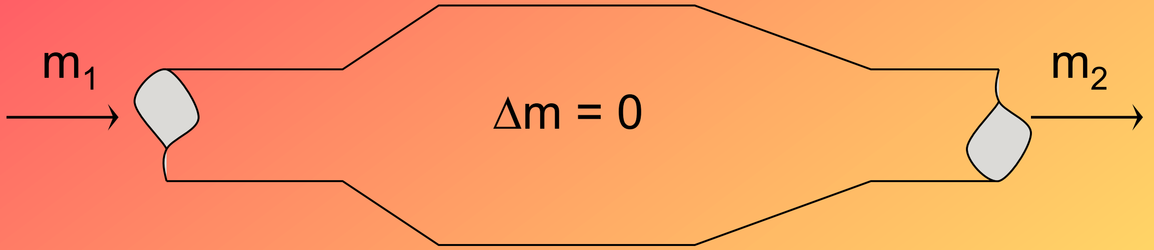
$$h = U + PV$$

LAW OF CONSERVATION OF MASS: Mass is indestructible. In applying this law we must except nuclear processes during which mass is converted into energy.

Verbal Form: Mass Entering – Mass Leaving = change of mass stored within the system

Equation Form: $m_1 - m_2 = \Delta m$

For an **Open System** (steady state, steady flow system) the $\Delta m = 0$.



$$\mathbf{m_1 - m_2 = 0}$$
$$\mathbf{m_1 = m_2}$$

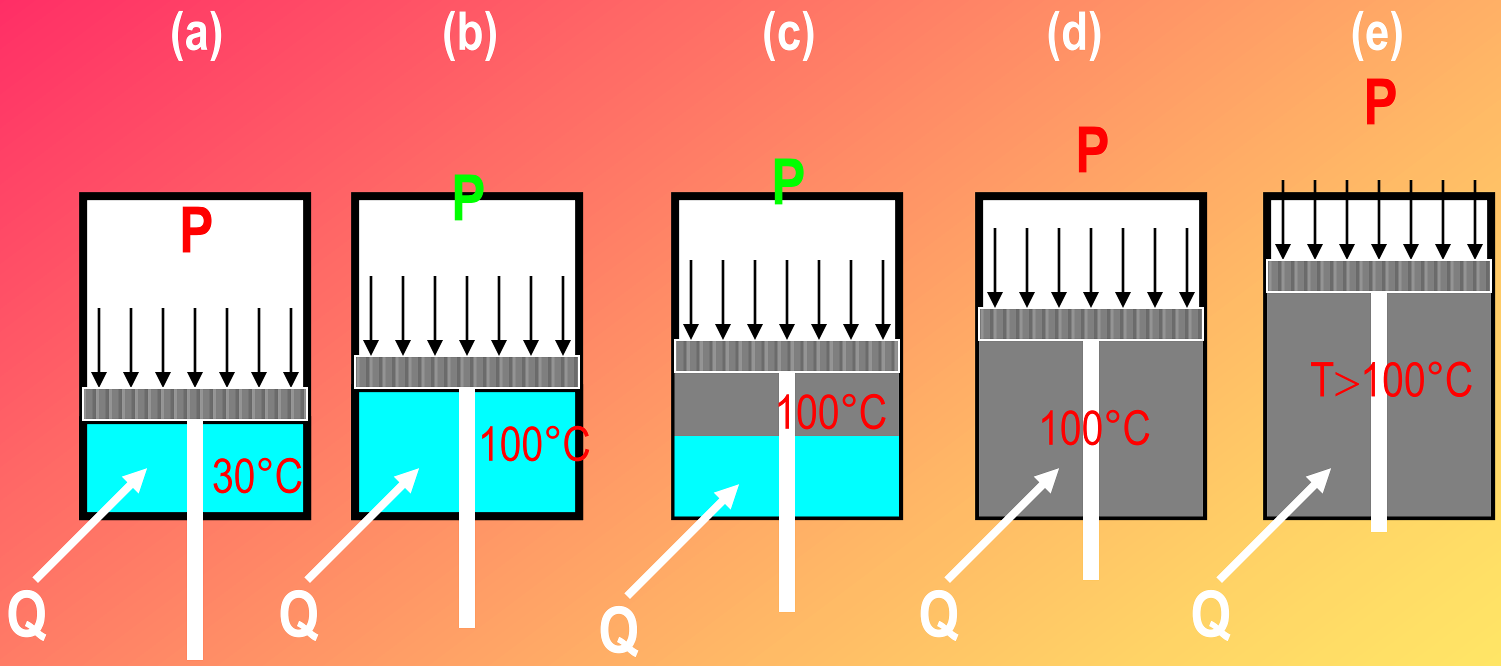
For one dimensional flow, the mass rate of flow entering or leaving a system is

$$m = \rho A v = \frac{Av}{\upsilon}$$
$$m_1 = m_2$$
$$\rho_1 A_1 v_1 = \rho_2 A_2 v_2$$
$$\frac{A_1 v_1}{\upsilon_1} = \frac{A_2 v_2}{\upsilon_2}$$

where:

m – mass flow rate, kg/sec
A – cross sectional area, m^2
v- velocity, m/sec
ρ - density, kg/m^3
υ - specific volume, m^3/kg

PROPERTIES OF PURE SUBSTANCE



Considering that the system is heated at constant pressure where P = 101.325 KPa, the 100°C is the saturation temperature corresponding to 101.325 KPa, and 101.325 KPa is the saturation pressure corresponding 100°C.

a - sub-cooled liquid
b - saturated liquid
c - saturated mixture
d - saturated vapor
e - superheated vapor

Saturation Temperature (tsat) - is the highest temperature at a given pressure in which vaporization takes place.

Saturation Pressure (Psat) - is the pressure corresponding to the temperature.

Sub-cooled Liquid - is one whose temperature is less than the saturation temperature corresponding to the pressure.

Compressed Liquid - is one whose pressure is greater than the saturation pressure corresponding to the temperature.

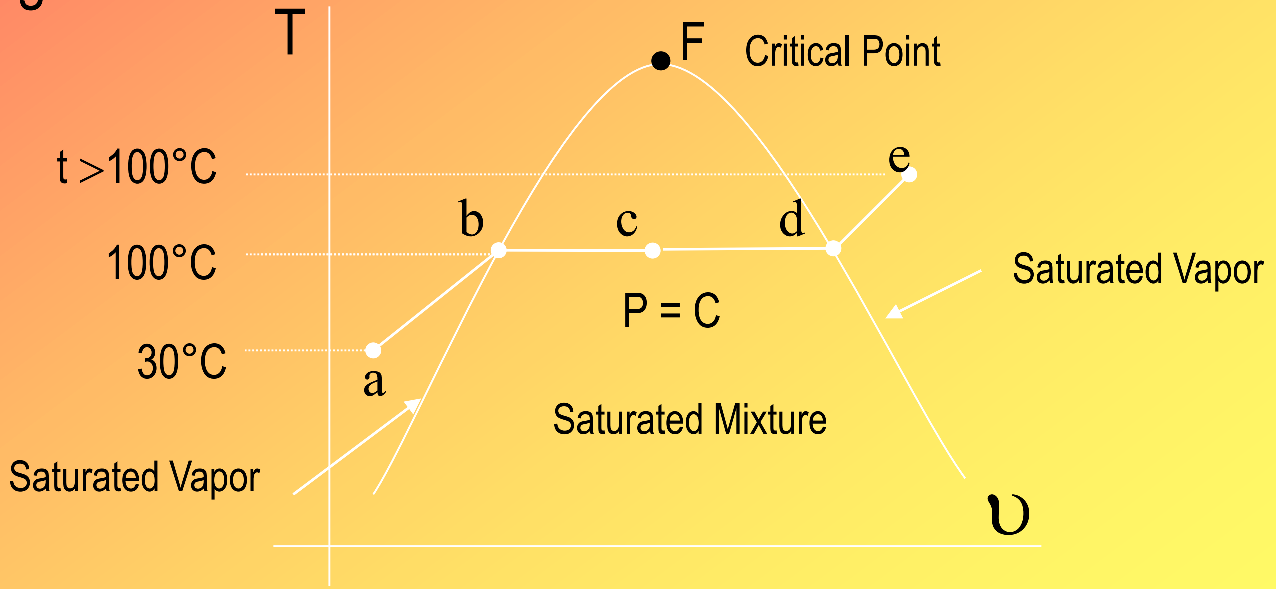
Saturated Liquid - a liquid at the saturation temperature

Saturated Vapor - a vapor at the saturation temperature

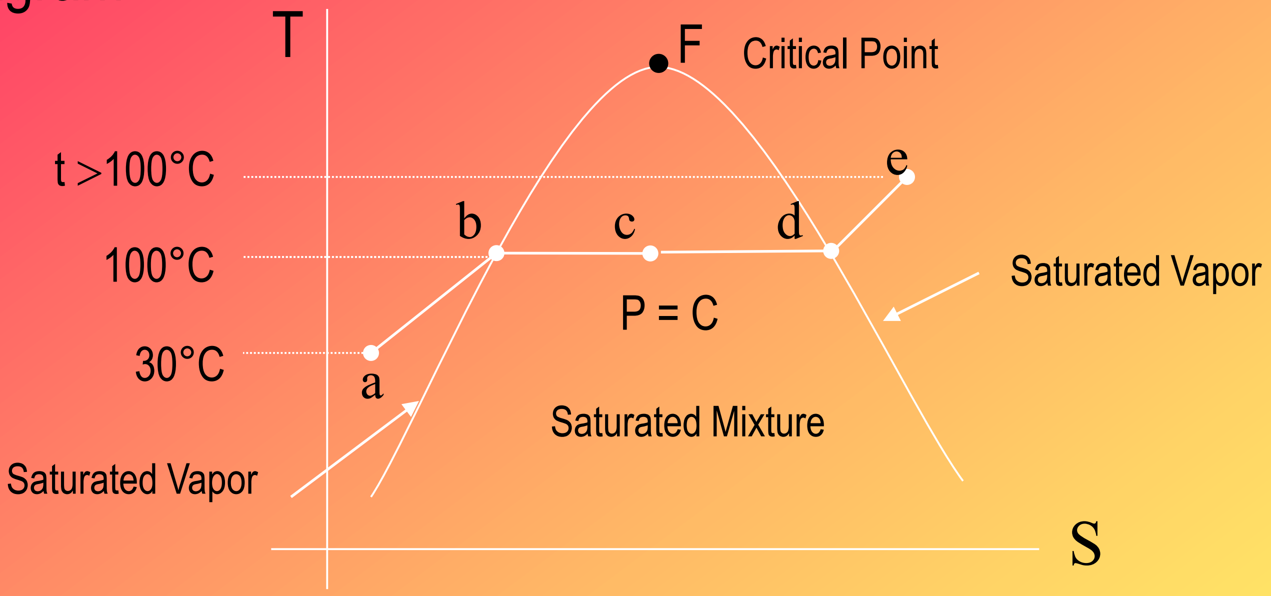
Saturated Mixture - a mixture of liquid and vapor at the saturation temperature.

Superheated Vapor - a vapor whose temperature is greater than the saturation temperature.

T-υ Diagram

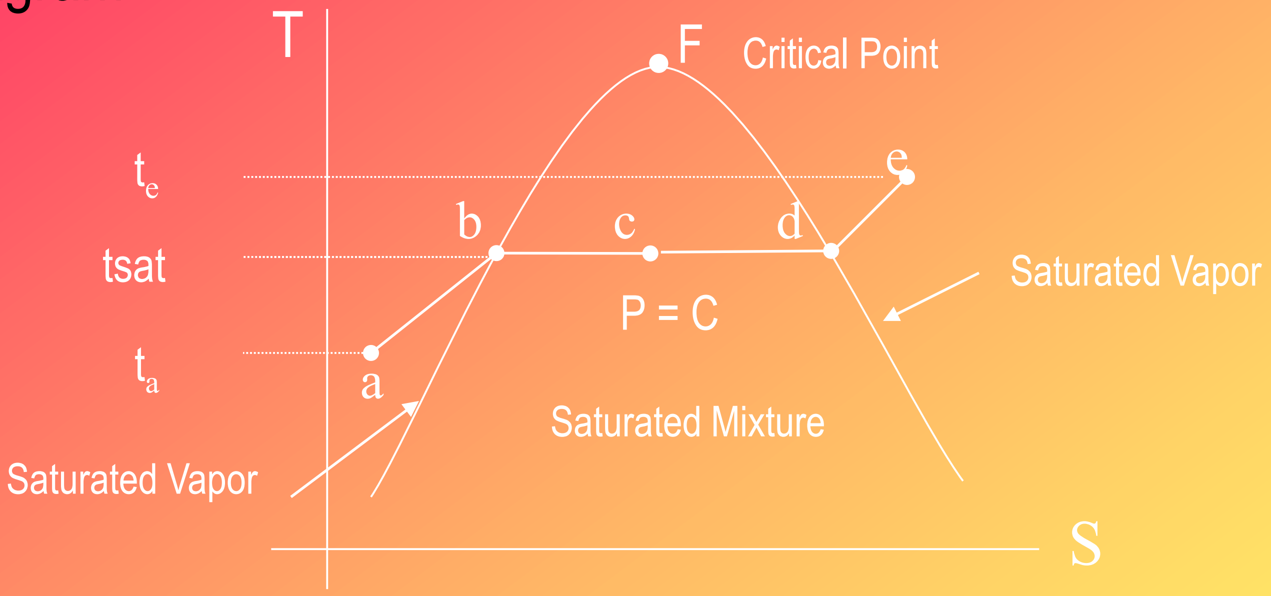


T-S Diagram



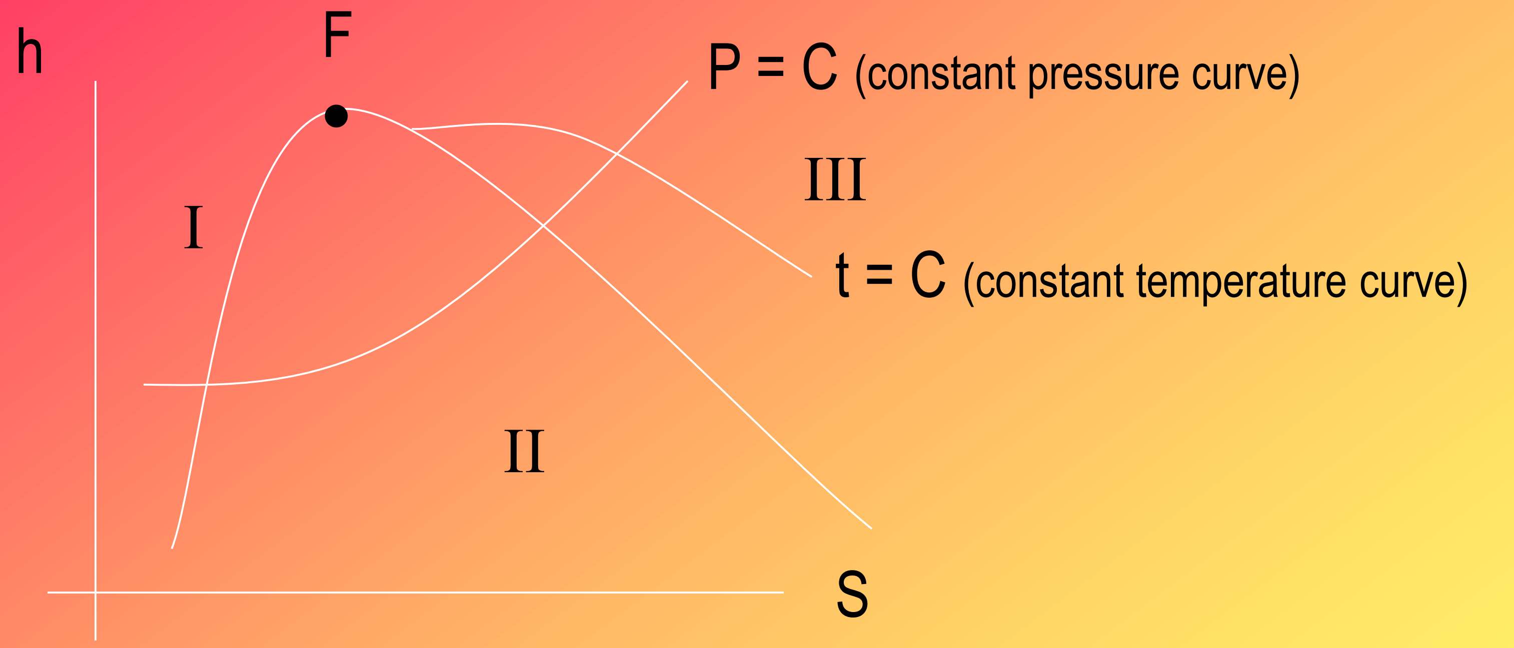
F(critical point)- at the critical point the temperature and pressure is unique.
For Steam: At Critical Point, P = 22.09 MPa; t = 374.136°C

T-S Diagram



t_{sat} - saturation temperature corresponding the pressure P
t_a - sub-cooled temperature which is less than tsat
t_e - superheated vapor temperature that is greater than tsat

h-S (Enthalpy-Entropy Diagram)



I - subcooled or compressed liquid region
II - saturated mixture region
III - superheated vapor region

Quality (x):

$$x = \frac{m_v}{m_v + m_L} = \frac{m_v}{m}$$

$$m = m_v + m_L$$

Where:

m_v – mass of vapor
m_L – mass of liquid
m – total mass
x- quality

The properties at saturated liquid, saturated vapor, superheated vapor and sub-cooled or compressed liquid can be determined from tables. But for the properties at saturated mixture (liquid and vapor) they can be determined by the equation

$$r_c = r_f + x(r_{fg})$$

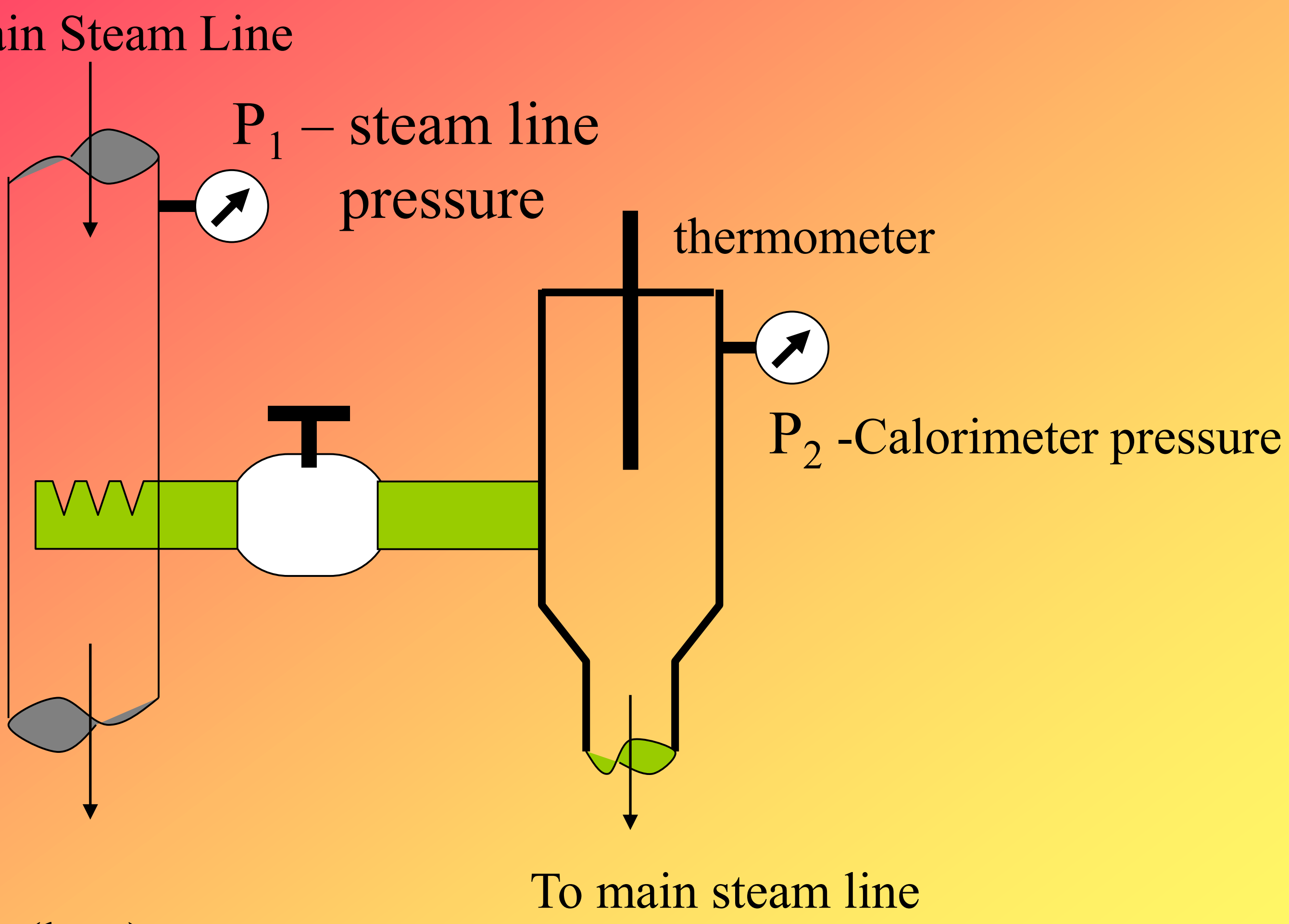
$$r_{fg} = r_g - r_f$$

Where: r stands for any property (υ, U, h and S)

r_g – property at saturated vapor (from table)
r_f – property at saturated liquid

Note: The properties at siub-cooled or compressed liquid is approximately equal to the properties at saturated liquid corresponding the sub-cooled temperature.

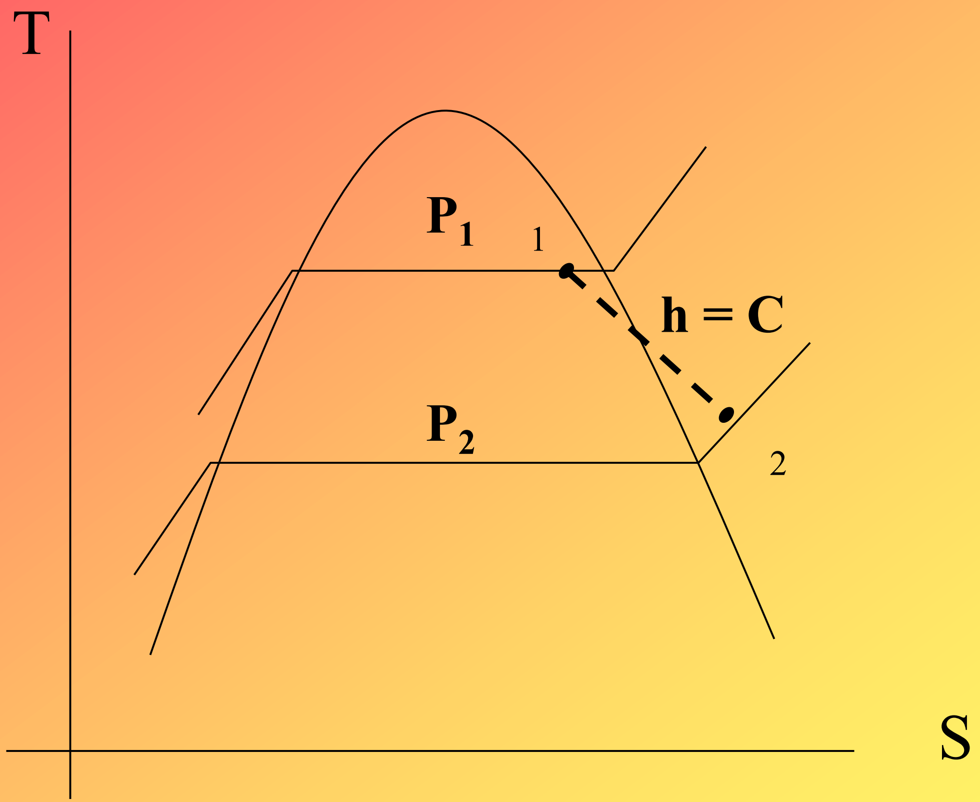
Throttling Calorimeter



$h_1 = h_2$
$h_1 = h_{f1} + x_1(h_{fg1})$
Where:

1 – main steam line
2 - calorimeter

T-S Diagram Throttling Process



P_1 – steam line pressure

P_2 – calorimeter pressure

Zeroth Law of Thermodynamics:

If two bodies are in thermal equilibrium with a third body, they are in thermal equilibrium with each other and hence their temperatures are equal.

Specific Heat:

It is the amount of heat required to raise the temperature of a 1 kg mass 1°C or 1°K.

$$C = \frac{dQ}{dt} = \frac{dQ}{dT}$$

$$dQ = CdT = CdT$$

by integration

$$Q = C(t_2 - t_1) = C\,(T_2 - T_1)\ \frac{KJ}{kg}$$

Considering the mass m,

$$Q = mC(t_2 - t_1) = mC\,(T_2 - T_1)\ \ KJ$$

Sensible Heat: It is the amount of heat that must be transferred (added or removed) when a substance undergoes a change in temperature without a change in phase.

$$Q = mC\Delta T = mC\,\Delta t$$

Heat of Transformation: It is the amount of heat that must be transferred when a substance completely undergoes a phase change without a change in temperature.

a. **Heat of Vaporization:** It is the amount of heat added to vaporize a liquid or amount of heat removed to condense a vapor or gas.

$$Q = mL$$

where: L – latent heat of vaporization, KJ/kg
m – mass, kg, kg/sec

b. **Heat of Fusion:** It is the amount of heat added to melt a solid or the amount of heat removed to freeze a liquid.

$$Q = mL$$

where: L – latent heat of fusion, KJ/kg

THE FIRST LAW OF THERMODYNAMICS (The Law of Conservation of (Energy)

"Energy can neither be created nor destroyed but can only be converted from one form to another."

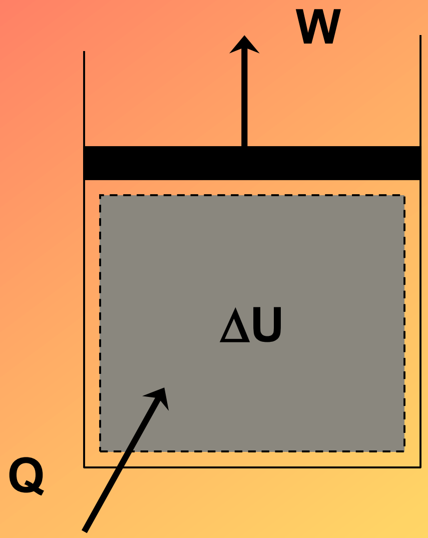
Verbal Form:

Energy Entering – Energy Leaving = Change of Energy stored in the system

Equation Form:

$$E_1 - E_2 = \Delta Es$$

1. First Corollary of the First Law: Application of first Law to a Closed System



For a Closed System (Non FlowSystem), PV, KE and PE are negligible, therefore the changeof stored energy **$\Delta Es = \Delta U$**

$$Q - W = \Delta U \rightarrow 1$$
$$Q = \Delta U + W \rightarrow 2$$

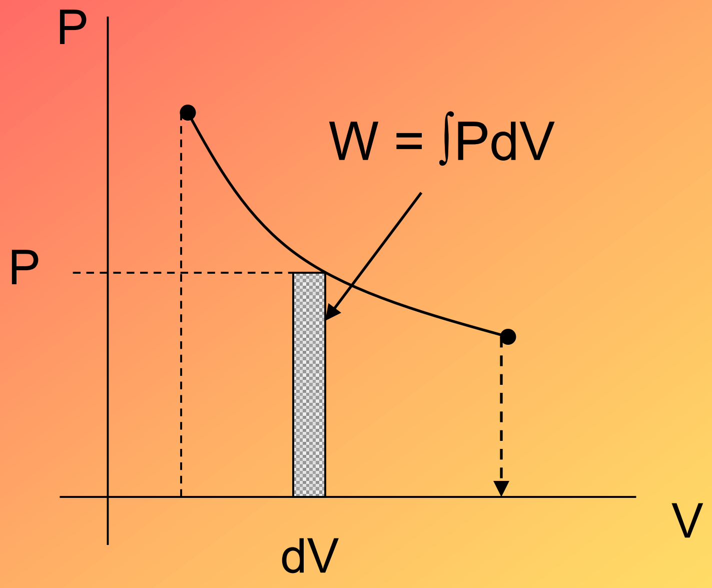
By differentiation:

$$\mathbf{dQ = dU + dW} \rightarrow 3$$

where:

$$\int \mathbf{dQ \neq Q_2 - Q_1}$$
$$\int \mathbf{dW \neq W_2 - W_1}$$

Work of a Closed System (NonFlow)



$W = \int Fdx$

$F = PA$

$W = \int PAdx$

$Adx = dV$

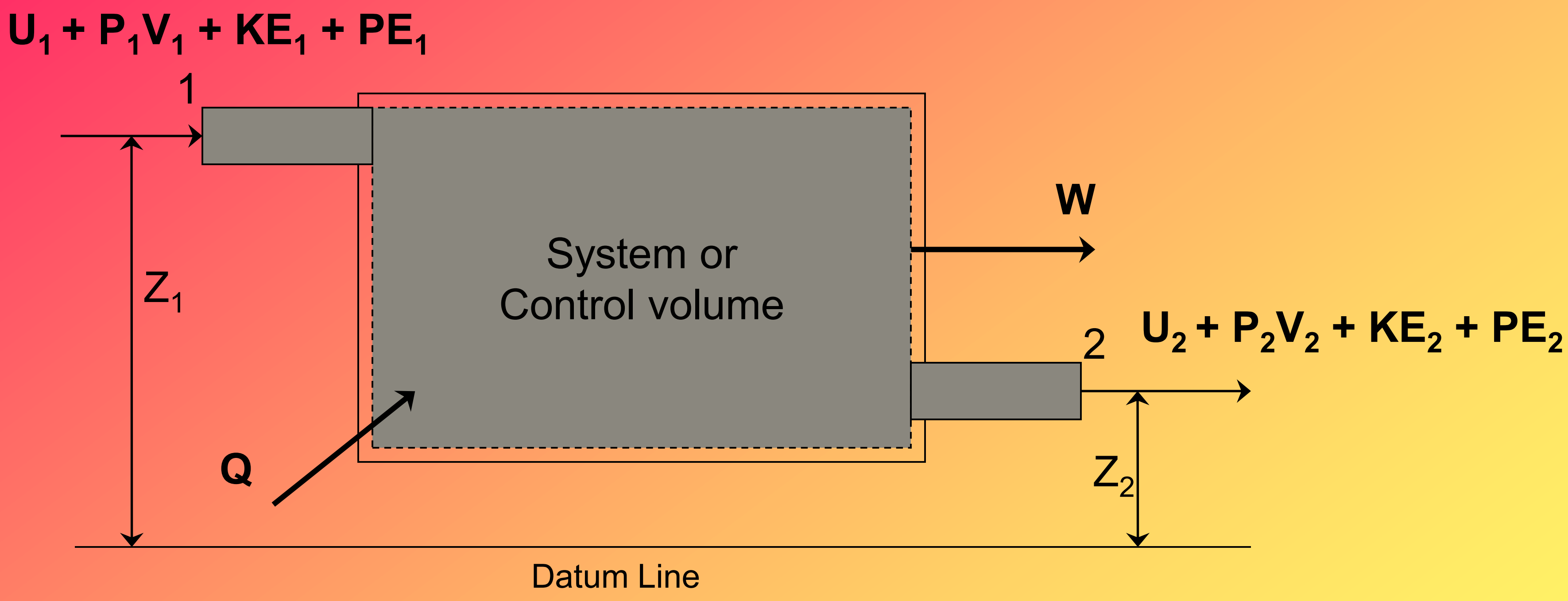
$W = \int PdV$

$dW = PdV$

From Eq. 3

$$\mathbf{dQ = dU + dW}$$
$$\mathbf{dQ = dU + PdV} \rightarrow 4$$

2. Second Corollary of the First Law: Application of First Law to an Open System



For an Open system (Steady state, Steady Flow system)
$\Delta Es = 0$, therefore
$E_1 – E_2 = 0$ or
$E_1 = E_2$ or
Energy Entering = Energy Leaving

$U_1 + P_1V_1 + KE_1 + PE_1 + Q = U_2 + P_2V_2 + KE_2 + PE_2 + W \rightarrow 1$

$Q = (U_2 - U_1) + (P_2V_2 - P_1V_1) + (KE_2 - KE_1) + (PE_2 - PE_1) + W \rightarrow 2$

$Q = \Delta U + \Delta(PV) + \Delta KE + \Delta PE + W \rightarrow 3$

By differentiation

$dQ = dU + d(PV) + dKE + dPE + dW \rightarrow 4$

But $\int dQ \neq Q_2 - Q_1$ and $\int dW \neq W_2 - W_1$

Enthalpy (h)

$h = U + PV$

$dh = dU + d(PV) \rightarrow 5$

$dh = dU + PdV + VdP \rightarrow 6$

But: $dQ = dU + PdV$

$dh = dQ + VdP \rightarrow 7$

From Eq. 3

$Q = \Delta h + \Delta KE + \Delta PE + W \rightarrow 8$

$dQ = dh + dKE + dPE + dW \rightarrow 9$

$dQ = dU + PdV + VdP + dKE + dPE + dW \rightarrow 10$

$dQ = dQ + VdP + dKE + dPE + dW$

$0 = VdP + dKE + dPE + dW$

$dW = -VdP - dKE - dPE \rightarrow 11$

By Integration

$W = -\int VdP - \Delta KE - \Delta PE \rightarrow 12$

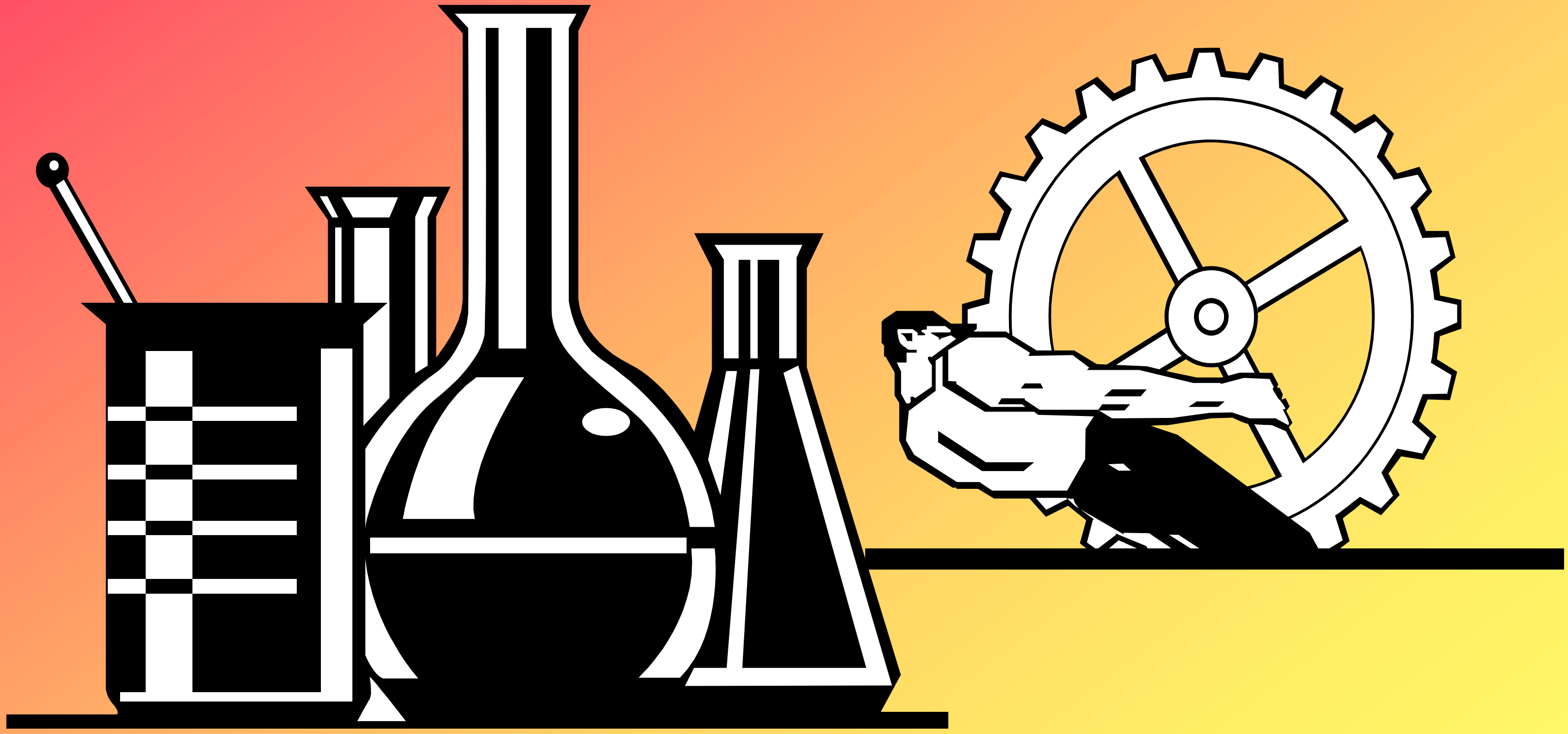
If $\Delta KE = 0$ and $\Delta PE = 0$

$Q = \Delta h + W \rightarrow 13$

$W = Q - \Delta h \rightarrow 14$

$W = -\int V dP \rightarrow 15$

IDEAL OR PERFECT GAS



Prepared By:Rashwinder singh

IDEAL OR PERFECT GAS

1. Ideal Gas Equation of State

$$PV = mRT$$

$$P\upsilon = RT$$

$$\rho = \frac{P}{RT}$$

$$\frac{PV}{T} = C$$

$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}$$

Where: P - absolute pressure in KPa
V - volume in m^3
m - mass in kg
R - Gas Constant in KJ/kg-°K
T - absolute temperature in°K

2. Gas Constant

$$R = \frac{\bar{R}}{M} \quad \frac{KJ}{kg - {}^{\circ}K}$$

$$\bar{R} = 8.3143 \quad \frac{KJ}{kg_m - {}^{\circ}K}$$

Where:

R- Gas Constant in KJ/kg-K

$\bar{R}$ – universal gas constant $\frac{KJ}{kg_m - {}^{\circ}K}$

M – Molecular weight kg/kg_m

3. Boyle's Law

If the temperature of a certain quantity of gas is held constant the volume V is inversely proportional to the absolute pressure P.

$$V \alpha P$$

$$V = C \frac{1}{P}$$

$$PV = C$$

$$P_1 V_1 = P_2 V_2 = C$$

4.Charle's Law

A. At Constant Pressure (P = C)

If the pressure of a certain quantity of gas is held constant, the volume V is directly proportional to the temperature T during a quasistatic change of state

$$\mathbf{V \propto T ; V = C\,T ; \frac{V}{T} = C}$$

$$\mathbf{\frac{V_1}{T_1} = \frac{V_2}{T_2}}$$

B. At Constant Volume (V = C)

If the volume of a certain quantity of gas is held constant, the pressure P varies directly as the absolute temperature T.

$$\mathbf{P \propto T ; P = C\ \ T ; \frac{P}{T} = C}$$

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

5. Avogadro's Law

All gases at the same temperature and pressure have the same number of molecules per unit of volume, and it follows that the specific weight γ is directly proportional to its molecular weight M.

$$\gamma \propto M$$

6. Specific Heat

Specific Heat or Heat Capacity is the amount of heat required to raise the temperature of a 1 kg mass 1°C or 1°K

A. SPECIFIC HEAT AT CONSTANT PRESSURE (Cp)

From: $dh = dU + PdV + VdP$

but $dU + VdP = dQ$; therefore

$dh = dQ + VdP \rightarrow 1$

but at P = C ; dP = 0; therefore

$$\mathbf{dh = dQ} \rightarrow 2$$

and by integration

$$\mathbf{Q = \Delta h} \rightarrow 3$$

considering m,

$$\mathbf{\Delta h = m(h_2 - h_1)} \rightarrow 4$$

$$\mathbf{Q = \Delta h = m\ (h_2 - h_1)} \rightarrow 5$$

From the definition of specific heat, C = dQ/T

$$\mathbf{Cp = dQ\ /dt} \rightarrow 6$$

Cp = dh/dT, then

$$\mathbf{dQ = CpdT} \rightarrow 7$$

and by considering m,

$$\mathbf{dQ = mCpdT} \rightarrow 8$$

then by integration

$$\mathbf{Q = m\ Cp\ \Delta T} \rightarrow 9$$

but $\Delta T = (T_2 - T_1)$

$$\mathbf{Q = m\ Cp\ (T_2 - T_1)} \rightarrow 10$$

B SPECIFIC HEAT AT CONSTANT VOLUME (Cv)

At $V = C$, $dV = O$, and from $dQ = dU + PdV$

$dV = 0$, therefore

$$\mathbf{dQ = dU} \rightarrow 11$$

then by integration

$$\mathbf{Q = \Delta U} \rightarrow 12$$

then the specific heat at constant volume Cv is;

$$\mathbf{Cv = dQ/dT = dU/dT} \rightarrow 13$$

$$\mathbf{dQ = CvdT} \rightarrow 14$$

and by considering m,

$$\mathbf{dQ = mCvdT} \rightarrow 15$$

and by integration

$$\mathbf{Q = m\Delta U} \rightarrow 16$$

$$\mathbf{Q = mCv\Delta T} \rightarrow 17$$

$$\mathbf{Q = m(U_2 - U_1)} \rightarrow 18$$

$$\mathbf{Q = m\ Cv(T_2 - T_1)} \rightarrow 19$$

From:

$h = U + P\upsilon$ and $P\upsilon = RT$

$$\mathbf{h = U + RT} \rightarrow 20$$

and by differentiation,

$$\mathbf{dh = dU + Rdt} \rightarrow 21$$

but $dh = CpdT$ and $dU = CvdT$, therefore

$$\mathbf{CpdT = CvdT + RdT} \rightarrow 22$$

and by dividing both sides of the equation by dT,

$$\mathbf{Cp = Cv + R} \rightarrow 23$$

7. Ratio Of Specific Heats

$k = Cp/Cv \rightarrow 24$

$k = dh/du \rightarrow 25$

$k = \Delta h/\Delta U \rightarrow 26$

From eq. 32,

$Cp = kCv \rightarrow 27$

substituting eq. 27 to eq. 24

$Cv = R/k-1 \rightarrow 28$

From eq. 24,

$Cv = Cp/k \rightarrow 29$

substituting eq. 29 to eq. 24

$Cp = Rk/k-1 \rightarrow 30$

8. Entropy Change (ΔS)

Entropy is that property of a substance that determines the amount of randomness and disorder of a substance. If during a process, an amount of heat is taken and is by divided by the absolute temperature at which it is taken, the result is called the ***ENTROPY CHANGE***.

$$dS = dQ/T \rightarrow 31$$

and by integration

$$\Delta S = \int dQ/T \rightarrow 32$$

and from eq. 39

$$dQ = TdS \rightarrow 33$$

GAS MIXTURE

- Total Mass of a mixture

$$m = \sum m_i$$

- Mass Fraction

$$x_i = \frac{m_i}{m}$$

- Total Moles of a mixture

$$n = \sum n_i$$

- Mole Fraction

$$y_i = \frac{n_i}{n}$$

Where:

m – total mass of a mixture
m_i – mass of a component
n – total moles of a mixture
n_i – moles of a component
x_i – mass fraction of a component
y_i - mole fraction of a component

☠ Equation of State

Mass Basis

A. For the mixture

$$PV = mRT$$

B. For the components

$$P_iV_i = m_iR_iT_i$$

Mole Basis

A. For the mixture

$$PV = n\bar{R}T$$

B. For the components

$$P_iV_i = n_i\bar{R}_iT_i$$

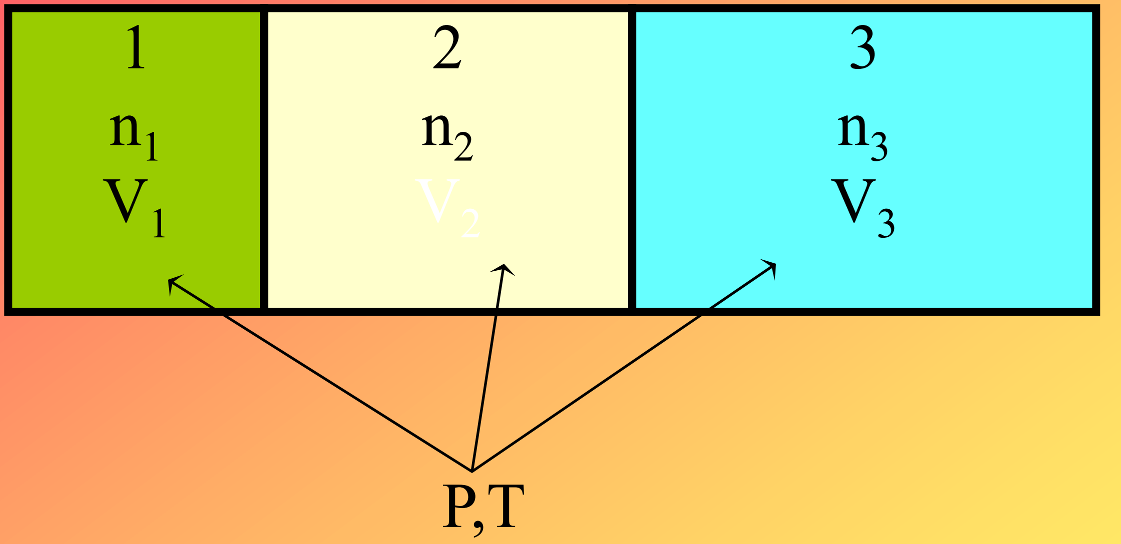
Where:

R – Gas constant of a mixture in KJ/kg-°K

$\bar{R}$ - universal gas constant in KJ/kg_m- °K

☠ AMAGAT'S LAW

The total volume of a mixture V is equal to the volume occupied by each component at the mixture pressure P and temperature T.



1 n_1 V_1

2 n_2 V_2

3 n_3 V_3

P,T

$$P = P_1 = P_2 = P_3$$

$$T = T_1 = T_2 = T_3$$

For the components:

$$n_1 = \frac{PV_1}{\bar{R}T} \; ; \; n_2 = \frac{PV_2}{\bar{R}T} \; ; \; n_3 = \frac{PV_3}{\bar{R}T}$$

The total moles n:

$$n = n_1 + n_2 + n_3$$

$$\frac{PV}{\bar{R}T} = \frac{PV_1}{\bar{R}T} + \frac{PV_2}{\bar{R}T} + \frac{PV_3}{\bar{R}T}$$

$$\left[\frac{PV}{\bar{R}T} = \frac{PV_1}{\bar{R}T} + \frac{PV_2}{\bar{R}T} + \frac{PV_3}{\bar{R}T}\right]\left(\frac{\bar{R}T}{P}\right)$$

$$V = V_1 + V_2 + V_3$$

The mole fraction

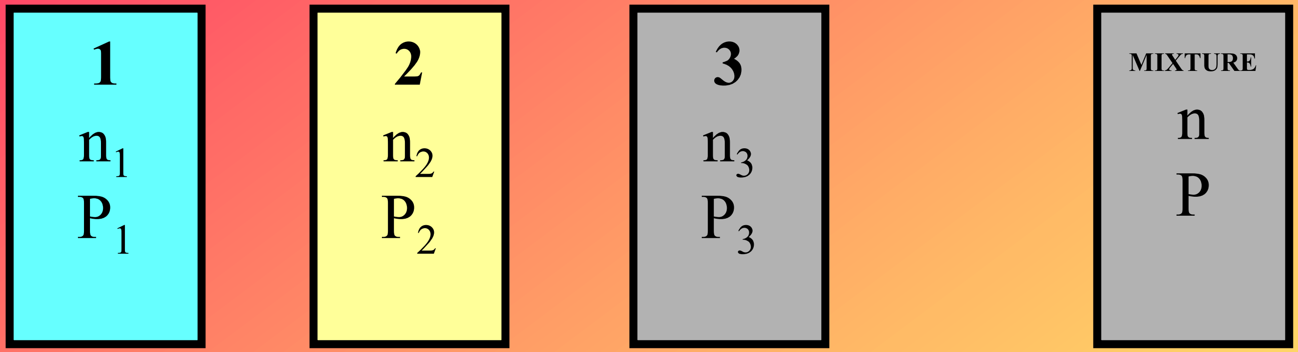
$$y_i = \frac{n_i}{n}$$

$$y_i = \frac{\frac{PV_i}{\bar{R}T}}{\frac{PV}{\bar{R}T}}$$

$$yi = \frac{V_i}{V}$$

☠ DALTON’S LAW

The total pressure of a mixture P is equal to the sum of the partial pressure that each gas would exert at mixture volume V and temperature T.



$$T_1 = T_2 = T_3 = T$$

$$V_1 = V_2 = V_3 = V$$

For the mixture

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

For the components

$$n_1 = \frac{P_1 V}{RT}$$

$$n_2 = \frac{P_2 V}{RT}$$

$$n_3 = \frac{P_3 V}{RT}$$

The total moles n:

$$n = n_1 + n_2 + n_3$$

$$\frac{PV}{\bar{R}T} = \frac{P_1V}{\bar{R}T} + \frac{P_2V}{\bar{R}T} + \frac{P_3V}{\bar{R}T}$$

$$\left[\frac{PV}{\bar{R}T} = \frac{P_1V}{\bar{R}T} + \frac{P_2V}{\bar{R}T} + \frac{P_3V}{\bar{R}T}\right]\left(\frac{\bar{R}T}{V}\right)$$

$$P = P_1 + P_2 + P_3$$

The mole fraction:

$$y_i = \frac{n_i}{n}$$

$$y_i = \frac{\frac{P_iV}{\bar{R}T}}{\frac{PV}{\bar{R}T}}$$

$$yi = \frac{P_i}{P}$$

- Molecular Weight of a mixture

$$M = \Sigma y_i M_i$$

$$M = \frac{\bar{R}}{R}$$

- Gas Constant of a mixture

$$R = \Sigma x_i R_i$$

$$R = \frac{\bar{R}}{M}$$

- Specific Heat of a mixture

$$C_p = \Sigma x_i C_{pi}$$

$$C_v = \Sigma x_i C_{vi}$$

$$C_p = C_v + R$$

- Ratio of Specific Heat

$$k = \frac{C_p}{C_v} = \frac{\Delta h}{\Delta u}$$

☠ Gravimetric and Volumetric Analysis

Gravimetric analysis gives the mass fractions of the components in the mixture. Volumetric analysis gives the volumetric or molal fractions of the components in the mixture.

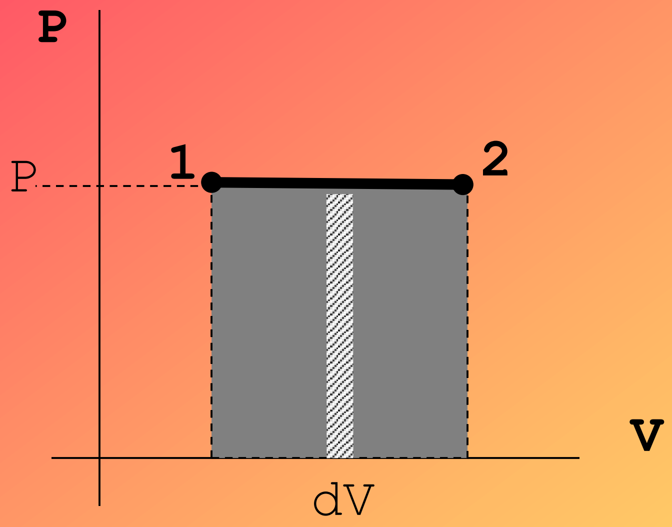
$$x_i = \frac{y_i M_i}{\Sigma y_i M_i}$$

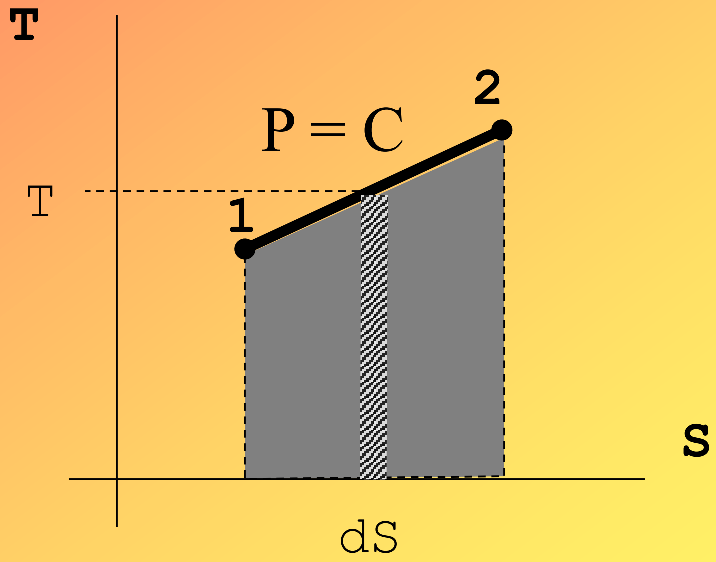
$$y_i = \frac{\dfrac{x_i}{M_i}}{\Sigma \dfrac{x_i}{M_i}}$$

PROCESSES OF FLUIDS

1. Isobaric Process (P = C): An Isobaric Process is an internally reversible constant pressure process.

A. Closed System: (Nonflow)





$Q = \Delta U + W$ → 1 any substance

$W = \int P dV$ → 2 any substance

$\Delta U = m(U_2 - U_1)$ → 3 any substance

$W = P(V_2 - V_1)$ → 4 any substance

$Q = \Delta h = m(h_2 - h_1)$ → 5 any substance

For Ideal Gas:

$PV = mRT$

$W = mR(T_2 - T_1) \rightarrow 5$

$\Delta U = mC_v(T_2 - T_1) \rightarrow 6$

$Q = \Delta h = mC_P\,(T_2 - T_1) \rightarrow 7$

Entropy Change

$\Delta S = \int dQ/T \rightarrow 8$ any substance

$dQ = dh$

For Ideal Gas

$dh = mC_P dT$

$\Delta S = \int dQ/T$

$\Delta S = mC_P \int dT/T$

$\Delta S = mC_P \ln(T_2/T_1) \rightarrow 9$

B. Open System:

$Q = \Delta h + \Delta KE + \Delta PE + W \rightarrow 10$ any substance

$W = -\int VdP - \Delta KE - \Delta PE \rightarrow 11$ any substance

$-\int VdP = 0$

$Q = \Delta h$ → 12

$W = -\Delta KE - \Delta PE$ → 13

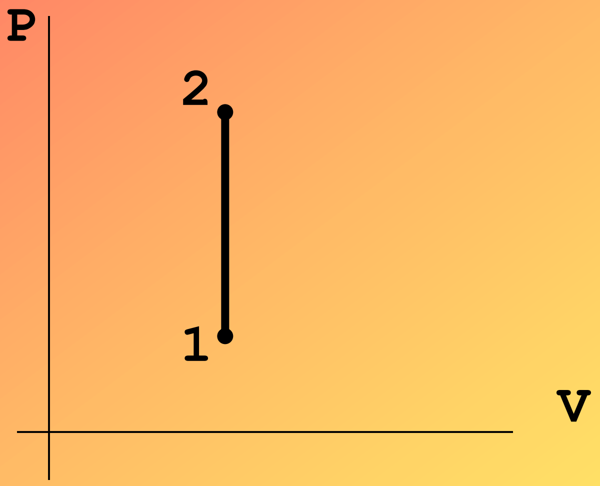
If $\Delta KE = 0$ and $\Delta PE = 0$

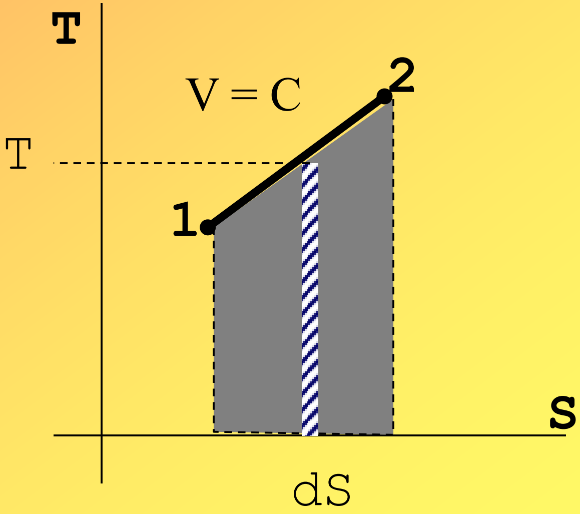
$W = 0$ → 14

$Q = mC_P(T_2 - T_1)$ → 15 Ideal Gas

2. Isometric Process (V = C): An Isometric process is internally reversible constant volume process.

A. Closed System: (Nonflow)





$Q = \Delta U + W \rightarrow 1$ any substance

$W = \int PdV$ at $V = C$; $dV = 0$

$W = 0$

$Q = \Delta U = m(U_2 - U_1) \rightarrow 2$ any substance

$\Delta h = m(h_2 - h_1) \rightarrow 3$ any substance

For Ideal Gas:

$Q = \Delta U = mC_v(T_2 - T_1) \rightarrow 4$

$\Delta h = mC_P(T_2 - T_1) \rightarrow 5$

Entropy Change:

$\Delta S = \int dQ/T \rightarrow 6$ any substance

$dQ = dU$

$dU = mC_v dT$ for ideal gas

$\Delta S = \int dU/T = mC_v \int dT/T$

$\Delta S = mC_v \ln(T_2/T_1) \rightarrow 6$

B. Open System:

$Q = \Delta h + \Delta KE + \Delta PE + W \rightarrow$ 7 any substance

$W = -\int VdP - \Delta KE - \Delta PE \rightarrow$ 8 any substance

$-\int VdP = -V(P_2 - P_1) \rightarrow$ 9 any substance

$Q = \Delta U = m(U_2 - U_1) \rightarrow$ 10 any substance

$\Delta h = m(h_2 - h_1) \rightarrow$ 11 any substance

For Ideal Gas:

$-\int VdP = -V(P_2 - P_1) = mR(T_1 - T_2)$

$Q = \Delta U = mC_v(T_2 - T_1) \rightarrow 12$

$\Delta h = mC_P(T_2 - T_1) \rightarrow 13$

If $\Delta KE = 0$ and $\Delta PE = 0$

$Q = \Delta h + W \rightarrow$ 14 any substance

$W = -\int VdP \rightarrow 15$

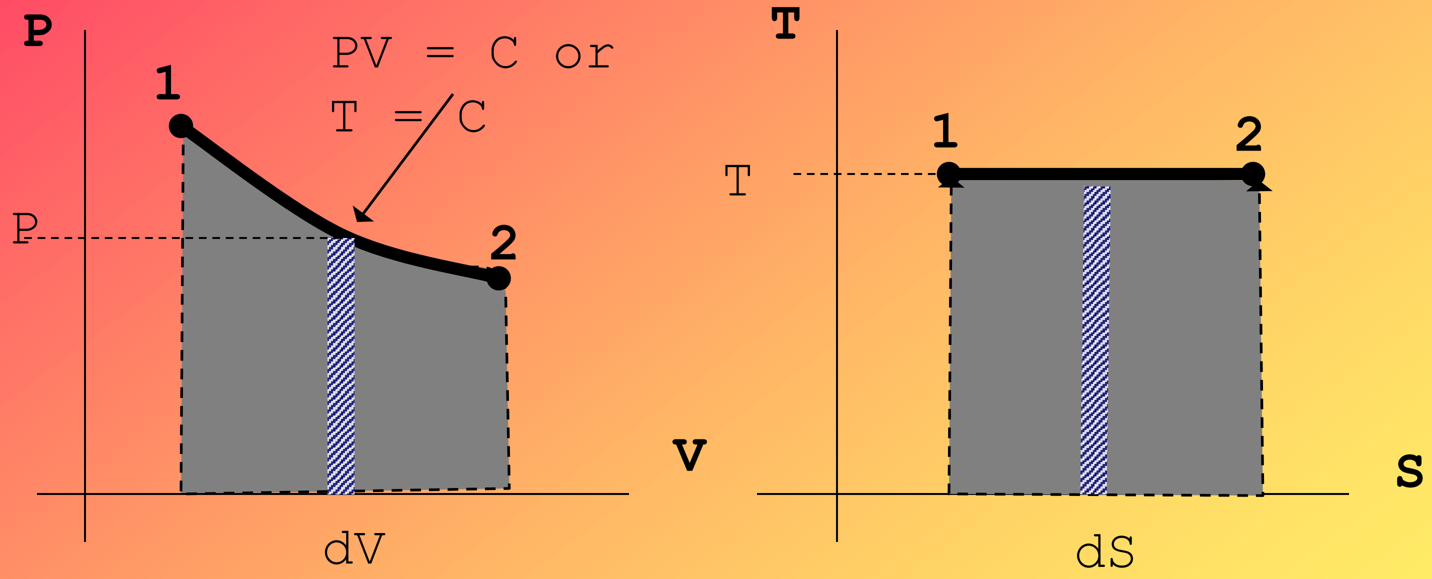
$W = -\int VdP = -V(P_2 - P_1) \rightarrow$ 16 any substance

$W = mR(T_1 - T_2) \rightarrow$ 16 ideal gas

$\Delta h = mC_P(T_2 - T_1) \rightarrow$ 17 ideal gas

3. Isothermal Process(T = C): An Isothermal process is reversible constant temperature process.

A. Closed System (Nonflow)



$Q = \Delta U + W \rightarrow 1$ any substance

$W = \int PdV \rightarrow 2$ any substance

$\Delta U = m(U_2 - U_1) \rightarrow 3$ any substance

For Ideal Gas:

$dU = mC_v\ dT$; at $T = C$; $dT = 0$

$Q = W \rightarrow 4$

$W = \int P dV$; at $PV = C$;

$P_1V_1 = P_2V_2 = C$; $P = C/V$

Substituting $P = C/V$ to $W = \int P dV$

$W = P_1V_1 \ln(V_2/V_1) \rightarrow 5$

Where $(V_2/V_1) = P_1/P_2$

$W = P_1V_1 \ln(P_1/P_2) \rightarrow 6$

$P_1V_1 = mRT_1$

Entropy Change:

$dS = dQ/T \rightarrow 7$

$\Delta S = \int dQ/T$

$dQ = TdS$;at $T = C$

$Q = T(S_2-S_1)$

$(S_2-S_1) = \Delta S = Q/T \rightarrow 8$

$\Delta S = Q/T = W/T \rightarrow 9$ For Ideal Gas

B. Open System (Steady Flow)

$Q = \Delta h + \Delta KE + \Delta PE + W$ → 10 any substance

$W = -\int VdP - \Delta KE - \Delta PE$ → 11 any substance

$-\int VdP = -V(P_2 - P_1)$ → 12 any substance

$\Delta h = m(h_2 - h_1)$ → 13 any substance

For Ideal Gas:

$-\int VdP = -P_1V_1\ln(P_2/P_1)$ → 14

$-\int VdP = P_1V_1\ln(P_1/P_2)$ → 15

$P_1/P_2 = V_2/V_1$ → 16

$dh = C_PdT$; at $T = C$; $dT = 0$

$\Delta h = 0$ → 16

If $\Delta KE = 0$ and $\Delta PE = 0$

$Q = \Delta h + W$ → 17 any substance

$W = -\int VdP = P_1V_1\ln(P_1/P_2)$ → 18

For Ideal Gas

$\Delta h = 0$ → 19

$Q = W = -\int VdP = P_1V_1\ln(P_1/P_2)$ → 20

4. Isentropic Process (S = C): An Isentropic Process is an internally "Reversible Adiabatic" process in which the entropy remains constant where S = C and $PV^k = C$ for an ideal or perfect gas.

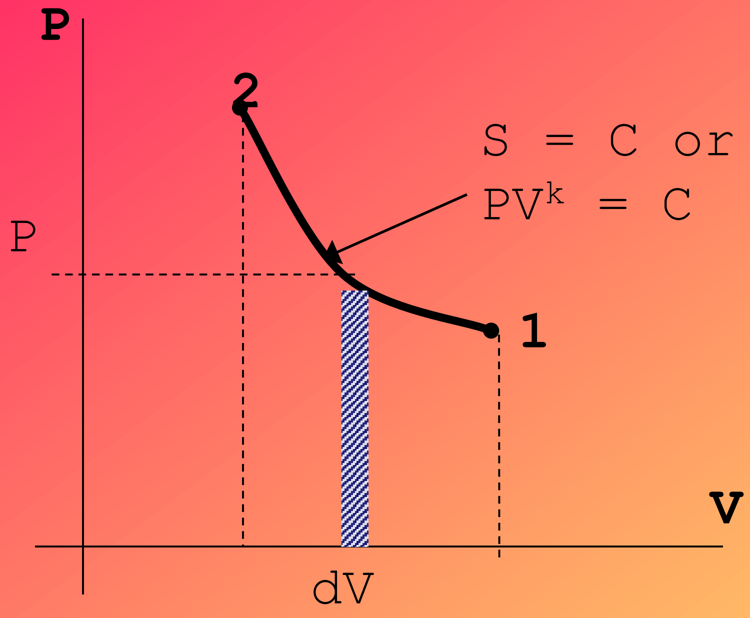
For Ideal Gas

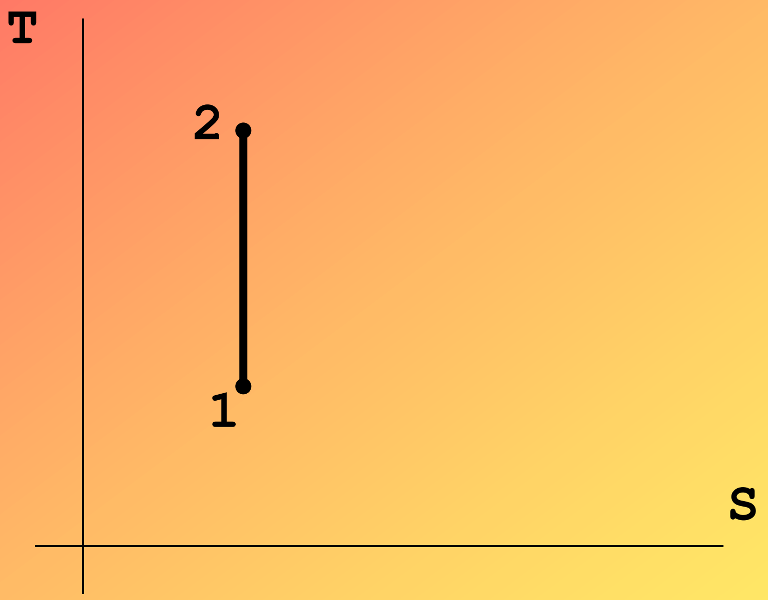
$$\text{Using } \frac{PV}{T} = C \text{ and } PV^k = C$$

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2} \quad \text{and } P_1 V_1^{\,k} = P_2 V_2^{\,k}$$

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}} = \left(\frac{V_1}{V_2}\right)^{k-1}$$

A. Closed System (Nonflow)





$Q = \Delta U + W \rightarrow$ 1 any substance

$W = \int PdV \rightarrow$ 2 any substance

$\Delta U = m(U_2 - U_1) \rightarrow$ 3 any substance

$Q = 0 \rightarrow 4$

$W = -\Delta U = \Delta U = -m(U_2 - U_1) \rightarrow 5$

For Ideal Gas

$\Delta U = mC_V(T_2 - T_1) \rightarrow 6$

From $PV^k = C$, $P = C/V^k$, and substituting $P = C/V^k$

to $W = \int PdV$, then by integration,

$$W = \int PdV = \frac{P_2V_2 - P_1V_1}{1 - k} \rightarrow 7$$

$$\int PdV = \frac{mR(T_2 - T_1)}{1 - k} = \frac{mRT_1}{1 - k}\left[\left(\frac{P_2}{P_1}\right)^{k-1/k} - 1\right] \rightarrow 8$$

$$\int PdV = \frac{P_1V_1}{1 - k}\left[\left(\frac{P_2}{P_1}\right)^{k-1/k} - 1\right] \rightarrow 9$$

$Q = 0$

Entropy Change

$\Delta S = 0$

$S_1 = S_2$

B. Open System (Steady Flow)

$Q = \Delta h + \Delta KE + \Delta PE + W$ → 10 any substance

$W = -\int VdP - \Delta KE - \Delta PE$ → 11 any substance

$\Delta h = m(h_2 - h_1)$ → 12 any substance

$Q = 0$

$W = -\Delta h - \Delta KE - \Delta PE$ → 13

From $PV^k = C$, $V = [C/P]^{1/k}$, substituting V to $-\int VdP$, then by integration,

$$-\int VdP = k\int PdV$$

$$-\int VdP = \frac{k\left(P_2V_2 - P_1V_1\right)}{1-k} \rightarrow 14$$

$$-\int VdP = \frac{kmR\left(T_2 - T_1\right)}{1-k} = \frac{kmRT_1}{1-k}\left[\left(\frac{P_2}{P_1}\right)^{k-1/k} - 1\right] \rightarrow 15$$

$$-\int VdP = \frac{kP_1V_1}{1-k}\left[\left(\frac{P_2}{P_1}\right)^{k-1/k} - 1\right] \rightarrow 16$$

If $\Delta KE = 0$ and $\Delta PE = 0$

$0 = \Delta h + W \rightarrow 17$ any substance

$W = -\int VdP = -\Delta h \rightarrow 18$ any substance

$\Delta h = m(h_2 - h_1) \rightarrow 19$ any substance

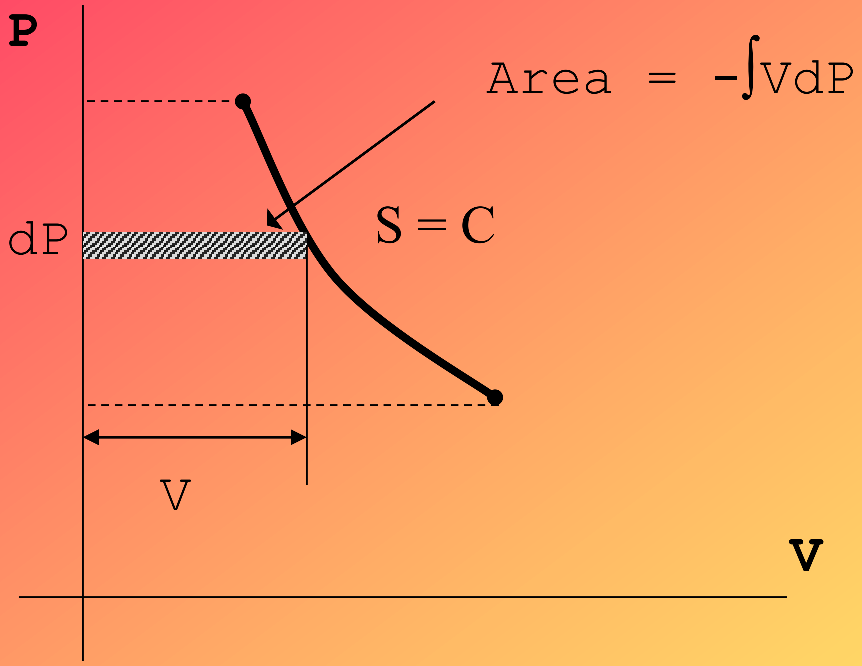
$Q = 0$

$$W = -\int VdP = k\int PdV = \frac{k\left(P_2V_2 - P_1V_1\right)}{1 - k} \rightarrow 20$$

$$W = \frac{kmR\left(T_2 - T_1\right)}{1 - k} = \frac{kmRT_1}{1 - k}\left[\left(\frac{P_2}{P_1}\right)^{k-1 \big/ k} - 1\right] \rightarrow 21$$

$$W = \frac{kP_1V_1}{1 - k}\left[\left(\frac{P_2}{P_1}\right)^{k-1 \big/ k} - 1\right] \rightarrow 22$$

$$W = -\Delta h = -mC_P\left(T_2 - T_1\right) \rightarrow 23$$


P
Area = $-\int VdP$
dP
S = C
V
V

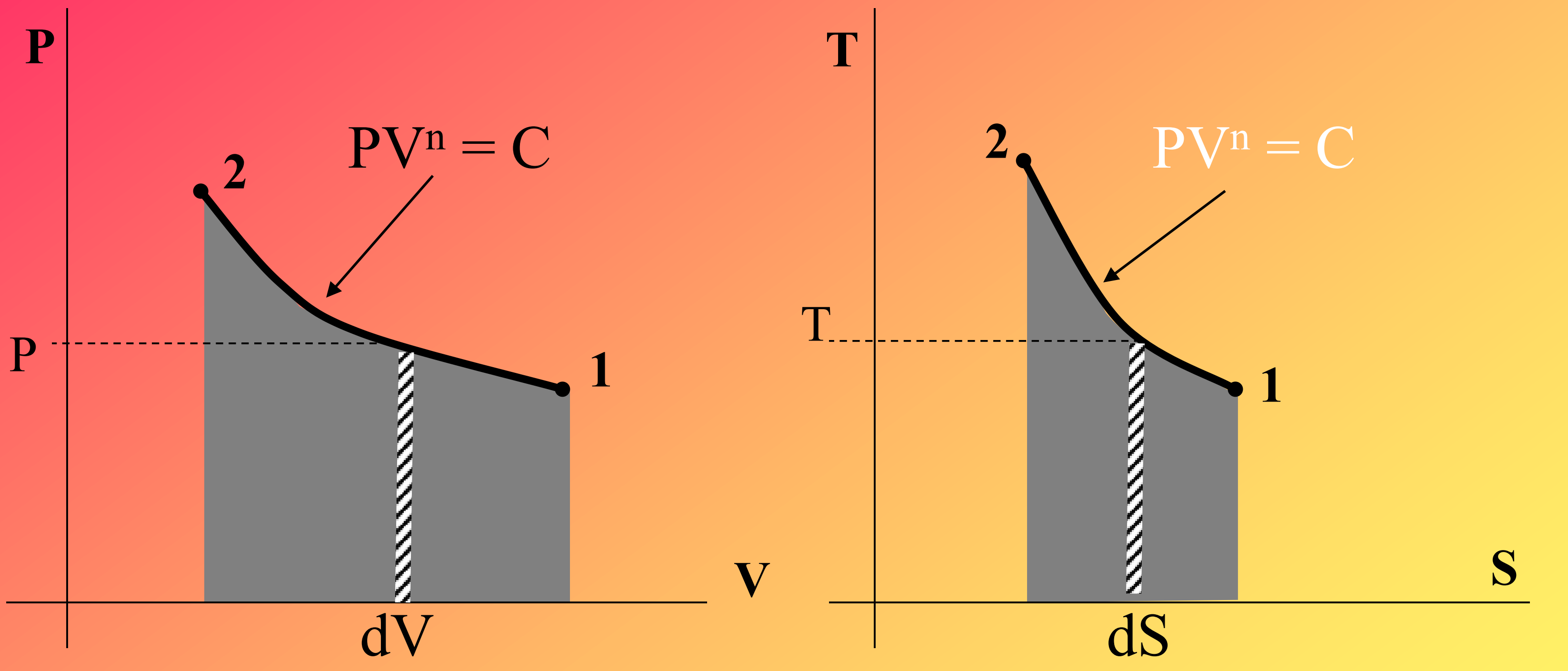
5. Polytropic Process (PVn = C): A Polytropic Process is an internally reversible process of an Ideal or Perfect Gas in which $PV^n = C$, where n stands for any constant.

$$\text{Using } \frac{PV}{T} = C \text{ and } PV^n = C$$

$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2} \quad \text{and } P_1V_1^{\,n} = P_2V_2^{\,n}$$

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} = \left(\frac{V_1}{V_2}\right)^{n-1}$$

A. Closed System: (Nonflow)



$Q = \Delta U + W \rightarrow 1$

$W = \int P dV \rightarrow 2$

$\Delta U = m(U_2 - U_1) \rightarrow 3$

$Q = mC_n(T_2 - T_1) \rightarrow 4$

$\Delta U = m(U_2 - U_1) \rightarrow 5$

From $PV^n = C$, $P = C/V^n$, and substituting $P = C/V^n$ to $W = \int PdV$, then by integration,

$$W = \int PdV = \frac{P_2V_2 - P_1V_1}{1 - n} \rightarrow 6$$

$$W = \int PdV = \frac{mR(T_2 - T_1)}{1 - n} = \frac{mRT_1}{1 - n}\left[\left(\frac{P_2}{P_1}\right)^{n-1/n} - 1\right] \rightarrow 8$$

$$W = \int PdV = \frac{P_1V_1}{1 - n}\left[\left(\frac{P_2}{P_1}\right)^{n-1/n} - 1\right] \rightarrow 9$$

Entropy Change

$dS = dQ/T$

$dQ = mC_n dT$

$\Delta S = mC_n \ln(T_2/T_1) \rightarrow 10$

B. Open System (Steady Flow)

$Q = \Delta h + \Delta KE + \Delta PE + W \rightarrow 11$

$W = -\int VdP - \Delta KE - \Delta PE \rightarrow 12$

$\Delta h = m(h_2 - h_1) \rightarrow 13$

$Q = mC_n(T_2 - T_1) \rightarrow 14$

$dQ = mC_n\, dT$

$W = Q - \Delta h - \Delta KE - \Delta PE \rightarrow 15$

From $PV^n = C$, $V = [C/P]^{1/n}$, substituting V to $-\int VdP$, then by integration,

$$-\int VdP = n\int PdV$$

$$-\int VdP = \frac{n\left(P_2V_2 - P_1V_1\right)}{1-n} \rightarrow 16$$

$$-\int VdP = \frac{nmR(T_2 - T_1)}{1 - n} = \frac{nmRT_1}{1 - n}\left[\left(\frac{P_2}{P_1}\right)^{n-1/n} - 1\right] \rightarrow 17$$

$$-\int VdP = \frac{nP_1V_1}{1 - n}\left[\left(\frac{P_2}{P_1}\right)^{n-1/n} - 1\right] \rightarrow 18$$

If $\Delta KE = 0$ and $\Delta PE = 0$

$Q = \Delta h + W \rightarrow 19$ any substance

$W = -\int VdP = Q - \Delta h \rightarrow 20$ any substance

$\Delta h = m(h_2 - h_1) \rightarrow 21$ any substance

$\Delta h = mC_p(T_2 - T_1)$

$Q = mC_n(T_2 - T_1) \rightarrow 22$

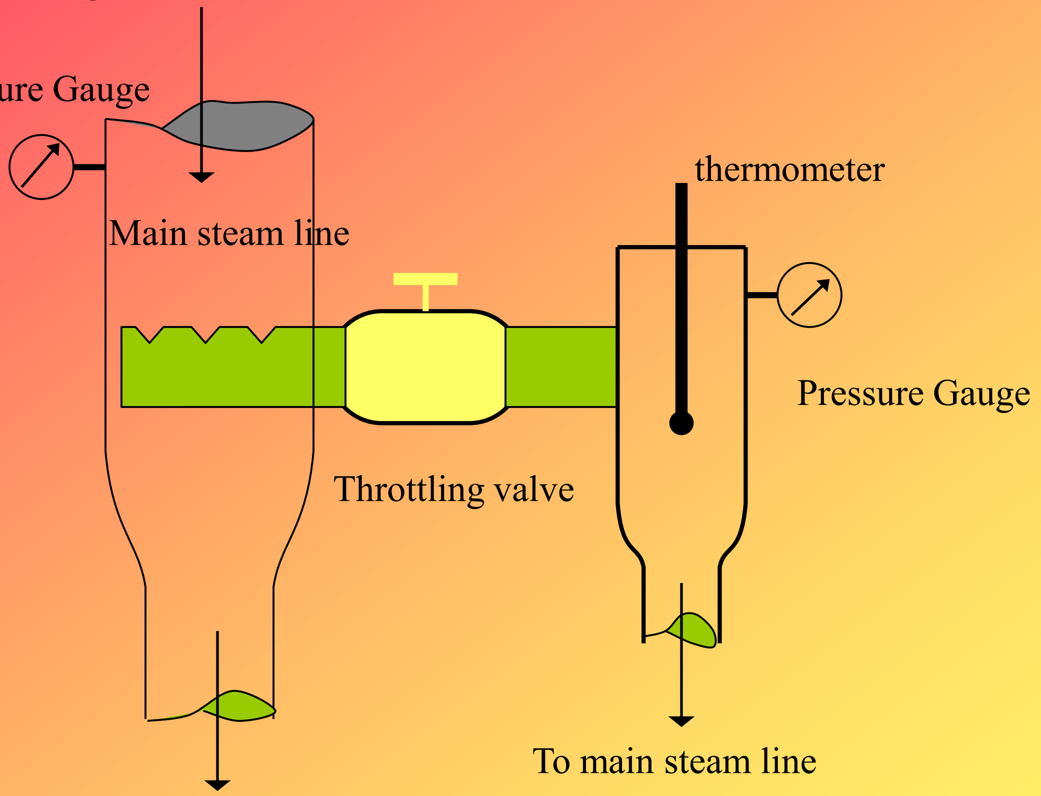
$$W = \frac{nmR\left(T_2 - T_1\right)}{1 - n} = \frac{nmRT_1}{1 - n}\left[\left(\frac{P_2}{P_1}\right)^{n-1/n} - 1\right] \rightarrow 23$$

$$W = \frac{nP_1V_1}{1 - n}\left[\left(\frac{P_2}{P_1}\right)^{n-1/n} - 1\right] \rightarrow 24$$

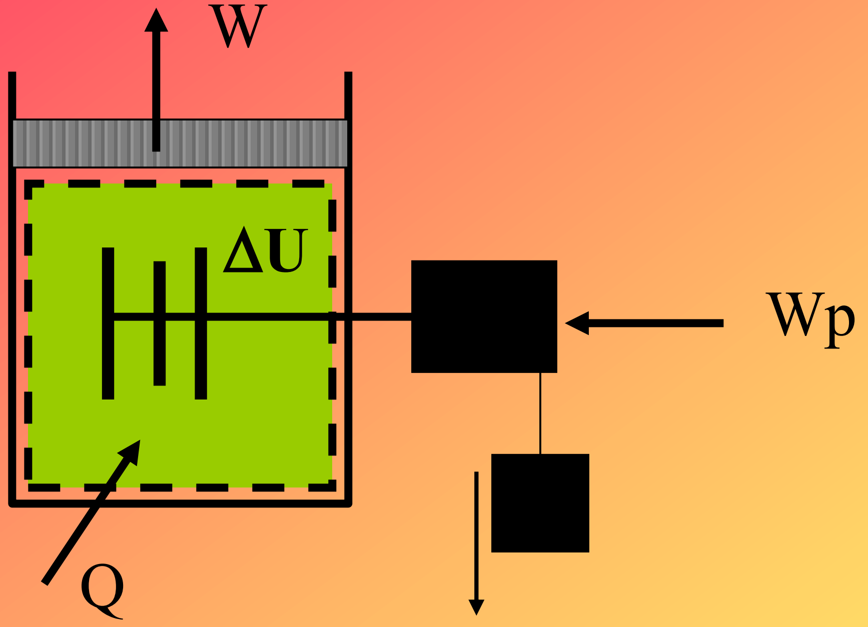
6. Isoenthalpic or Throttling Process: It is a steady - state, steady flow process in which Q = 0; ΔPE = 0; ΔKE = 0; W = 0 and the enthalpy remains constant.

$$\mathbf{h_1 = h_2 \quad or \quad h = C}$$

Throttling Calorimeter



Irrversible and Paddle Work



$Q = \Delta U + W - W_p$

where: Wp - irreversible or paddle work

Second Law of Thermodynamics:

Whenever energy is transferred, the level of energy cannot be conserved and some energy must be permanently reduced to a lower level.

When this is combined with the first law of thermodynamics,the law of energy conservation, the statement becomes:

Whenever energy is transferred, energy must be conserved,but the level of energy cannot be conserved and some energy must be permanently reduced to a lower level.

Kelvin-Planck statement of the second law:

No cyclic process is possible whose sole result is the flow of heat from a single heat reservoir and the performance of an equivalent amount of work.

For a system undergoing a cycle: The net heat is equal to the network.

$$\oint dQ = \oint dW$$

$$W = \sum Q$$

Where:

W - net work

ΣQ - net heat

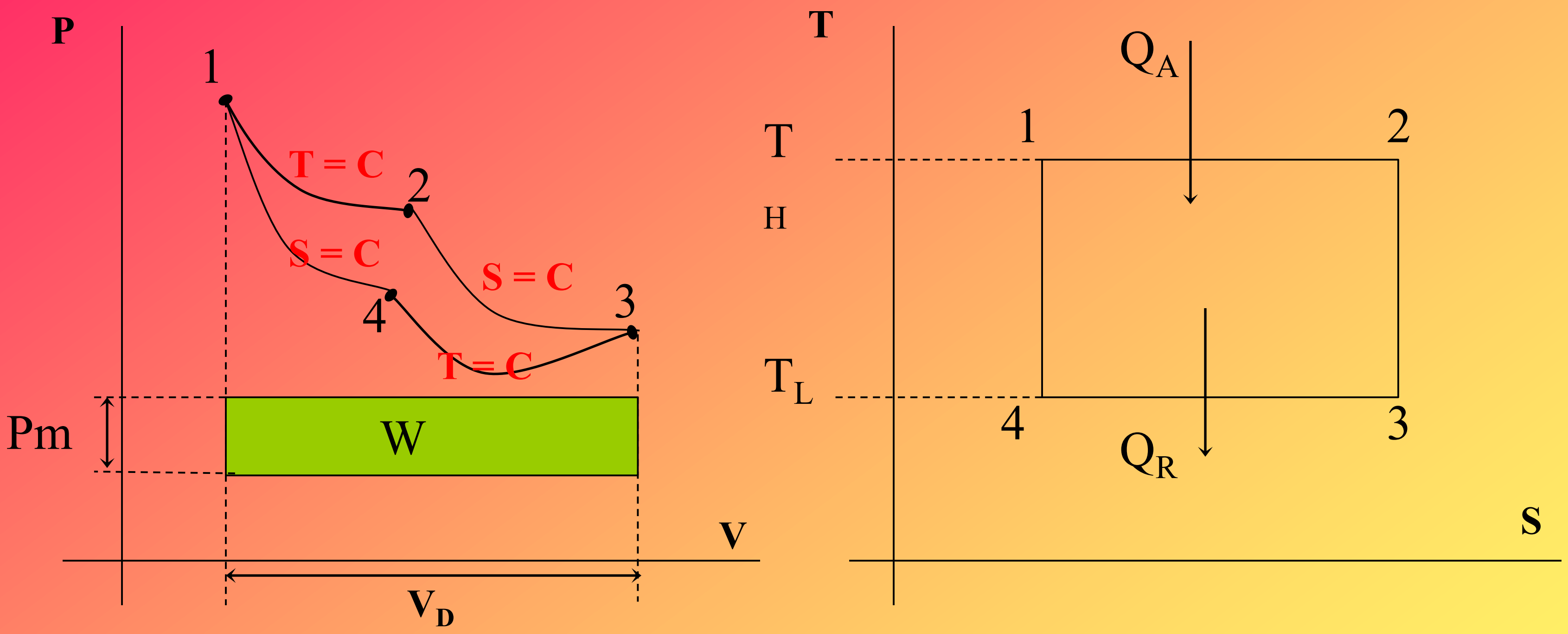
CARNOT CYCLE

Nicolas Leonard Sadi Carnot 1796-1832

1. Carnot Engine

Processes:

1 to 2 - Heat Addition (T = C)
2 to 3 - Expansion (S = C)
3 to 4 - Heat Rejection (T = C)
4 to 1 - Compression (S = C)



Heat Added (T = C)

$$Q_A = T_H(\Delta S) \rightarrow 1$$

Heat Rejected (T = C)

$$Q_R = T_L(\Delta S) \rightarrow 2$$

$$\Delta S = S_2 - S_1 = S_4 - S_3 \rightarrow 3$$

Net Work

$$W = \Sigma Q = Q_A - Q_R \rightarrow 4$$

$$W = (T_H - T_L)(\Delta S) \rightarrow 5$$

$$e = \frac{W}{Q_A} \times 100\% \quad \rightarrow 6$$

$$e = \frac{Q_A - Q_R}{Q_A} \times 100\% \quad \rightarrow 7$$

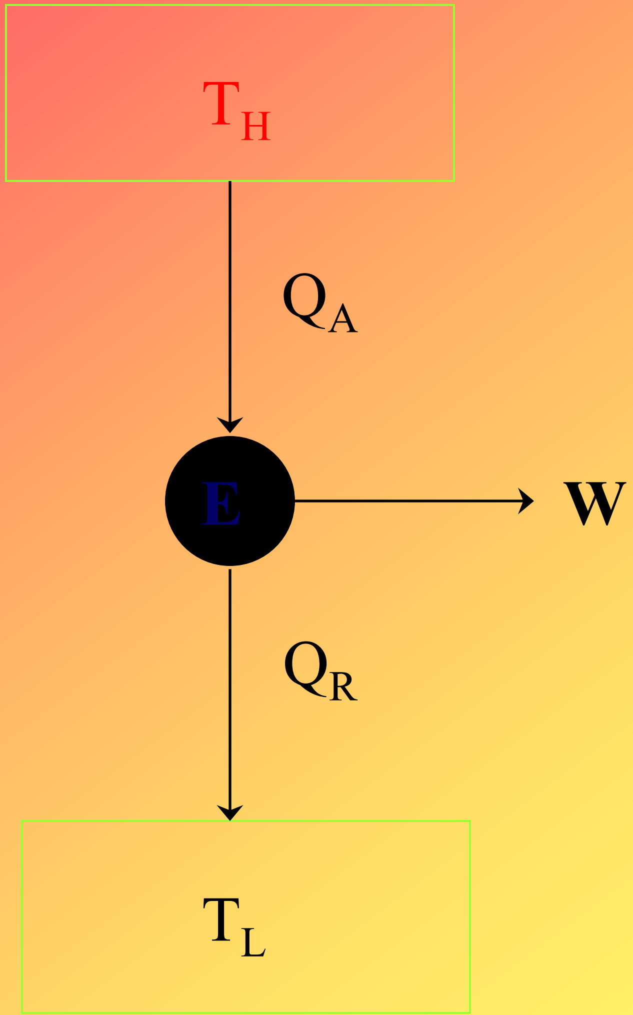
$$e = 1 - \frac{Q_R}{Q_A} \times 100\% \quad \rightarrow 8$$

Substituting eq.1 and eq. 5 to eq 6

$$e = \frac{T_H - T_L}{T_H} \times 100\% \quad \rightarrow 9$$

$$e = 1 - \frac{T_L}{T_H} \times 100\% \quad \rightarrow 10$$

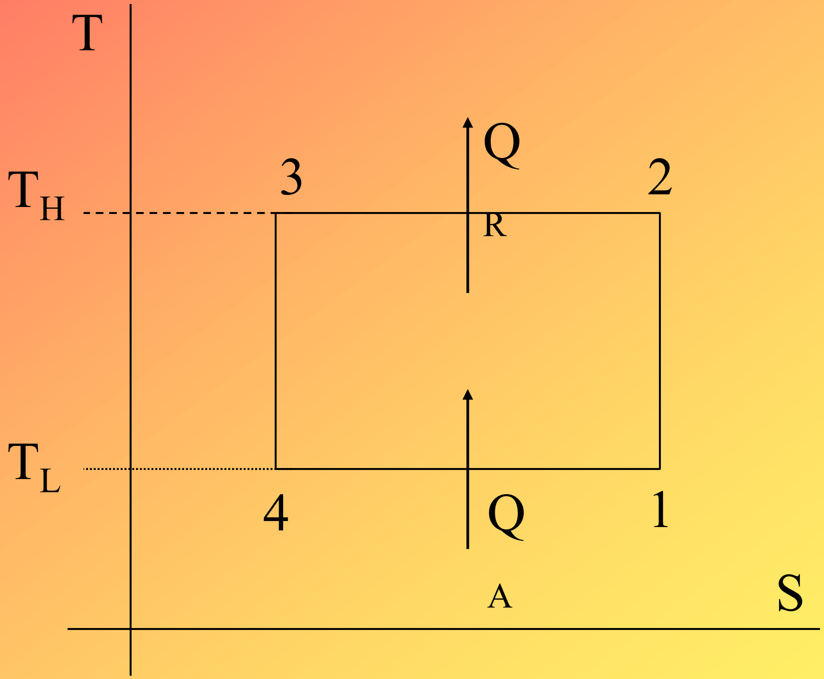
Carnot Engine



2. Carnot Refrigerator: Reversed Carnot Cycle

Processes:

1 to 2 - Compression (S =C)
2 to 3 - Heat Rejection (T = C)
3 to 4 - Expansion (S = C)
4 to 1 - Heat Addition (T = C)



Heat Added (T=C)

$$Q_A = T_L(\Delta S) \rightarrow 1$$

Heat Rejected (T=C)

$$Q_R = T_H(\Delta S) \rightarrow 2$$

$$\Delta S = S_1 - S_4 = S_2 - S_3 \rightarrow 3$$

Net Work

$$W = \Sigma Q \rightarrow 4$$

$$W = Q_R - Q_A \rightarrow 5$$

$$W = (T_H - T_L)(\Delta S) \rightarrow 6$$

Coefficient of Performance

$$COP = \frac{Q_A}{W} \rightarrow 7$$

$$COP = \frac{T_L}{T_H - T_L} \rightarrow 8$$

$$\mathrm{COP} = \frac{T_L}{T_H} - 1 \quad \rightarrow 9$$

Tons of Refrigeration

211 KJ/min = 1 TR

3. Carnot Heat Pump: A heat pump uses the same components as the refrigerator but its purpose is to reject heat at high energy level.

Performance Factor:

$$\mathrm{PF} = \frac{Q_R}{W} \quad \rightarrow 10$$

$$\mathrm{PF} = \frac{Q_R}{Q_R - Q_A} \quad \rightarrow 11$$

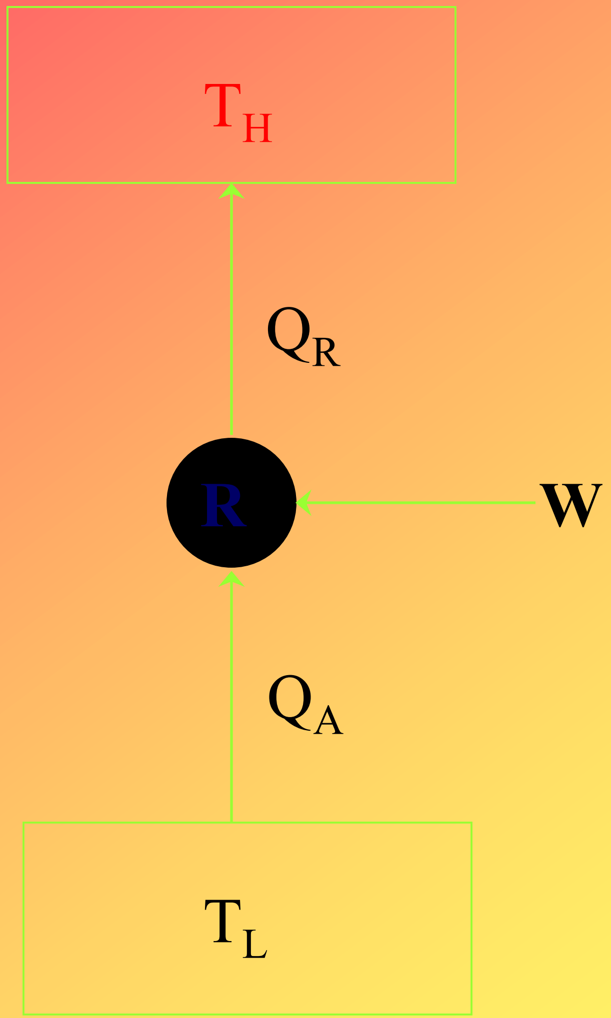
$$PF = \frac{T_H}{T_H - T_L} \rightarrow 12$$

$$PF = 1 - \frac{Q_R}{Q_A} \rightarrow 13$$

$$PF = 1 - \frac{T_H}{T_L} \rightarrow 14$$

$$PF = COP + 1 \rightarrow 15$$

Carnot Refrigerator



Vapor Power Cycle

RANKINE CYCLE

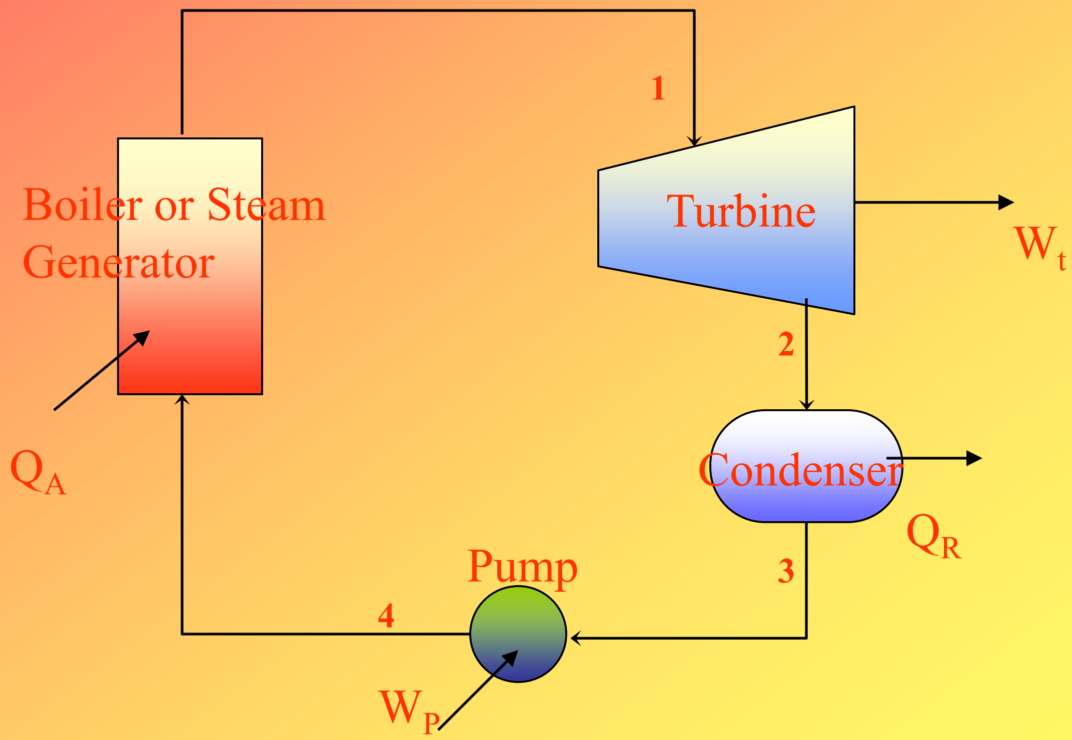
Processes:

1 to 2 - Expansion (S = C)

2 to 3 - Heat Rejection (P = C)

3 to 4 - Compression or Pumping (S = C)

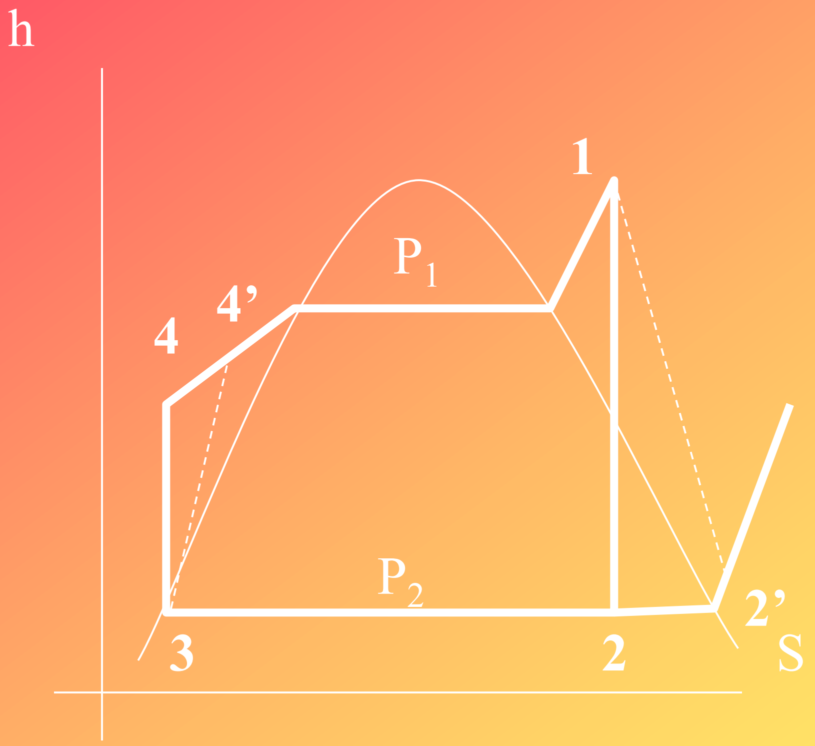
4 to 1 - Heat Addition (P = C)

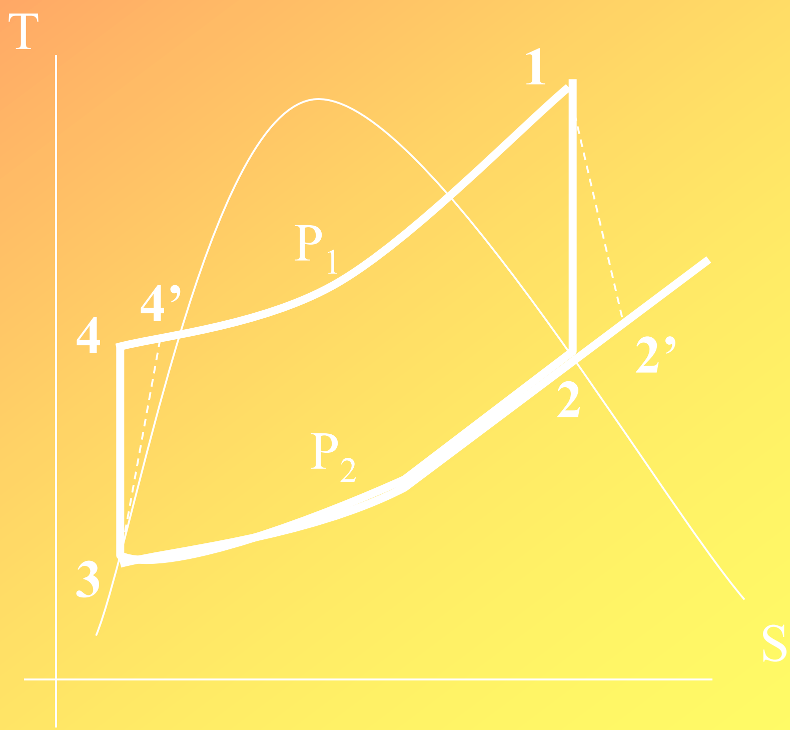


Major Components of a Rankine Cycle

1. **Steam Generator or Boiler:** The working substance absorbs heat from products of combustion or other sources of heat at constant pressure which in turn changes the state of the working substance (water or steam) from sub-cooled liquid and finally to superheated vapor whence at this point it enters the turbine.
2. **Steam Turbine:** A steady state, steady flow device where steam expands isentropically to a lower pressure converting some forms of energy (h, KE, PE) to mechanical work that finally be converted into electrical energy if the turbine is used to drive an electric generator.
3. **Condenser:** Steam exiting from the turbine enters this device to reject heat to the cooling medium and changes its state to that of the saturated liquid at the condenser pressure which occurred at a constant pressure process.

4. **Pump:** It is also a steady state, steady flow machine where the condensate leaving the condenser at lower pressure be pumped back to the boiler in an isentropic process in order to raise the pressure of the condensate to that of the boiler pressure.





Turbine Work

a) Ideal Cycle

$$W_t = (h_1 - h_2) \text{ KJ/kg}$$

$$W_t = m_s(h_1 - h_2) \text{ KW}$$

b) Actual Cycle

$$W_{t'} = (h_1 - h_{2'}) \text{ KJ/kg}$$

$$W_{t'} = m_s(h_1 - h_{2'}) \text{ KW}$$

where: m_s - steam flow rate in kg/sec

Turbine Efficiency

$$\eta_t = \frac{W_{t'}}{W_t} \times 100\%$$

$$\eta_t = \frac{h_1 - h_{2'}}{h_1 - h_2} \times 100\%$$

Pump Work

a) Ideal Cycle

$$W_P = (h_4 - h_3) \text{ KJ/kg}$$

$$W_P = m_s(h_4 - h_3) \text{ KW}$$

b) Actual Cycle

$$W_{P'} = (h_{4'} - h_3) \text{ KJ/kg}$$

$$W_{P'} = m_s(h_{4'} - h_3) \text{ KW}$$

Pump Efficiency

$$\eta_p = \frac{W_p}{W_{p'}} \times 100\%$$

$$\eta_p = \frac{h_4 - h_3}{h_{4'} - h_3} \times 100\%$$

Heat Rejected

a) Ideal Cycle

$Q_R = (h_2 - h_3)$ KJ/kg

$Q_R = m_s(h_2 - h_3)$ KW

$Q_R = m_s(h_2 - h_3)$ KW $= m_w C_{pw}(t_{wo} - t_{wi})$ KW

b) Actual Cycle

$Q_R = (h_{2'} - h_3)$ KJ/kg

$Q_R = m_s(h_{2'} - h_3)$ KW $= m_w C_{pw}(t_{wo} - t_{wi})$ KW

Where: m_w - cooling water flow rate in kg/sec

t_{wi} - inlet temperature of cooling water in°C

t_{wo} - outlet temperature of cooling water in°C

C_{pw} - specific heat of water in KJ/kg- °C or KJ/kg-°K

C_{pw} = 4.187 KJ/kg- °C or KJ/kg- °K

Heat Added:

a) Ideal Cycle

$$Q_A = (h_1 - h_4) \text{ KJ/kg}$$

$$Q_A = m_s\,(h_1 - h_4) \text{ KW}$$

b) Actual Cycle

$$Q_A = (h_1 - h_{4'}) \text{ KJ/kg}$$

$$Q_A = m_s\,(h_1 - h_{4'}) \text{ KW}$$

Steam Generator or boiler Efficiency

$$\eta_B = \frac{Q_A}{Q_S} \times 100\%$$

$$\eta_B = \frac{m_s (h_1 - h_4)}{m_f (HV)} \times 100\%$$

Where: Q_A - heat absorbed by boiler in KW

Q_S - heat supplied in KW

m_f - fuel consumption in kg/sec

HV - heating value of fuel in KJ/kg

Steam Rate

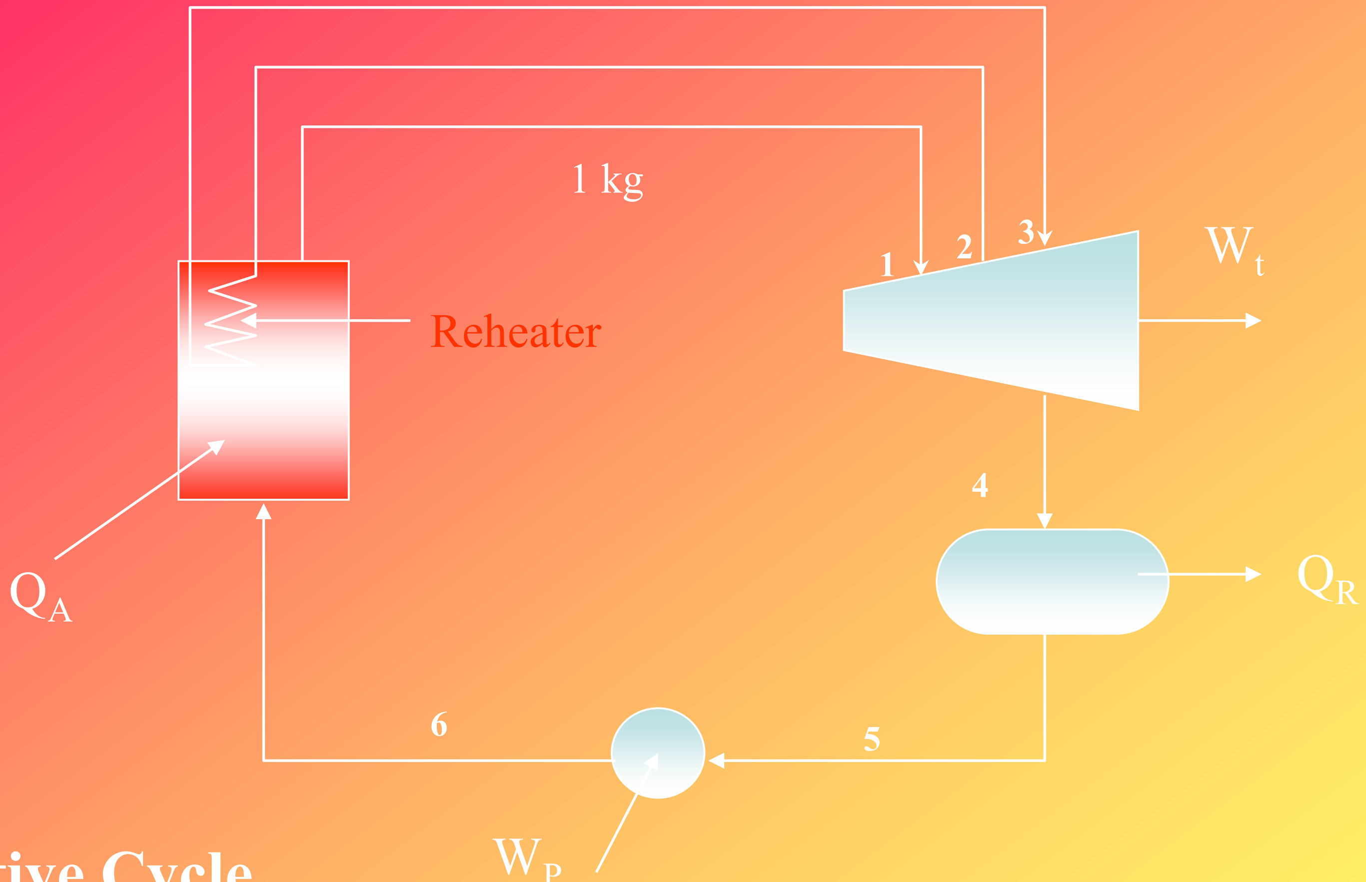
$$SR = \frac{\text{Steam Flow rate}}{\text{KW Produced}} \quad \frac{\text{kg}}{\text{sec - KW}}$$

Heat Rate

$$HR = \frac{\text{Heat Supplied}}{\text{KW Produced}} \quad \frac{\text{KJ}}{\text{sec - KW}}$$

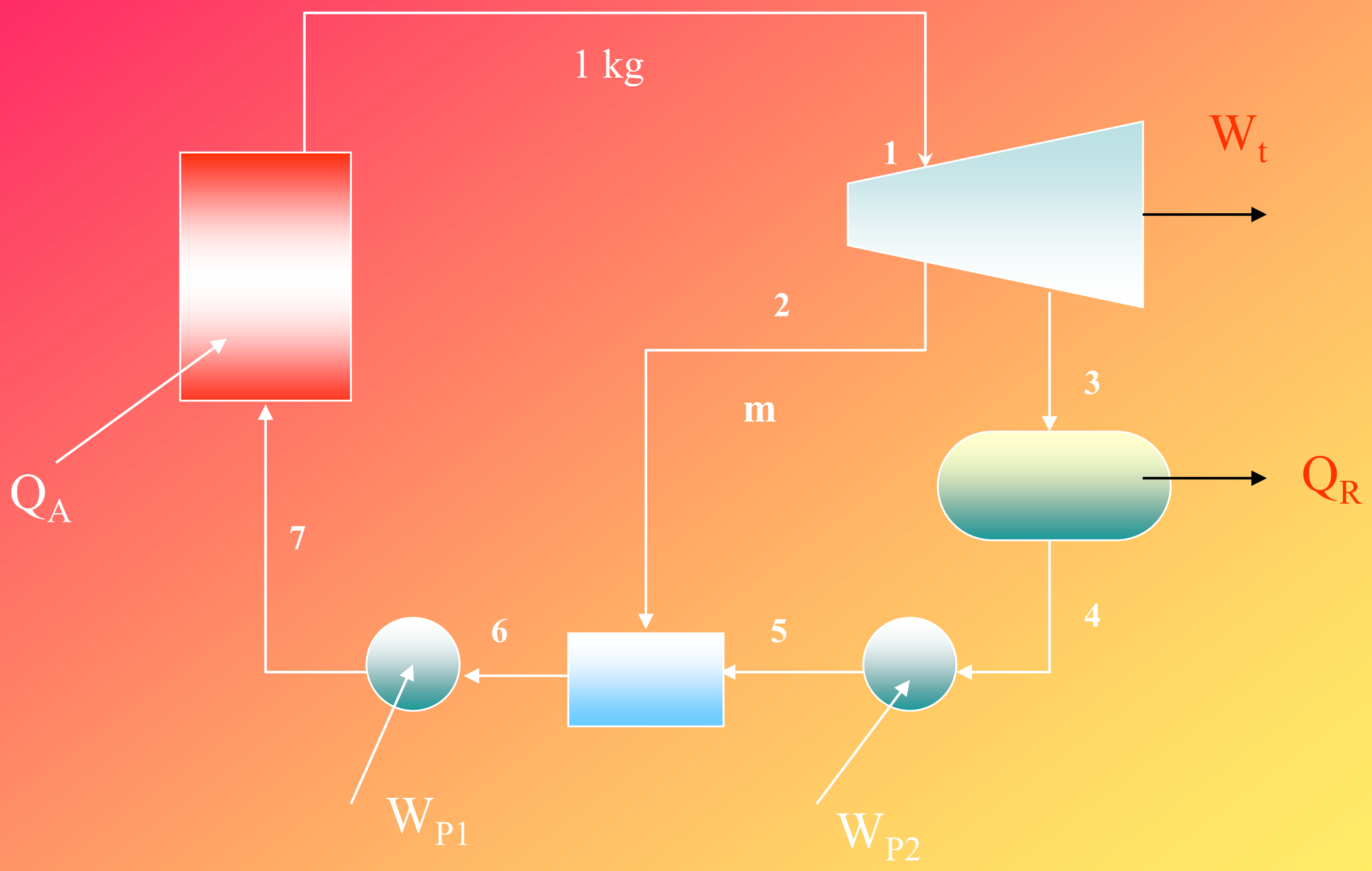
Reheat Cycle

A steam power plant operating on a reheat cycle improves the thermal efficiency of a simple Rankine cycle plant. After partial expansion of the steam in the turbine, the steam flows back to a section in the boiler which is the re-heater and it will be reheated almost the same to its initial temperature and expands finally in the turbine to the condenser pressure.



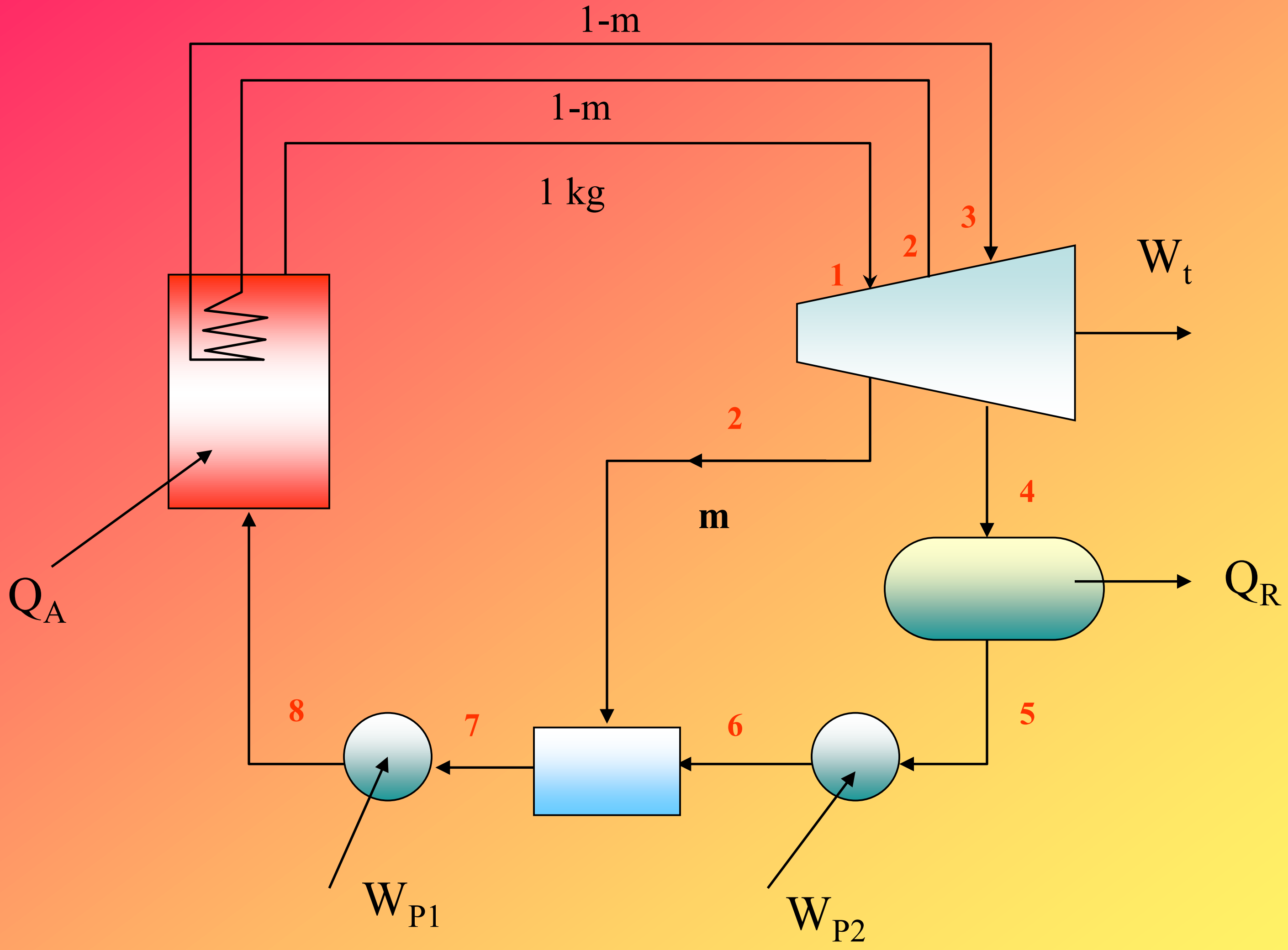
Regenerative Cycle

In a regenerative cycle, after partial expansion of the steam in the turbine, some part of it is extracted for feed-water heating in an open or close type feed-water heater. The bled steam heats the condensate from the condenser or drains from the previous heater causing a decrease in heat absorbed by steam in the boiler which result to an increase in thermal efficiency of the cycle.



Reheat-Regenerative Cycle

For a reheat - regenerative cycle power plant, part of the steam is re-heated in the re-heater and some portion is bled for feed-water heating to an open or closed type heaters after its partial expansion in the turbine. It will result to a further increase in thermal efficiency of the plant.



For a 1 kg basis of circulating steam, m is the fraction of steam extracted for feed-water heating as shown on the schematic diagram above, where the reheat and bled steam pressure are the same.

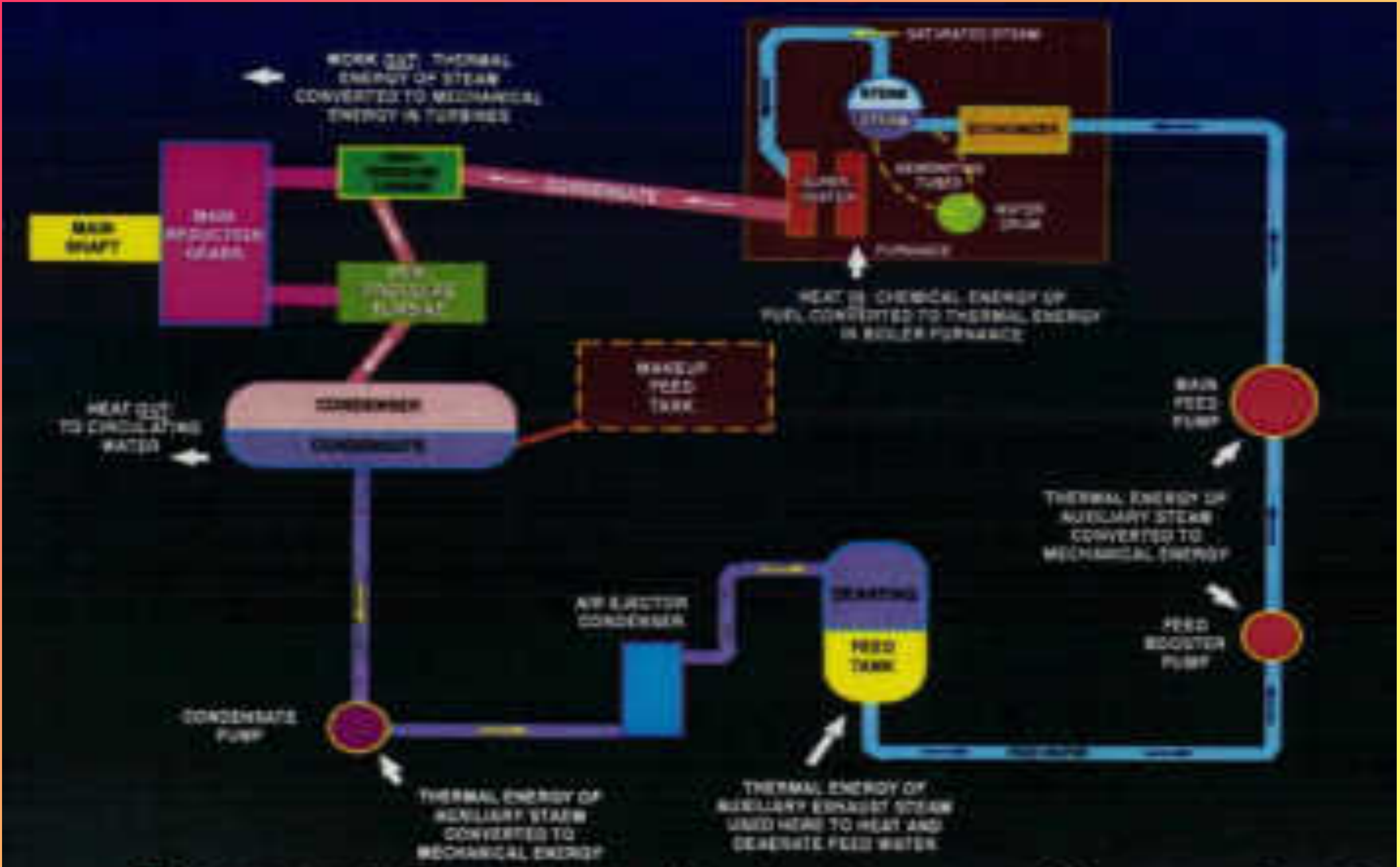
Introduction

- Parts of the Main Steam Cycle
- Four Phases of the cycle
  - Definitions of each phase
  - Components involved with phases
  - Press-temp relationships

Parts of Main Steam Cycle

- Steam Generator (nuclear) or Boiler (conventional)
- Turbines
- Condenser
- Main Condensate Pumps
- Deaerating Feed Tank / Reserve Feed Tanks
- Main Feed Pumps

Main Steam Cycle



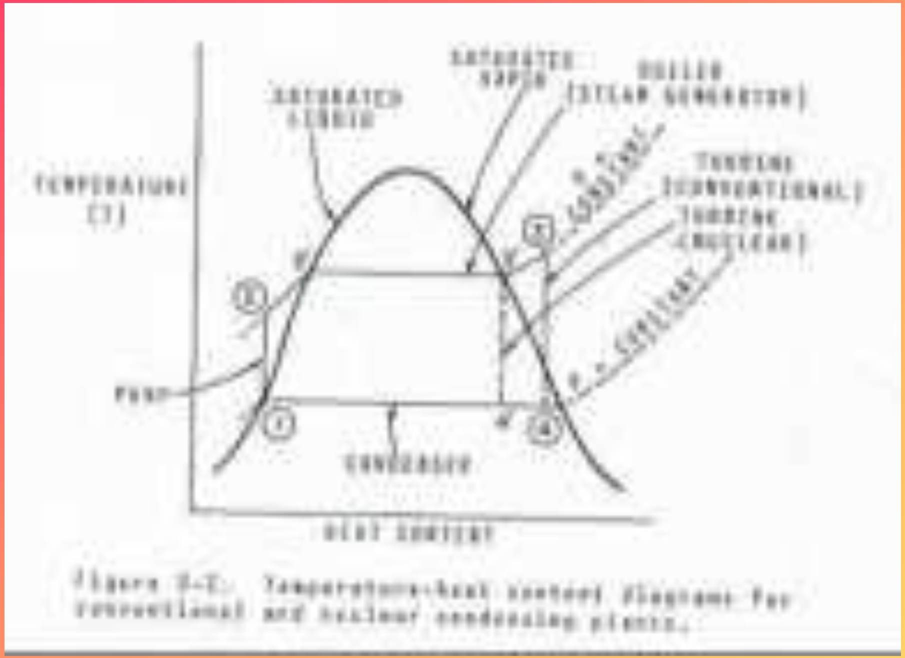
- Energy relationship in the basic propulsion cycle of conventional stream-driven ship.

Background

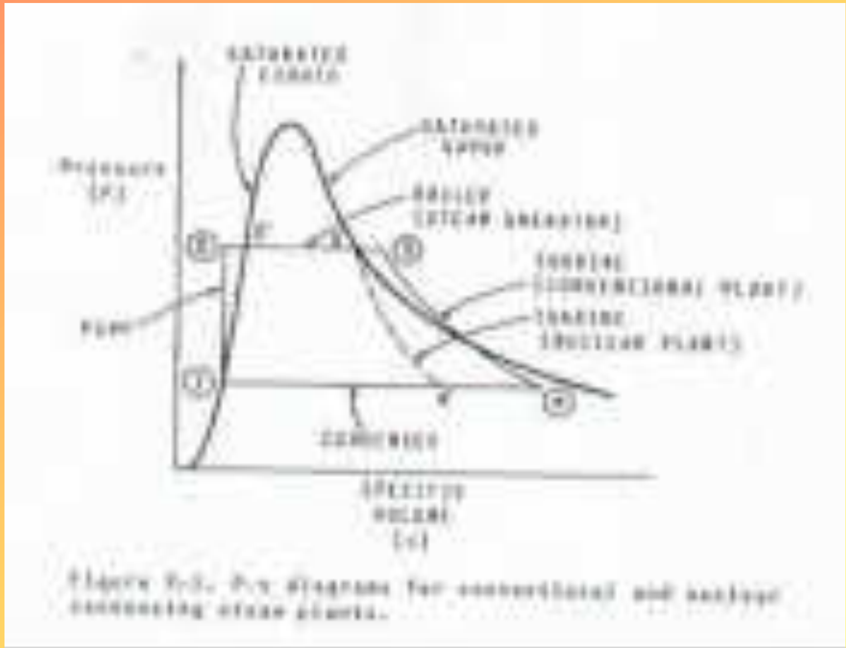
- Cycle used is a Rankine cycle
- P-v and T-s Diagrams
  - Trace the points of cycle
  - Provide graphical understanding of cycle
- Four phases of cycle
- Conventional vs. Nuclear

Rankine Cycle

T-s Diagram



P-v Diagram



1-2: Feed Phase ($\Delta Q=0$, $\Delta S=0$), W_{in}
2-3: Generation Phase ($\Delta P=0$), Q_{in}
3-4: Expansion Phase ($\Delta Q=0$, $\Delta S=0$), W_{out}
4-1: Condensation Phase ($\Delta P=0$), Q_{out}

Generation Phase - Conventional

- Boiler (1200 # steam)
  - Fuel burned to produce heat -> transferred to water which boils to steam
  - Steam collects in steam drum (saturated)
- Superheater
  - Increase temp of steam and dries steam
  - Three reasons for superheating?
    - Minimize erosion (dry steam better for blading)
    - Minimize corrosion (less chemicals entrained)
    - Maximize ΔT (Carnot efficiency)

Boiler and Superheater

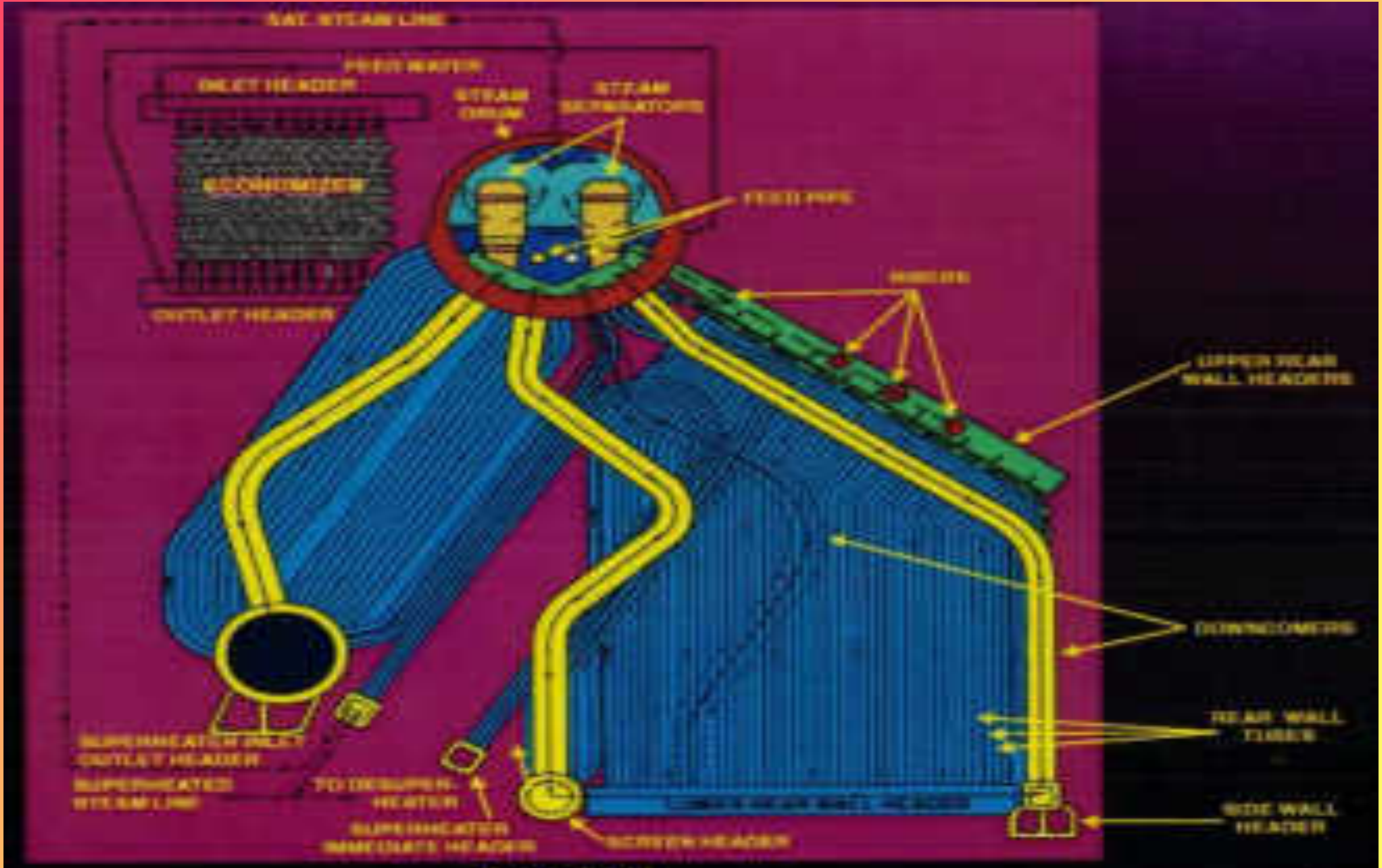
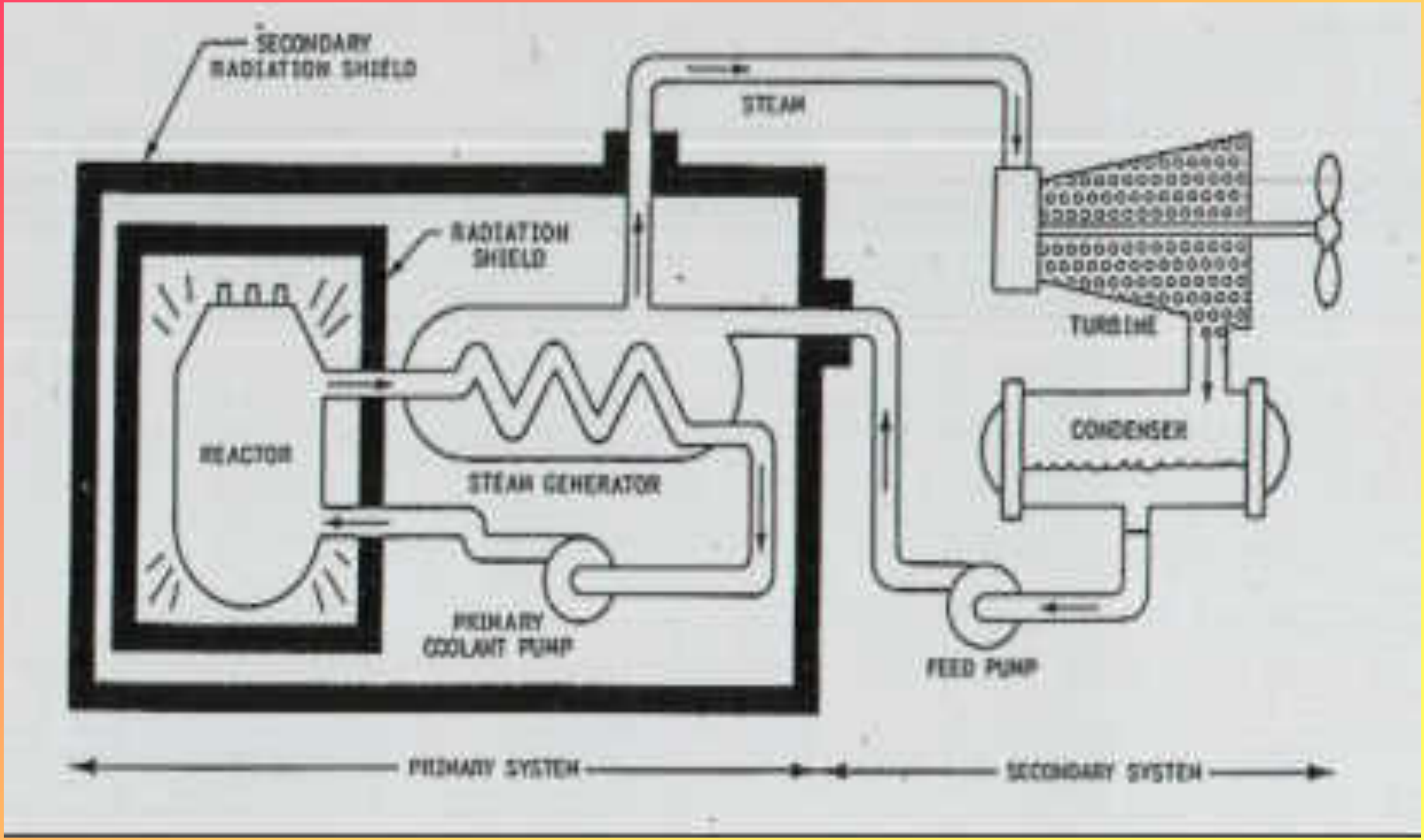


Figure 5-13
BOILER WATER AND STEAM FLOW

Generation Phase - Nuclear

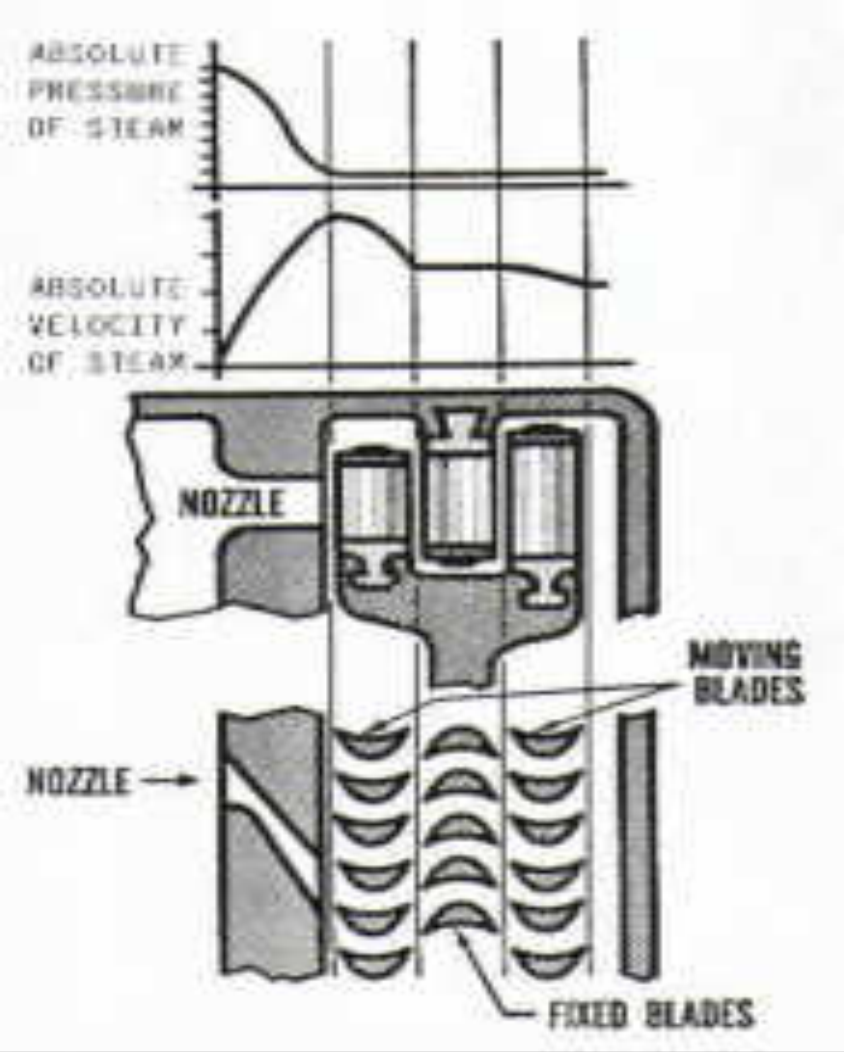
- Reactor (Rx) Plant
  - Fission in Rx core transforms nuclear energy to thermal energy
- Steam Generator
  - Water Space
  - U-tubes
  - Steam Space
  - Moisture Separators

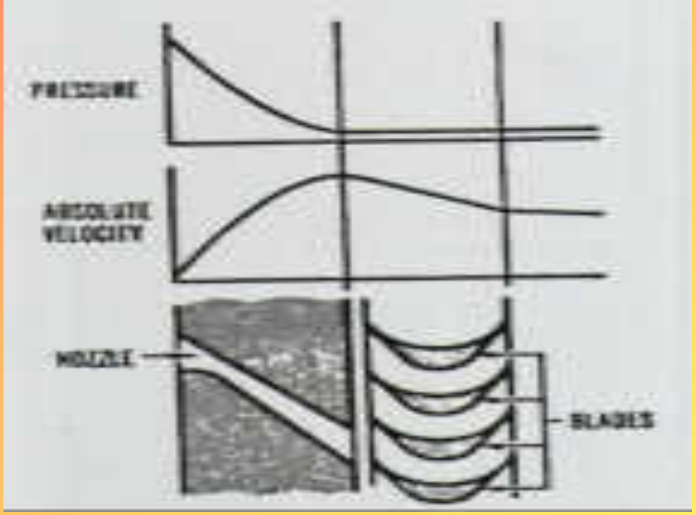
Reactor Plant

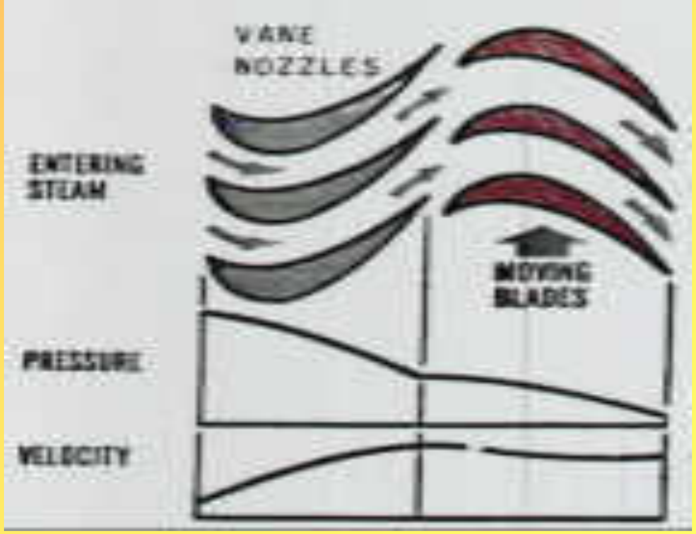


Expansion Phase

- Steam travels down main steam piping
- Turbines convert thermal energy -> mechanical energy (nozzles) and then work (blading) -> turn rotor/shaft
- Pressure drops as steam goes through
- Work performed on turbine blading
  - Main Engines (ME) -> propulsion
  - Ship's Service Turbine Generators (SSTG) -> electricity


ABSOLUTE PRESSURE OF STEAM
ABSOLUTE VELOCITY OF STEAM
NOZZLE
MOVING BLADES
NOZZLE →
FIXED BLADES


PRESSURE
ABSOLUTE VELOCITY
NOZZLE
BLADES


VANE NOZZLES
ENTERING STEAM
MOVING BLADES
PRESSURE
VELOCITY

Feed Phase

- Deaerating Feed Tank (DFT)
  - Direct-type HX (Aux Steam used)
  - Purposes
    - preheats feed
    - storage/surge volume
    - removes dissolved oxygen to minimize corrosion
  - FYI: RFT’s often used instead
- Main Feed Pump
  - Supplies feed water to Steam Generator (must be high pressure to overcome pressure)

IC Engines

“An internal combustion is defined as an engine in which the chemical energy of the fuel is released inside the engine and used directly for mechanical work, as opposed to an external combustion engine in which a separate combustor is used to burn the fuel.”

IC Engine Classifications

On the basis of thermodynamic cycle

- Constant volume combustion (Otto Cycle)
- Constant pressure combustion (Diesel Cycle)
- Mixed Cycle

On the basis of working cycle

- Four Stroke
- Two-Stroke

On the basis of fuel used

- Gasoline
- Diesel or Fuel Oil
- Natural Gas
- Propane (LPG)

On the basis of field of application

- Stationary engines
- Mobile Engines

On the basis of method of ignition

- Spark Ignition
- Compression Ignition

On the basis of cooling system

- Air Cooling
- Liquid Cooled, (Water Cooled)

On the basis of fuel supply system

- Carburettor engines
- Air injection engines
- Airless injection

On the basis of lubrication system

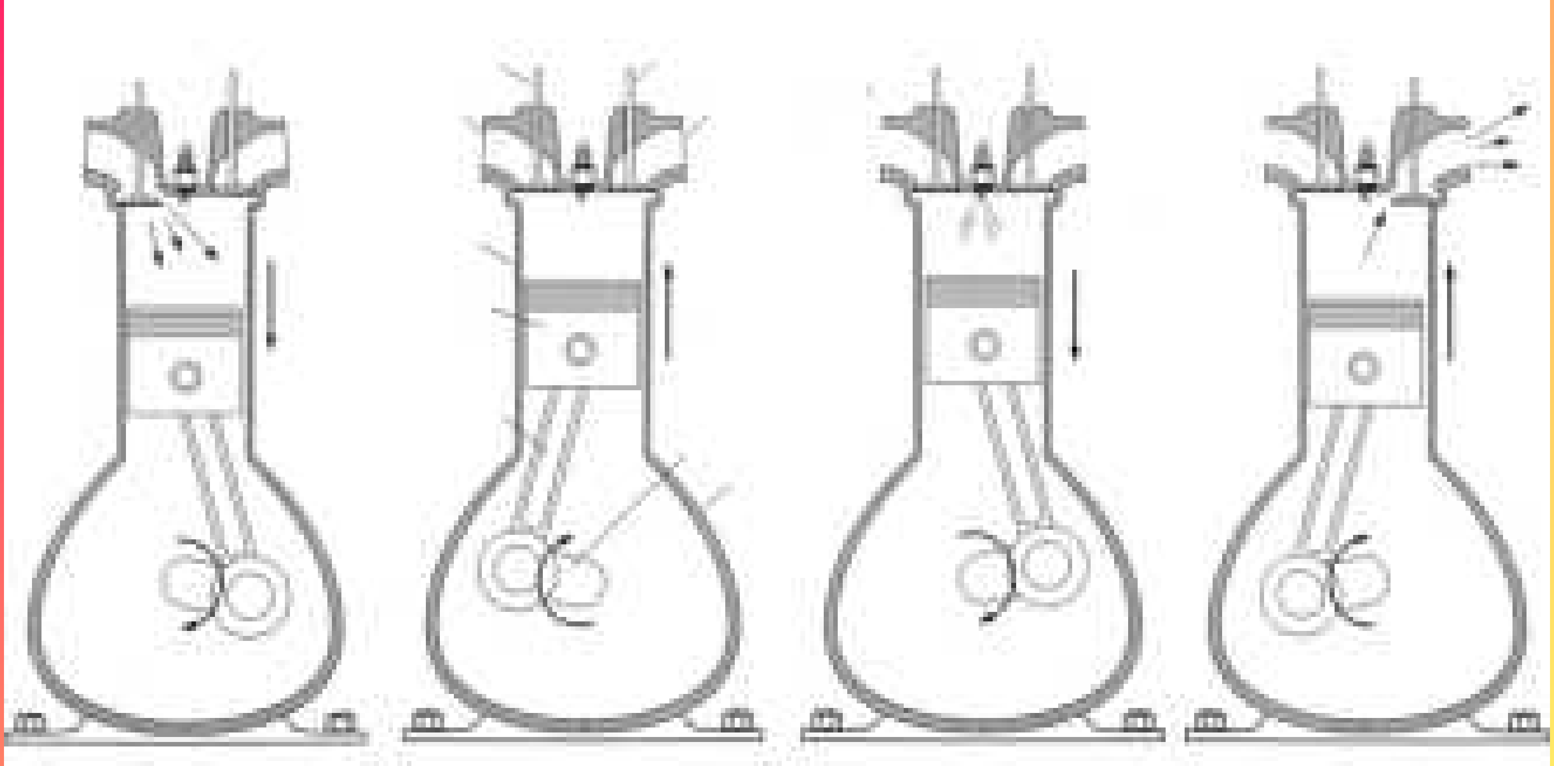
- Wet sump lubrication
- Dry sump lubrication
- Pressure lubrication

Method of control

Quality control
Quantity control
Combined control

4 strokes of the Internal Combustion Engine

1. Intake
2. Compression
3. Combustion
4. Exhaust



Intake Stroke

Intake valve opens, admitting fuel and air. Exhaust valve closed for most of stroke

I.C.ENGINES

I have always considered that the substitution of the Internal Combustion Engine for the horse marked a very gloomy milestone in the progress of mankind.

-Winston Churchill

If all the perverted ingenuity which was put into making automobiles had only gone into improving the breed of horses, we might be a lot better off today.

-Joe Gould

ENGINES!
BOON OR BANE?

- Greatest invention since the wheel?
- Made transportation easy!
- Made life easy!

OR DID IT?

- Increased pollution
- Increased fossil fuel consumption
- Increased congestion on roads

CLASSIFICATION OF INTERNAL COMBUSTION ENGINES

VARIOUS TYPES OF ENGINES

CLASSIFICATION OF INTERNAL COMBUSTION ENGINES

1. Application
2. Basic Engine Design
3. Operating Cycle
4. Working Cycle
5. Valve/Port Design and Location
6. Fuel
7. Mixture Preparation
8. Ignition
9. Stratification of Charge
10. Combustion Chamber Design
11. Method of Load Control
12. Cooling

CLASSIFICATION OF INTERNAL COMBUSTION ENGINES

1. 1. Application

2. Automotive: (i) Car
   (ii) Truck/Bus
   (iii) Off-highway
2. Locomotive
3. Light Aircraft
4. Marine: (i) Outboard
   (ii) Inboard
   (iii) Ship
5. Power Generation: (i) Portable (Domestic)
   (ii) Fixed (Peak Power)
6. Agricultural: (i) Tractors
   (ii) Pump sets
7. Earthmoving: (i) Dumpers
   (ii) Tippers
   (iii) Mining Equipment
8. Home Use: (i) Lawnmowers
   (ii) Snow blowers
   (iii) Tools
9. Others

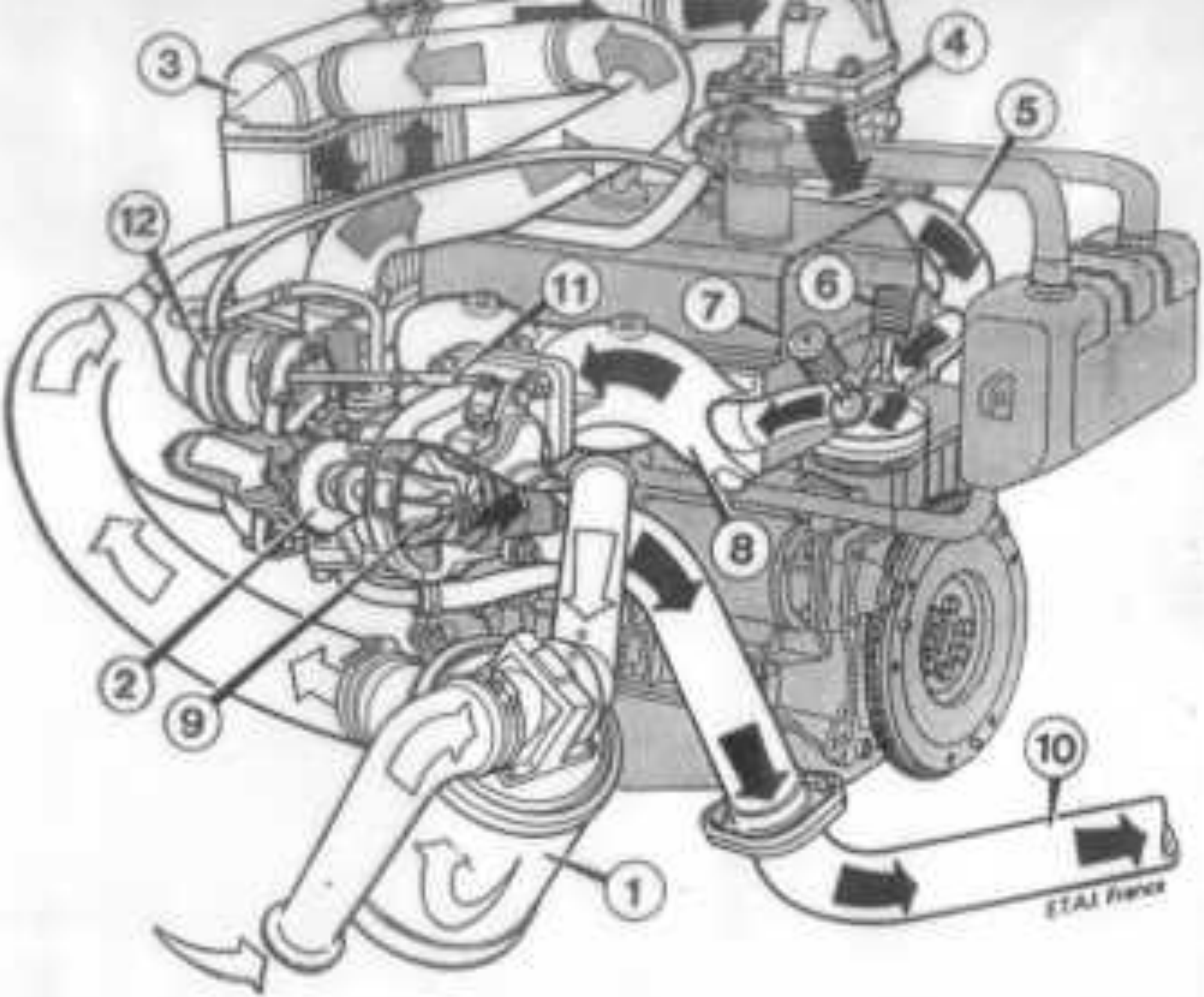


FIGURE 1-10
Turbocharged four-cylinder automotive spark-ignition engine. (Courtesy Regie Nationale des Usines

Automotive Diesel Engine

FIGURE 1-21
Four-cylinder naturally aspirated indirect-injection automobile Volkswagen diesel engine.
placed volume 1.47 liters, bore 76.5 mm, stroke 80 mm, maximum power 37 kW at 5000 rev/min

Large Two-stroke Marine Engine

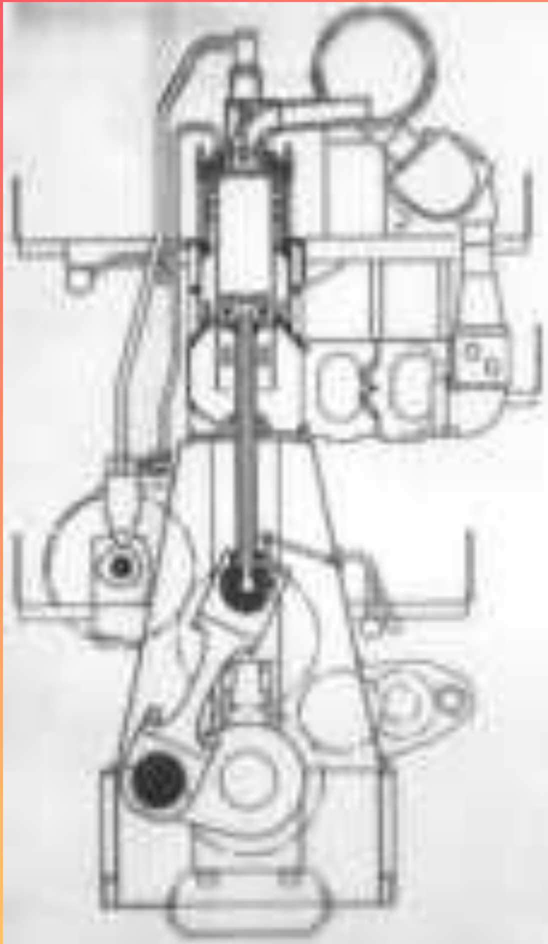


FIGURE 1-34
Large Sulzer two-stroke turbocharged marine diesel engine. Bore 840 mm, stroke 2900 mm, rated power 1.9 MW per cylinder at 78 rev/min. 4 to 12 cylinders. (Courtesy Sulzer Brothers Ltd.)

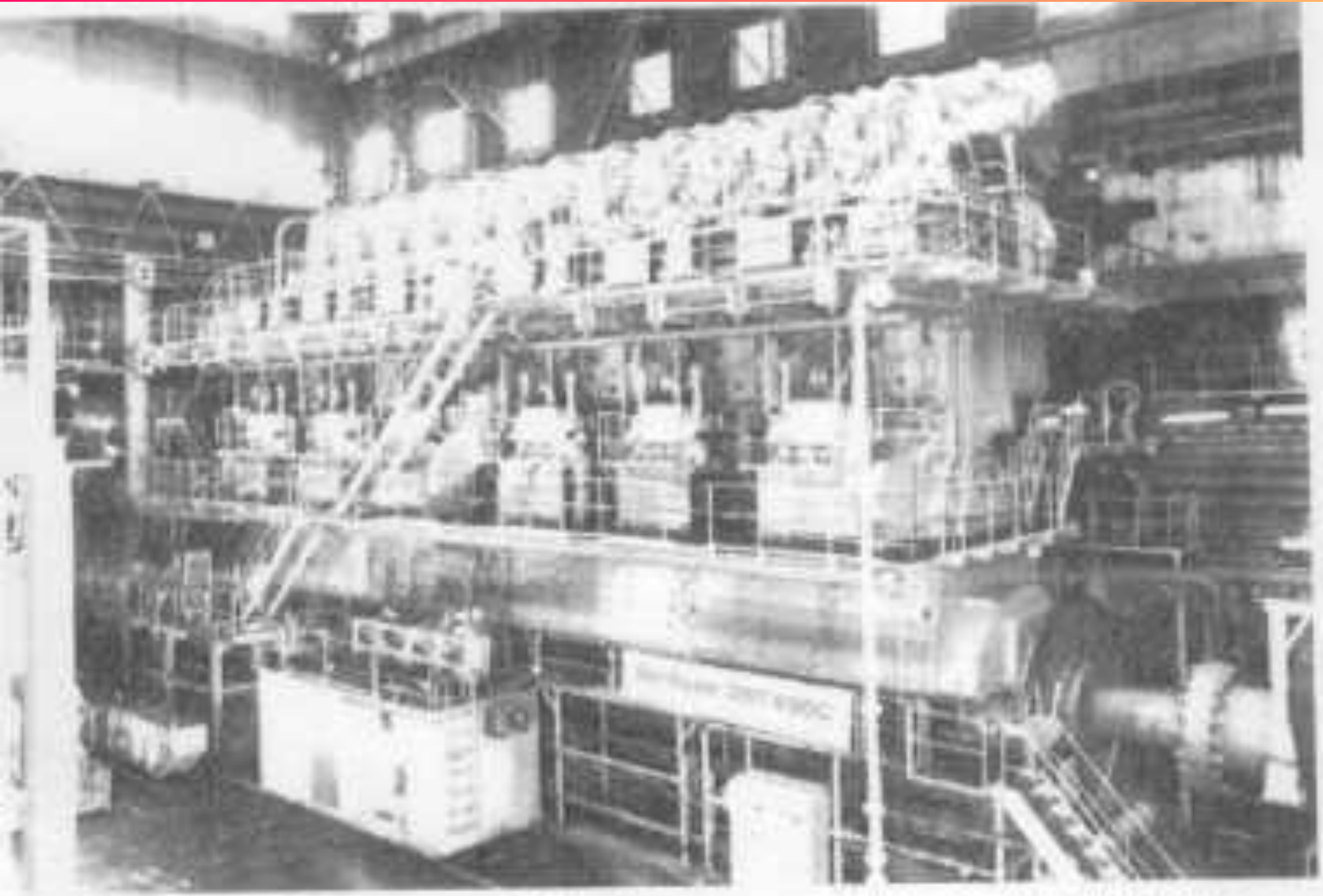
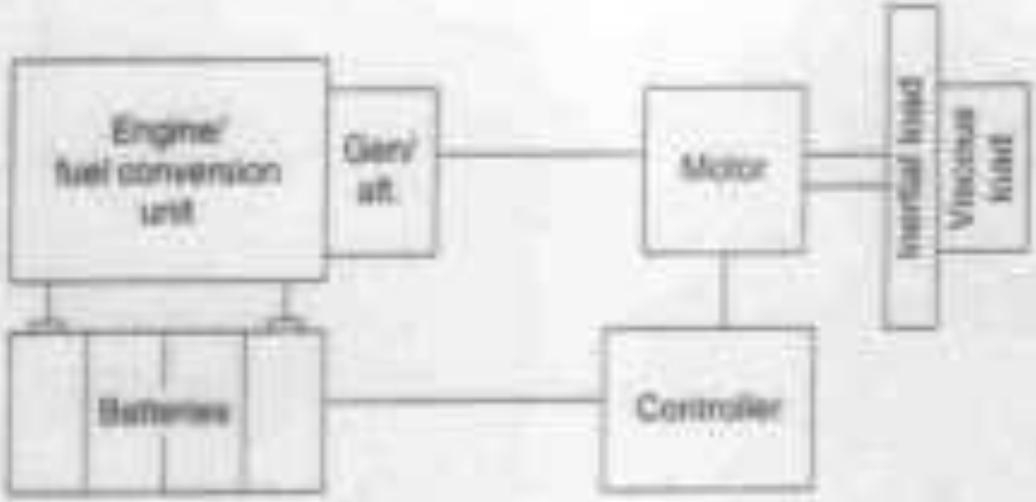
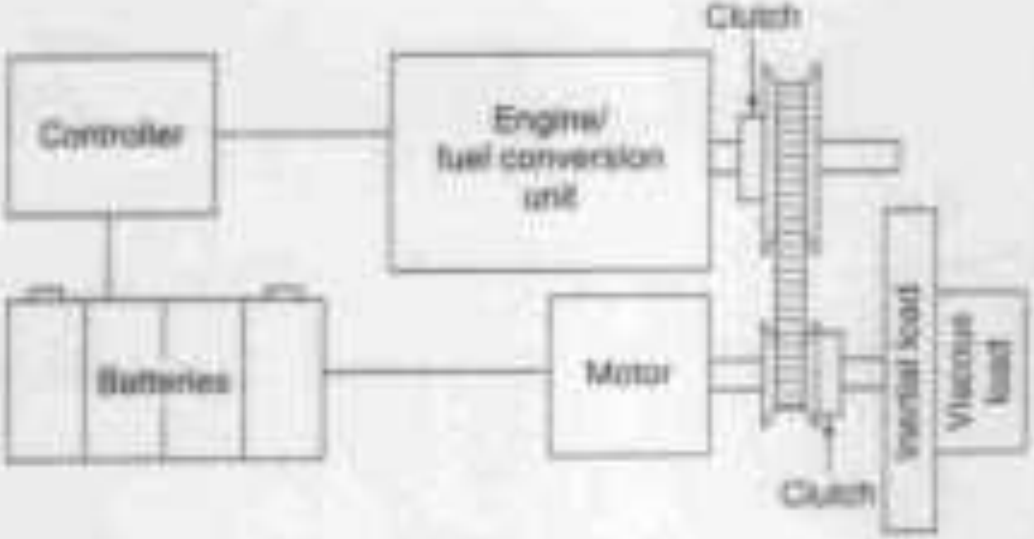


Figure 1.8 The world's most powerful diesel engine was tested by Diesel United in Japan in 1997. The 12-cylinder Sulzer 12RTA96C, destined for a containership, developed 65 880 kW at 100 rev/min



(a) Series configuration



(b) Parallel configuration

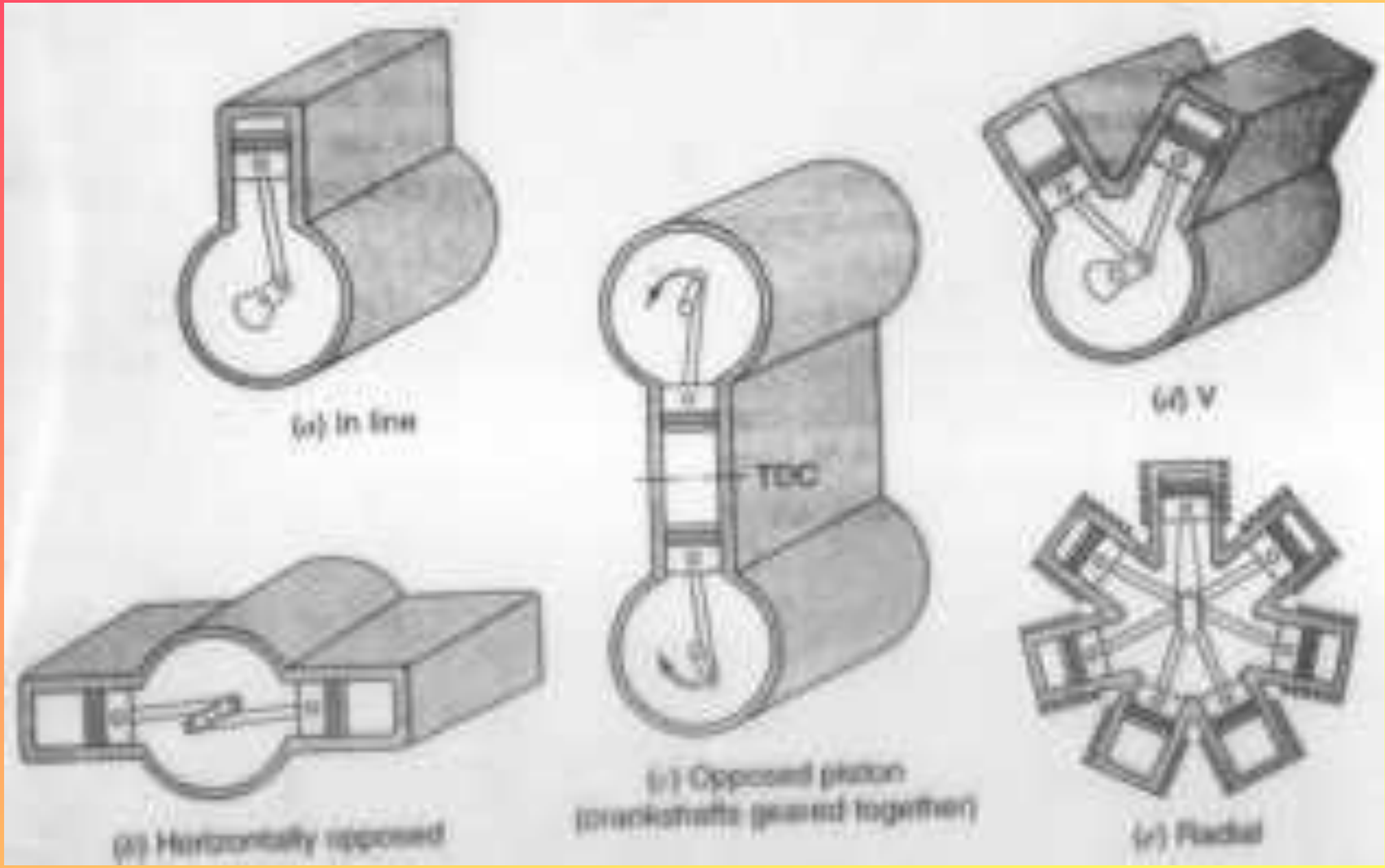
Figure 1-25 Hybrid electric vehicle powertrain configurations.

CLASSIFICATION OF INTERNAL COMBUSTION ENGINES

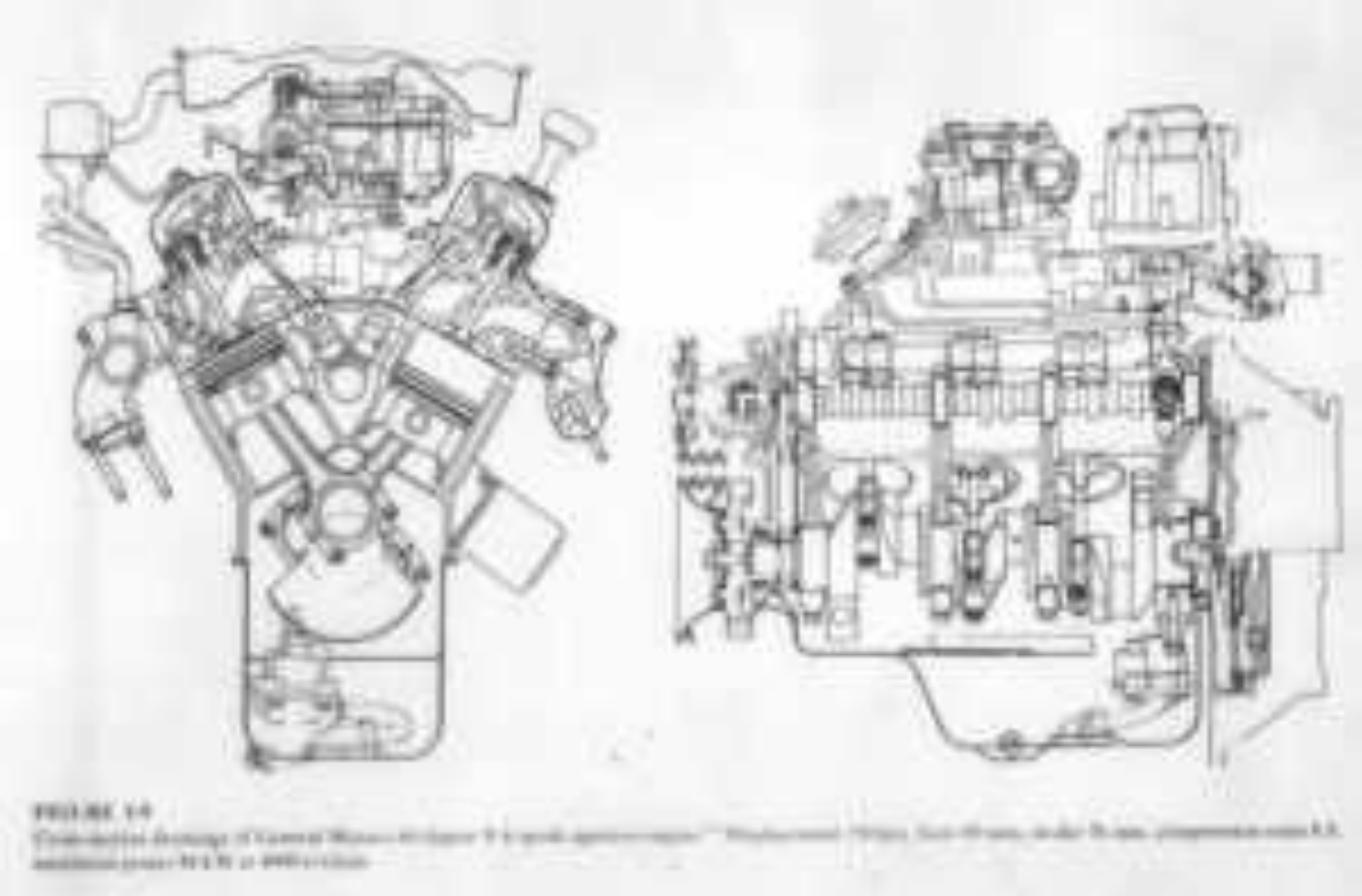
2. Basic Engine Design:

- 1. Reciprocating
  - (a) Single Cylinder
  - (b) Multi-cylinder
    - (I) In-line
    - (ii) V
    - (iii) Radial
    - (iv) Opposed Cylinder
    - (v) Opposed Piston
- 2. Rotary:
  - (a) Single Rotor
  - (b) Multi-rotor

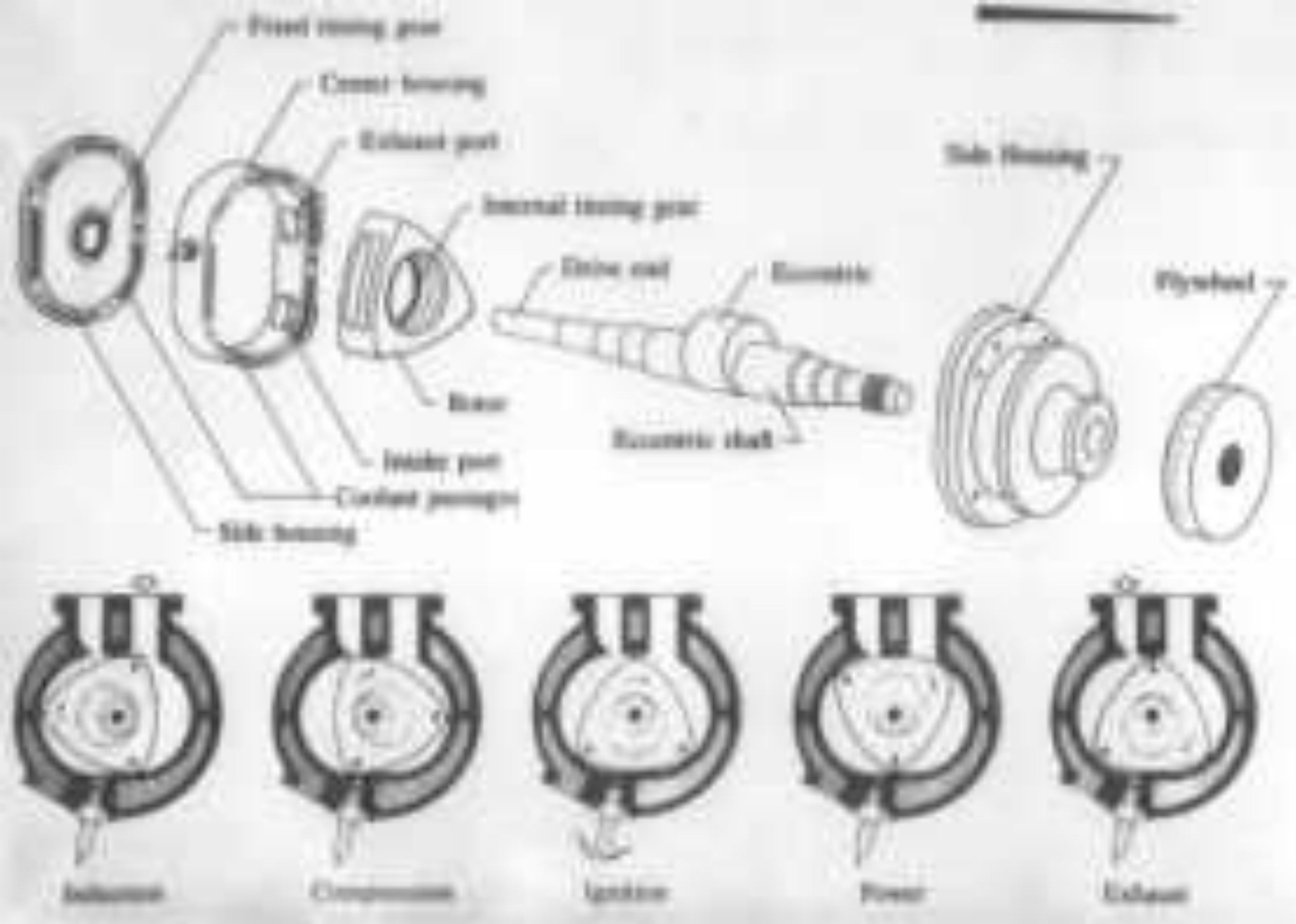
Types of Reciprocating Engines



V Engine



Wankel Rotary Piston Engine



Types of Rotary Engines

IGURE 7.1a A turbocharged RX-7 rotary engine. (Photo courtesy of Mazda Motors of America.)

FIGURE 7.1b An RX-7 rotary engine turbocharger. (Photo courtesy of Mazda Motors of America.)

Wankel Engine Parts

Twin-rotor Wankel

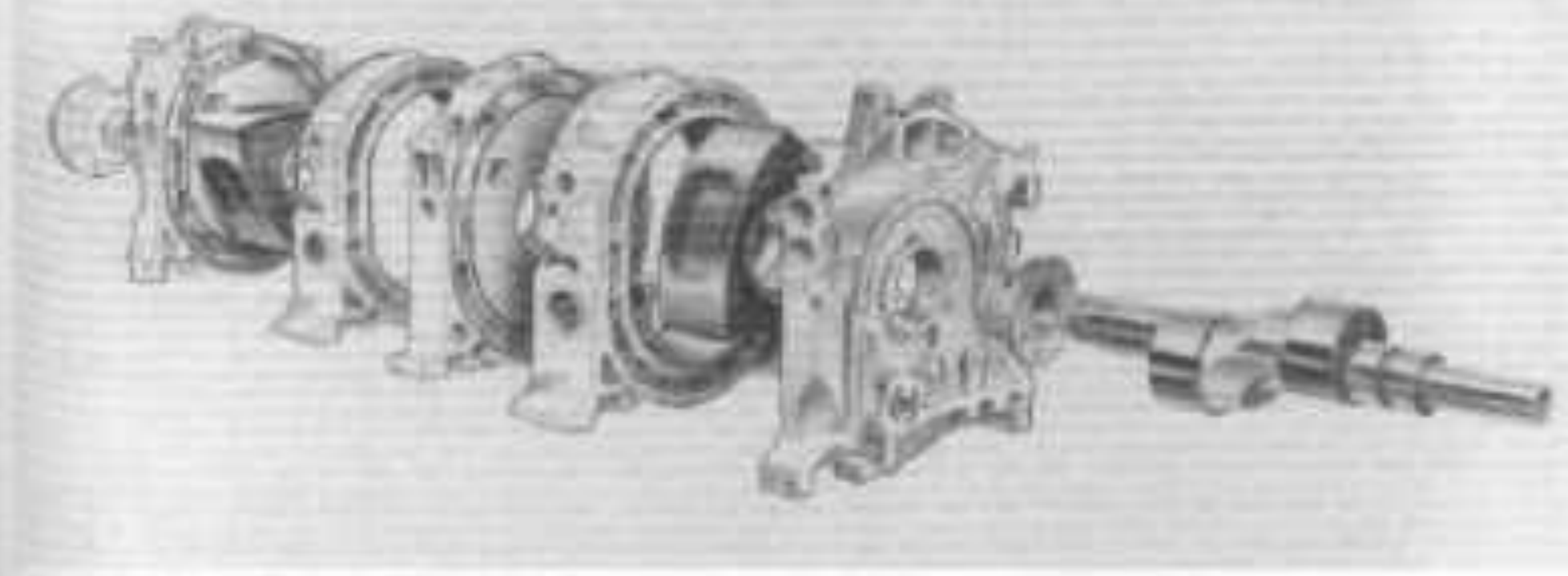


FIGURE 7.9 Exploded view of a twin-rotor rotary engine. (Courtesy of Mazda Motors of America.)

Apex Seals

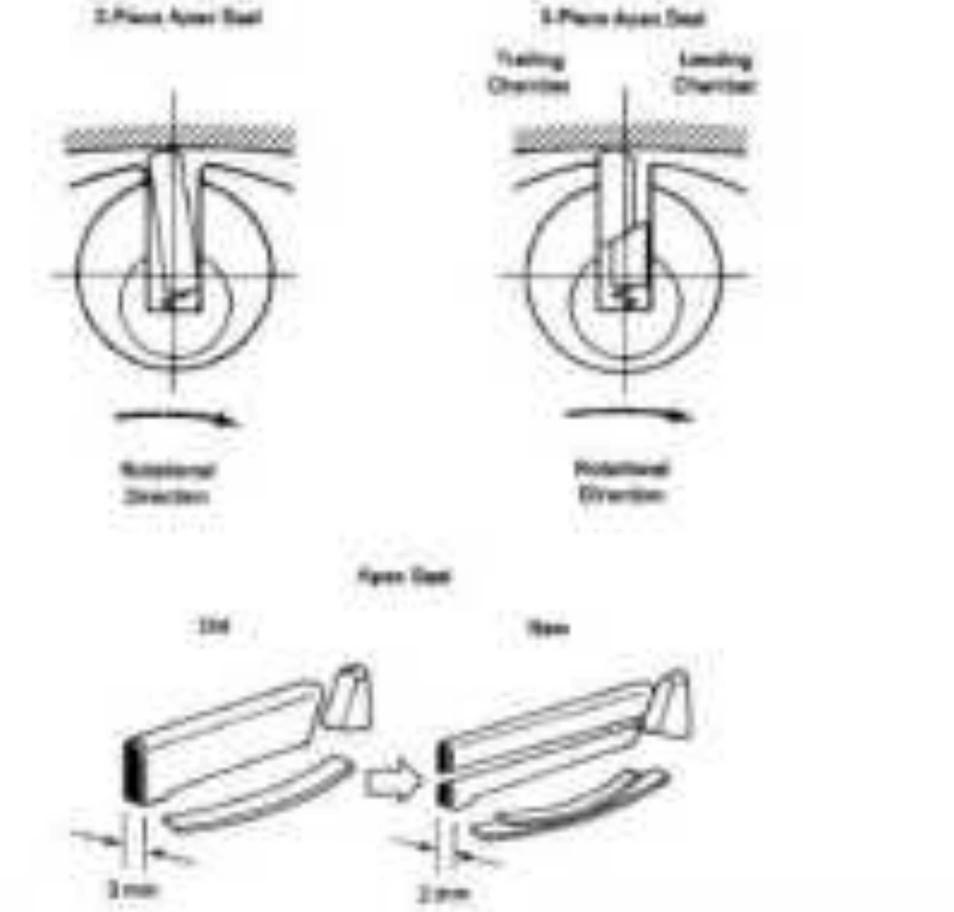


FIGURE 7.11 Design improvements in the apex seals of the Mazda RX-7 rotary engine. (Reprinted with permission. ©1987, Society of Automotive Engineers, Inc.) (See ref. 6.)

CLASSIFICATION OF INTERNAL COMBUSTION ENGINES

3. Operating Cycle

- Otto (For the Conventional SI Engine)
- Atkinson (For Complete Expansion SI Engine)
- Miller (For Early or Late Inlet Valve Closing type SI Engine)
- Diesel (For the Ideal Diesel Engine)
- Dual (For the Actual Diesel Engine)

Engine Information

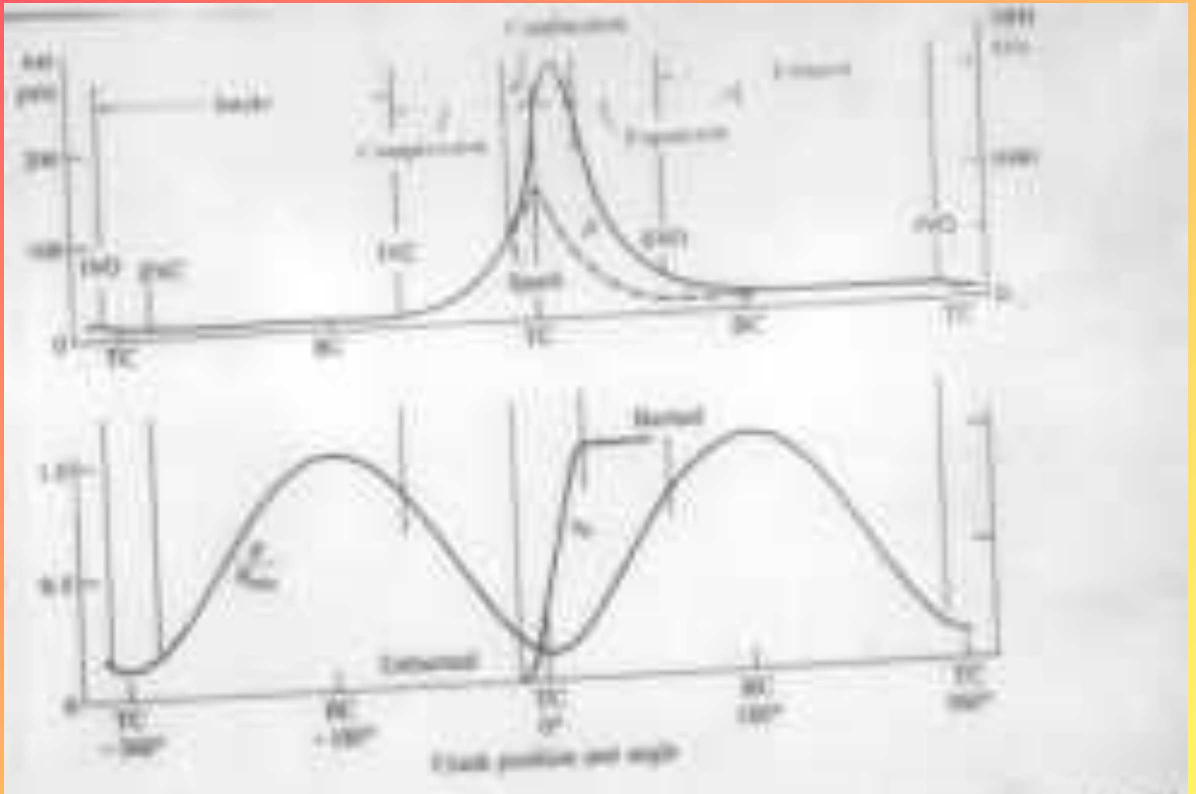


FIGURE 1-4
Sequence of events in four-stroke spark-ignition engine operating cycle. Cylinder pressure p (solid line, firing cycle; dashed line, motored cycle), cylinder volume V/V_{max}, and mass fraction burned x_b are plotted against crank angle.

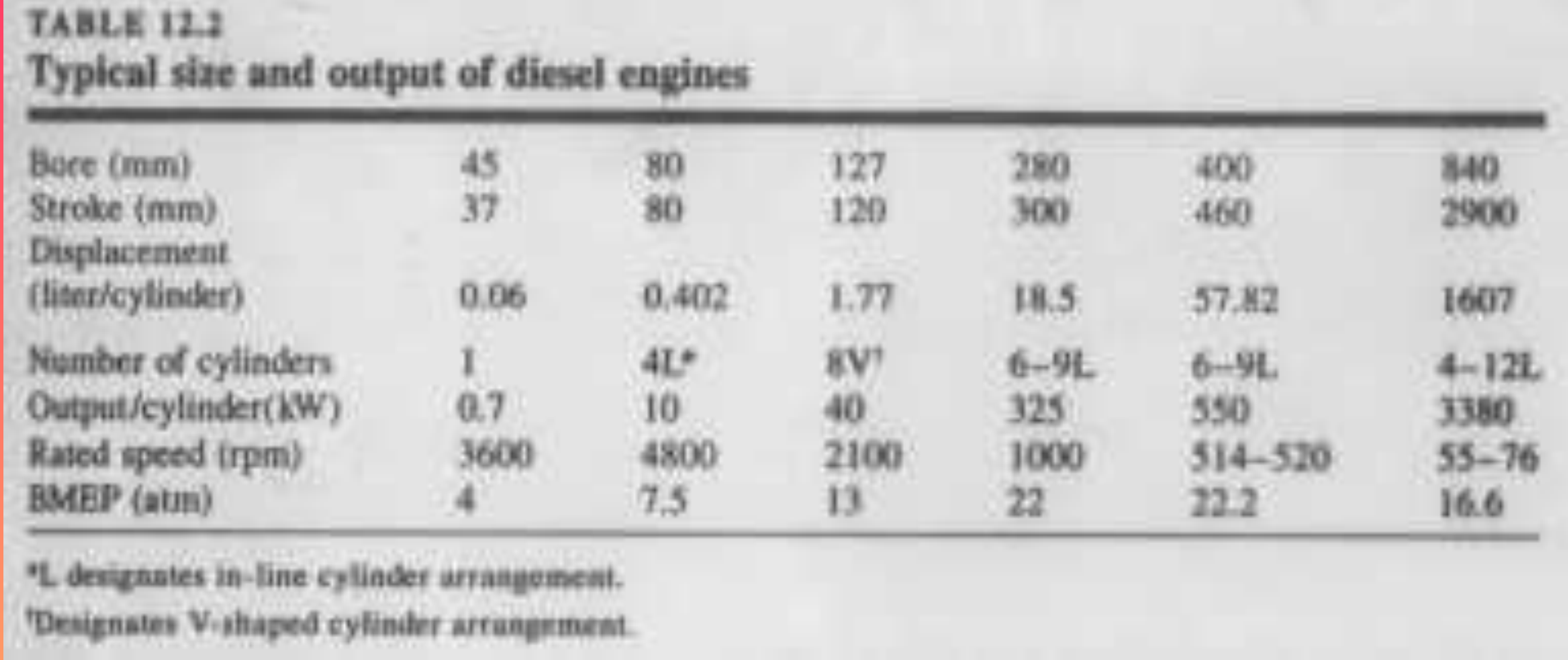


TABLE 12.2

Typical size and output of diesel engines

Bore (mm)	45	80	127	280	400	840
Stroke (mm)	37	80	120	300	460	2900
Displacement (liter/cylinder)	0.06	0.402	1.77	18.5	57.82	1607
Number of cylinders	1	4L*	8V†	6–9L	6–9L	4–12L
Output/cylinder(kW)	0.7	10	40	325	550	3380
Rated speed (rpm)	3600	4800	2100	1000	514–520	55–76
BMEP (atm)	4	7.5	13	22	22.2	16.6

*L designates in-line cylinder arrangement.

†Designates V-shaped cylinder arrangement.

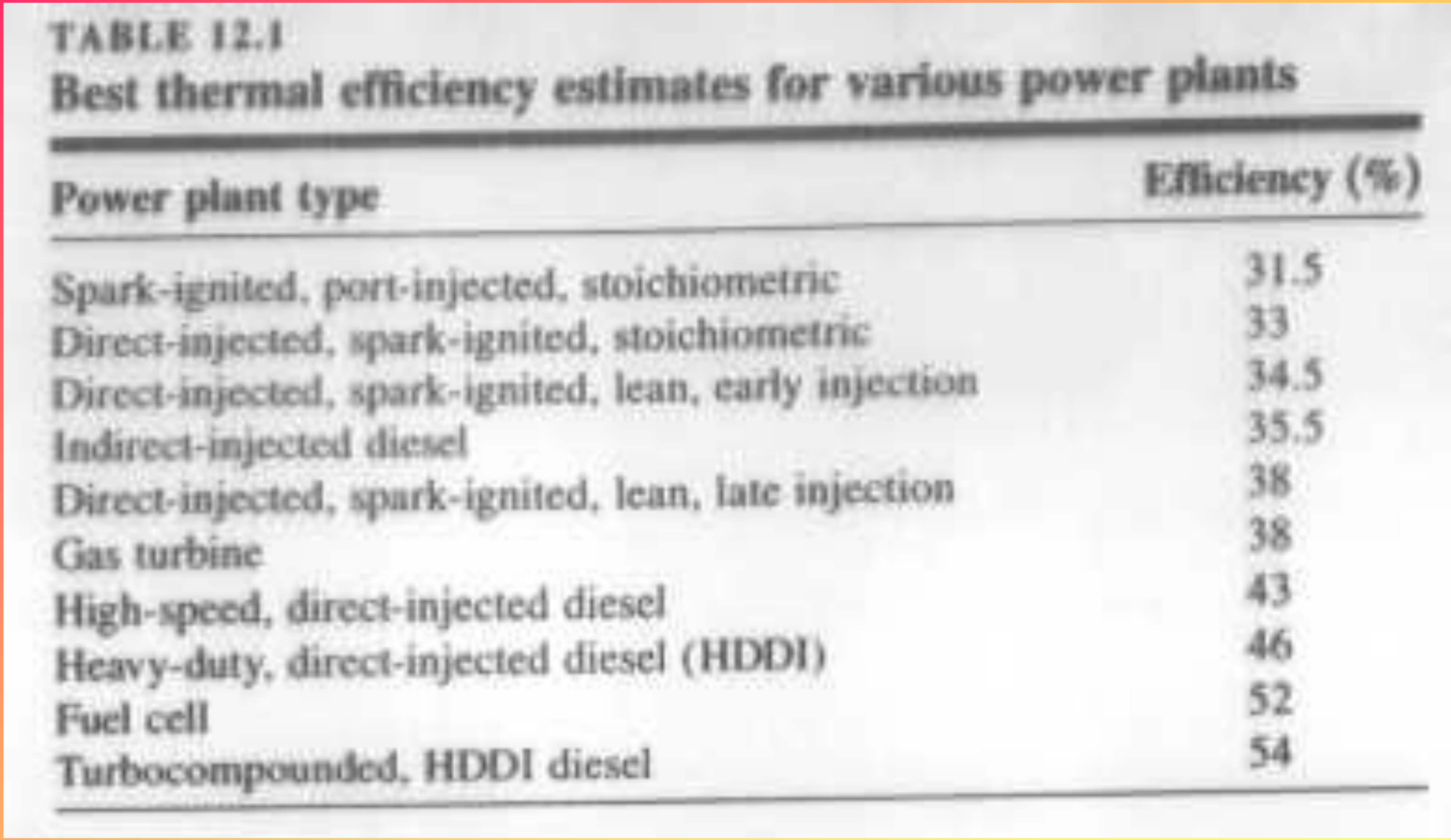


TABLE 12.1

Best thermal efficiency estimates for various power plants

Power plant type	Efficiency (%)
Spark-ignited, port-injected, stoichiometric	31.5
Direct-injected, spark-ignited, stoichiometric	33
Direct-injected, spark-ignited, lean, early injection	34.5
Indirect-injected diesel	35.5
Direct-injected, spark-ignited, lean, late injection	38
Gas turbine	38
High-speed, direct-injected diesel	43
Heavy-duty, direct-injected diesel (HDDI)	46
Fuel cell	52
Turbocompounded, HDDI diesel	54

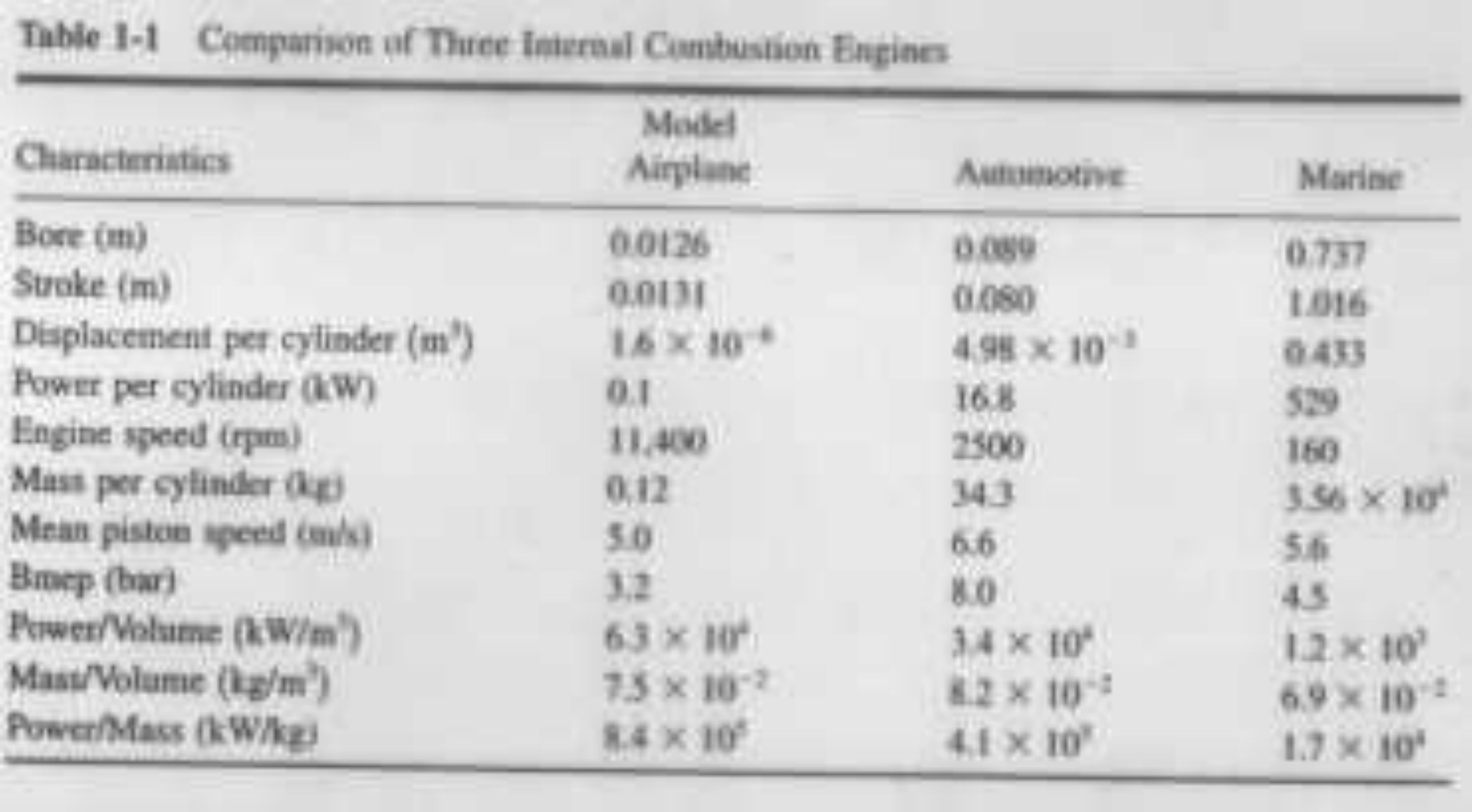


Table 1-1 Comparison of Three Internal Combustion Engines

Characteristics	Model Airplane	Automotive	Marine
Bore (m)	0.0126	0.089	0.737
Stroke (m)	0.0131	0.080	1.016
Displacement per cylinder (m^3)	1.6×10^{-6}	4.98×10^{-3}	0.433
Power per cylinder (kW)	0.1	16.8	529
Engine speed (rpm)	11,400	2500	160
Mass per cylinder (kg)	0.12	34.3	3.56×10^4
Mean piston speed (m/s)	5.0	6.6	5.6
Bmep (bar)	3.2	8.0	4.5
Power/Volume (kW/m^3)	6.3×10^4	3.4×10^4	1.2×10^3
Mass/Volume (kg/m^3)	7.5×10^{-2}	8.2×10^{-2}	6.9×10^{-2}
Power/Mass (kW/kg)	8.4×10^5	4.1×10^5	1.7×10^4

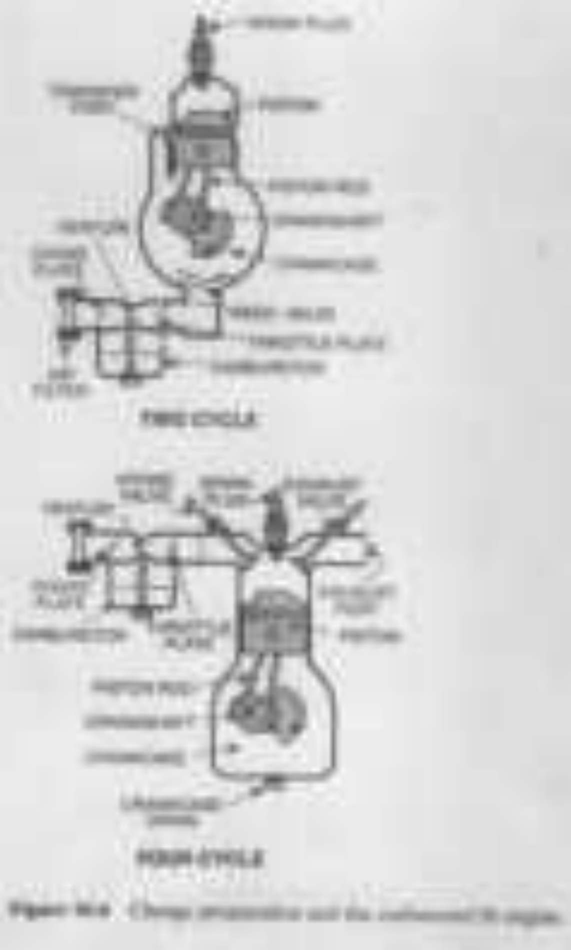
CLASSIFICATION OF INTERNAL COMBUSTION ENGINES

4. Working Cycle (Strokes)

1. Four Stroke Cycle:(a) Naturally Aspirated
   (b)Supercharged/Turbocharged
2. Two Stroke Cycle: (a) Crankcase Scavenged
   (b) Uniflow Scavenged
      (i) Inlet valve/Exhaust Port
      (ii) Inlet Port/Exhaust Valve
      (iii) Inlet and Exhaust Valve

May be Naturally Aspirated
Turbocharged

Four Stroke & Two stroke SI Engines



Four Stroke & Two Stroke CI Engines

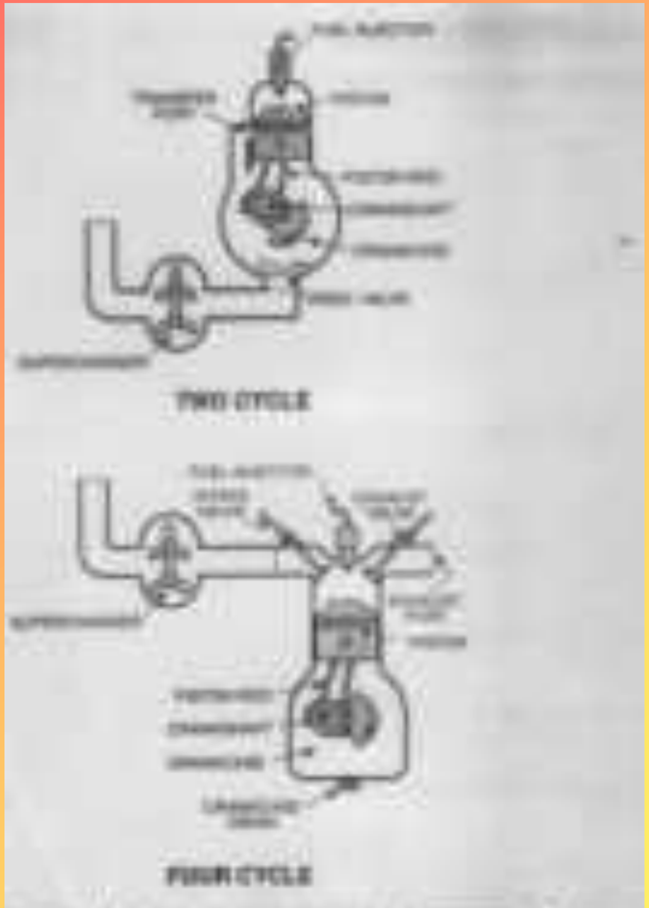
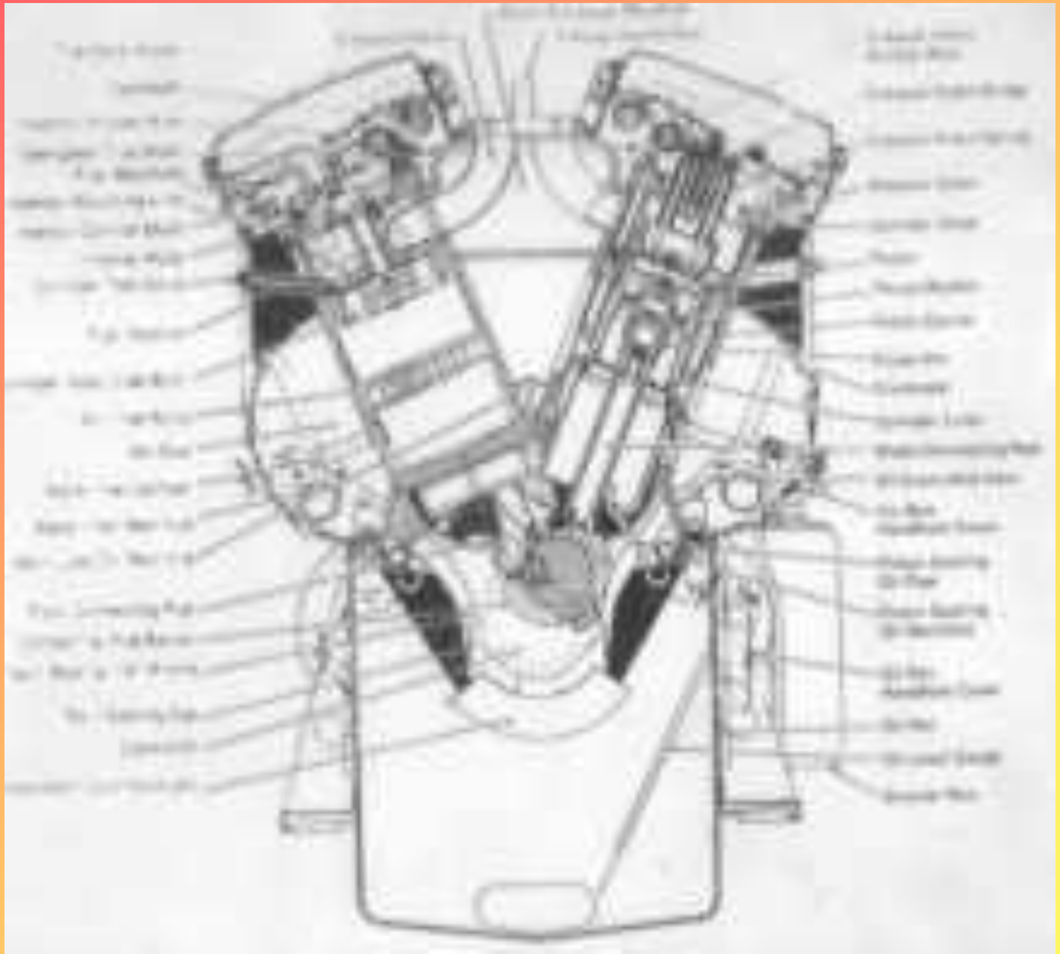
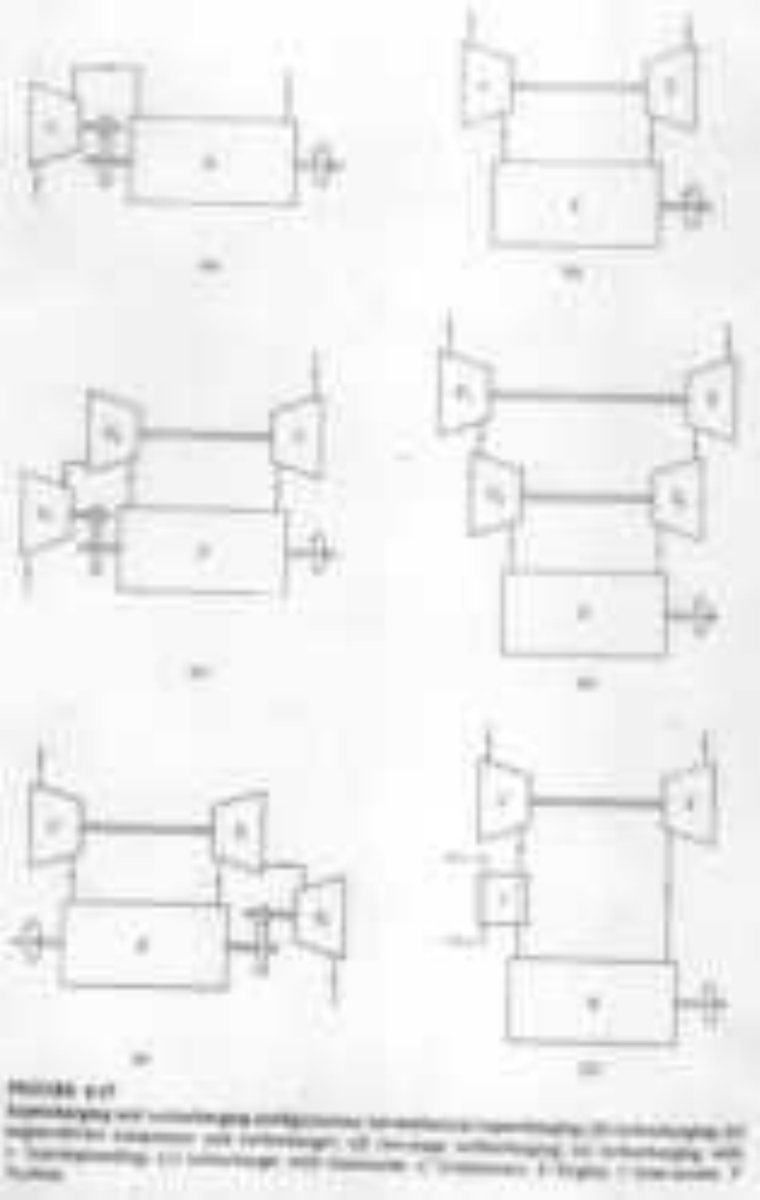


Figure 11.4 Charge preparation and the compression CI engine.

Two-stroke Engine



Supercharging Types



CLASSIFICATION OF INTERNAL COMBUSTION ENGINES

5. (a) Valve/Port Design

1. Poppet Valve
2. Rotary Valve
3. Reed Valve
4. Piston Controlled Porting

5. (b) Valve Location

1. The T-head
2. The L-head
3. The F-head
4. The I-head:
    - (i) Over head Valve (OHV)
    - (ii) Over head Cam (OHC)

Poppet Valve

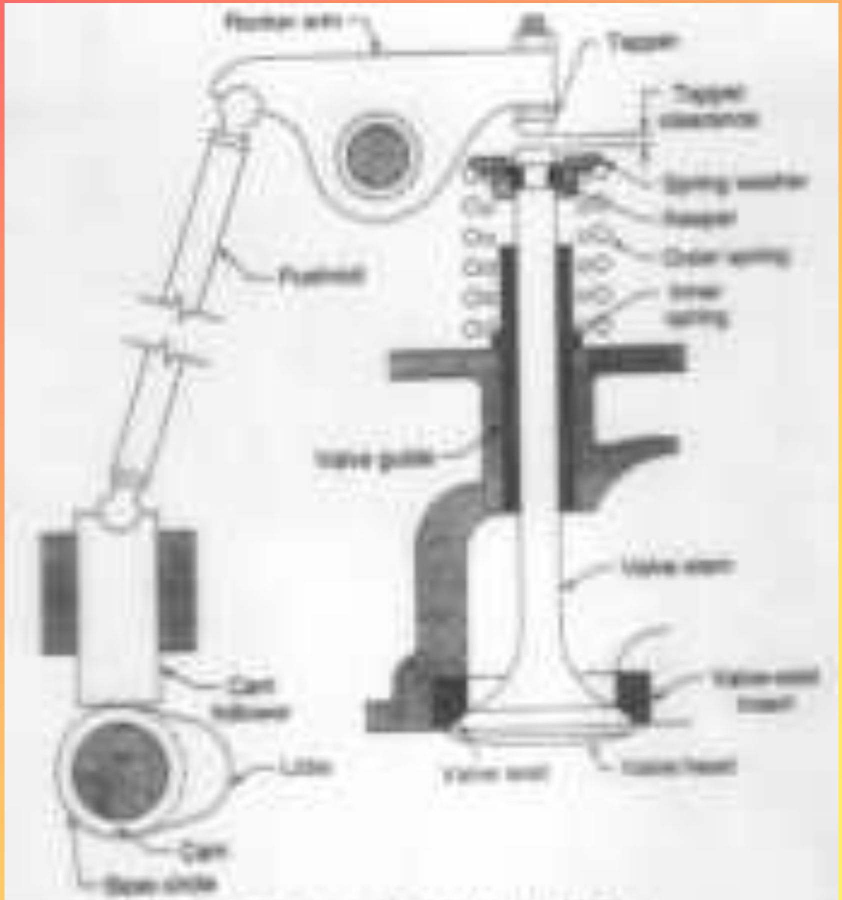


Figure 1-12 Poppet-valve nomenclature (Taylor, 1985).

Valve Locations

Valve Timing Profile

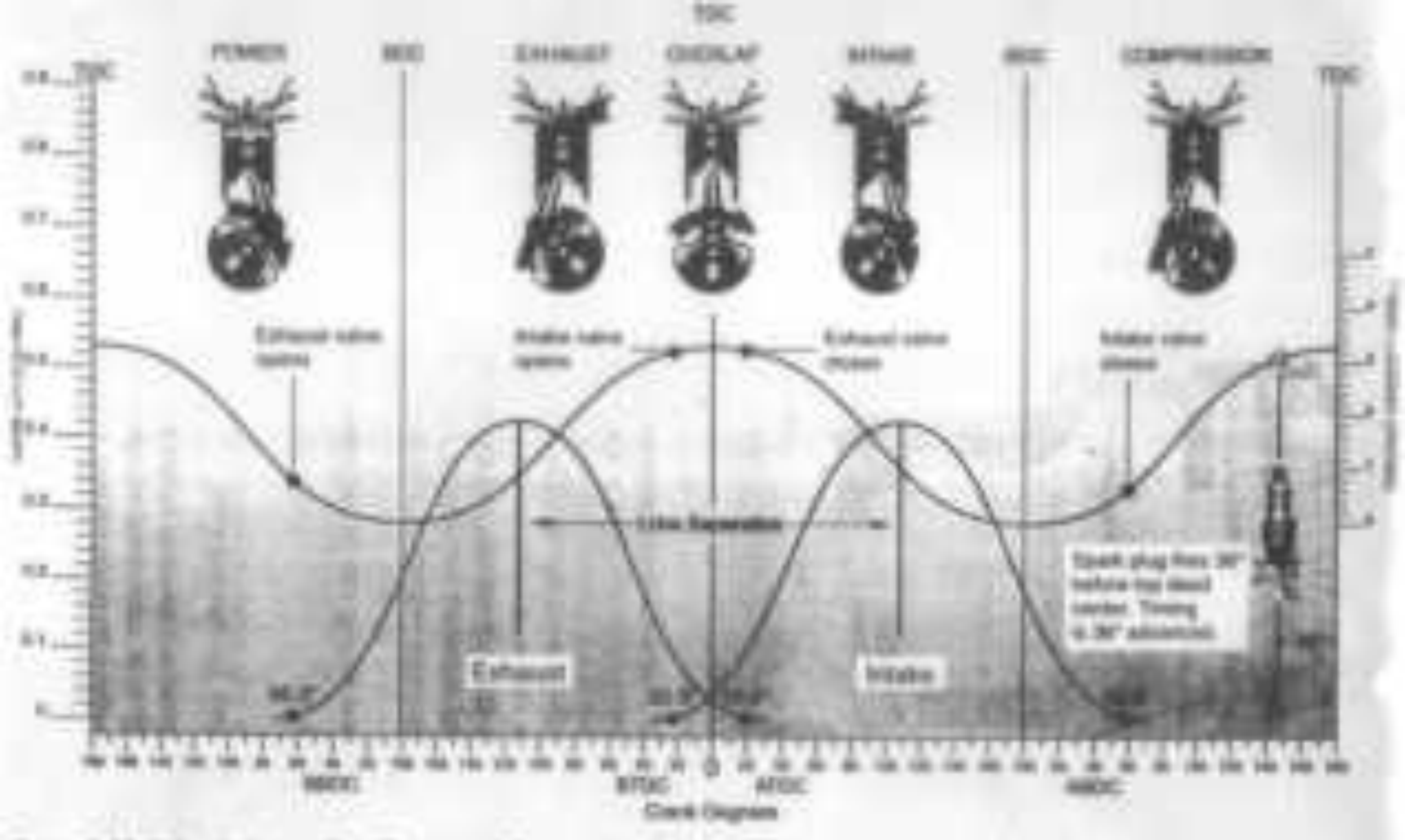


Figure 1-13 Valve timing profile. (Courtesy of Competition Cams, Inc.)

CLASSIFICATION OF INTERNAL COMBUSTION ENGINES

6. Fuel

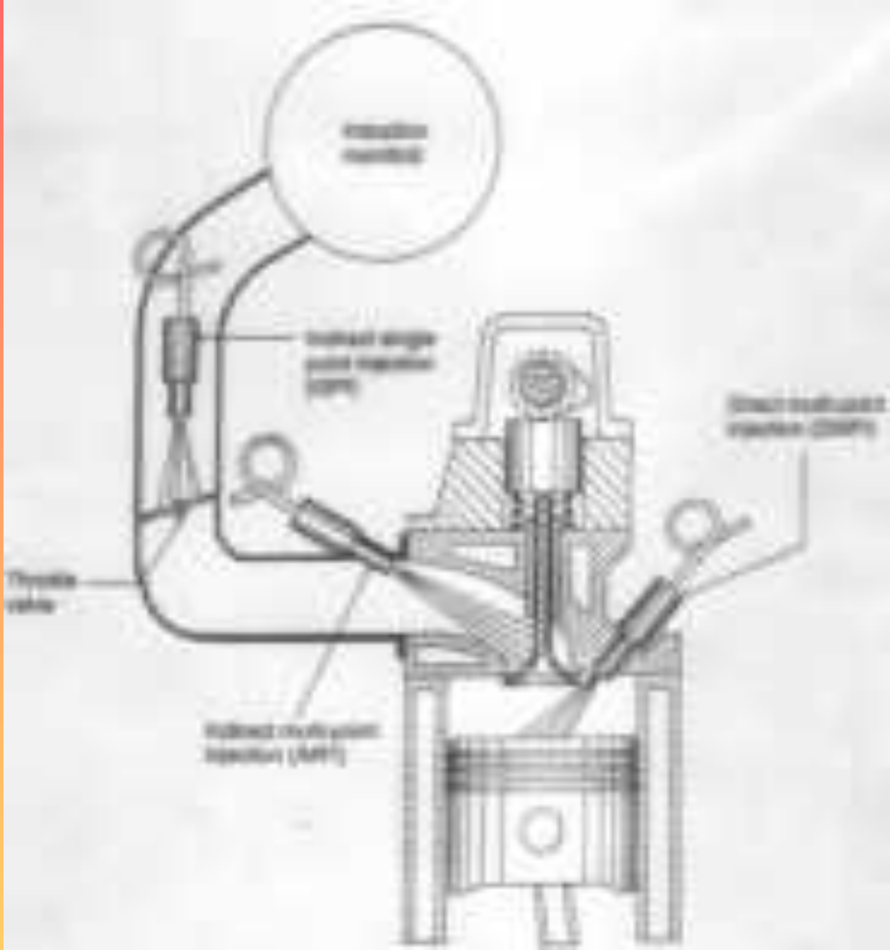
1. Conventional: (a) Crude oil derived (i) Petrol
    - (ii) Diesel
    - (b) Other sources: (i) Coal
        - (ii) Wood (includes bio-mass)
        - (iii)Tar Sands
        - (iv)Shale
2. Alternate: (a) Petroleum derived (i) CNG
    - (ii) LPG
    - (b) Bio-mass Derived (i) Alcohols (methyl and ethyl)
        - (ii) Vegetable oils
        - (iii) Producer gas and biogas
        - (iv) Hydrogen
3. Blending
4. Dual fueling

CLASSIFICATION OF INTERNAL COMBUSTION ENGINES

7. Mixture Preparation

1. Carburetion
2. Fuel Injection
   - (i) Diesel
   - (ii) Gasoline
     - (a) Manifold
     - (b) Port
     - (c) Cylinder

Gasoline Fuel Injection



CLASSIFICATION OF INTERNAL COMBUSTION ENGINES

8. Ignition

1. Spark Ignition
   - (a) Conventional
     - (i) Battery
     - (ii) Magneto
   - (b) Other methods
2. Compression Ignition

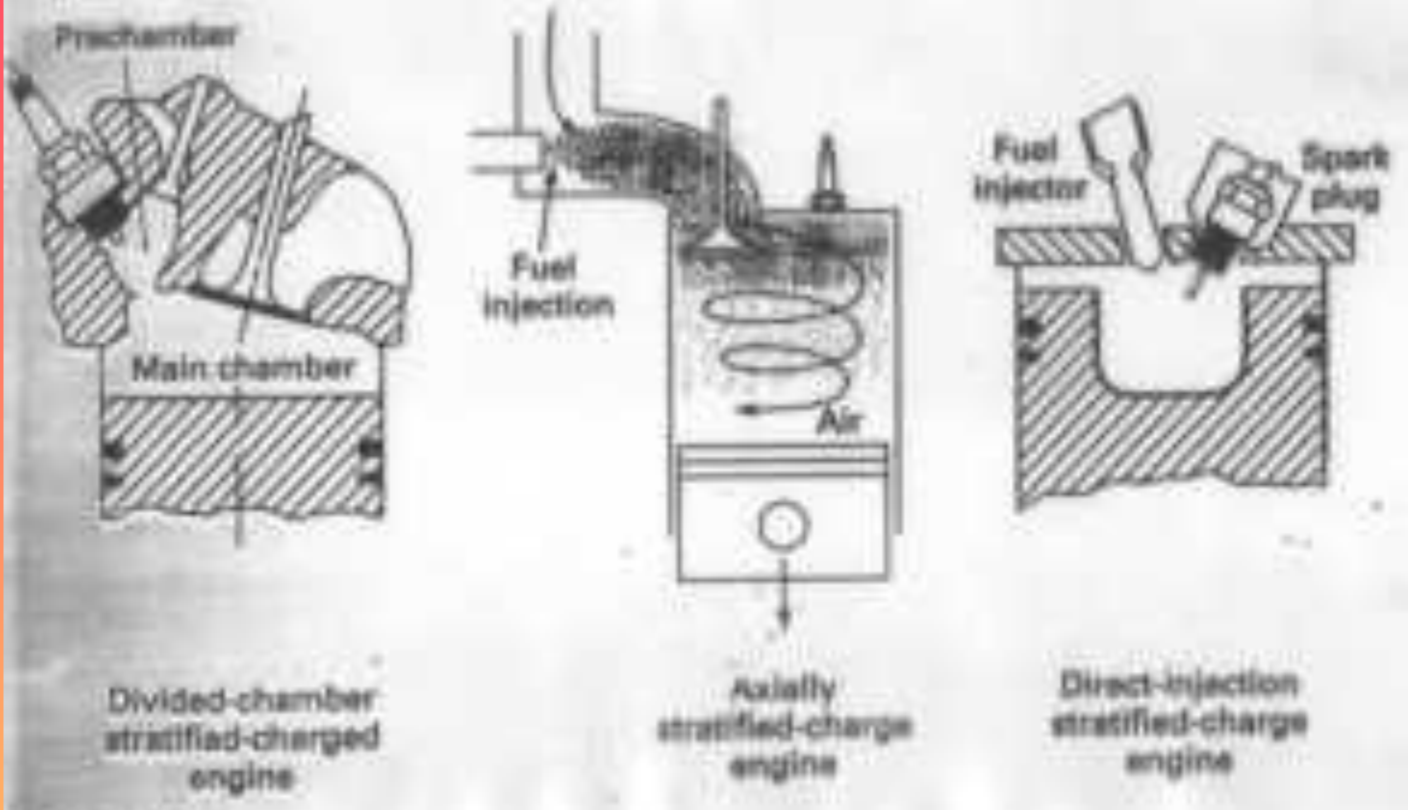
CLASSIFICATION OF INTERNAL COMBUSTION ENGINES

9. Charge Stratification

1. Homogeneous Charge (Also Pre-mixed charge)

2. Stratified Charge (i) With carburetion
   (ii) With fuel injection

Charge Stratification



Divided-chamber stratified-charged engine

Axially stratified-charge engine

Direct-injection stratified-charge engine

IGURE 7.20
ypes of spark-ignited-stratified charge engines [Amann, by courtesy of General Motors Corp.]

Compression Stroke

Both valves closed, Fuel/air mixture is compressed by rising piston. Spark ignites mixture near end of stroke.

Power Stroke

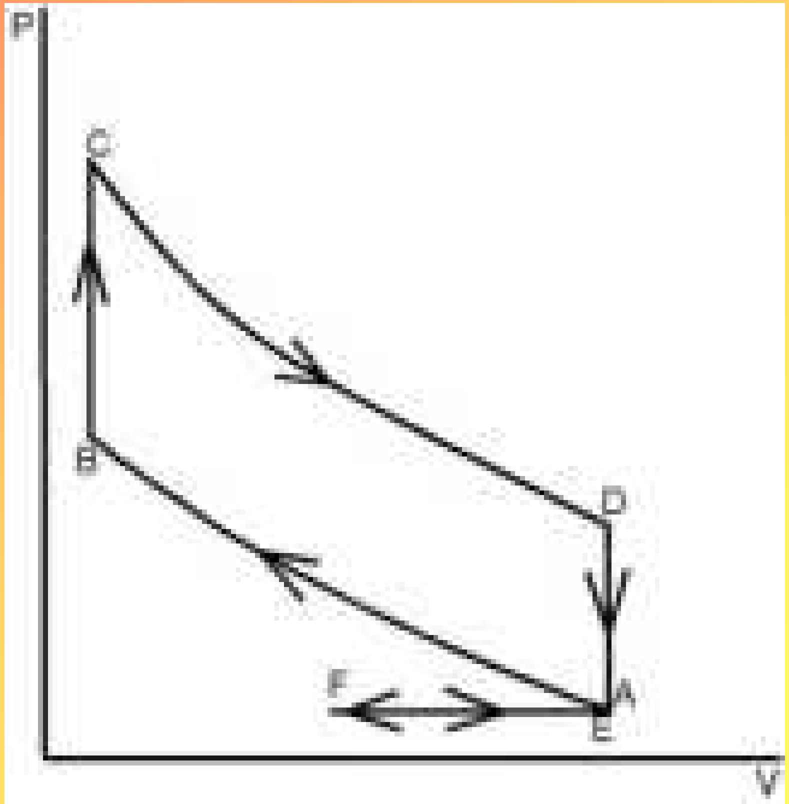
Fuel-air mixture burns, increasing temperature and pressure, expansion of combustion gases drives piston down. Both valves closed – exhaust valve opens near end of stroke

Exhaust Stroke

Exhaust valve open, exhaust products are displaced from cylinder.Intake valve opens near end of stroke.

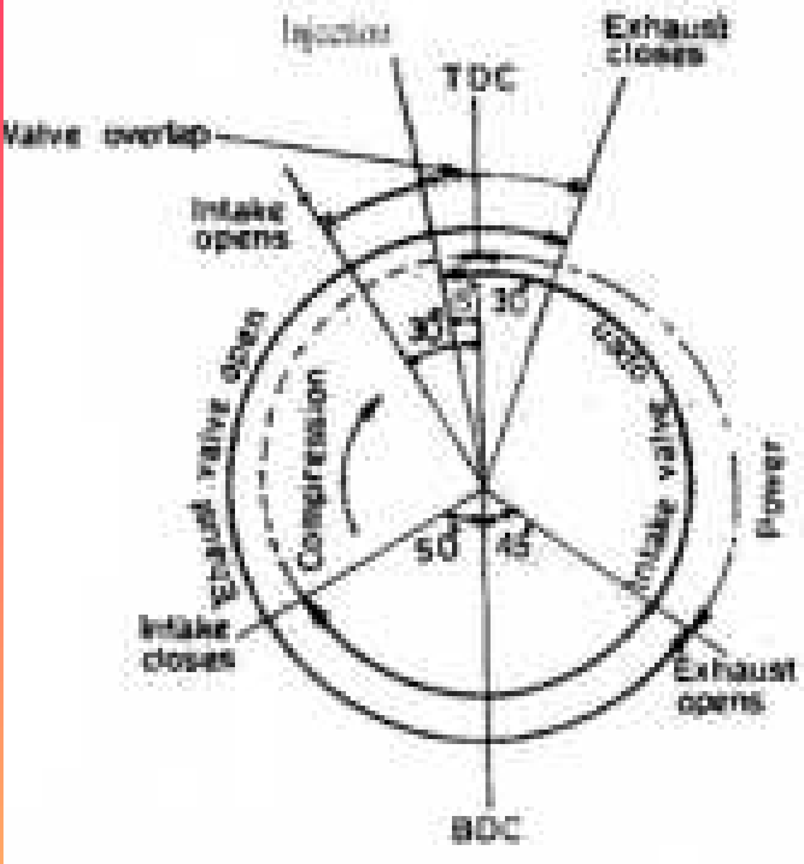
Four basic steps or strokes:

1. An intake stroke that draws a combustible mixture of fuel and air into the cylinder
2. A compression stroke with the valves closed which raises the temperature of the mixture. A spark ignites the mixture towards the end of this stroke.
3. An expansion or power stroke. Resulting from combustion.
4. An Exhaust stroke the pushes the burned contents out of the cylinder



The image part with relationship ID rId2 was not found in the file.

Ideal & Actual Indicator
Diagrams For 4-stroke SI Engine



[Valve Timing
Diagram for 4-stroke CI Engine]