Thermal Engineering-II
MODULE-1

Introduction

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Department of Mechanical Engineering

<table>
<tr><td>2018-19
Onwards
(MR-18)</td><td>MALLA REDDY ENGINEERING COLLEGE
(Autonomous)</td><td colspan="3">B.Tech.
V Semester</td></tr>
<tr><td>Code: 80324</td><td rowspan="2">THERMAL ENGINEERING - II
<i>(Use of standard Steam Tables is permitted)</i></td><td>L</td><td>T</td><td>P</td></tr>
<tr><td>Credits: 3</td><td>3</td><td>-</td><td>-</td></tr>
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Prerequisites: Thermal Engineering - I

Course Objectives:

The objective of this subject is to provide knowledge about different cycle used in power plants, combustion of fuels and to provide knowledge about boilers, Steam Turbines, Steam Condensers & Steam Nozzles, Gas Turbines, Jet Propulsion & Rockets and their principle of operations.

MODULE I: Basic Concepts 10 Periods

Basic Concepts: Rankine cycle - Schematic layout, Thermodynamic Analysis, Concept of Mean Temperature of Heat addition, Methods to improve cycle performance – Regeneration & reheating. Combustion: Fuels and combustion, concepts of heat of reaction, adiabatic flame temperature, stoichiometry and flue gas analysis.

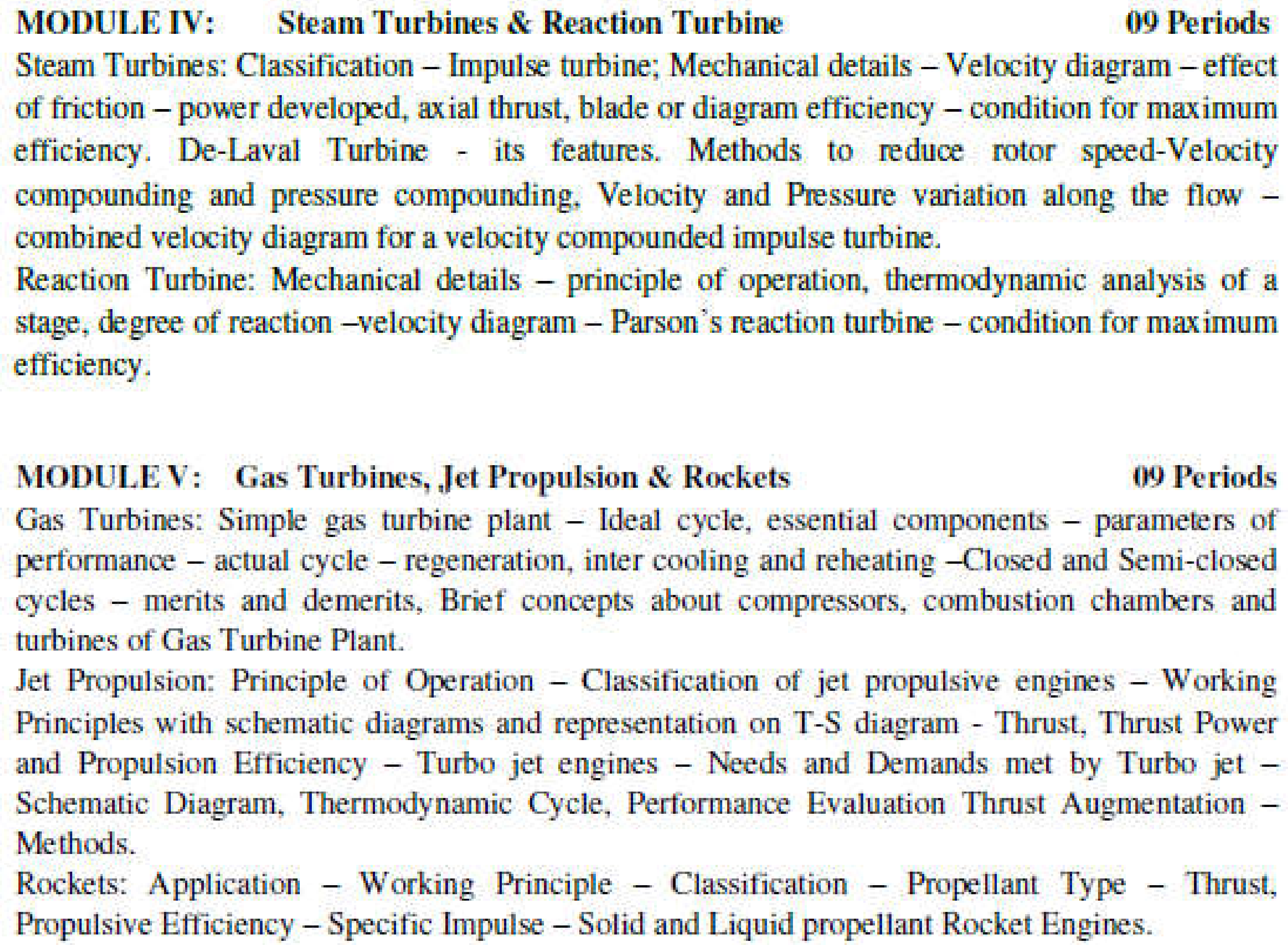
MODULE II: Boilers 10 Periods

Boilers : Classification – Working principles – with sketches including H.P. boilers – Mountings and Accessories – Working principles, Boiler horse power, equivalent evaporation, efficiency and heat balance – Draught, classification – Height of chimney for given draught and discharge, condition for maximum discharge, efficiency of chimney – artificial draught, induced and forced draught.

MODULE III: Steam Condensers & Steam Nozzles 10 Periods

A: Steam Condensers: Requirements of steam condensing plant – Classification of condensers – working principle of different types of condensers vacuum efficiency and condenser efficiency – air leakage, sources and its effects, air pump- cooling water requirement.

B: Steam Nozzles: Function of nozzle – applications - types, Flow through nozzles, thermodynamic analysis – assumptions -velocity of nozzle at exit-Ideal and actual expansion in nozzle, velocity coefficient, condition for maximum discharge, critical pressure ratio, criteria to decide nozzle shape: Super saturated flow, its effects, degree of super saturation and degree of under cooling - Wilson line.



MODULE IV: Steam Turbines & Reaction Turbine 09 Periods

Steam Turbines: Classification – Impulse turbine; Mechanical details – Velocity diagram – effect of friction – power developed, axial thrust, blade or diagram efficiency – condition for maximum efficiency. De-Laval Turbine - its features. Methods to reduce rotor speed-Velocity compounding and pressure compounding, Velocity and Pressure variation along the flow – combined velocity diagram for a velocity compounded impulse turbine.

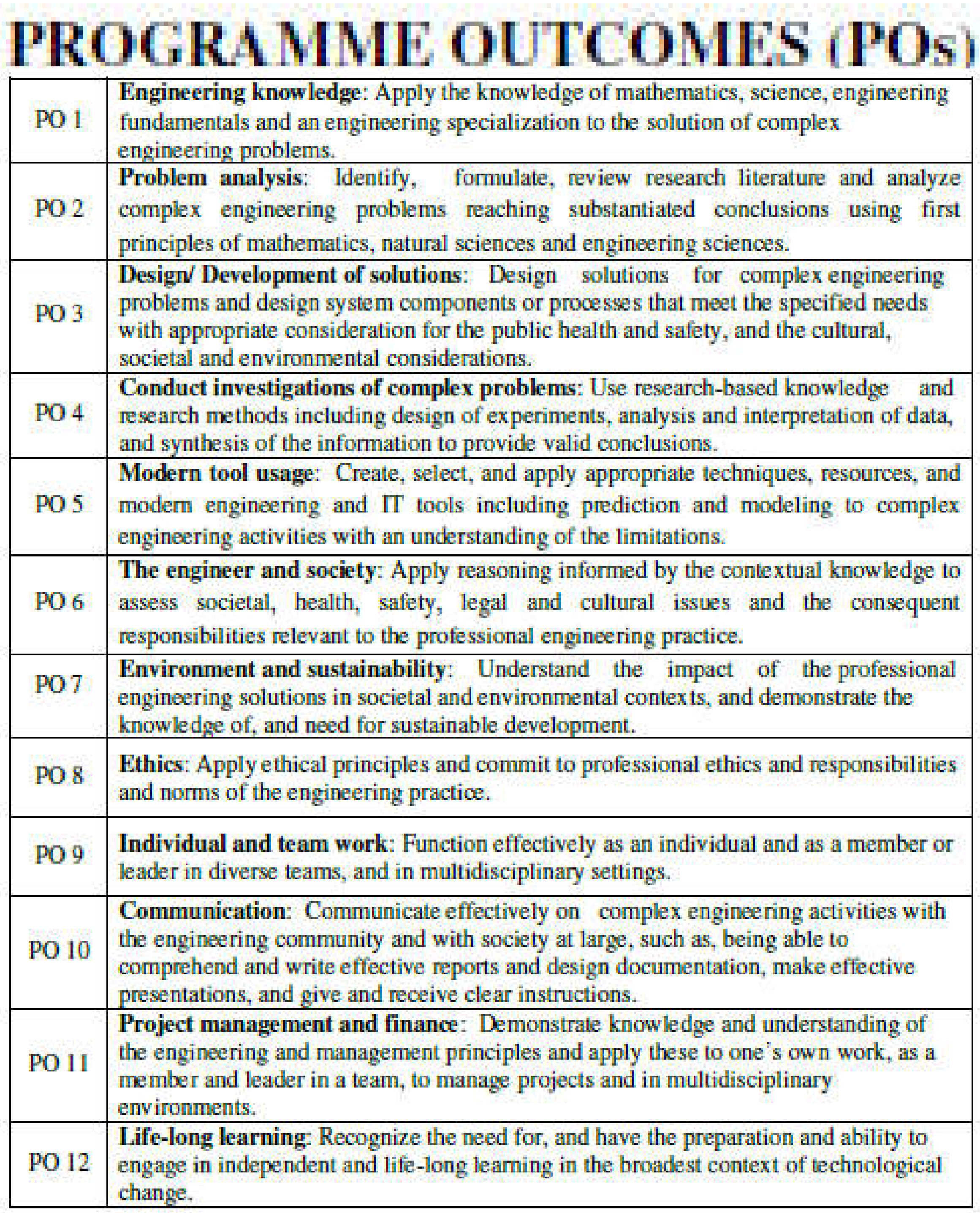
Reaction Turbine: Mechanical details – principle of operation, thermodynamic analysis of a stage, degree of reaction –velocity diagram – Parson's reaction turbine – condition for maximum efficiency.

MODULE V: Gas Turbines, Jet Propulsion & Rockets 09 Periods

Gas Turbines: Simple gas turbine plant – Ideal cycle, essential components – parameters of performance – actual cycle – regeneration, inter cooling and reheating –Closed and Semi-closed cycles – merits and demerits, Brief concepts about compressors, combustion chambers and turbines of Gas Turbine Plant.

Jet Propulsion: Principle of Operation – Classification of jet propulsive engines – Working Principles with schematic diagrams and representation on T-S diagram - Thrust, Thrust Power and Propulsion Efficiency – Turbo jet engines – Needs and Demands met by Turbo jet – Schematic Diagram, Thermodynamic Cycle, Performance Evaluation Thrust Augmentation – Methods.

Rockets: Application – Working Principle – Classification – Propellant Type – Thrust, Propulsive Efficiency – Specific Impulse – Solid and Liquid propellant Rocket Engines.



PROGRAMME OUTCOMES (POs)

PO 1	**Engineering knowledge**: Apply the knowledge of mathematics, science, engineering fundamentals and an engineering specialization to the solution of complex engineering problems.
PO 2	**Problem analysis**: Identify, formulate, review research literature and analyze complex engineering problems reaching substantiated conclusions using first principles of mathematics, natural sciences and engineering sciences.
PO 3	**Design/ Development of solutions**: Design solutions for complex engineering problems and design system components or processes that meet the specified needs with appropriate consideration for the public health and safety, and the cultural, societal and environmental considerations.
PO 4	**Conduct investigations of complex problems**: Use research-based knowledge and research methods including design of experiments, analysis and interpretation of data, and synthesis of the information to provide valid conclusions.
PO 5	**Modern tool usage**: Create, select, and apply appropriate techniques, resources, and modern engineering and IT tools including prediction and modeling to complex engineering activities with an understanding of the limitations.
PO 6	**The engineer and society**: Apply reasoning informed by the contextual knowledge to assess societal, health, safety, legal and cultural issues and the consequent responsibilities relevant to the professional engineering practice.
PO 7	**Environment and sustainability**: Understand the impact of the professional engineering solutions in societal and environmental contexts, and demonstrate the knowledge of, and need for sustainable development.
PO 8	**Ethics**: Apply ethical principles and commit to professional ethics and responsibilities and norms of the engineering practice.
PO 9	**Individual and team work**: Function effectively as an individual and as a member or leader in diverse teams, and in multidisciplinary settings.
PO 10	**Communication**: Communicate effectively on complex engineering activities with the engineering community and with society at large, such as, being able to comprehend and write effective reports and design documentation, make effective presentations, and give and receive clear instructions.
PO 11	**Project management and finance**: Demonstrate knowledge and understanding of the engineering and management principles and apply these to one's own work, as a member and leader in a team, to manage projects and in multidisciplinary environments.
PO 12	**Life-long learning**: Recognize the need for, and have the preparation and ability to engage in independent and life-long learning in the broadest context of technological change.

PROGRAMME SPECIFIC OUTCOMES (PSOs)

PSO1: Understand the problem and apply design and analysis tools to find solution in the domains of Structural, thermal and Fluid Mechanics.

PSO2: Engage professionally in industries or as an entrepreneur by applying Manufacturing concepts.

PSO3: Systemize the Engineering and manufacturing practices using TQM concepts and Optimization techniques.

Course Outcomes

At the end of the course, students will be able to

1. Understand different cycles used in power plant.
2. Understand working principles of boiler and its accessories.
3. Analyse the performance of steam nozzle and condenser.
4. Analyse the performance of steam and reaction turbine.
5. Analyse the performance of gas turbines and jet propulsions.

CO- PO Mapping
(3/2/1 indicates strength of correlation) 3-Strong, 2-Medium, 1-Weak

COs	Programme Outcomes(POs)												PSOs		
	PO1	PO2	PO3	PO4	PO5	PO6	PO7	PO8	PO9	PO10	PO11	PO12	PSO1	PSO2	PSO3
CO1	2			3	1	1						2	3		
CO2	2			3	1	1						2	3		
CO3	2			3	1	1						2	3		
CO4	2			3	1	1						2	3		
CO5	2			3	1	1						2	3		

TEXT BOOKS

1. R.K. Rajput, "**Thermal Engineering**", Lakshmi Publications, 10th edition, 2017.
2. V.Ganesan "**Gas Turbines**", TMH Publishers, 3rd edition, 2010.

REFERENCES

1. R. Yadav "**Thermodynamics and Heat Engines**", Central Book Depot,7th edition, 2007.
2. P.Khajuria & S.P.Dubey "**Gas Turbines and Propulsive Systems**", Dhanpatrai Publications, 2012.
3. Cohen, Rogers and Saravana Muttoo, Addison Wesley – Longman "**Gas Turbines**", Pearson publishers, 5th edition, 2001.
4. P.L.Bellaney "**Thermal Engineering**", khanna publishers. 5th edition, 2010.
5. M.L.Marthur & Mehta "**Thermal Engineering**", Jain bros Publishers, 3rd edition, 2014.

E - RESOURCES

1. http://nptel.ac.in/courses/112106133/
2. https://www.journals.elsevier.com/applied-thermal-engineering
3. http://www.personal.utulsa.edu/~kenneth-weston/chapter5.pdf
4. https://www.irjet.net/archives/V2/i5/IRJET-V2I5185.pdf
5. http://nptel.ac.in/courses/114105029/
6. http://nptel.ac.in/courses/108105058/

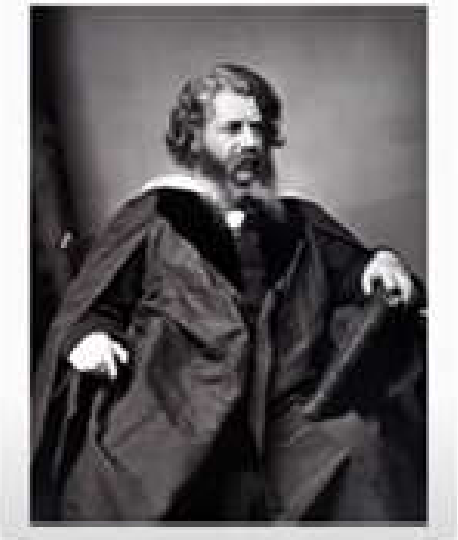
Work Producing Cycle's		Work Consuming Cycle's
1. Carnot Cycle		1. Reversed Carnot Cycle
2. Stirling Cycle	These cycles are rarely used	2. Vapour Absorption Cycle
3. Ericson Cycle		3. Vapour Compression Cycle
4. Lenior Cycle		4. Bell Coleman Cycle (or) Reversed Brayton Cycle
5. Atkinson Cycle		
6. Otto Cycle	Used in Automobiles	
7. Diesel Cycle		
8. Duel Cycle		
9. Brayton Cycle	Gas Turbine	
10. Rankin Cycle	Steam Power Plant	

MODULE-1

Lecture on **Rankine Cycle**

INTRODUCTION

- Who is Rankine and What is Rankine Cycle?
- A Scottish CIVIL ENGINEER, physicist and mathematician. He was a founding contributor, with Rudolf Clausius and William Thomson, to the science of thermodynamics, particularly focusing on the first of the three thermodynamic laws.
- The Rankine cycle is a cycle that converts heat into work. The heat is supplied externally to a closed loop, which usually uses water. This cycle generates about 90% of all electric power used throughout the world.



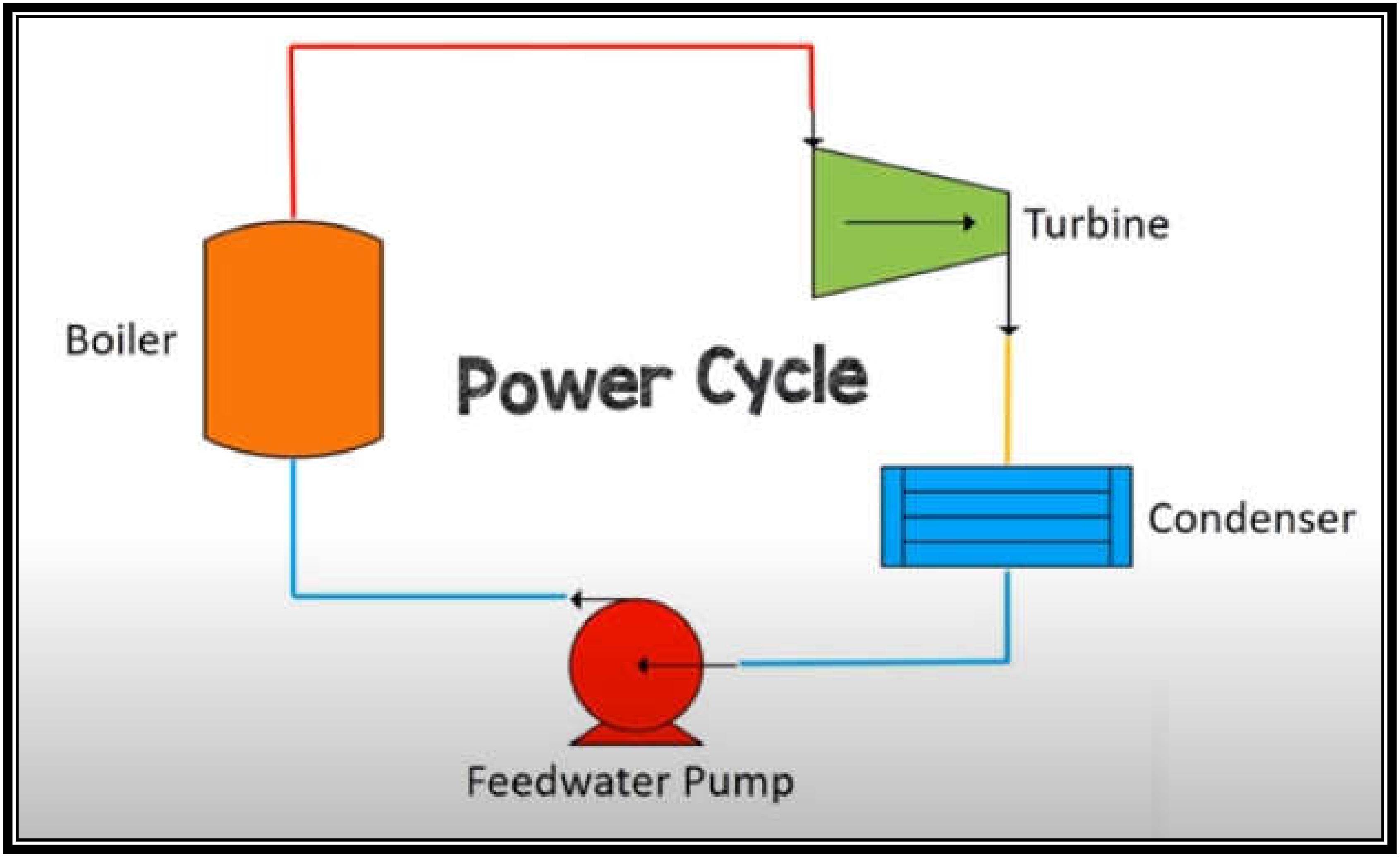
Macquorn Rankine

William John Macquorn Rankine

Rankine cycle is an external combustion engine in which:-

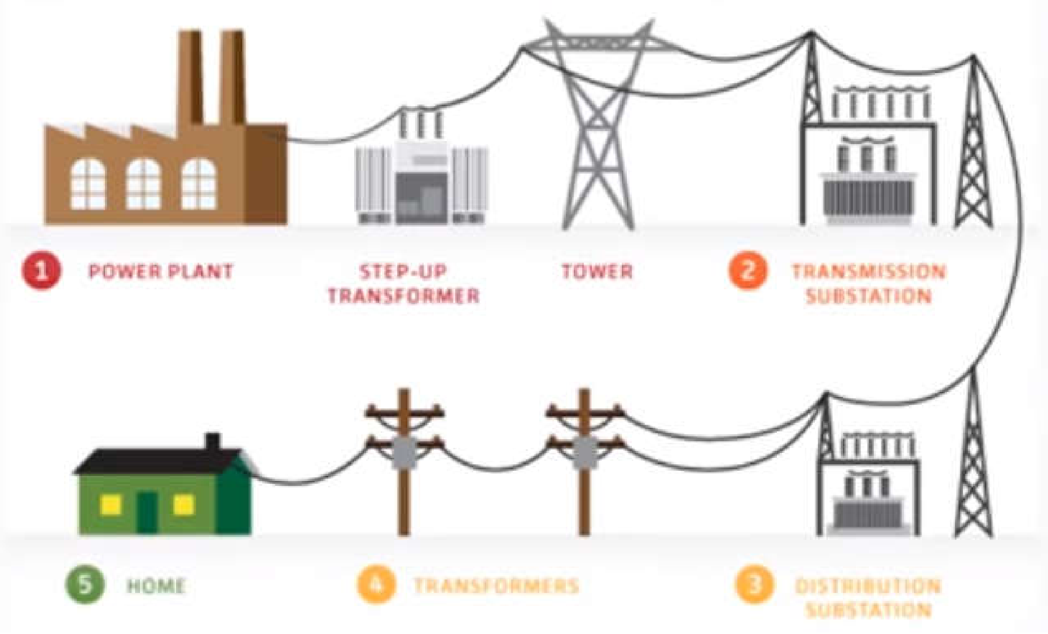
- High energy steam is developed in a boiler
- It is passed through a turbine to develop power.
- The exit steam from turbine then passed through a condenser to convert it into liquid water.
- The liquid water is sent back by the help of a pump to the boiler for generation of steam.

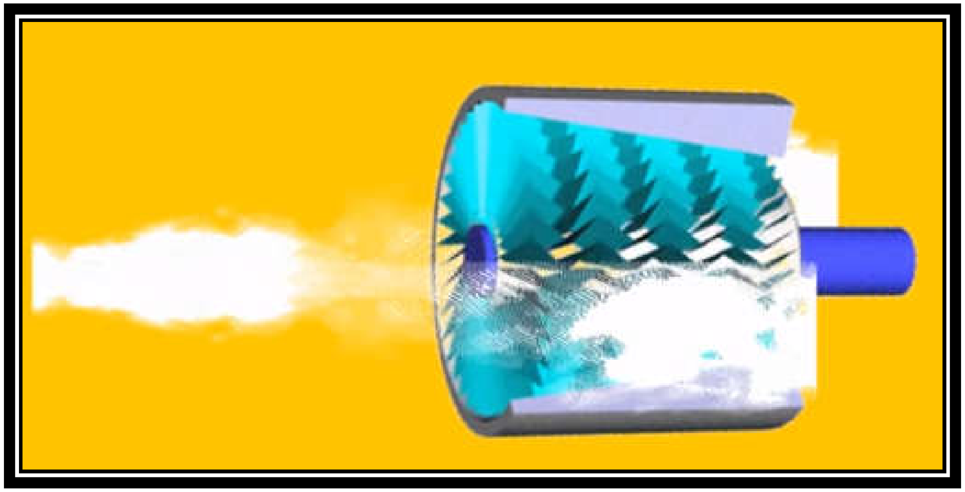
Rankine Cycle

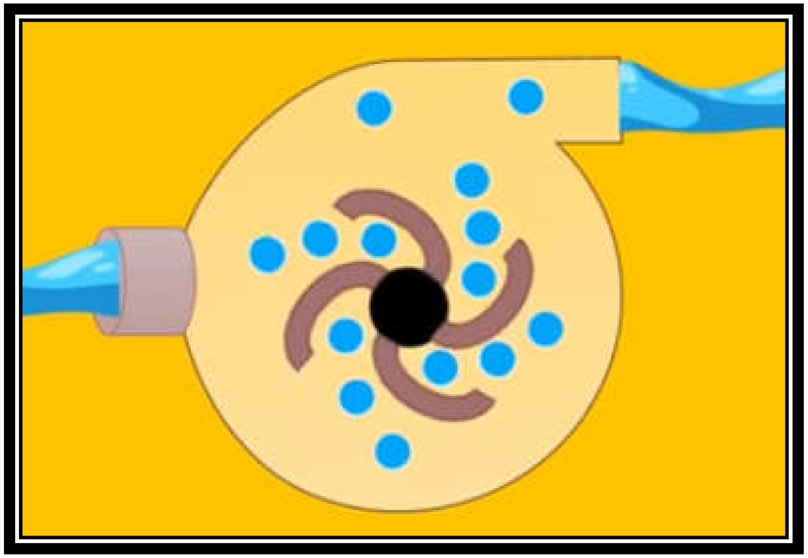


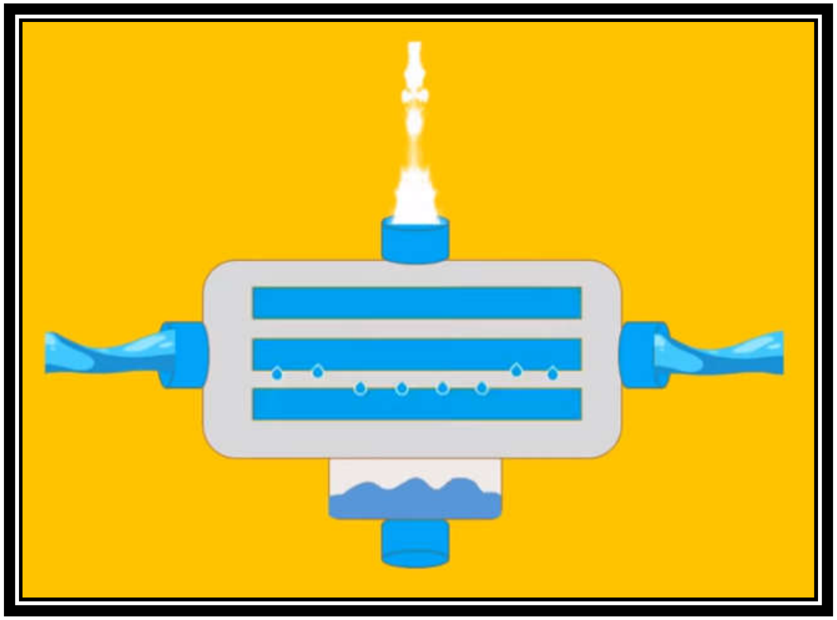
Types of fuel used

Converts mechanical energy to electrical energy



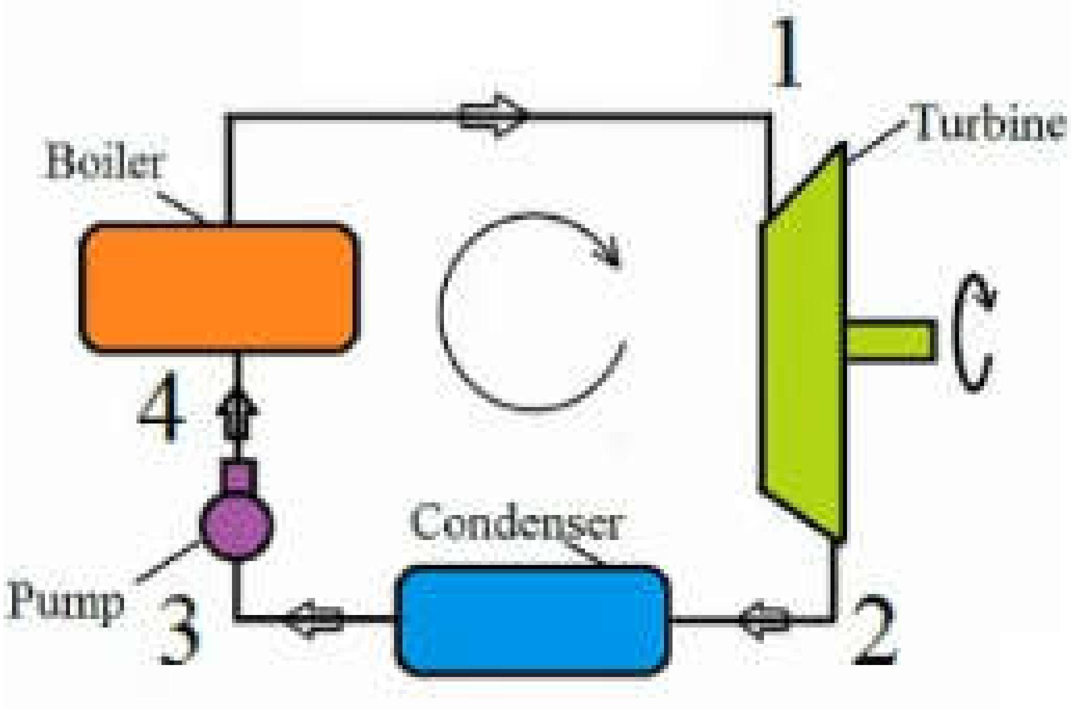






The Rankine cycle It comprises of the following *processes* :

Process 1-2 : Reversible adiabatic expansion in the turbine (or steam engine).
Process 2-3 : Constant-pressure transfer of heat in the condenser.
Process 3-4 : Reversible adiabatic pumping process in the feed pump.
Process 4-1 : Constant-pressure transfer of heat in the boiler.

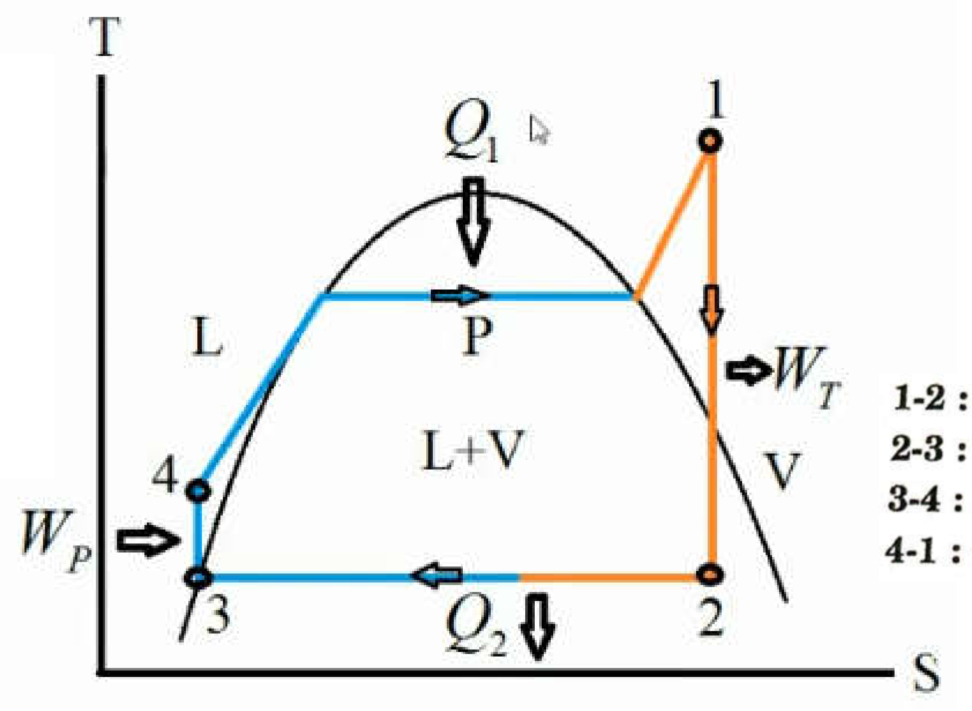


$$\eta = \frac{W_T - W_P}{Q}$$

$$\eta = \frac{(h_1 - h_2) - (h_4 - h_3)}{h_1 - h_4}$$

(Pump Neglected)

$$\eta = \frac{(h_1 - h_2)}{h_1 - h_4}$$

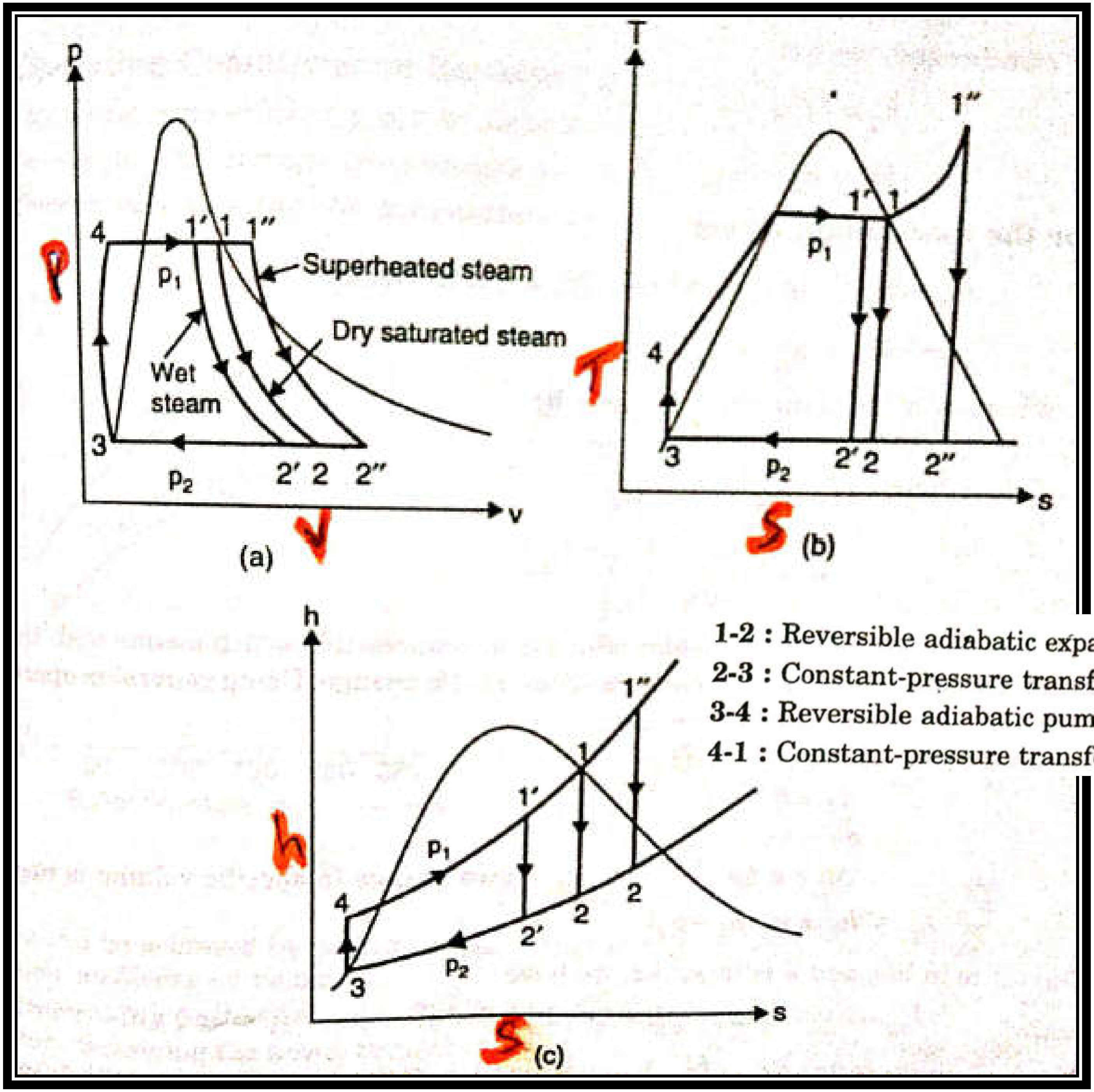


1-2 : Reversible adiabatic expansion in the turbine

2-3 : Constant-pressure transfer of heat in the condenser

3-4 : Reversible adiabatic pumping process in the feed pump

4-1 : Constant-pressure transfer of heat in the boiler



1-2 : Reversible adiabatic expansion in the turbine
2-3 : Constant-pressure transfer of heat in the condenser
3-4 : Reversible adiabatic pumping process in the feed pump
4-1 : Constant-pressure transfer of heat in the boiler

Considering 1 kg of fluid :

Applying *steady flow energy equation* (S.F.E.E.) to boiler, turbine, condenser and pump :

(*i*) **For boiler** (as control volume), we get

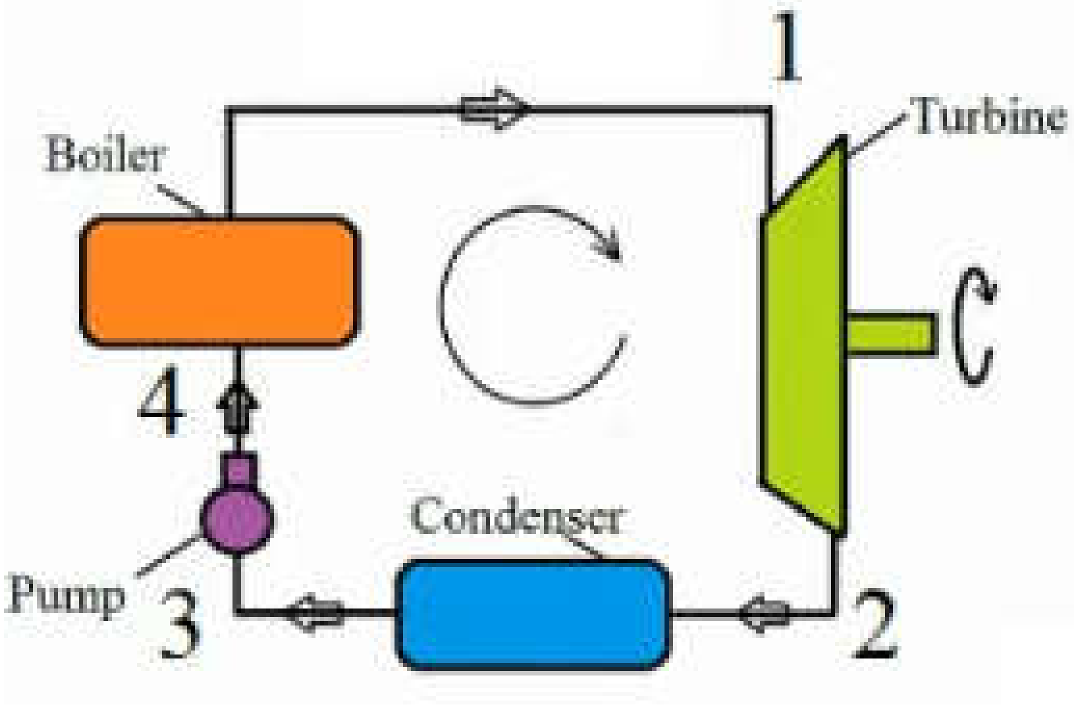
$$h_{f_4} + Q_1 = h_1$$

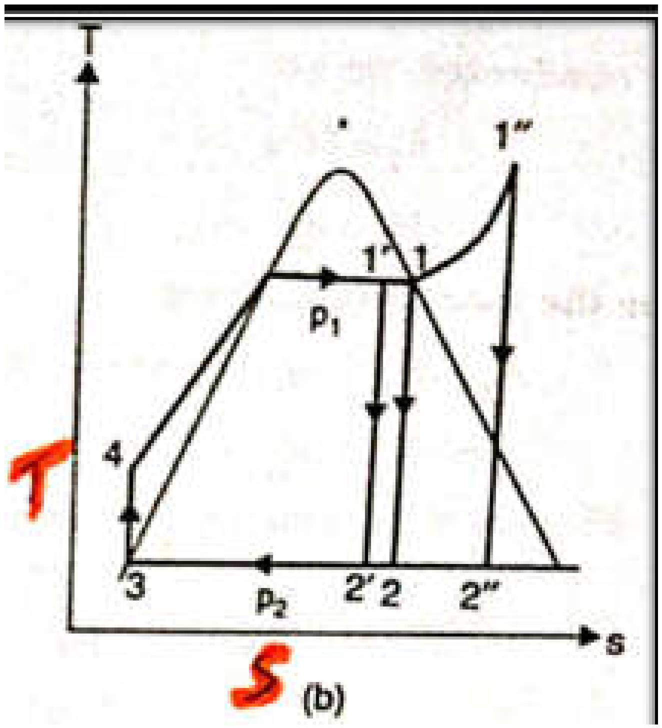
$$\therefore \quad Q_1 = h_1 - h_{f_4}$$

(*ii*) **For turbine** (as control volume), we get

$$h_1 = W_T + h_2, \text{ where } W_T = \text{turbine work}$$

$$\therefore \quad W_T = h_1 - h_2$$





(b)

(*iii*) **For condenser,** we get

$$h_2 = Q_2 + h_{f_3}$$

$$\therefore \qquad Q_2 = h_2 - h_{f_3}$$

(*iv*) **For the feed pump,** we get

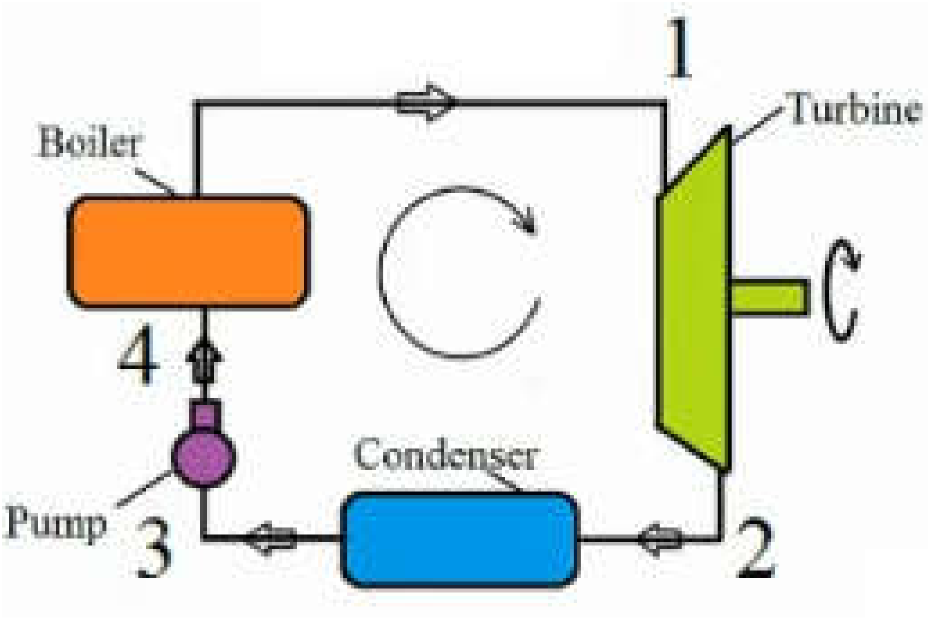
$$h_{f_3} + W_P = h_{f_4}, \qquad \text{where, } W_P = \text{Pump work}$$

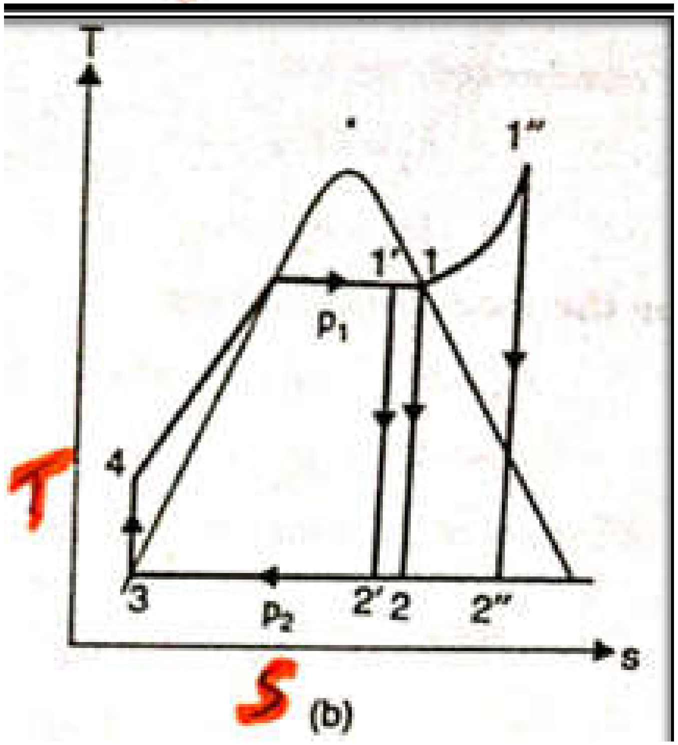
$$\therefore \qquad W_P = h_{f_4} - h_{f_3}$$

Now, efficiency of Rankine cycle is given by

$$\eta_{\text{Rankine}} = \frac{W_{\text{net}}}{Q_1} = \frac{W_T - W_P}{Q_1}$$

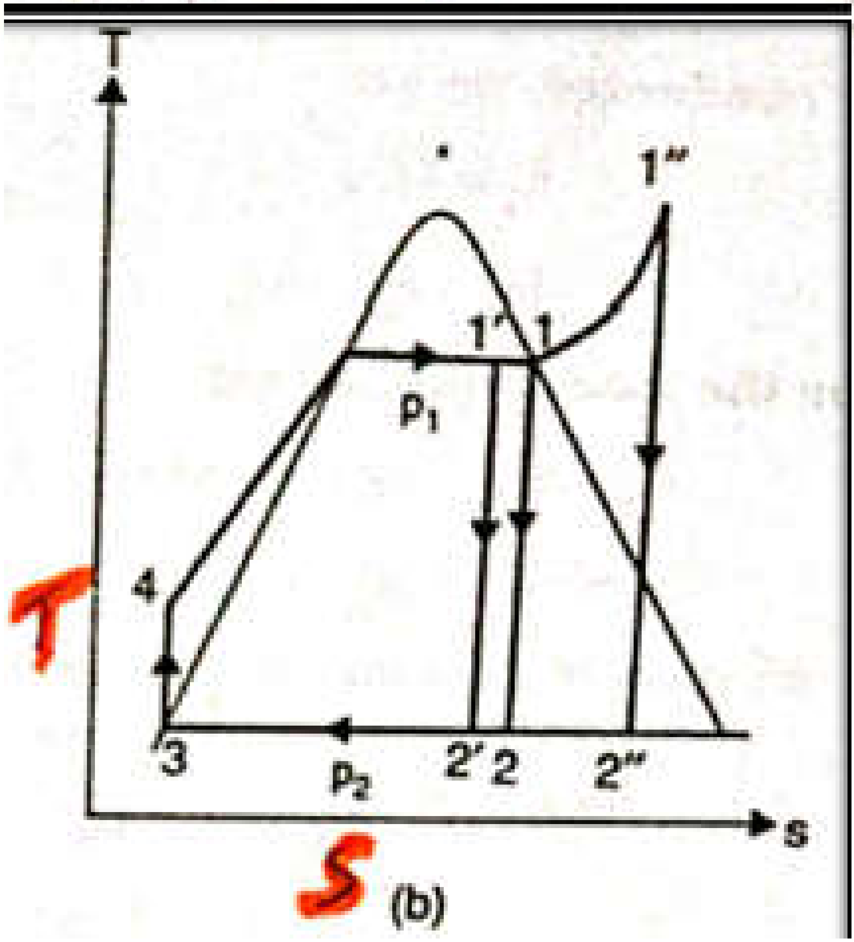
$$= \frac{(h_1 - h_2) - (h_{f_4} - h_{f_3})}{(h_1 - h_{f_4})}$$





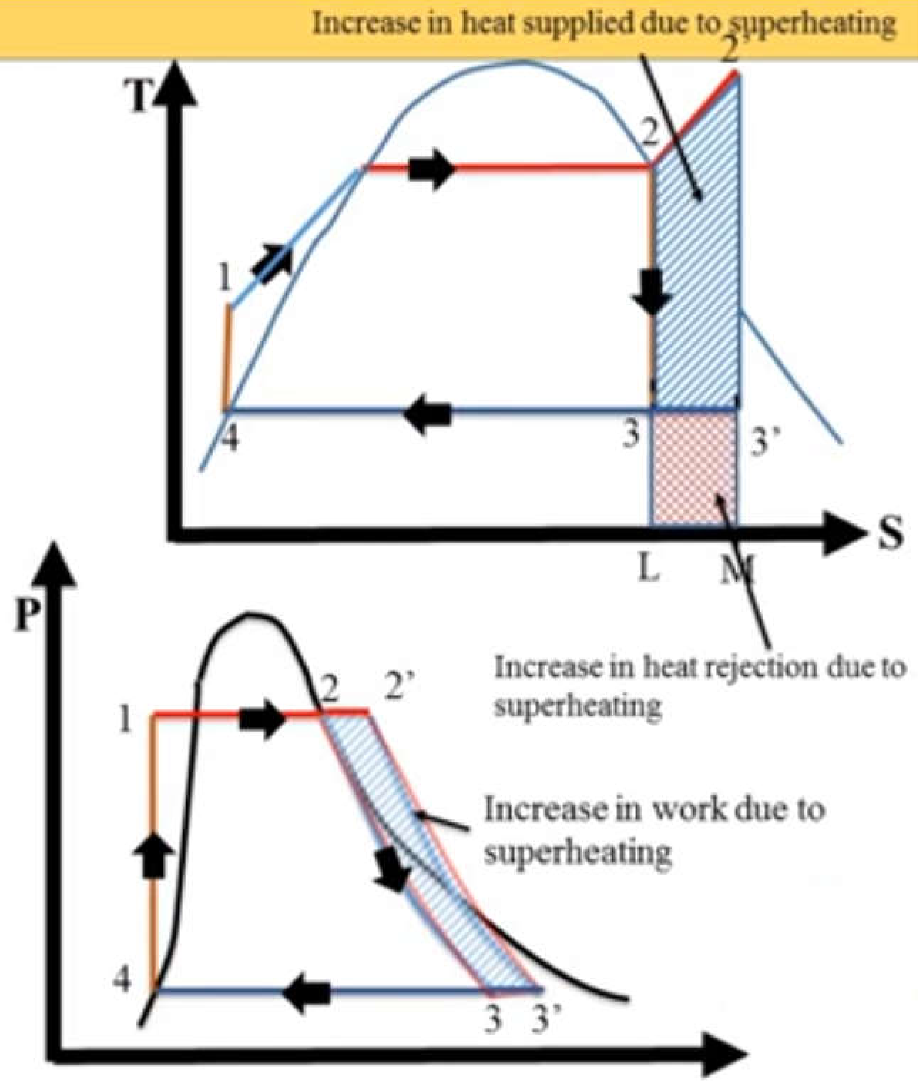
The feed pump term ($h_{f_4} - h_{f_3}$) being a small quantity in comparison with turbine work, W_T, is usually neglected, *especially when the boiler pressures are low.*

Then, $$\eta_{\text{Rankine}} = \frac{h_1 - h_2}{h_1 - h_{f_4}}$$



Variables Affecting Efficiency of Rankine Cycle
OR
Methods Of Improving Efficiency of Rankine Cycle

Variables Affecting Efficiency of Rankine Cycle



1. Effect of superheating of steam :

Rankine cycles (1-2-3-4-1) and (1-2'-3'-4-1) using dry saturated steam and superheated steam respectively are shown in Fig.

It is obvious from the Figure that superheat cycle delivers **more work** by an amount equal to the shaded area (2- 2'-3'-3-2).

The **heat supplied to steam is also increased** by an amount equal to area under the curve (2-2') i.e. area (2-2'-M-L-2) in T—S diagram.

However, the ratio of increase in work output to increase in heat supplied to steam is more than the ratio of work done to heat supplied for Rankine cycle (1-2-3-4-1) due to which the cycle efficiency increases.

Due to the superheating of steam the average temperature of heat addition to the cycle increases while the average temperature of heat rejection from the cycle remains the same.

So there should be an **increase in the thermal efficiency** compared to the cycle using dry and saturated steam.

Variables Affecting Efficiency of Rankine Cycle

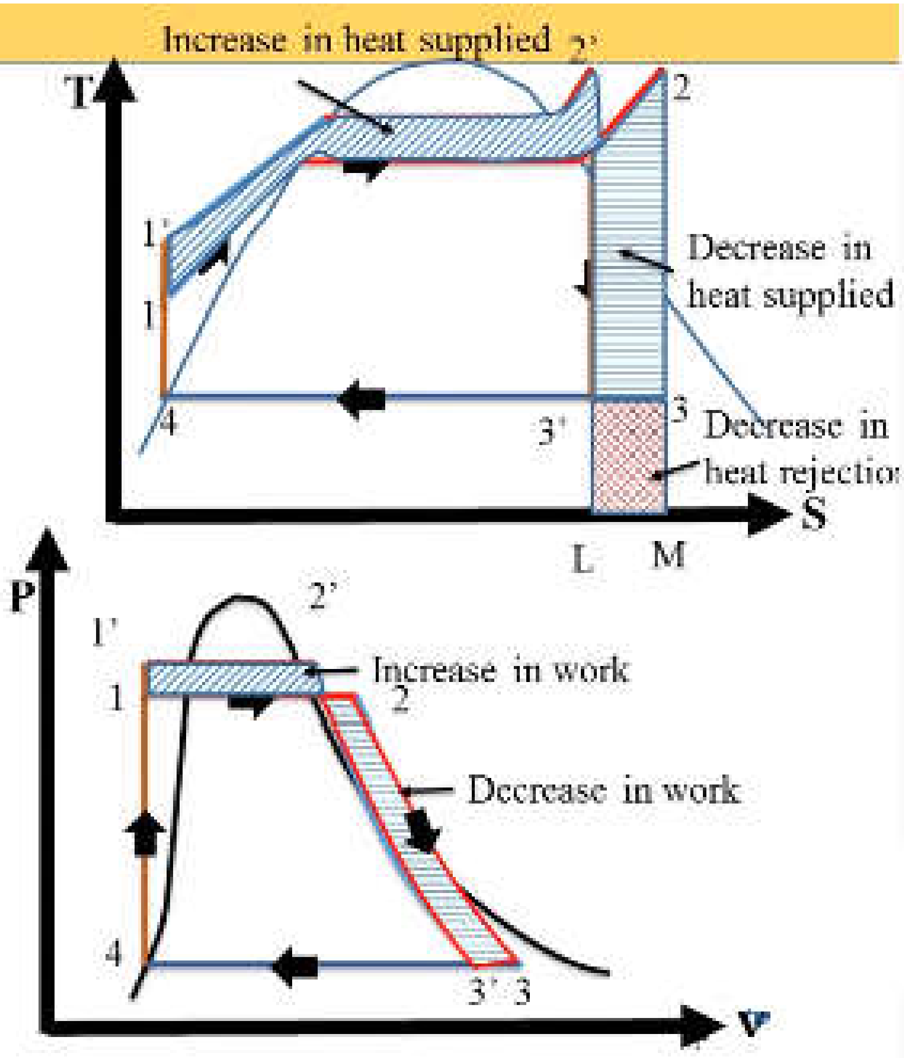
2. Effect of Increase in Boiler pressure :

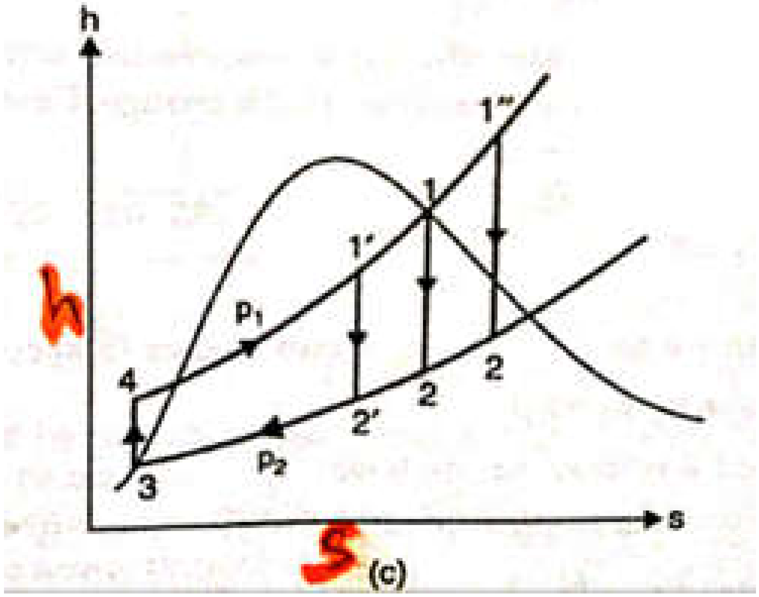
Rankine cycles (1-2-3-4-1) and (1'-2'-3'-4-1') have the same maximum temperature $T_2 = T_2'$ but different maximum pressure p_1 and p_1' respectively are shown in Fig. The condenser pressure p_2 is same in both the cases.

It is obvious from the Figure that due to increase in maximum pressure from pressure p_1 to p_1', the net work increases by an area shown by the oblique hatching and decreases by the area shown by horizontal hatching due to the increased pressure of the cycle.

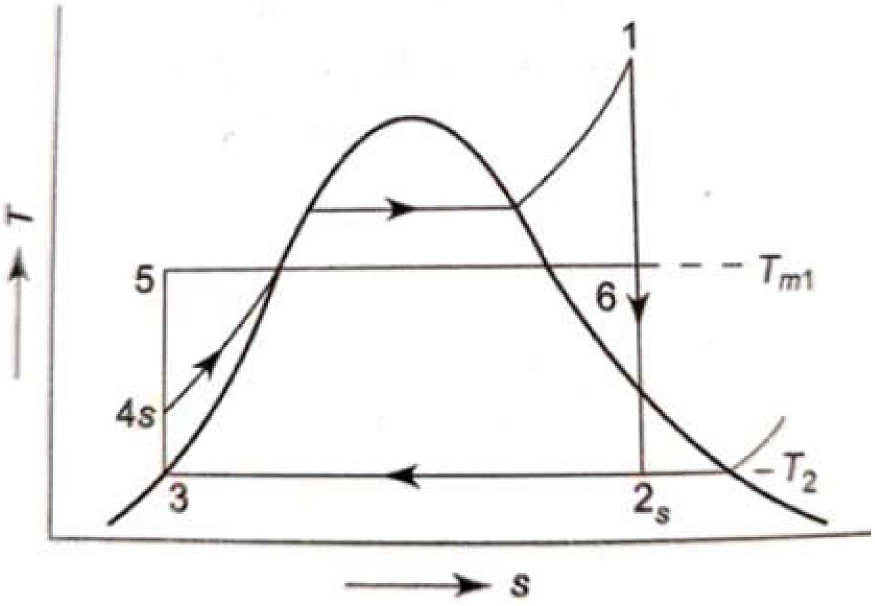
These two approximately work done (areas) are the same but the heat rejected in the condenser decreases by the area (3'-3-M-L-3').

Since heat rejection is reduced in the case of increasing boiler pressure, so the **Rankine efficiency increases** with the increase in the maximum pressure of the cycle.





Mean temperature of heat addition



$dQ = Tds$

$\swarrow$

Area under T-s plot.

$\therefore \quad ds = \frac{dQ}{T}$

Area under 4s – 1 = area under 5 – 6

$$Q_1 = h_1 - h_{4s} = T_{m1}\left(s_1 - s_{4s}\right)$$

$$T_{m1} = \frac{h_1 - h_{4s}}{s_1 - s_{4s}}$$

$$Q_2 = \text{heat rejected} = h_{2s} - h_3 = T_2\left(s_{2s} - s_3\right) = T_2\left(s_1 - s_{4s}\right)$$

$$\eta_{Rankine} = 1 - \frac{Q_2}{Q_1} = 1 - \frac{T_2\left(s_1 - s_{4s}\right)}{T_{m1}\left(s_1 - s_{4s}\right)}$$

$$\eta_{Rankine} = 1 - \frac{T_2}{T_{m1}}$$

$$\uparrow \quad \eta_{Rankine} = 1 - \frac{T_2 \downarrow}{T_{ml}}$$

$$\uparrow \eta_{Rankine} = 1 - \frac{T_2}{T_{ml} \uparrow}$$

$$\eta_{Rankine} = f\left(T_{ml}\right)\text{only}$$

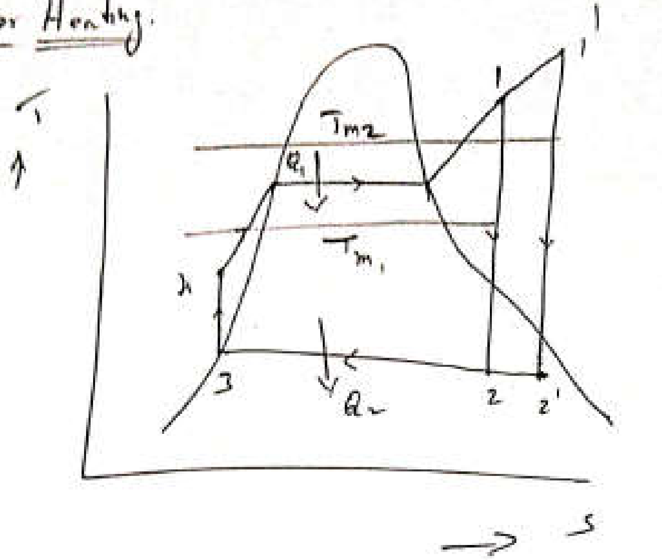
Conditions:

✓If T_2 is Decreased, then Efficiency will increase. (Cannot go below the Atmospheric pressure).

✓If T_{M1} Is Increased, Then Efficiency will Increase.

Mean Temp. @ Q_1 & Q_2

1) Super Heating.



W_T ↑, W_p remain same, Q_1 ↑, Q_2 ↑

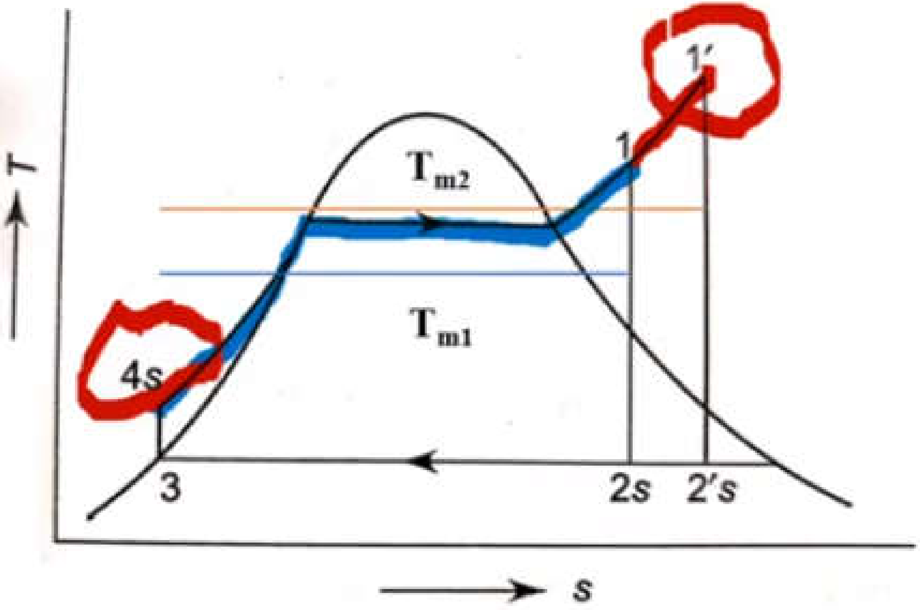
x ↑

$$\eta_R = \frac{W_{net}\ (\uparrow)}{Q_1\ (\uparrow)}$$

$$= \frac{W_T - W_P}{Q_1}$$

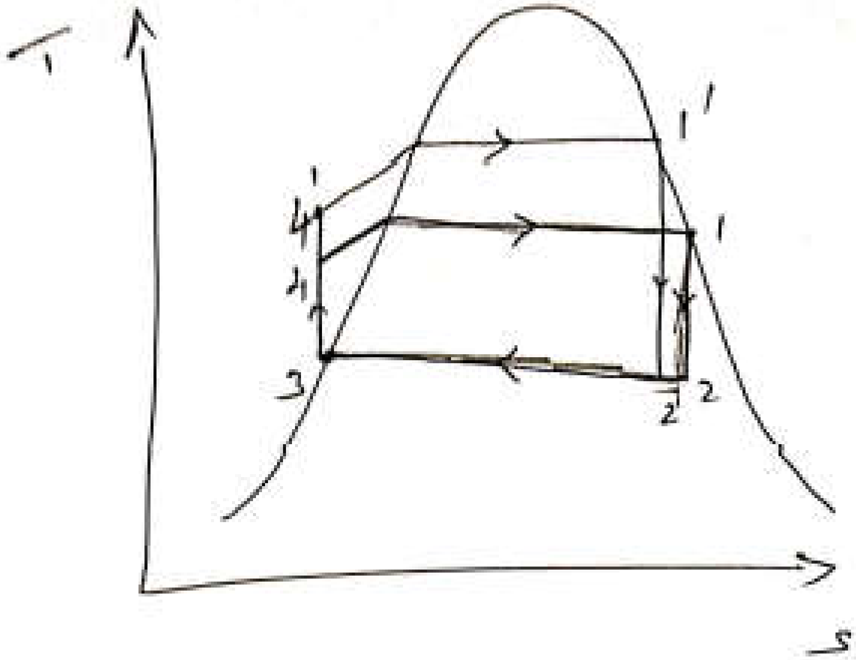
$$\therefore \boxed{\eta = 1 - \frac{T_2\ (\text{constant})}{T_m \uparrow}}$$

∴ The efficiency will Increase.



$$\uparrow \eta_{Rankine} = 1 - \frac{T_2}{T_{m1}} \uparrow$$

② Increase in Boiler Pressure.



$W_P = \uparrow$, $W_T = \uparrow$ (or) $W_{net}\uparrow$, $Q_1 = \uparrow$, $Q_R \downarrow$

$x = \downarrow$, T_2 (or) T_{atm} (or) T_{rej} = no change.

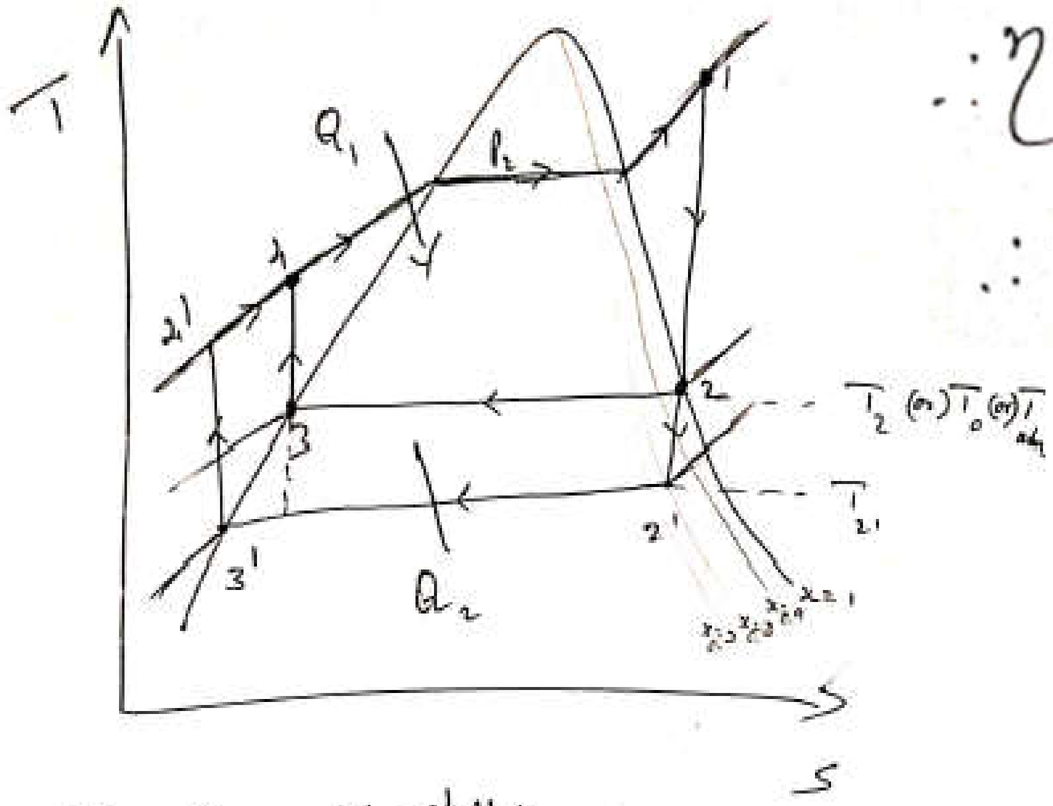
$T_m \uparrow$.

$$\eta_R = \frac{W_{net}\uparrow}{Q_1\uparrow}$$

$$\therefore \eta = 1 - \frac{T_2 \text{ (or) } T_{atm} \text{ (or) } T_{rej}}{T_m (\uparrow)}$$

∴ The efficiency will Increase.

③ Decrease in Condenser Pressure:-



$W_T = \uparrow$, W_p = slight ↑ (or) Cant goodfied. , Q_2 = Cannot say. (or) slight ↓

$Q_1 = \uparrow$, $x = \downarrow$

$$\eta_R = \frac{W_{net} \uparrow}{Q_1 \uparrow}$$

$$\therefore \eta = 1 - \frac{\overline{T_2} \text{ (or) } \overline{T_0} \downarrow}{\overline{T_m} \text{ (slightly Decrease)}}$$

∴ The efficiency will Increase.

Suppose:-

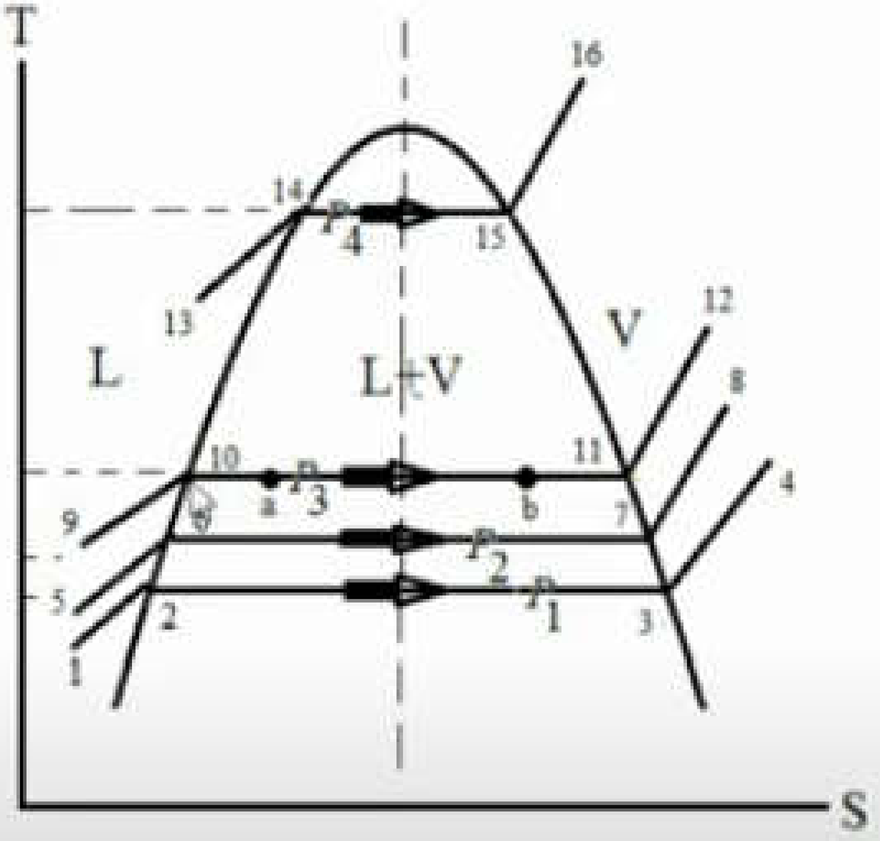
for (4-1) Process

$$\overline{T_m} = \frac{20+120^{\circ}}{2} : 70$$

for (4'-1) Process

$$\overline{T_m} = \frac{15+120^{\circ}}{2} = 67.5$$

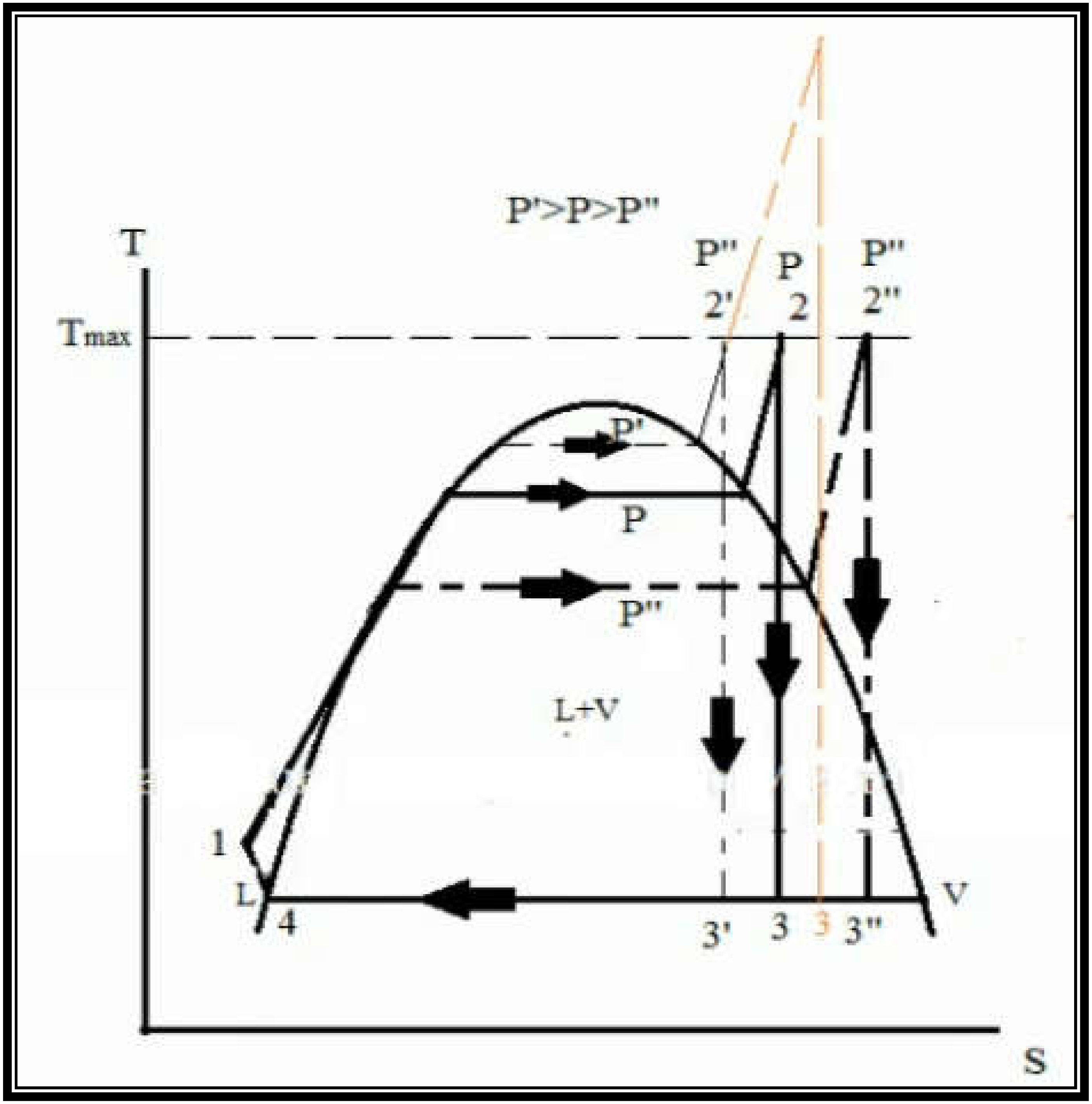
Reheating or Reheat Cycle



For Turbine , the X must be > 0.85

$$X = \frac{\text{Amount of dry steam}}{\text{Amount of total steam}}$$

If steam quality is less than 85% Erosion of turbine blade take place Which decrease the life of turbine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2''
P'
P
P''
L+V
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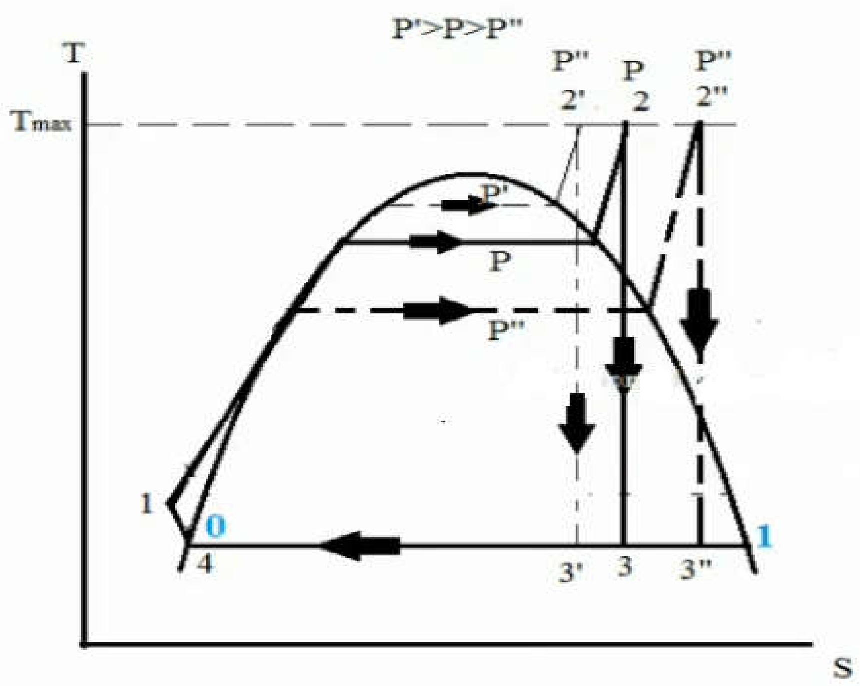
L
4
3'
3
3
3''
V
S

Why we need reheating ?

To increase the boiler pressure, reduce the steam quality which results erosion of turbine blade or pitting take place in turbine, Hence the life of turbine blade is decreased.

To reduce erosion of the blade the quality of steam is above 85% and this achievement is possible if we use reheating method in steam power plant

Reheating increase the mean temperature compared to earlier case and improves the efficiency.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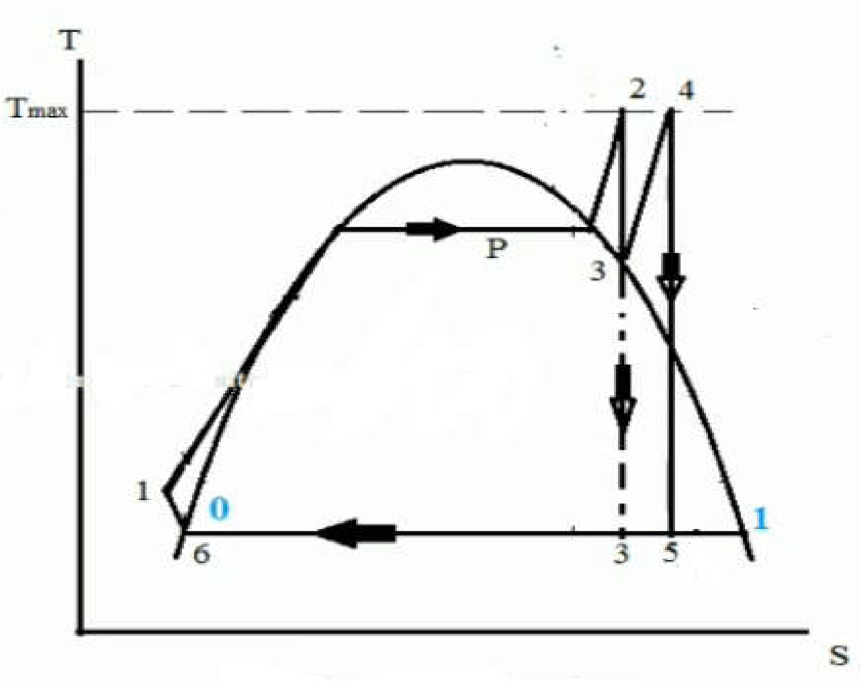
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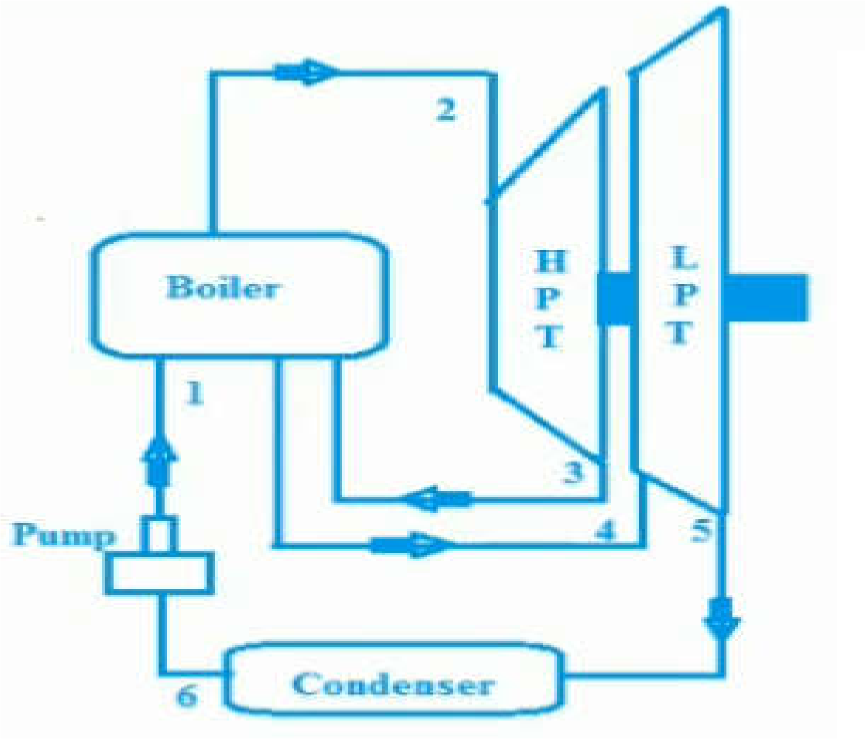

2
Boiler
H
P
T
L
P
T
1
3
Pump
4
5
6
Condenser

The efficiency of the simple Rankine cycle can be improved by **increasing the pressure and temperature** of the steam entering into the turbine.

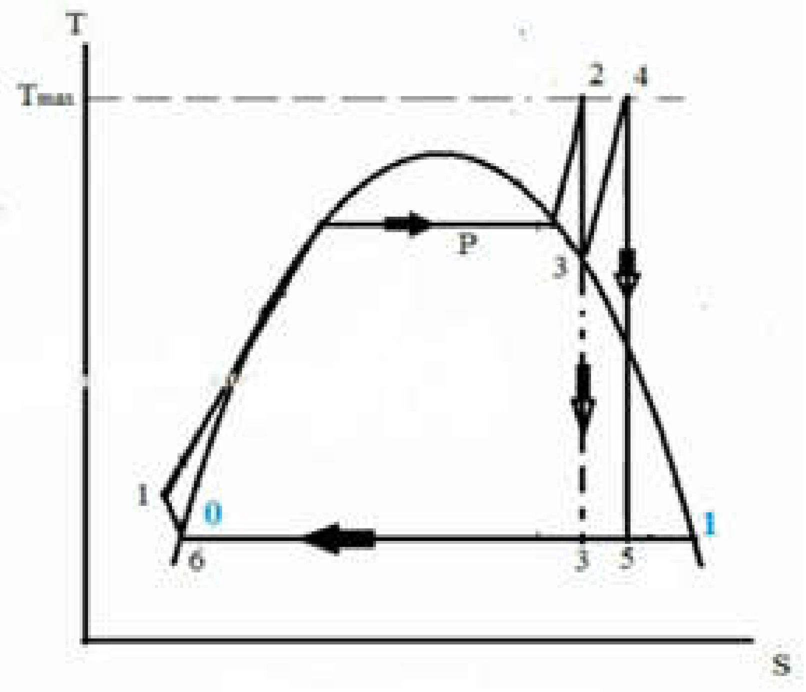
As the initial pressure of steam increases, the expansion ratio in the turbine also increases and the steam becomes quite wet at the end of expansion.

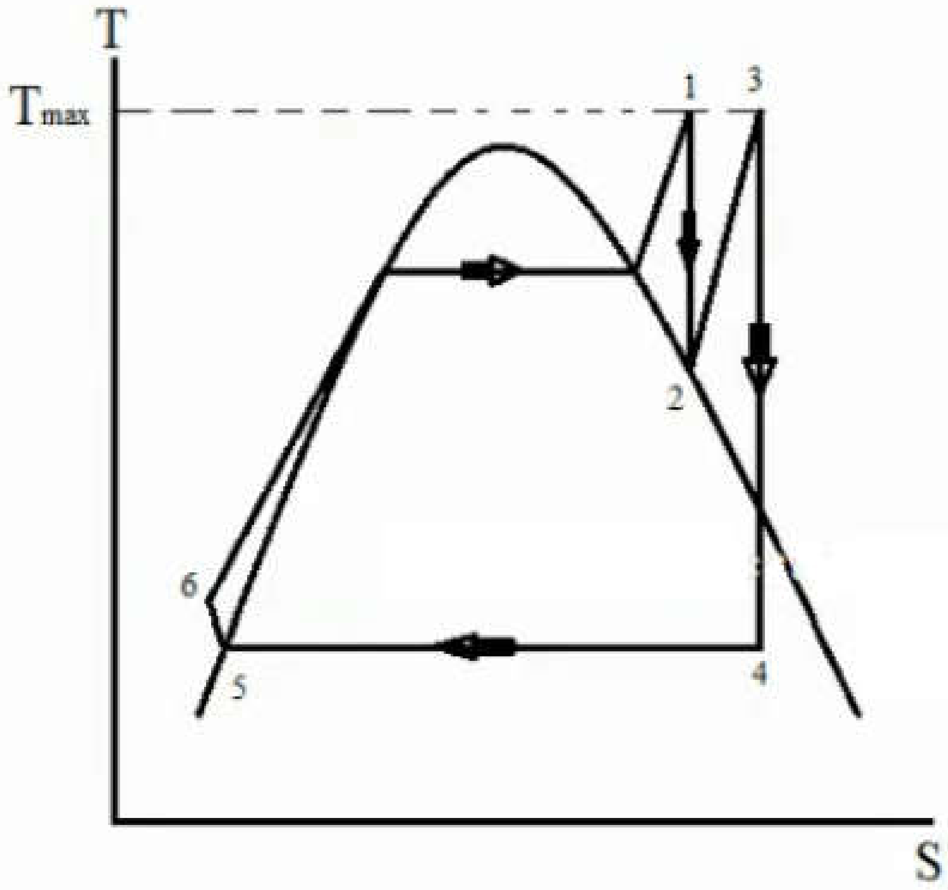
This wet steam passing over the turbine blades for a prolonged period will **corrode and erode the turbine blades** and increase the losses.

This reduces the nozzle and blade efficiency. The dryness fraction of steam is allowed to fall upto 0.88 but not below it during its expansion in the turbine.

The **erosion and corrosion** difficulties due to the presence of water particles in the steam can be avoided by reheating of steam, because the steam becomes dry after reheating.

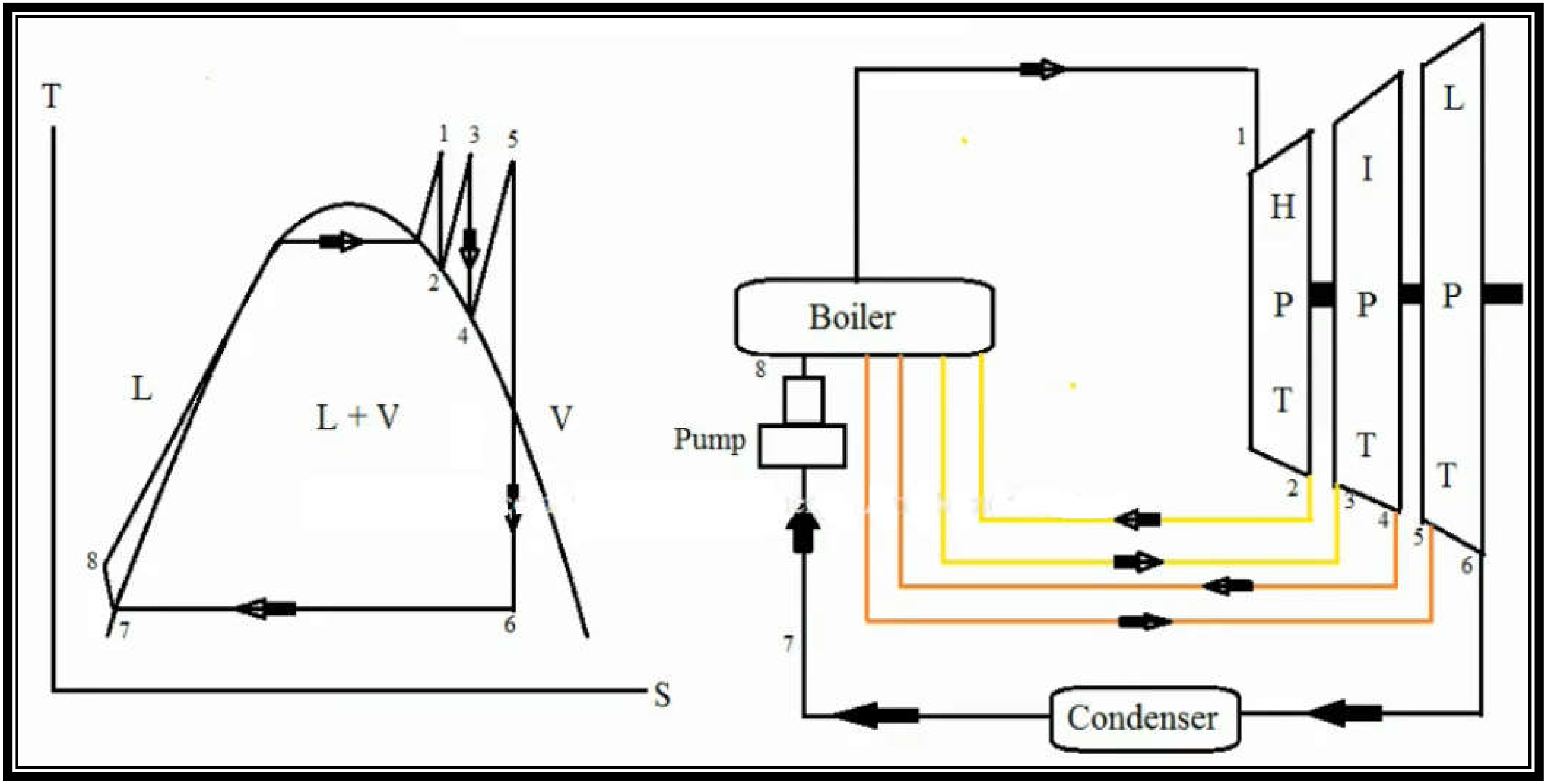
In reheating, the whole steam is extracted from a suitable point in the turbine (before reaching 0.88 dryness) and is reheated with the help of the flue gases in the boiler furnace as shown in Fig.





$$\eta = \frac{(h_1 - h_2) + (h_3 - h_4) - (h_6 - h_5)}{(h_1 - h_6) + (h_3 - h_2)}$$

Rankine cycle with two Reheats


T
1
3
5
2
4
L
L + V
V
8
7
6
S
1
H
P
T
2
I
P
T
3
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L
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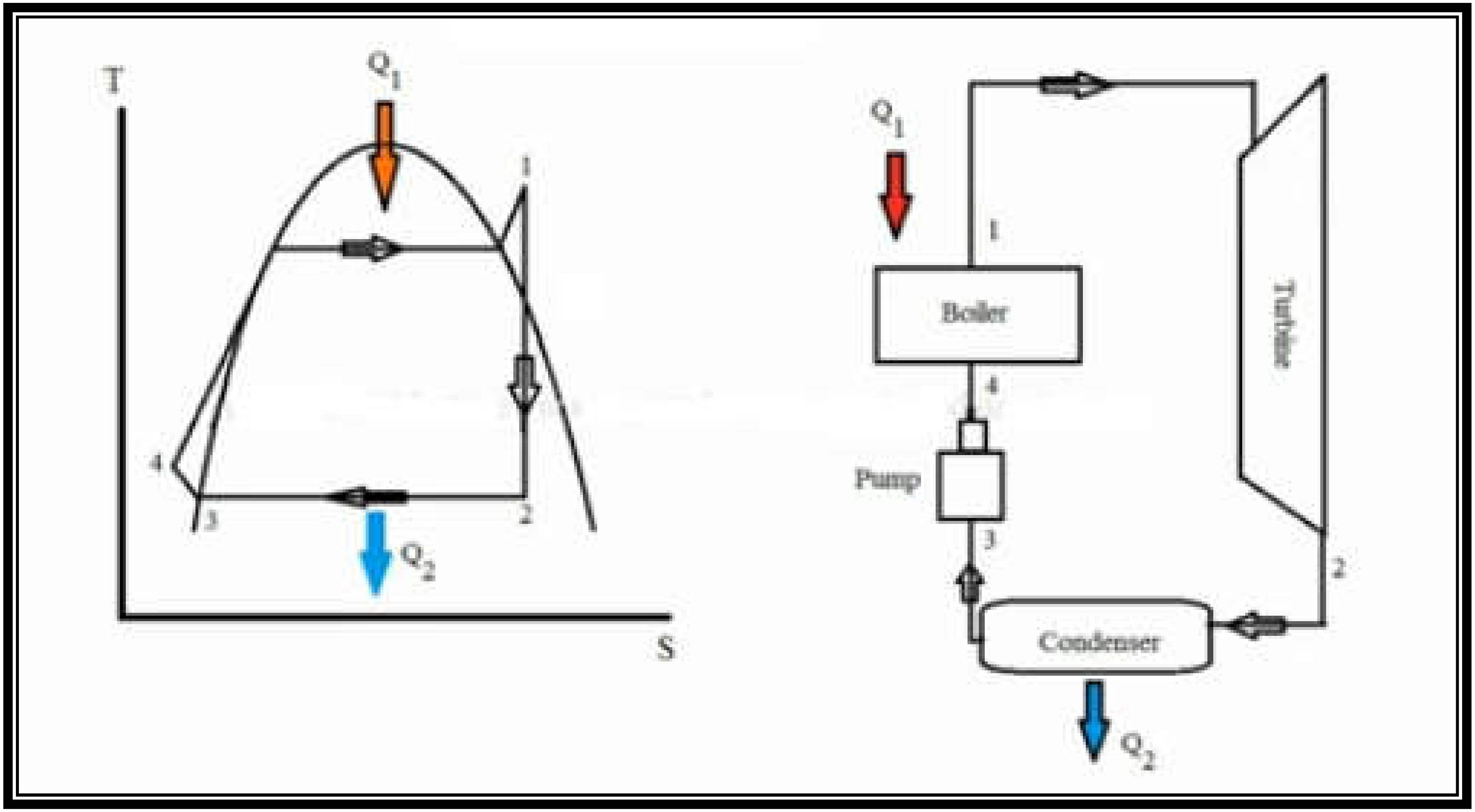
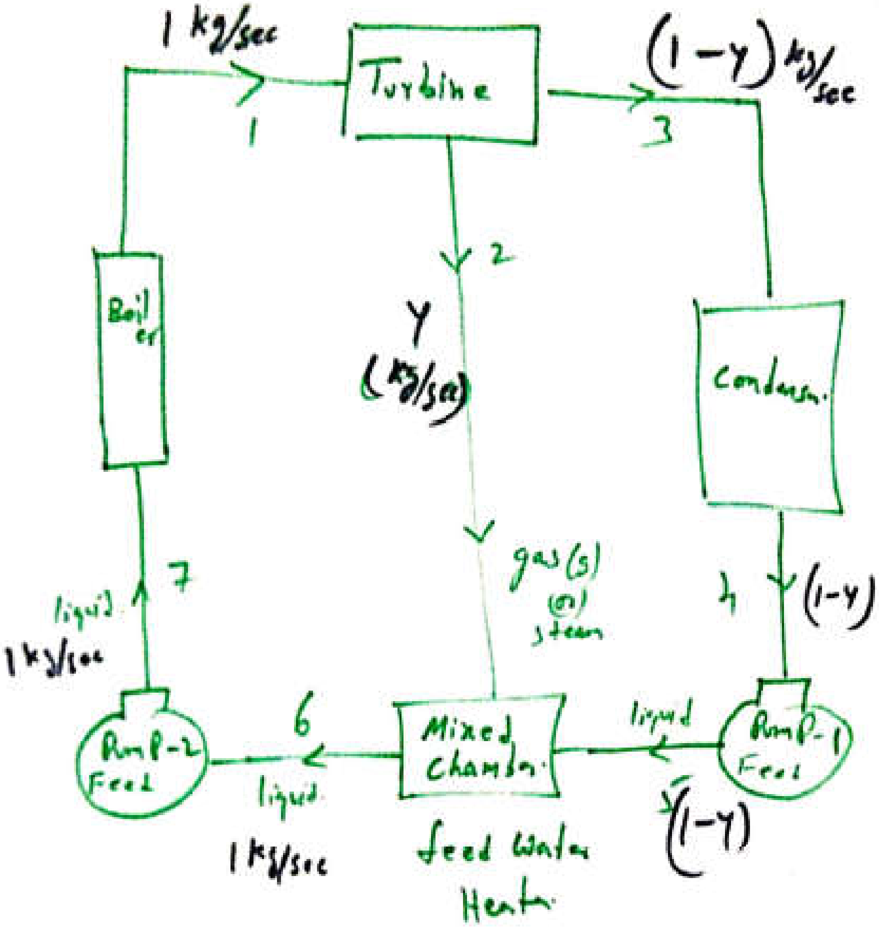
5
6
Boiler
8
Pump
7
Condenser

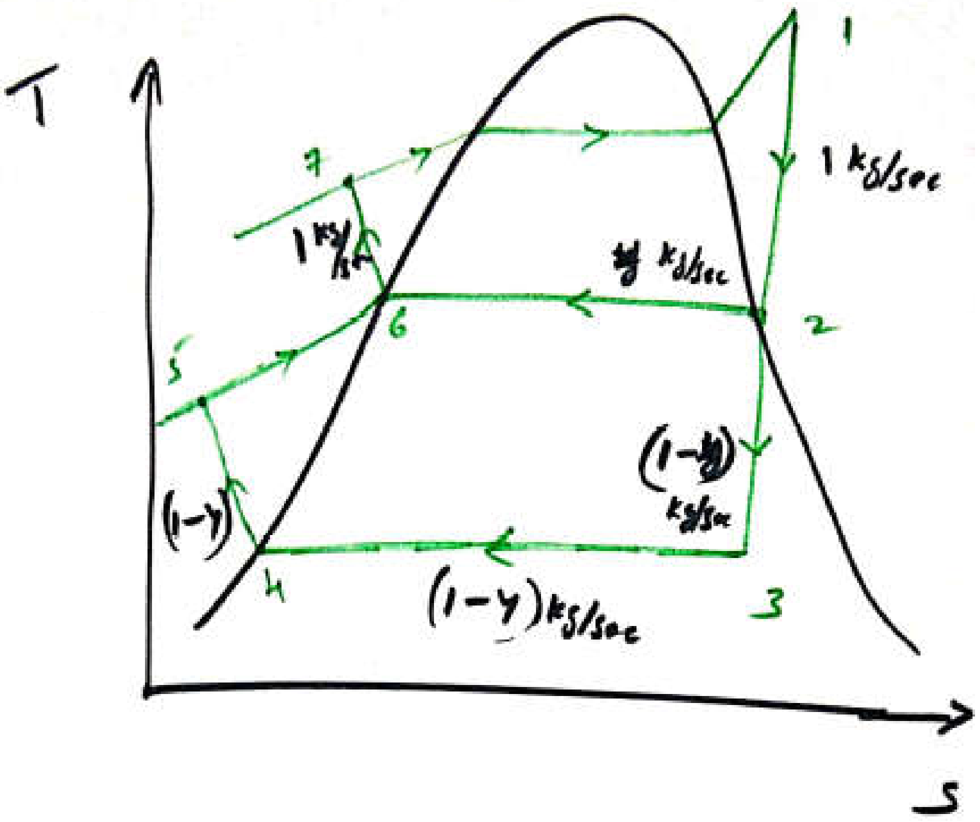
Regeneration in Rankine Cycle

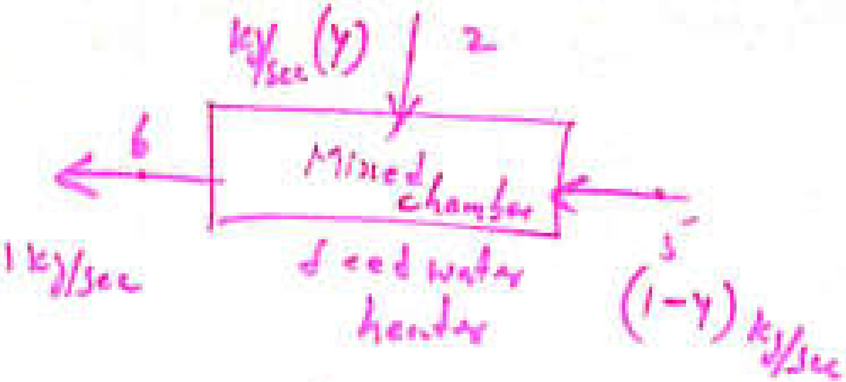
Ideal Rankine cycle



Basic Concept of Regeneration in Rankine Cycle

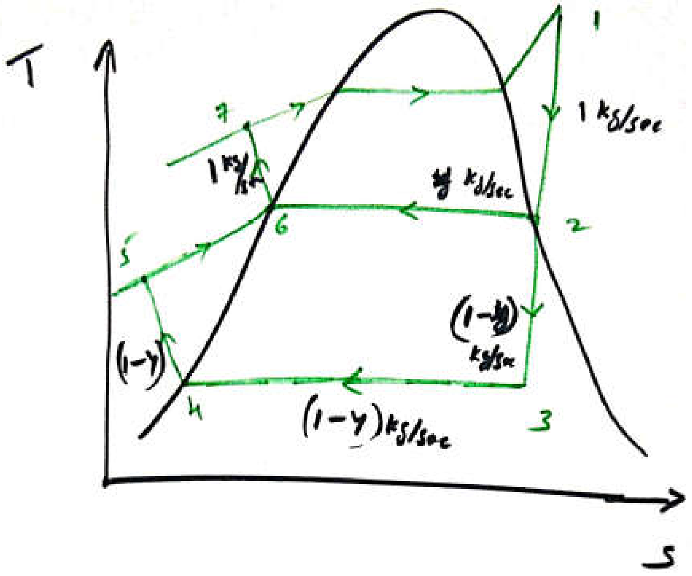






Let us have Mass Balance

$$m_2 + m_5 = m_6$$



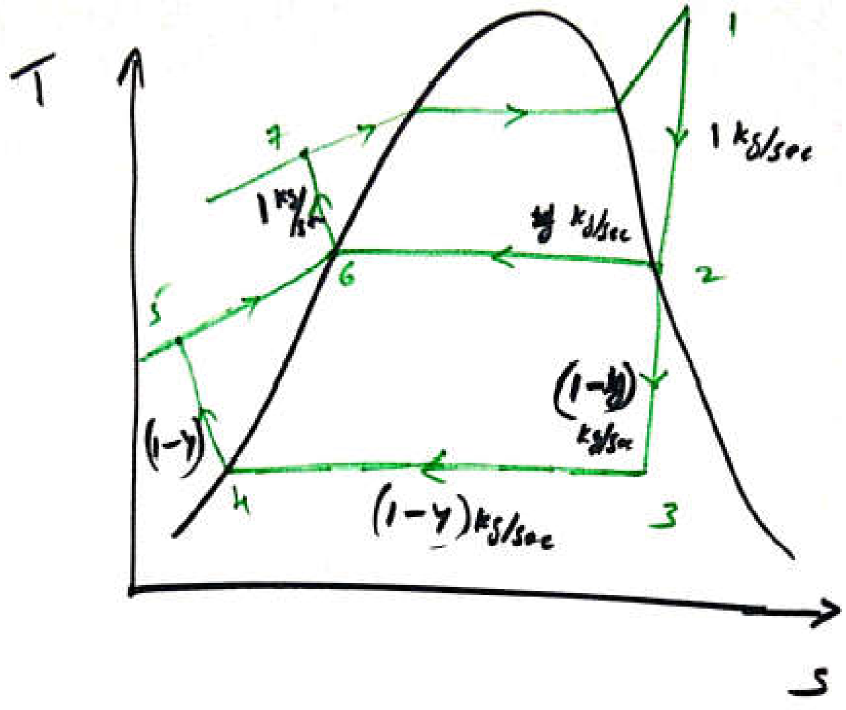
energy conservation,

$$m_2 h_2 + m_5 h_5 = m_6 h_6$$

$$\therefore \boxed{m_6 = 1 \text{ kg/sec}}$$

$\therefore m_2 = y$, $m_6 = 1$ & $m_5 = 1-y$

Now, $y h_2 + (1-y) h_5 = h_6$



$$W_T = 1(h_1 - h_2) + (1-y)(h_2 - h_3)$$

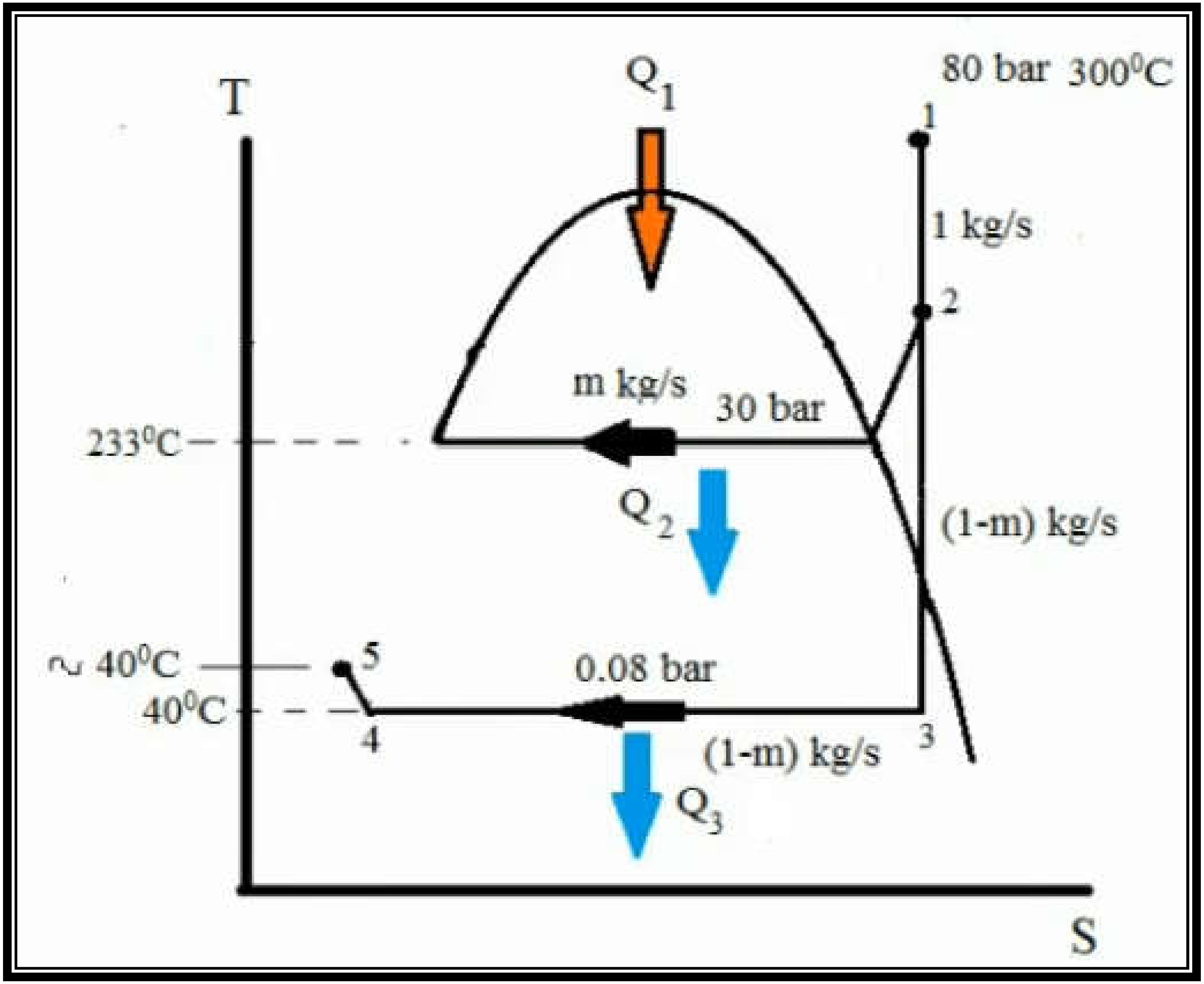
$$W_p = (1-y)(h_5 - h_4) + 1(h_7 - h_6)$$

$$Q_{add} = 1(h_1 - h_7)$$

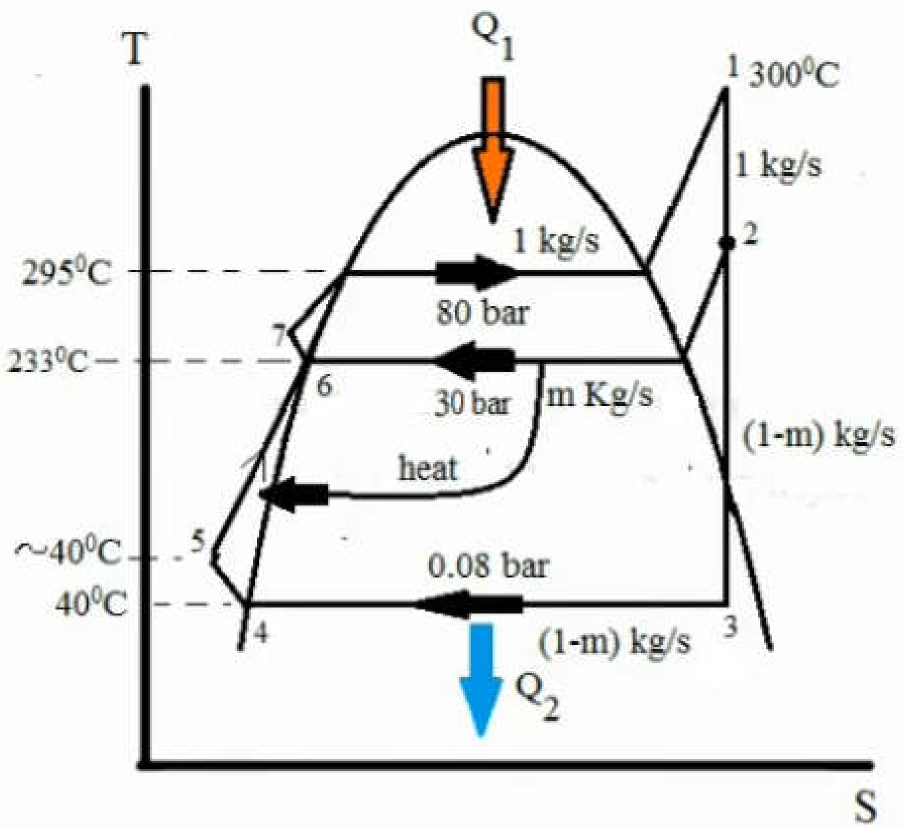
$$Q_{rej} = (1-y)(h_3 - h_4)$$

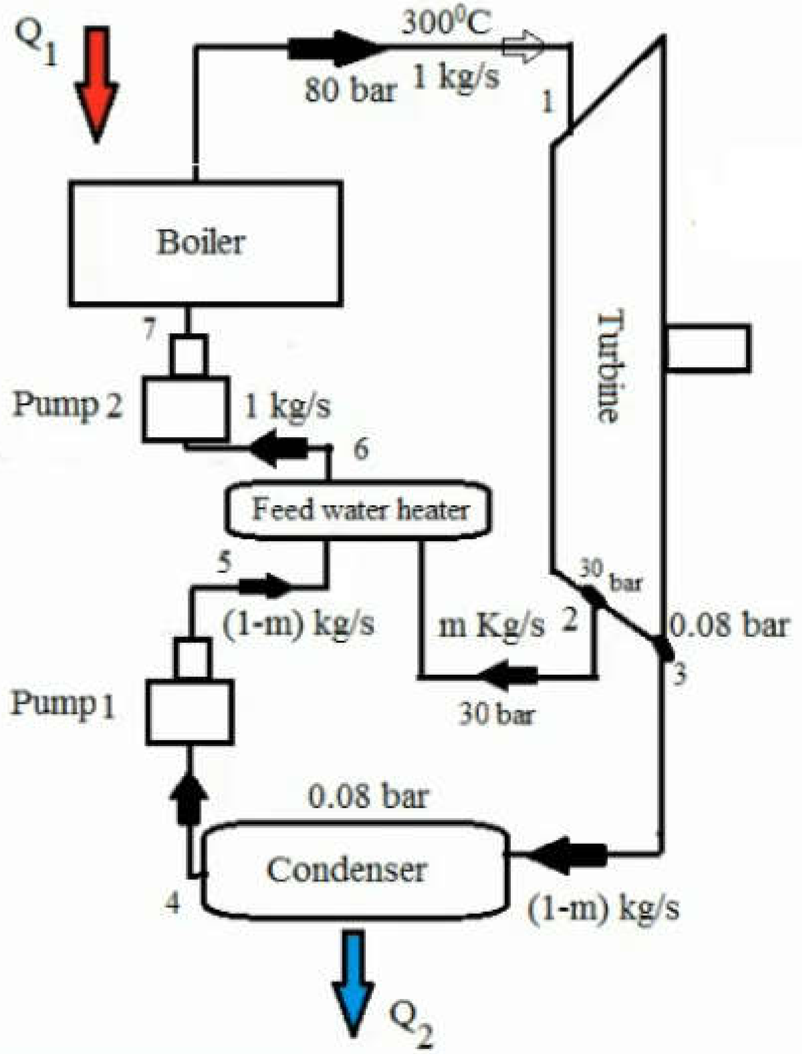
$$\eta = \frac{W_T - W_p}{Q_{add}}$$

$$= \frac{\left((h_1 - h_2) + (1-y)(h_3 - h_3)\right) - \left((1-y)(h_5 - h_4) + (h_7 - h_6)\right)}{h_1 - h_7}$$

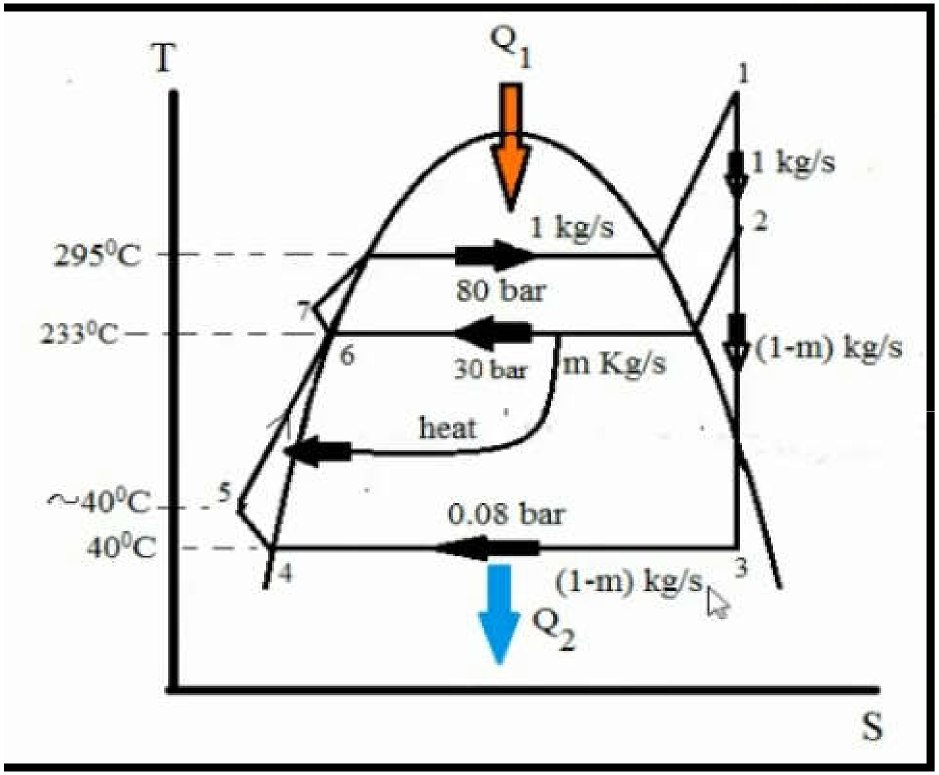

T
Q_1
80 bar 300°C
1
1 kg/s
2
m kg/s
30 bar
233°C
Q_2
(1-m) kg/s
~ 40°C
5
0.08 bar
40°C
4
3
(1-m) kg/s
Q_3
S

Regeneration in Rankine Cycle





In order to find Mass flow rate (m):



$$\dot{m}(h_2-h_6) = (1-m)(h_6-h_5)$$

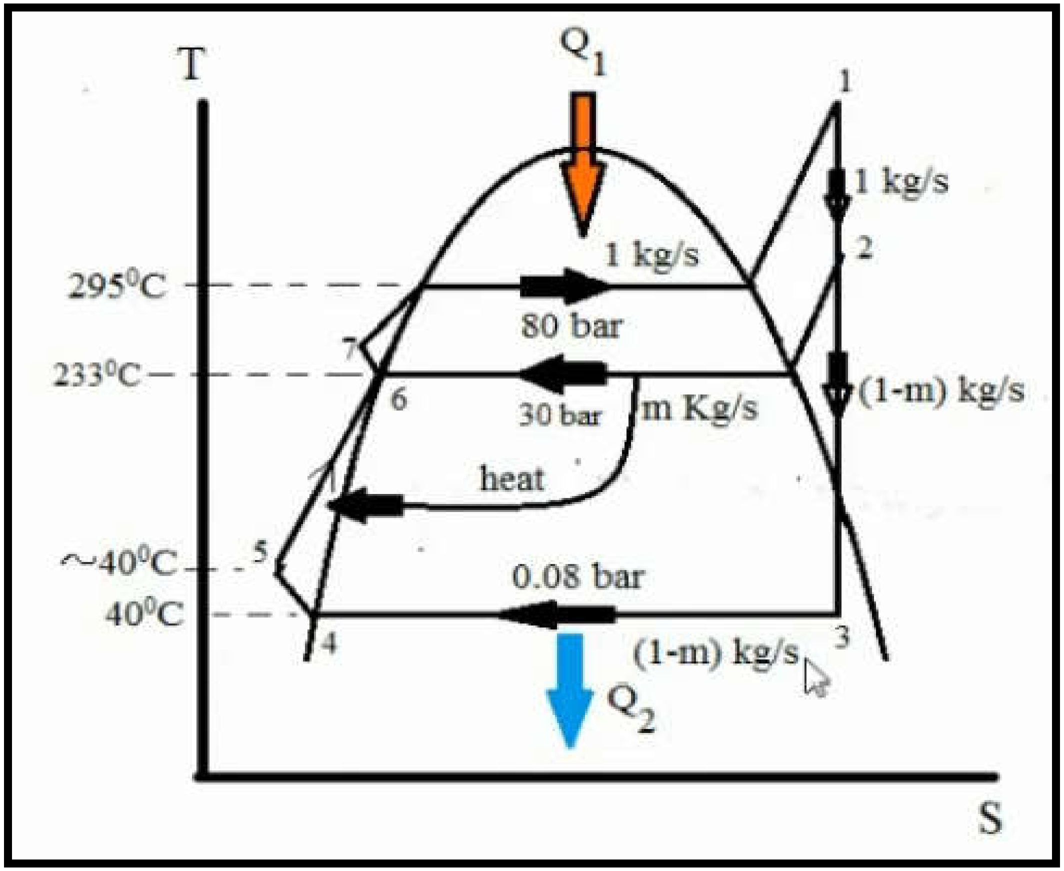
$$m(h_2-h_6) = (h_6-h_5) - m(h_6-h_5)$$

$$m(h_2-h_6) + m(h_6-h_5) = h_6-h_5$$

$$mh_2 - m\cancel{h_6} + m\cancel{h_6} - mh_5 = h_6-h_5$$

$$m(h_2-h_5) = h_6-h_5$$

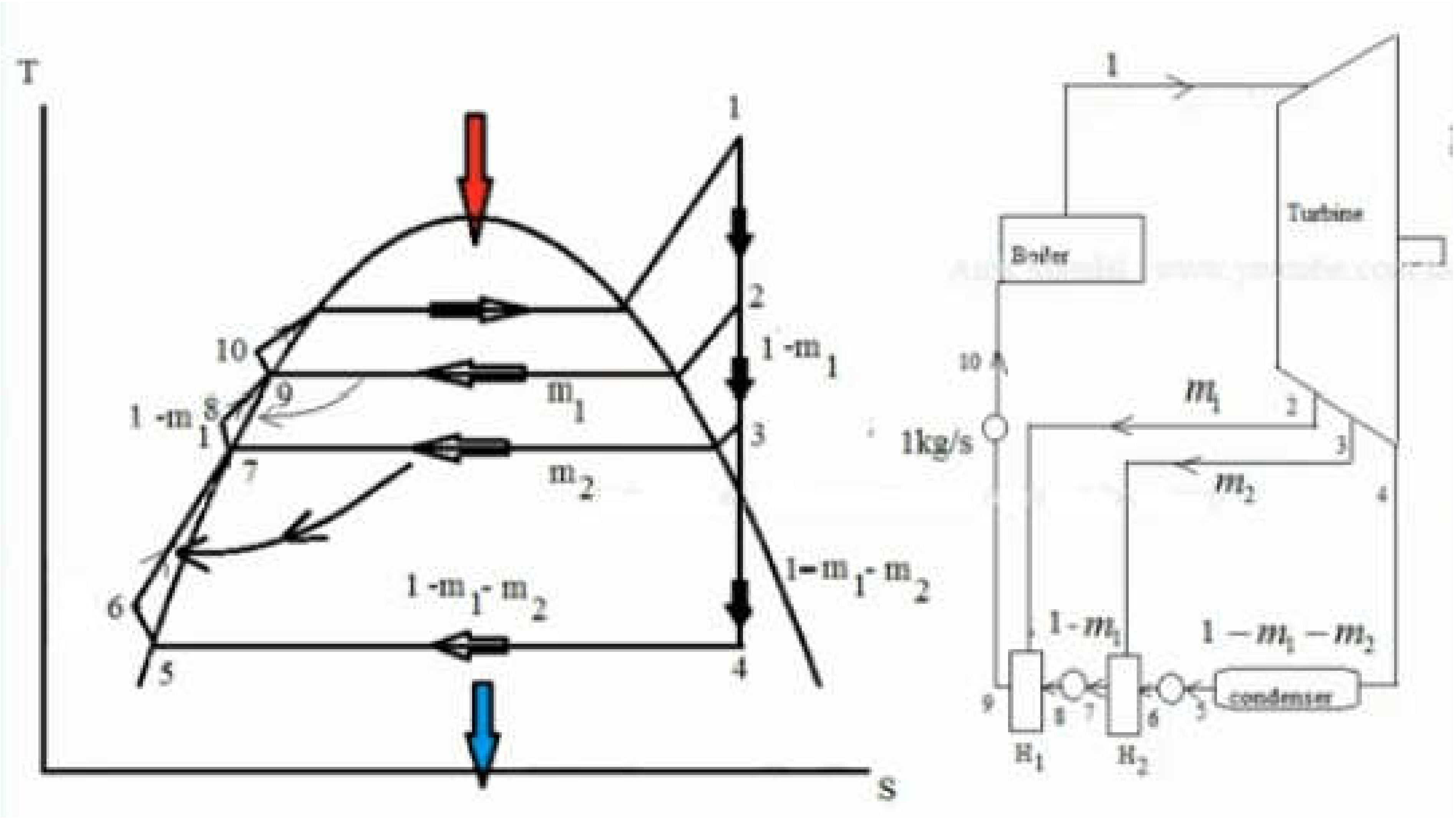
$$m = \frac{h_6-h_5}{h_2-h_5}$$

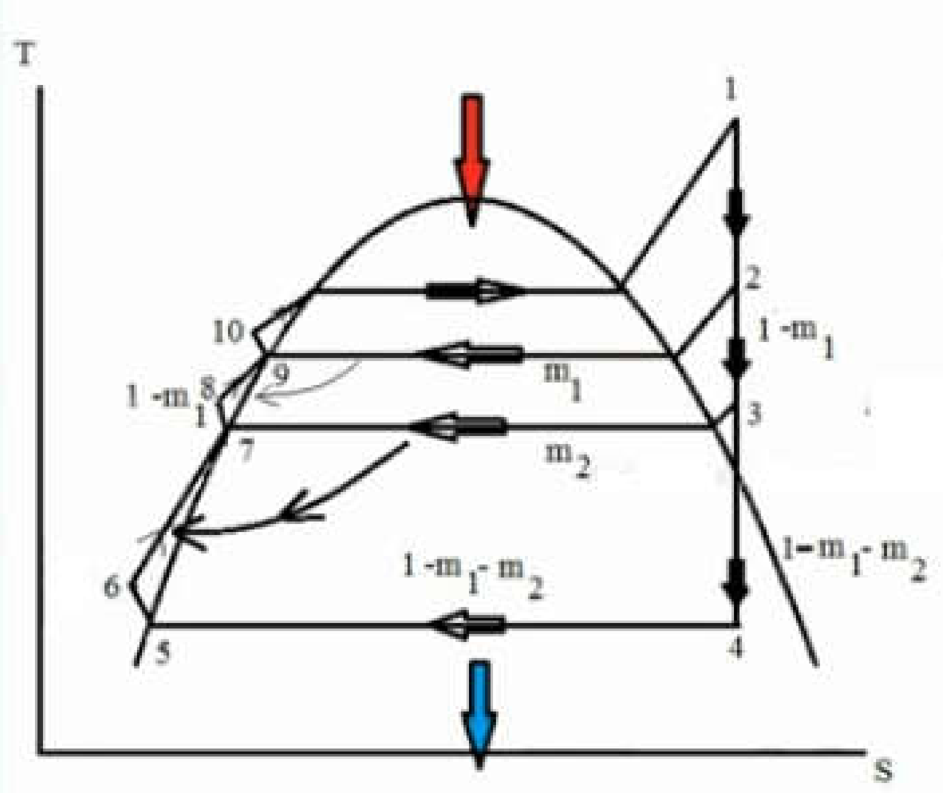


$$\eta = \frac{W_T - W_P}{Q_1}$$

$$= \frac{[1.(h_1 - h_2) + (1-m).(h_2 - h_3)] - [(1-m).(h_5 - h_4) + 1.(h_7 - h_6)]}{1.(h_1 - h_7)}$$

Two Regeneration (or) In case of Three pumps.





Efficiency

$$W_T = 1(h_1 - h_2) + (1 - m_1)(h_2 - h_3) + (1 - m_1 - m_2)(h_3 - h_4)$$

$$W_P = (1 - m_1 - m_2)(h_6 - h_5) + (1 - m_1)(h_8 - h_7) + 1(h_{10} - h_9)$$

$$Q = 1(h_1 - h_{10})$$

$$\eta = \frac{W_T - W_P}{Q}$$

Important Terms of Steam

Wet steam:-

When the steam contains moisture (or) particles of water in suspension, is called it as "Wet steam".

Dry saturated steam:-

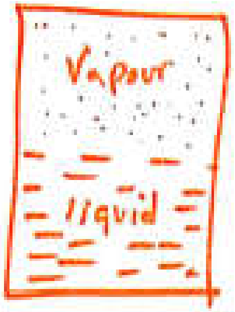
When the wet steam is further heated, it does not contain any suspended particles of water. So it is called it as "Dry saturated steam".

Super Heated steam:

On further heating the dry saturated steam at constant pressure, its temperature increase. Thus it is called as "Super Heated Steam".

Vaporization

$\therefore$ m (kg of liquid) ⟶ m (kg of Vapour)



To find the Quality of steam:

Let m_v = mass of Vapour

m_L = mass of liquid (or) water

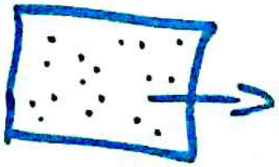
$m = m_v + m_L$ $\therefore$ m = Total Mass of mixture.

x = Dryness fraction

$$\therefore \quad x = \frac{m_v}{m_L + m_v}$$

Suppose,

$m_L = 0$ for dry Vapour



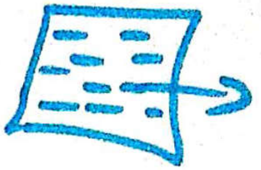
Vapour
(or)
No moisture content

$$\therefore x = \frac{m_V}{0 + m_V} = 1$$

$\therefore \boxed{x = 1}$ for dry saturated Vapour.

Suppose, $m_V = 0$ for saturated liquid

$$\therefore x = \frac{0}{m_L + 0} = 0$$



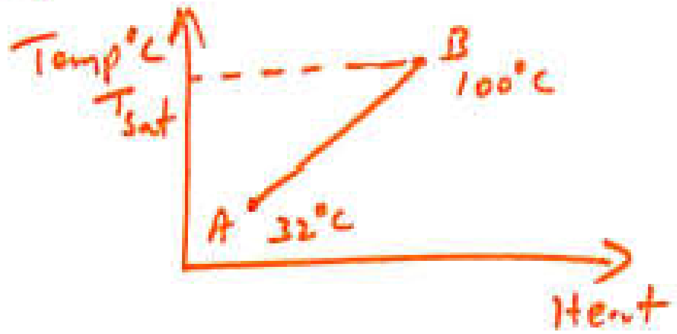
liquid.

$\therefore \boxed{x = 0}$ for saturated liquid

Sensible Heat of Water (h_f) :-

It is the amount of heat absorbed by 1 kg of water, when heated at constant pressure, from a given temp Range.

from figure, m = 1 kg of water



S·H of Water = $M \times C_{p_w} \Delta T$

∴ $C_{p_w} = 4.18$ kJ/kg K

$= 1 \times 4.18 [373 - 305)$

$= 285.6$ kJ

(or)

285.6 kJ/kg

Latent Heat of Vaporization (h_{fg}) (or) Hidden Heat

It is the amount of heat absorbed to evaporate 1 kg of water, at its boiling point (or Saturated temp) without change in temp.

∴ At 100°c of boiling Point.

$$h_{fg_{water}} = 2257 \text{ kJ/kg} \text{ at atm. pressure}$$

∴ The value of the latent heat is not constant & it varies according to pressure variation.

enthalpy of steam (or) Total Heat of steam (h_g):-

It is defined as the amount of heat absorbed by water during sensible heating plus the heat absorbed during evaporation (or) latent Heat.

enthalpy of steam (h_g) = Sensible + latent heat

$$= h_f + h_{fg}$$

$$\therefore h_g = 28.6 + 2257$$

$$= 2542.6 \text{ kJ/kg}$$

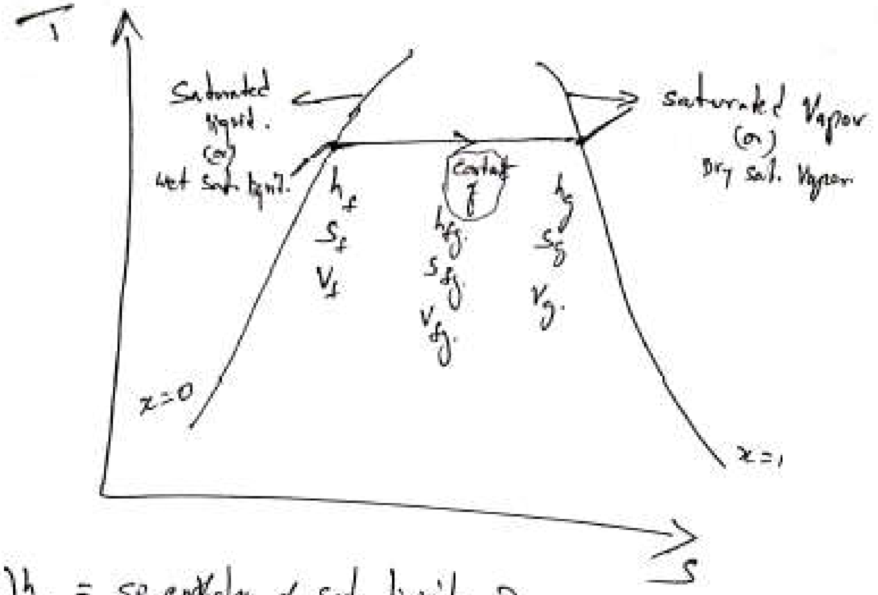
$$\boxed{h_g = h_f + h_{fg}}$$

Degree of super heat:-

on further heating the dry saturated steam at constant Pressure, we get super heated.

∴ Thus Degree of superheated $= T_{\text{superheated}} - T_{\text{saturated}}$

Nomenclature in T-S Diagram



(kJ/kg) h_f = sp. enthalpy of sat. liquid.
(kJ/kg K) S_f = sp. entropy of sat. liquid.
(m^3/kg) V_f = sp. Volume of sat. liquid

} at a certain pressure. (or) constant pressure

h_g = sp. enthalpy of sat. Vapor
S_g = sp. entropy of sat. Vapor
V_g = sp. Volume of sat. Vapor

} at a certain pressure. (or) constant pressure.

~~for~~ Phase change::

h_{fg} = sp. enthalpy of Vaporization ∴ $h_{fg} = h_g - h_f$ ..... change of enthalpy during evaporation.

S_{fg} = sp. entropy of Vaporization $S_{fg} = S_g - S_f$ .... change of entropy during evaporation.

V_{fg} = sp. Volume of Vaporization $V_{fg} = V_g - V_f$. .... change of Volume during evaporation.

In Case of Dryness fraction (known)

$\Rightarrow$ h = sp. enthalpy of wet Vapour

$$h = h_f + x\,h_{fg}.$$

$$= h_f + x\,(h_g - h_f)$$

$\Rightarrow$ s = sp. entropy of wet Vapour

$$s = s_f + x\,s_{fg}$$

$$= s_f + x\,(s_g - s_f)$$

$\Rightarrow$ v = sp. Volume of wet Vapor

$$v = v_f + x\,v_{fg}$$

$$= v_f + x\,(v_g - v_f)$$

Thermal Engineering-II
MODULE-2

Introduction

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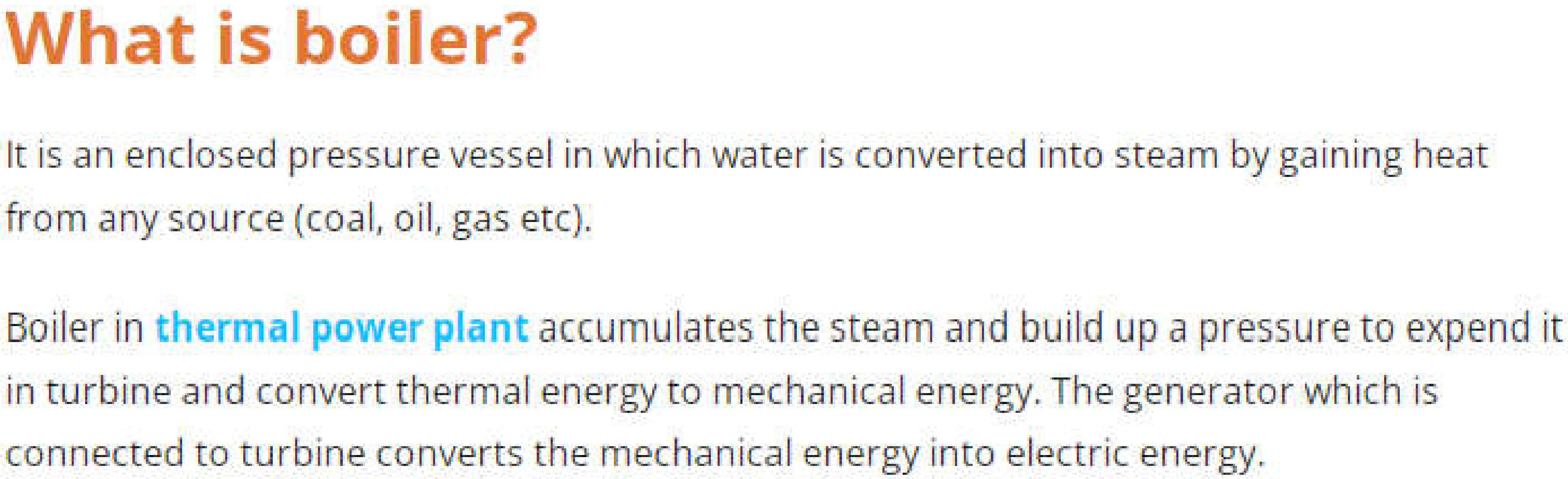
Associate Professor
Email ID: vijaykumar.iitm37@gmail.com
Contact Number: 9701339886
Department of Mechanical Engineering

MODULE-2

Boilers



What is boiler?

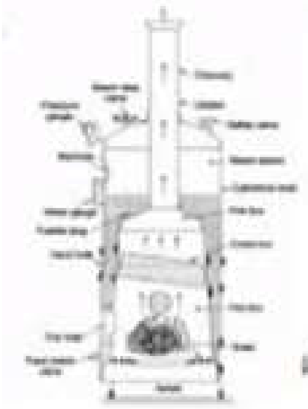
It is an enclosed pressure vessel in which water is converted into steam by gaining heat from any source (coal, oil, gas etc).

Boiler in **thermal power plant** accumulates the steam and build up a pressure to expend it in turbine and convert thermal energy to mechanical energy. The generator which is connected to turbine converts the mechanical energy into electric energy.

Classification of Boiler

(1) According to geometric orientation of boiler:

- If the axis of the boiler is horizontal, the boiler is known as horizontal boiler,
  Example : Lancashire Boiler, Locomotive Boiler
- If the axis of the boiler is vertical, it is known as vertical boiler,
  Example :Cochran Boiler
- If the axis of the boiler is inclined it is known as inclined boiler



(2) According to relative position of water and hot gases :

Fire Tube boilers :-

If the hot gases of combustion from the furnace pass through the tubes and water is surrounding (outside) the tubes is called water tube boilers. **Example :** Cochran Boiler, Lancashire, Locomotive.

Water tube boiler :

If the water passes through the tubes and hot gases surrounding (outside) the tubes is called water tube boiler.

Example : Babcock and Wilcox boiler.

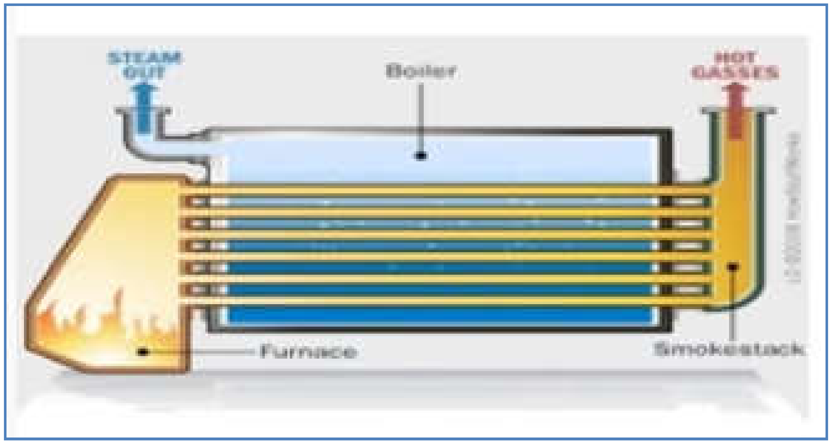


Figure . 1

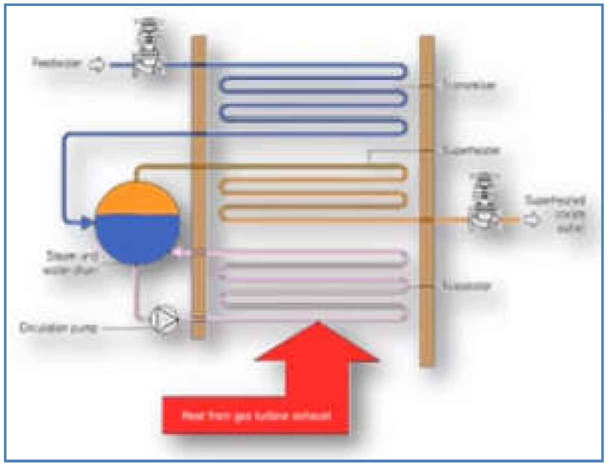


Figure . 2

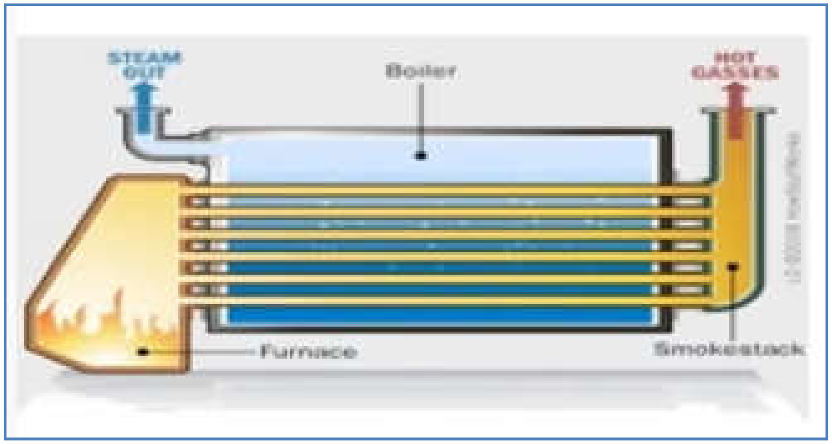
(3) According to location of furnace:

Externally Fired boilers: Furnace is placed outside the boiler shell. Water tube boilers are always externally fired.

Example : Babcock and Wilcox boiler.

Internally fired boiler: Furnace is placed inside the boiler shell. Most of fire tube boilers are internally fired boiler.

Example : Cochran Boiler, Lancashire.



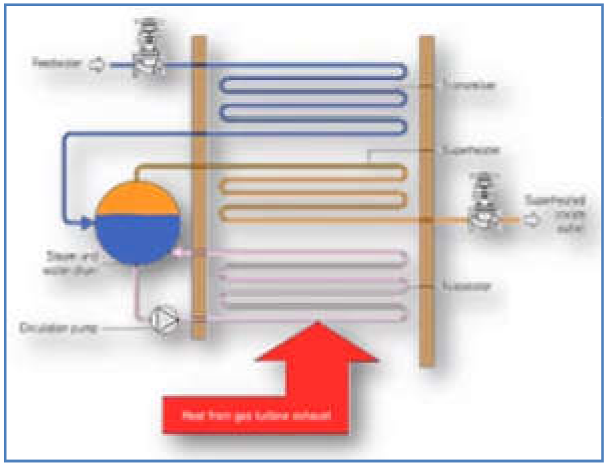
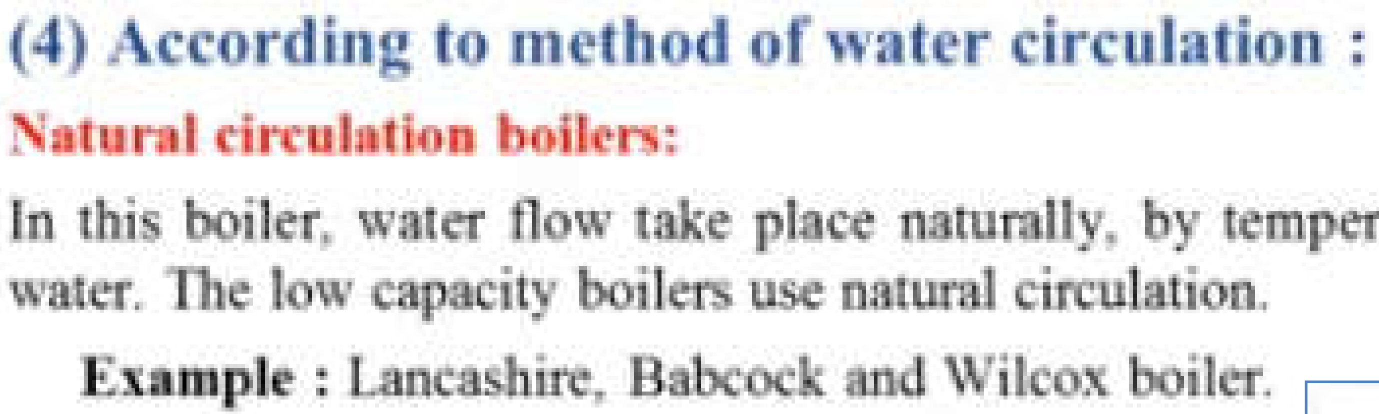


Figure . 1

Figure . 2



(4) According to method of water circulation :

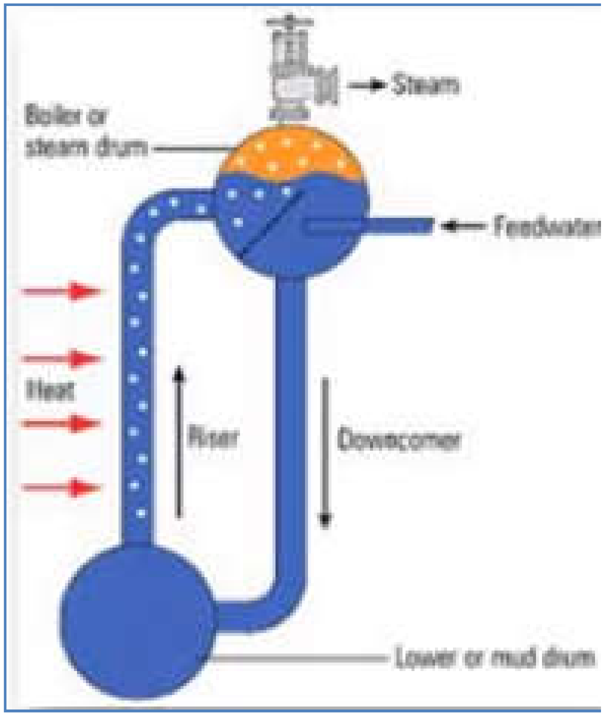
Natural circulation boilers:

In this boiler, water flow take place naturally, by temperature difference of water. The low capacity boilers use natural circulation.

Example : Lancashire, Babcock and Wilcox boiler.

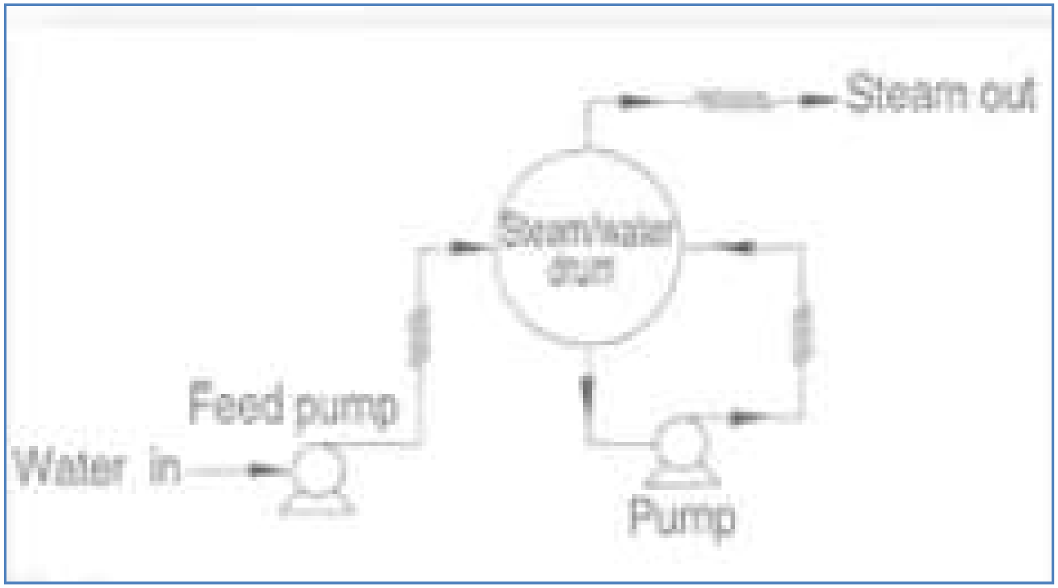
Or

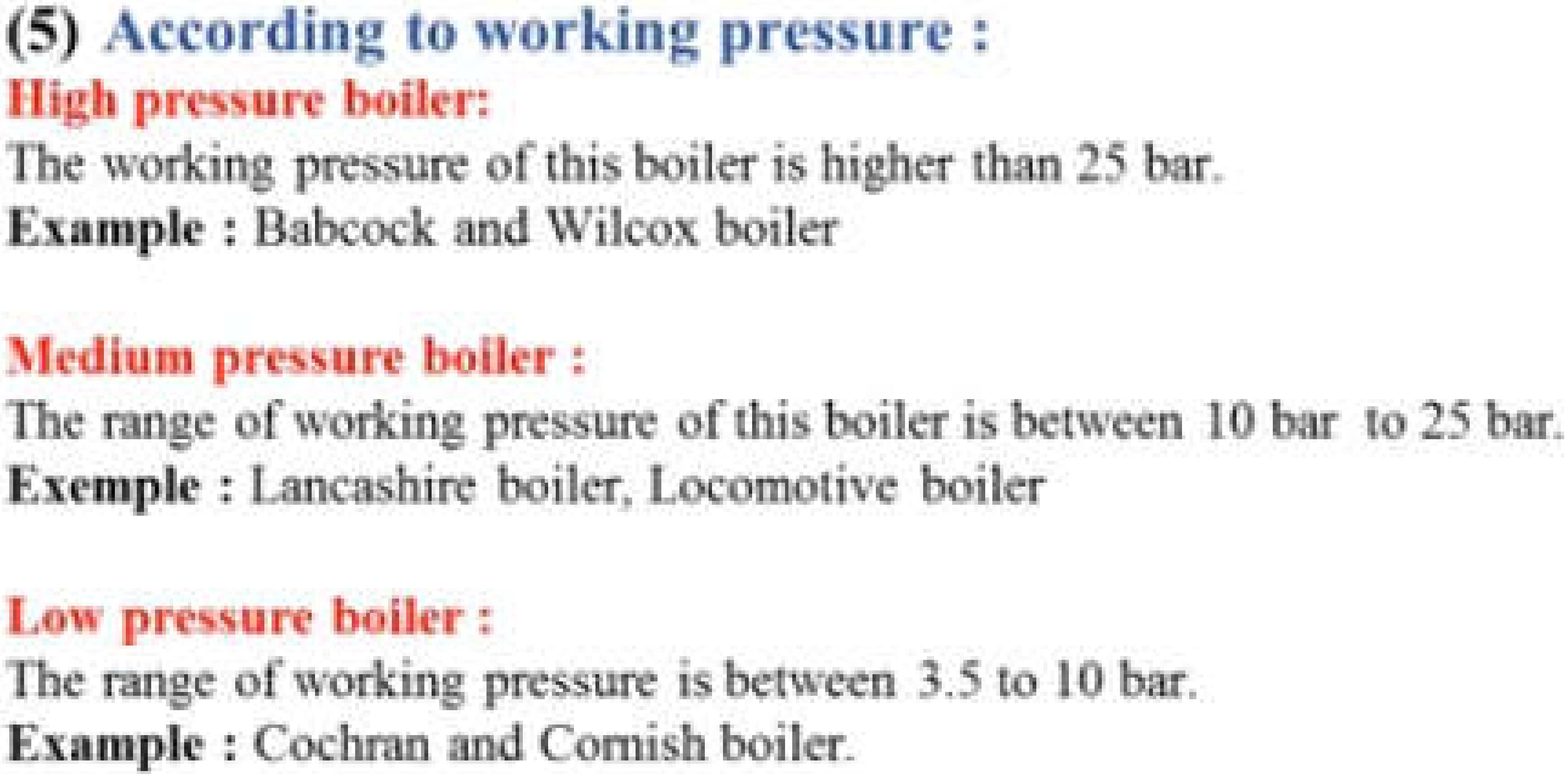
In Natural circulation type boilers, circulation of water in the boiler takes place due to natural convection current produced by the application of heat



Forced circulation boilers :

In this boiler, water flow (circulation) is take place by a pump. High pressure boilers are forced circulation boilers.





(5) According to working pressure :

High pressure boiler:

The working pressure of this boiler is higher than 25 bar.

Example : Babcock and Wilcox boiler

Medium pressure boiler :

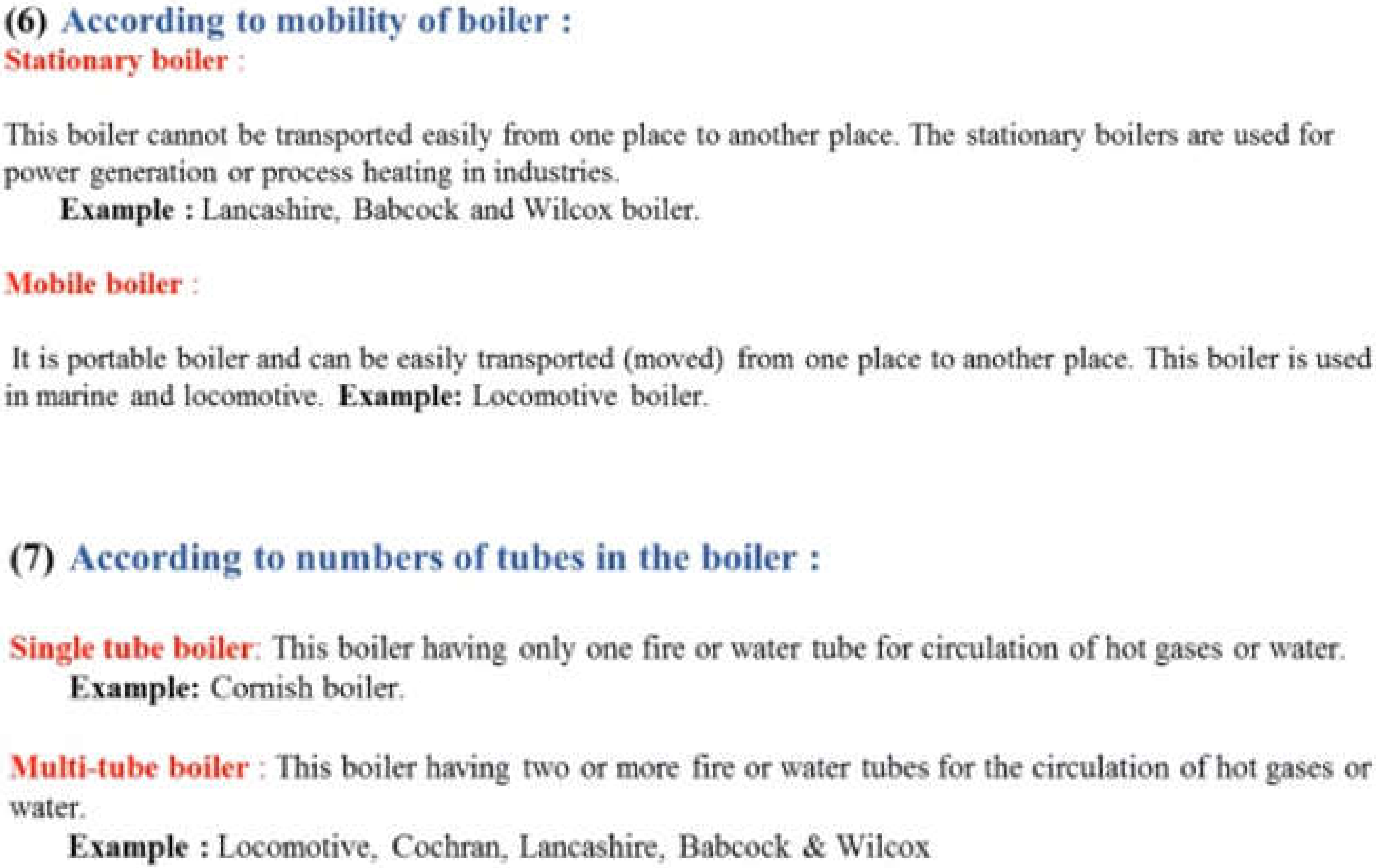
The range of working pressure of this boiler is between 10 bar to 25 bar.

Exemple : Lancashire boiler, Locomotive boiler

Low pressure boiler :

The range of working pressure is between 3.5 to 10 bar.

Example : Cochran and Cornish boiler.



(6) According to mobility of boiler :

Stationary boiler :

This boiler cannot be transported easily from one place to another place. The stationary boilers are used for power generation or process heating in industries.

Example : Lancashire, Babcock and Wilcox boiler.

Mobile boiler :

It is portable boiler and can be easily transported (moved) from one place to another place. This boiler is used in marine and locomotive. **Example:** Locomotive boiler.

(7) According to numbers of tubes in the boiler :

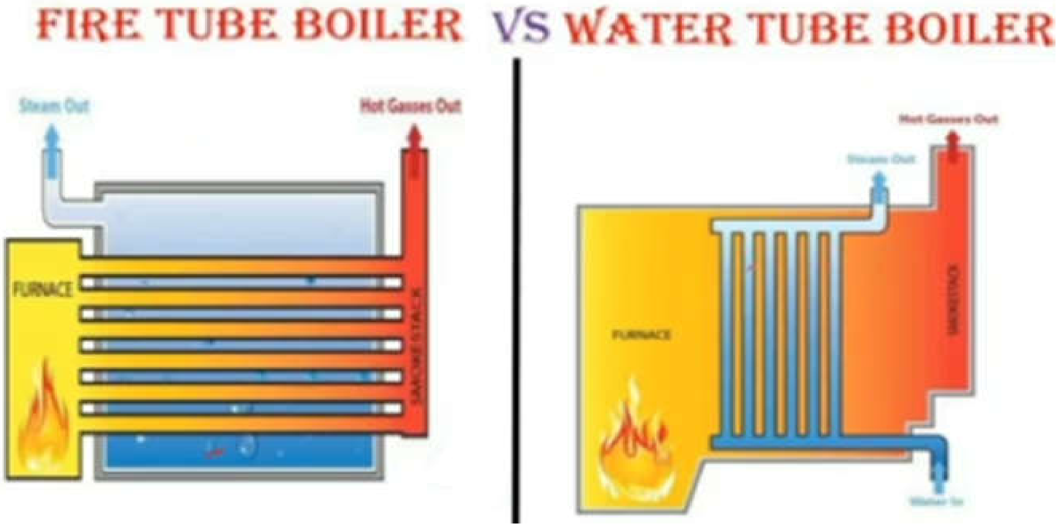
Single tube boiler: This boiler having only one fire or water tube for circulation of hot gases or water.

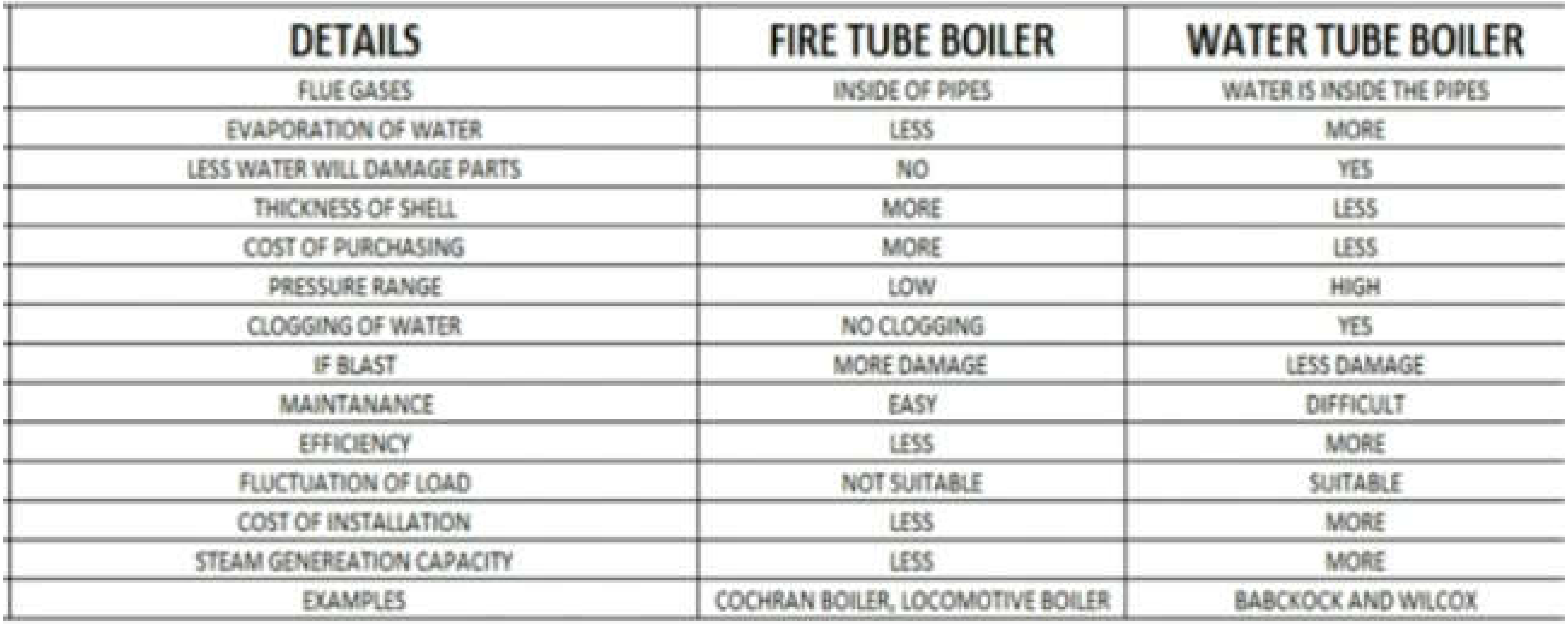
Example: Cornish boiler.

Multi-tube boiler : This boiler having two or more fire or water tubes for the circulation of hot gases or water.

Example : Locomotive, Cochran, Lancashire, Babcock & Wilcox

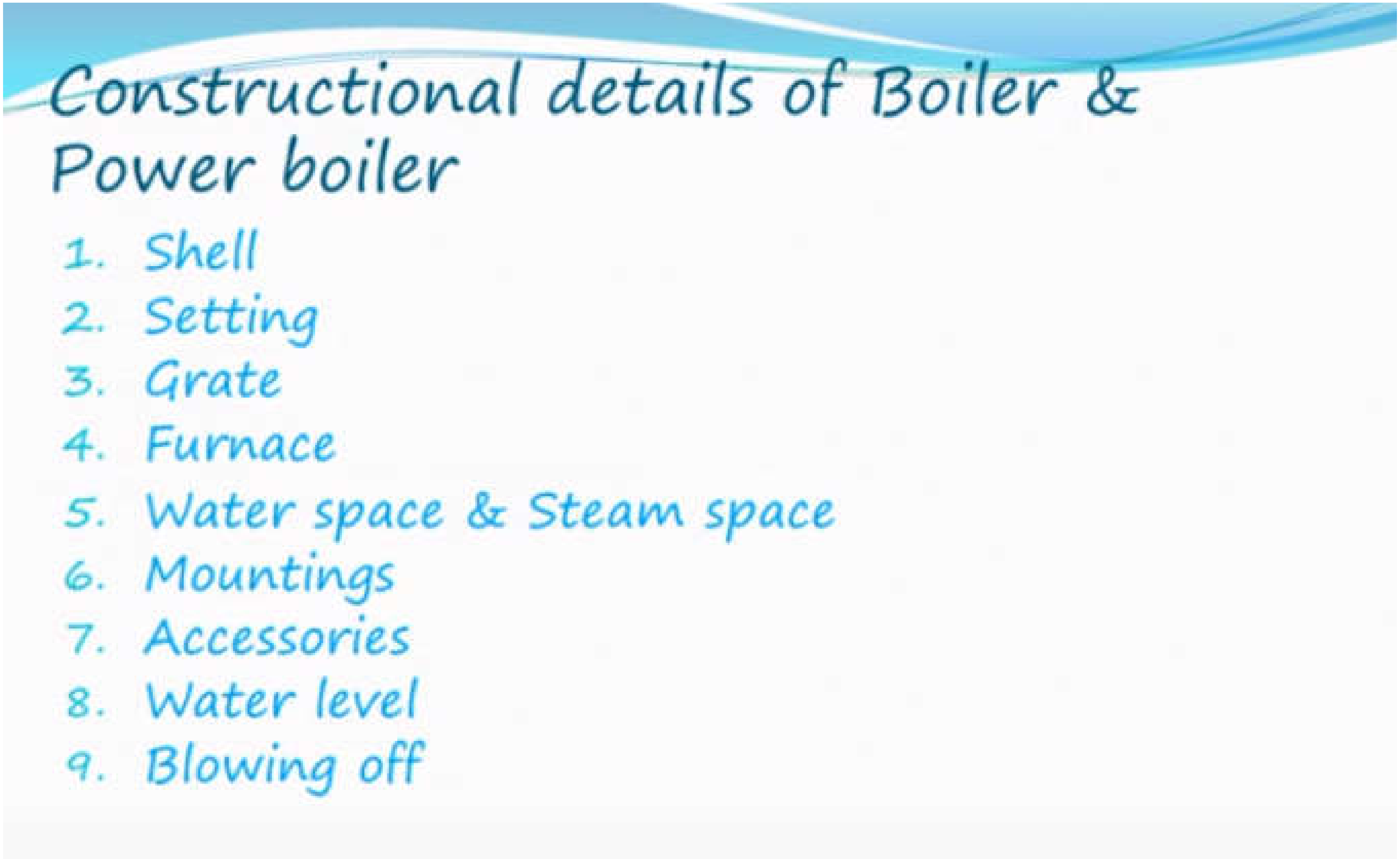
Comparison of Fire Tube Boiler & Water Tube Boiler





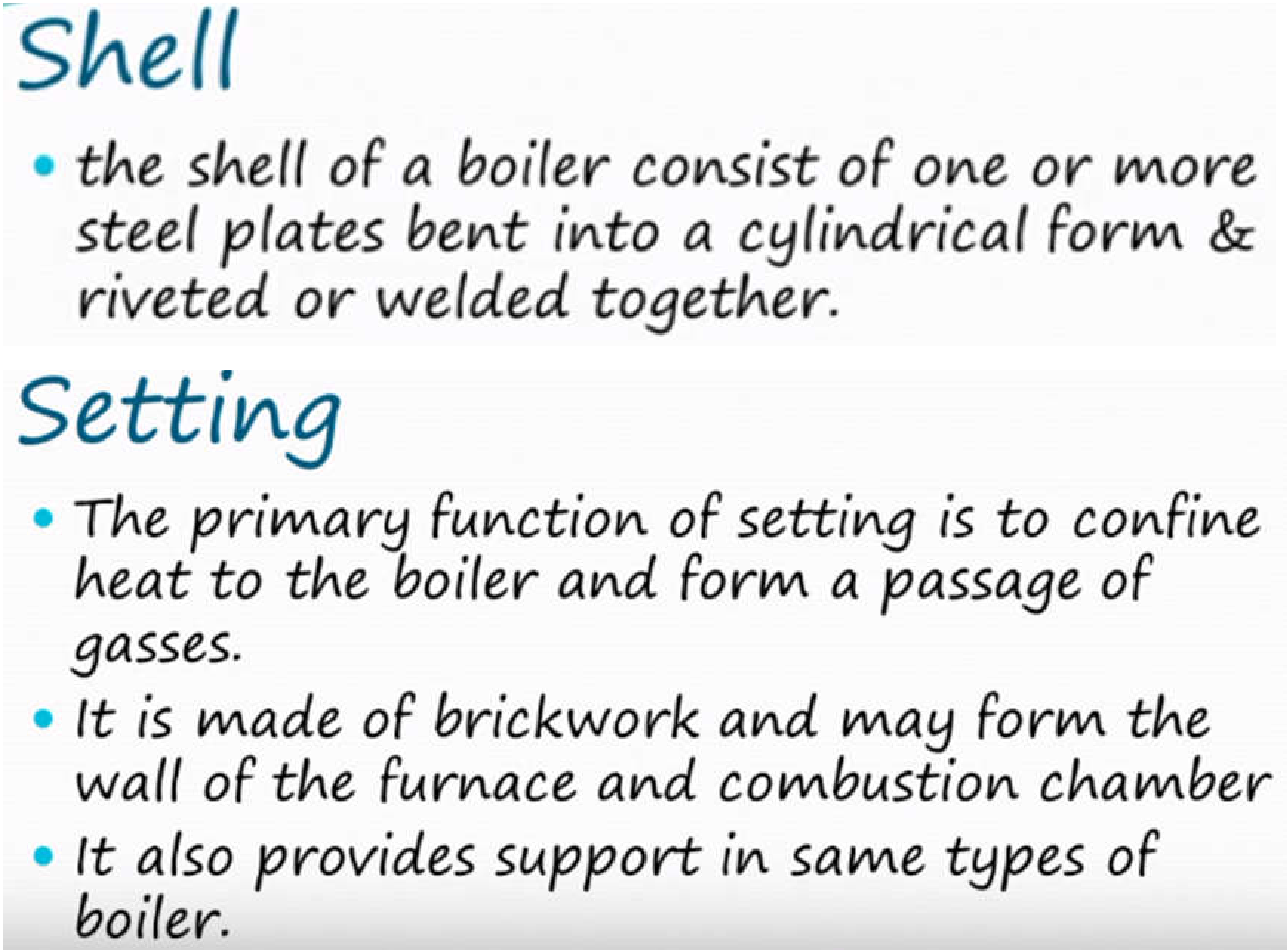
DETAILS	FIRE TUBE BOILER	WATER TUBE BOILER
FLUE GASES	INSIDE OF PIPES	WATER IS INSIDE THE PIPES
EVAPORATION OF WATER	LESS	MORE
LESS WATER WILL DAMAGE PARTS	NO	YES
THICKNESS OF SHELL	MORE	LESS
COST OF PURCHASING	MORE	LESS
PRESSURE RANGE	LOW	HIGH
CLOGGING OF WATER	NO CLOGGING	YES
IF BLAST	MORE DAMAGE	LESS DAMAGE
MAINTANANCE	EASY	DIFFICULT
EFFICIENCY	LESS	MORE
FLUCTUATION OF LOAD	NOT SUITABLE	SUITABLE
COST OF INSTALLATION	LESS	MORE
STEAM GENEREATION CAPACITY	LESS	MORE
EXAMPLES	COCHRAN BOILER, LOCOMOTIVE BOILER	BABCKOCK AND WILCOX

Constructional details of Boiler & Power boiler



Constructional details of Boiler & Power boiler

1. Shell
2. Setting
3. Grate
4. Furnace
5. Water space & Steam space
6. Mountings
7. Accessories
8. Water level
9. Blowing off

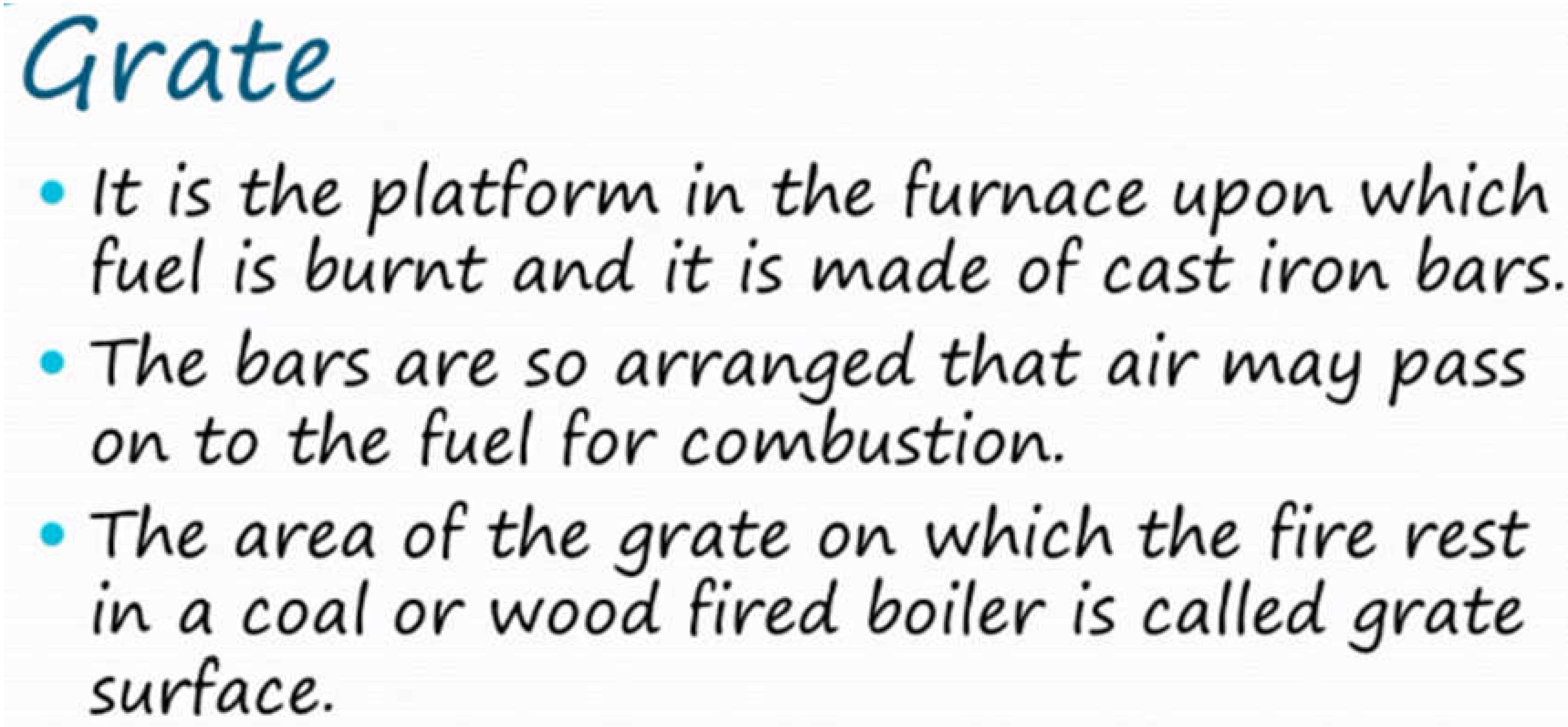


Shell

- the shell of a boiler consist of one or more steel plates bent into a cylindrical form & riveted or welded together.

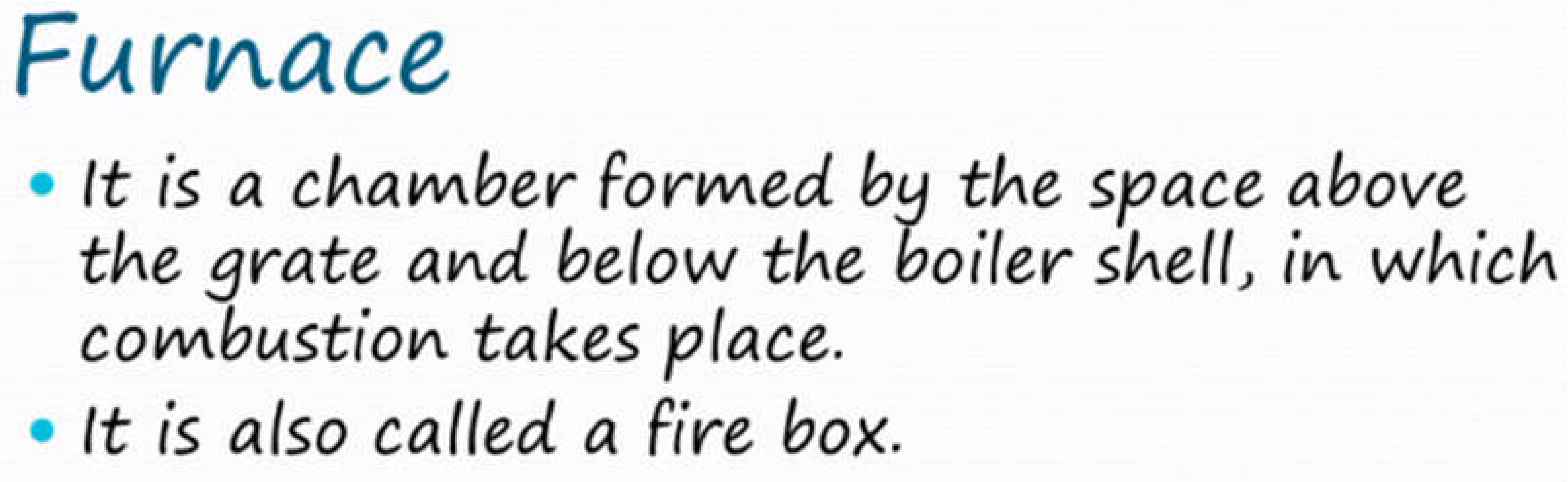
Setting

- The primary function of setting is to confine heat to the boiler and form a passage of gasses.
- It is made of brickwork and may form the wall of the furnace and combustion chamber
- It also provides support in same types of boiler.



Grate

- It is the platform in the furnace upon which fuel is burnt and it is made of cast iron bars.
- The bars are so arranged that air may pass on to the fuel for combustion.
- The area of the grate on which the fire rest in a coal or wood fired boiler is called grate surface.



Furnace

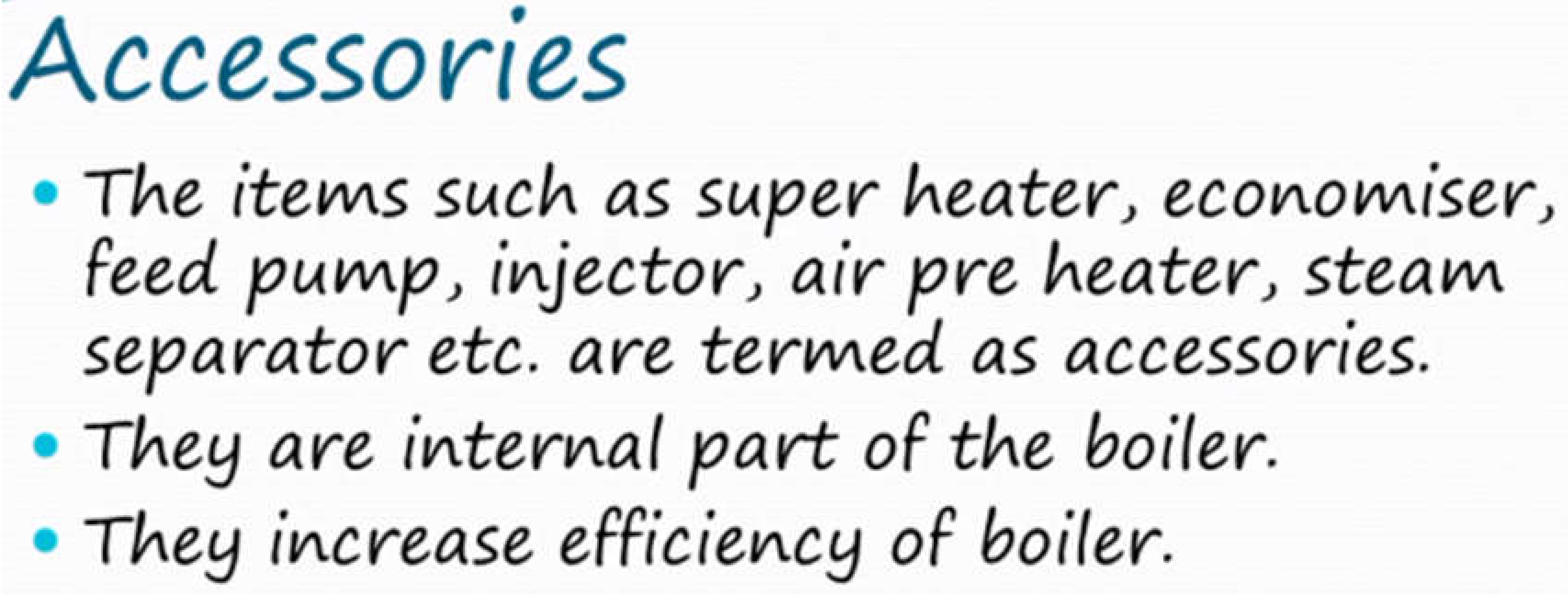
- It is a chamber formed by the space above the grate and below the boiler shell, in which combustion takes place.
- It is also called a fire box.

Water space & Steam Space

- The volume of the shell that is occupied by the water is termed water space while the entire shell volume less the water and tube space is called steam space.

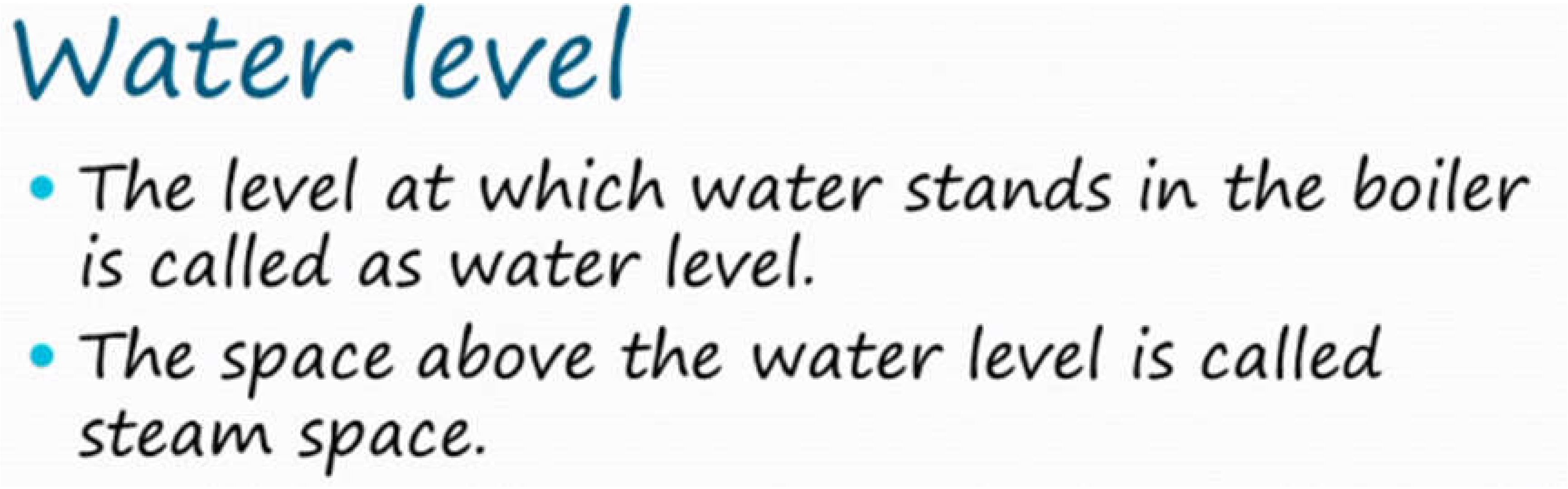
Mountings

- The items such as Stop valve, safety valve, water level gauges, fusible plug, blow off cock, Pressure gauge, water level indicator, dead weight safety valve, lever safety valve, spring loaded safety valve, feed check valve etc. are termed as mountings.
- They are external part of boiler.
- They are used for safety assurance.



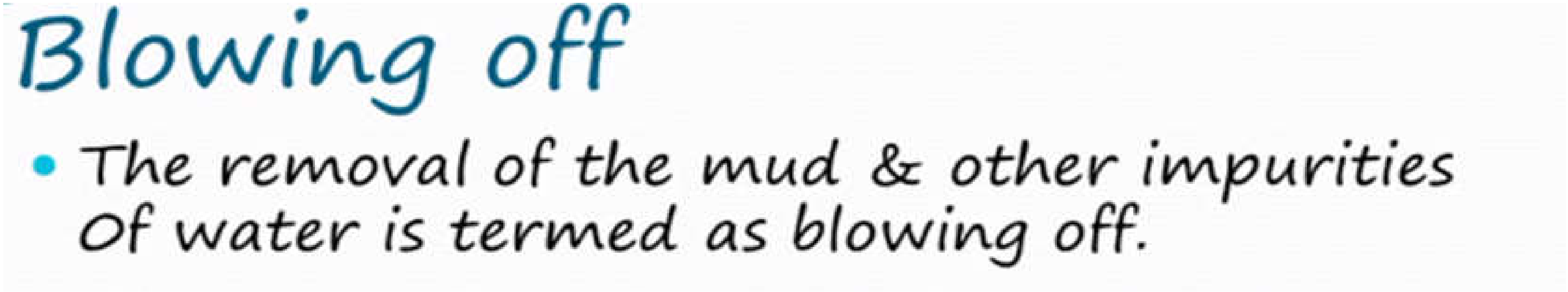
Accessories

- The items such as super heater, economiser, feed pump, injector, air pre heater, steam separator etc. are termed as accessories.
- They are internal part of the boiler.
- They increase efficiency of boiler.



Water level

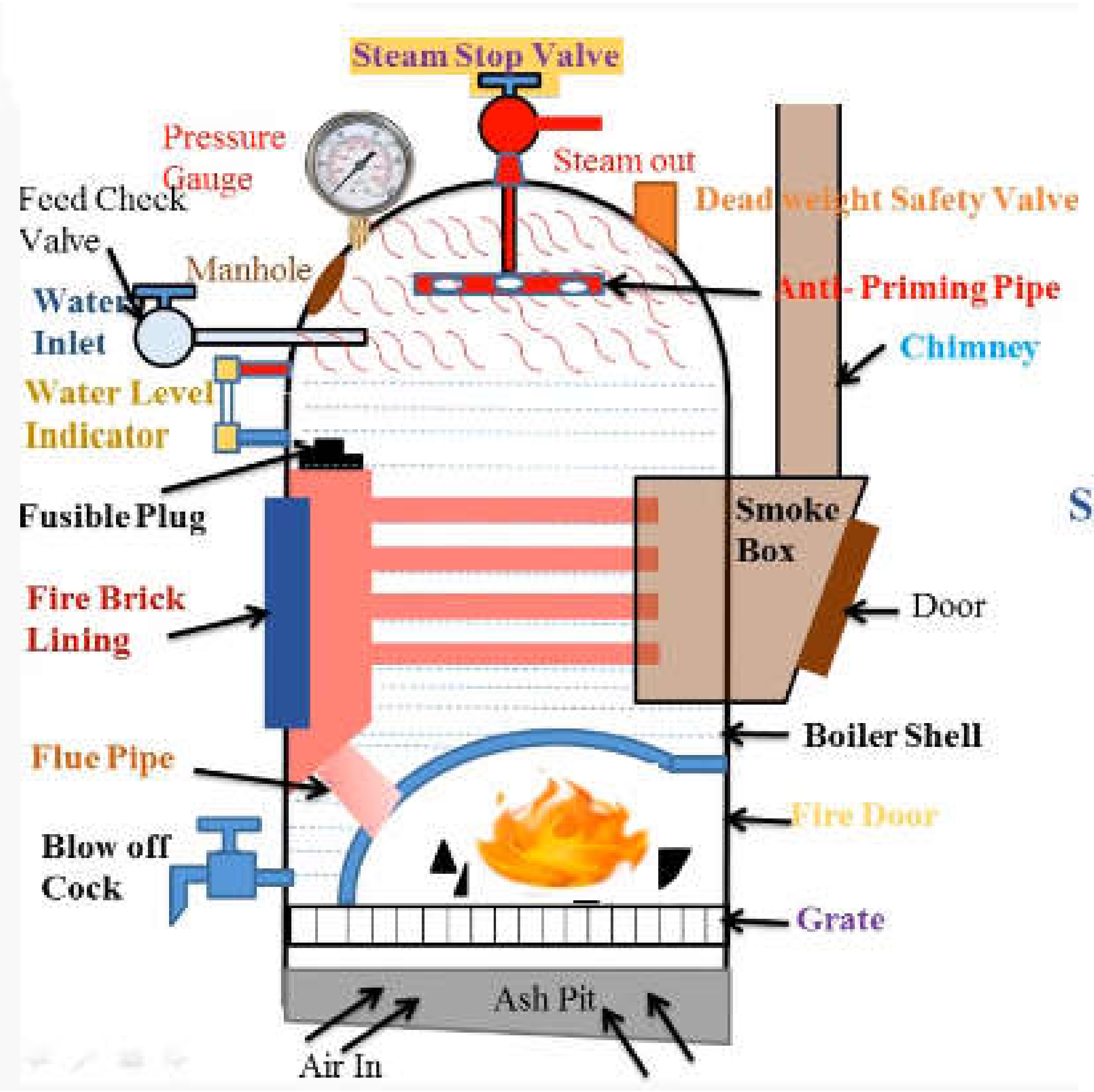
- The level at which water stands in the boiler is called as water level.
- The space above the water level is called steam space.



Blowing off

- The removal of the mud & other impurities Of water is termed as blowing off.

Cochran Boiler

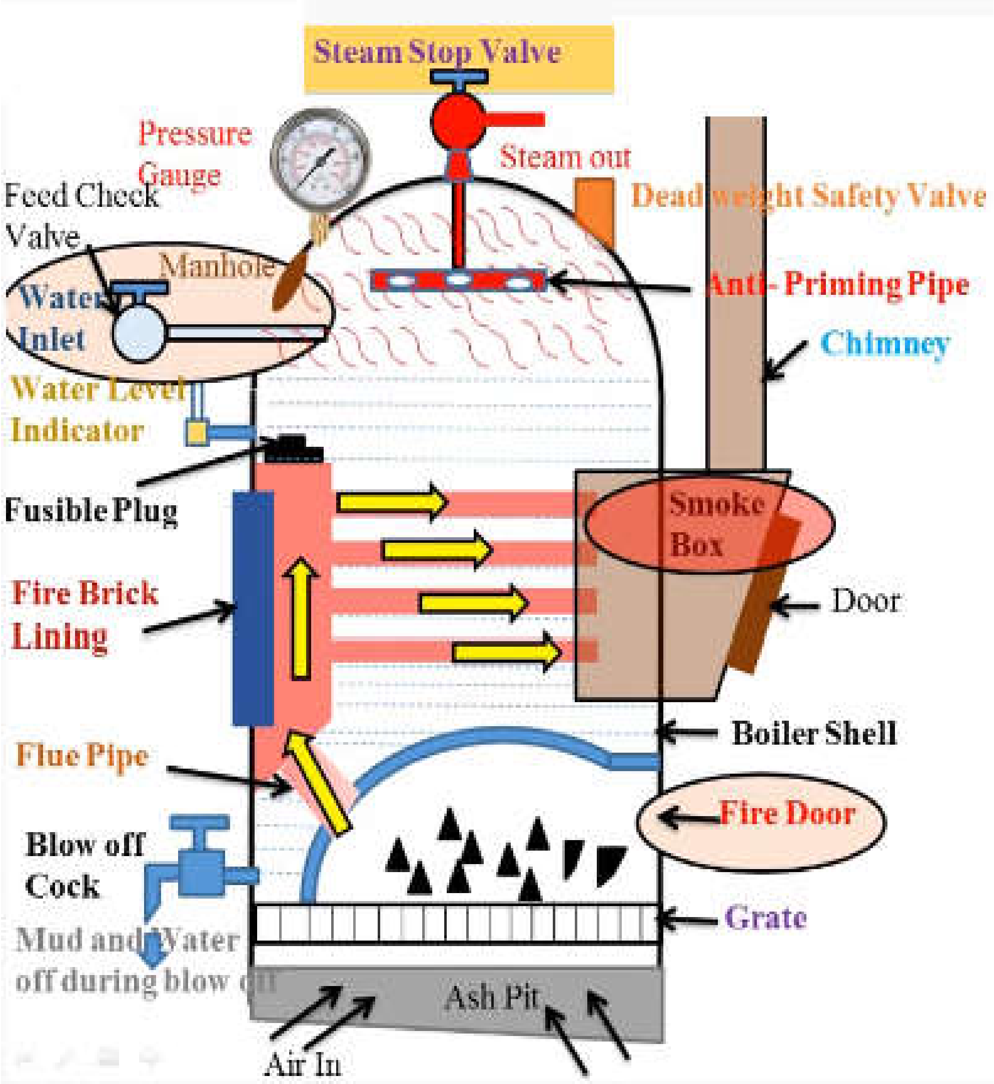


Characteristics of boiler:

- A vertical,
- Internally fired,
- Natural circulated boiler.
- Multifire-tube

Specification:

Shell Diameter : 2.75 m,
Height : 5.75 m,
Heating Surface Area : 120 m^2 ,
Working Pressure 6.5 bar,
Steam Capacity : 3500 kg/hr,

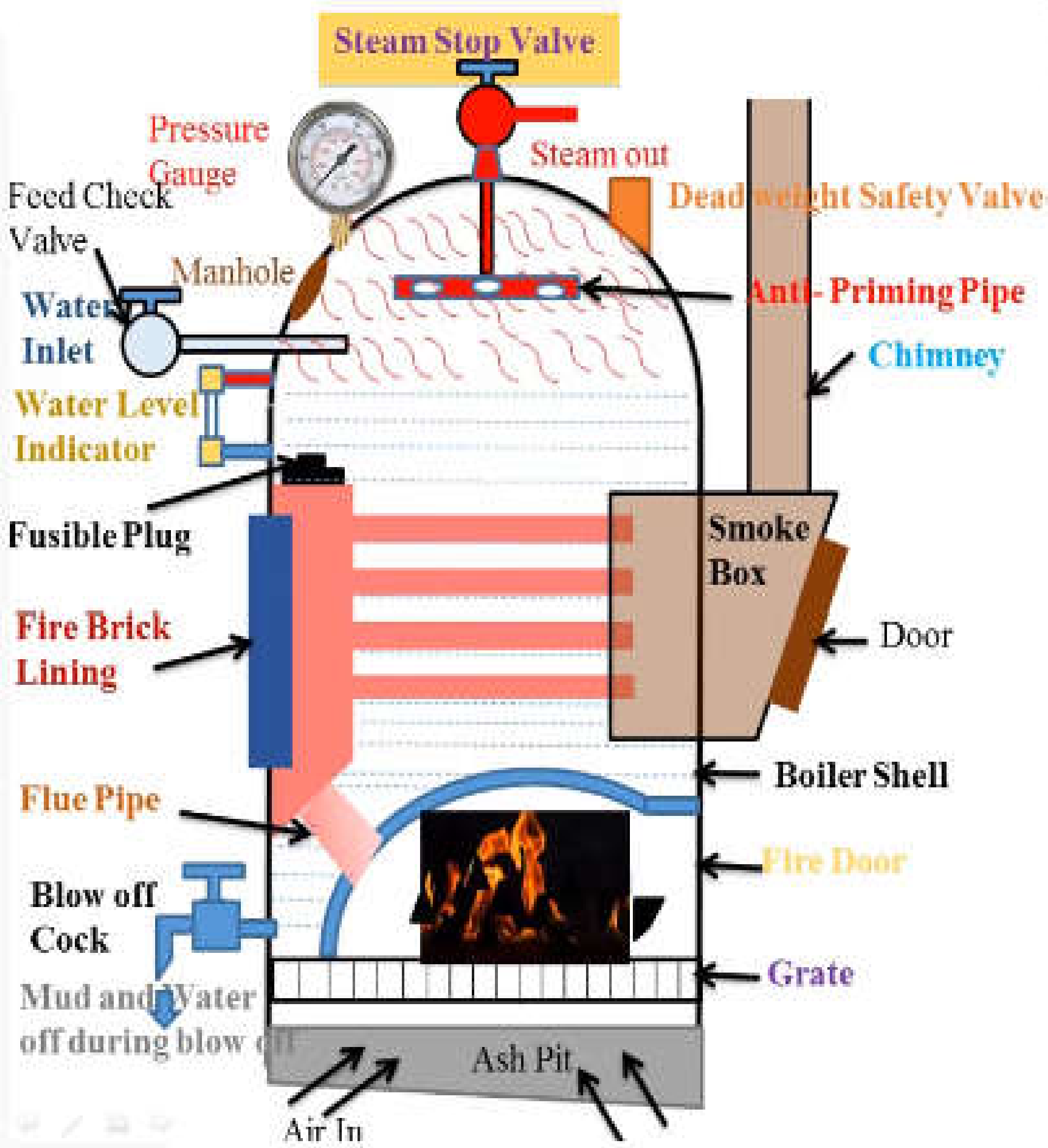


Mounting :

- Steam Pressure Gauge,
- Water Level indicator,
- Dead Weight Safety Valve,
- Feed Check Valve,
- Blow Of Cock,
- Steam Stop Valve,
- Man Hole,

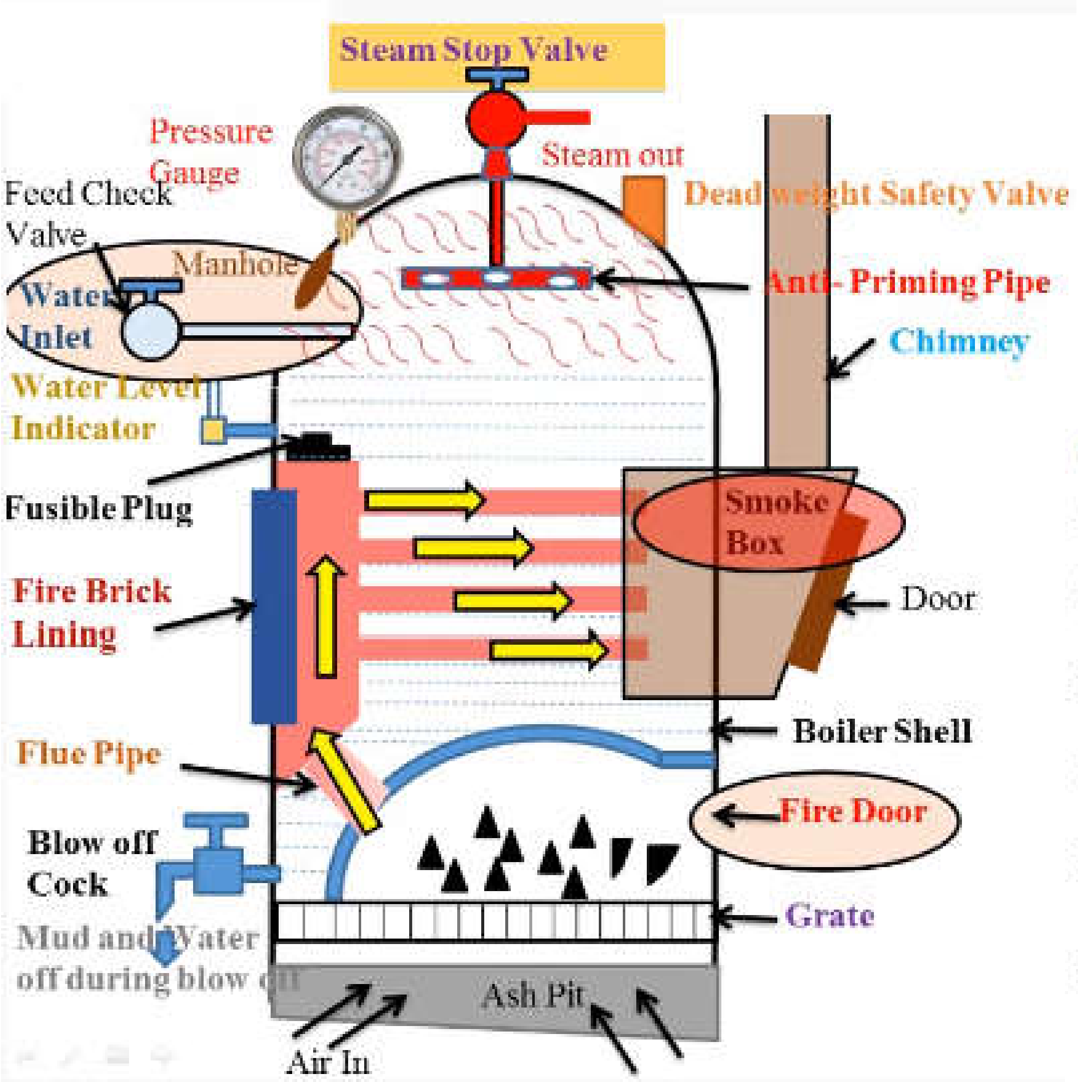
Fusible Plug: To stop firing when water level in the boiler is lower than safe limit.

Anti-priming Pipe :To separate water particle from steam and to collect the dry saturated steam from boiler through the steam stop valve.



Construction :

- The boiler consists of a cylindrical shell, hemispherical fire box, fire tubes and chimney.
- The top of the shell having hemispherical shaped crown as shown in fig.
- The hemispherical crown of boiler gives good strength to withstand pressure of steam inside the boiler..
- The hemispherical shape of furnace can withstand high heat and is also useful to increase radiant heat transfer from the furnace to hemispherical furnace wall.
- The grate is placed at the bottom of furnace and ash pit is located below the grate.
- The furnace and the combustion are connected by short flue pipe.
- The wall of the combustion chamber is lined with the fire bricks.



Working :

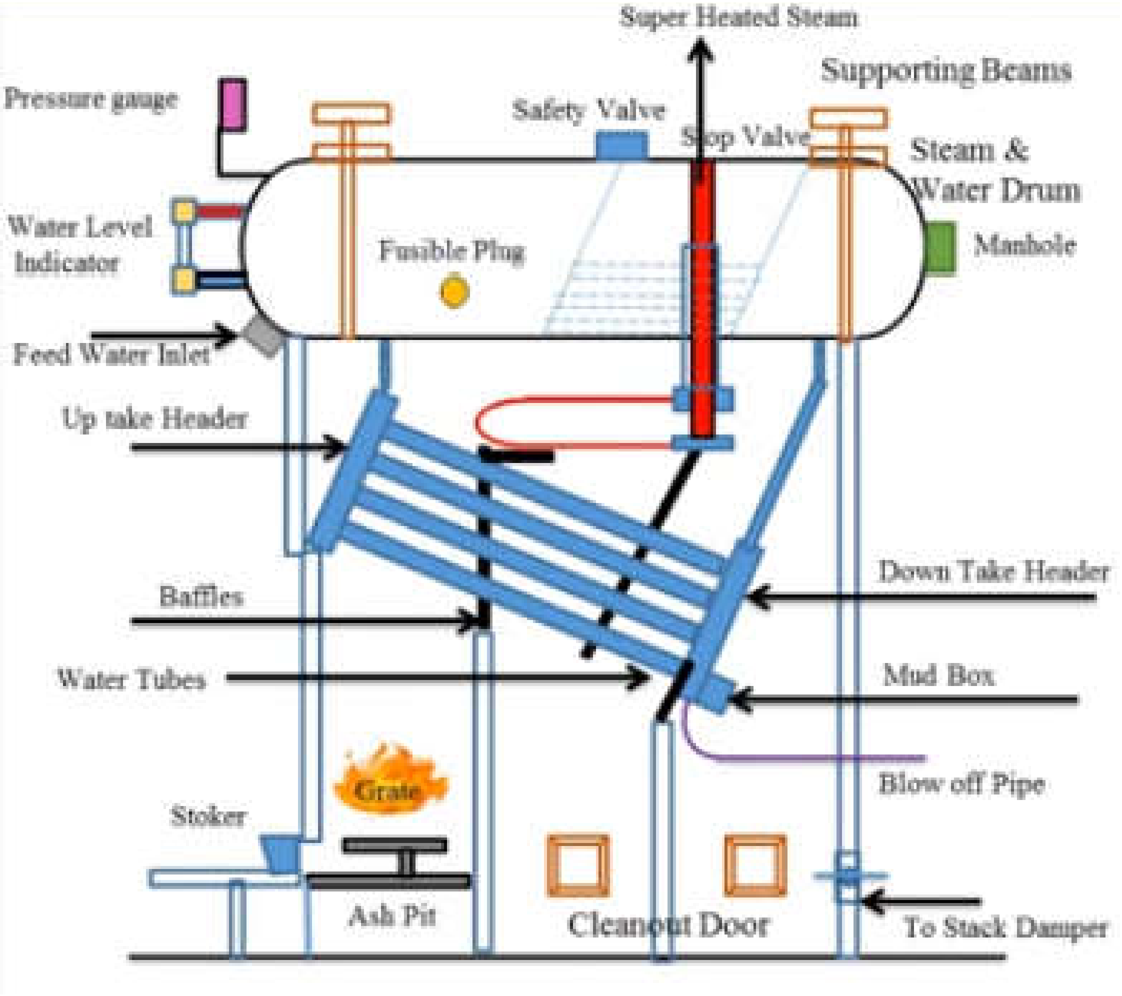
- The water is supplied to the boiler through feed check valve.
- The coal is introduced to the grate through the fire door.
- The hot gases from furnace enters combustion chamber through flue pipe.
- This hot gases enters into horizontal fire tubes.
- Heat transfer take place from flue gases passing inside the tubes to water surrounded the tubes by convection.
- The flue gases coming from fire tubes enters into smoke box and then finally discharged to atmosphere through chimney.
- The ash formed is collected in the ash pit.
- The steam is collected through anti priming pipe on top of the shell.

Babcock and Wilcox Boiler

It is a water tube boiler and used in stationary and marine engine.

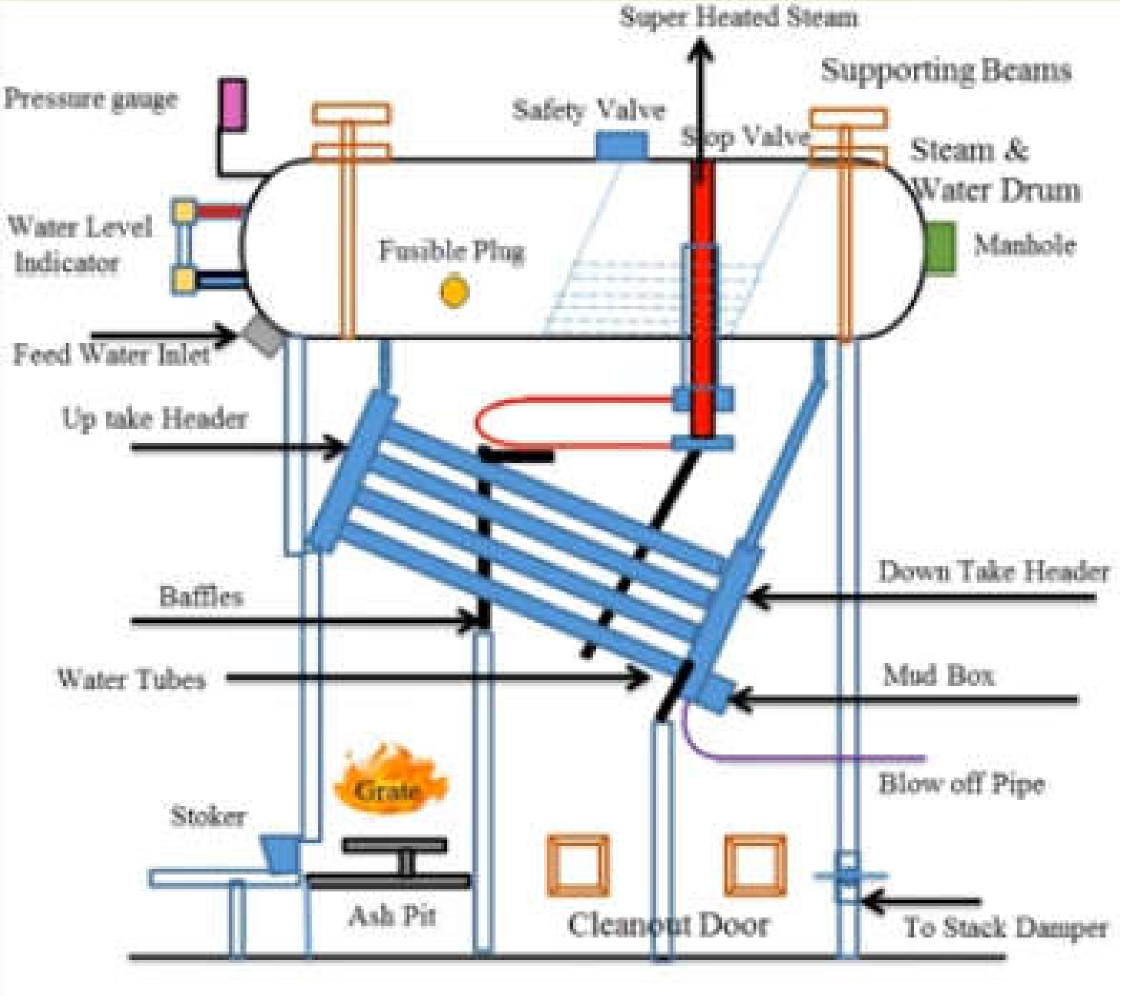
The efficiency of this boiler is much greater than that of the fire tube boiler.

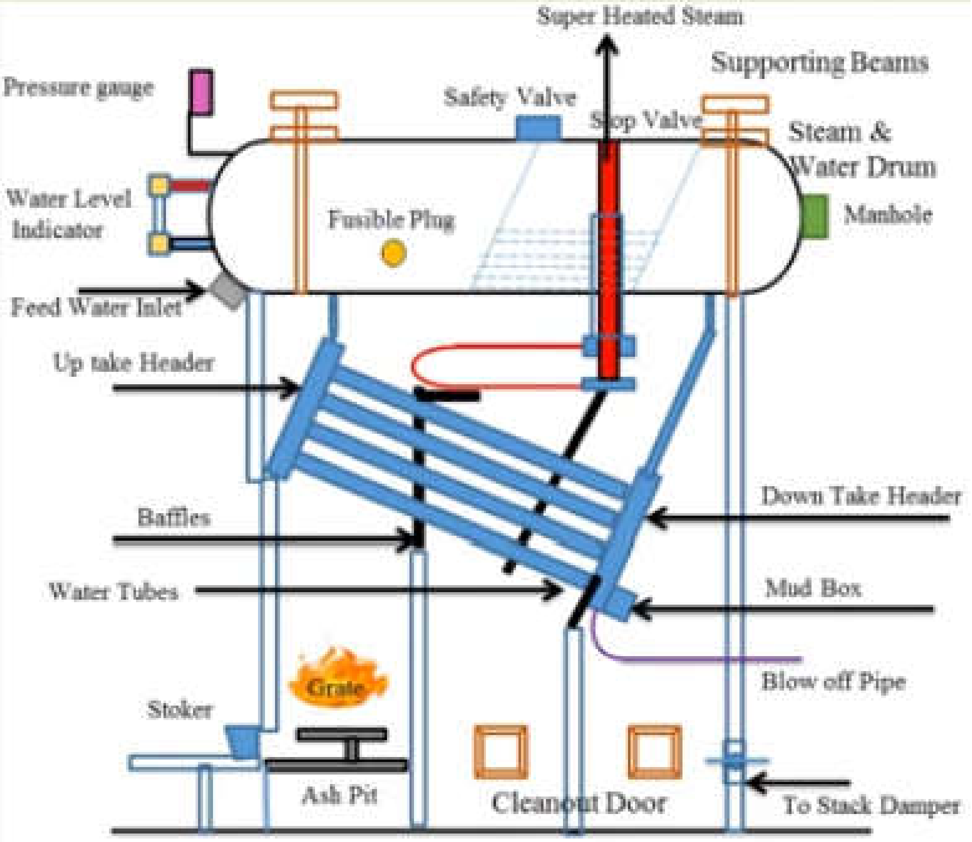
This boiler is exclusively used when pressure is above 10 bar and steam generating capacity is required higher than 7000 kg/hr.



Specification:

Diameter of the drum = 2000 to 4000 mm.
Length = 6000 to 9000 mm.
Size of the water tube = 76.2 to 101.6 mm
Size of upper header tube = 38.4 to 57.1 mm
Maximum working pressure = 42 bar
Maximum steam capacity = 40,000 kg/hr
Efficiency = 60 to 80 %





Working:

The water feed into the boiler shell through the feed check valve.

Due to gravity water passes through the vertical tubes, headers and fills up the inclined tubes first.

Then the water collects in the drum. Initially one half of drum is filled up with water.

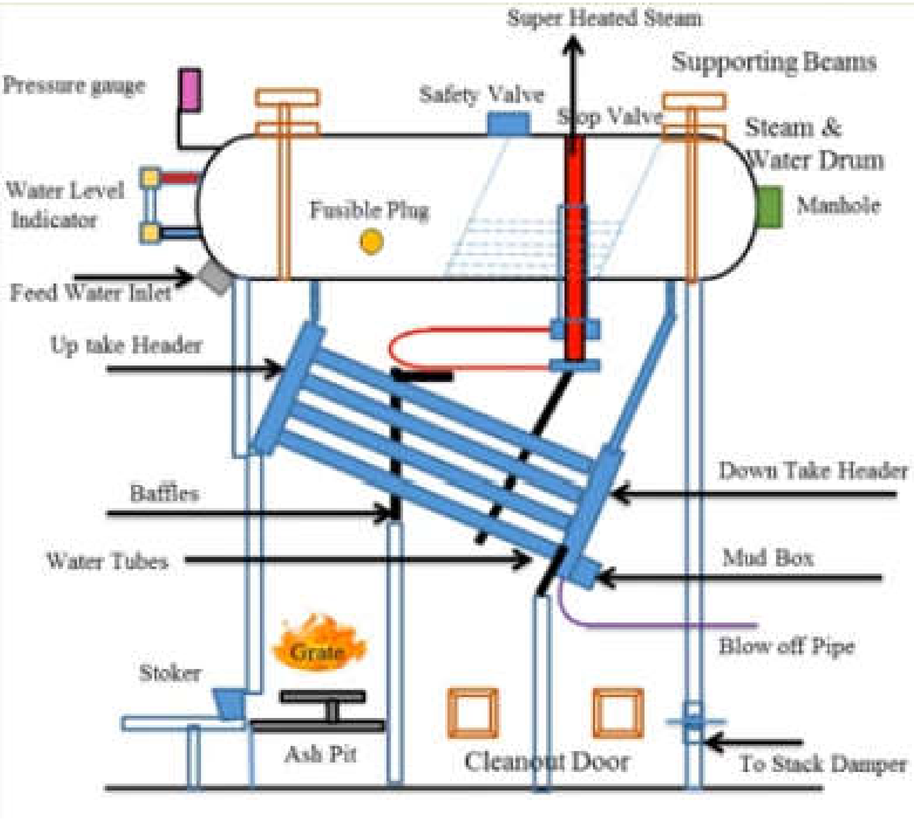
The coal is introduced to furnace grate by help of stoker.

The coal is fired, hot gases produced is first forced to move upward through passage between tubes.

The baffles plates make flow of hot gases in sine wave, as move down and then move upward over the water tubes.

The damper controls the flow of air into the furnace.

Water in the drum comes down through [redacted] header and enter the tubes.



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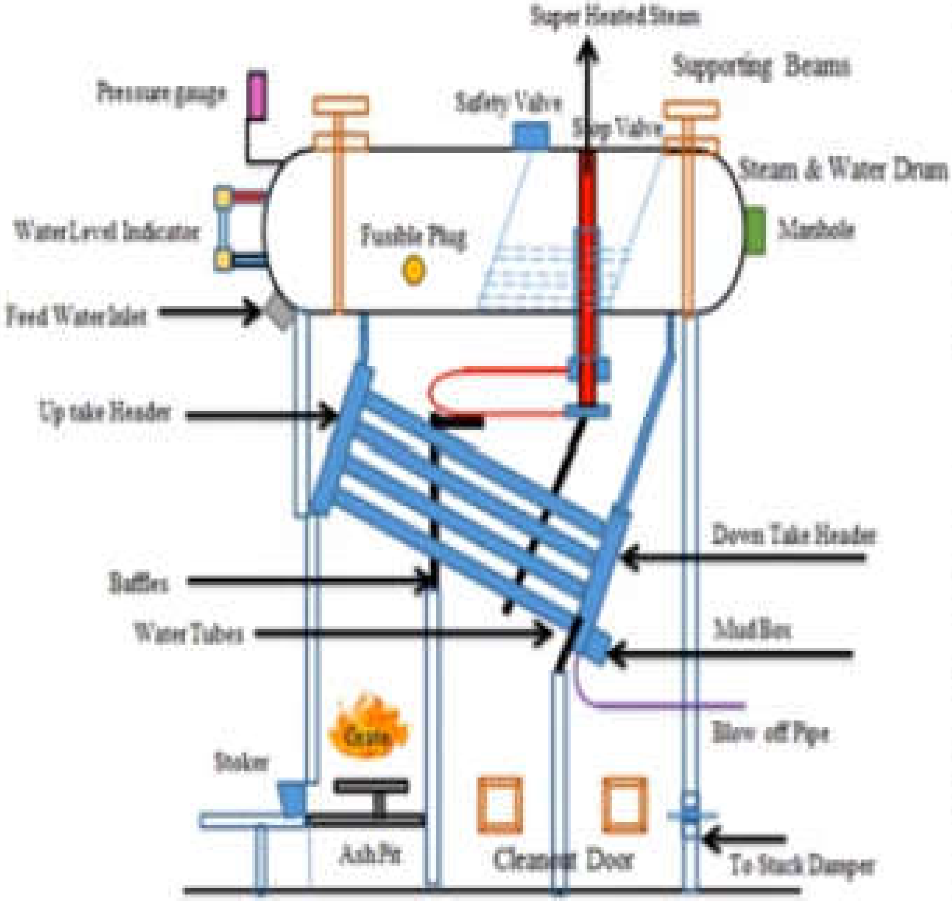


Working:

They are heated by hot gases coming from furnace. Due to heating of the water, density of water decreases. Low density water moves upward in water tubes.

The water tubes just above the furnace are heated comparatively at a higher temperature than the rest of it. Therefore low density water is gradually converted into steam in their path and rises into drum through up take header.

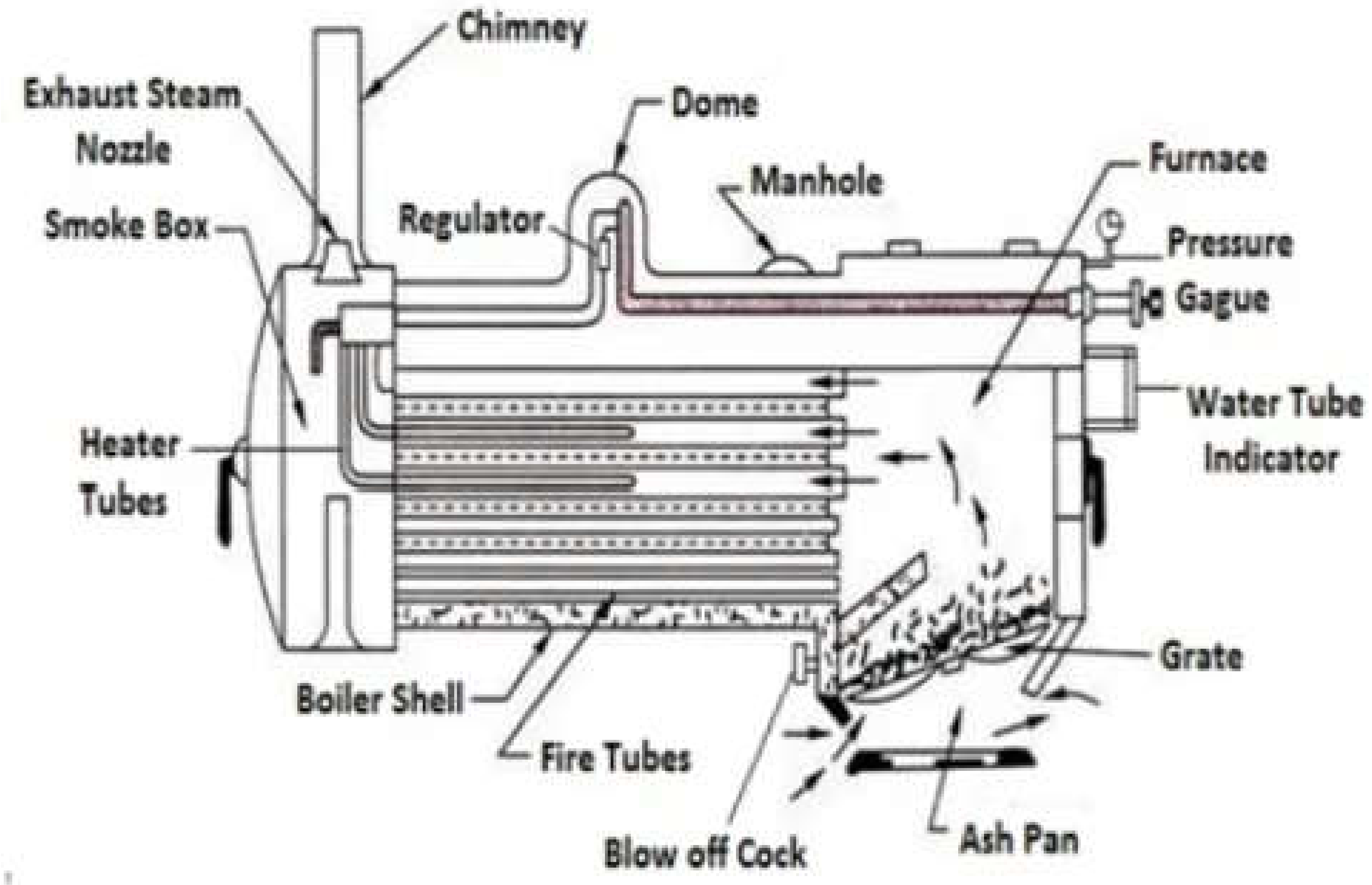
Thus a continuous circulation of water from drum to water tubes and water tubes to drum is maintained due to density difference of water and gravity, without any pump.

The steam then enters to the ant-priming pipe and flows in the super heater tubes where it is further heated and is finally taken out thorough the main steam stop valve and supplied to the engine when needed.

At lowest point of the header, mud collector is provided to remove the mud particles through a blow down cock

Advantages:

1. The steam generation capacity of the boiler is very high, about 2000 to 40000 kg/hr.
2. Replacement of defective tubes is easy.
3. The draught losses as compared to other boilers are minimum.



Locomotive Boiler

Working of Locomotive Boiler

- In a locomotive boiler, first, the solid fuel (coal) is inserted on the grate and is ignited from the fire hole. The burning of the fuel starts and it creates hot exhaust gases. A fire brick arch is provided that makes the flow of hot exhaust gases to a definite path before entering into the long tubes (fire tubes). It also prevents the entry of burnt solid fuel particles into the fire tubes

- The hot exhaust gases pass through the long fire tubes and heat the water surrounding them. Due to the heating, water gets transformed into saturated steam and collected at the top. Saturated steam from a dome enters into the steam pipe with the help of a regulator valve. The steam travels in the main steam pipe and reaches the superheater header. From the header, the steam enters into the superheater element pipes.

- Here it is superheated and then the superheated steam enters into the steam pipe of the smokebox. The steam from the superheater goes to the cylinder containing the piston. The superheated steam made the piston moves within the cylinder. The piston is connected to the wheels of the steam engine and the wheels start rotating. The exhaust steam from the cylinder enters the blast pipe.

- The burnt gases and smoke after passing through the fire tubes enter into the smokebox. The exhaust steam coming out from the blast pipe pushes the smoke out of the boiler through the chimney. Here the smoke cannot escape out from the boiler on its own, so an artificial draft is created by exhaust steam coming out from the steam engine. This artificial draft created pushes the smoke out of the smokebox and creates suction for the hot exhaust gases.

Advantages of Locomotive Boiler

1. It is portable.
2. This boiler is capable of meeting sudden and fluctuating demands of steam.
3. It is a cost-effective boiler.
4. High steam generation rate.
5. It is compact in size and its operation is easy.

Disadvantages of Locomotive Boiler

1. It faces the problems of corrosion and scale formation.
2. Unable to work under heavy load conditions because of overheating problems.
3. Some of its water space are difficult to clean.
4. The overall efficiency is less.

Application of Locomotive Boiler

1. Locomotive boilers are used in railways and marines.
2. This type of boiler is used in traction engines.
3. This is also used in steam rollers.
4. It is can be used in portable steam engines and some other steam road vehicles.

Thermal Engineering-II
MODULE-2-II

Introduction

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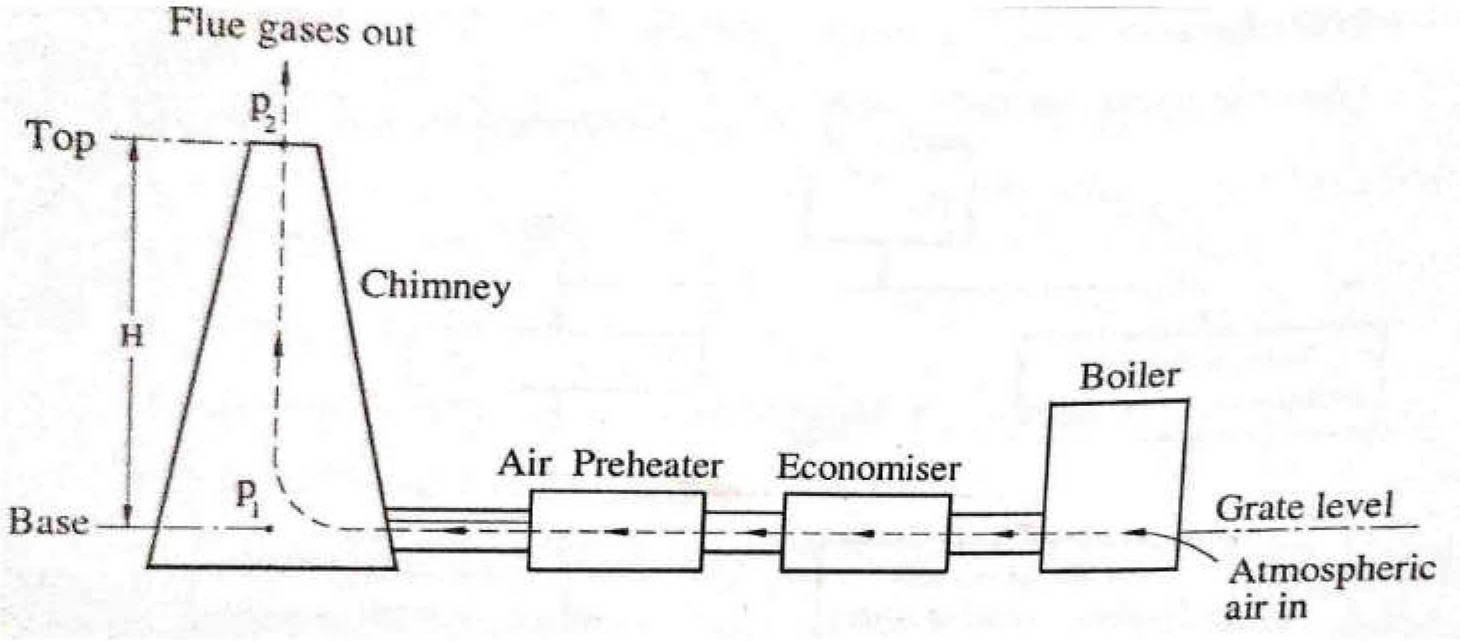
MODULE-2

Boiler Draught

- The small Pressure difference which cause the flow of gas to take place is termed as Draught.

or

- Draught is a small pressure difference between air outside the boiler and gases within the Furnace.



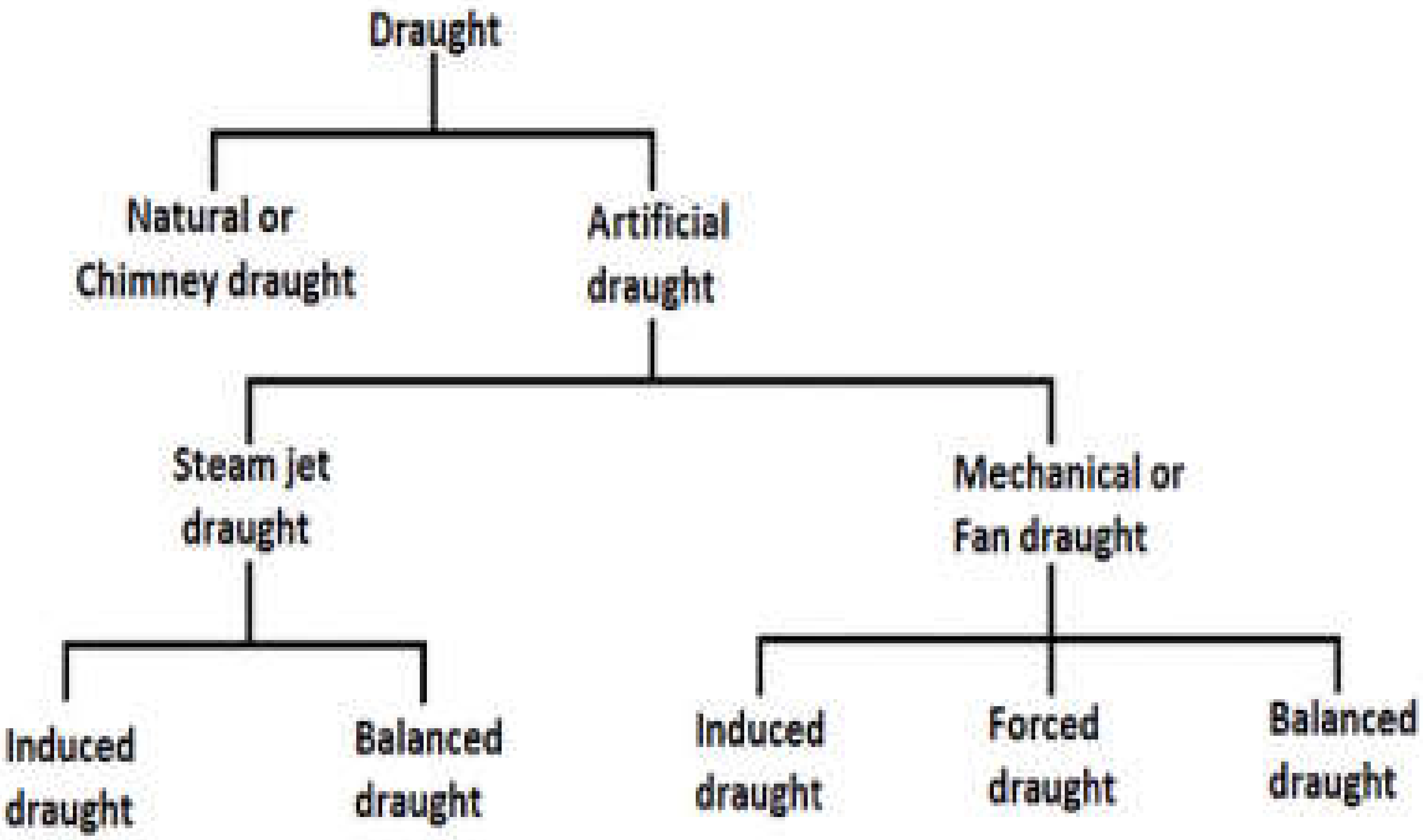
- The Function of draught in case of boiler, is to force the air to the Grate for Combustion and carry away the flue gases outside the Chimney.

- In Boiler furnace. The proper combustion takes place only when sufficient quantity of air is supplied to the burning fuel.

Necessity of boiler draught

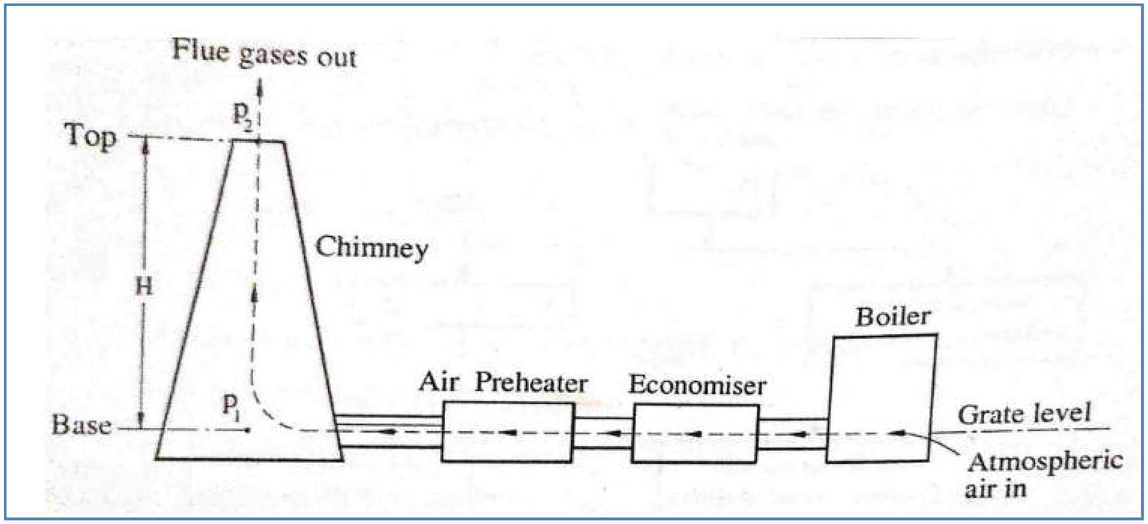
1. To provide sufficient quantity of air for combustion.
2. To expel out the hot gases to flow through the boiler.
3. To discharge these gases to atmosphere through chimney.

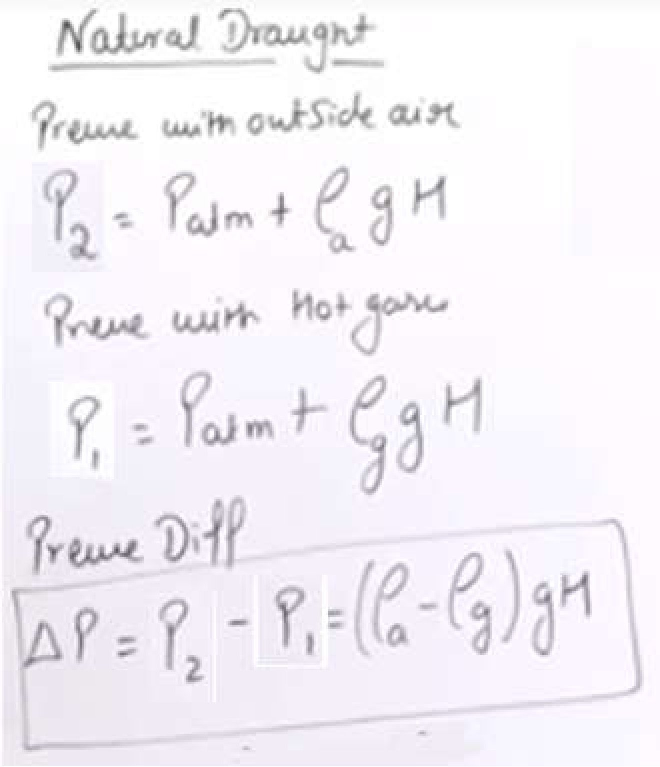
Classification of Draught



- Draught
  - Natural or Chimney draught
  - Artificial draught
    - Steam jet draught
      - Induced draught
      - Balanced draught
    - Mechanical or Fan draught
      - Induced draught
      - Forced draught
      - Balanced draught

Natural draught




Natural Draught

Pressure with outSide air

$$P_2 = P_{atm} + \rho_a g H$$

Pressure with Hot gases

$$P_1 = P_{atm} + \rho_g g H$$

Pressure Diff

$$\boxed{\Delta P = P_2 - P_1 = (\rho_a - \rho_g) g H}$$

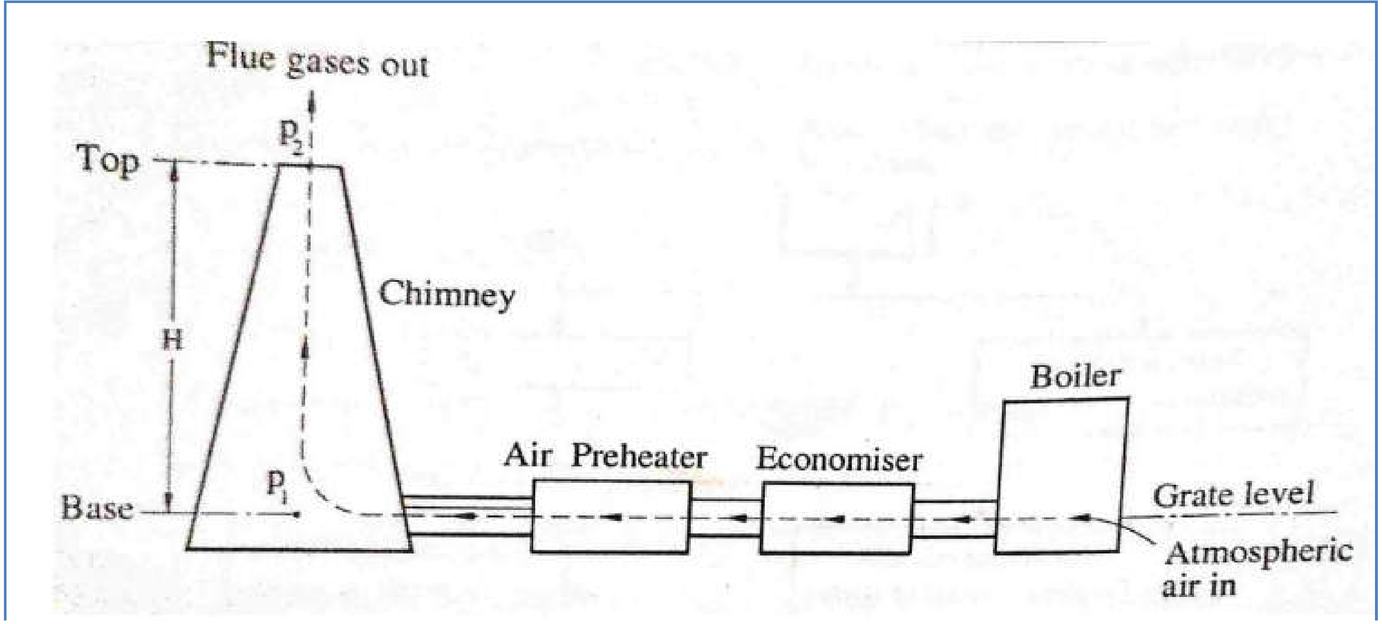
- Its value is very small, so it is generally the pressure values are measure by Water manometer.
- It is noted that the pressure difference in chimney is generally less than 12mm of water.

The natural draught is obtained by the use of chimney. The chimney in the power plant performs the following two functions.

(i) It produces draught (create pressure difference) which required to force air and gases through the furnace, boiler accessories and settings.

(ii) It comes the product of combustion to such a height that they will not be objectionable or injurious to surrounding.

The chimney is vertical tabular structure build either of masonary, concrete or steel. The draught produces by the chimney is due to density difference between the column of hot gases inside the chimney and cold air outside the chimney and also on the height of the chimney above the level of the furnace grate. The density difference depends on the temperature of flue gases passing in chimney and temperature of atmospheric air.



Advantages of chimney or natural draught:

(1) Chimney draught does not require any external power to produce draught.

(2) Simple in construction, less cost and has long life.

(3) Non-mechanical parts and hence maintenance cost is negligible.

(4) Chimney keeps flue gases at a high place in the atmosphere which prevents the contamination of atmosphere and maintains the cleanliness.

Disadvantages / Limitations of chimney or natural draught:

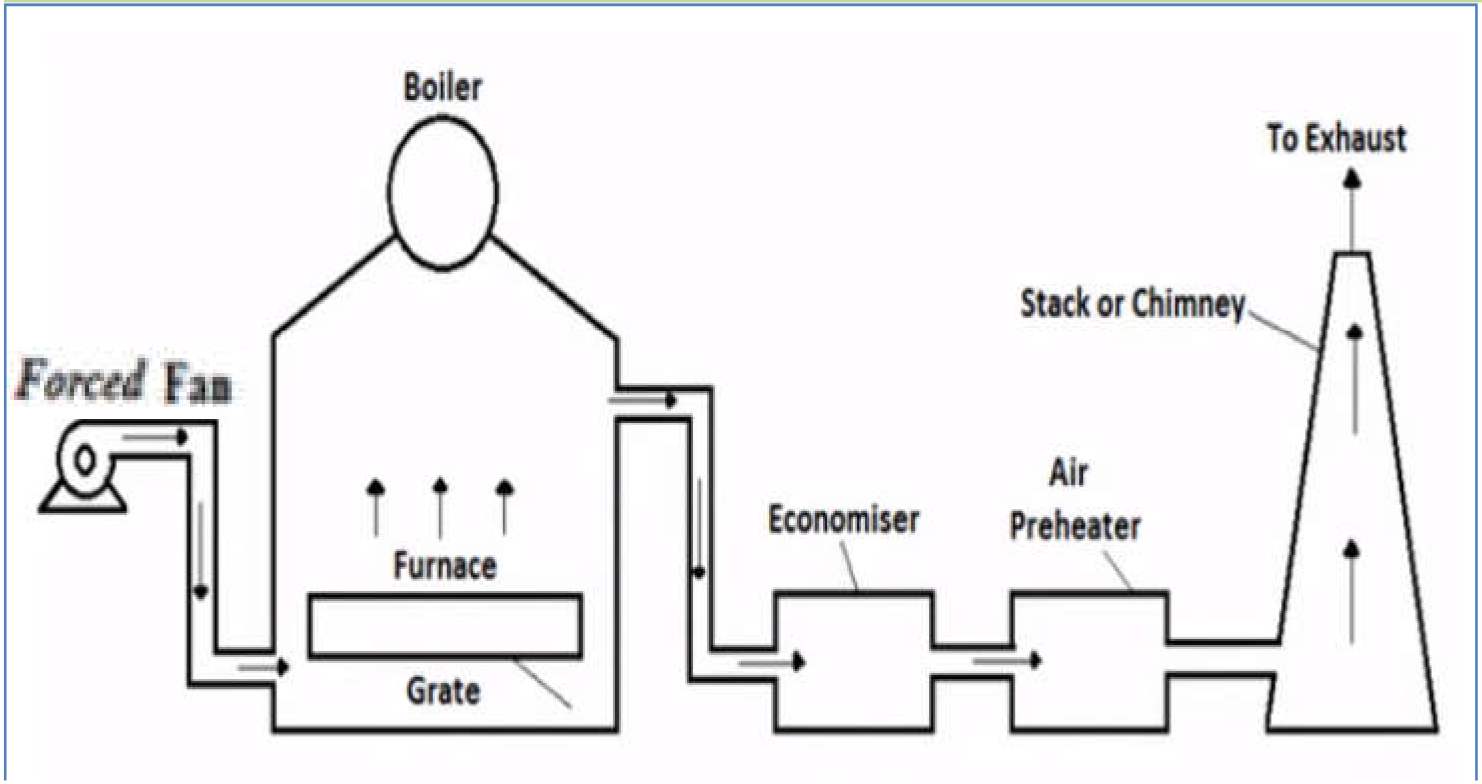
(1) The maximum pressure available for producing natural draught by chimney is hardly 10 to 20 mm of water. Hence it is only used for very small boilers.

(2) Due to low velocity of air, the mixing process of air and fuel is not proper and hence combustion is very poor. This increases the specific fuel combustion of boiler.

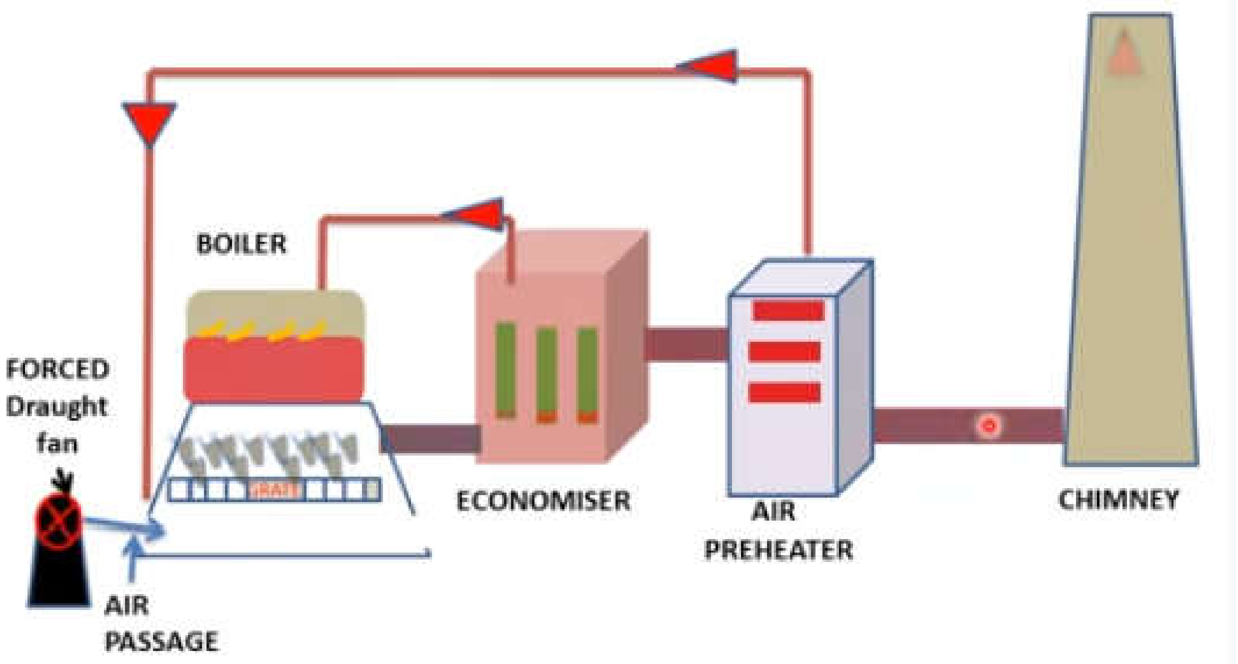
(3) In case of modem power plant, the draught produced by chimney is insufficient for high generating capacity and also reduces thermal efficiency. Therefore, now a days chimney is used with artificial draught system in all power plant only to discharge the flue gases high in the atmosphere to maintain the cleanliness of atmospheric air.

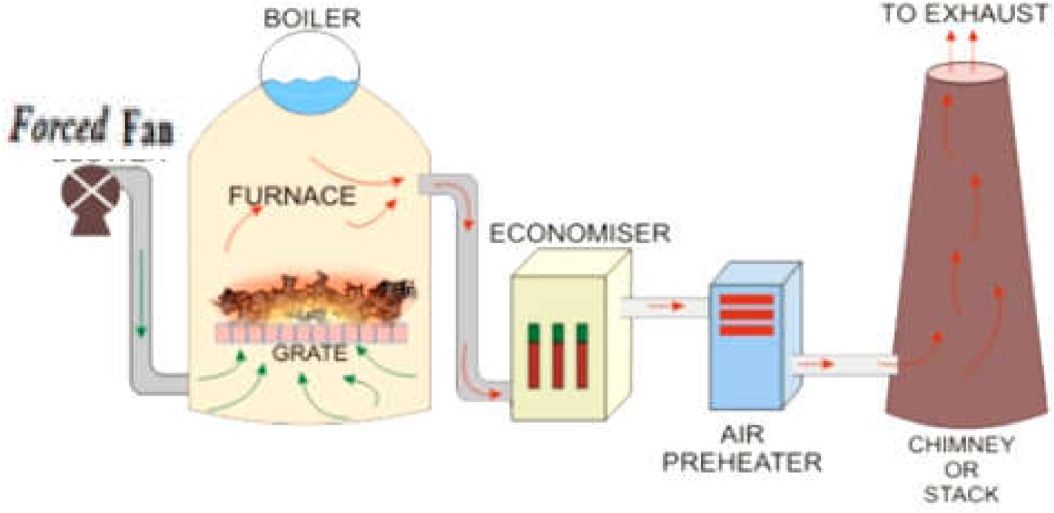
Forced Draught

In a forced draught system, a fan is install near the base of boiler furnace and air is forced to pass through the furnace, flues, economizer, air pre-heater and chimney. It is known as forced draught because the pressure of air throughout the system above atmospheric pressure.



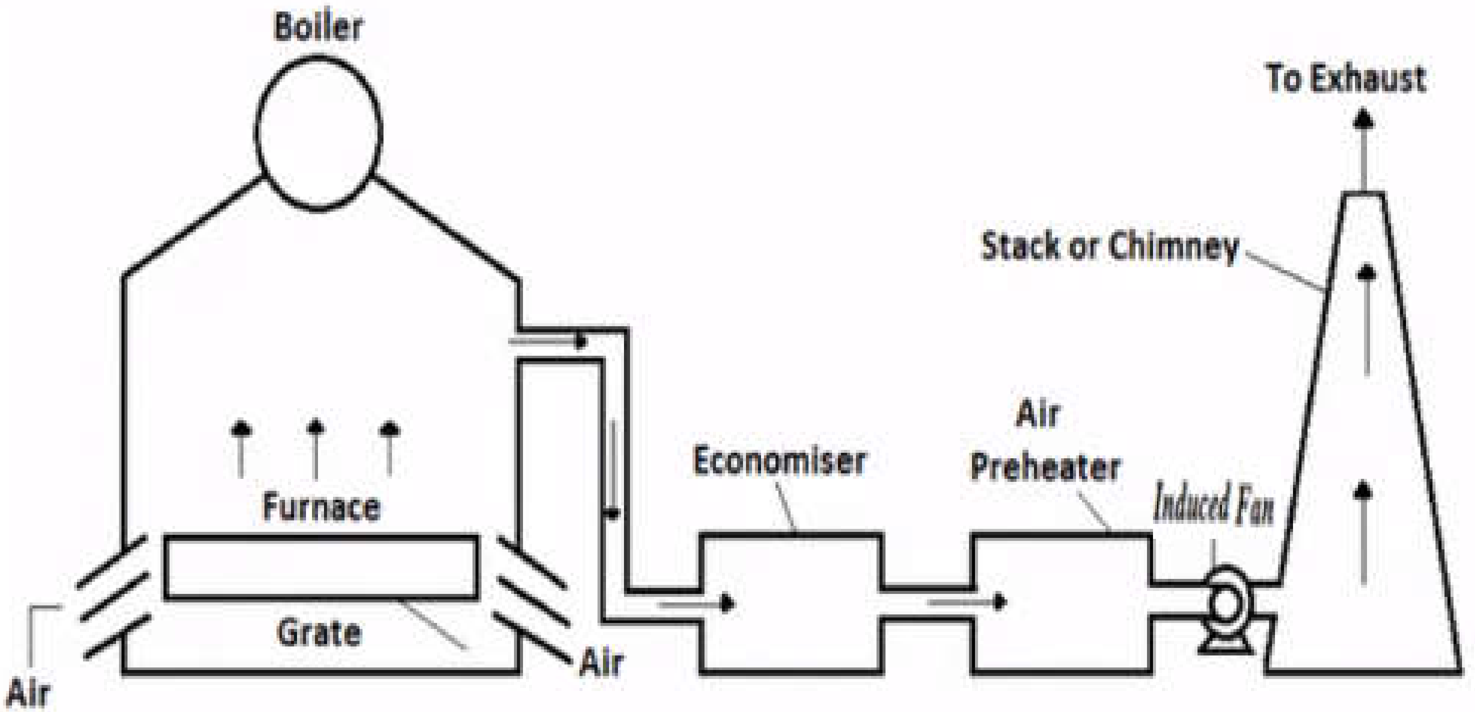
Forced Draught



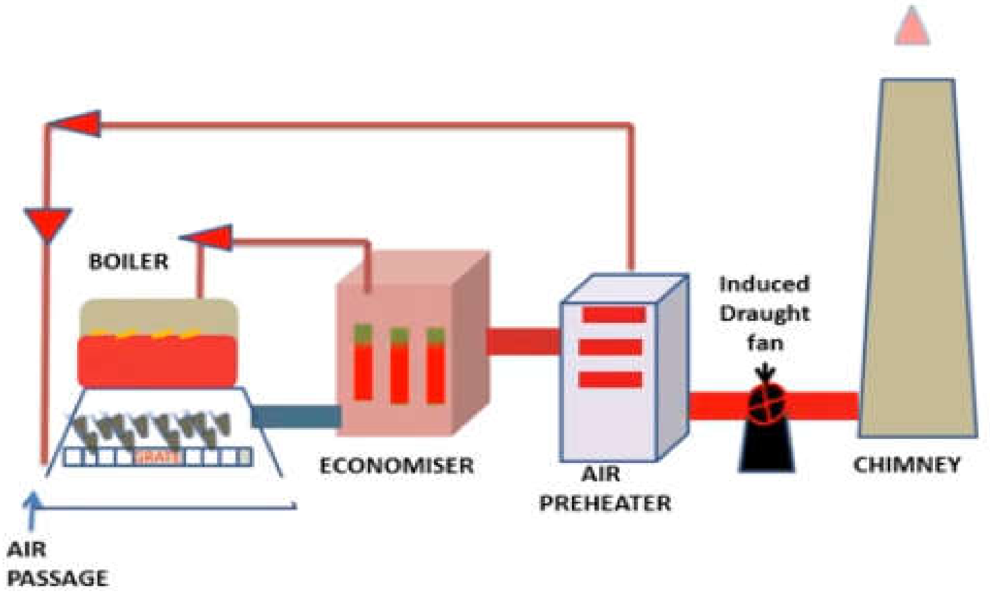


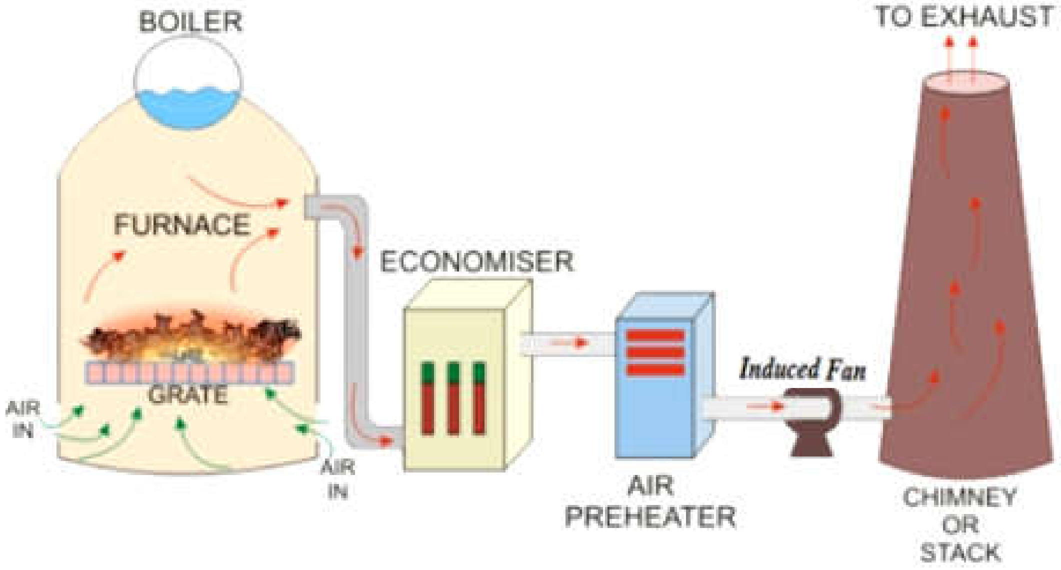
Induced Draught

In induced draught , the fan is install near the base of chimney. The air is sucked into the system by reducing the pressure through the system below the atmospheric pressure. In this draught fan suck the gases from the furnace and the pressure inside the furnace reduced below atmosphere pressure. Due to this pressure difference air suck in furnace and gases remove to surrounding



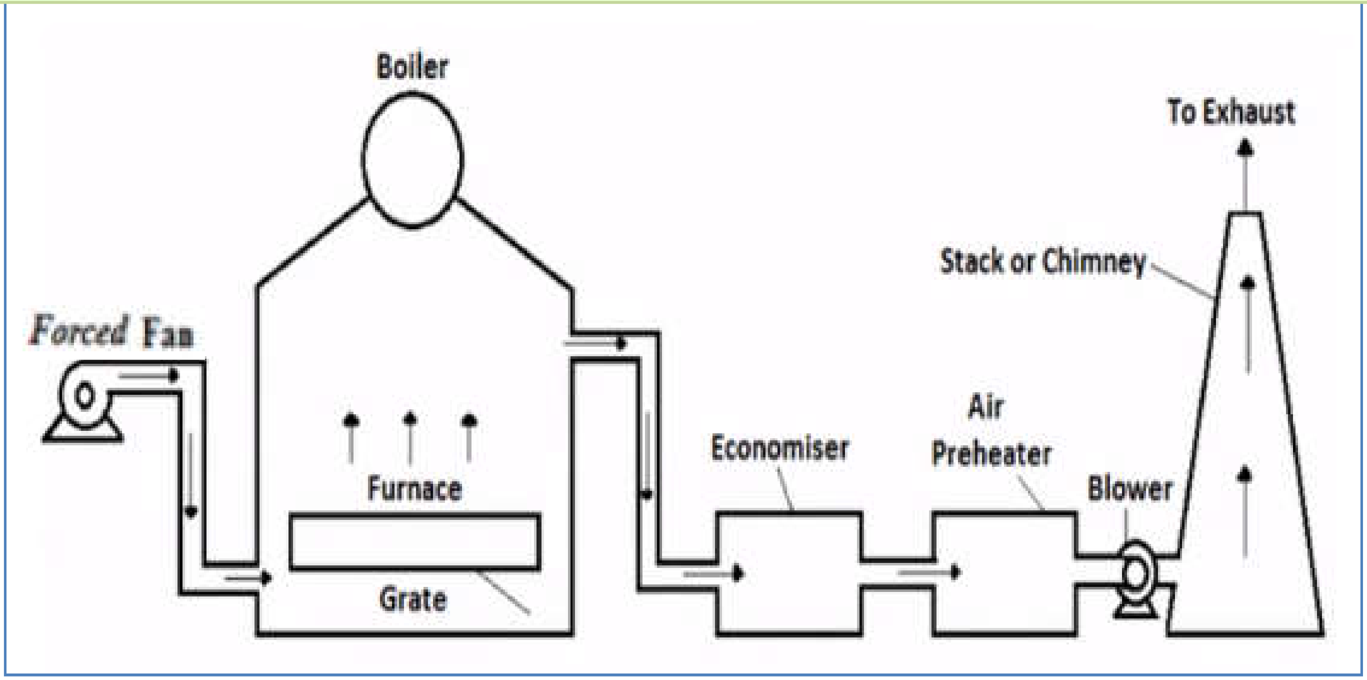
Induced Draught



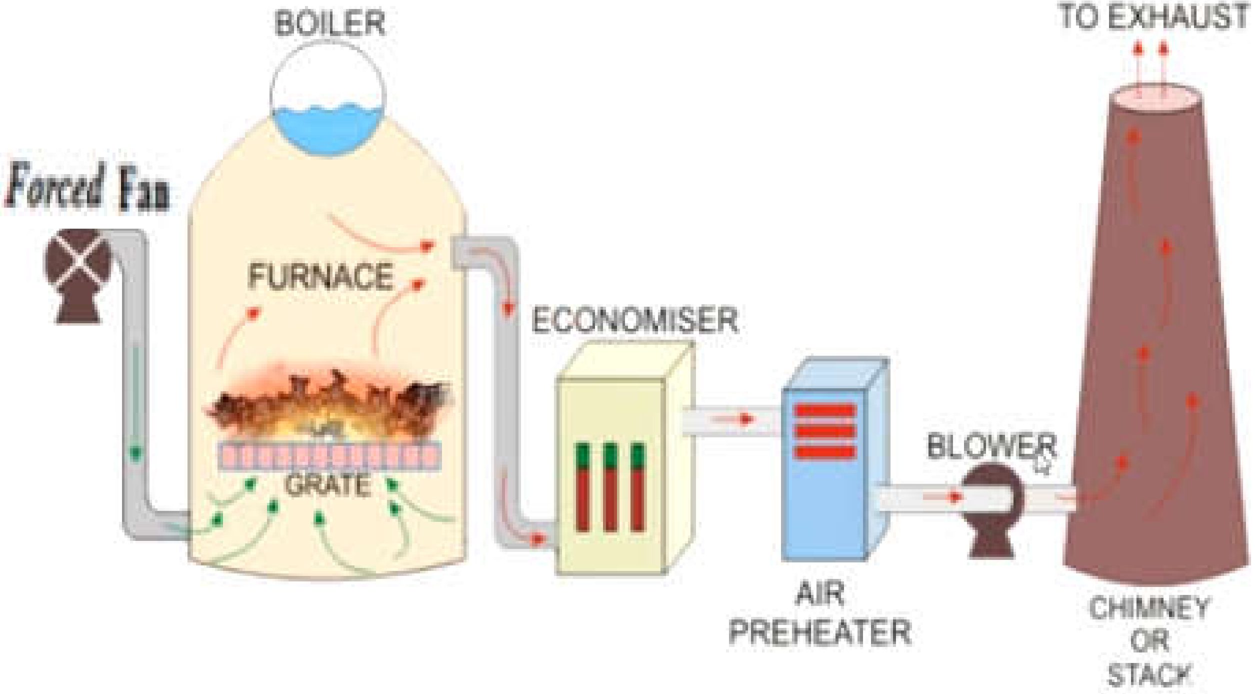


Balanced Draught

A balanced draught is a combination of forced and induced draughts. The force draught supplied sufficient air in boiler furnace for proper & complete combustion of fuel. The induced draught fan removes the gases from furnace and maintaining the pressure in the furnace below atmospheric pressure.

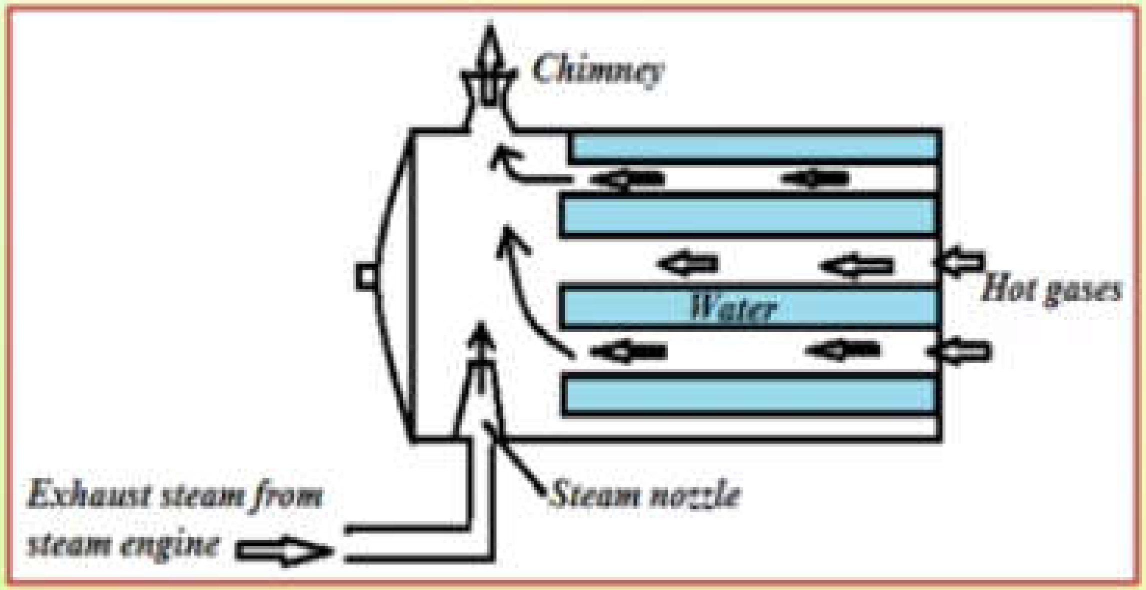


Balanced Draught



Steam jet draught

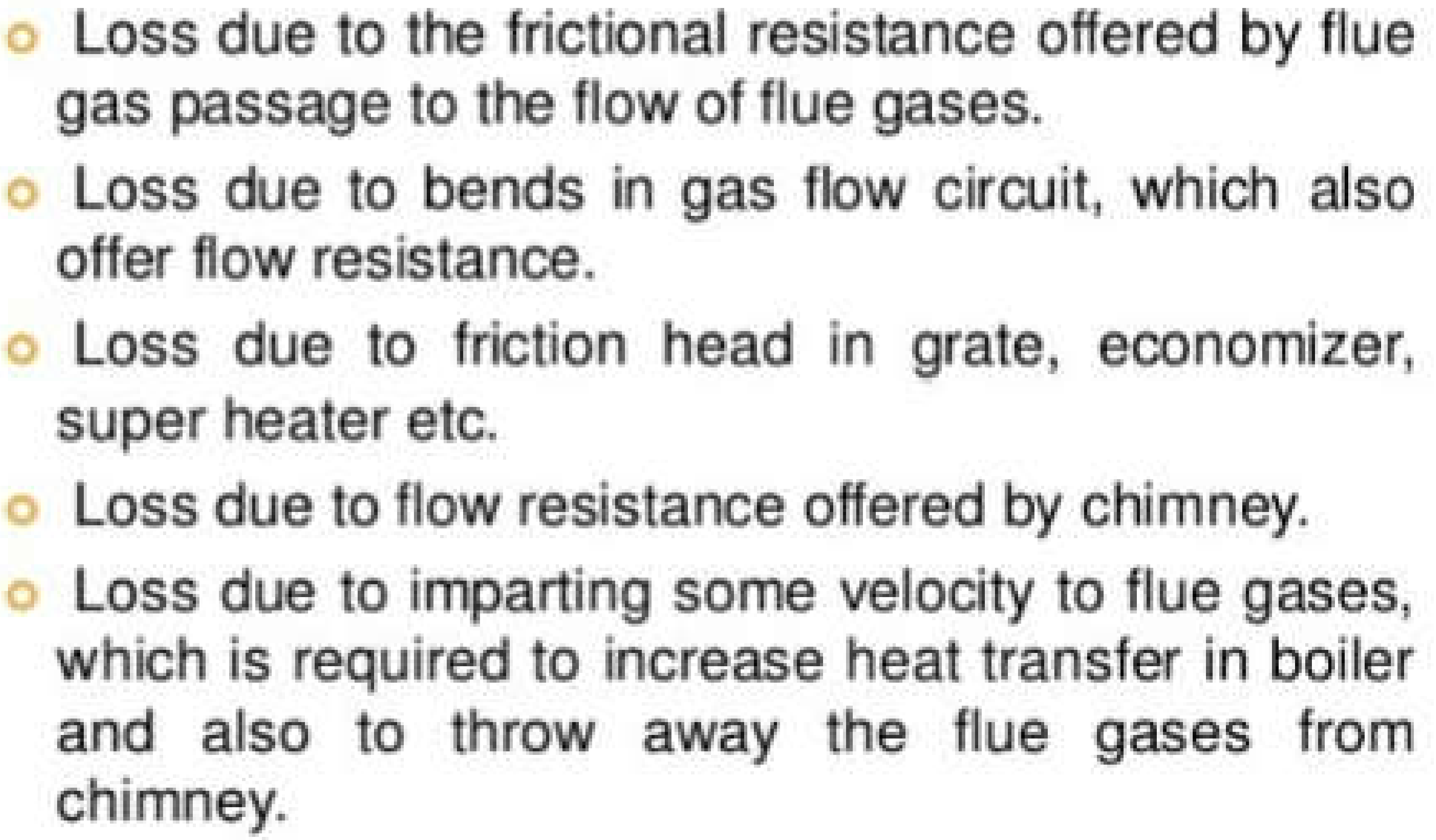
In steam jet draught the exhausted steam of turbine or steam engine use for producing draught. In this draught the steam nozzle located near the smoke box induces the flow of gases through the tubes, ash pit, and grate. It is generally used in locomotive boiler.



Comparison of Forced and Induced Draught

Forced Draught	Induced Draught
1. Fan is placed before the fire grate.	1. Fan is placed after the fire grate.
2. The pressure inside the furnace is above the atmospheric pressure.	2. The pressure inside the furnace is below the atmospheric pressure.
3. Forces fresh air into combustion chamber.	3. Forces hot gases to chimney.
4. It requires less power as fan has to handle cold air only.	4. It requires more power as fan has to handle hot air and flue gases.
5. Flow of air through the furnace is more uniform.	5. Flow of air through the furnace is less uniform.

DRAUGHT LOSSES



- Loss due to the frictional resistance offered by flue gas passage to the flow of flue gases.
- Loss due to bends in gas flow circuit, which also offer flow resistance.
- Loss due to friction head in grate, economizer, super heater etc.
- Loss due to flow resistance offered by chimney.
- Loss due to imparting some velocity to flue gases, which is required to increase heat transfer in boiler and also to throw away the flue gases from chimney.

This loss in Draught in a chimney is 20% of the total Draught produced in it.

Thermal Engineering-II
MODULE-3

Introduction

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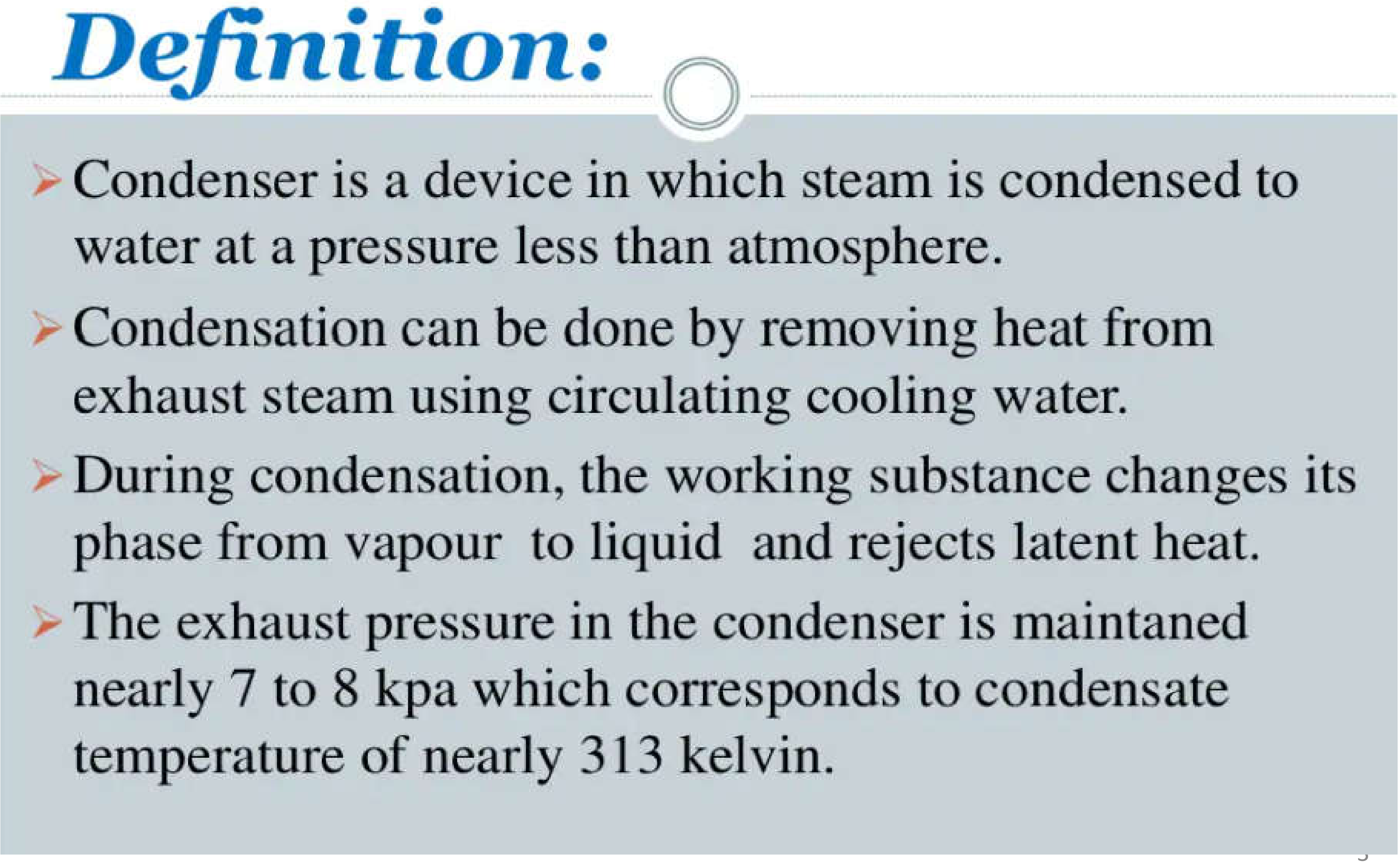
MODULE-3

Steam Condenser



Definition:

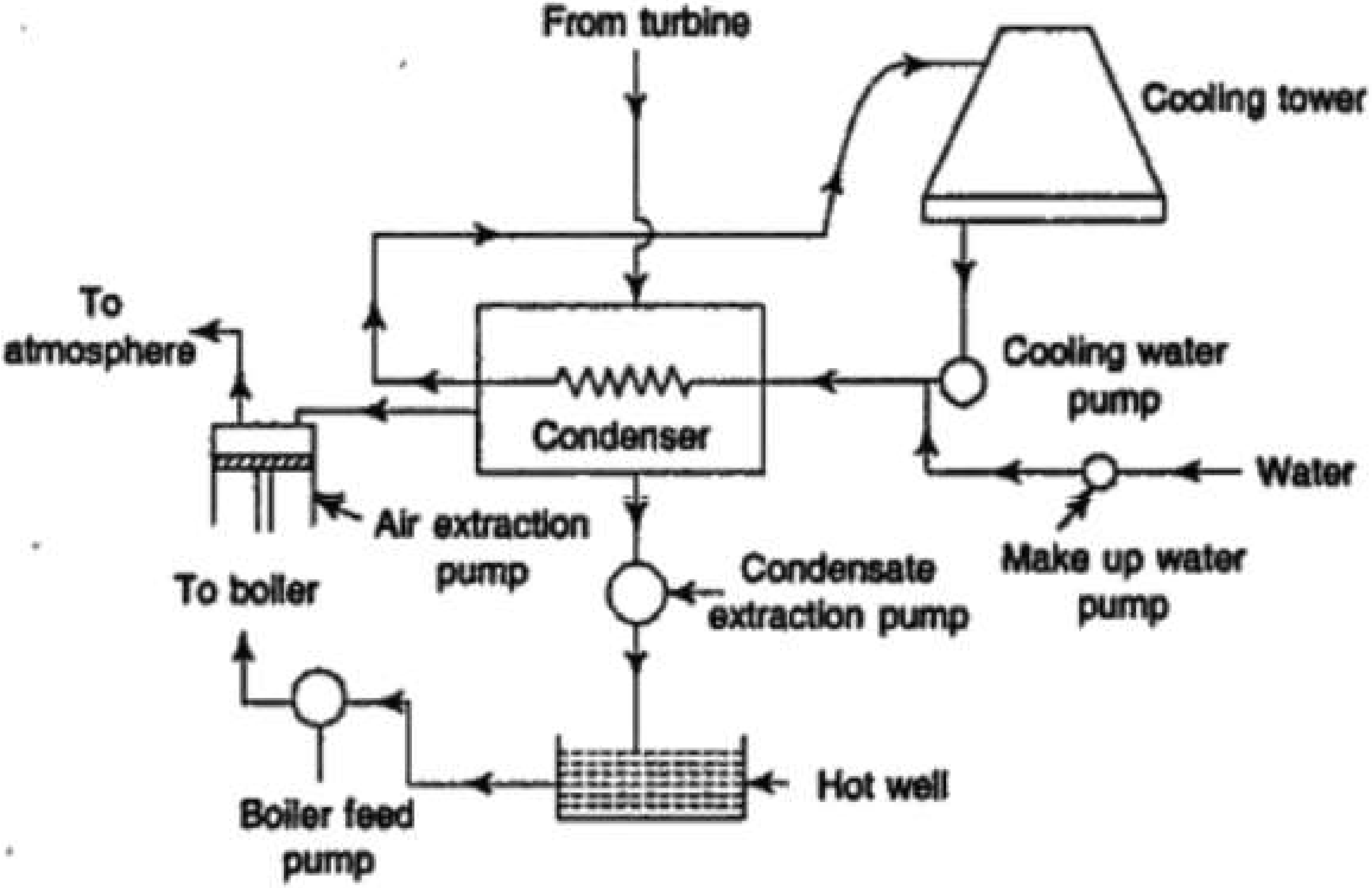
- Condenser is a device in which steam is condensed to water at a pressure less than atmosphere.
- Condensation can be done by removing heat from exhaust steam using circulating cooling water.
- During condensation, the working substance changes its phase from vapour to liquid and rejects latent heat.
- The exhaust pressure in the condenser is maintaned nearly 7 to 8 kpa which corresponds to condensate temperature of nearly 313 kelvin.

Functions of Condenser:

- To reduce the turbine exhaust pressure so as to increase the specific output and hence increase the plant efficiency and decrease the specific steam consumption.
- To condense the exhaust steam from the turbine and reuse it as pure feed water in the boiler. Thus only make up water is required to compensate loss of water
- Enables removal of air and other non condensable gases from steam. Hence improved heat transfer.

Elements of Condensing Plant:

- Condenser
- Air Extraction Pump
- Condensate Extraction Pump
- Cooling Water Circulating Pump
- Hot Well
- Cooling Tower
- Make up Water Pump
- Boiler Feed Pump



Elements of steam condensing plant

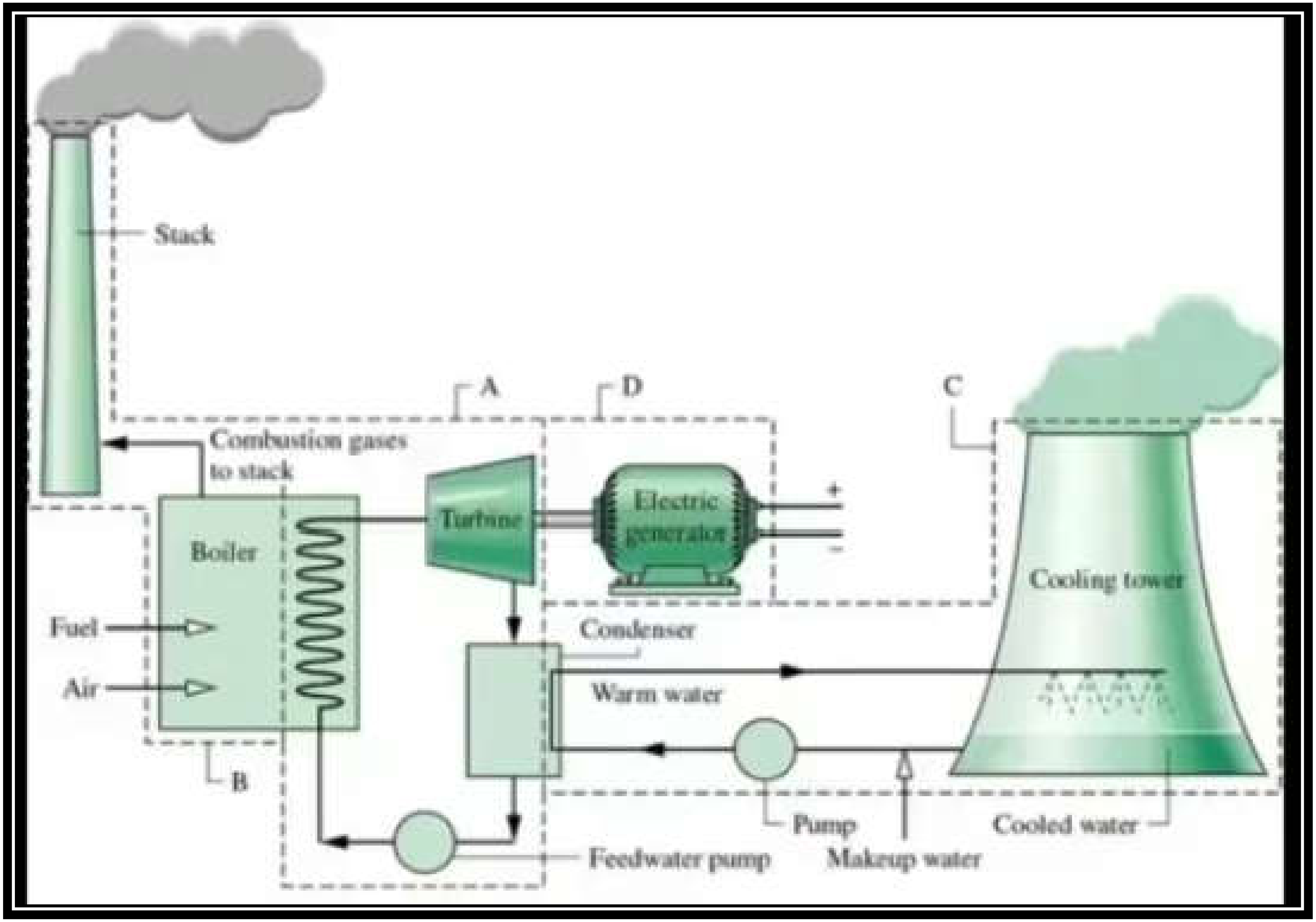


Fig. Steam Power Plant

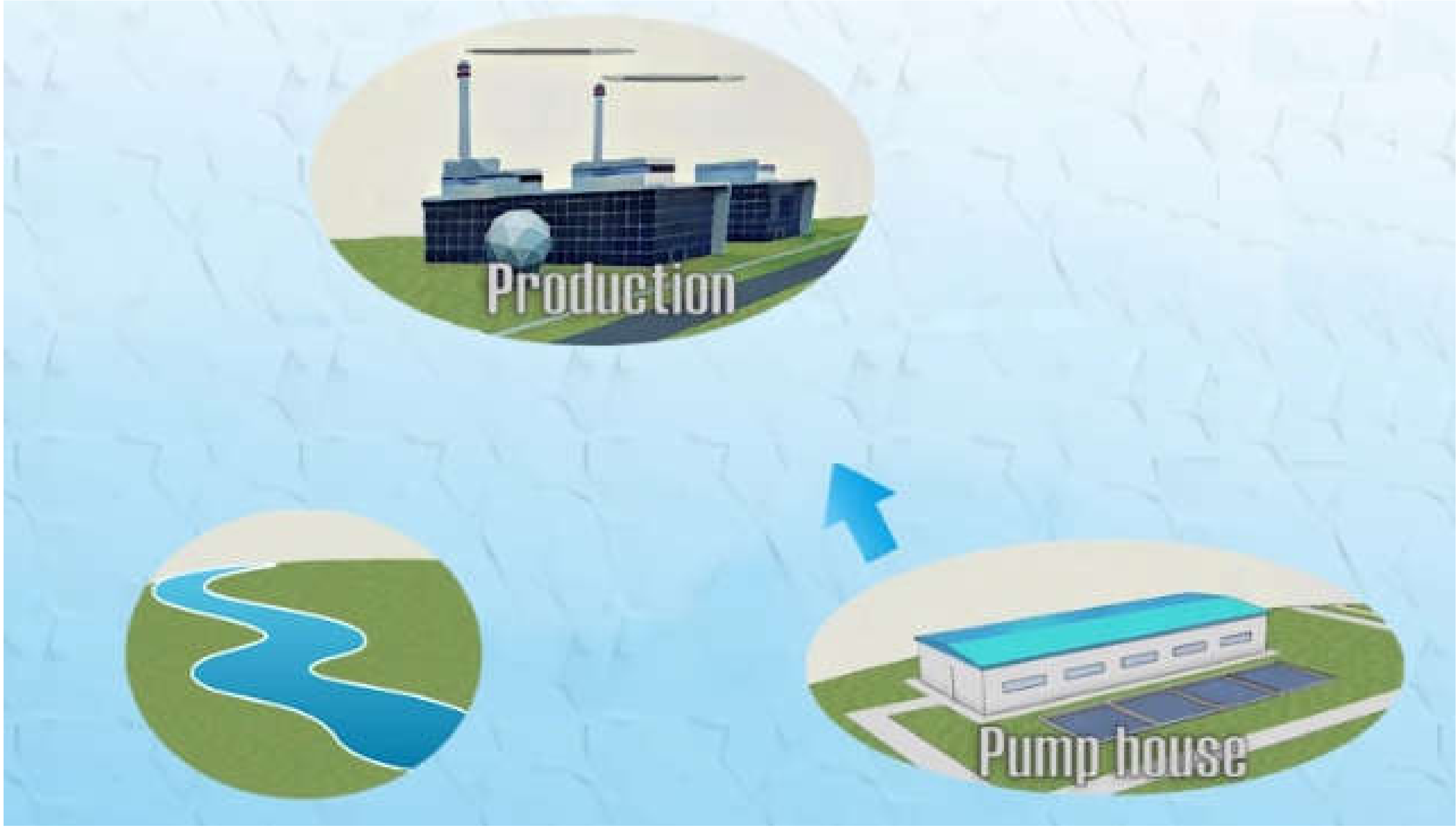
Advantage of a Condenser

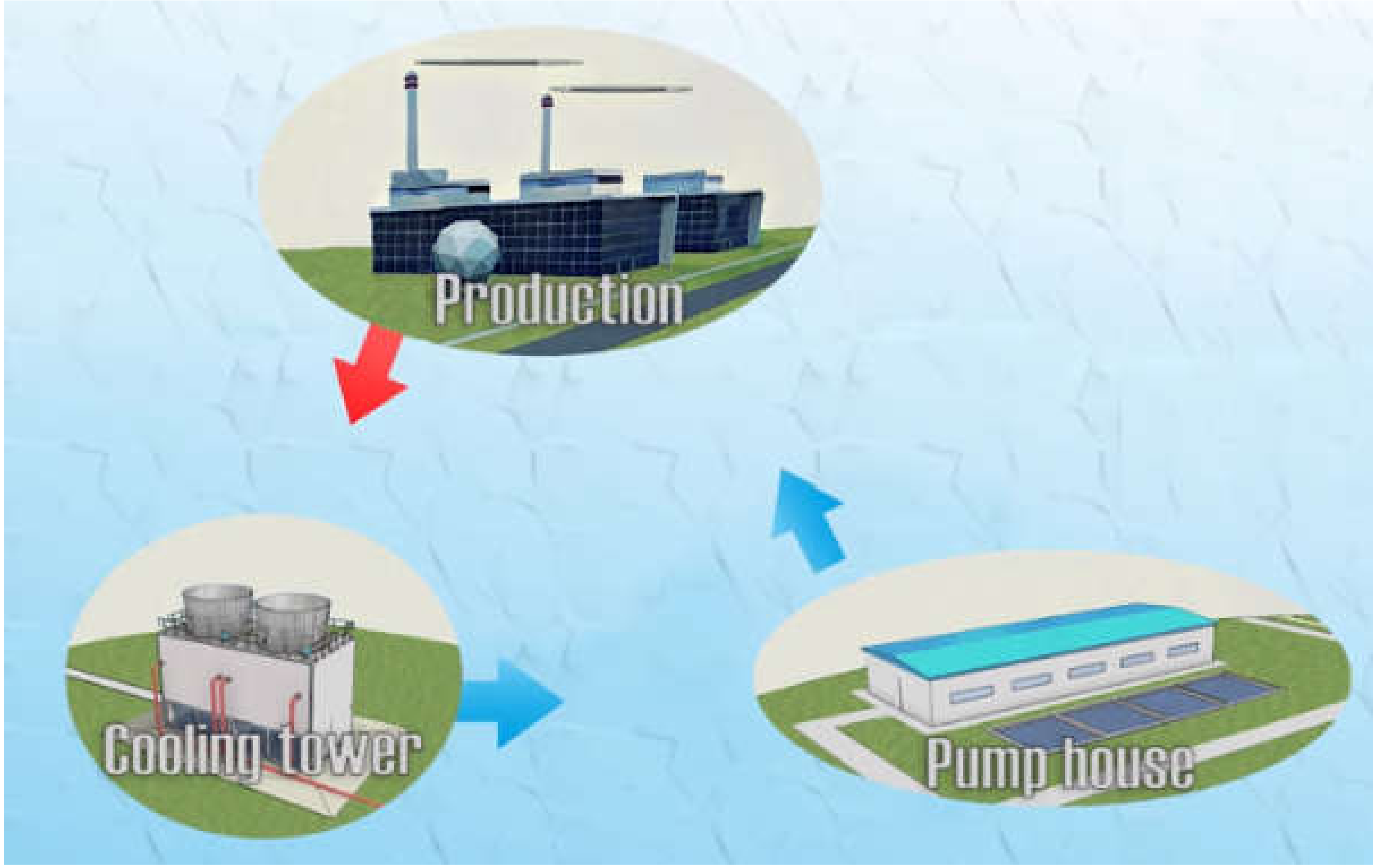
- It increases the work output per kg of steam supplied to the power plant. It also reduces the specific steam consumption, therefore reduces the size of power plant of given capacity.
- It improves the thermal efficiency of the power plant.
- It affects the saving in cost of water to be supplied to the boiler since the condensate is returned to the boiler.
- Cost of water softening plant is also reduced since pure feed water is available for the boiler.

Cooling Towers

Cooling Towers

The Purpose of a **cooling tower** is to reduce the temperature of circulating hot water to re-use this water again in the boiler. This hot water is coming from the condenser.


Production
Pump house


Production
Cooling tower
Pump house

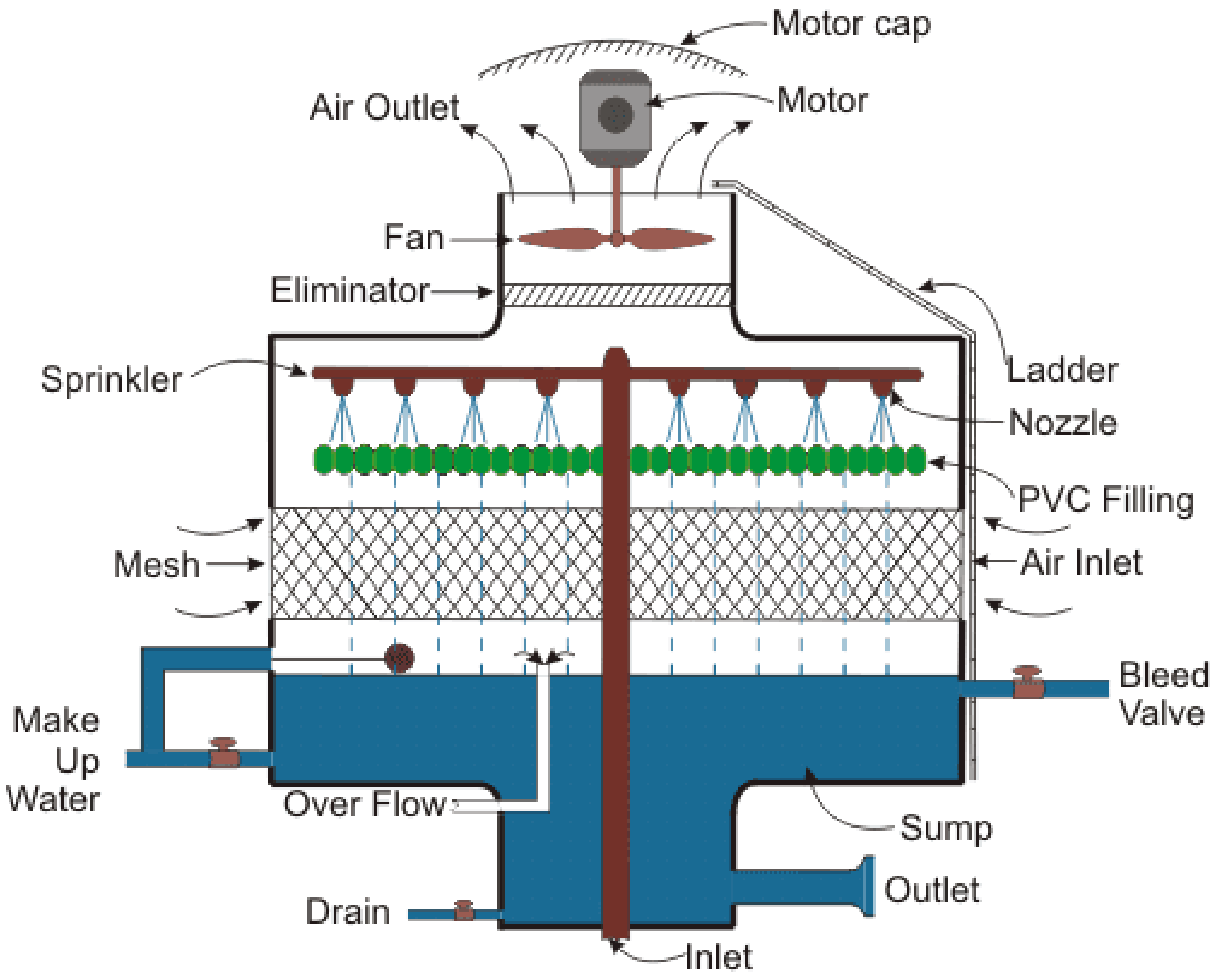


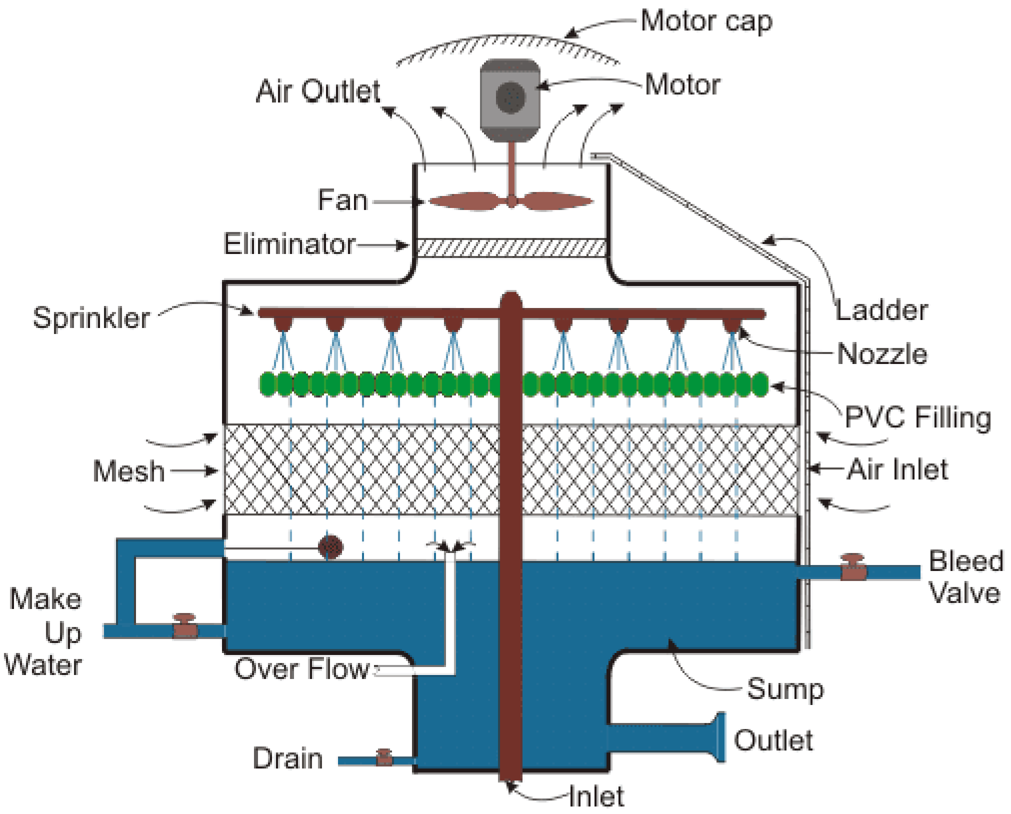
Fig. Schematic Diagram of Cooling tower

Parts of Cooling Tower

Eliminator: It is not allowed to pass water. Eliminator is placed the at top of tower, from which only hot air can pass.

Spray Nozzles and Header: These parts are used to increase the rate of evaporation by increasing surface area of water.

PVC Filling: It reduces the falling speed of hot water.

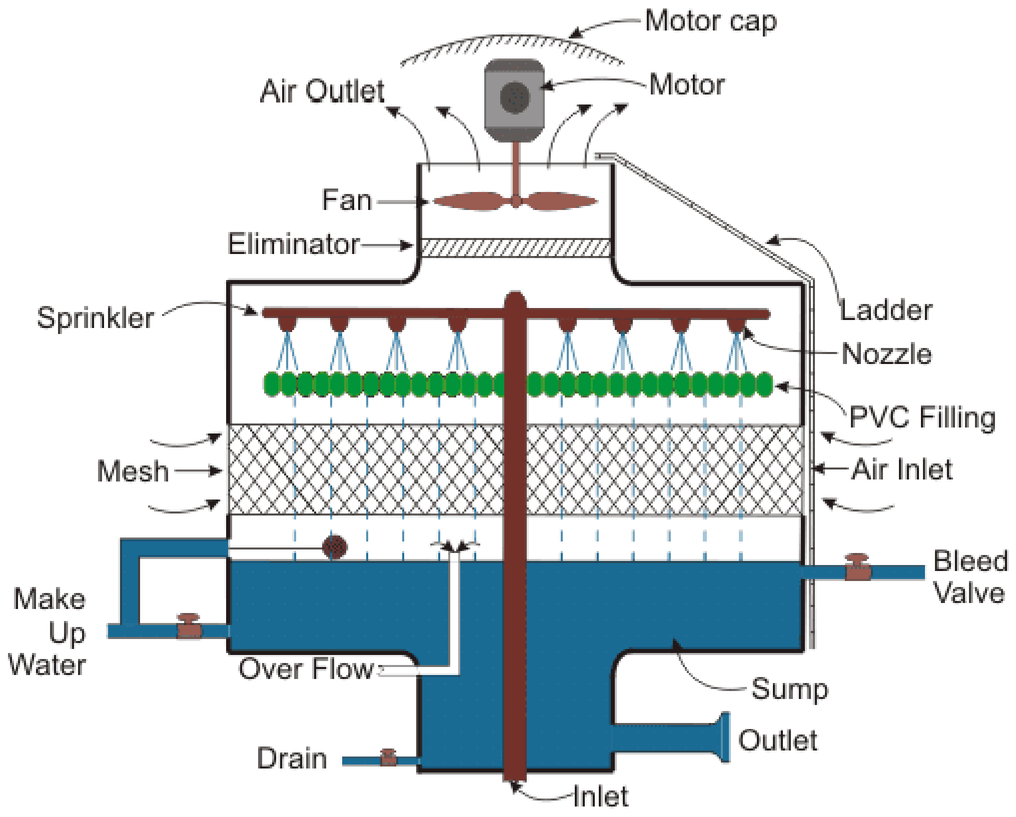


Mesh: When the fan is ON, it uses atmosphere air which contains some unwanted dust particles. Mesh is used to stop these particles and do not allow to enter dust in to **cooling tower**.

Float Valve: It is used to maintain level of water.

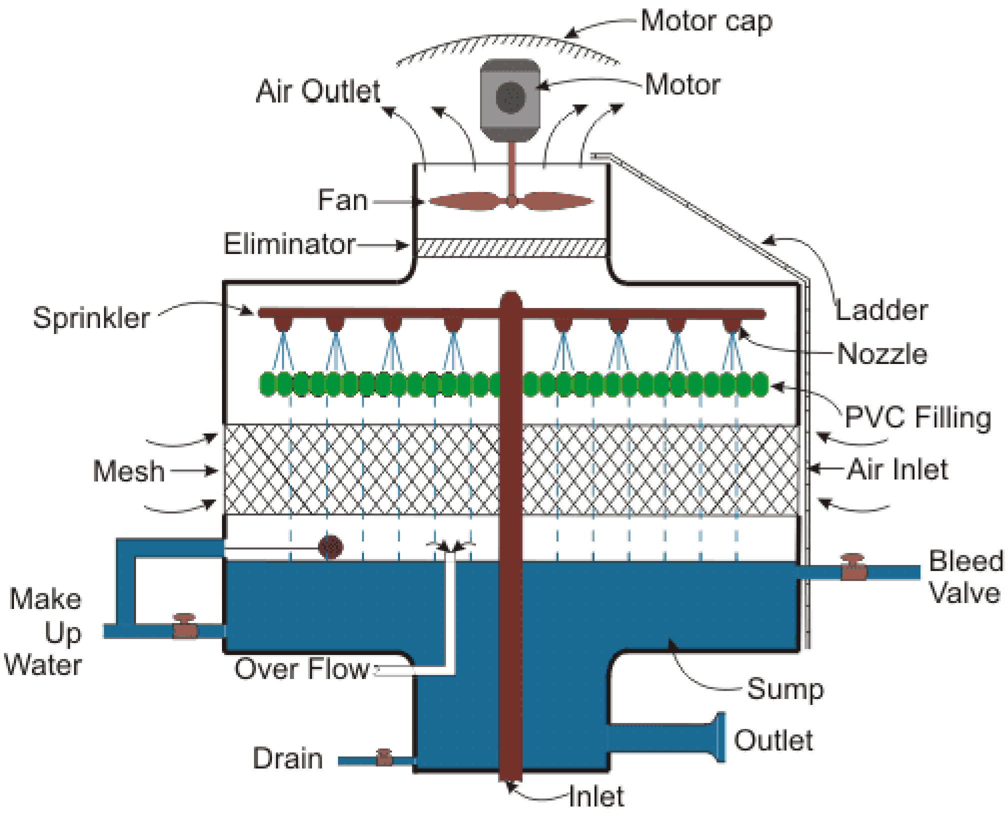
Bleed Valve: It is used to control the concentration of minerals and salt.

Body: Body or outer surface of cooling tower is often made up from FRP (fiber reinforced plastic), which protects the internal parts of cooling tower.

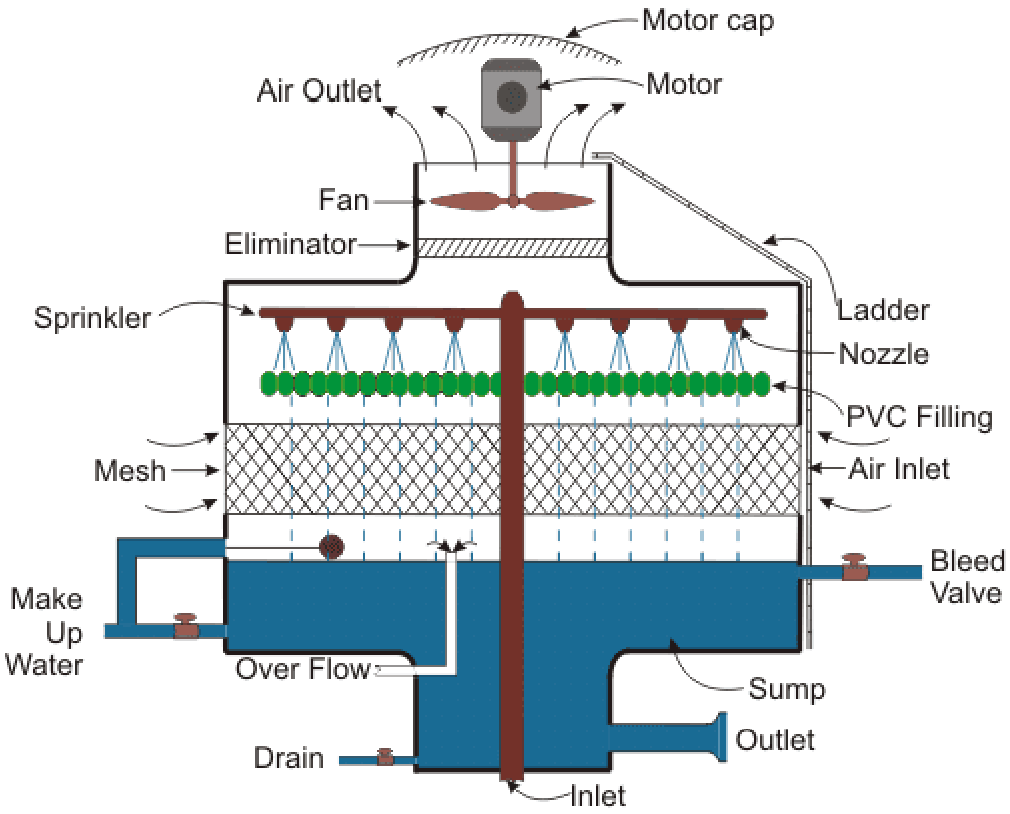


Working of Cooling Tower

- Hot water is coming at the inlet of the tower and pumped up to the header.
- The header contains nozzles and sprinklers which is used to spray water, and it will increase the surface area of water.
- After that, water comes to PVC filling; it used to reduce the speed of water.



- At the top the cooling tower, fans are used to lift air from bottom to the top. Because of slow speed and more contact area of water, it makes a good connection between air and hot water. The process will reduce the temperature of water by evaporation process and cooled water is collected at the bottom of the cooling tower, and this cooled water is used again in the boiler.



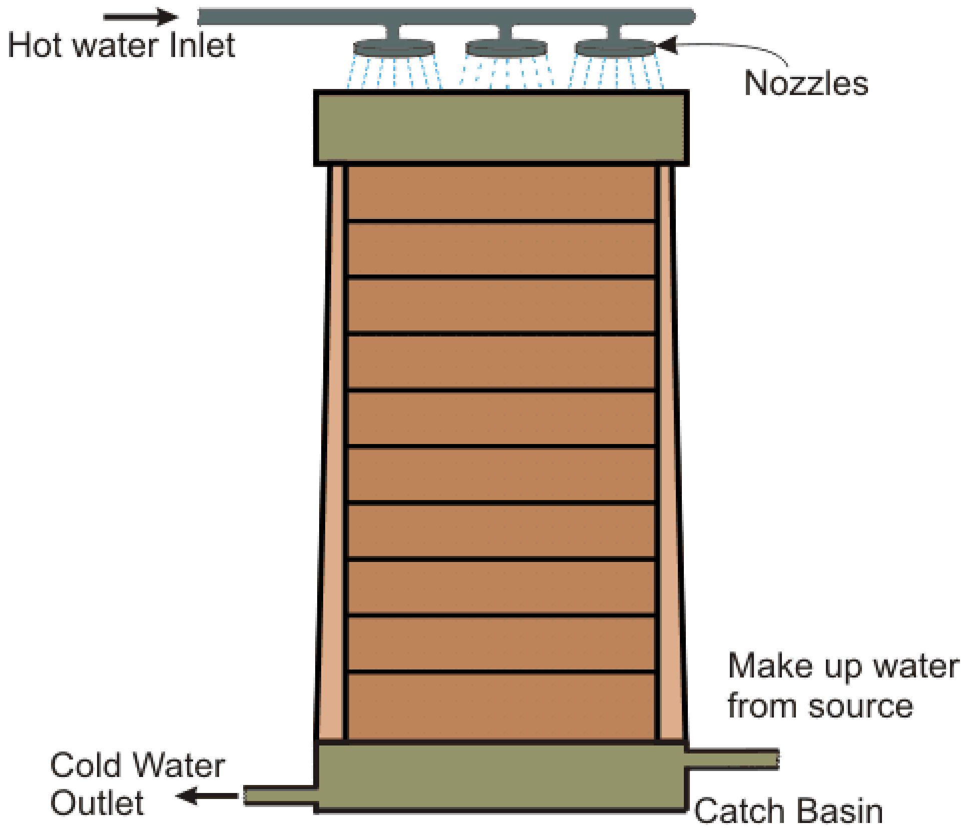
Cooling towers can be classified in two types:

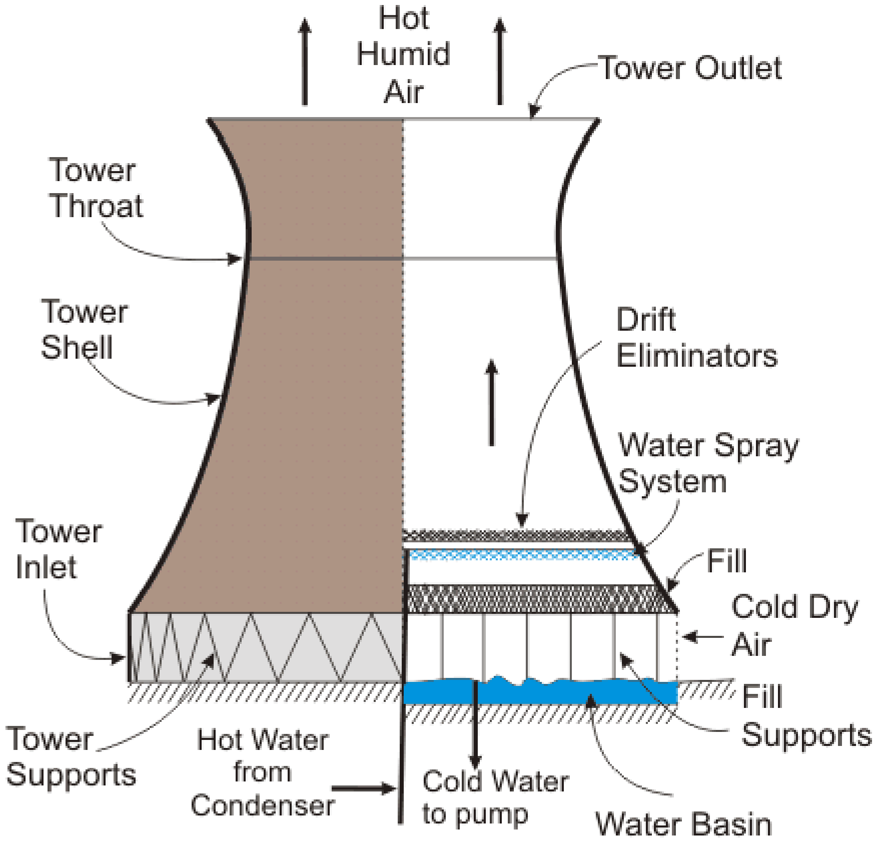
1. Natural Draught Cooling Tower:
2. Mechanical or Forced Draught Cooling Tower

1. Natural Draught Cooling Tower:

In this type of cooling tower, fan is not used for circulating air but here, by enclosing the heated air in the chimney and it will create pressure difference between heated air and surrounding air. Because of this pressure difference air enters in to the cooling tower. It requires large hyperbolic tower, so capital cost is high but operating cost is low because of absence of electrical fan.

There are two types of natural draught cooling tower, rectangular timber tower and reinforced concrete hyperbolic tower.





2. Mechanical or Forced Draught Cooling Tower

➢In this type of cooling tower, fan is used to circulate the air.

➢When power plant runs on peak load, it requires a very high rate of cooling water. To rotate fan, it uses motor with speed around 1000 rpm.

➢Working principle is same as **natural draught cooling tower**, only difference is that here fan is mounted on the cooling tower.

➢If fan is mounted on the top of the tower is called as **induced draught cooling tower.** It contains a vertical shaft. which is most popular for very large capacity installation and requires large capacity of fan.

➢So, **forced draught cooling tower** contains horizontal shaft for the fan and it is placed at bottom of the tower and

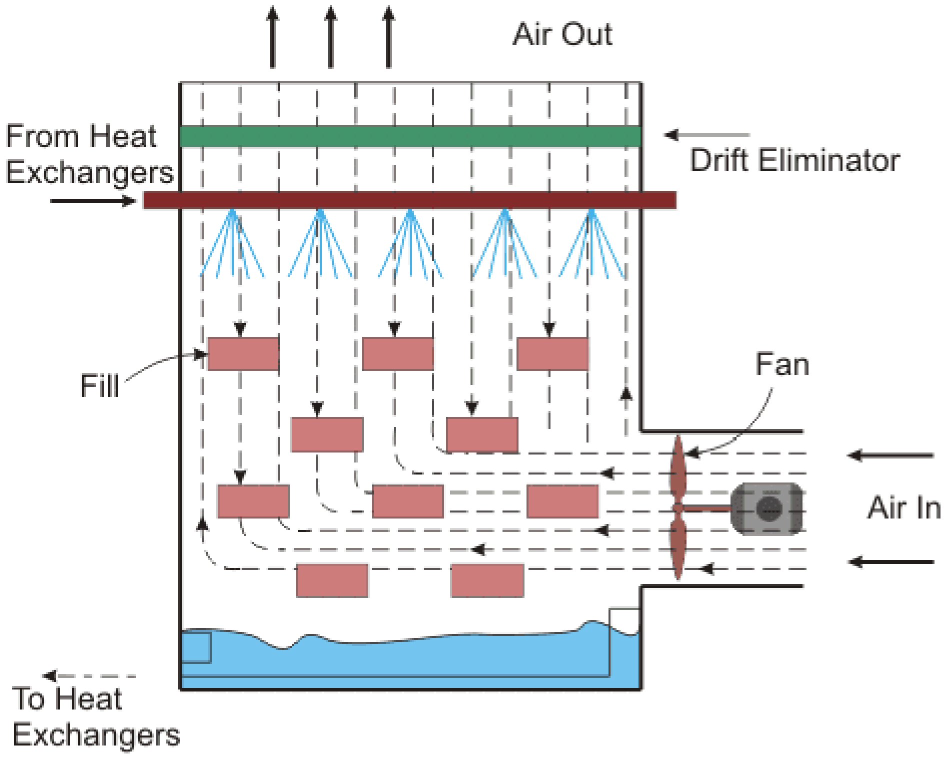


Fig. Forced draught cooling tower

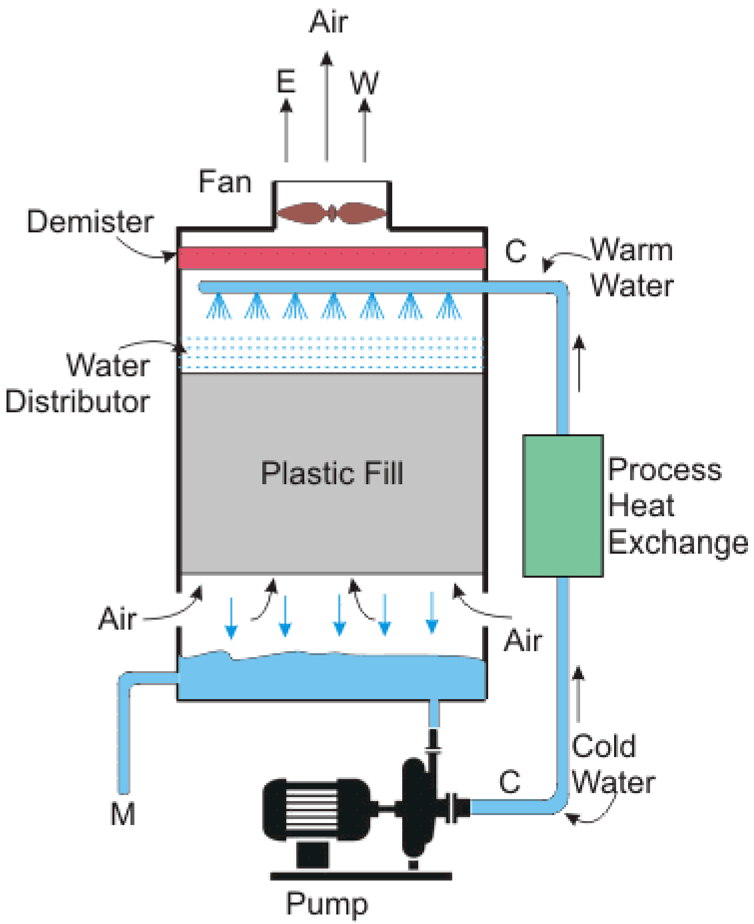
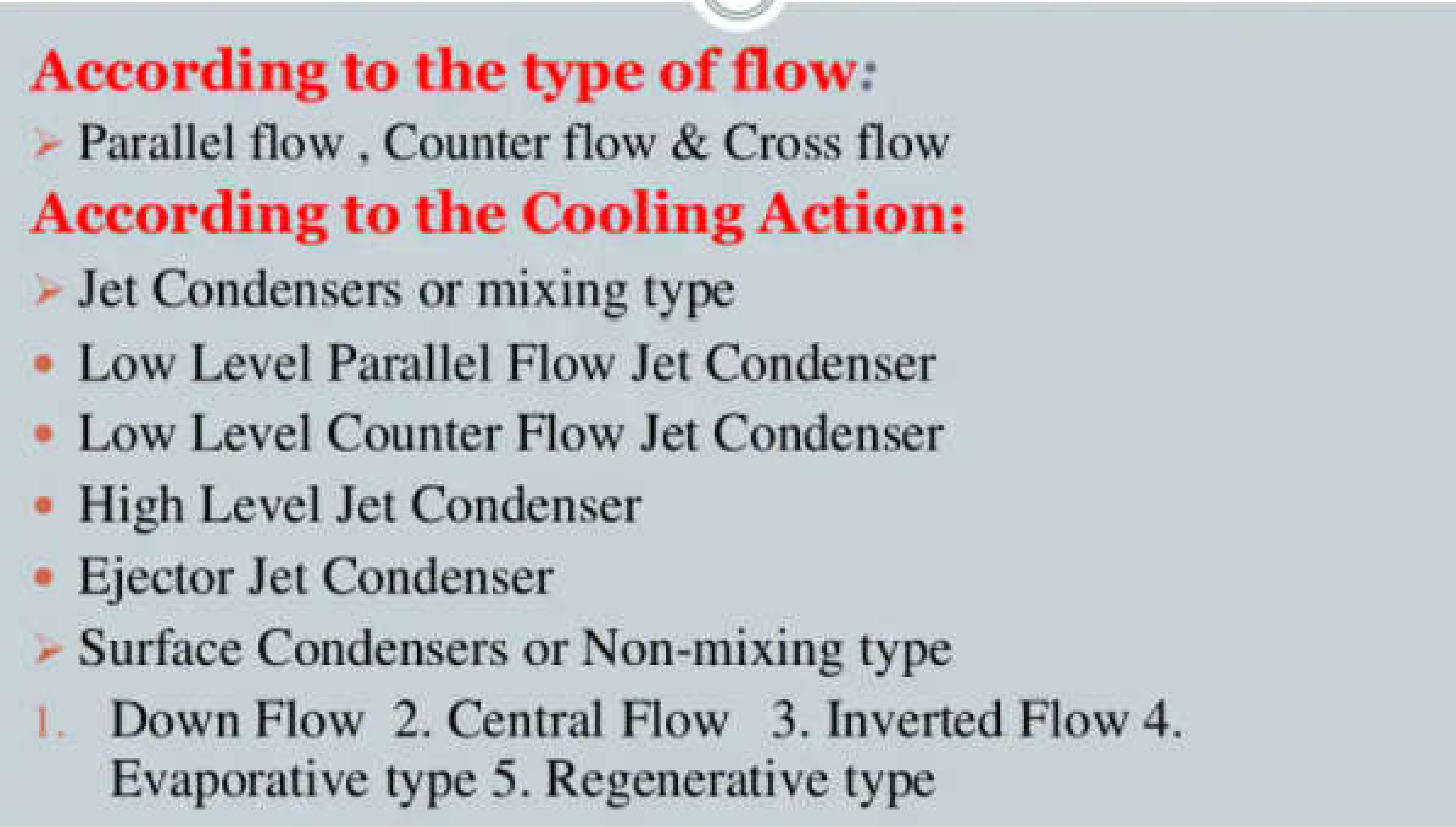


Fig. Induced draught cooling tower

Classification of Condensers:



According to the type of flow:

- Parallel flow , Counter flow & Cross flow

According to the Cooling Action:

- Jet Condensers or mixing type
- Low Level Parallel Flow Jet Condenser
- Low Level Counter Flow Jet Condenser
- High Level Jet Condenser
- Ejector Jet Condenser
- Surface Condensers or Non-mixing type

1. Down Flow 2. Central Flow 3. Inverted Flow 4. Evaporative type 5. Regenerative type

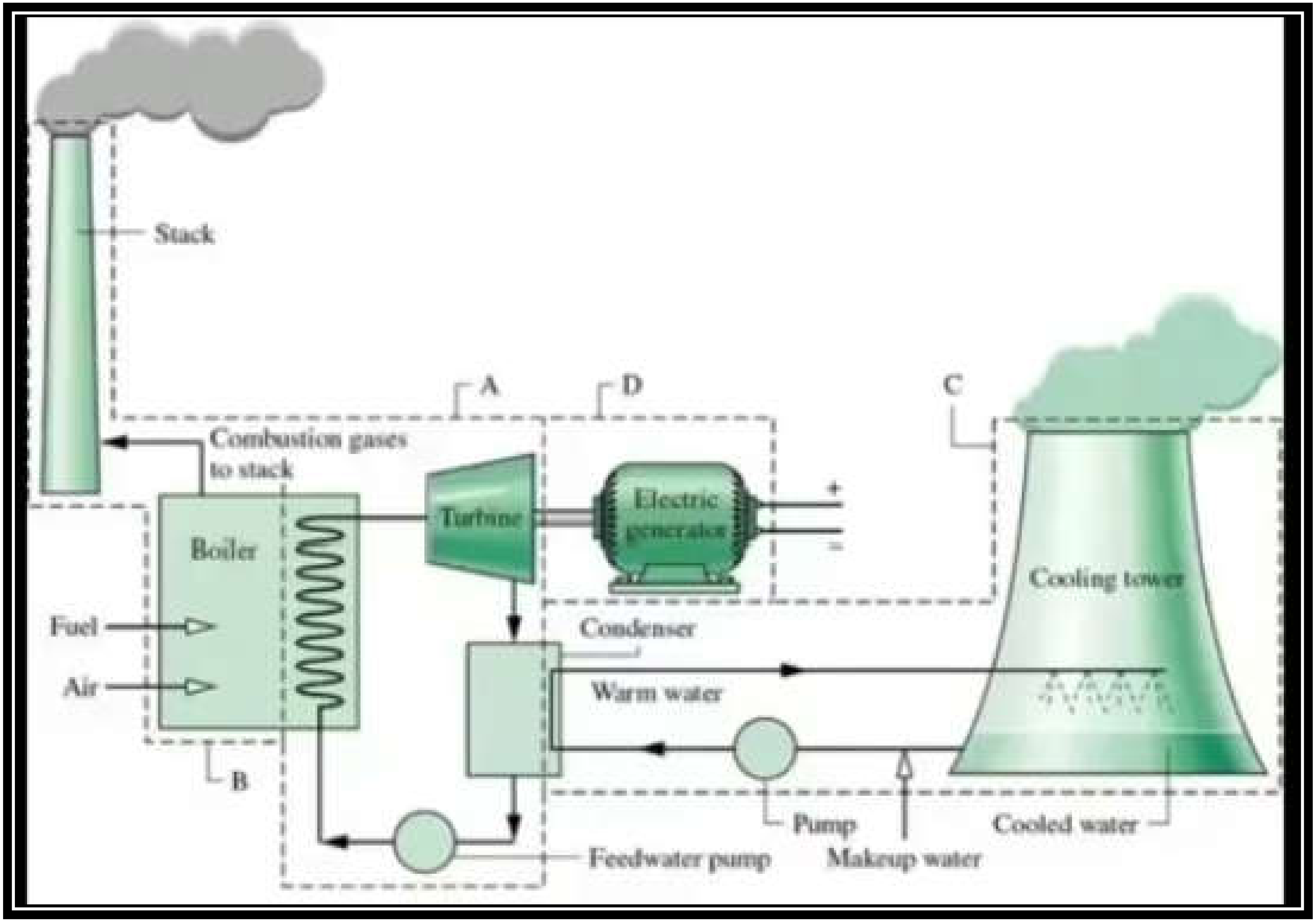
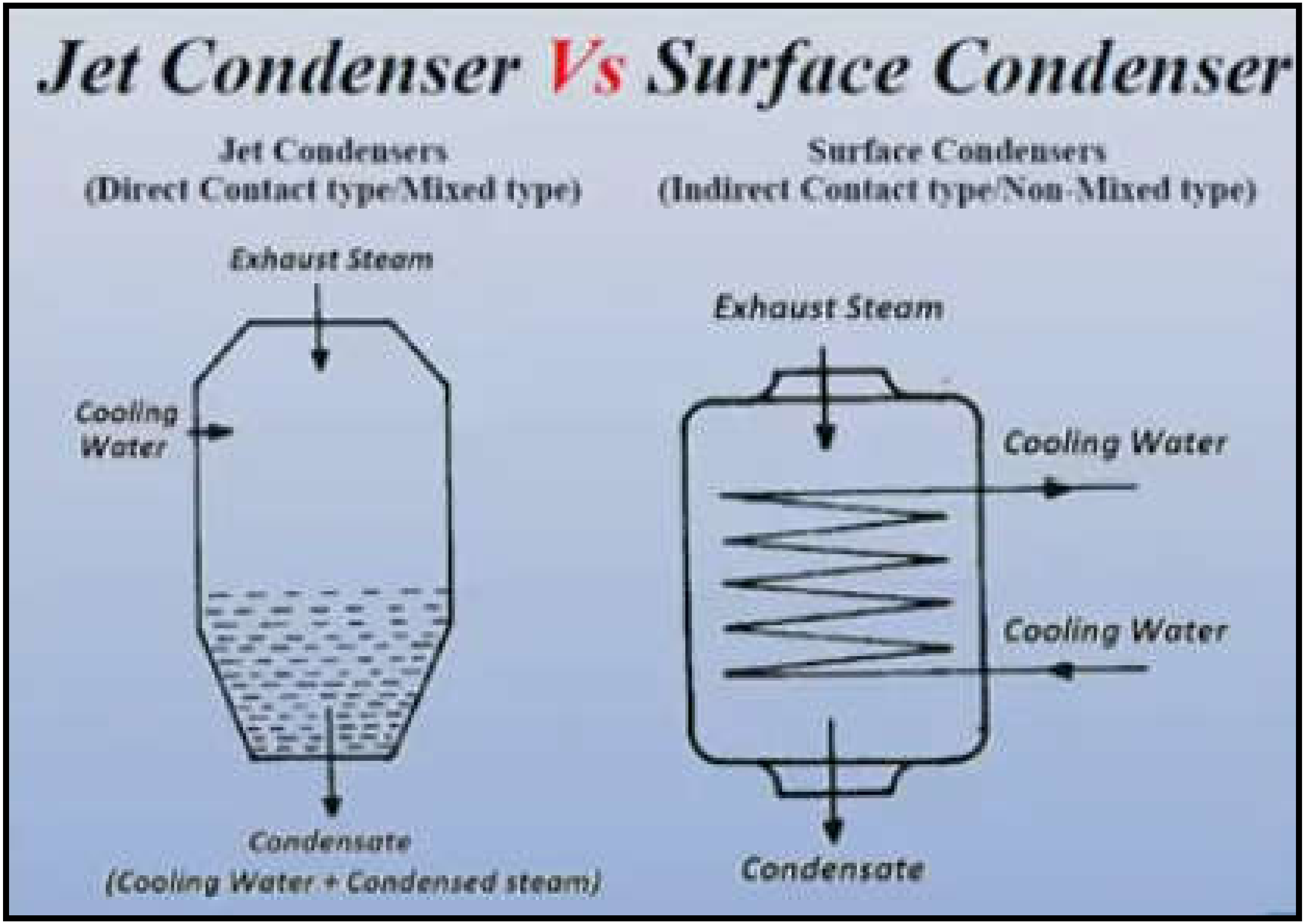


Fig. Steam Power Plant



Jet Condenser Vs Surface Condenser

Jet Condensers
(Direct Contact type/Mixed type)

Surface Condensers
(Indirect Contact type/Non-Mixed type)

Jet Condensers

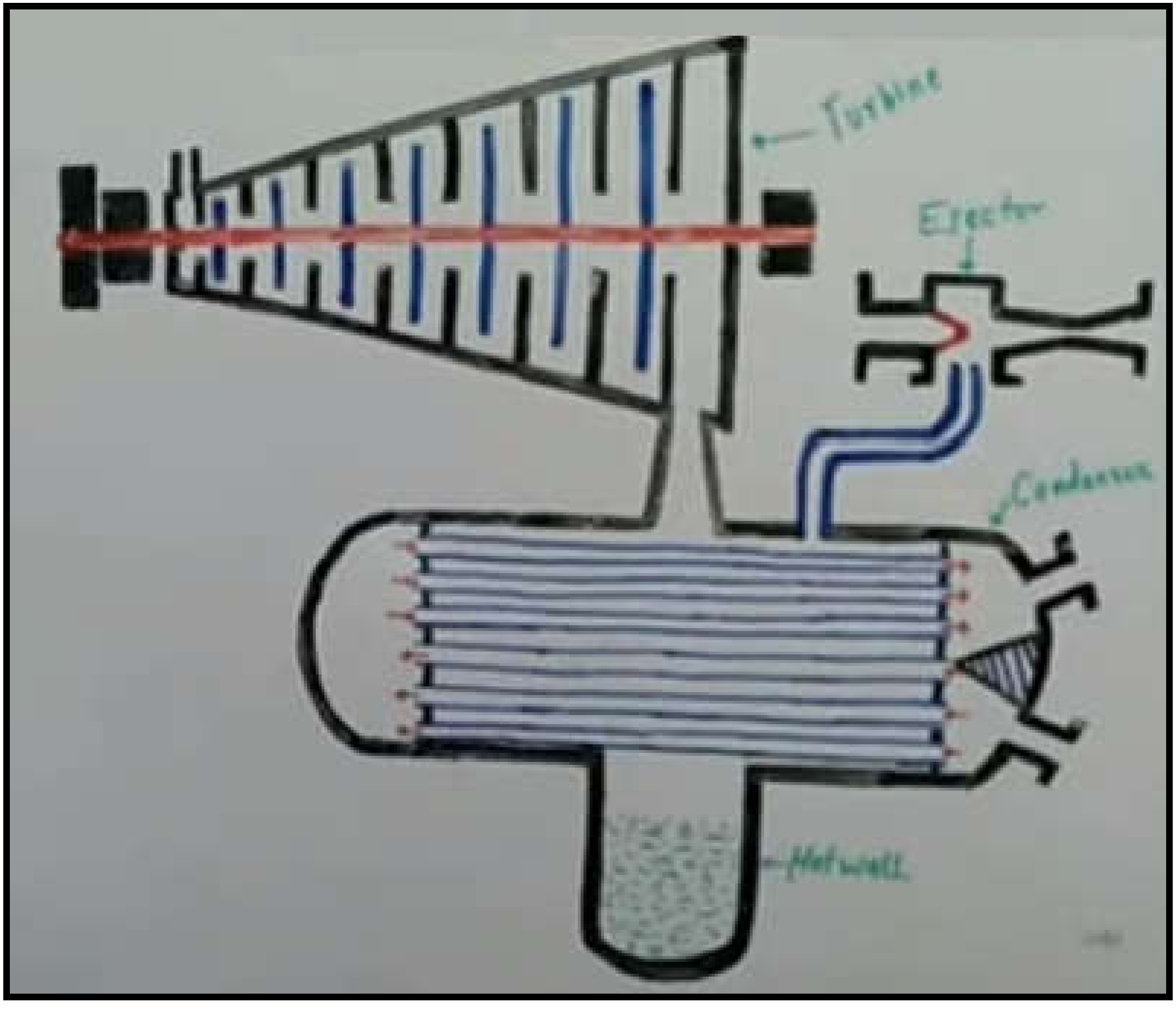
- In jet condensers exhaust steam and cooling water come in direct contact and mix up together. Thus, the final temperature of condensate and cooling water leaving the condenser is same.
- Such condensers are normally used for small power units.
- It can be used when cooling water is cheaply and easily available.
- These condensers are not usually employed since the Condensate collected can not be reused in boiler, because it contains impurities like dust, oil, metal particles etc in the condensate.

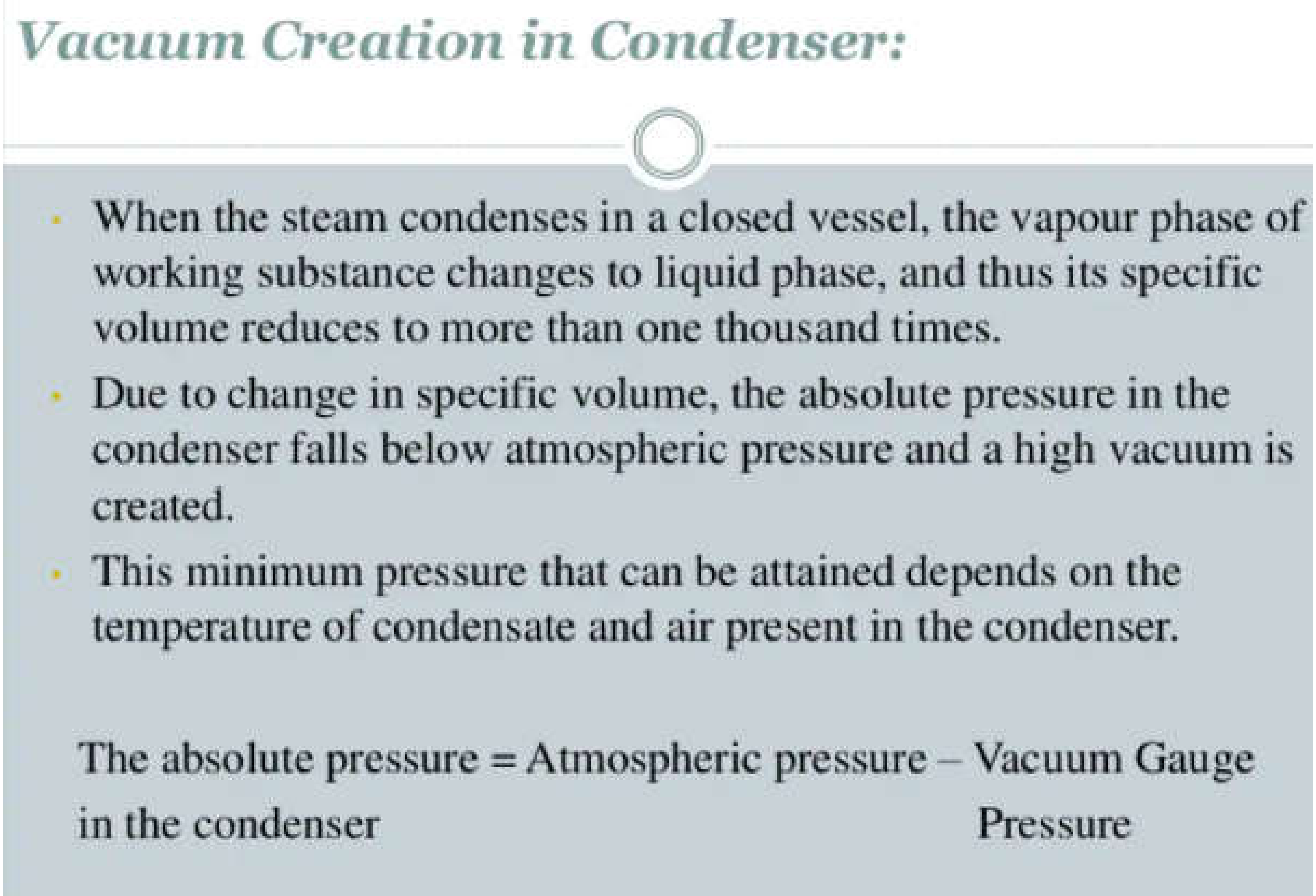
Jet Condensers

- CONDENSATE CAN'T BE REUSED DUE TO IMPURITIES OF THE COOLANT.
- IMPURE CONDENSATE WILL CORRODE THE PLANT TUBES.
- RISE SCALE FORMATION IN BOILER TUBES.
- SCALE FORMATION WOULD REDUCE THE EFFICIENCY OF BOILER.

SCALE FORMATION

Why vacuum is created in Condenser…?



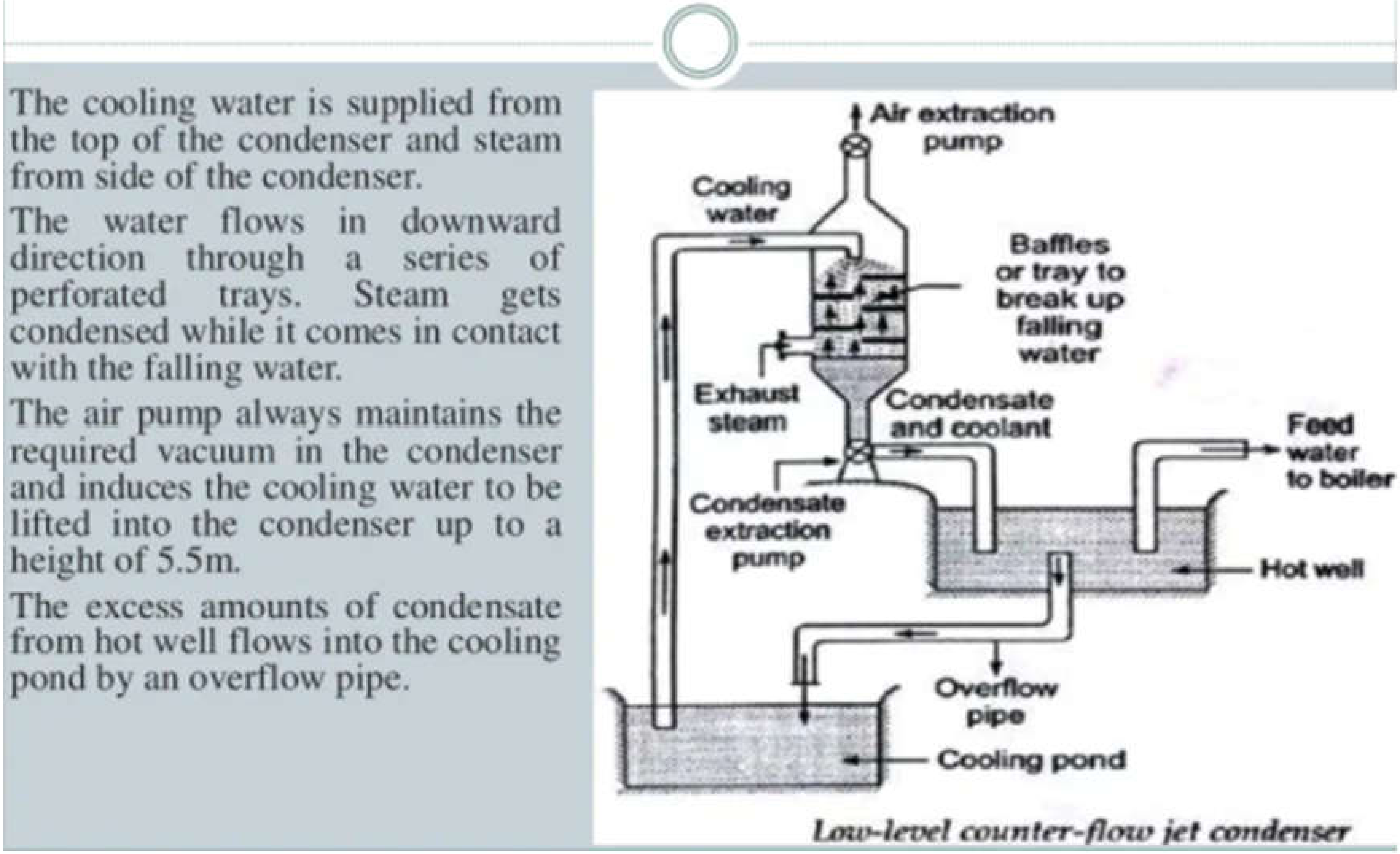


Vacuum Creation in Condenser:

- When the steam condenses in a closed vessel, the vapour phase of working substance changes to liquid phase, and thus its specific volume reduces to more than one thousand times.
- Due to change in specific volume, the absolute pressure in the condenser falls below atmospheric pressure and a high vacuum is created.
- This minimum pressure that can be attained depends on the temperature of condensate and air present in the condenser.

The absolute pressure = Atmospheric pressure – Vacuum Gauge
in the condenser Pressure

Counter Flow Low Level Jet Condenser



The cooling water is supplied from the top of the condenser and steam from side of the condenser.

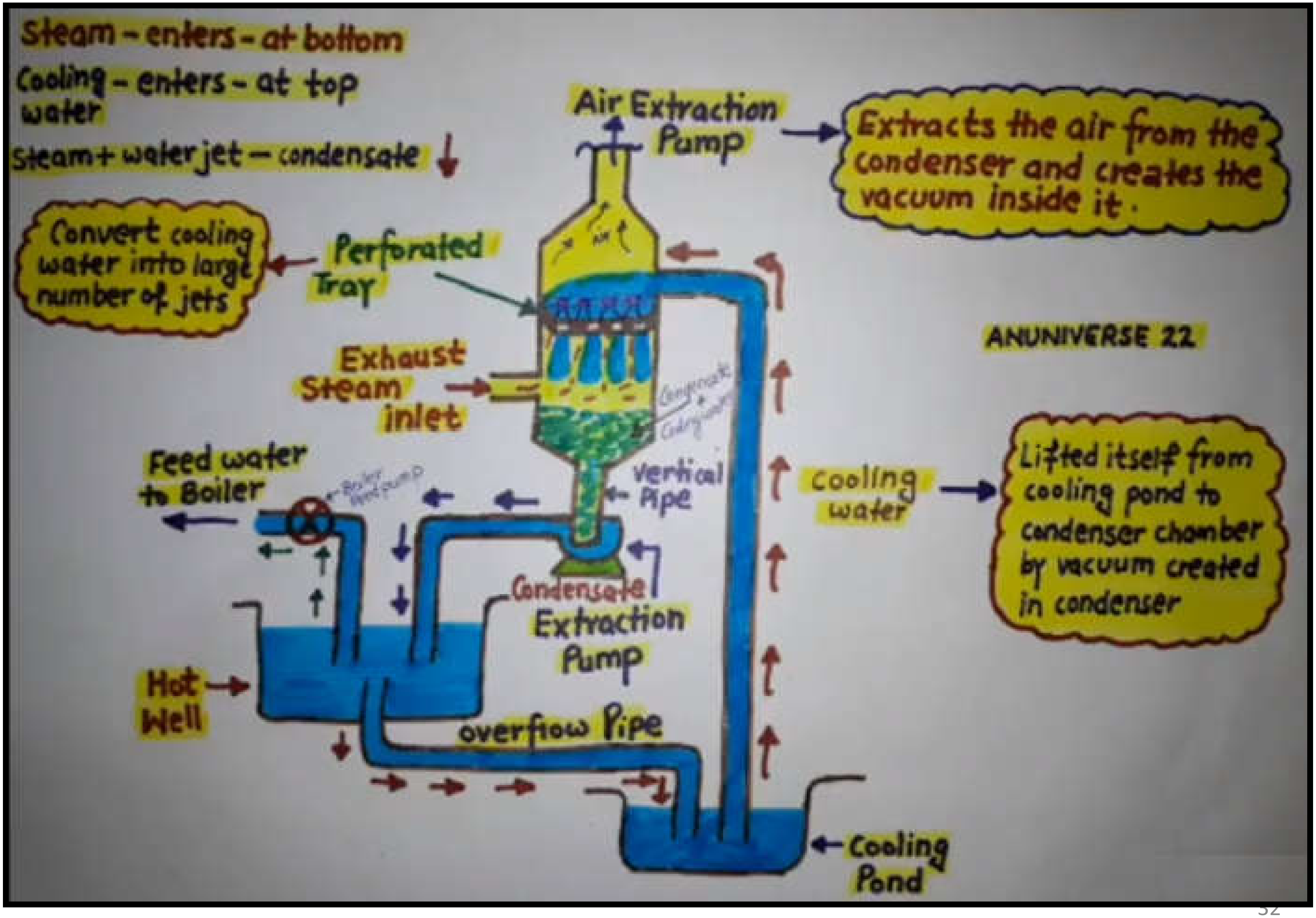
The water flows in downward direction through a series of perforated trays. Steam gets condensed while it comes in contact with the falling water.

The air pump always maintains the required vacuum in the condenser and induces the cooling water to be lifted into the condenser up to a height of 5.5m.

The excess amounts of condensate from hot well flows into the cooling pond by an overflow pipe.

Low-level counter-flow jet condenser

Counter Flow Low Level Jet Condenser


Steam - enters - at bottom

Cooling water - enters - at top

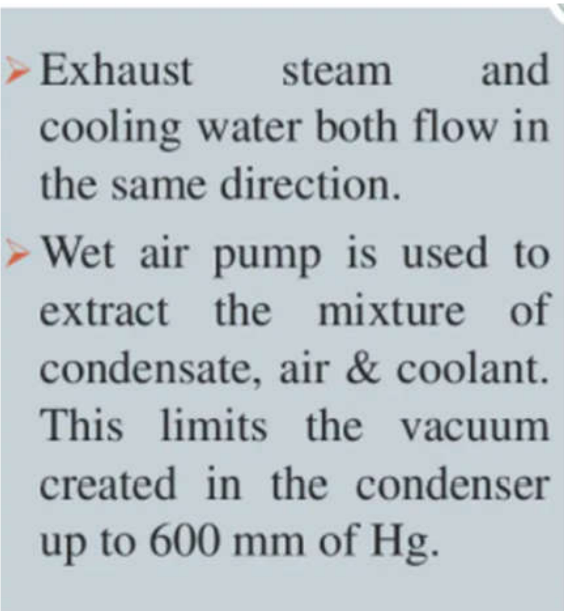
Steam + water jet — condensate ↓

Convert cooling water into large number of jets

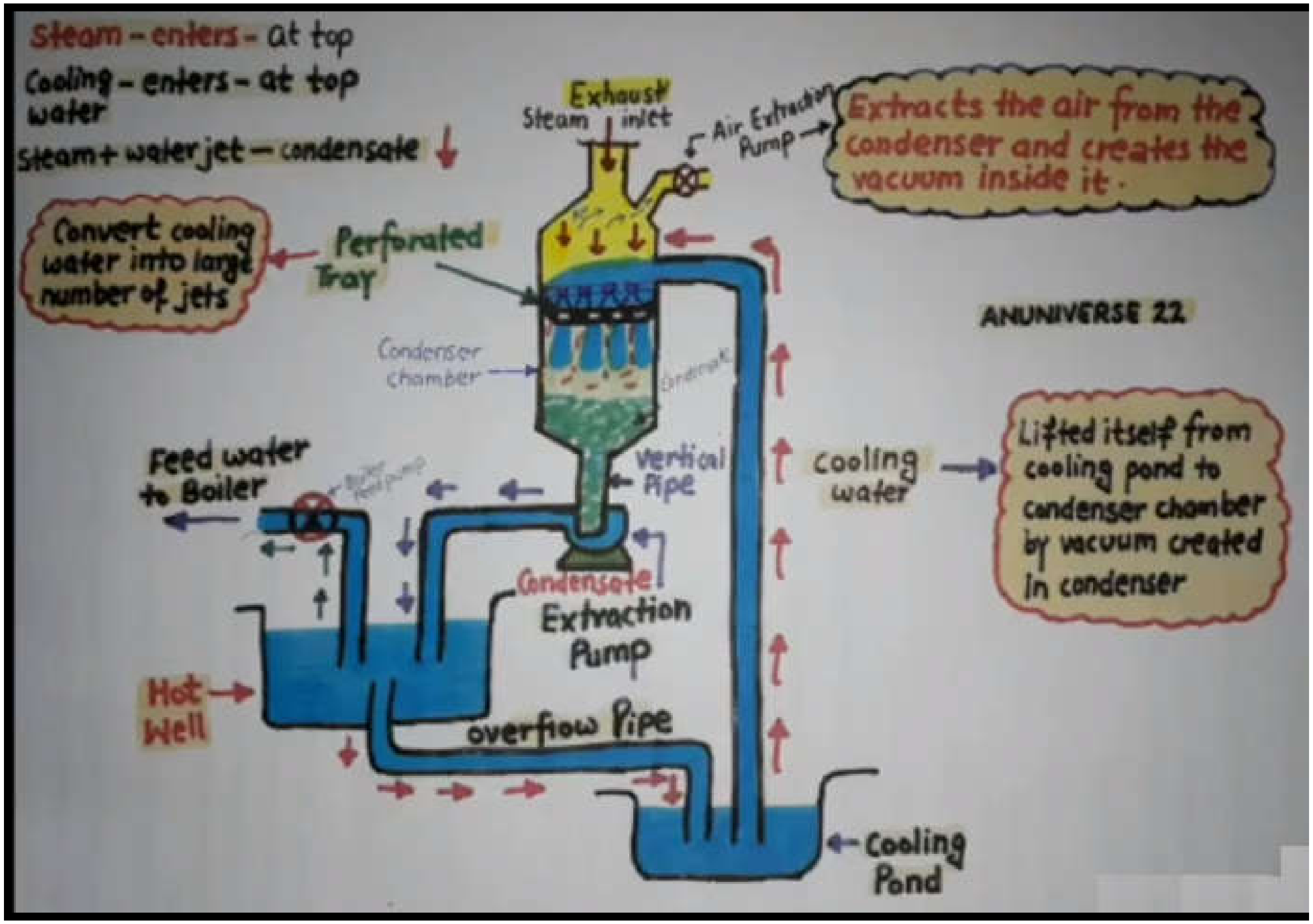
Extracts the air from the condenser and creates the vacuum inside it.

Lifted itself from cooling pond to condenser chamber by vacuum created in condenser

Parallel Flow Low Level Jet Condenser



- Exhaust steam and cooling water both flow in the same direction.
- Wet air pump is used to extract the mixture of condensate, air & coolant. This limits the vacuum created in the condenser up to 600 mm of Hg.

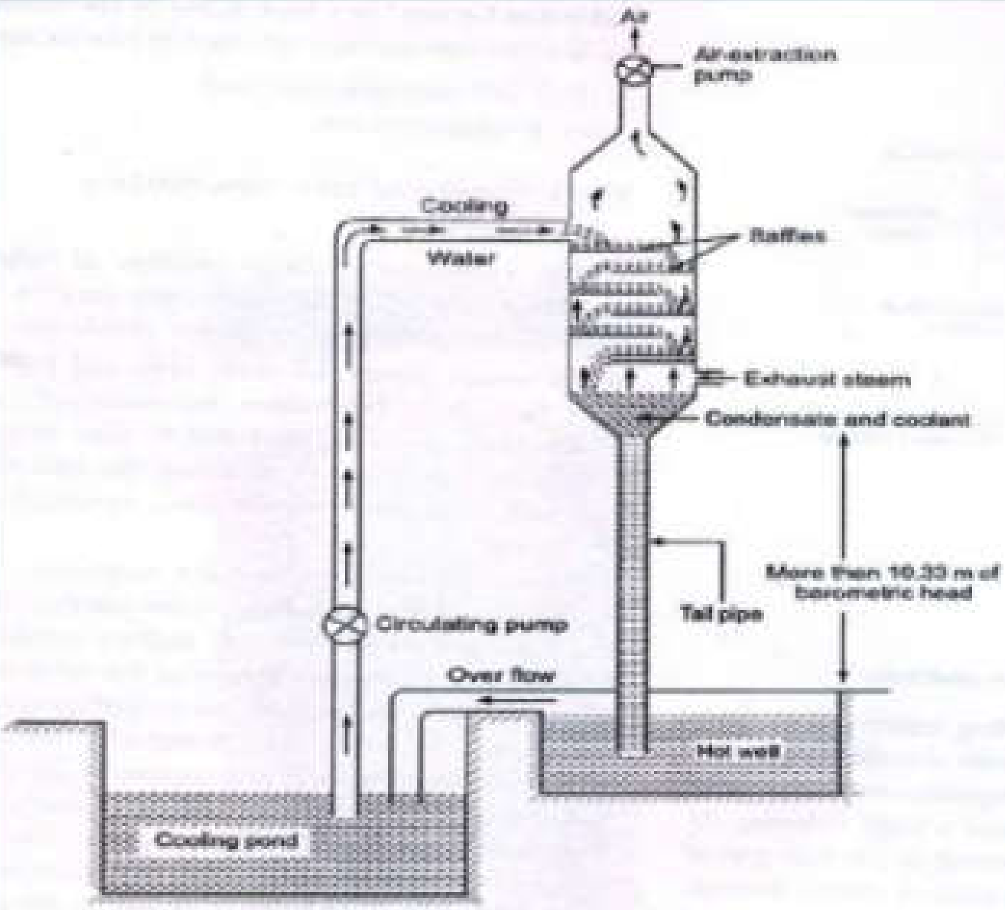


High Level Jet Condenser or Barometric jet condenser

Condenser shell is installed at height greater than that of atmospheric pressure in water column i.e. 10.33 m.

A tall pipe more than 10.33m length is attached to the bottom of the condenser. This allows the condensate and coolant to be discharged from condenser under the gravity action; hence a condensate extraction pump is not required.

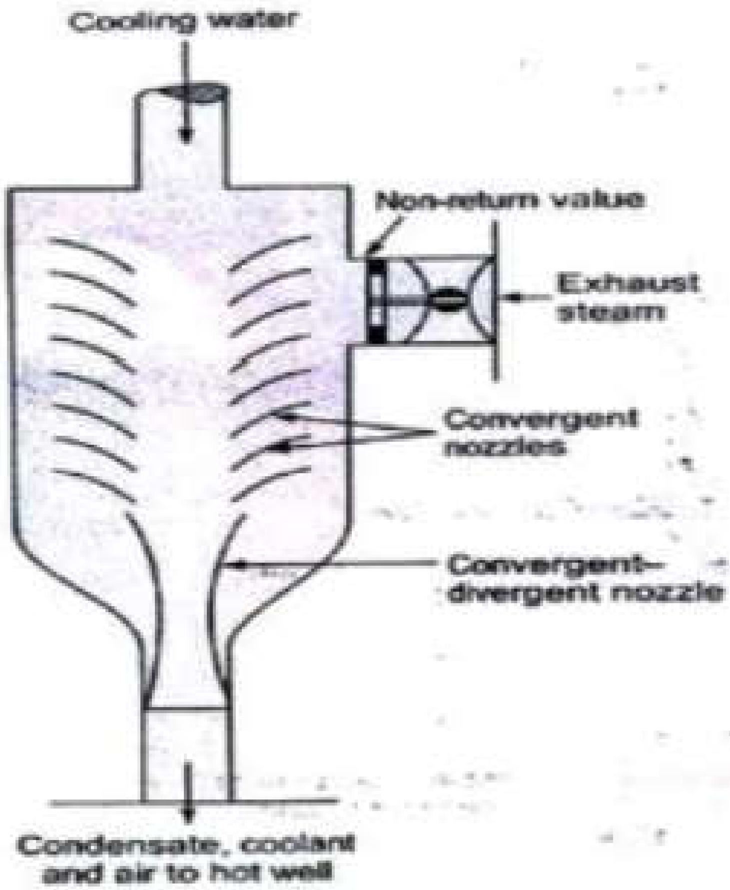
The water from the hot well will not be able to rise into the condenser and flood the turbine due to vacuum pr. Maintained in condenser.



High-level jet condenser

Ejector Condenser:

- In this cooling water enters from the top of the condenser at least under a head of 6m of water pressure with the help of a centrifugal pump and then it passes over a series of convergent nozzles and finally it leaves through a convergent divergent nozzle.
- The non return valve helps in preventing the rush of water from hot well to the engine in case the cooling water supply fails.
- Momentum of flowing water is used to remove the mixture of condensate & coolant from condenser without the use of any extraction pump.



Ejector condenser

Advantages & Disadvantages of Jet Condensers:

Advantages:

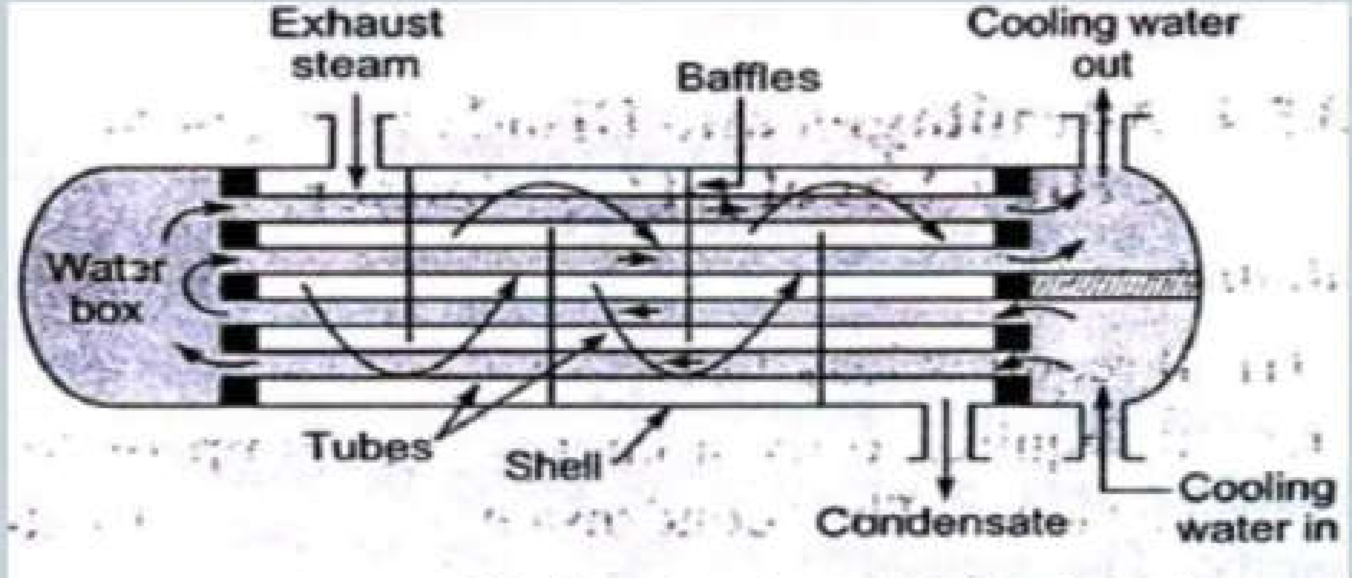
- Simple in design & cheaper.
- Less floor area is required.

Disadvantages:

- Condensate is not pure hence can not be reused.
- Low vacuum efficiency.

Surface Condensers

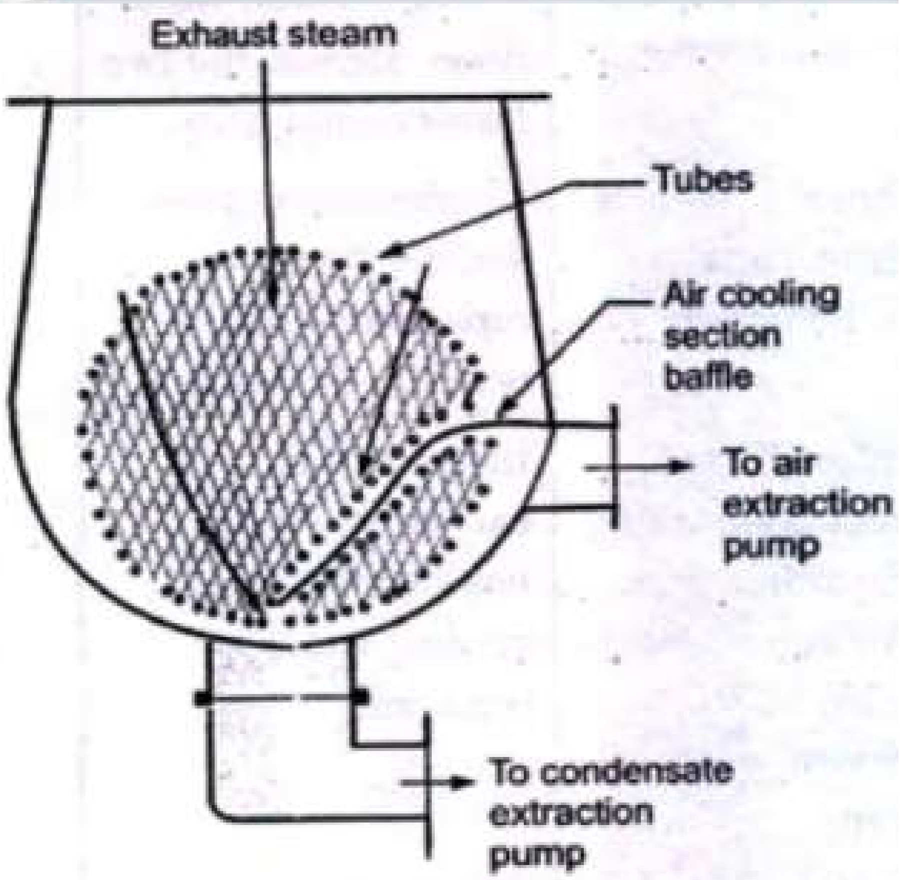
- In surface condenser, the exhaust steam and cooling water do not come in physical contact, rather they are separated by heat transfer wall. Hence condensate remains pure & can be reused.



Shell and tube type condenser

Down Flow Surface Condenser:

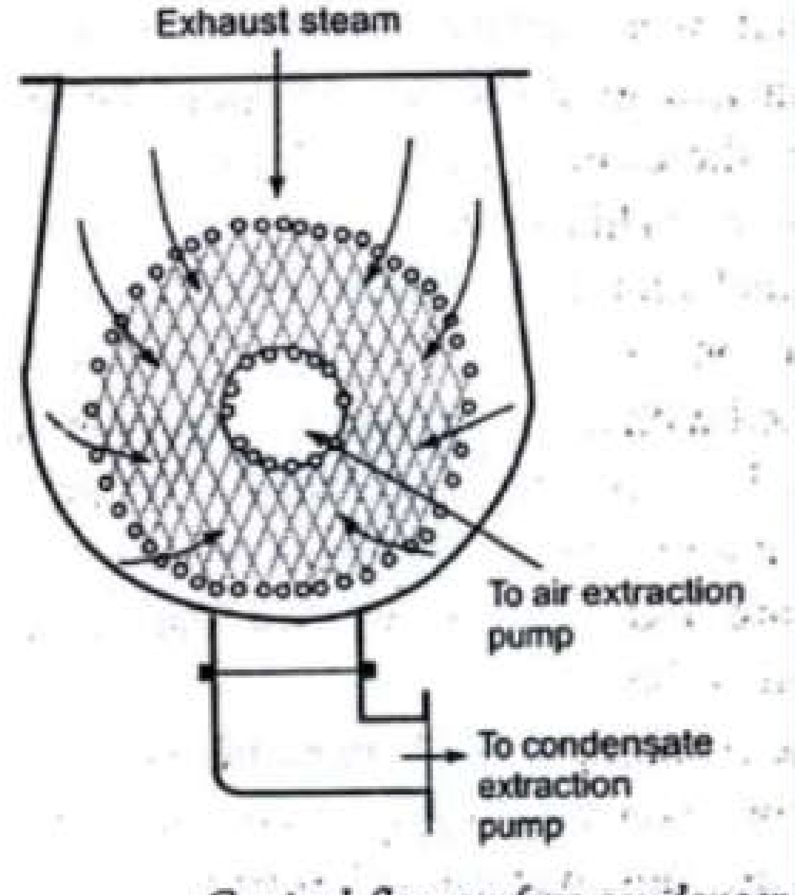
- Exhaust steam enters the top of condenser shell & flows downward over water tubes.
- Water tubes are double passed. The cold water flows in lower side first & then in upper side in the reverse direction, which enables the maximum heat transfer.



Down-flow surface condenser

Central Flow Surface Condenser

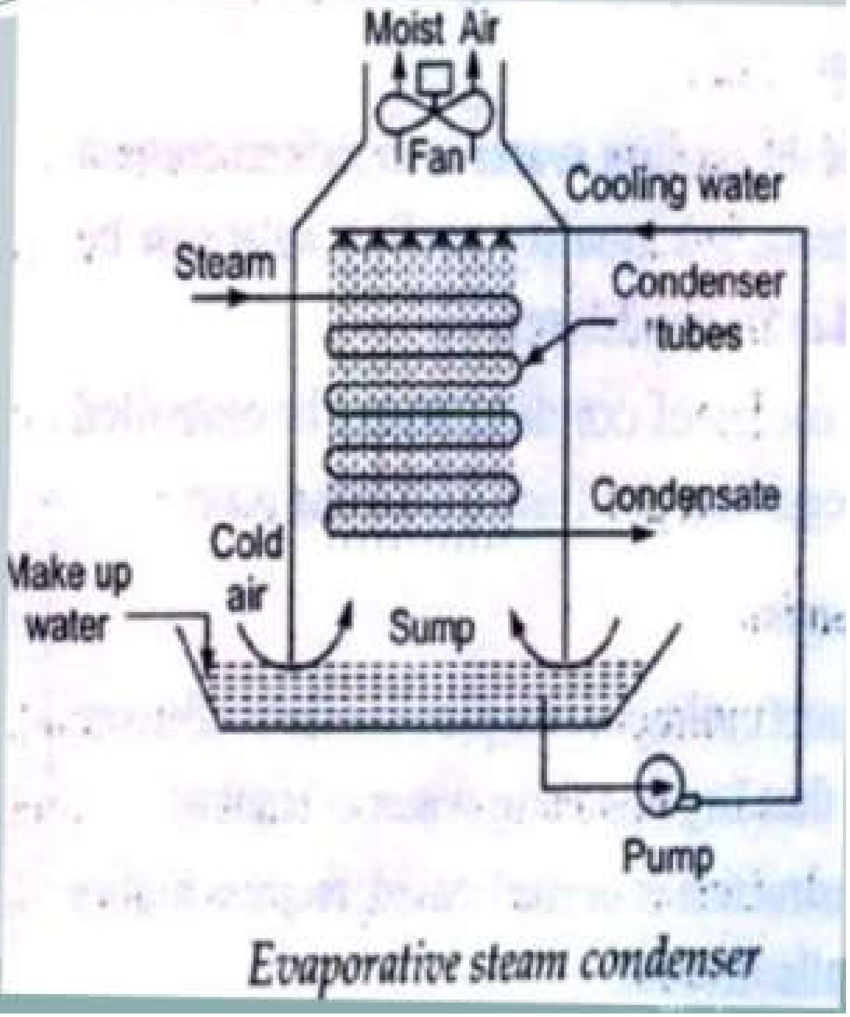
- The steam flows radially inward
- The condensate is collected at the bottom of the shell from where it is taken out by the condensate extraction pump.
- The steam gets access to the entire periphery of tubes, and thus a large surface area for the hear transfer is available as compared to the down flow.



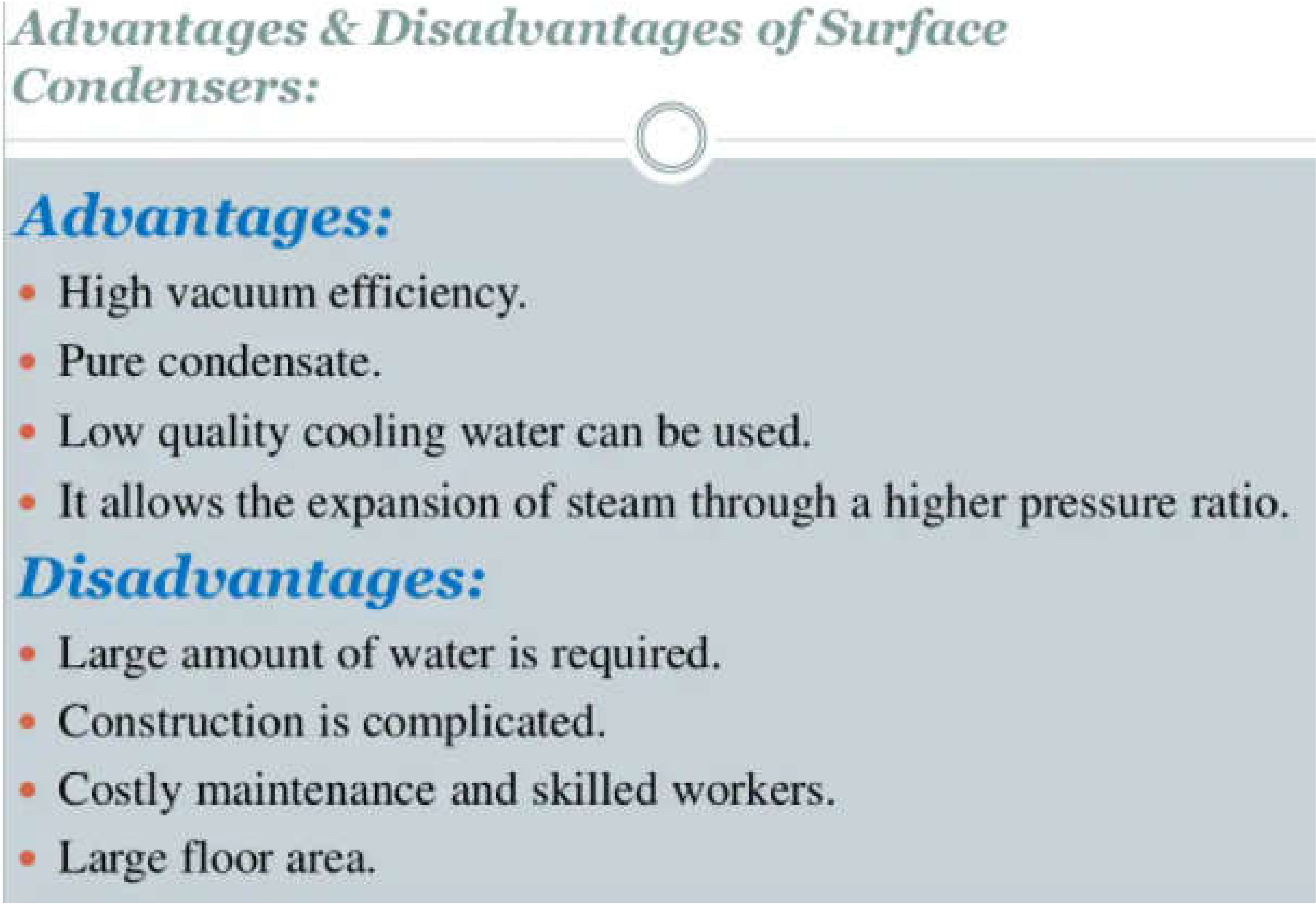
Central-flow surface condenser

Evaporative Condenser:

- The evaporation of some cooling water provides the cooling effect, thereby steam condenses.
- Steam to be condensed is passed through grilled tubes & cooling water is sprayed over outer surface of tubes.
- The evaporative condensers are most suitable for small plants, where supply of cold water is limited.



Evaporative steam condenser



Advantages & Disadvantages of Surface Condensers:

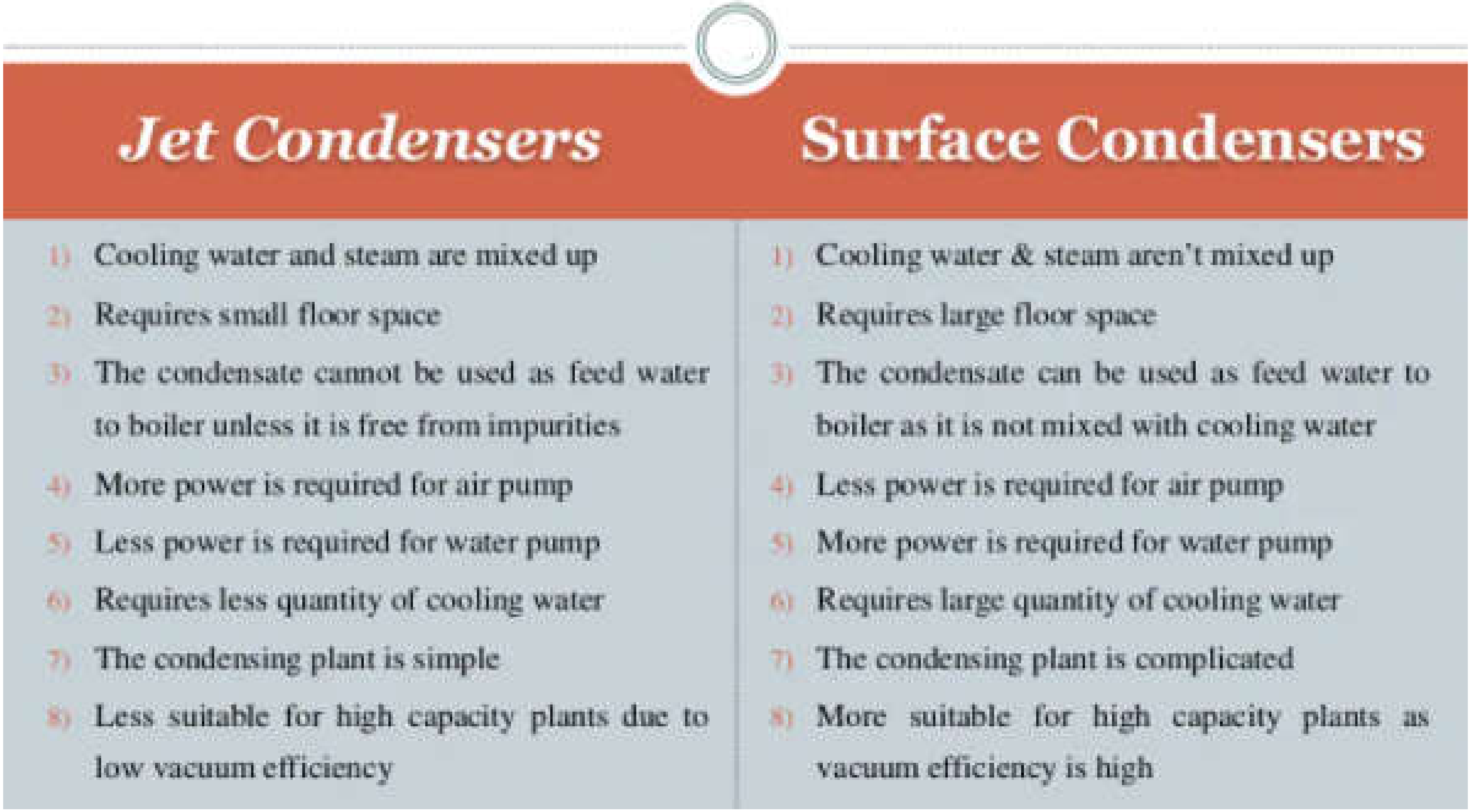
Advantages:

- High vacuum efficiency.
- Pure condensate.
- Low quality cooling water can be used.
- It allows the expansion of steam through a higher pressure ratio.

Disadvantages:

- Large amount of water is required.
- Construction is complicated.
- Costly maintenance and skilled workers.
- Large floor area.

Comparison of Jet & Surface Condensers:



Jet Condensers	Surface Condensers
1) Cooling water and steam are mixed up	1) Cooling water & steam aren't mixed up
2) Requires small floor space	2) Requires large floor space
3) The condensate cannot be used as feed water to boiler unless it is free from impurities	3) The condensate can be used as feed water to boiler as it is not mixed with cooling water
4) More power is required for air pump	4) Less power is required for air pump
5) Less power is required for water pump	5) More power is required for water pump
6) Requires less quantity of cooling water	6) Requires large quantity of cooling water
7) The condensing plant is simple	7) The condensing plant is complicated
8) Less suitable for high capacity plants due to low vacuum efficiency	8) More suitable for high capacity plants as vacuum efficiency is high

Sources of Air in the Condenser:

- The ambient air leaks to the condenser chamber at the joints & glands which are internally under pressure lower than that of ambient.
- Another source of air is the dissolved air with feed water. The dissolved air in feed water enters into boiler and it travels with steam into condenser.

Effects of Air Leakage:

- The presence of air lowers vacuum in the condenser. Thus back pressure of the plant increases, and consequently, the work output decreases.
- Air has very poor thermal conductivity. Hence, the rate of heat transfer from vapour to cooling medium is reduced.
- The presence of air in the condenser corrodes to the metal surfaces. Therefore, the life of condenser is reduced.

Effect of Condenser Pressure on Rankine Efficiency:

- Lowering the condenser pressure will increase the area enclosed by the cycle on a T-s diagram which indicates that the net work will increase. Thus, the thermal efficiency of the cycle will be increased
- Lowering the back pressure causes an increase in moisture content of steam leaving the turbine.
- Increase in moisture content of steam in low pressure stages, there is decrease in efficiency & erosion of blade may be a very serious problem and also the pump work required will be high.

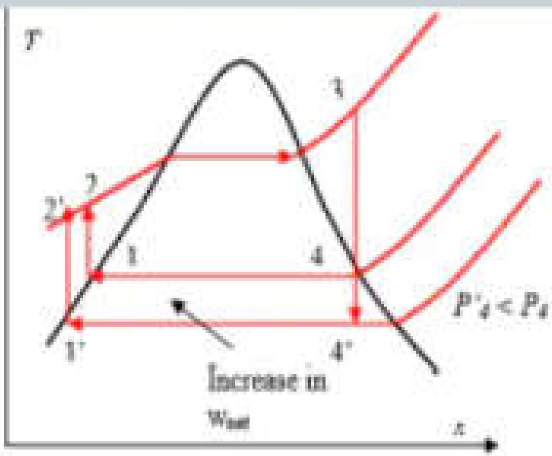


Fig. 4: Effect of lowering the condenser pressure on ideal Rankine cycle

Thermal Engineering-II
MODULE-3-II

Introduction

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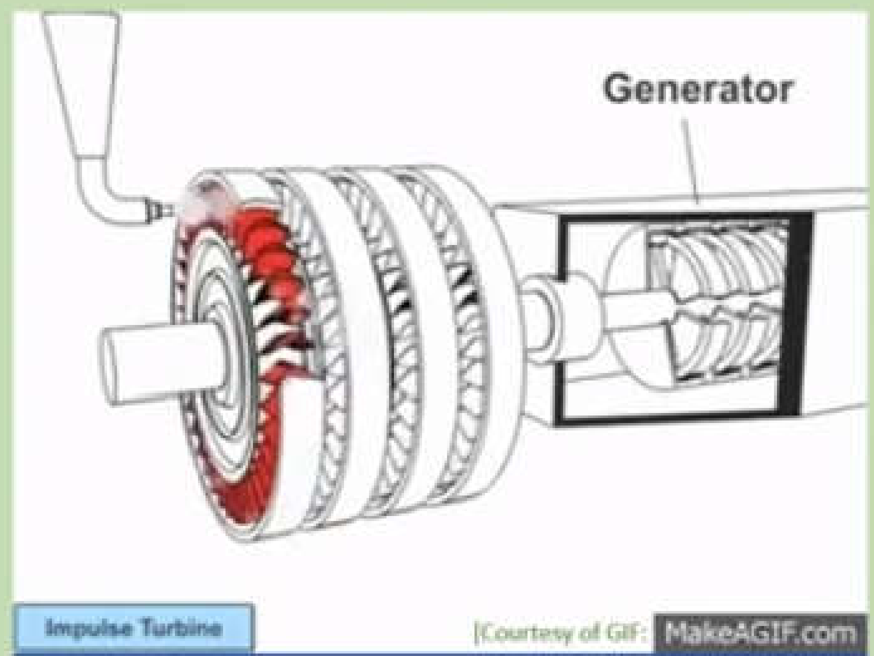
Department of Mechanical Engineering

Steam Nozzle

Steam Nozzles

- Turbo machines like steam turbines produce power by utilising kinetic energy of steam jet produced by passing high pressure steam through the devices called as nozzles.



Steam Turbine Rotor with Steam Nozzle

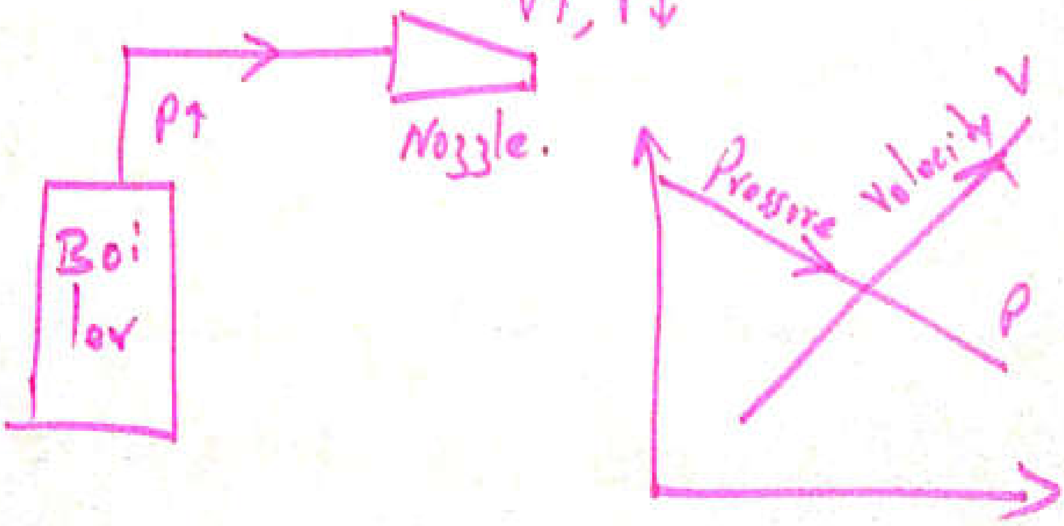
- It is a passage of varying cross sectional area by means of which pressure energy of working fluid as steam is converted into kinetic energy.

Steam Nozzle:.

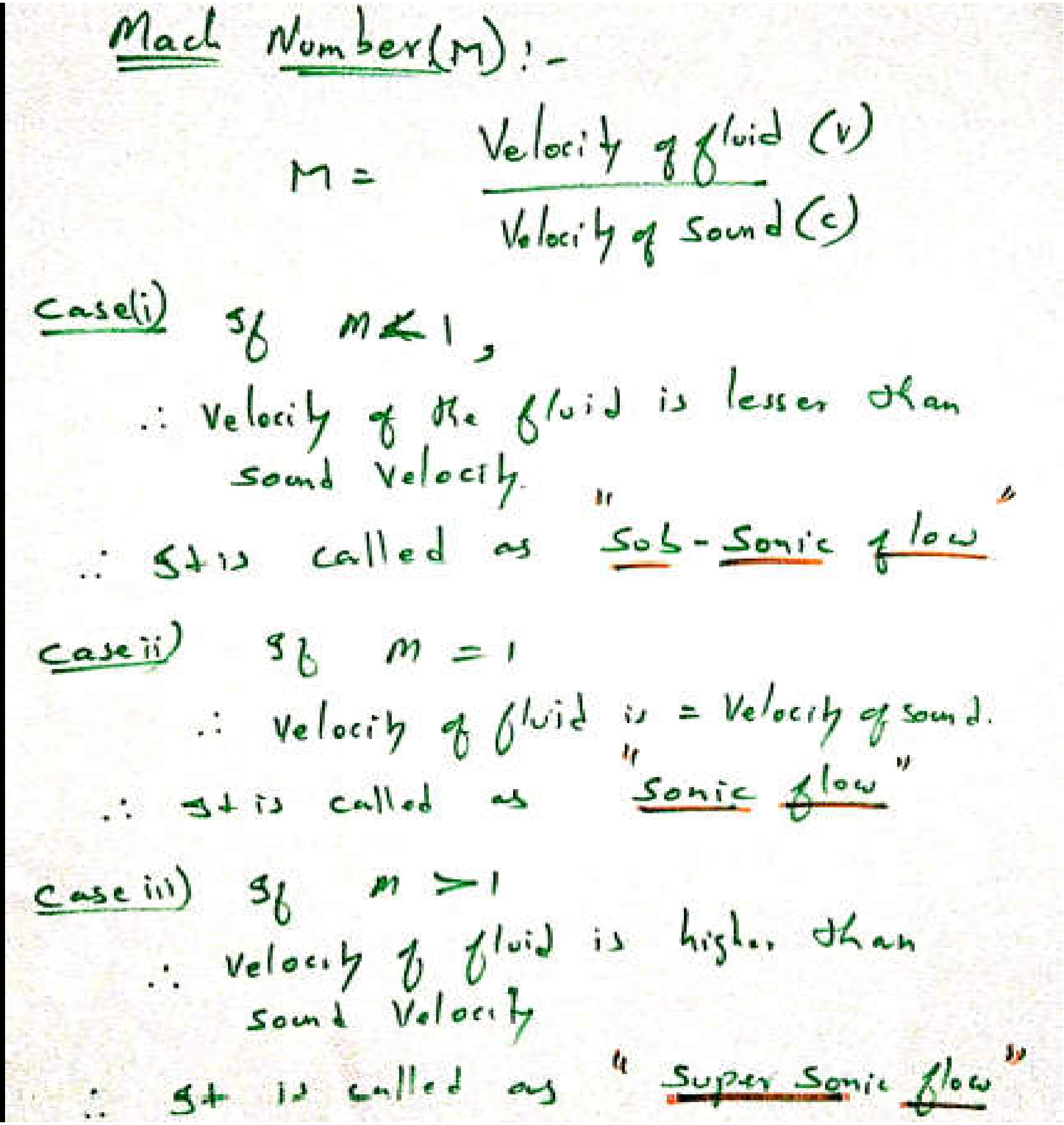
Nozzle is a device used to increase the velocity of flow with drop in Pressure.

↓

To utilize the K.E for Turbines.



Mach Number



Mach Number(M):-

$$M = \frac{\text{Velocity of fluid } (v)}{\text{Velocity of Sound } (c)}$$

case(i) If $M < 1$,

∴ Velocity of the fluid is lesser than sound velocity.

∴ It is called as "Sub-Sonic flow"

case ii) If $M = 1$

∴ velocity of fluid is = Velocity of sound.

∴ It is called as "Sonic flow"

case iii) If $M > 1$

∴ velocity of fluid is higher than sound Velocity

∴ It is called as "Super Sonic flow"

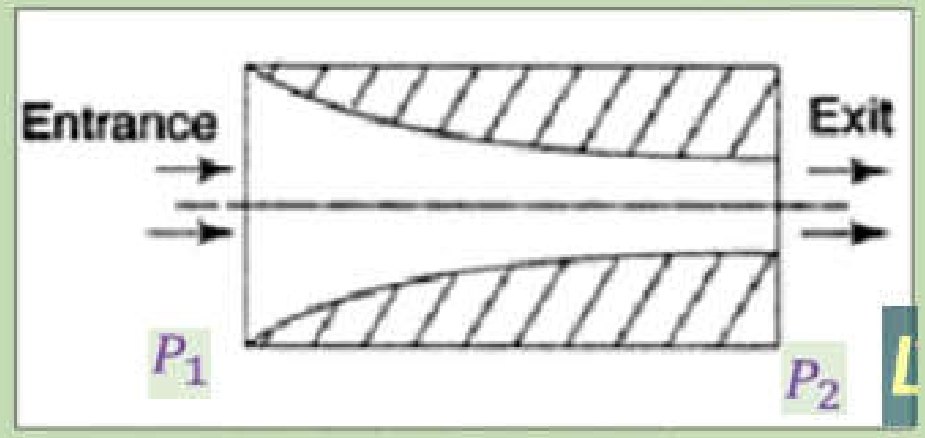
Types of Nozzles

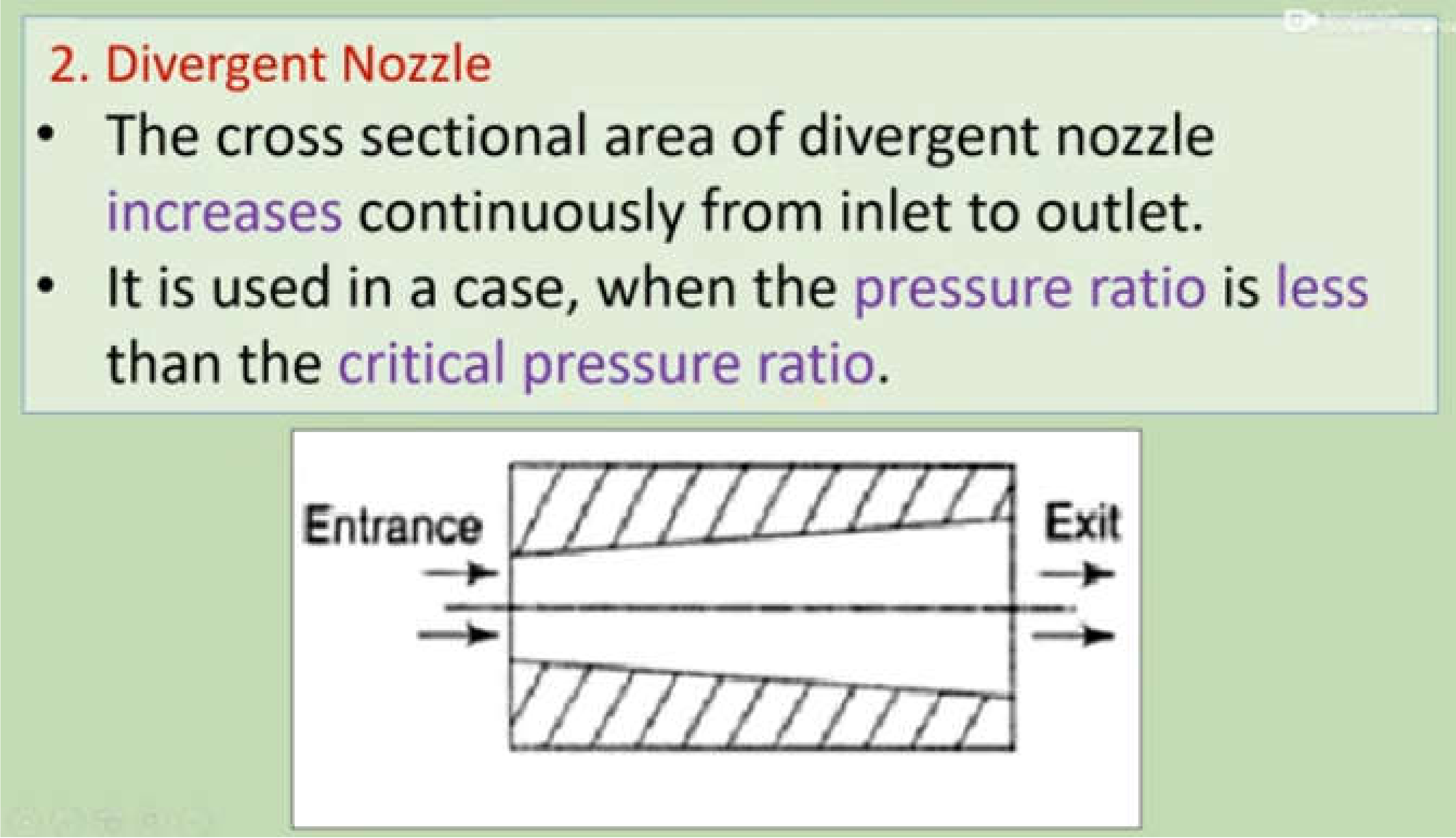
1. Convergent Nozzle
2. Divergent Nozzle
3. Convergent-Divergent Nozzle

1. Convergent Nozzle

- In convergent nozzle the cross sectional area decreases continuously from inlet to outlet.
- It is used in a case when pressure ratio $(\frac{P_2}{P_1})$ is equal to or greater than the critical pressure ratio (0.58)

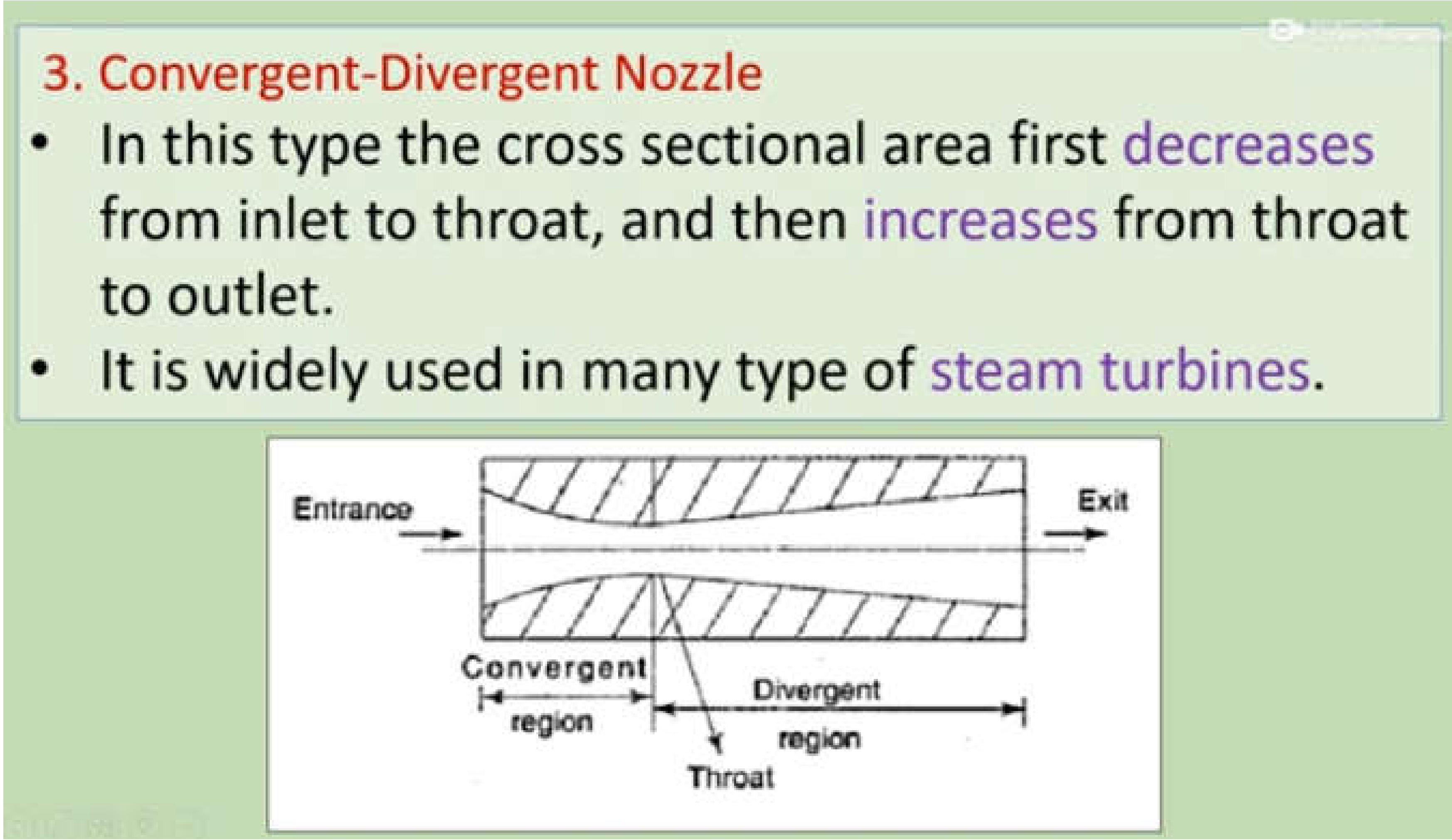
[Courtesy of Image: https://www.indiamart.com]





2. Divergent Nozzle

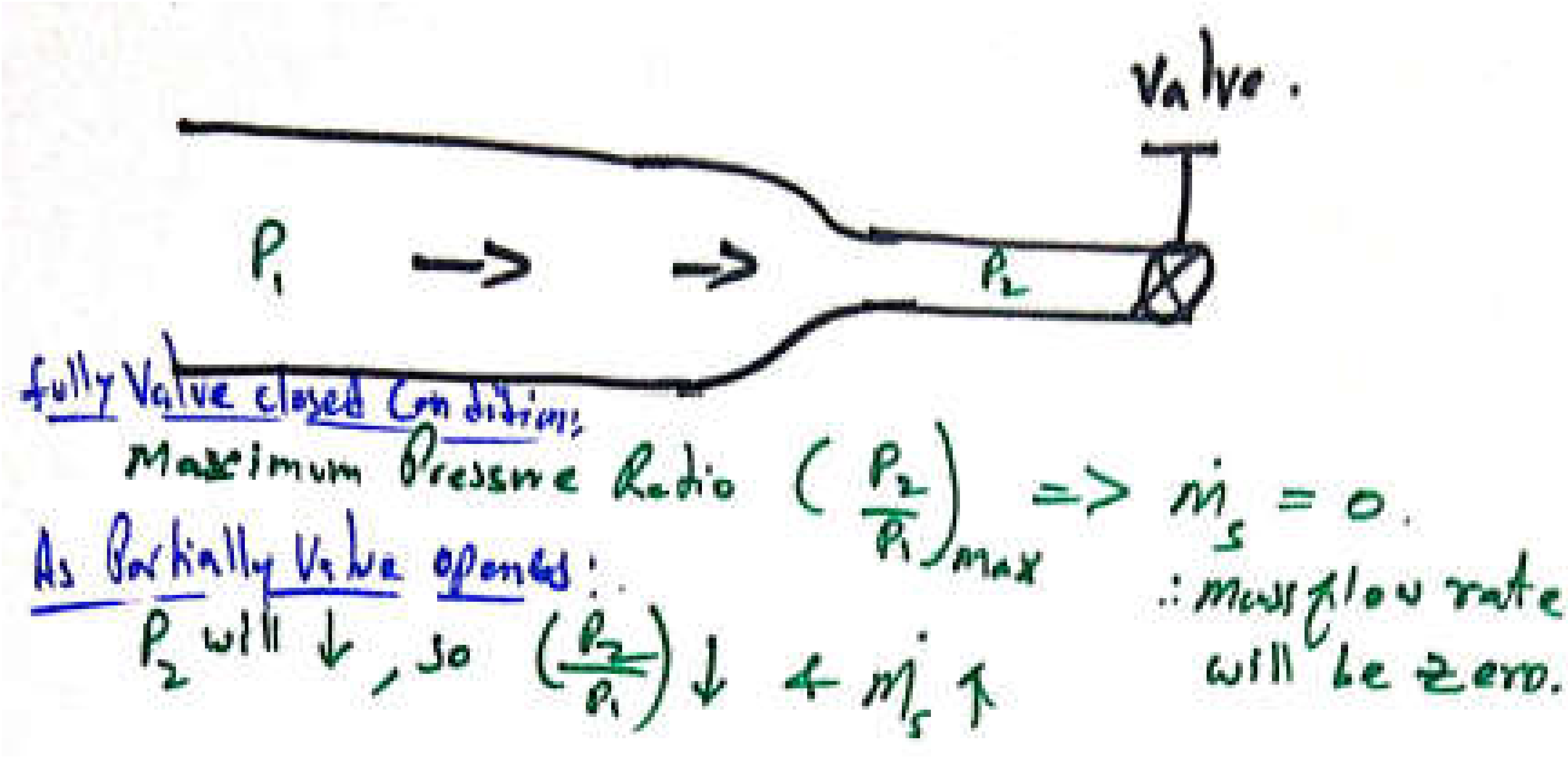
- The cross sectional area of divergent nozzle increases continuously from inlet to outlet.
- It is used in a case, when the pressure ratio is less than the critical pressure ratio.



3. Convergent-Divergent Nozzle

- In this type the cross sectional area first decreases from inlet to throat, and then increases from throat to outlet.
- It is widely used in many type of steam turbines.

Significance of Critical Pressure ratio



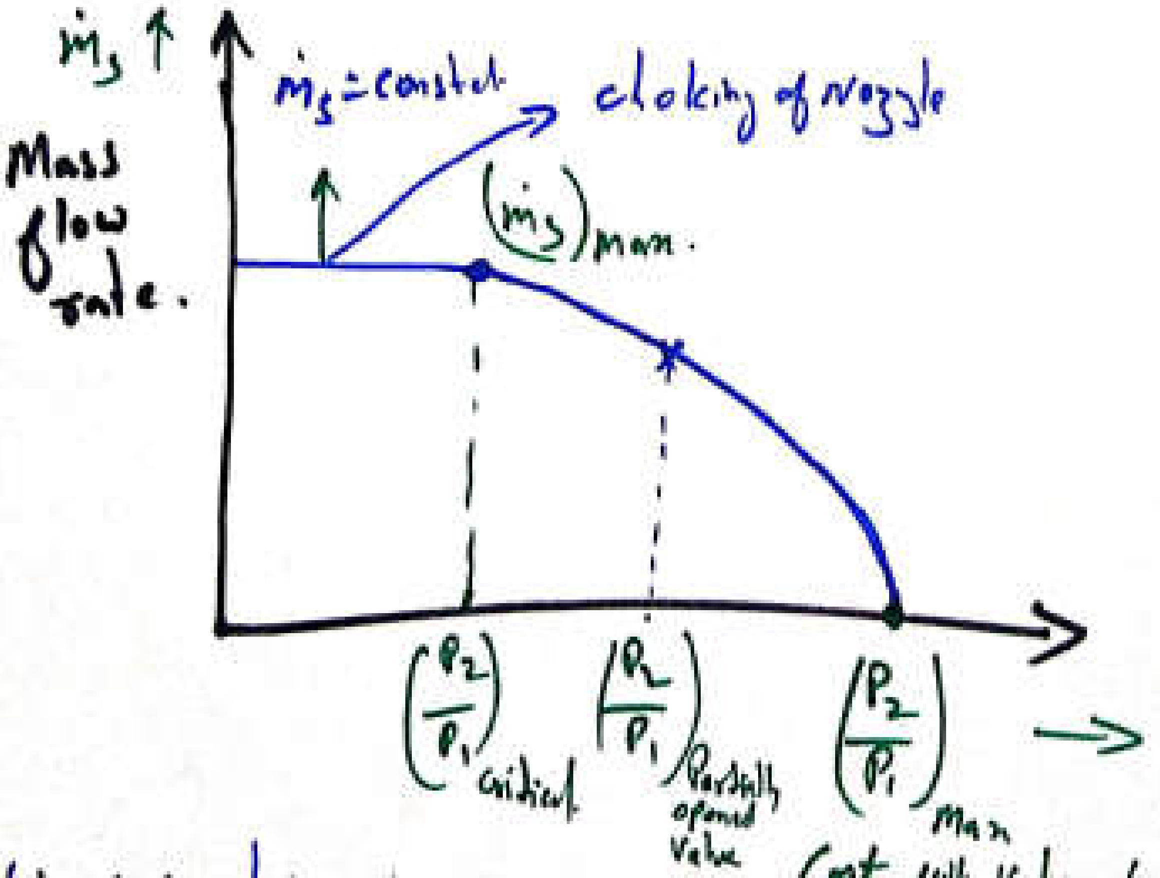
fully Valve closed Condition:

Maximum Pressure Ratio $\left(\frac{P_2}{P_1}\right)_{max}$ => $\dot{m}_s = 0$.

∴ mass flow rate will be zero.

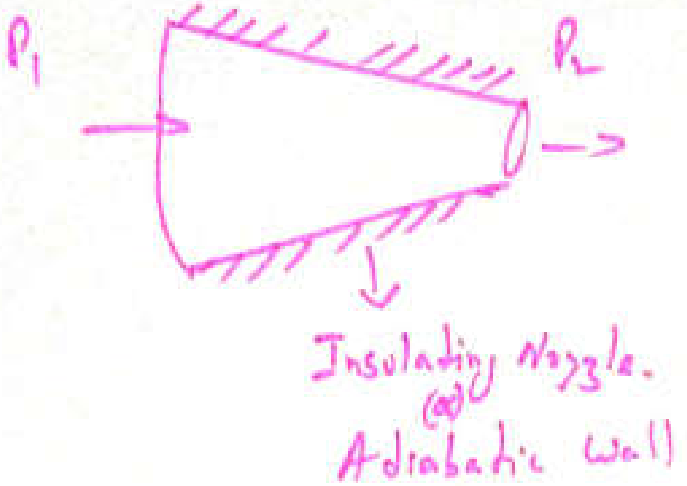
As Partially Valve opens:

P_2 will ↓, so $\left(\frac{P_2}{P_1}\right)$ ↓ & $\dot{m}_s$ ↑

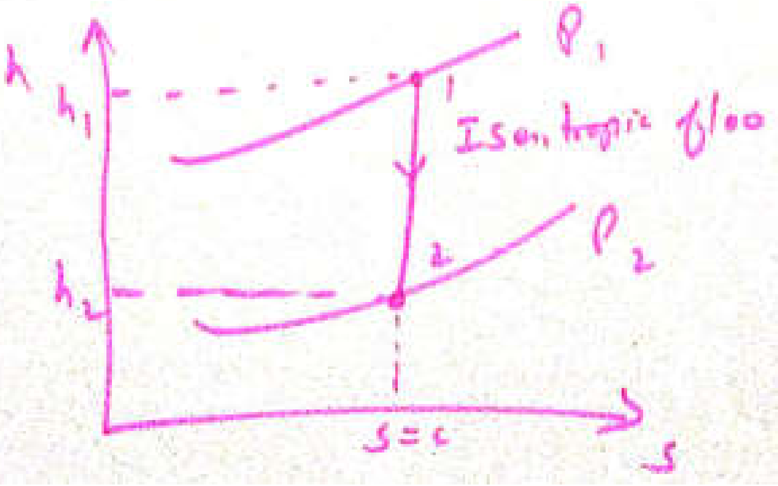


<u>chocking of Nozzles</u>. where Mass flow rate & exit velocity will not change on further decrease in Pressure Ratio

Flow of the Nozzle

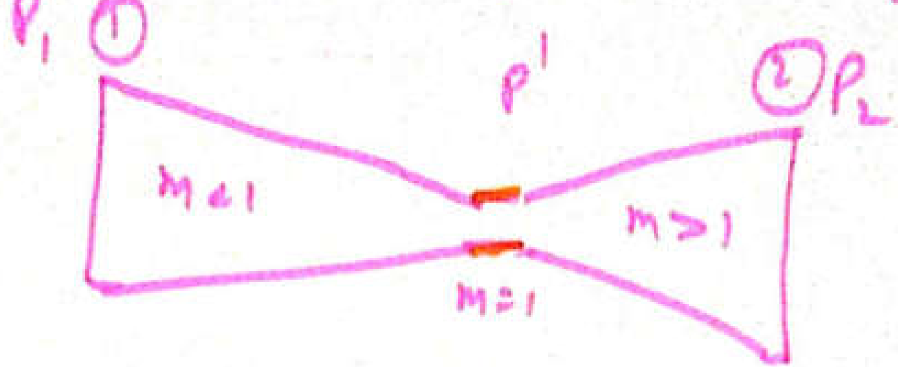


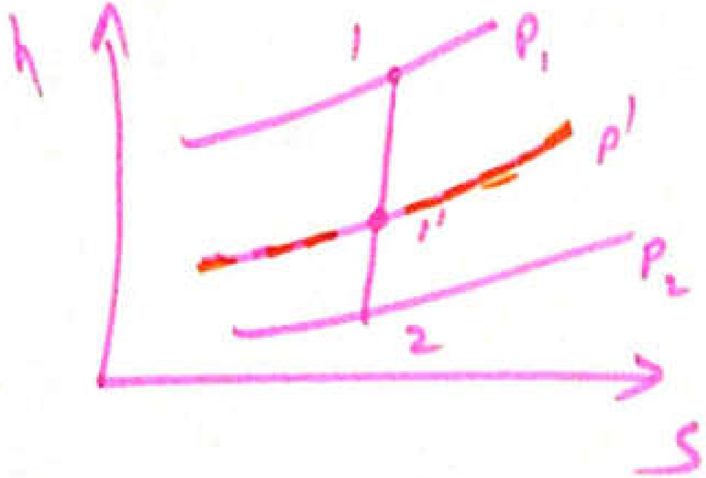
∴ ~~The~~ when the steam is flowing through a Nozzle, the Process is called as Reversible Adiabatic Process (or) Isentropic process (s = const)



If suppose for,

Convergent - Divergent Nozzle

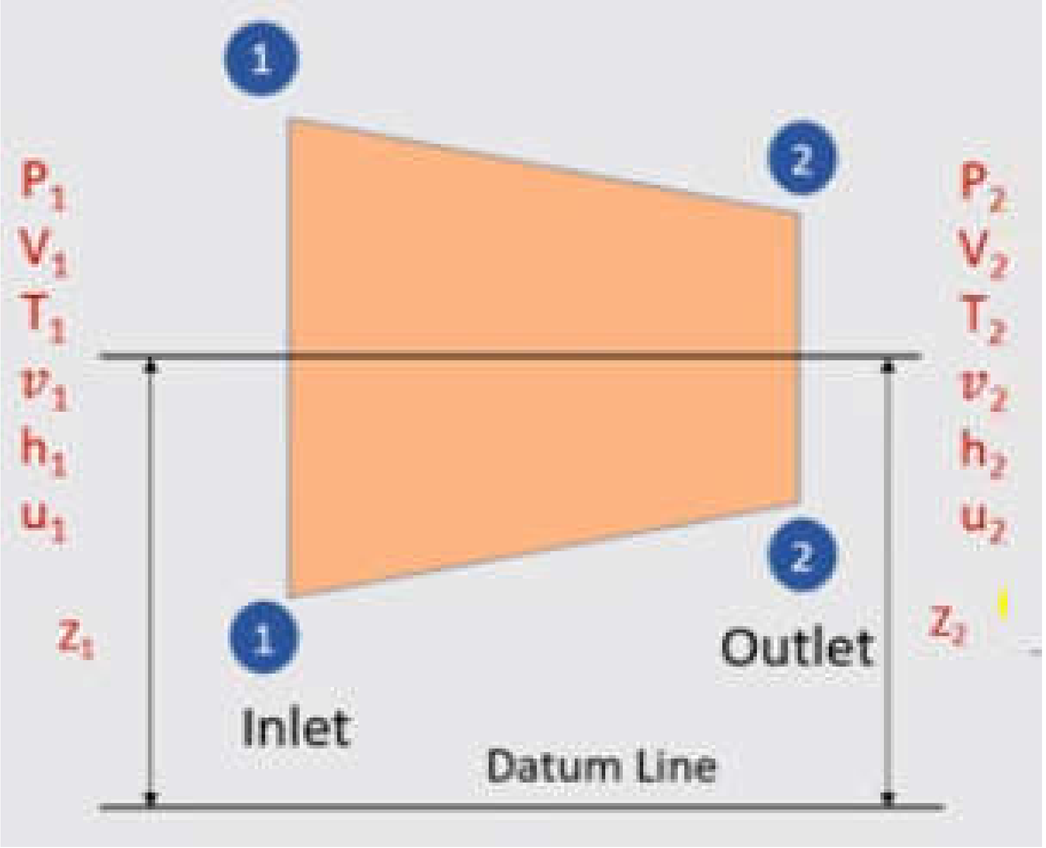


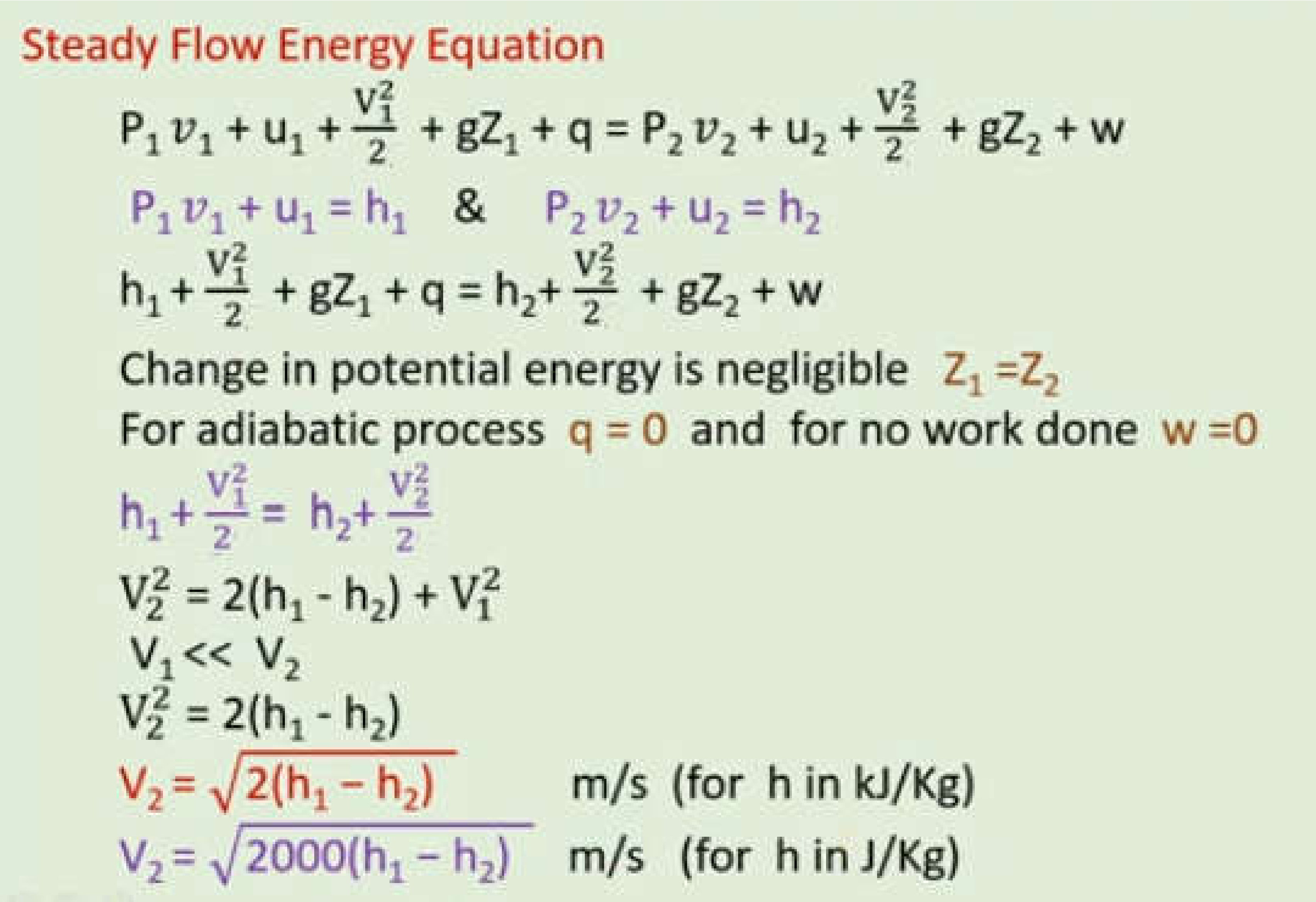


Equation of Velocity in Nozzles

Consider steam passing through nozzle from inlet 1-1 to outlet 2-2.

P_1 - Pressure of steam
V_1 - Velocity of steam
T_1- Temperature of steam
v_1- Sp. Volume of steam
h_1 - Sp. Enthalpy of steam
u_1 - Internal energy of steam
Z_1 – Datum level





Steady Flow Energy Equation

$$P_1 v_1 + u_1 + \frac{V_1^2}{2} + gZ_1 + q = P_2 v_2 + u_2 + \frac{V_2^2}{2} + gZ_2 + w$$

$P_1 v_1 + u_1 = h_1$ & $P_2 v_2 + u_2 = h_2$

$$h_1 + \frac{V_1^2}{2} + gZ_1 + q = h_2 + \frac{V_2^2}{2} + gZ_2 + w$$

Change in potential energy is negligible $Z_1 = Z_2$

For adiabatic process $q = 0$ and for no work done $w = 0$

$$h_1 + \frac{V_1^2}{2} = h_2 + \frac{V_2^2}{2}$$

$$V_2^2 = 2(h_1 - h_2) + V_1^2$$

$V_1 << V_2$

$$V_2^2 = 2(h_1 - h_2)$$

$V_2 = \sqrt{2(h_1 - h_2)}$ m/s (for h in kJ/Kg)

$V_2 = \sqrt{2000(h_1 - h_2)}$ m/s (for h in J/Kg)

$$\therefore \quad V_2 = \sqrt{2000(h_1-h_2)}$$

∴ $h_1 - h_2$ = heat drop (or) Enthalpy drop.

$$\boxed{h_1 - h_2 = h_d}$$

$$V_2 = 44.72\sqrt{h_1-h_2}$$

Exist Vel. of Nozzle $\boxed{V_2 = 44.72\sqrt{h_d}}$ m/s

∴ Exist Vel. of Nozzle ∝ Enthalpy drop.

(↑) (↑)
(or) (or)
(↓) (↓)

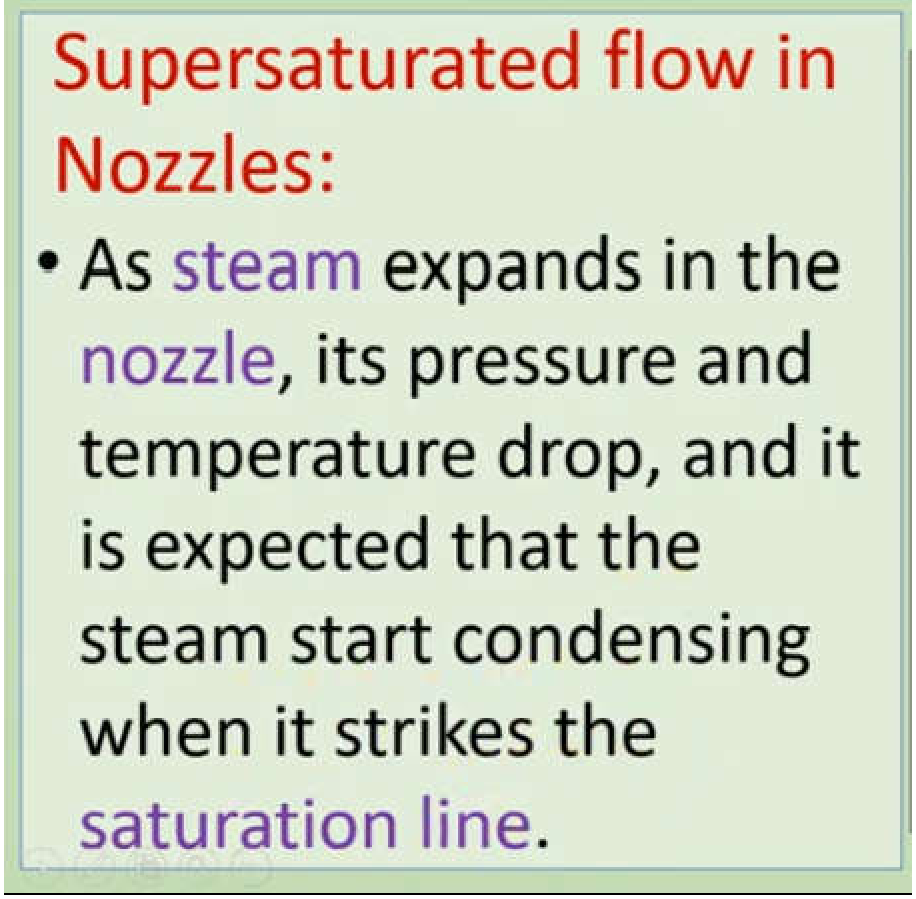
Let enthalpy drop after deducting friction loss will be

$$\boxed{V_2 = 44.72\sqrt{k\,h_d}} \text{ m/s}$$

Isentropic Expansion of Steam in a Nozzle

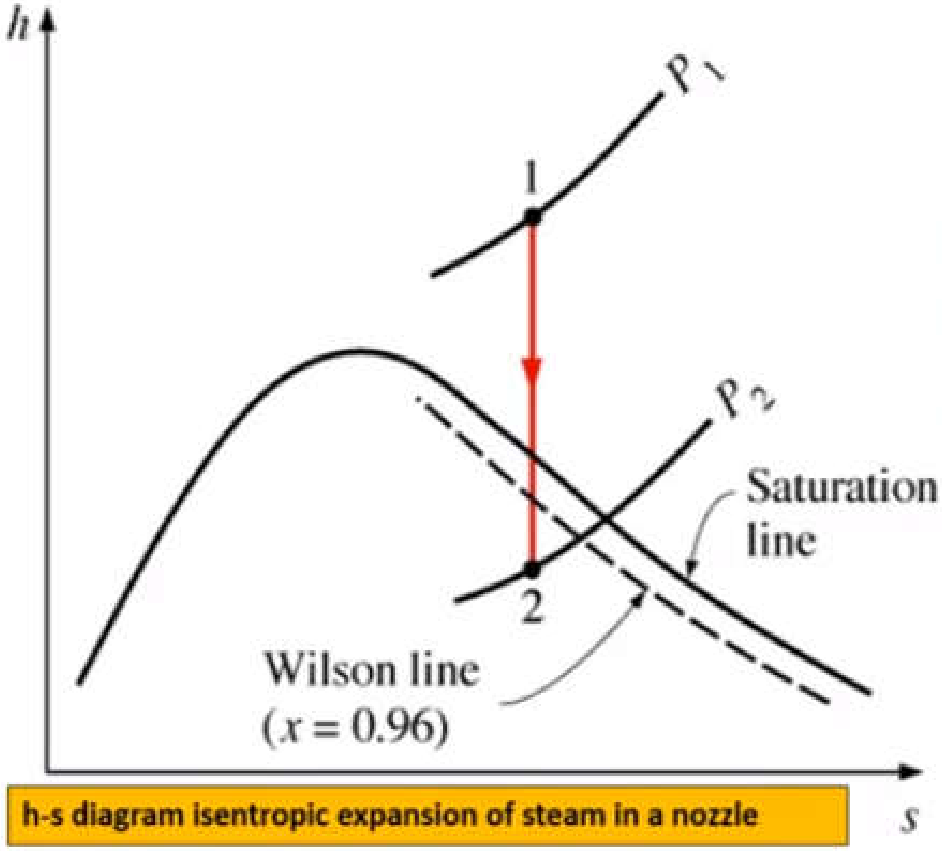
or

Supersaturated Nozzle



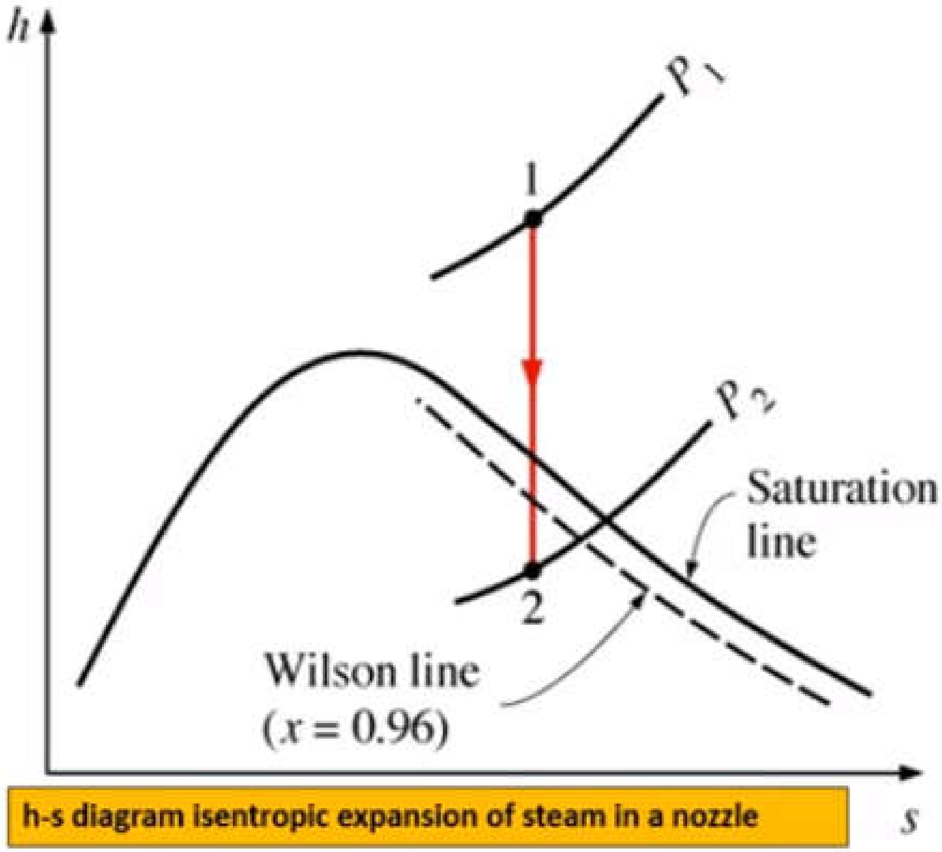
Supersaturated flow in Nozzles:

- As steam expands in the nozzle, its pressure and temperature drop, and it is expected that the steam start condensing when it strikes the saturation line.



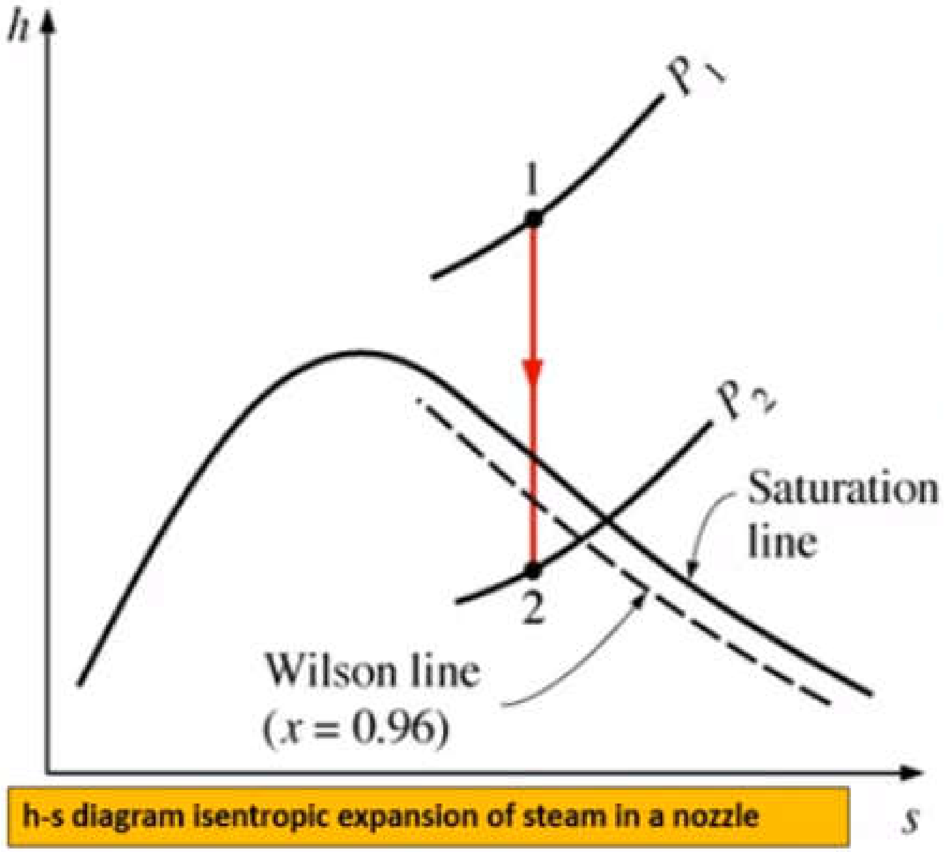
h-s diagram isentropic expansion of steam in a nozzle

- Due to high velocities, the residence time of the steam in the nozzle is small, and there may not sufficient time for the necessary heat transfer and the formation of liquid droplets.



h-s diagram isentropic expansion of steam in a nozzle

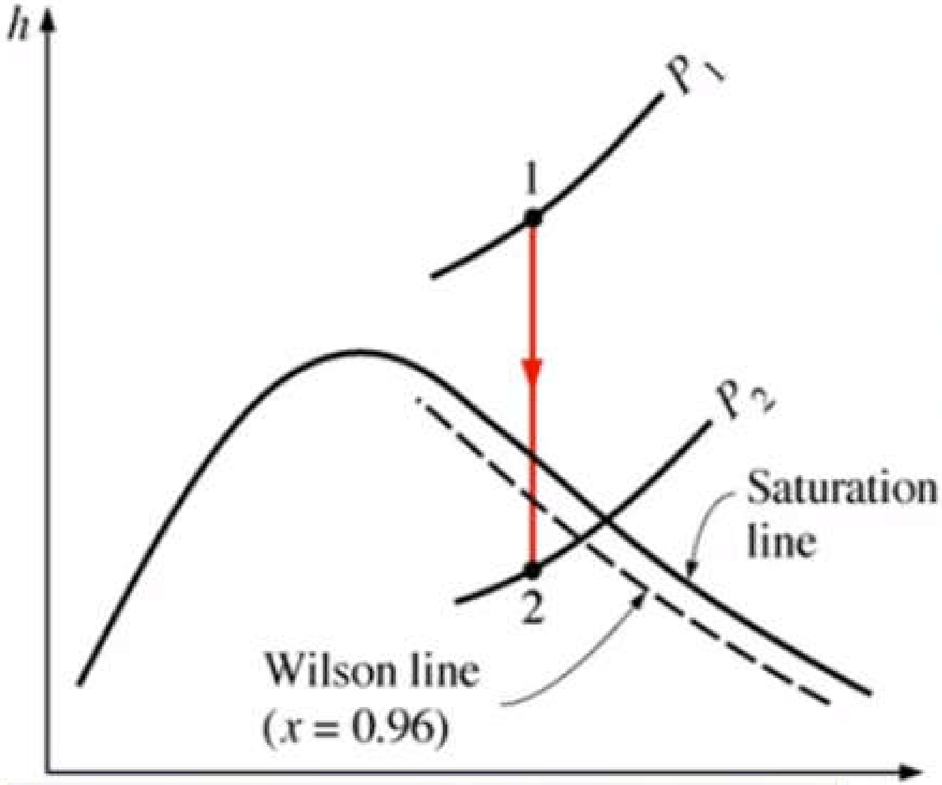
- Consequently, the condensation of steam is delayed for a little while. This phenomenon is known as super saturation, and the steam that exists in the wet region without containing any liquid is known as supersaturated steam.



h-s diagram isentropic expansion of steam in a nozzle

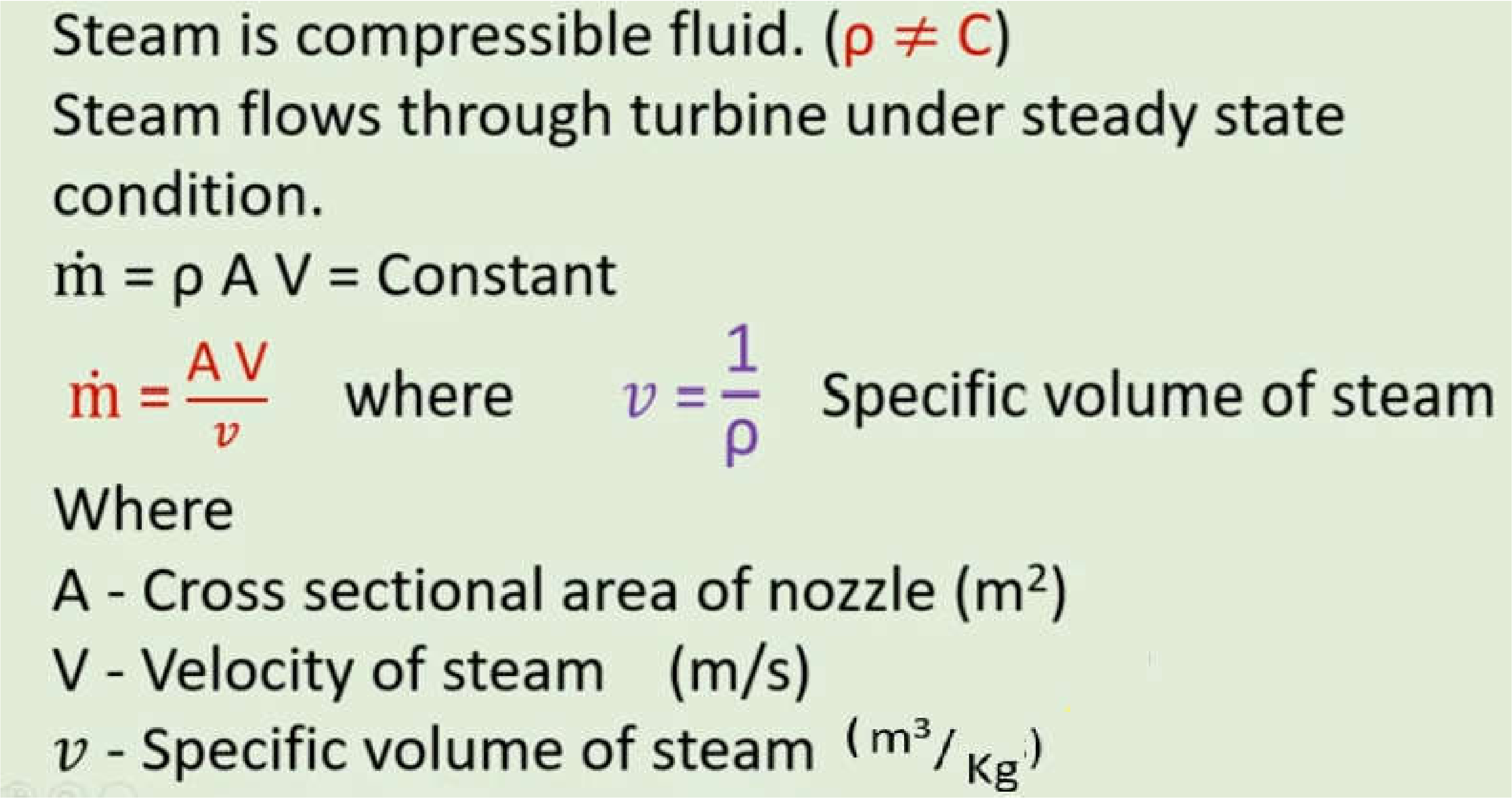
- The locus of points where condensation will take place regardless of the initial temperature and pressure at the nozzle inlet is called the Wilson line.

- The Wilson line lies between 4 and 5 percent moisture curves in the saturation region on the h-s diagram for steam, and is often approximated by the 4 percent moisture line.



h-s diagram isentropic expansion of steam in a nozzle

Mass Flow Rate of Steam



Steam is compressible fluid. ($\rho \neq C$)

Steam flows through turbine under steady state condition.

$\dot{m} = \rho A V =$ Constant

$\dot{m} = \frac{A V}{v}$ where $v = \frac{1}{\rho}$ Specific volume of steam

Where

A - Cross sectional area of nozzle (m^2)

V - Velocity of steam (m/s)

v - Specific volume of steam ($m^3/_{Kg}$)

$$\dot{m} = \frac{A \cdot V}{\nu} = \text{const.}$$

Taking log on both side.

$$\log\left(\frac{A \cdot V}{\nu}\right) = \log(\text{const.})$$

$$\log A + \log V - \log \nu = 0$$

Now, Differentiating the above eq. we get,

$$\boxed{\frac{dA}{A} + \frac{dV}{V} - \frac{d\nu}{\nu} = 0} \quad \text{— ①}$$

According to S.F.E. equation.

$$Q - W = \Delta H + \Delta PE + \Delta K \cdot E$$

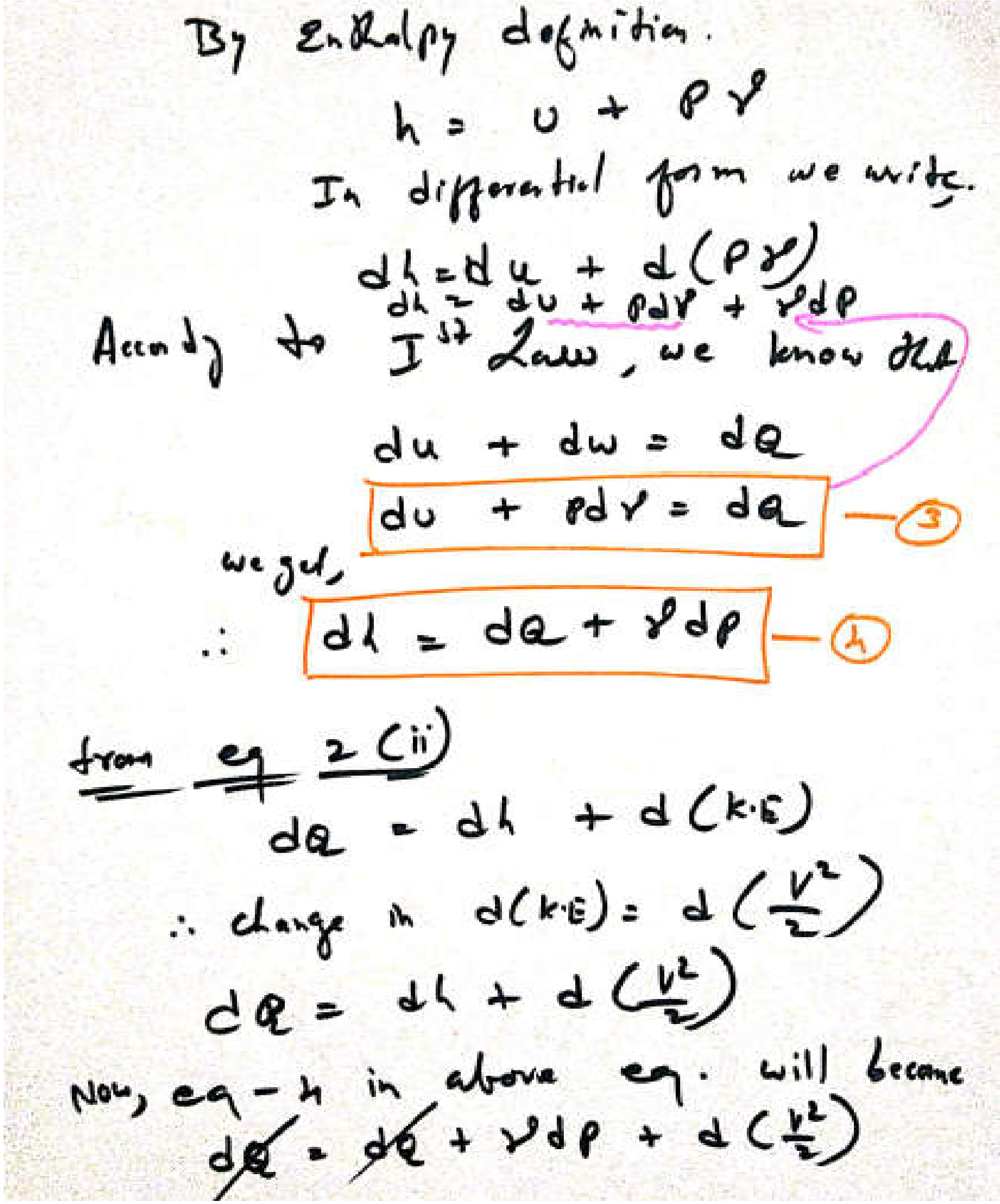
In the form of differential,

$$\boxed{dQ - dW = dh + d(PE) + d(KE)} \quad \text{— 2(i)}$$

∴ Nozzle is horizontal $d(PE) = 0$.

No work in nozzle $dW = 0$

$$\boxed{dQ - 0 = dh + 0 + d(k \cdot E)} \quad \text{— 2(ii)}$$



By Enthalpy definition.

$$h = u + Pv$$

In differential form we write.

$$dh = du + d(Pv)$$

$$dh = du + Pdv + vdp$$

According to I^{st} Law, we know that

$$du + dw = dQ$$

$$\boxed{du + Pdv = dQ} \text{ — } ③$$

we get,

$$\therefore \boxed{dh = dQ + vdp} \text{ — } ④$$

from eq 2 (ii)

$$dQ = dh + d(K.E)$$

$$\therefore \text{change in } d(K.E) = d\left(\frac{V^2}{2}\right)$$

$$dQ = dh + d\left(\frac{V^2}{2}\right)$$

Now, eq-4 in above eq. will become

$$\cancel{dQ} = \cancel{dQ} + vdp + d\left(\frac{V^2}{2}\right)$$

$$-\nu\, dp = d\left(\frac{V^2}{2}\right)$$

$$-\nu\, dp = \frac{1}{2}\, d(V^2)$$

$$-\nu\, dp = \frac{1}{\cancel{2}}\, \cancel{2} V.dV$$

$$-\nu\, dp = V dV$$

$$\boxed{dV = \frac{-\nu\, dp}{V}} \text{ — ⑤}$$

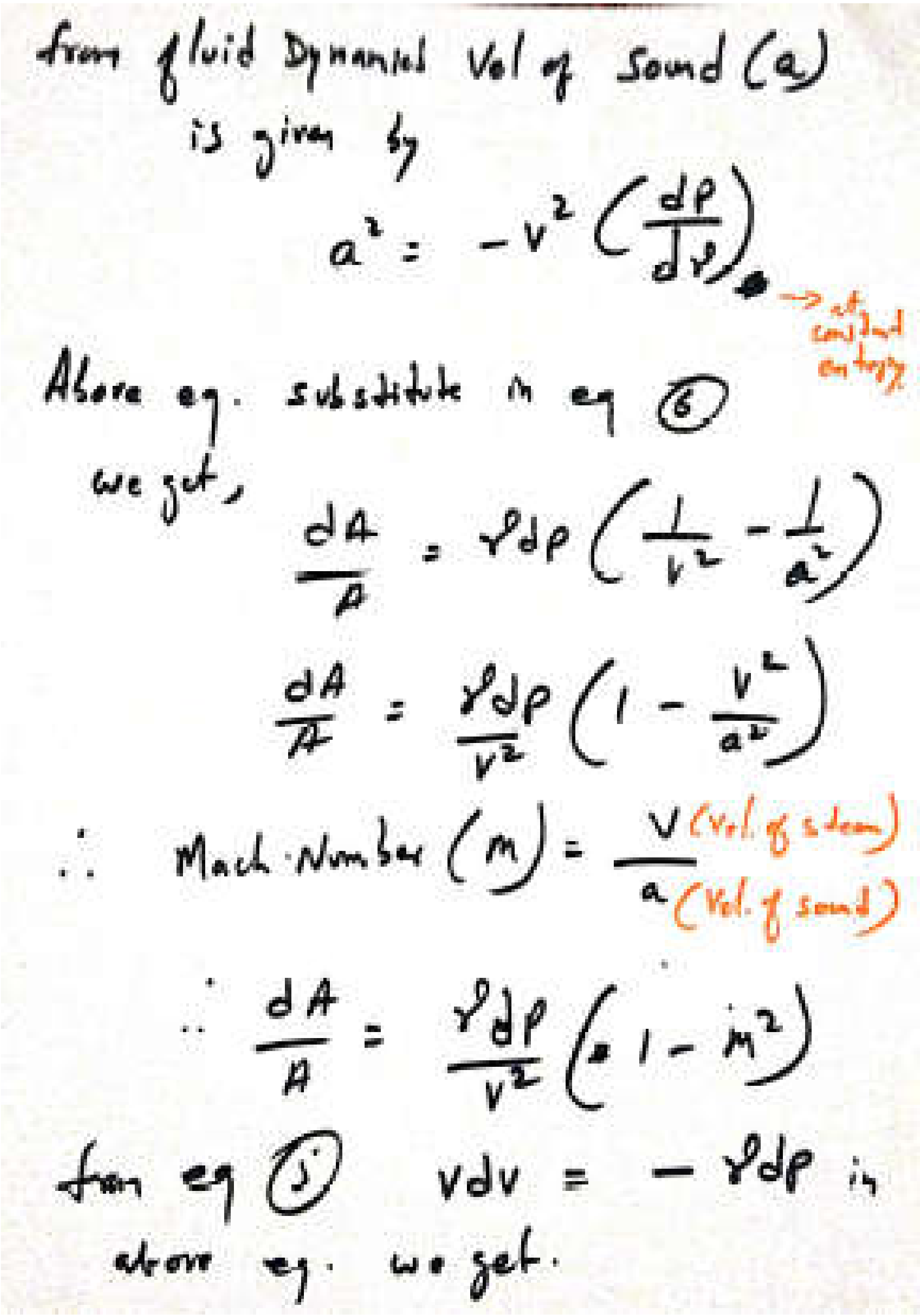
from eq ① & ⑤

$$\frac{dA}{A} + \frac{\frac{-\nu\, dp}{V}}{V} \pm \frac{d\nu}{\nu} = 0$$

$$\frac{dA}{A} - \frac{\nu\, dp}{V^2} \pm \frac{d\nu}{\nu} = 0$$

$$\frac{dA}{A} = \frac{\nu\, dp}{V^2} + \frac{d\nu}{\nu}$$

$$\boxed{\frac{dA}{A} = \nu\, dp\left(\frac{1}{V^2} + \frac{d\nu}{V^2 dp}\right)} \text{ ⑥}$$



from fluid Dynamics Vel of Sound (a) is given by

$$a^2 = -v^2\left(\frac{dp}{dv}\right)_s$$

→ at constant entropy

Above eq. substitute in eq ⑥ we get,

$$\frac{dA}{A} = v\,dp\left(\frac{1}{V^2} - \frac{1}{a^2}\right)$$

$$\frac{dA}{A} = \frac{v\,dp}{V^2}\left(1 - \frac{V^2}{a^2}\right)$$

∴ Mach Number (M) = $\frac{V \text{ (Vel. of stream)}}{a \text{ (Vel. of sound)}}$

$$\therefore \frac{dA}{A} = \frac{v\,dp}{V^2}\left(1 - M^2\right)$$

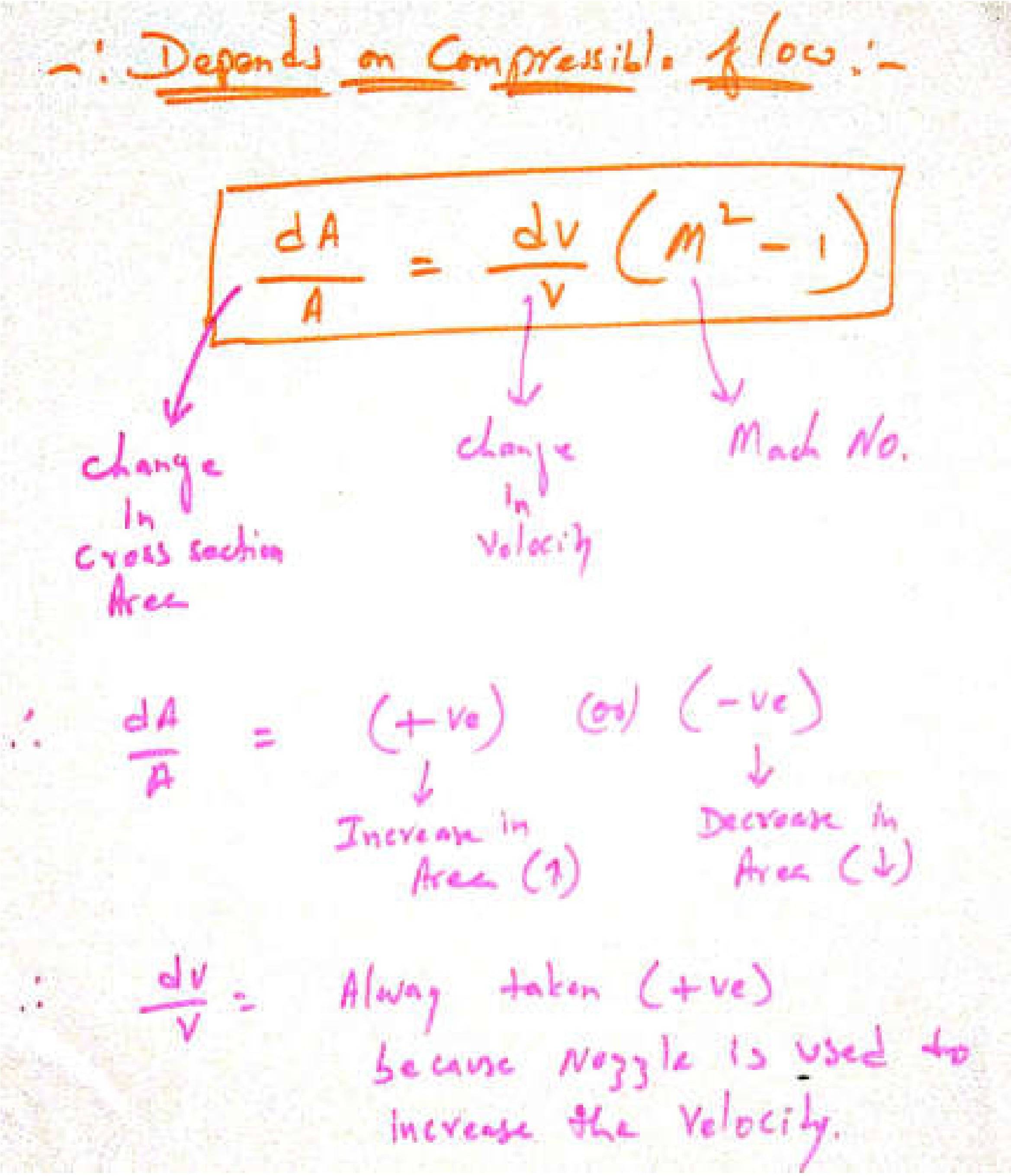
from eq ⑤ $VdV = -v\,dp$ in above eq. we get.

$$\frac{dA}{A} = \frac{-\cancel{V}dV}{\cancel{V}^2}\left(1-M^2\right)$$

$$\frac{dA}{A} = \frac{-dV}{V}\left(1-M^2\right)$$

$$\therefore \underline{\underline{\boxed{\frac{dA}{A} = \frac{dV}{V}\left(M^2-1\right)}}}$$

∴ The above eq. is used to find the type of Nozzle.



-: Depends on Compressible flow :-

$$\boxed{\frac{dA}{A} = \frac{dv}{v}\left(M^2 - 1\right)}$$

$\downarrow$ change in cross section Area

$\downarrow$ change in velocity

$\downarrow$ Mach No.

$$\therefore \frac{dA}{A} = (+ve) \text{ (or) } (-ve)$$

(+ve) ↓ Increase in Area (↑)

(−ve) ↓ Decrease in Area (↓)

$\therefore \frac{dv}{v} =$ Always taken (+ve) because Nozzle is used to increase the velocity.

Case (i) Subsonic flow $(M < 1)$

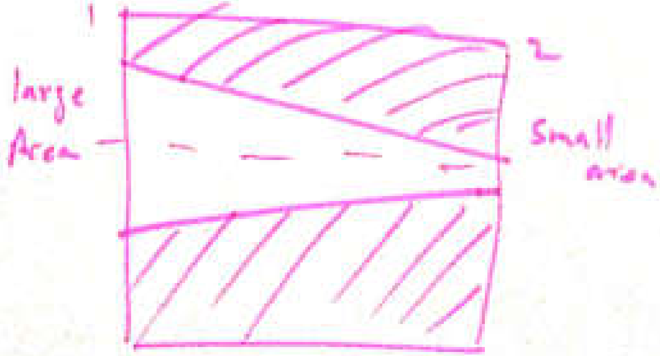
Vel. of steam < Vel. of sound.

$\therefore$ Mach Number is "-ve"

$$\therefore \frac{dA}{A} = \frac{\overset{\text{"+ve"}}{dV}}{V}\left(\overset{\text{"-ve"}}{M^2 - 1}\right)$$

$$\frac{dA}{A} = -ve \;(\therefore \text{Area is decreasing} \downarrow)$$

$$\therefore -dA = \text{Small Area} - \text{large Area.}$$



$\therefore$ It is Convergent Nozzle.

Case (ii) Super sonic $(M > 1)$

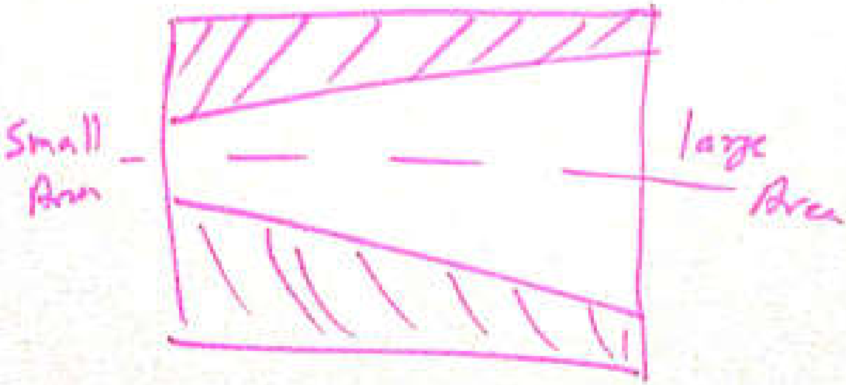
Vel. of steam > Vel. of sound.

∴ Mach Number is "+ve"

$$\therefore \frac{dA}{A} = \frac{\overset{+ve}{dv\downarrow}}{V}\left(\overset{(+ve)}{\checkmark M^2} - 1\right)$$

$$\frac{dA}{A} = +ve \quad (\therefore \text{Area is increasing})$$

∴ dA = large Area − Small Area.



∴ It is Divergent Nozzle.

case(iii) Sonic flow ($M = 1$)

∴ Vel. of stream = Vel. of sound.

∴ Mach Number is 'Same"

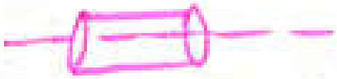
$$\therefore \frac{dA}{A} = \frac{dV}{V}(M^2 - 1)$$

$$= \frac{dV}{V}(1^2 - 1)$$

$$= \frac{dV}{V}(0)$$

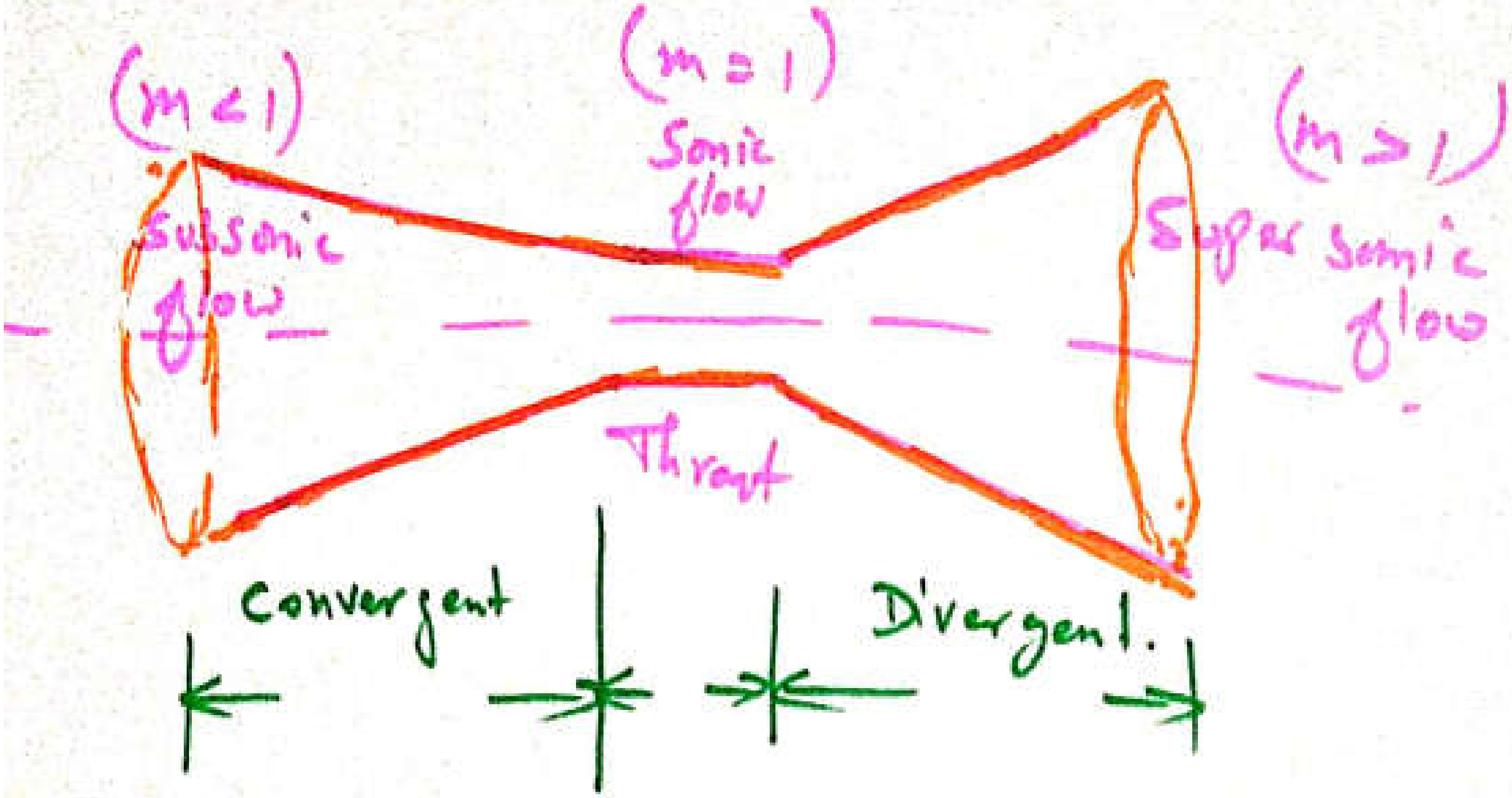
$$\therefore \frac{dA}{A} = 0$$ (∴ Area(A) = Constant)

$dA = 0$ (∴ No change in Area)



∴ It is called as a 'Pipe";

If we combine the, Convergent, Divergent pipe.



Mass of Steam Discharge Through a Nozzle

PDF:

3. Module- 3-II.pdf

Thermal Engineering-II
MODULE-4

Introduction

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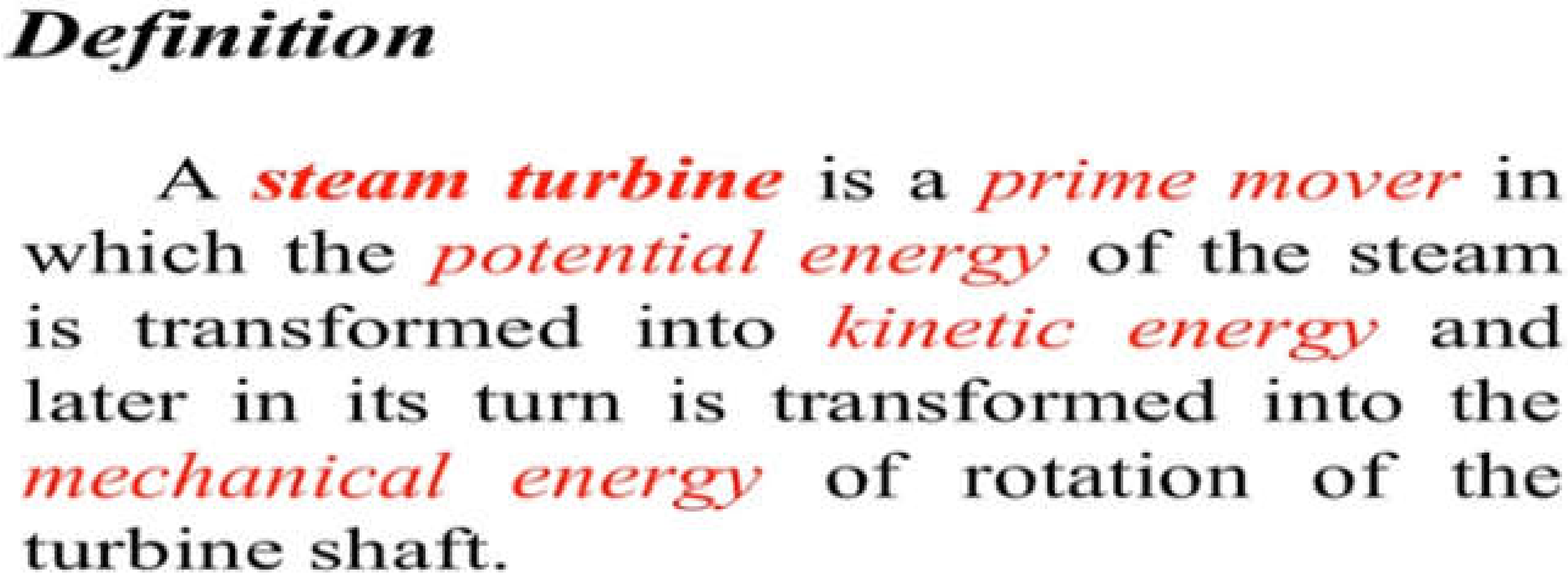
Department of Mechanical Engineering

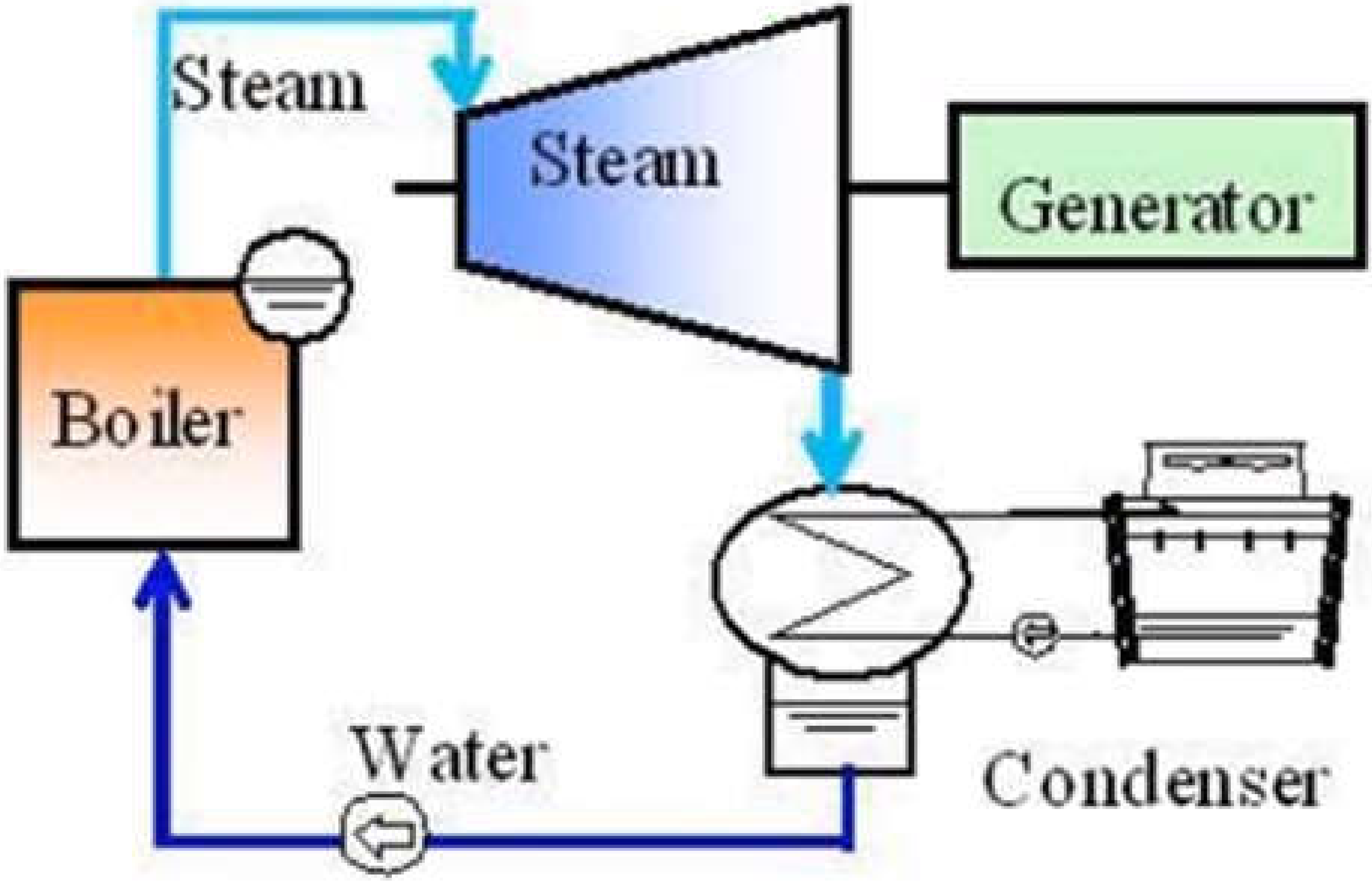
Steam Turbine

Steam Turbine

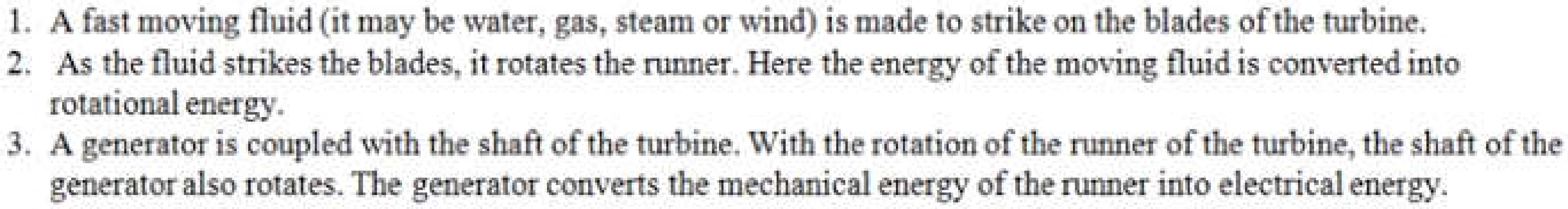


Definition

A ***steam turbine*** is a *prime mover* in which the *potential energy* of the steam is transformed into *kinetic energy* and later in its turn is transformed into the *mechanical energy* of rotation of the turbine shaft.


Steam
Steam
Generator
Boiler
Water
Condenser

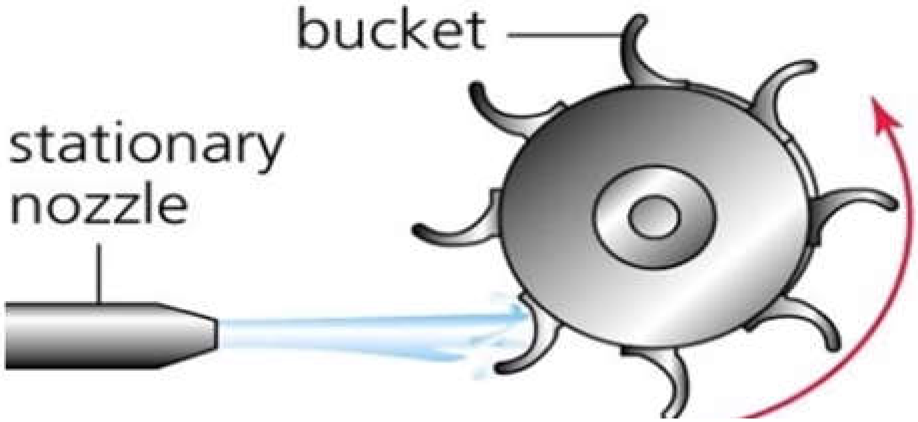
Working Principle of Turbine



1. A fast moving fluid (it may be water, gas, steam or wind) is made to strike on the blades of the turbine.
2. As the fluid strikes the blades, it rotates the runner. Here the energy of the moving fluid is converted into rotational energy.
3. A generator is coupled with the shaft of the turbine. With the rotation of the runner of the turbine, the shaft of the generator also rotates. The generator converts the mechanical energy of the runner into electrical energy.

Main Parts of the Impulse Turbine

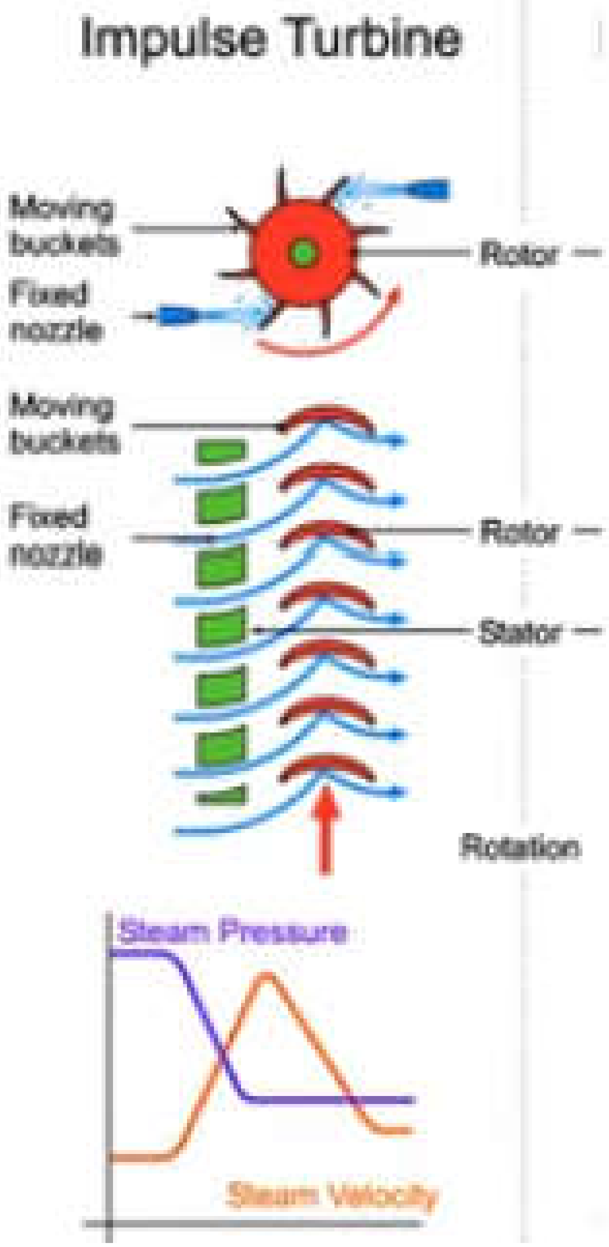
1. Nozzle: It guides the steam to flow in designed direction and velocity.
2. Runner: it is the rotating part of the turbine and blades are attached to the runner.
3. Blades: It is that part of the turbine on which the fast moving fluid strikes and rotates the runner.
4. Casing: It is the outer air tight covering of the turbine which contains the runner and blades. It protects the internal parts of the turbine.



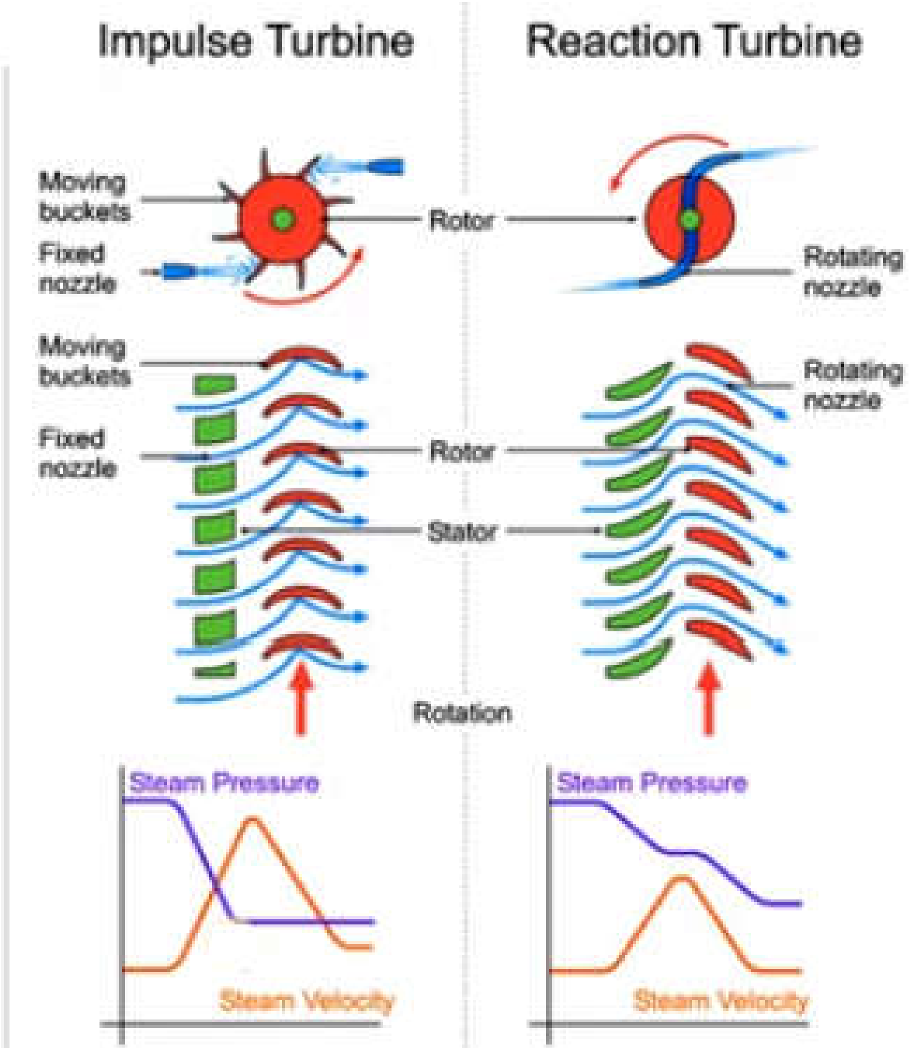
Classification of Steam Turbines

According to the action of steam:

- **Impulse turbine:** In impulse turbine, steam coming out through a fixed nozzle at a very high velocity strikes the blades mounted on the periphery of a rotor.
- So energy at inlet of turbine is only K.E.
- The moving blades change the direction of steam flow without changing its pressure.
- Ex: De-Laval, Curtis and Rateau Turbines

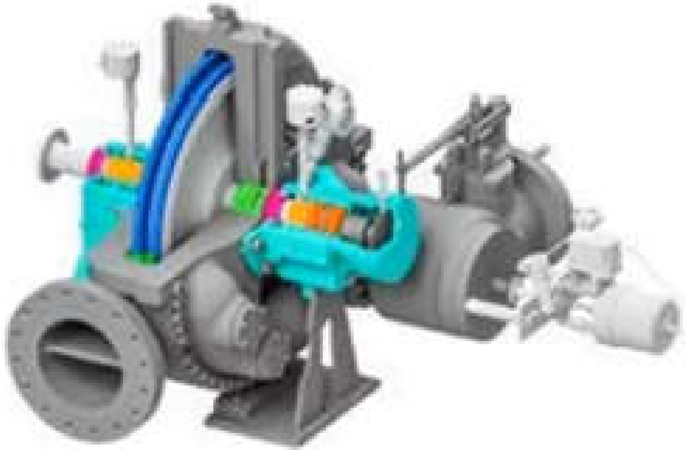


- **Reaction turbine:** In reaction turbine, steam expands both in fixed and moving blades continuously as the steam passes over them.
- The pressure drop occurs continuously over both moving and fixed blades.
- Energy at inlet of turbine is K.E. and Pressure energy (P.E.)
- Ex: Parson's Turbine



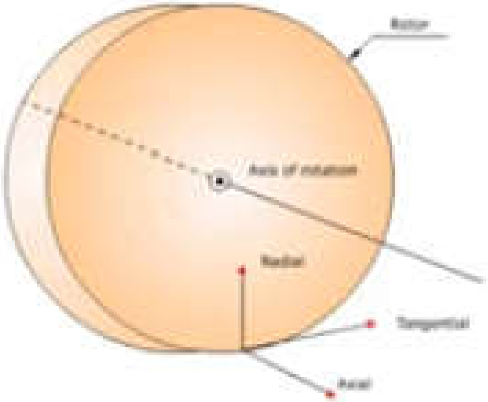
According to the number of pressure stages:

- **Single stage turbines:** These turbines are mostly used for driving centrifugal compressors, blowers and other similar machinery.
- **Multistage Impulse and Reaction turbines:** They are made in a wide range of power capacities varying from small to large.



According to the type of steam flow:

- **Axial flow turbines:** In these turbines, steam flows in a direction parallel to the axis of the turbine rotor.
- **Radial flow turbines:** In these turbines, steam flows in a direction perpendicular to the axis of the turbine rotor.
- **Tangential flow turbines:** In these turbines, steam flows in a tangential direction.



According to the inlet steam pressure:

- **Low pressure turbines:** These turbines use steam at a pressure of 1.2 bar to 2 bar
- **Medium pressure turbines:** These turbines use steam up to a pressure of 40 bar.
- **High pressure turbines:** These turbines use steam at a pressure above 40 to 170 bar.
- **Very high pressure turbines:** These turbines use steam at a pressure of 170 bar and higher and temperatures of 550^0C and higher.
- **Supercritical pressure turbines:** These turbines use steam at a pressure of 225 bar and higher.

According to their usage in industry:

- **Stationary turbines with constant speed of rotation:** These turbines are primarily used for driving alternators.
- **Stationary turbines with variable speed of rotation:** These turbines are meant for driving turbo-blowers, air circulators, pumps, etc.
- **Mobile turbines with variable speed:** These turbines are usually employed

in steamers, ships and railway locomotives.

According to the number of shafts:

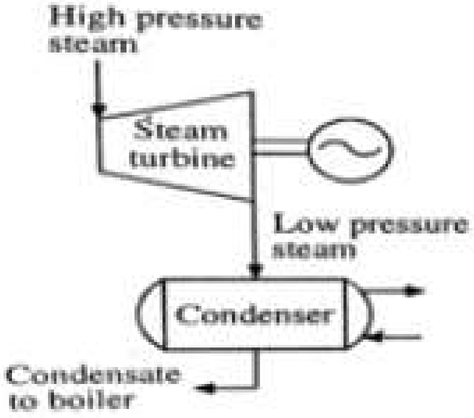
- Single shaft turbines
- Multi-shaft turbines

According to the method of governing:

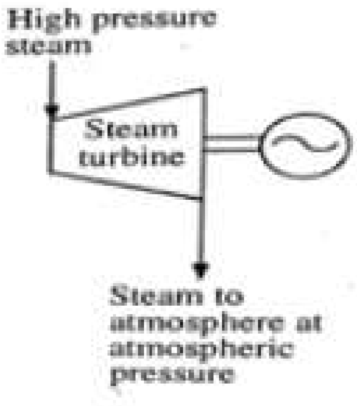
- Turbines with throttle governing
- Turbines with nozzle governing
- Turbines with by-pass governing

According to the heat drop process:

1.Condensing and non condensing turbines :

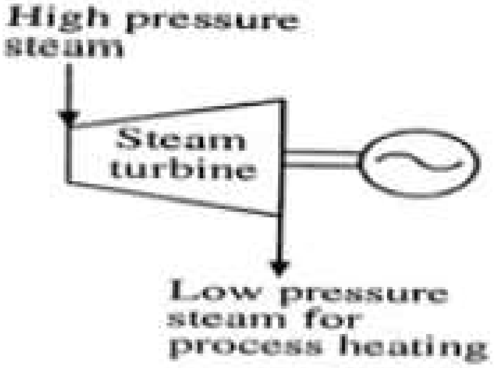


Condensing turbine



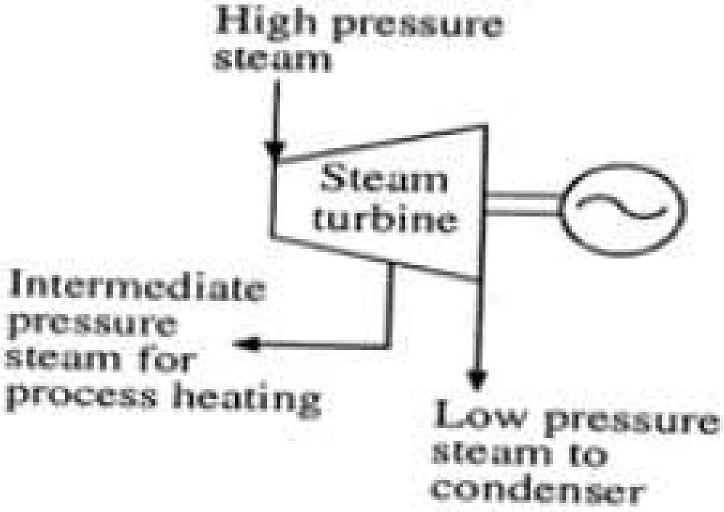
Non-Condensing turbine

2. Back pressure or topping turbine:

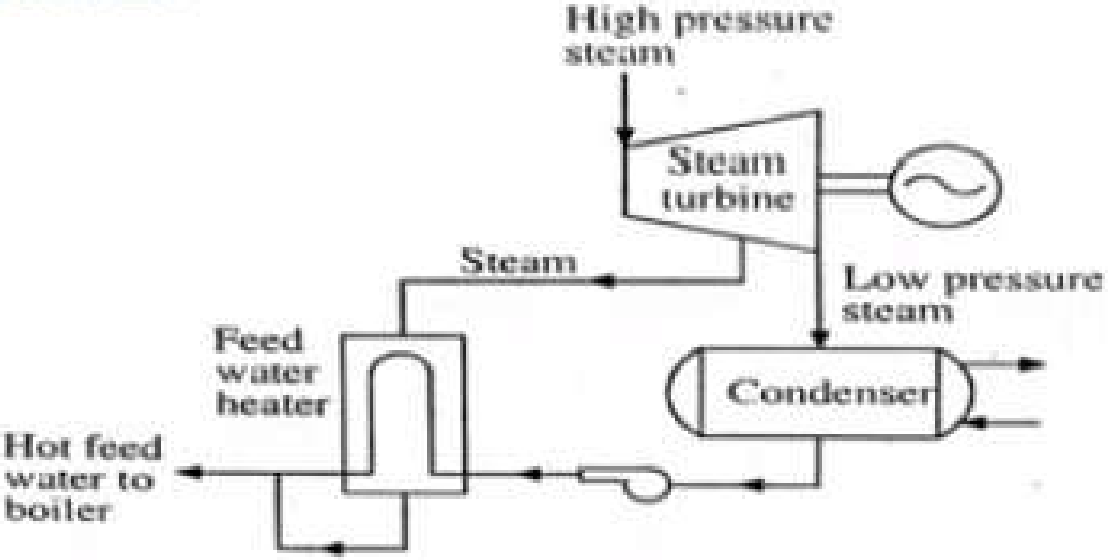


Back pressure turbine

3.Pass-out Turbine:



4.Regenerative Turbine:



COMPARISION BETWEEN IMPULSE AND REACTION TURBINE

S.No.	Impulse Turbine	Reaction Turbine
1	It consists of nozzles and moving blades	It consists of fixed blades which act as nozzles and moving blades
2	Steam is expanded completely in the nozzle. All the pressure energy is converted into kinetic energy	Steam is partially expanded in the fixed blades. Some amount of pressure energy is converted into kinetic energy
3	Pressure of steam is constant over the moving blades.	Pressure drop takes place in the moving blades.
4.	Because of high pressure drop in the nozzles, blade speed and steam speed are high.	Because of small pressure drop, blade speed and steam speed are less.
5.	Low Efficiency	High Efficiency
6.	Occupies less space per unit power	Occupies more space per unit power.

Merits and Demerits of Steam Turbine

Merits:

- Ability to utilize high pressure and high temperature steam.
- High component efficiency.
- High rotational speed.
- High capacity/weight ratio.
- Smooth, nearly vibration-free operation.
- No internal lubrication.
- Oil free exhaust steam.
- Can be built in small or very large units (up to 1200 MW).

Demerits:

- For slow speed application reduction gears are required.
- The steam turbine cannot be made reversible.
- The efficiency of small simple steam turbines is poor

Application

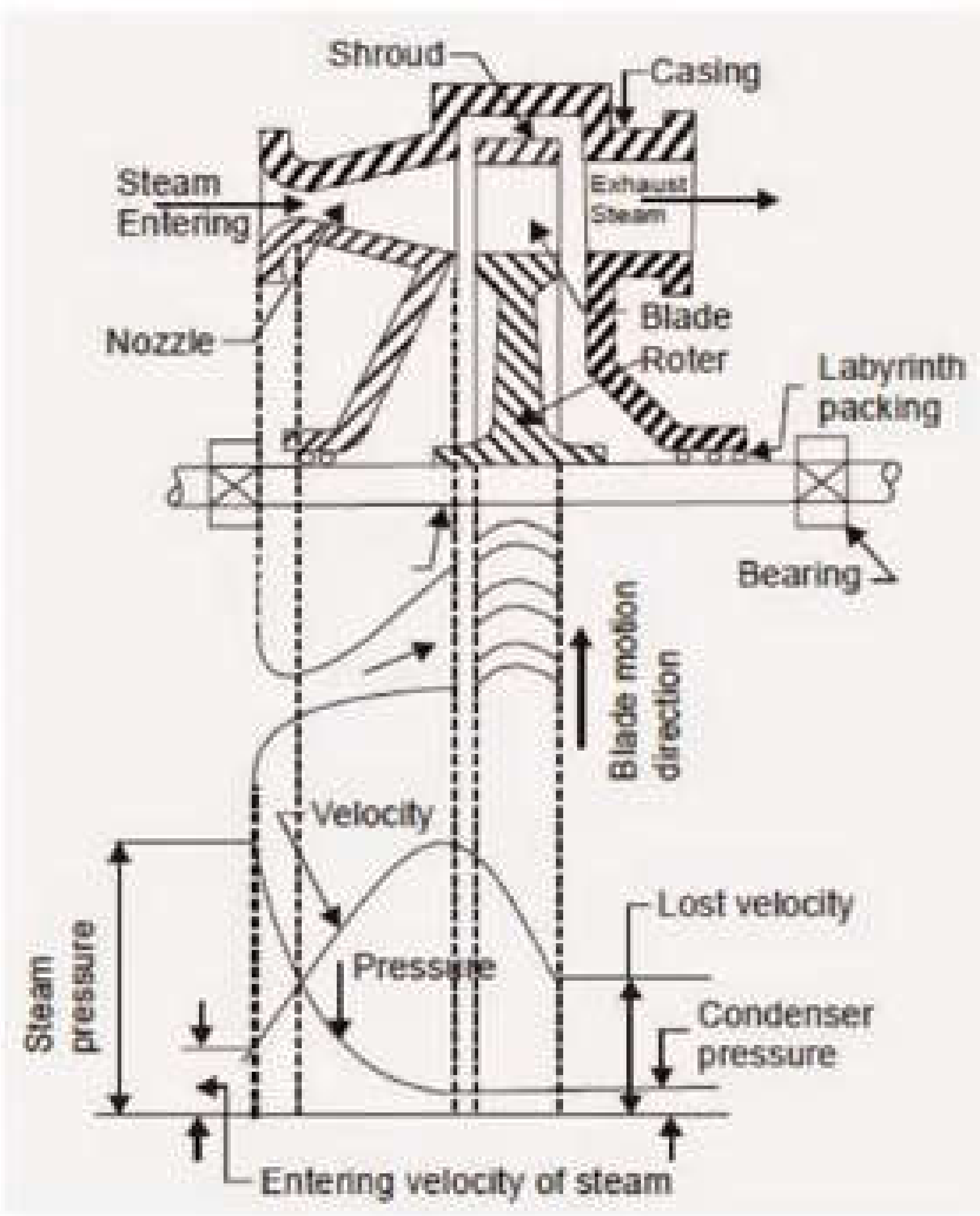
- Power generation
- Refinery, Petrochemical,
- Pharmaceuticals,
- Food processing,
- Petroleum/Gas processing,
- Pulp & Paper mills,
- Waste-to-energy

Turbine Selection

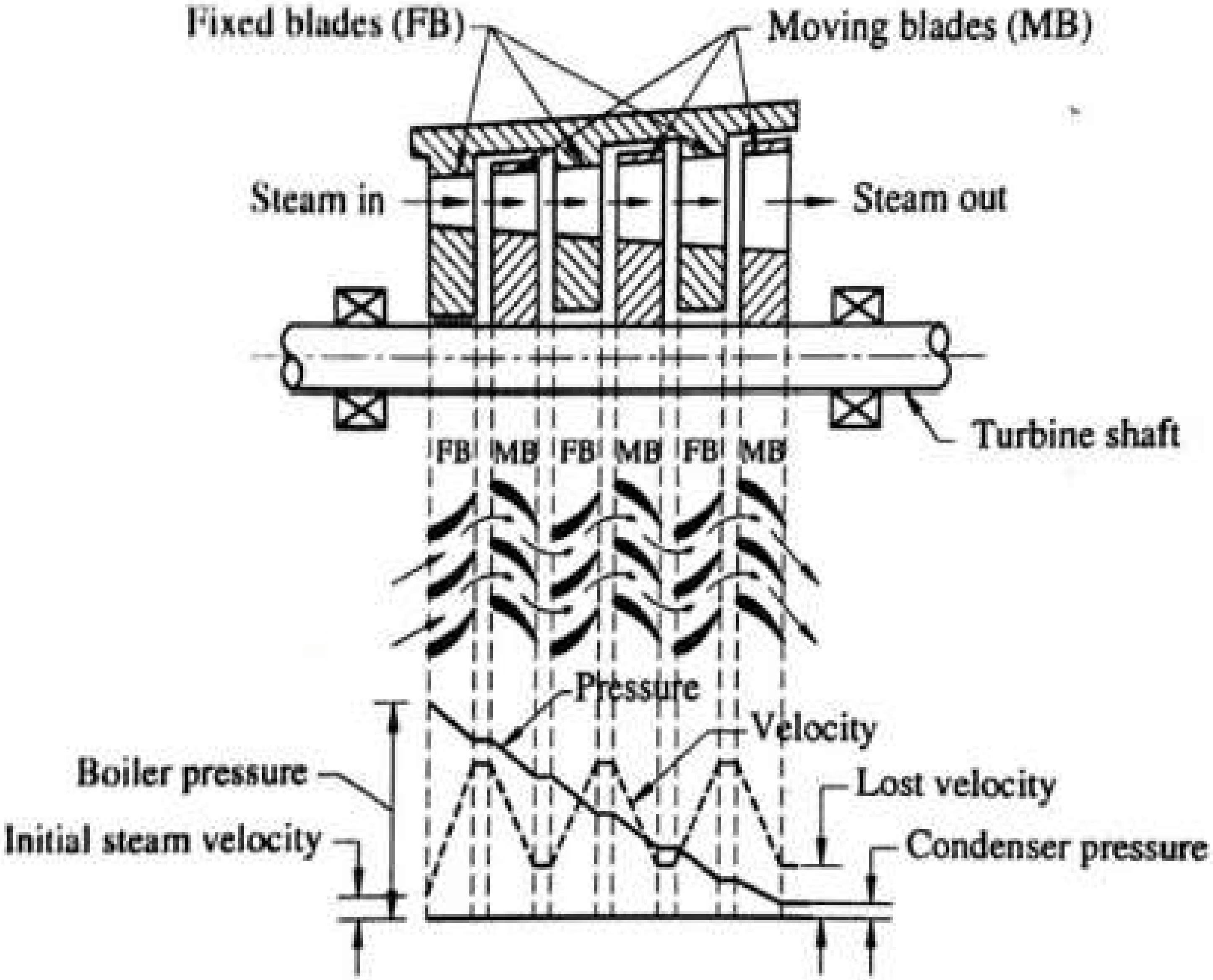
In all fields of application the competitiveness of a turbine is a combination of several factors:

- Efficiency
- Life
- Power density (power to weight ratio)
- Direct operation cost
- Manufacturing and maintenance costs

Impulse Turbine Pr. & Vel. Variation



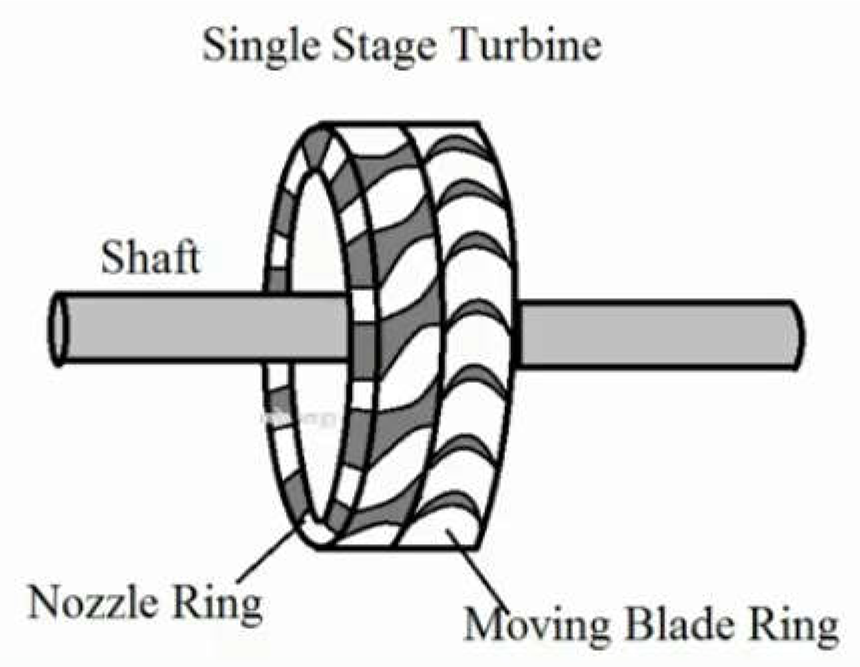
Reaction Turbine Pr. & Vel. Variations



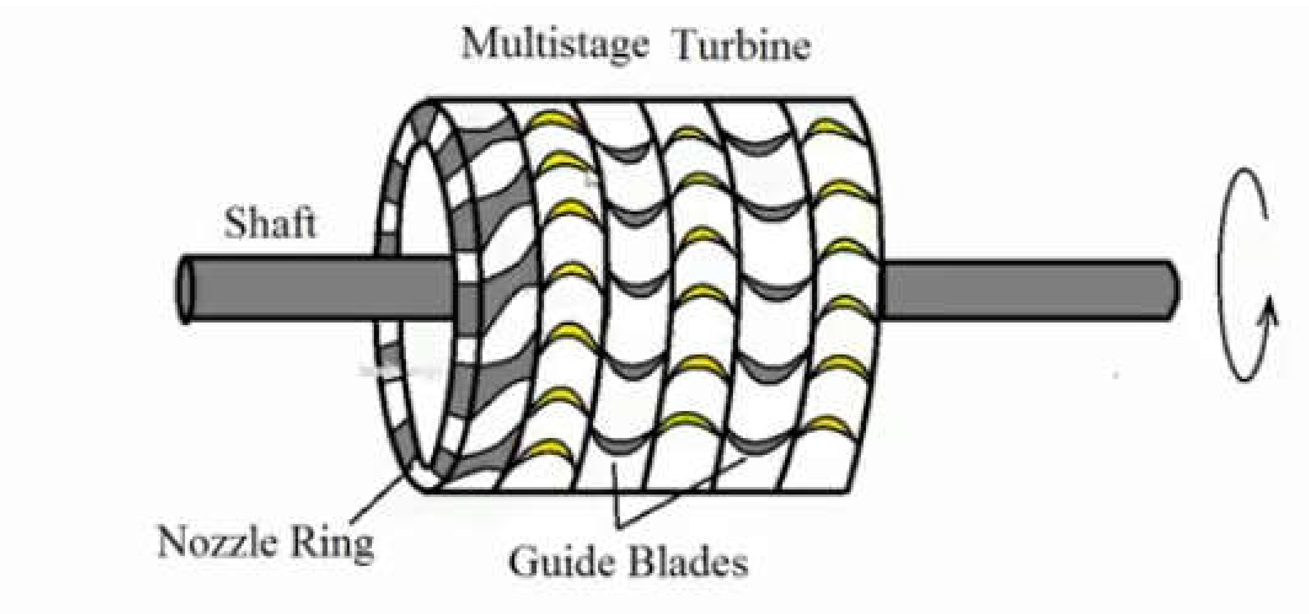
Compounding of Steam Turbine

OR

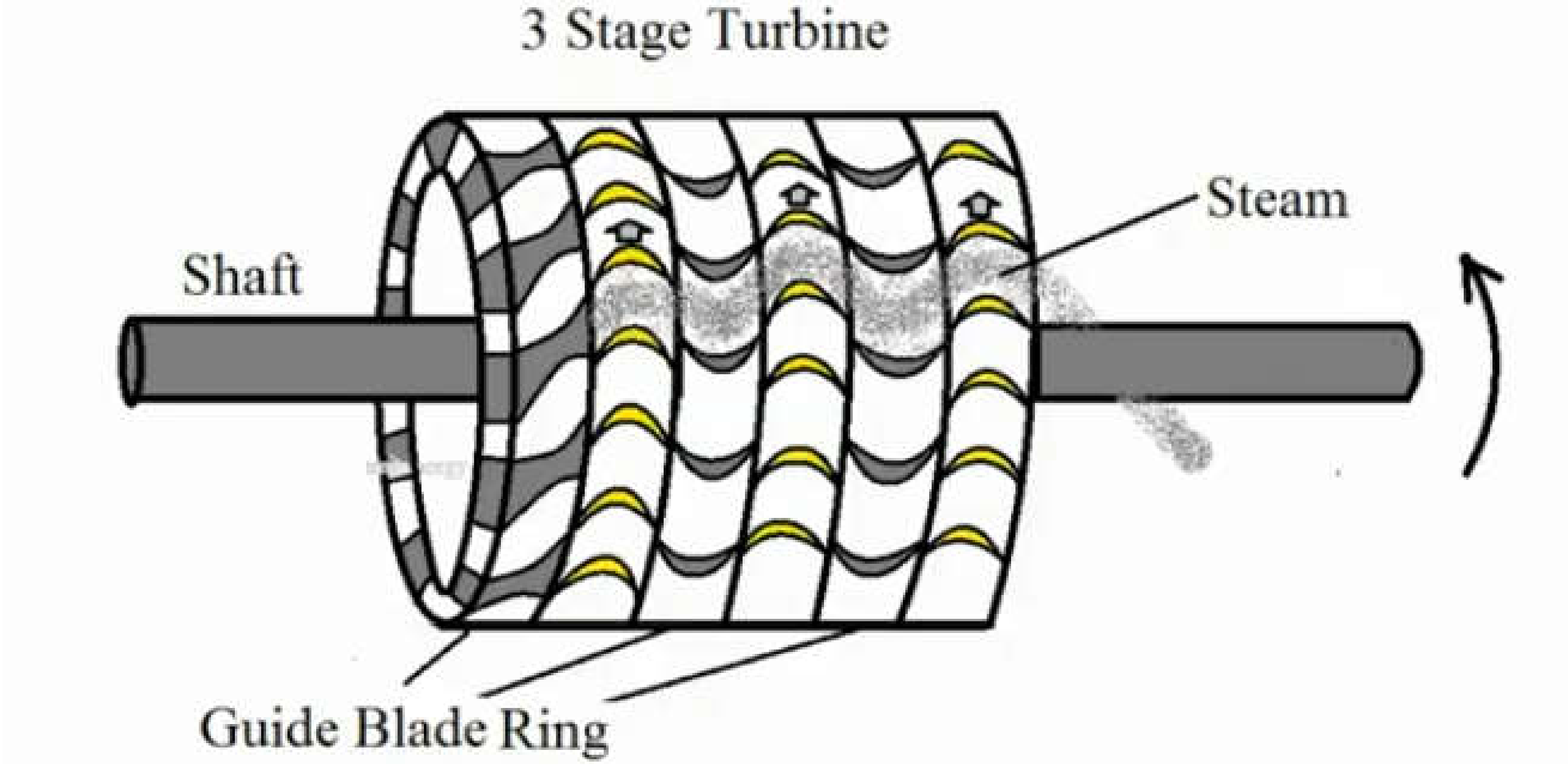
Staging of Steam Turbine

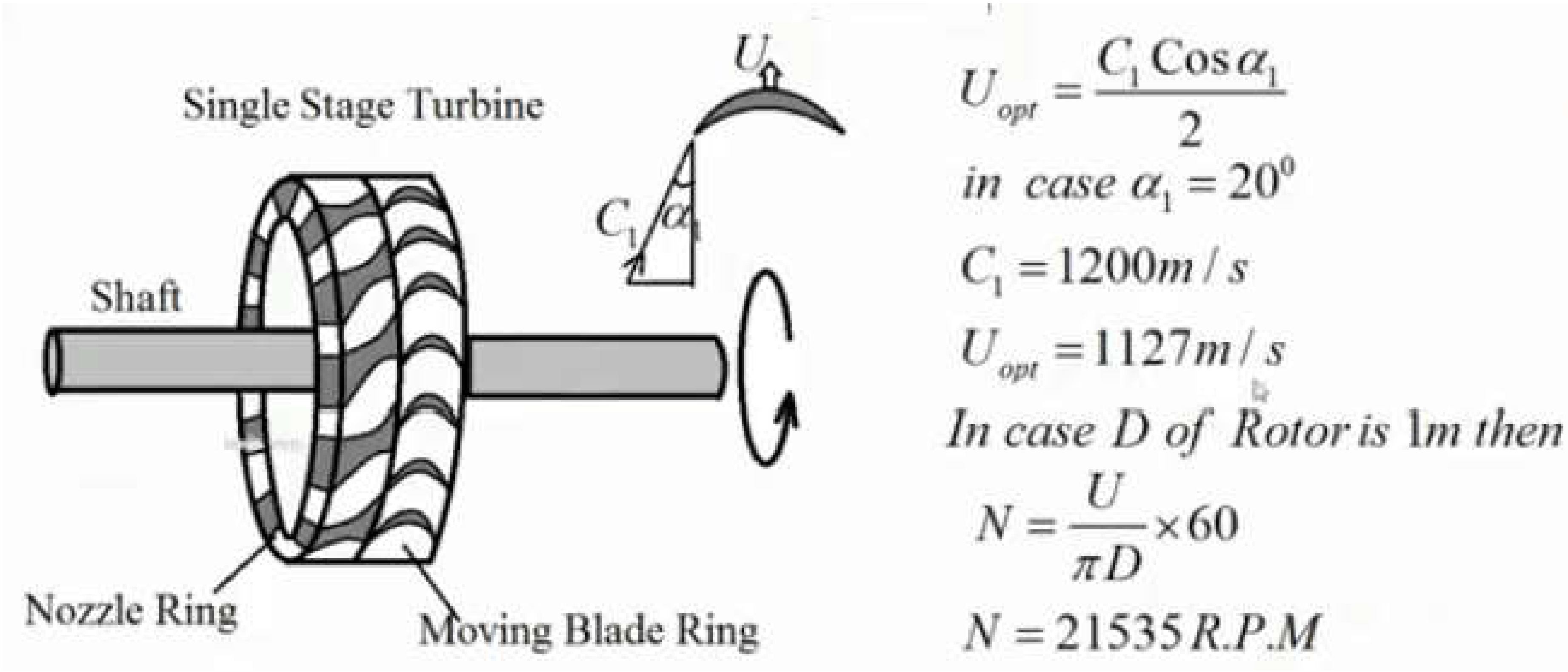


Single Stage Turbine



Multistage Turbine


3 Stage Turbine
Steam
Shaft
Guide Blade Ring



$$U_{opt} = \frac{C_1 \operatorname{Cos} \alpha_1}{2}$$

$$in\ \ case\ \alpha_1 = 20^0$$

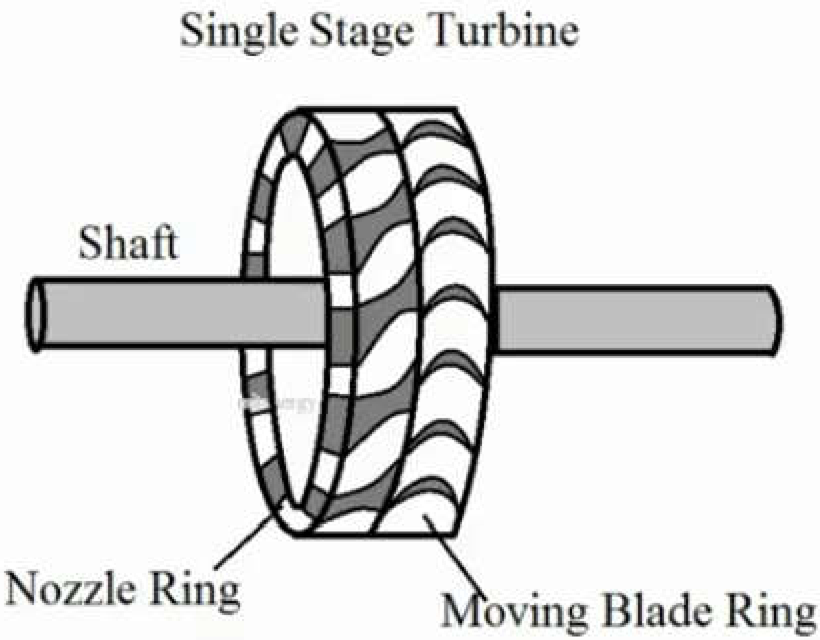
$$C_1 = 1200 m / s$$

$$U_{opt} = 1127 m / s$$

In case D of Rotor is 1m then

$$N = \frac{U}{\pi D} \times 60$$

$$N = 21535\, R.P.M$$



Problem

Without Losing power,RPM to be controlled.

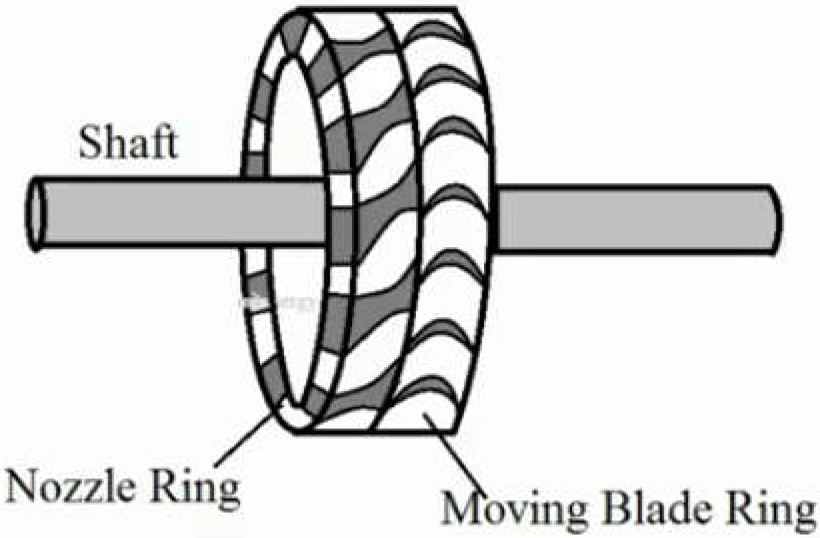
Solution

1) Increase the Rotor Diameter
2) Use Gear Box
3) Do Not Run Blade with optimum Speed
4) Multistaging

- In a steam turbine (impulse) , high velocity of steam is allowed to flow through **one row** of moving blades, it produces a rotor speed of about **30000 rpm** which is too high for practical use. **Generator Speed : 3600 rpm for 60Hz; 3000 rpm for 50Hz.**
- Not only this the leaving losses are also very high.
- These difficulties can be reduced by **use of more than one set of nozzles**, blades and rotors, in a series, keyed to a common shaft so that either the steam pressure or the jet velocity is absorbed by the turbine in stages. This is called **compounding or staging of turbines.**

- Compounding is a method for reducing the rotational speed of the impulse turbine to practical limits.

Single Stage Turbine



Problem

Without Losing power,RPM to be controlled.

Solution

1) Increase the Rotor Diameter

2) Use Gear Box

3) Do Not Run Blade with optimum Speed

4) Multistaging

- The high rotational speed of the turbine can be reduced by the following methods of compounding:
  1) Velocity compounding
  2) Pressure compounding, and
  3) Pressure-Velocity compounding

Velocity Compounding Variations

In velocity compounded impulse turbine, the pressure drop is in one row of nozzles like that in simple impulse turbine

but the resulting kinetic energy is absorbed by the rotor in a number of rows of moving blades with a ring of fixed blades in between two rows of moving blades.

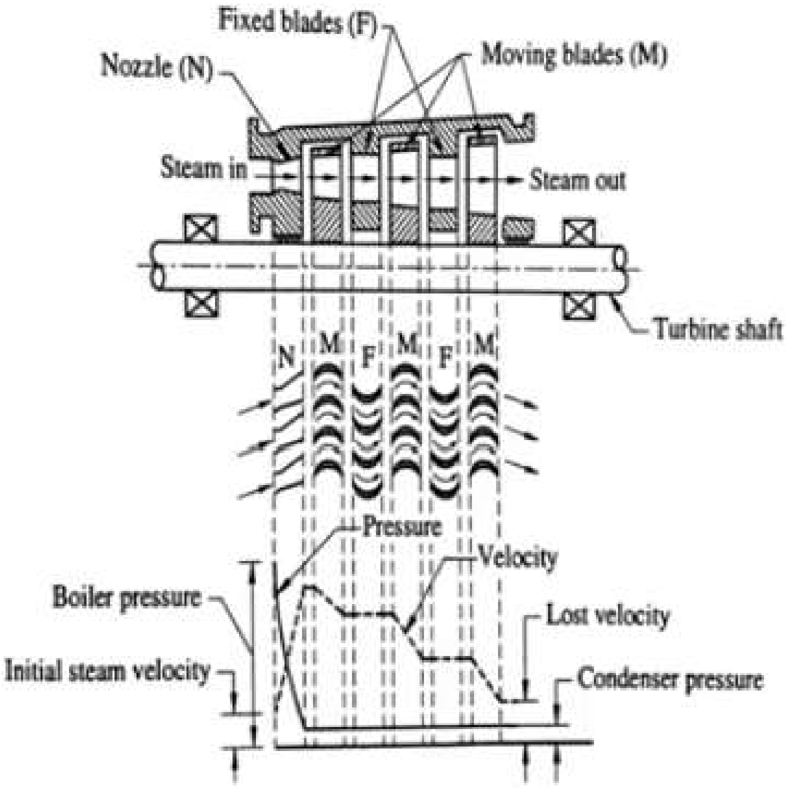
The fixed blades are mounted on the casing, while the moving blades are keyed in series on a common shaft.

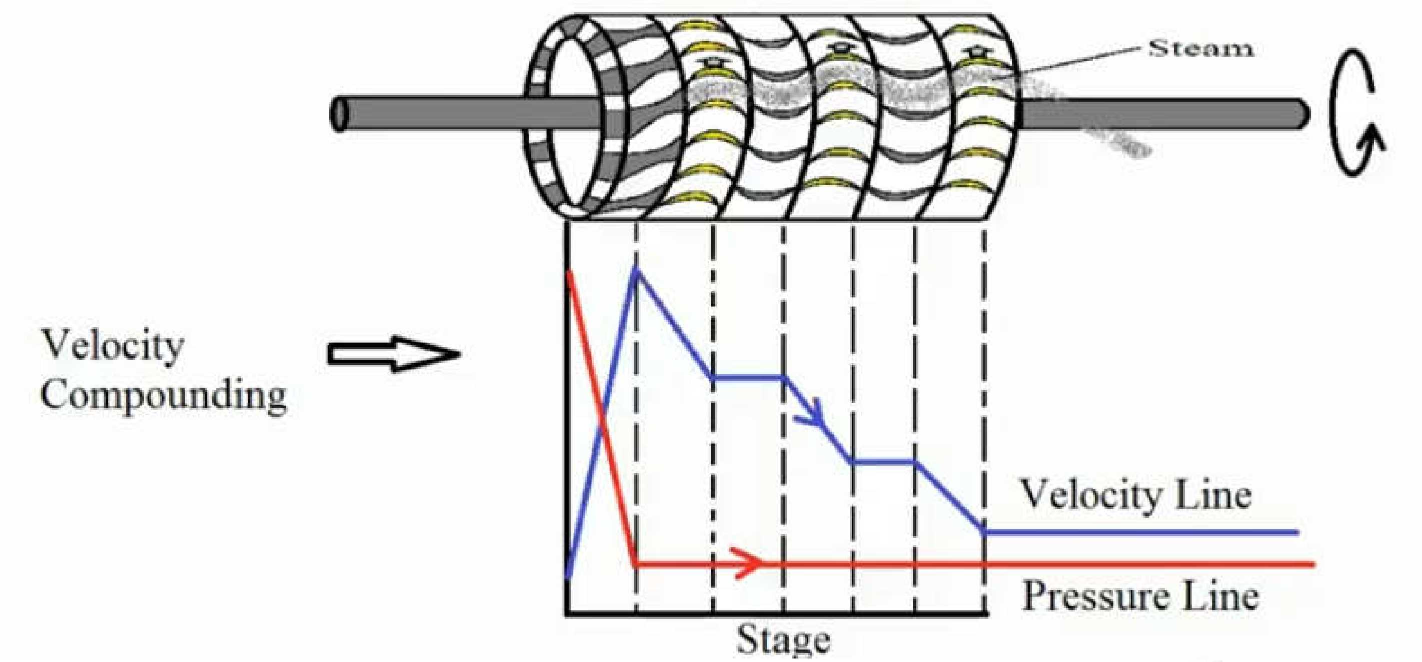
The function of the fixed blades is to correct the direction of entry of steam to the next row of moving blades.

The high velocity steam leaving the nozzles passes on to the first row of moving blades where it suffers a partial velocity drop as shown in Fig.

The direction of steam is then corrected by the next row of fixed blades and then it enters the second row of moving blades.

Here the steam velocity is again partially reduced. Since only part of the velocity of the steam is used up in each row of the moving blades, a slower turbine results.





Advantages :

(1) It requires less number of stages and less space.

(2) The pressure drop takes place in nozzles, hence turbine casing has to withstand low pressure.

(3) It's initial cost is low.

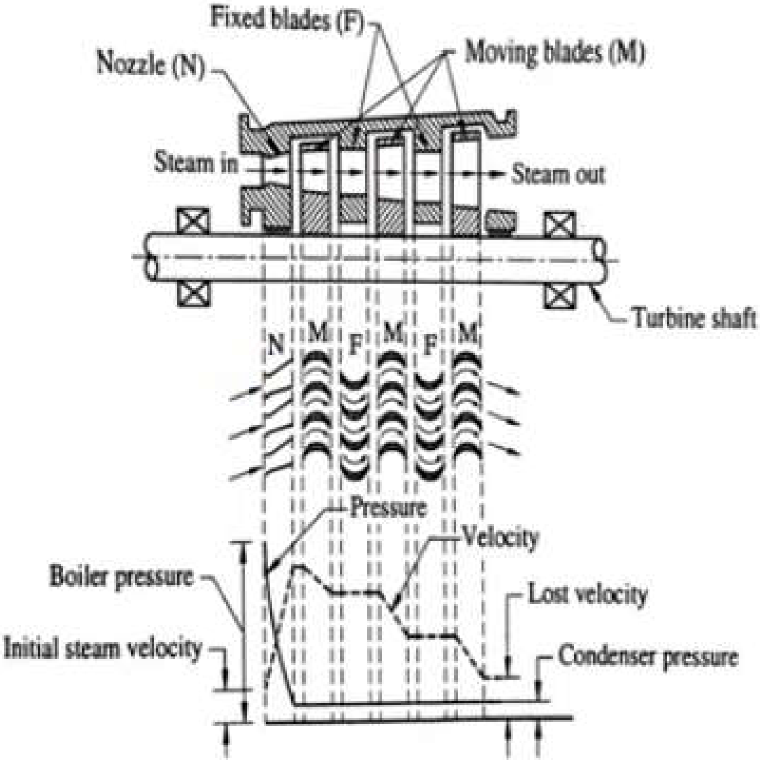
(4) Its stalling is easier.

Disadvantages :

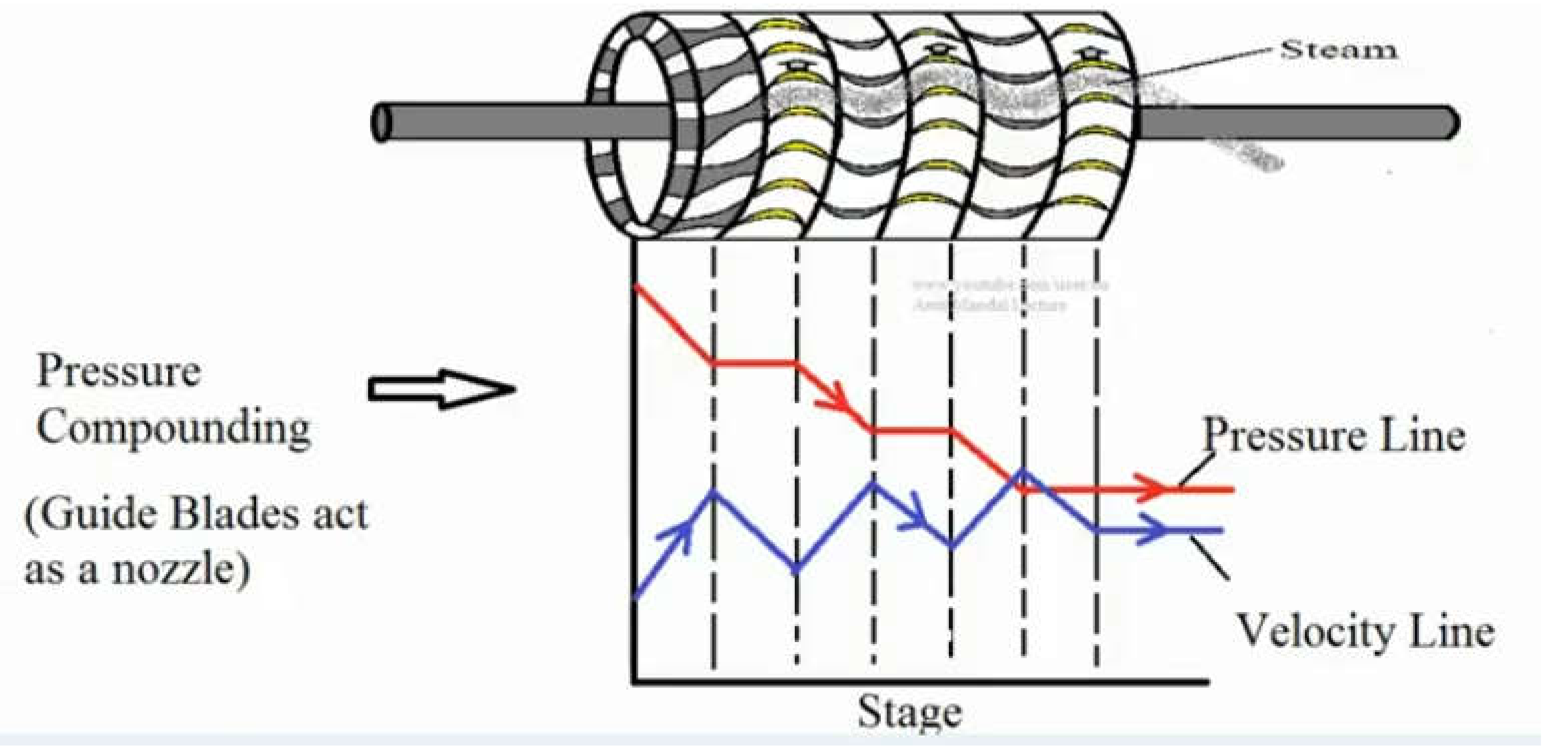
(1) Due to high velocity of steam friction losses are more.

(2) (2) Its efficiency is low and keeps on decreasing with number of stages.

(3) Blade velocity to steam velocity ratio is not optimum for all the rows.



Pressure Compounding Variations



In this type of turbine, the total pressure drop (steam generator pressure to condenser pressure) is divided into number of stages.

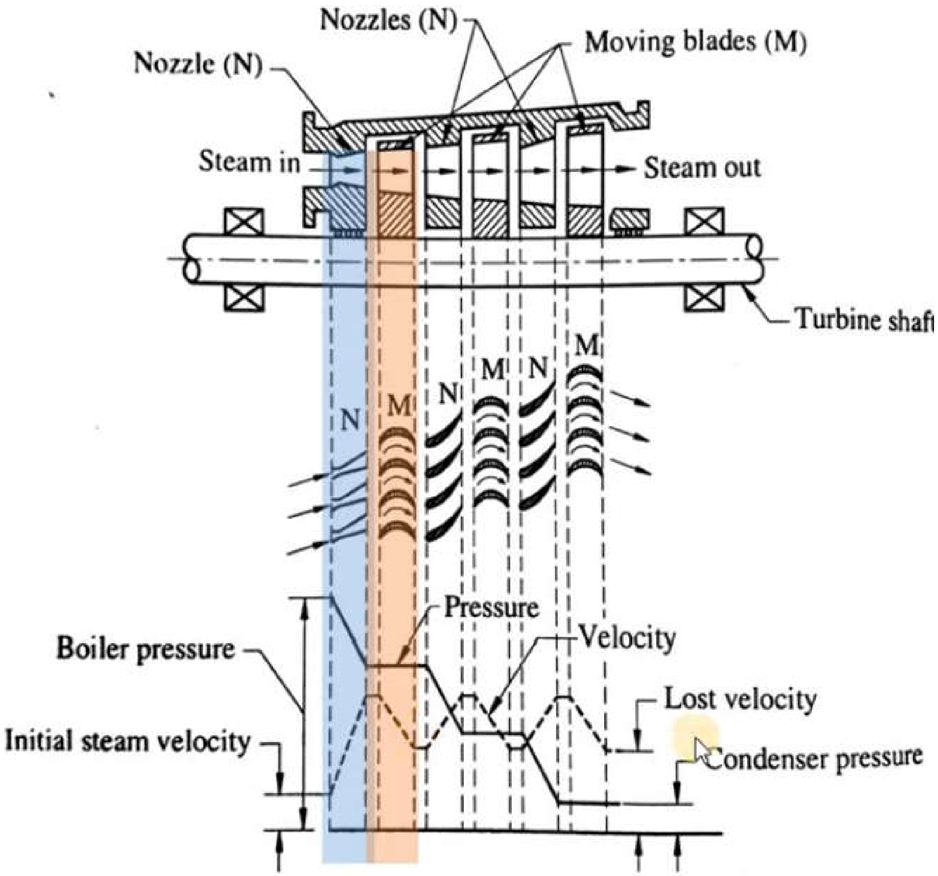
Each turbine stage is provided with one raw of **fixed blades which work** as nozzles followed by a **row of moving blades** as shown in Fig

Steam enters the **first row of nozzles** where it suffers a **partial drop of pressure** and in result of that its **velocity increases.**

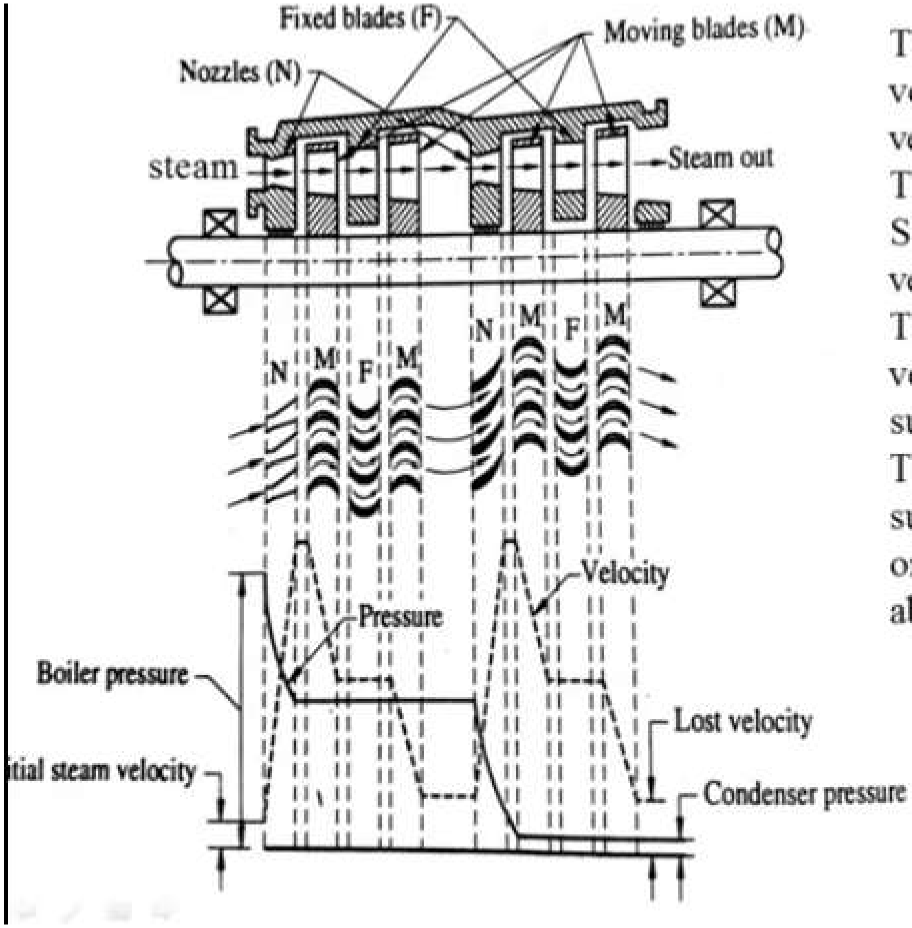
The high velocity steam passes on to the first raw of **moving blades** where its velocity is reduced as shown in Fig.

The steam then passes into the second row of nozzles where its pressure is again partially reduced and velocity is again increased.

This high velocity steam passes from the nozzles to the second row of moving blades where its velocity is again reduced.



Pressure & Velocity Compounding



To take advantage of both pressure compounding and velocity compounding, a combination of pressure and velocity compounding is used.

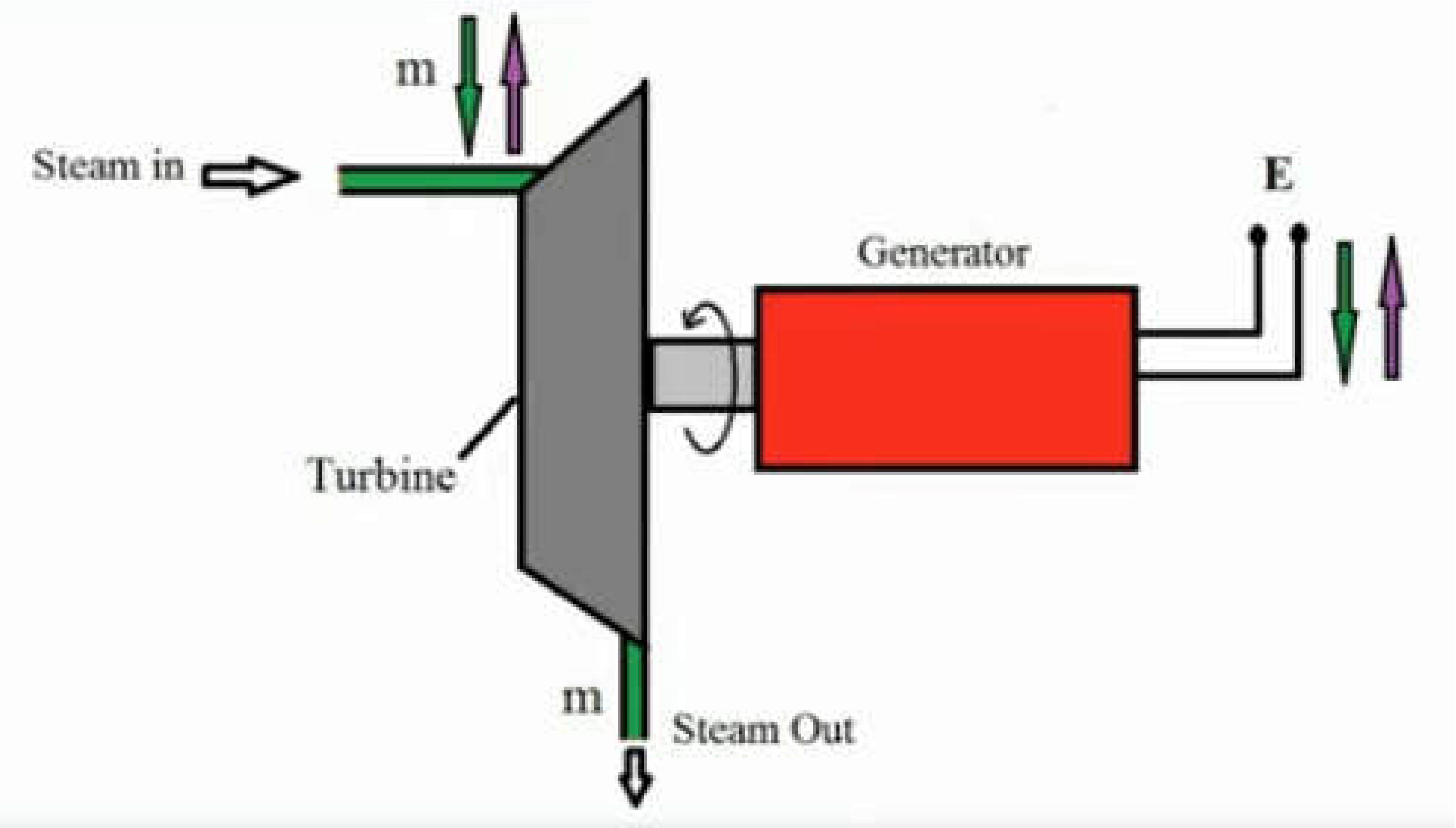
The arrangement of this turbine is shown in Fig.

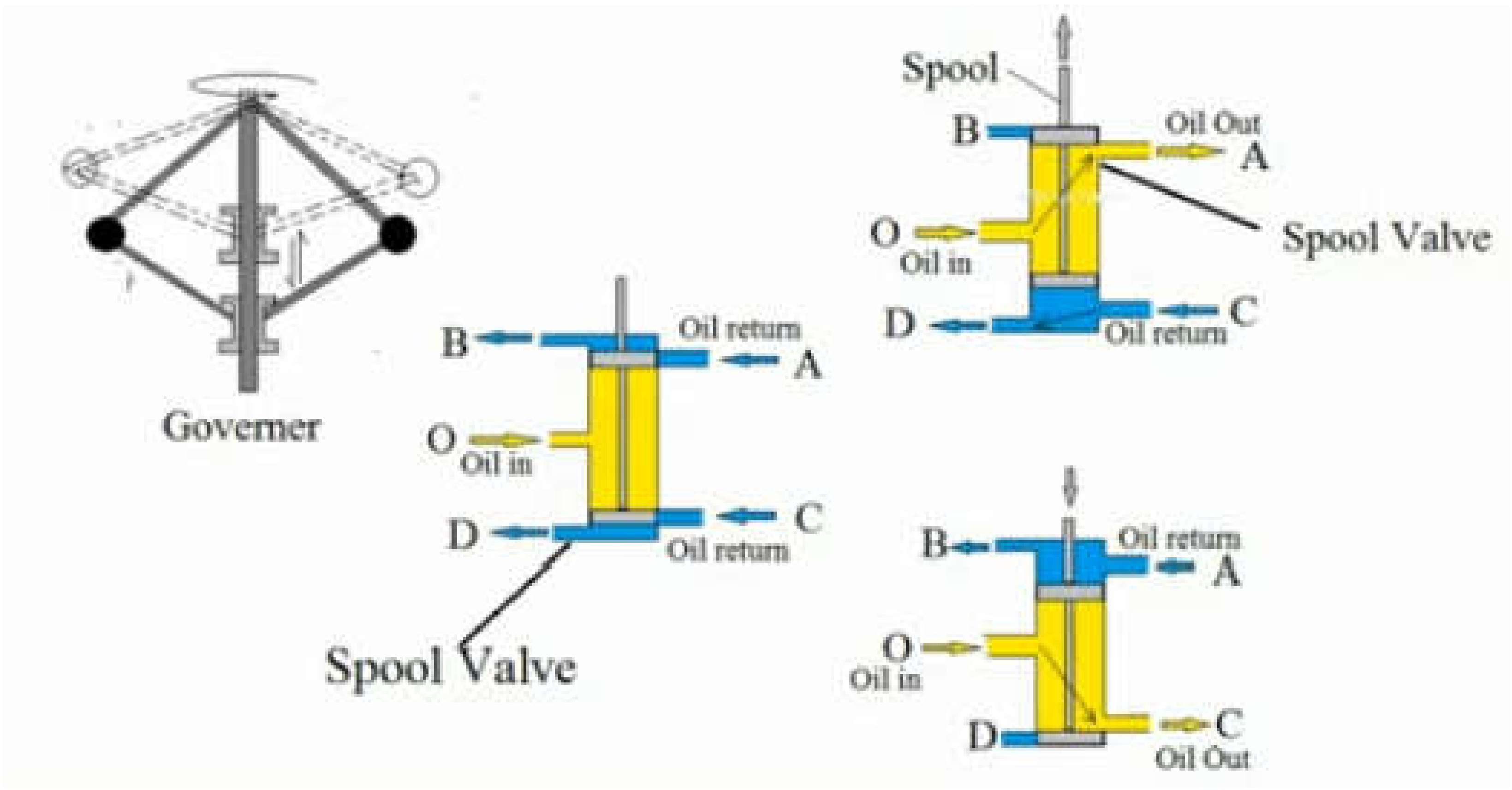
Steam is expanded partially in a row of nozzles where its velocity gets increased.

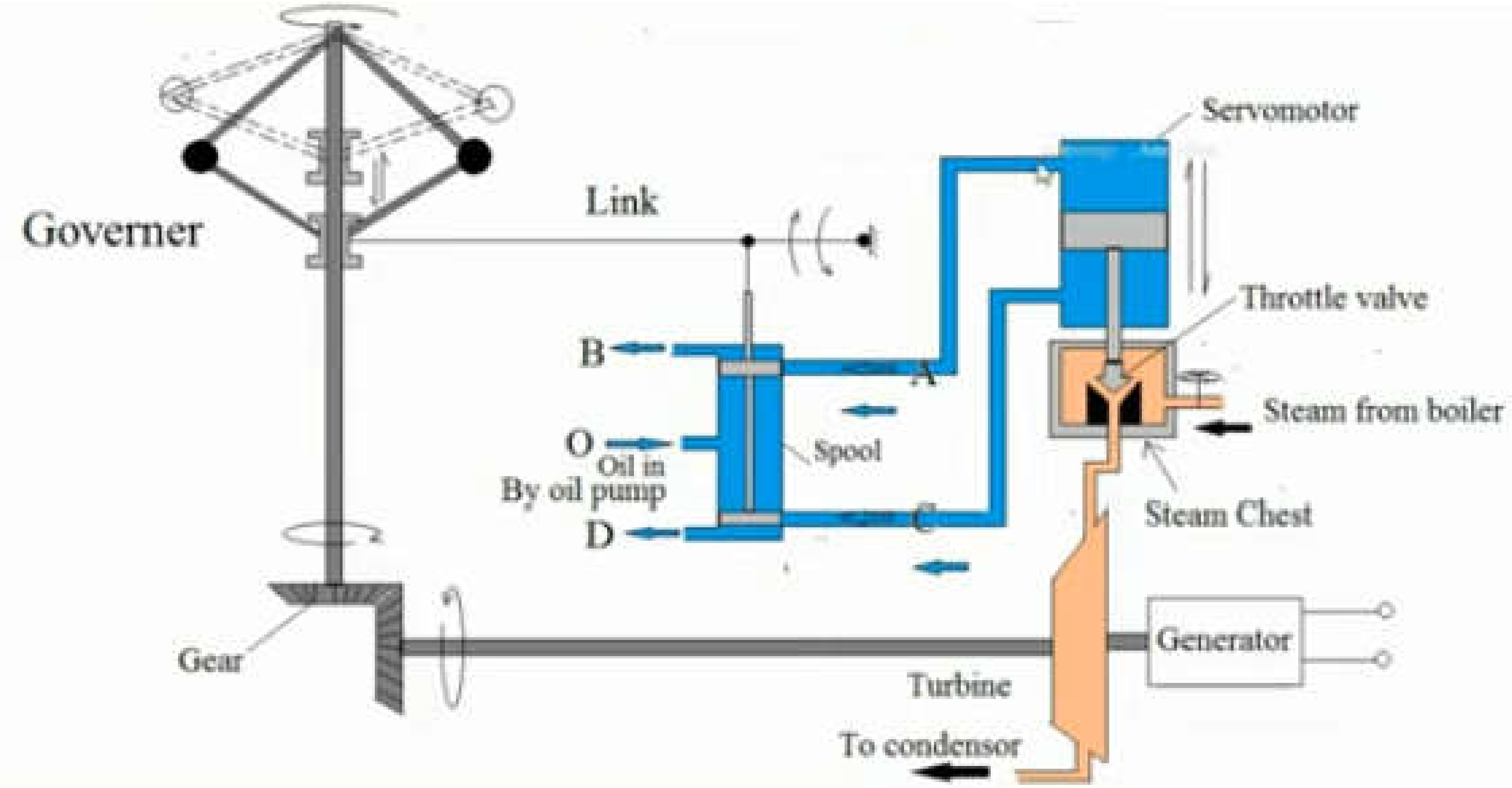
This high velocity steam then enters a few rows of velocity-compounding where its velocity gets successively reduced.

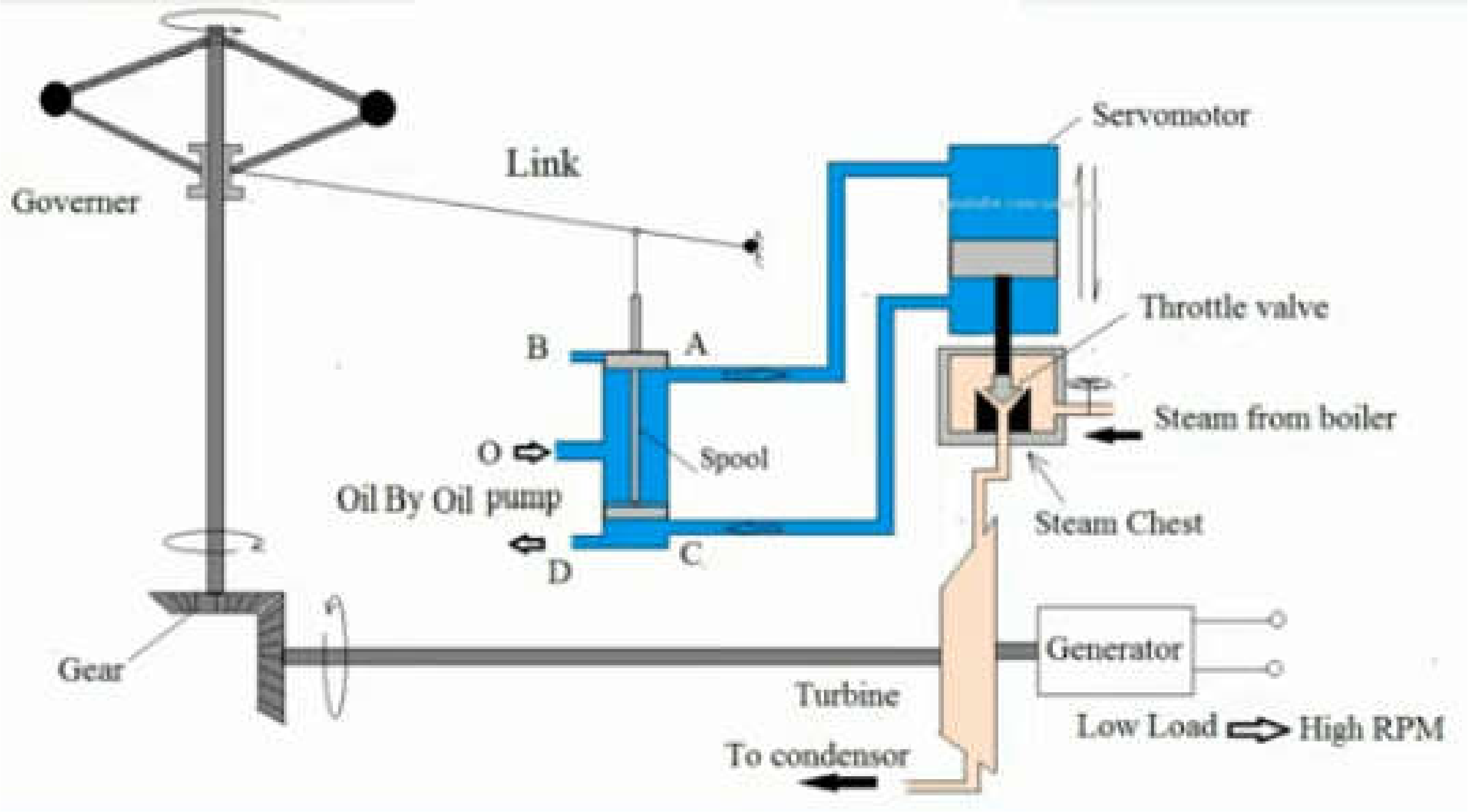
The velocity of the steam is again increased in the subsequent row of nozzles and then it is allowed to pass onto another set of velocity compounding that brings about a stage wise reduction of velocity of the steam.

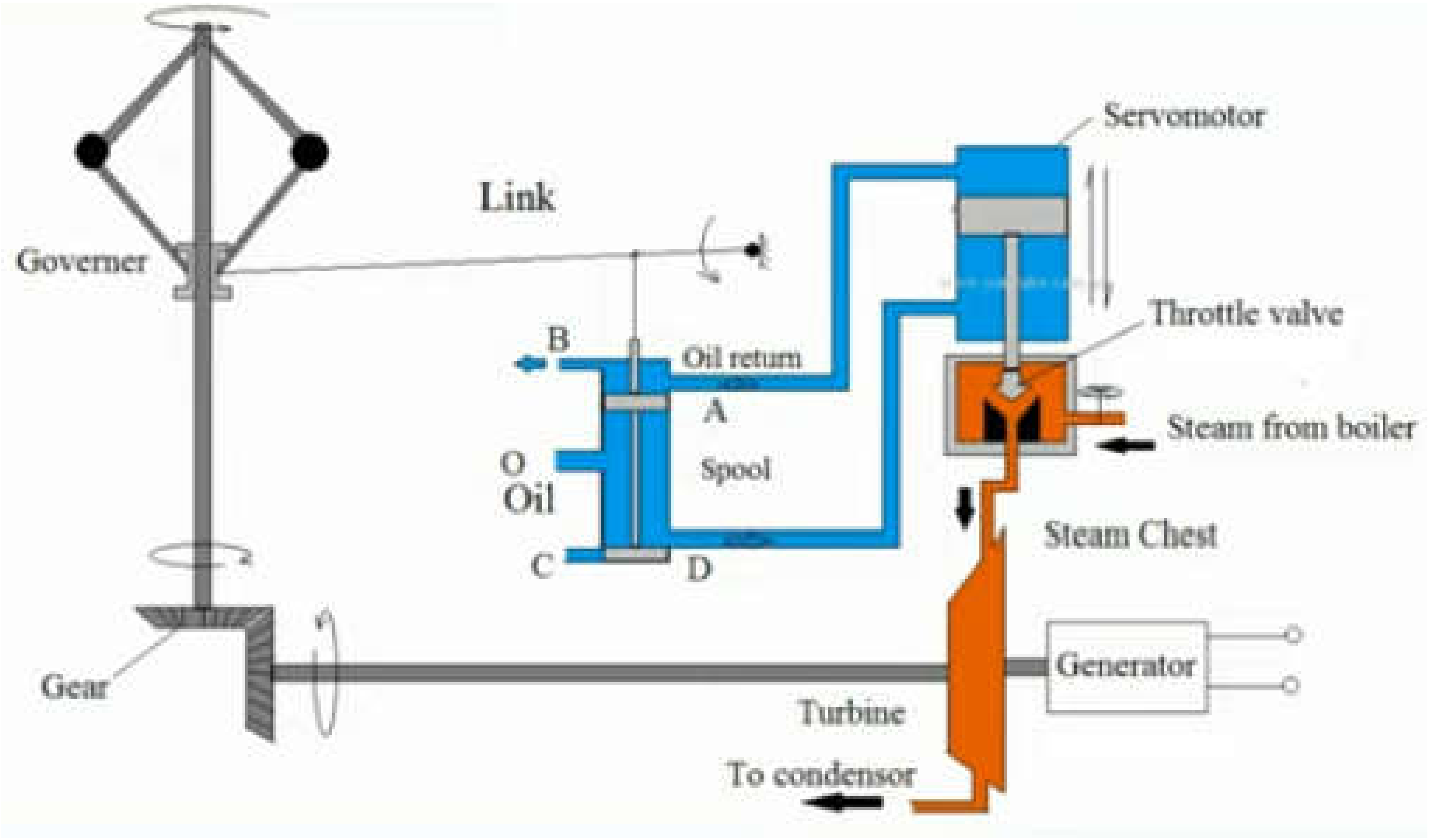
Throttle Governing of steam turbines




Governer
B
Oil return
A
O
Oil in
D
C
Oil return
Spool Valve
Spool
B
Oil Out
A
Spool Valve
O
Oil in
D
C
Oil return
B
Oil return
A
O
Oil in
D
C
Oil Out


Servomotor
Link
Governer
Throttle valve
B
A
Steam from boiler
O
Oil in
By oil pump
Spool
Steam Chest
D
C
Gear
Generator
Turbine
To condensor


Governer
Link
Servomotor
Throttle valve
Steam from boiler
Steam Chest
B
A
O
Spool
Oil By Oil pump
D
C
Gear
Turbine
Generator
To condensor
Low Load
High RPM


Servomotor
Link
Governer
Throttle valve
B
Oil return
A
Steam from boiler
O
Oil
Spool
Steam Chest
C
D
Gear
Generator
Turbine
To condensor

Thermal Engineering-II
MODULE-5

Introduction

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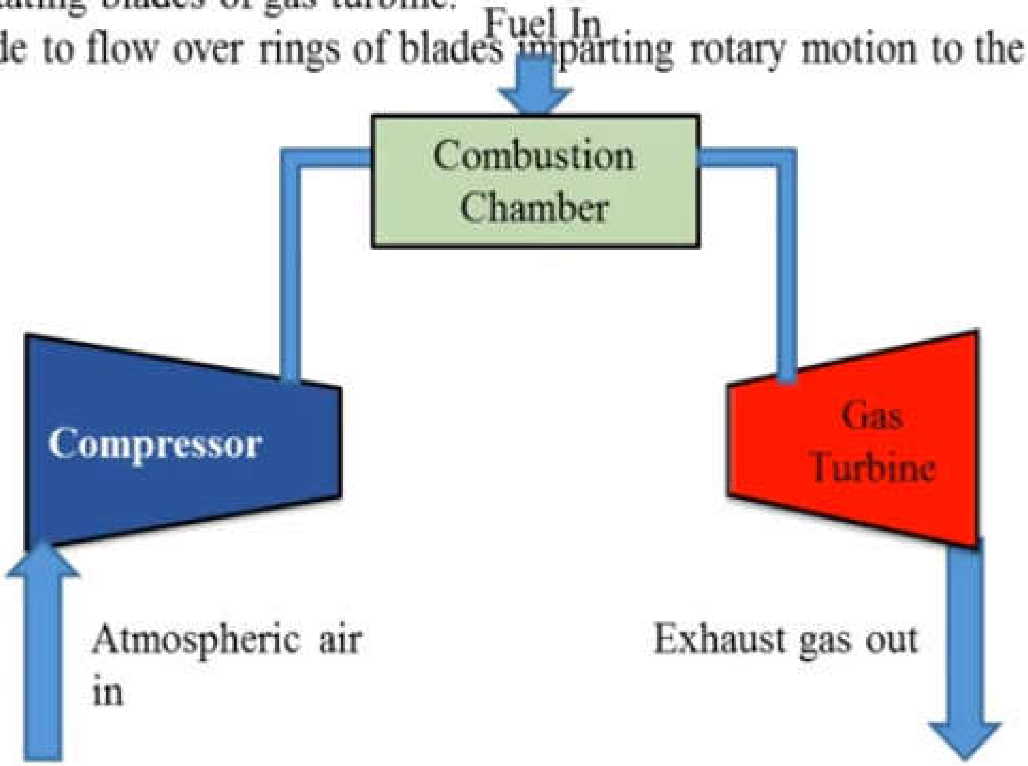
Department of Mechanical Engineering

Gas Turbine

Basic Working Principle of Gas Turbine Power Plant

- In a gas turbine first air is obtained from the atmosphere and compressed in an air compressor as shown in Fig.
- This high pressure air is then passed into the combustion chamber, where it is heated due to combustion of fuel.
- The product of combustion (hot gases) of high pressure and temperature passes through the passages formed by the stationary and rotating blades of gas turbine.
- A jet of hot gases is made to flow over rings of blades imparting rotary motion to the shaft of the turbine.



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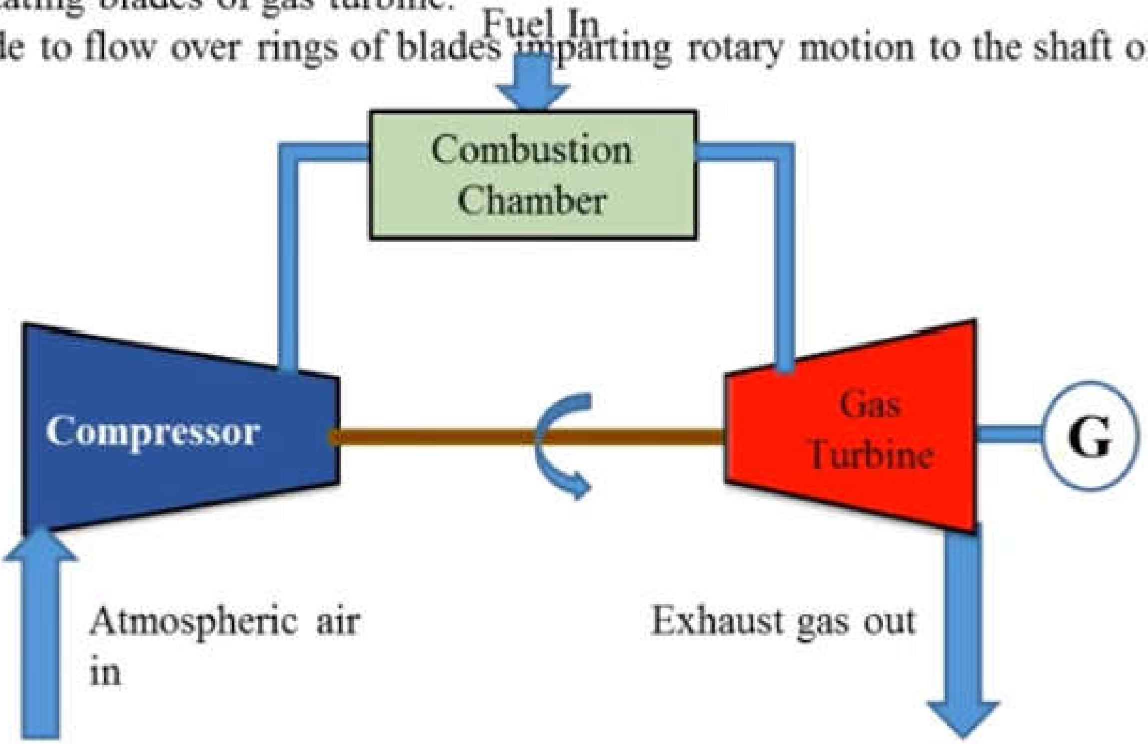
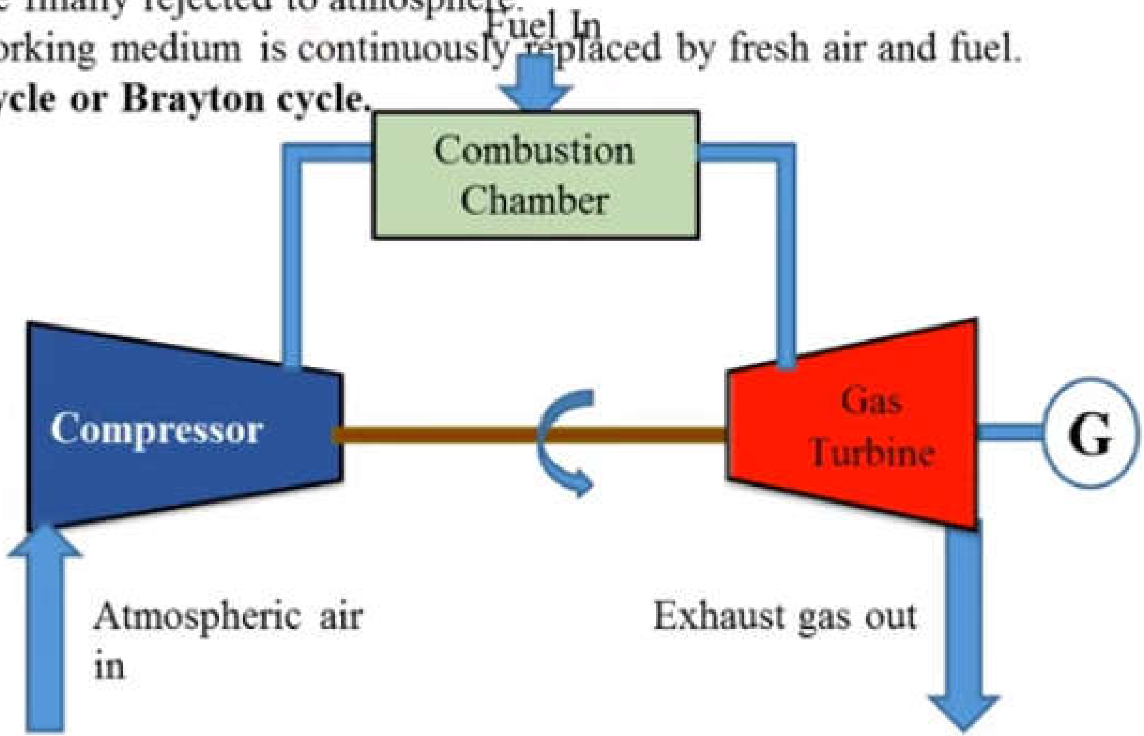
- This high pressure air is then passed into the combustion chamber, where it is heated due to combustion of fuel.
- The product of combustion (hot gases) of high pressure and temperature passes through the passages formed by the stationary and rotating blades of gas turbine.
- A jet of hot gases is made to flow over rings of blades imparting rotary motion to the shaft of the turbine.
- A larger part of the power developed by the turbine rotor is consumed for driving a compressor which supplies air under pressure to combustion chamber, while remaining power is utilized for doing the external work.

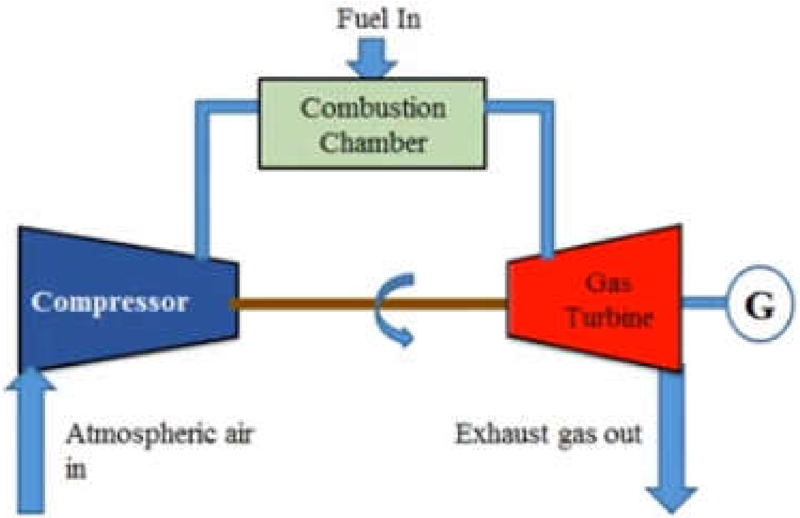


Simple Open Cycle Gas Turbine

- A simple open cycle gas turbine consists of a **(i) compressor, (ii) combustion chamber** and **(iii) gas turbine.**
- In the open cycle gas turbine, ambient air enters at the compressor
- and after the compression of air, fuel is burned in the air itself to raise it to a high temperature
- and then product of combustion are passed on to the turbine for expansion. After delivering the work combustion products are finally rejected to atmosphere.
- In the open cycle the working medium is continuously replaced by fresh air and fuel.
- It works on the **Joule cycle or Brayton cycle.**



- A schematic arrangement for simple open gas turbine plant is shown in Fig.
- The air is sucked in by the compressor from the atmosphere through the filter which removes the dust from the air.
- The rotary blades of the compressor push the air between the stationary blades to raise its pressure to 4-5 atmosphere. Hence air is available at high pressure at output of the compressor.
- Then high pressure air passes through combustion chamber, in which heat added to the air at constant pressure by burning the fuel and raises temperature (about 1650°C) of working medium.



- This high temperature must be brought down to a level so that the thermal stresses in the turbine blades do not become excessive. This is achieved by allowing the excess air to enter the combustion chamber at downstream to mix and cool down the Combustion gases.
- The products of combustion comprising of mixture of gases at high pressure and temperature are passed through the gas turbine. These gases in passing over the turbine blades expand and thus result in motion of rotor and finally discharged to the atmosphere at the temperature about 540°C.

Advantages of open cycle :

(i) Simplicity : There are only few rotating parts as turbine, compressor and gear train driving the auxiliaries. Hence problem of vibrations and lubrication is not so severe,
The ignition system is also simple compared to closed cycle.

(ii) Flexibility : Since different processes within the cycle take place in separate components, a great variety in the arrangement of the system is possible.

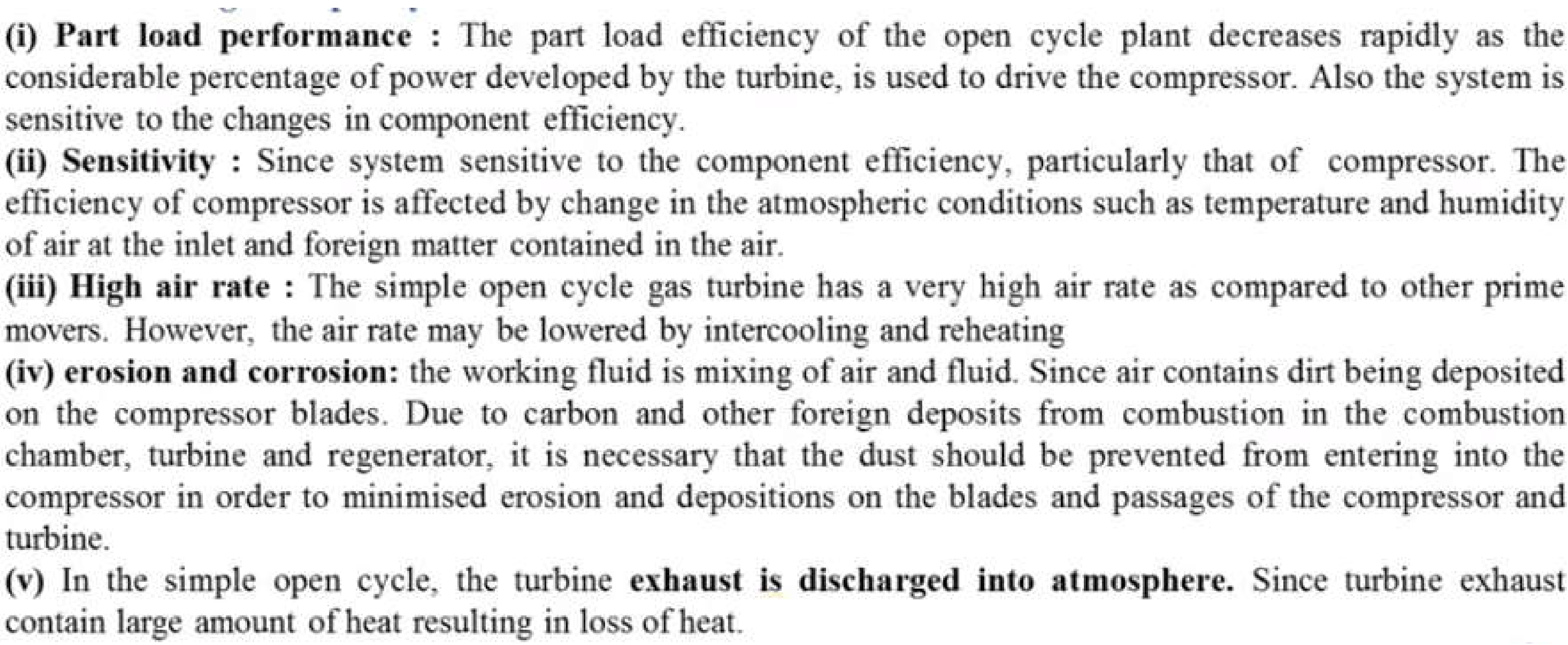
(iii) Low weight and size : The weight in kg. per kW developed is less.

(iv) Independent system : Open cycle gas turbine power plant, except those having intercooler, does not require cooling water. Therefore the plant is independent of cooling medium and becomes self-contained.

(v) Fuels : Almost any hydrocarbon fuel from high octane gasoline to heavy diesel oils including some solid fuels can be burned in the combustion chamber.

(vi) Warm-up time : After the turbine has been brought up to speed by the starting motor and the fuel ignited the gas turbine will accelerate from cold start to full load without a warm up time. This is particularly important in stand by emergency plants.

Disadvantages of open cycle :



(i) Part load performance : The part load efficiency of the open cycle plant decreases rapidly as the considerable percentage of power developed by the turbine, is used to drive the compressor. Also the system is sensitive to the changes in component efficiency.

(ii) Sensitivity : Since system sensitive to the component efficiency, particularly that of compressor. The efficiency of compressor is affected by change in the atmospheric conditions such as temperature and humidity of air at the inlet and foreign matter contained in the air.

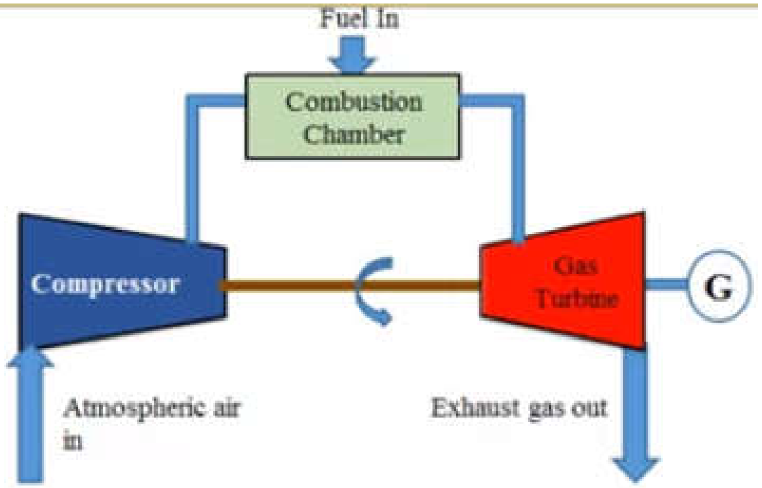
(iii) High air rate : The simple open cycle gas turbine has a very high air rate as compared to other prime movers. However, the air rate may be lowered by intercooling and reheating

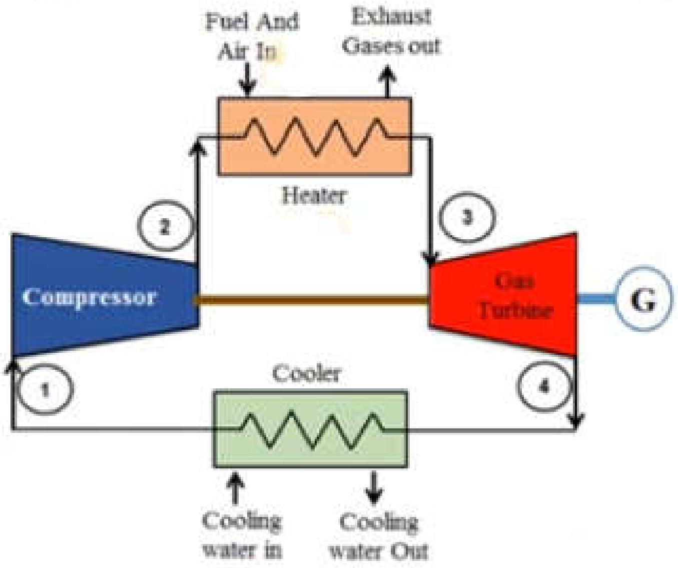
(iv) erosion and corrosion: the working fluid is mixing of air and fluid. Since air contains dirt being deposited on the compressor blades. Due to carbon and other foreign deposits from combustion in the combustion chamber, turbine and regenerator, it is necessary that the dust should be prevented from entering into the compressor in order to minimised erosion and depositions on the blades and passages of the compressor and turbine.

(v) In the simple open cycle, the turbine **exhaust is discharged into atmosphere.** Since turbine exhaust contain large amount of heat resulting in loss of heat.

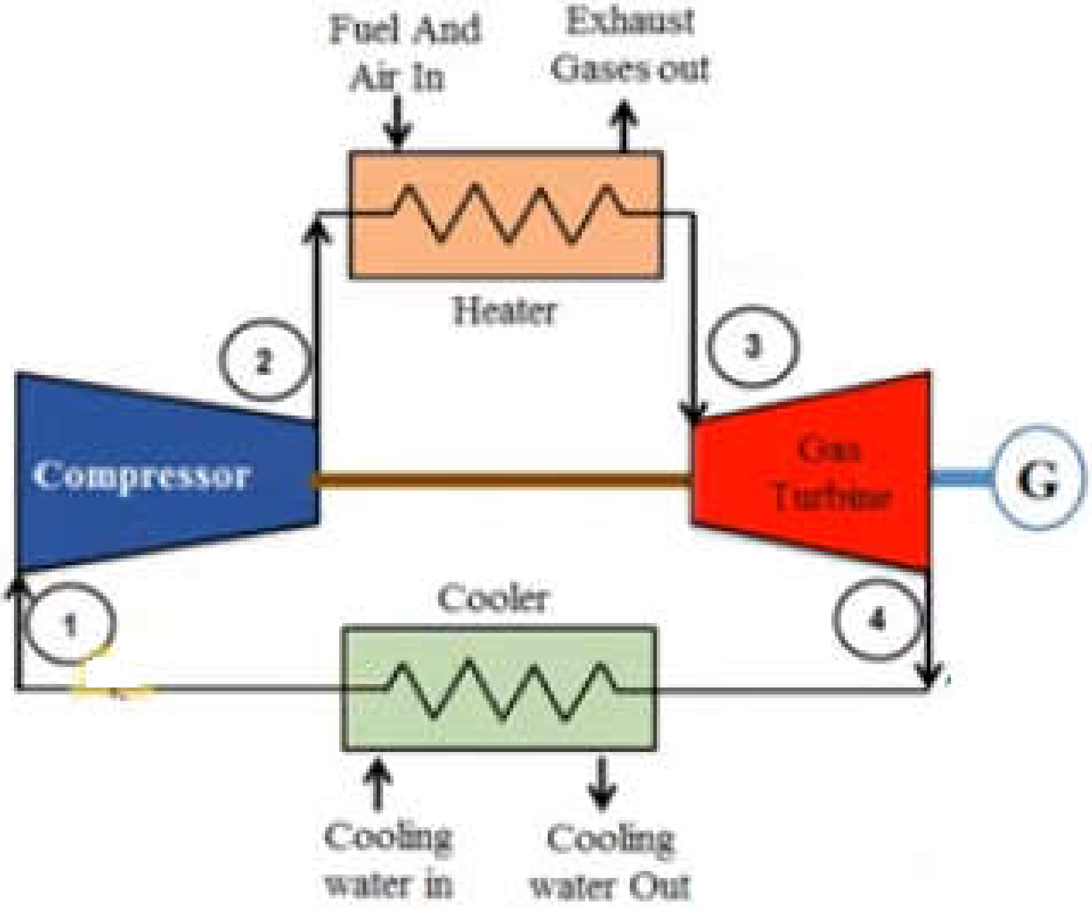
Closed Cycle Gas Turbine

- As we know that in **open cycle gas turbine** power plant, the **fuel is mixed with air in the combustion chamber** and the combustion gases are expanded in the gas turbine which **causes erosion and corrosion** of turbine blades and therefore it is necessary to use fuel superior quality in the combustion chamber in order to minimise erosion and corrosion.
- This negative effect is overcome in closed gas turbine power plant.
- In the **closed gas turbine power plant**, the same air or the **working fluid** is circulated over and over again.
- The **working medium is not mixed with the fuel,** but it is heated by the burning of fuel in a separate supply of air in the combustion chamber and transferring this heat to the working fluid which passes through tubes fitted in the combustion chamber.
- The working fluid does not come into direct contact with products of combustion.

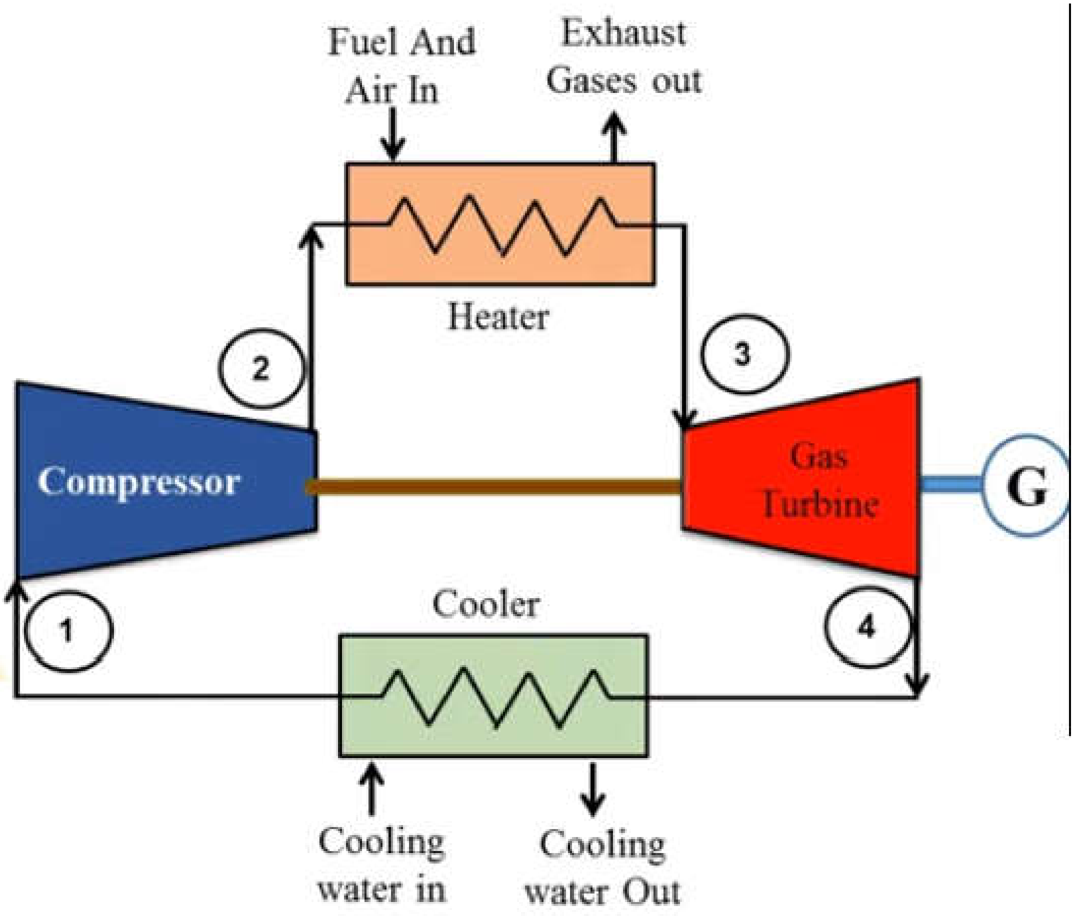


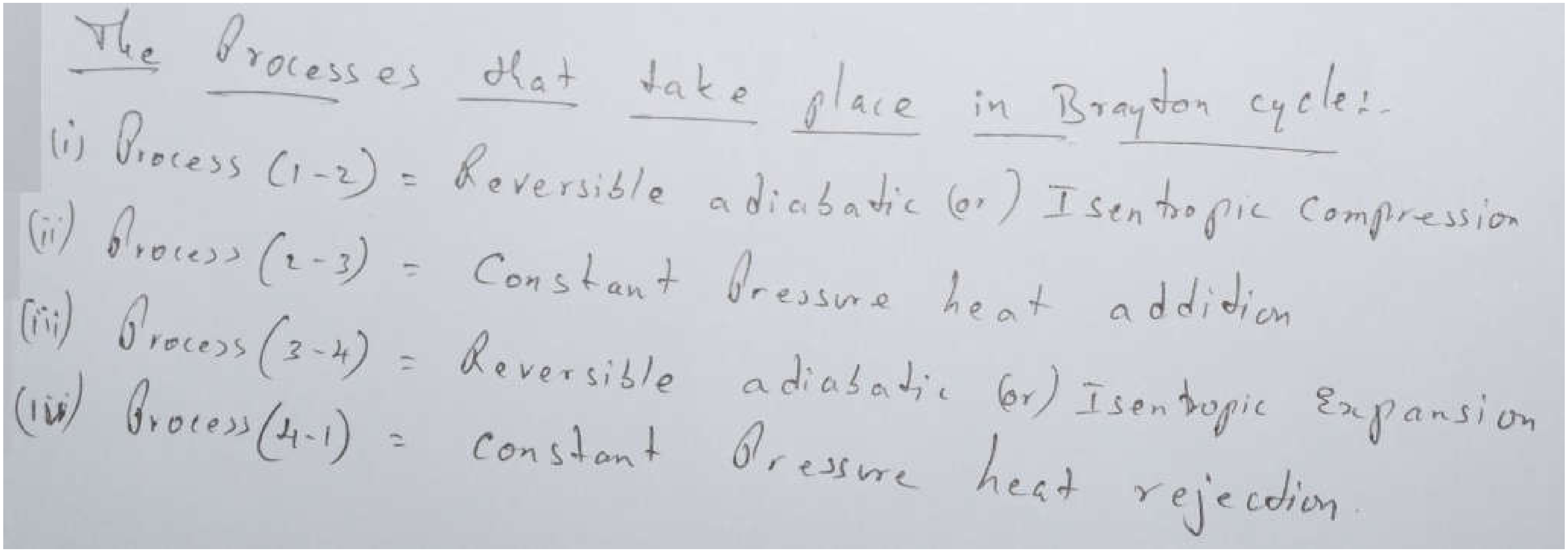


- The other disadvantages of open cycle plant is that the **turbine exhaust is discharged into the atmosphere** resulting in rejection of heat of exhaust gases to the atmosphere.
- In case of closed cycle these heat are recovered in a heat exchanger or cooler.



- A schematic arrangement of closed cycle gas turbine plant is shown in Fig.
- The working fluid (air or any other suitable gas such as helium, argon, hydrogen and neon) coming out from compressor is heated in a heat exchanger (heater) by an external source at constant pressure.
- The high temperature and high pressure air coming out from the external heater is passed through the gas turbine.
- The working fluid coming out from the turbine is cooled to its original temperature in the heat exchanger (cooler) using external cooling source before passing to the compressor.
- In the closed cycle, the working fluid is continuously circulated through compressors, cooler, heater and turbine without its change of phase, the required heat addition and rejection taken place in the heater and cooler respectively.





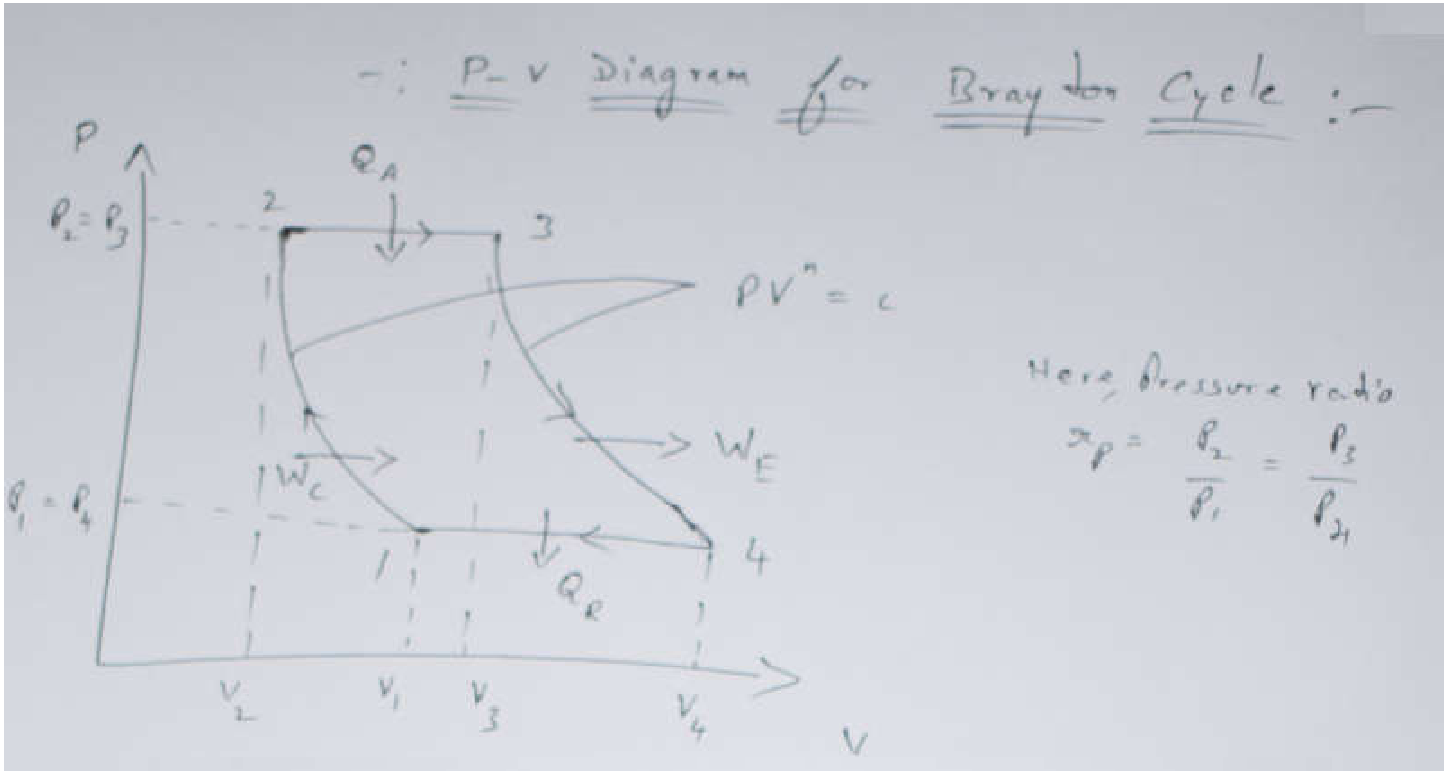
The Processes that take place in Brayton cycle:-

(i) Process (1-2) = Reversible adiabatic (or) Isentropic Compression

(ii) Process (2-3) = Constant Pressure heat addition

(iii) Process (3-4) = Reversible adiabatic (or) Isentropic Expansion

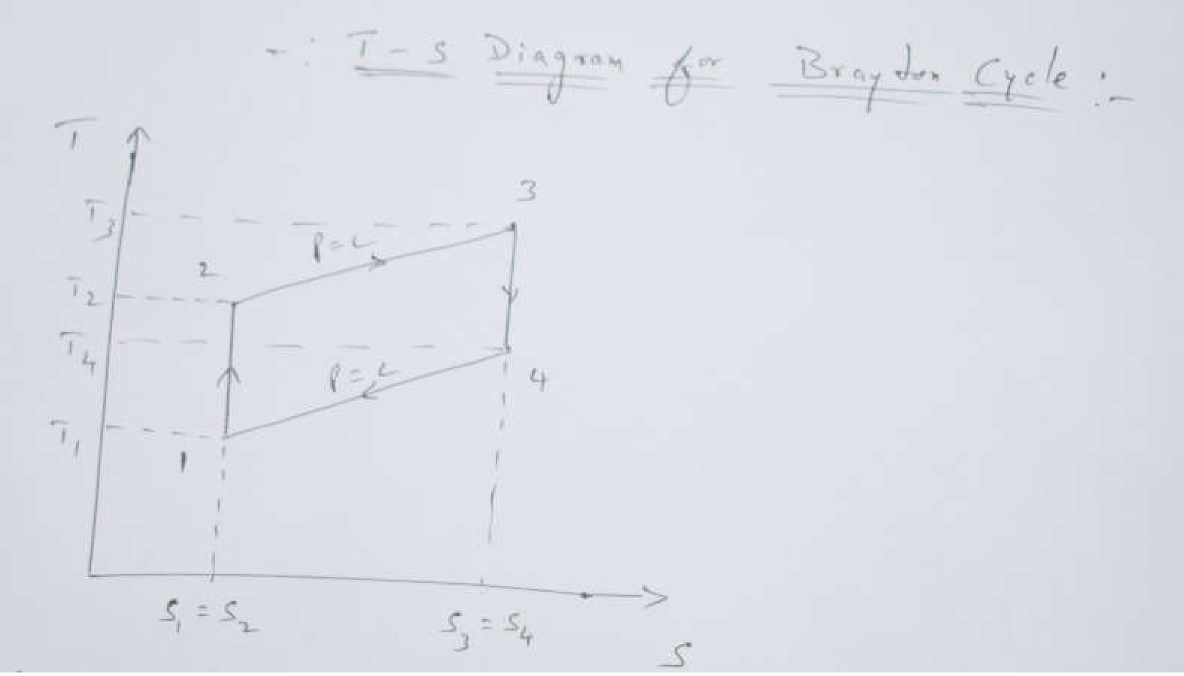
(iv) Process (4-1) = Constant Pressure heat rejection.



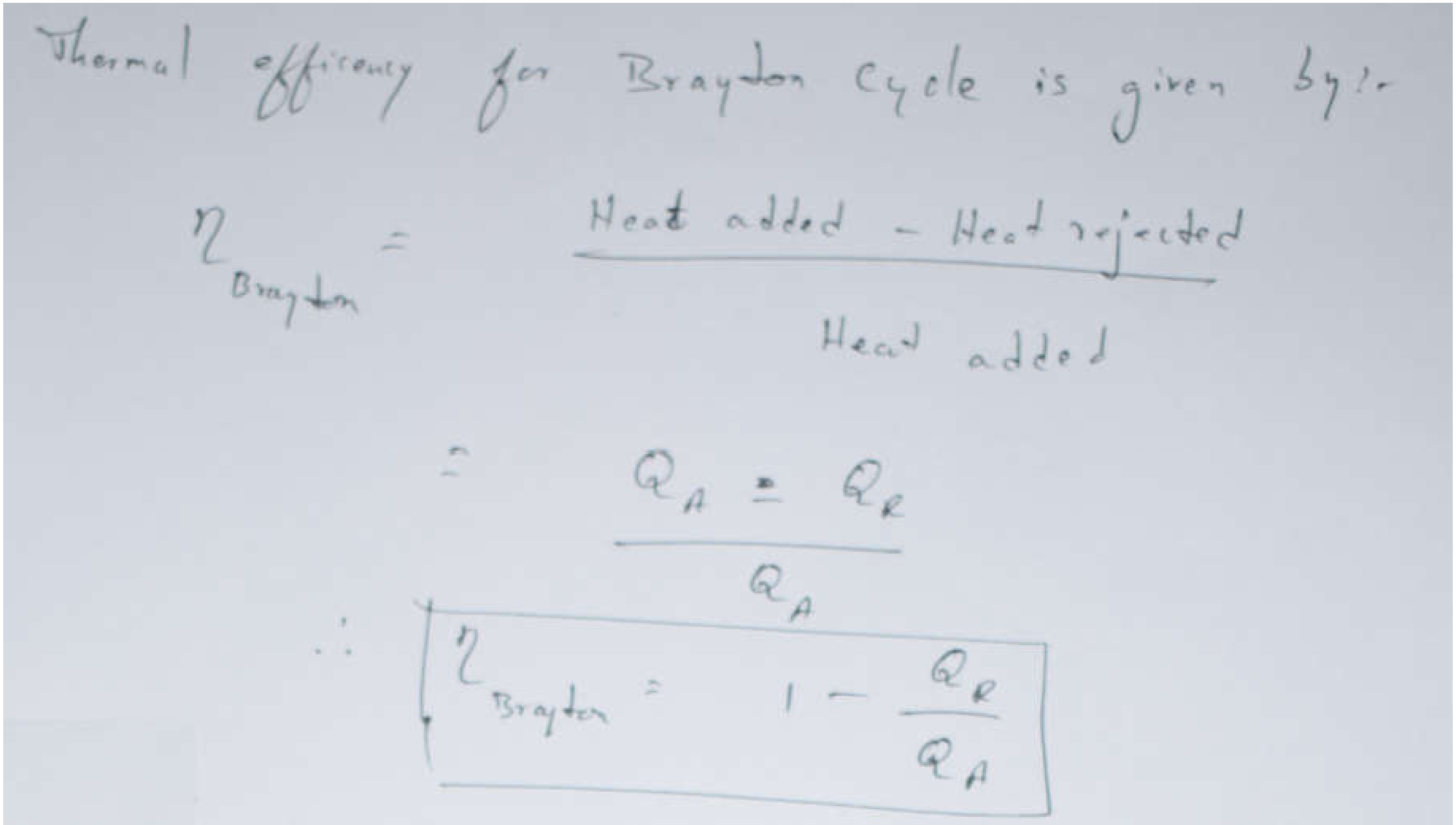
-: P-V Diagram for Brayton Cycle :-

Here, Pressure ratio

$$r_p = \frac{P_2}{P_1} = \frac{P_3}{P_4}$$



-: T-S Diagram for Brayton Cycle :-

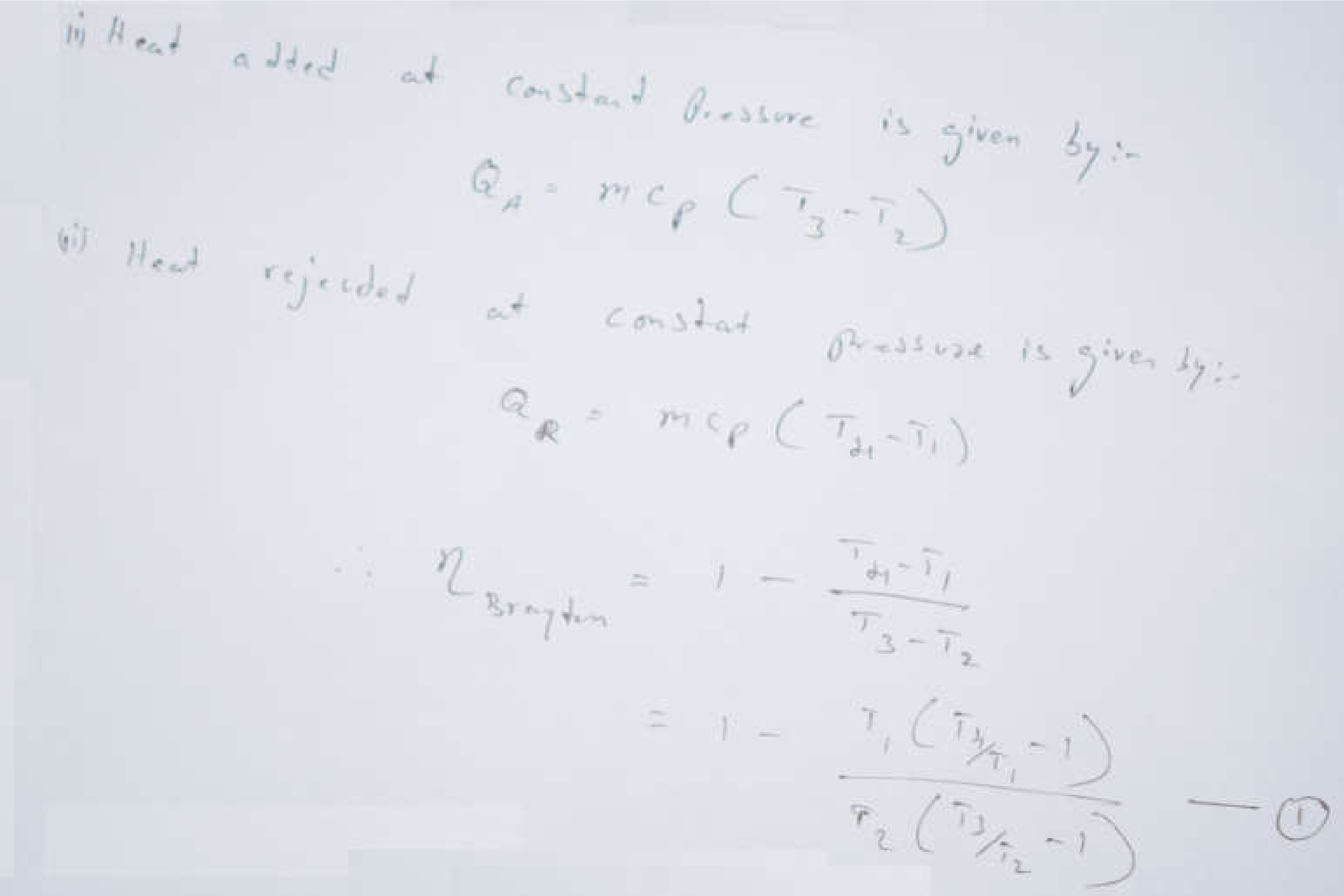


Thermal efficiency for Brayton cycle is given by :-

$$\eta_{Brayton} = \frac{\text{Heat added} - \text{Heat rejected}}{\text{Heat added}}$$

$$= \frac{Q_A - Q_R}{Q_A}$$

$$\therefore \boxed{\eta_{Brayton} = 1 - \frac{Q_R}{Q_A}}$$



(i) Heat added at constant Pressure is given by:-

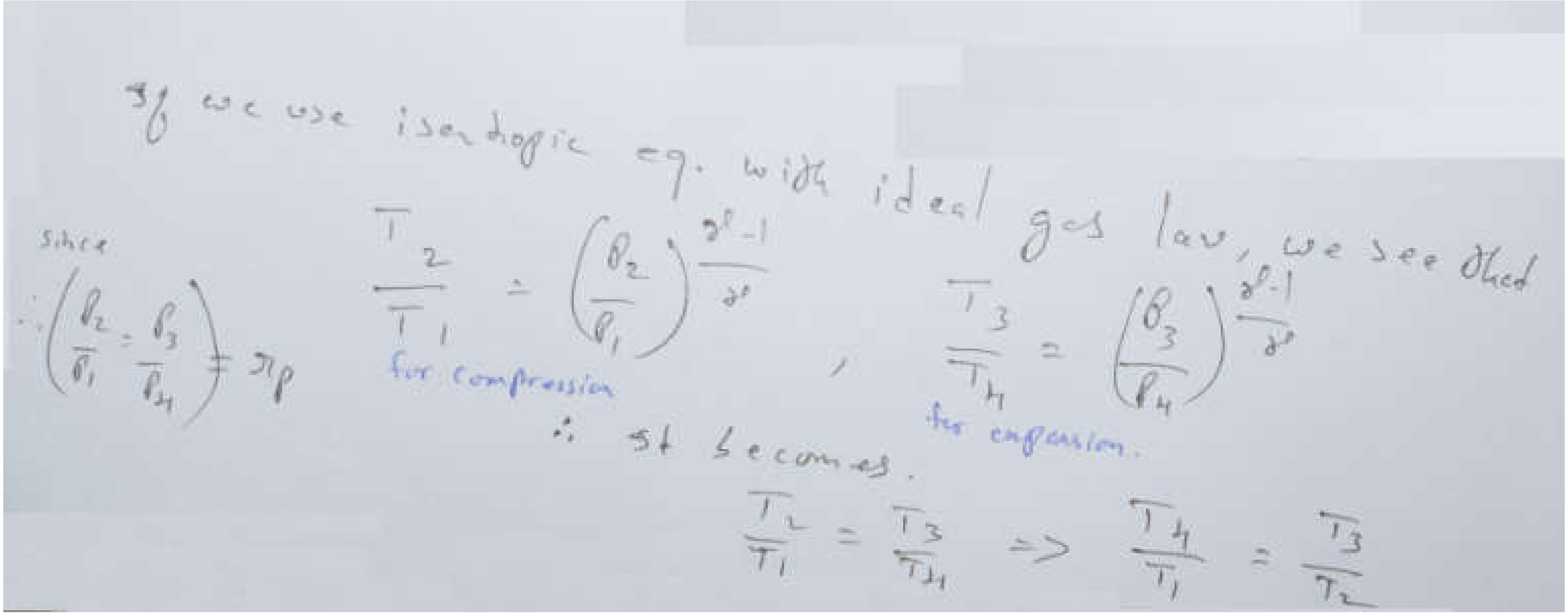
$$Q_A = m c_p (T_3 - T_2)$$

(ii) Heat rejected at constat Pressure is given by:-

$$Q_R = m c_p (T_{41} - T_1)$$

$$\therefore \eta_{Brayton} = 1 - \frac{T_{41} - T_1}{T_3 - T_2}$$

$$= 1 - \frac{T_1 \left(T_4/T_1 - 1 \right)}{T_2 \left(T_3/T_2 - 1 \right)} \quad \text{---} \; ①$$



If we use isentropic eq. with ideal gas law, we see that

since $\therefore \left(\frac{P_2}{P_1} = \frac{P_3}{P_4}\right) = r_p$

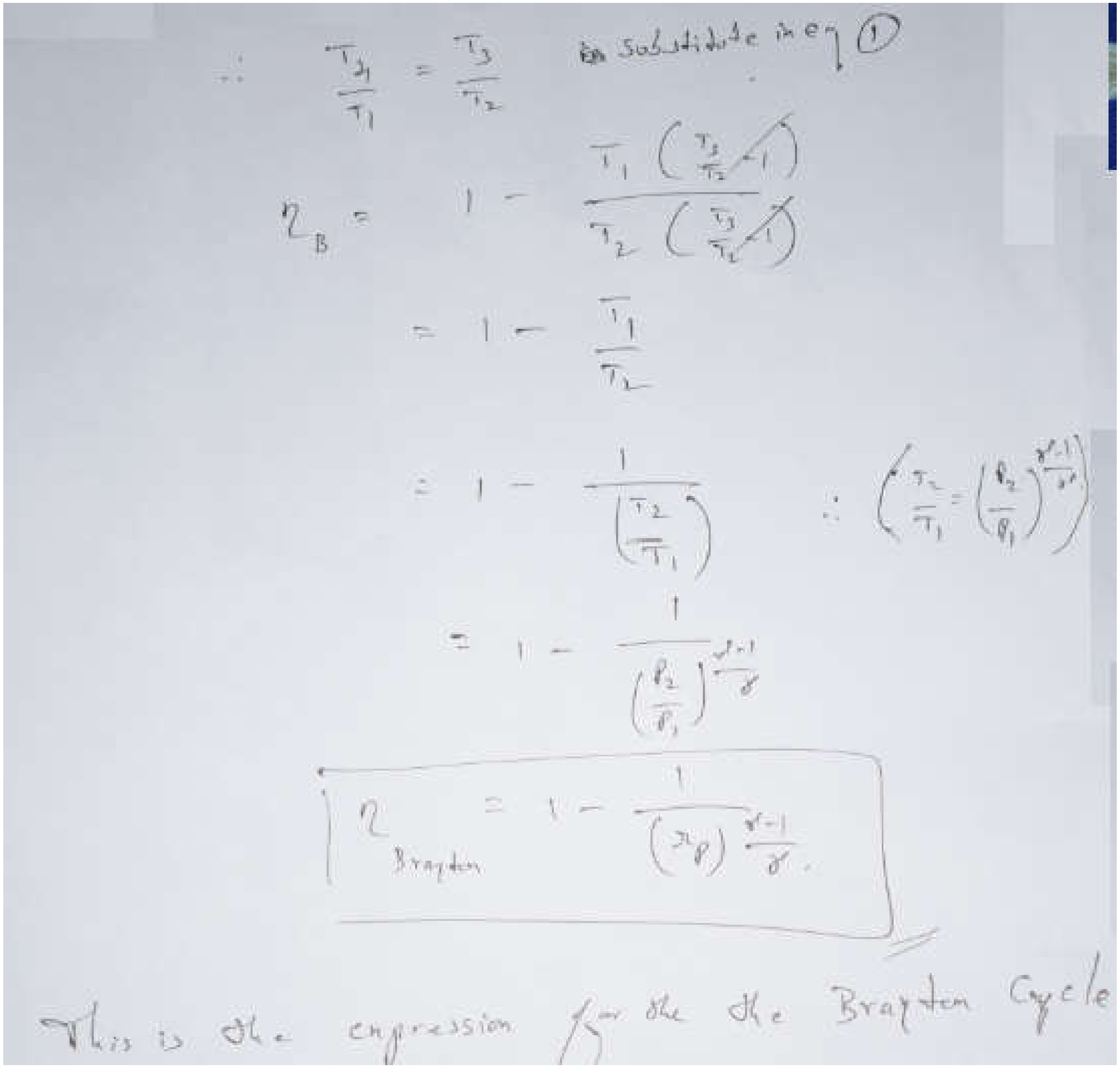
$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} , \quad \frac{T_3}{T_4} = \left(\frac{P_3}{P_4}\right)^{\frac{\gamma-1}{\gamma}}$$

for compression

for expansion.

$\therefore$ It becomes.

$$\frac{T_2}{T_1} = \frac{T_3}{T_4} \Rightarrow \frac{T_4}{T_1} = \frac{T_3}{T_2}$$



$$\therefore \quad \frac{T_4}{T_1} = \frac{T_3}{T_2}$$ Substitute in eq ①

$$\eta_B = 1 - \frac{T_1\left(\cancel{\frac{T_3}{T_2}-1}\right)}{T_2\left(\cancel{\frac{T_3}{T_2}-1}\right)}$$

$$= 1 - \frac{T_1}{T_2}$$

$$= 1 - \frac{1}{\left(\frac{T_2}{T_1}\right)} \qquad \therefore \left(\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}}\right)$$

$$= 1 - \frac{1}{\left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}}}$$

$$\boxed{\eta_{\text{Brayton}} = 1 - \frac{1}{(r_p)^{\frac{\gamma-1}{\gamma}}}}.$$

This is the expression for the the Brayton Cycle

Comparison Between The Open Cycle And Closed Cycle Gas Turbine

particulars	Open cycle gas turbine	Close cycle gas turbine
1.opration of cycle	The same working fluid is not recirculated again and again. The fresh charge is supplied to each cycle and after combustion and expansion it is discharge to the atm.	The working fluid is recirculated again and again,
2. Working fluid	Air fluid Mixture	The working fluid air or any other suitable gas as argon, helium, helium-CO_2 mixture. Etc., can be used, which more favorable properties than air
3. Manner of heat transfer	Fuel is directly mixed with air, direct heat supply and heat is generated in the combustion chamber itself	Fuel is not mixed with working medium, and heat produced by fuel is transfer to working fluid through heat exchanger
4. Quality of heat input	It requires high grade heat energy	The heat can be supplied from source like low grade fuel, waste heat, solar heat, nuclear heat

particulars	Open cycle gas turbine	Close cycle gas turbine
5. Type of fuel	It require high quality oil or gaseous fuel because combustion is internal part of the system	Any type of fuel can be used because heat is transfer externally
6. Efficiency	Lower thermal efficiency for given temperature limit	High thermal efficiency for given temperature limits.
7. Part load performance	Comparative less thermal efficiency	Comparatively better thermal efficiency
8. Compactness	Size of plant is less	Size of plant is large
9. Control	Poor control on power production	Better control on power production
10. Life	The combustion product directly passes through the turbine, and hence blades are subjected to higher thermal stresses and fouling. Therefore life of blades is shorter	Due to indirect heat transfer, combustion products do not come in contact of turbine blade, thus there is no blade fouling and longer blade life
11. Complexity	It do not require heater and cooler and hence less complex	It require heater and cooler and hence plant is more complex large
12. Cost	Less	Large