STELLA MARY'S COLLEGE OF ENGINEERING

(Accredited by NAAC, Approved by AICTE - New Delhi, Affiliated to Anna University Chennai)

Aruthenganvilai, Azhikal Post, Kanyalumari District, Tamilnadu - 629202.

ME8595 THERMAL ENGINEERING – II

(Anna University: R2017)

Prepared By

Mr. S. AJITH KUMAR

Assistant Professor

DEPARTMENT OF MECHANICAL ENGINEERING

2021-2022 (ODD)

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Aruthenganvilai, Kallukatti Junction Azhikal Post, Kanyakumari District-629202, Tamil Nadu.

DEPARTMENT OF MECHANICAL ENGINEERING

COURSE MATERIAL

REGULATION	**2017**
YEAR	**III**
SEMESTER	**05**
COURSE NAME	**THERMAL ENGINEERING – II**
COURSE CODE	**ME8595**
NAME OF THE COURSE INSTRUCTOR	**Mr. S. AJITH KUMAR**

SYLLABUS:

UNIT I STEAM NOZZLE 9

Types and Shapes of nozzles, Flow of steam through nozzles, Critical pressure ratio, Variation of mass flow rate with pressure ratio. Effect of friction. Metastable flow.

UNIT II BOILERS 9

Types and comparison. Mountings and Accessories. Fuels - Solid, Liquid and Gas. Performance calculations, Boiler trial.

UNIT III STEAM TURBINES 9

Types, Impulse and reaction principles, Velocity diagrams, Work done and efficiency – optimal operating conditions. Multi-staging, compounding and governing.

UNIT IV COGENERATION AND RESIDUAL HEAT RECOVERY 9

Cogeneration Principles, Cycle Analysis, Applications, Source and utilisation of residual heat. Heat pipes, Heat pumps, Recuperative and Regenerative heat exchangers. Economic Aspects.

UNIT V REFRIGERATION AND AIR – CONDITIONING 9

Vapour compression refrigeration cycle, Effect of Superheat and Sub-cooling, Performance calculations, Working principle of air cycle, vapour absorption system, and Thermoelectricrefrigeration. Air conditioning systems, concept of RSHF, GSHF and ESHF, Cooling load calculations. Cooling towers – concept and types.

TEXT BOOKS :

1. Kothandaraman, C.P., Domkundwar .S and Domkundwar A.V.,"A course in Thermal Engineering", Dhanpat Rai & Sons, 2016.
2. Mahesh. M. Rathore, "Thermal Engineering", 1st Edition, Tata Mc Graw Hill Publications, 2010.

REFERENCES:

1. Arora .C.P., "Refrigeration and Air Conditioning", Tata Mc Graw Hill, 2008
2. Ballaney. P.L ." Thermal Engineering", Khanna publishers, 24th Edition 2012
3. Charles H Butler : Cogeneration" McGraw Hill, 1984.
4. Donald Q. Kern, " Process Heat Transfer", Tata Mc Graw Hill, 2001.
5. Sydney Reiter "Industrial and Commercial Heat Recovery Systems" Van Nostrand Reinhols, 1985.

Course Outcome Articulation Matrix

	Program Outcome												***PSO***		
Course Code / CO No	***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***	***10***	***11***	***12***	***1***	***2***	***3***
ME8595 / C301.1	3	3	1	0	3	0	0	0	1	0	0	3	3	2	2
ME8595 / C301.2	3	3	1	0	3	0	0	0	1	0	0	3	3	2	2
ME8595 / C301.3	3	3	1	0	3	0	0	0	1	0	0	3	3	2	2
ME8595 / C301.4	3	3	1	0	3	0	0	0	1	0	0	3	3	2	2
ME8595 / C301.5	3	3	1	0	3	0	0	0	1	0	0	3	3	2	2
Average	3	3	1	0	3	0	0	0	1	0	0	3	3	2	2

STELLA MARYS COLLEGE OF ENGINEERING

ME8595

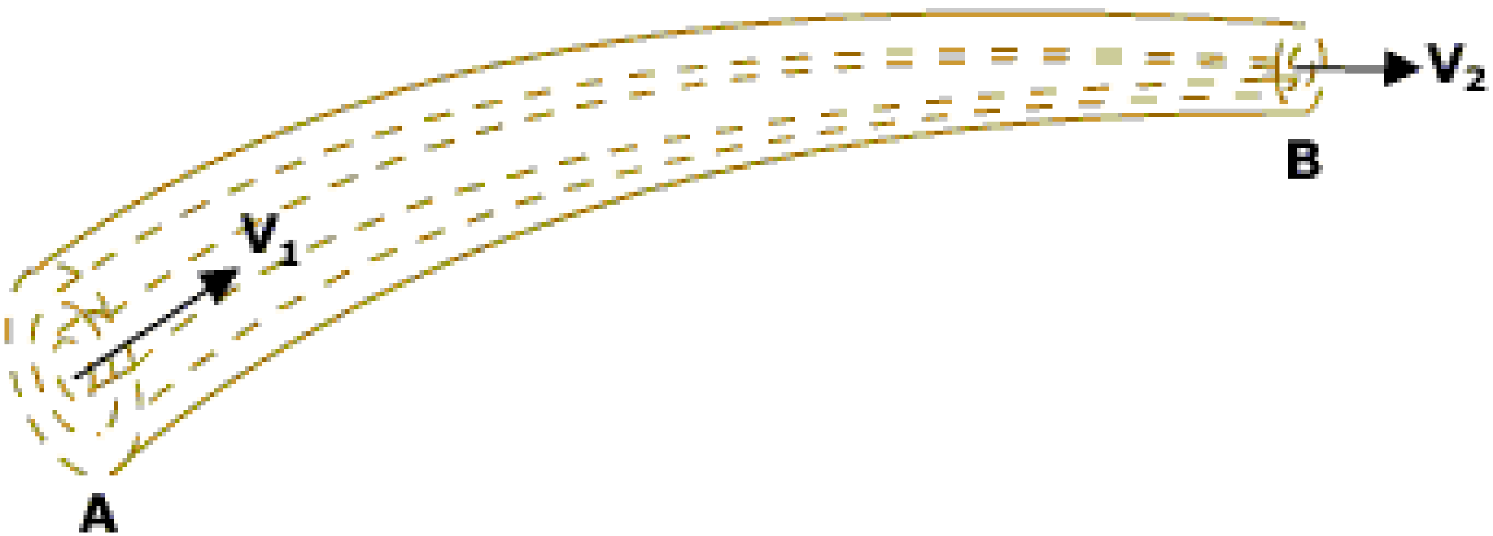
THERMAL ENGINEERING – II

UNIT I STEAM NOZZLE

Types and Shapes of nozzles, Flow of steam through nozzles, Critical pressure ratio, Variation of mass flow rate with pressure ratio. Effect of friction. Metastable flow.

Equations of Continuity

Consider a non-viscous liquid in streamline flow through a tube AB, of varying cross-section



Let A_1 and A_2 be the area of cross-section at A and B respectively.

The volume of water entering A per second = A_1V_1

Volume = Area x distance

$$\frac{\text{Volume}}{\text{time}} = \text{Area} \times \frac{\text{dis tance}}{\text{time}}$$

$$= \text{Area} \times \text{velocity}$$

where V_1 is the velocity of the flow of liquid at A

The volume of water leaving B per second = A_2V_2

$\therefore$ Mass of liquid entering per second at A = $A_1V_1\rho_1$

and Mass of liquid leaving per second at B = $A_2V_2\rho_2$

Assuming there is no loss of liquid in tube and for free steady flow,

Mass of liquid entering per second at A= Mass of liquid leaving per second at B

i.e. $A_1 V_1 \rho_1 = A_2 V_2 \rho_2$

Since the density is uniform throughout, $\rho_1 = \rho_2$

$$A_1 V_1 = A_2 V_2$$

or AV = constant.

This is the equation of continuity.

Steam Nozzle

Steam nozzle is an insulated passage of varying cross-sectional area through which heat energy (Enthalpy), pressure of steam is converted into kinetic energy.

Steam Nozzle

Functions of Nozzle :-

1) The main function of the steam nozzle is to convert heat energy to kinetic energy.
2) To direct the steam at high velocity into blades of turbine at required angle.

Applications :-

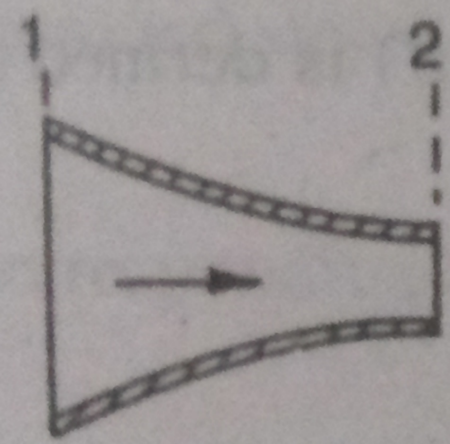
1) Steam & gas turbines are used to produces a high velocity jet.
2) Jet engines and rockets to produce thrust (propulsive force)

Types of nozzles

1) Convergent nozzle
2) divergent nozzle
3) convergent - divergent nozzle

Convergent nozzle

- It is a nozzle with large entrance and tapers gradually to a smallest section at exit.
- It has no diverging portion.

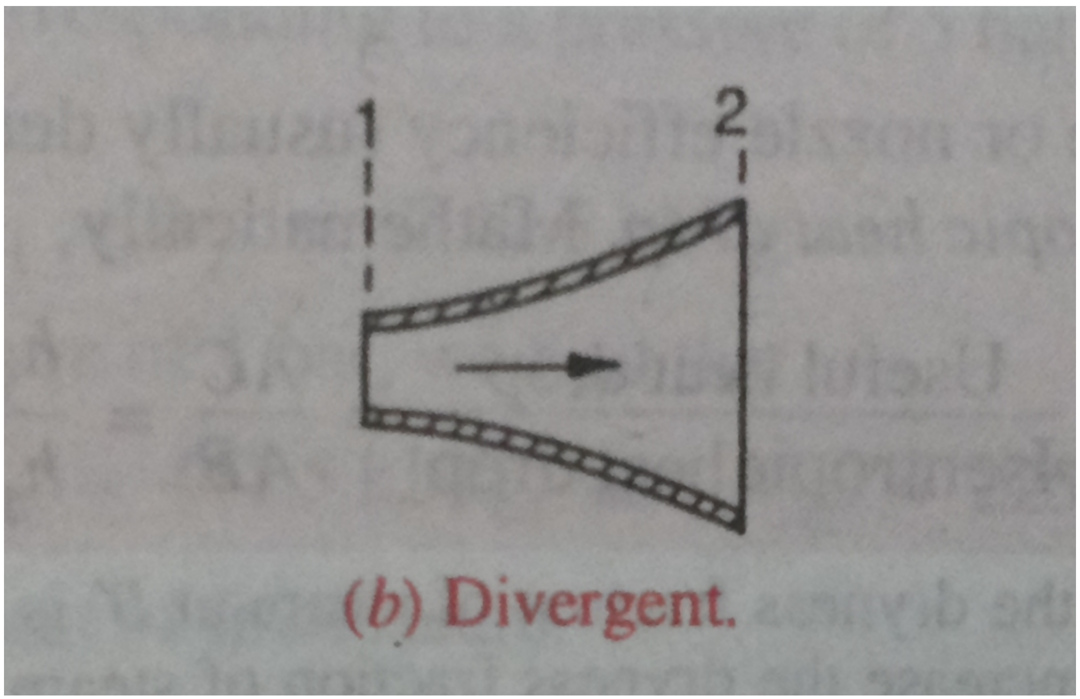


(a) Convergent.

Divergent nozzle :-

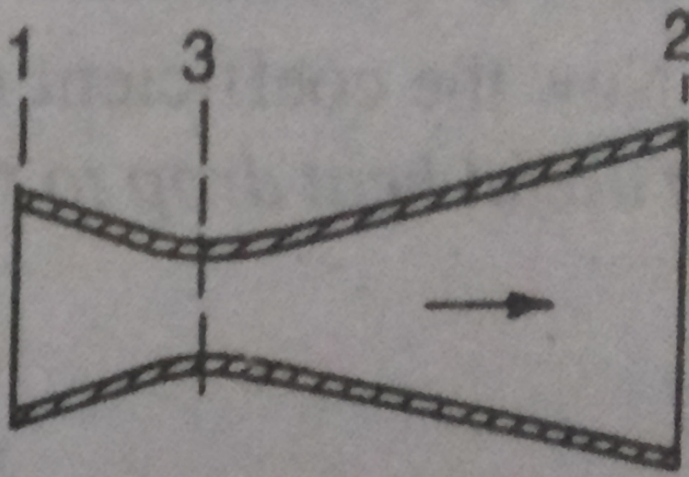
It is a nozzle with small entrance and tapers gradually to a large section at exit.

It has no converging portion at entry.



(*b*) Divergent.

- convergent - divergent nozzle :-
- convergent - divergent nozzle is widely used in steam turbines.
- The nozzle converges first to the smallest section and then diverges up to exit.
- The smallest section of the nozzle is called throat.
- The divergent portion of nozzle allows higher expansion ratio i.e., increases pressure drop.



(c) Convergent-divergent.

<u>convergent - divergent nozzle</u> :

- The taper of diverging sides of the nozzle ranges from 6^0 to 15^0 .
- if the taper is above 15^0 turbulent is increased.
- However if it is less than 6^0, the length of the nozzle will increases

Mach number

- the ratio of speed of an object moving through a fluid and the local speed of sound.

$$M = \frac{v}{v_{\mathrm{sound}}}$$

Where,

- M is the Mach number, v is the velocity of the source relative to the medium, and v_{sound} is the speed of sound in the medium.
- Mach number varies by the composition of the surrounding medium and also by local conditions, especially temperature and pressure.

Mach number

- $M< 1$, the flow is called subsonic.
- $M=1$, the flow is called sonic.
- $M>1$, the flow is called supersonic.
- $M>5$, the flow is called hypersonic.

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THERMAL ENGINEERING – II

UNIT II

BOILERS

Types and comparison. Mountings and Accessories. Fuels - Solid, Liquid and Gas. Performance calculations, Boiler trial.

STEAM BOILERS, MOUNTINGS & ACCESSORIES

STEAM GENERATOR/ BOILER

?

The equipment used for producing and transferring steam is called

Steam generators/ Boilers.

Principle of Steam Generators/ Boilers:

The fluid (water) contained in the boiler called *shell* and the thermal energy released during combustion of fuel, which may be solid, liquid or gaseous, is transferred to water and this converts water into steam at the desired temperature and pressure.

Commercial usage of

Steam

?

Commercial usage of Steam:

i) Power generation

ii) Heating the residential and commercial buildings in cold weather countries.

iii) Other industrial usages e.g. sugar industries and chemical industries etc.

Classification of

Boilers

Classification of Boilers:

Boilers may be classified according to the following-

1. ***Relative position of Hot gases and Water***

a) Fire tube boiler:

The hot gases passes through the tubes that are surrounded by water. Fire tube boilers are also known by certain common names-

i) Horizontal return tubular

ii) Locomotive fire box

iii) Scotch marine and,

iv) Vertical tubular

b) Water tube Boiler:

The water passes through the tubes and the hot gases produced by combustion of fuel, flow outside. This type of Boilers designated by the following common names:

i) Babcock and Wilcox Boiler (straight but inclined tubes which connect the headers).

ii) Stirling Boiler (multitubular boiler having bent tubes that connect boiler drums to headers).

2. ***Method of firing***

a) Internally fired Boilers:

The furnace is provided *inside* the boiler shell and is completely surrounded by water cooled surfaces. This method of firing is used in:

- Lancashire Boilers
- Locomotive Boilers and
- Scotch Boilers

b) Externally fired Boilers:

The furnace is provided *outside/ under* the boiler. It has an advantage that its furnace is simple to construct and can easily be enlarged, as and when required. This method of firing is used in Babcock and Wilcox Boiler.

3) Pressure of Steam:

i) High pressure Boilers:

Boilers producing steam ***80 bar*** and above are called High pressure boilers. E.g.

* Babcock and Wilcox Boiler
* Lamont Boilers
* Velox Boilers and
* Benson Boilers etc.

ii) Low pressure Boilers:

Boilers producing steam Lower than ***80 bar*** are called Low pressure boilers. E.g.

- Cochran Boilers
- Cornish Boiler
- Lancashire Boiler
- Locomotive Boiler

4. Method of circulation of water:

a) **Natural circulation method**

Circulation set up by convection current or by gravity.

b) **Forced circulation method**

Circulation set up for high pressure steam through pumps.

5. Nature of service to be performed:

a) Land Boilers:

Boilers which are used with stationary plants

b) Portable Boilers:

Boilers which can be readily dismentaled and easily carried out from one site to another.

c) Mobile Boilers:

Boilers which are fitted on mobile carriages are called Mobile Boilers. E.g. marine and locomotive boilers.

6. Once through Boilers:

The boilers in which no circulation of water takes place i.e. the feed water leaves the tube as steam e.g. Benson Boilers.

7. Position and No. of Drums:

Single or multidrums may be positioned longitudinally or crosswise.

8. Design of gas passages:

a) Single pass

b) Return pass

c) Multipass

9. Nature of Draught:

a) **Natural Draught:**

when the fuel burns in the furnace of the boiler, with the circulation of air, the draught is named as Natural Draught.

b) **Artificial Draught:**

When the air is forced by means of forced fan, the draught is named as Artificial Draught.

10.Heat Source:

a) Combustion of solid, liquid or gaseous fuel.

b) Electrical and nuclear energy.

c) Hot waste gases of other chemical reactions.

11. Fluid Used:

a) Steam Boilers- use *water* as a fluid.

b) Mercury Boilers- use *mercury* as a fluid.

c) Other Boilers- use *special chemicals* as a fluid.

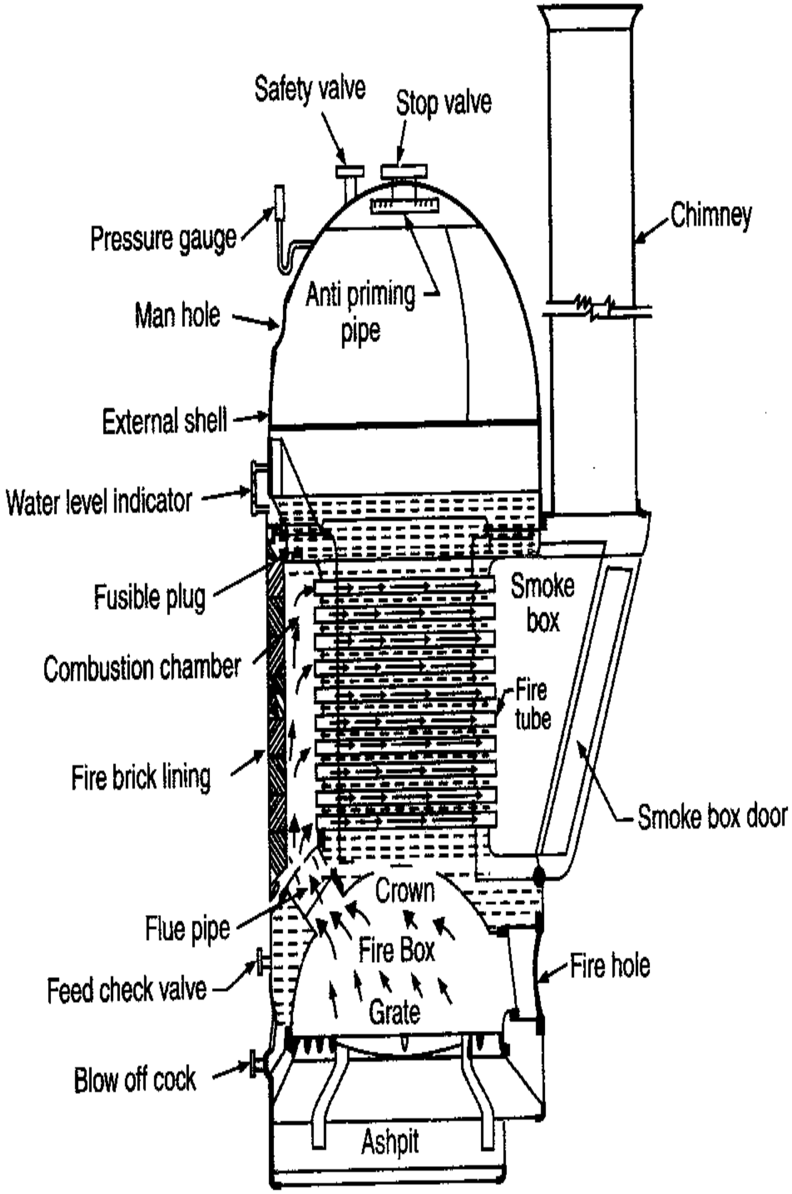
12. Material of construction of Boiler Shell:

a) **Cast Iron Boilers:** Low pressure heating Boilers.

b) **Steel Boilers:** Low pressure heating Boilers.

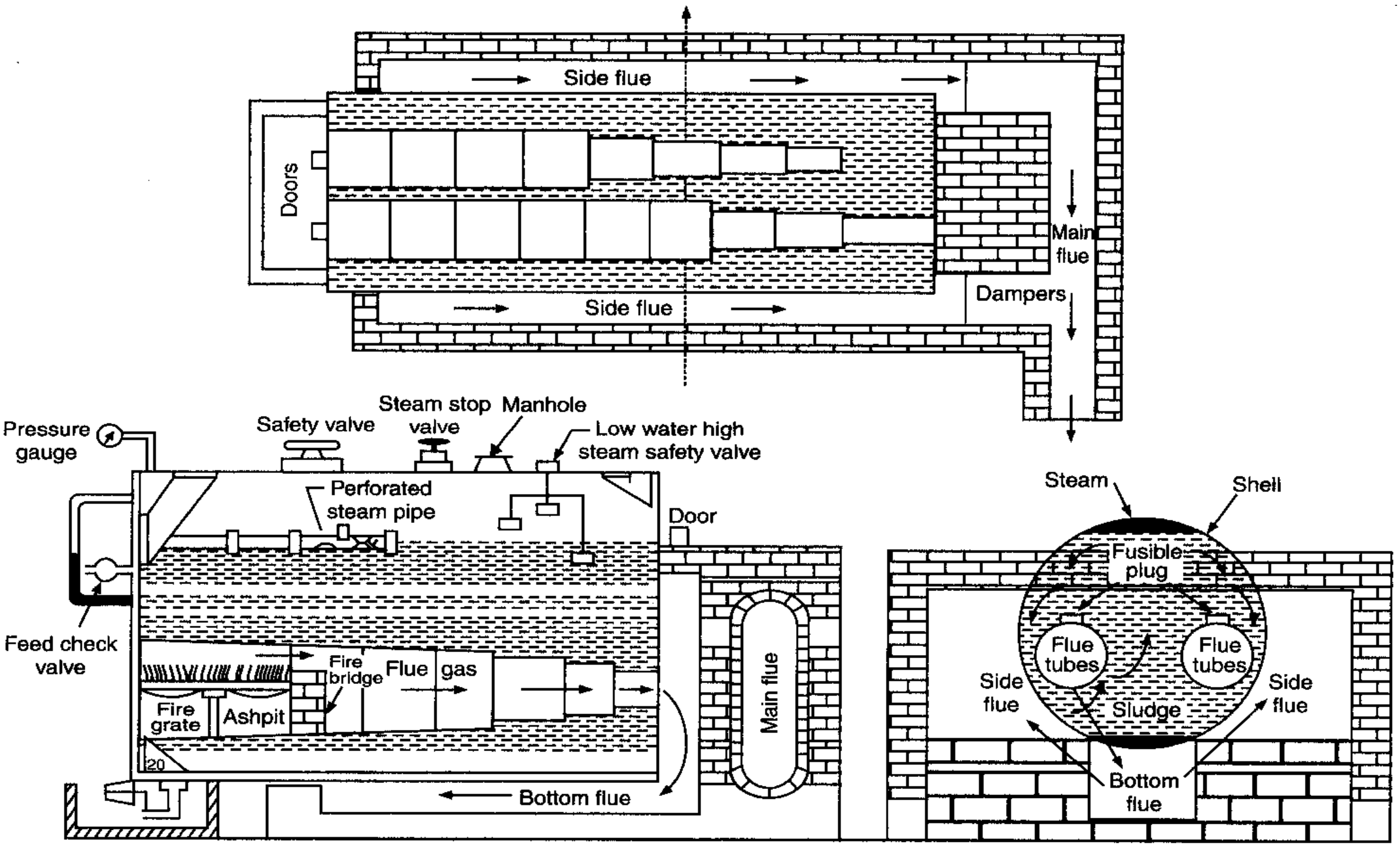
c) **Copper and Stainless steel Boilers:** Miniature Boilers.

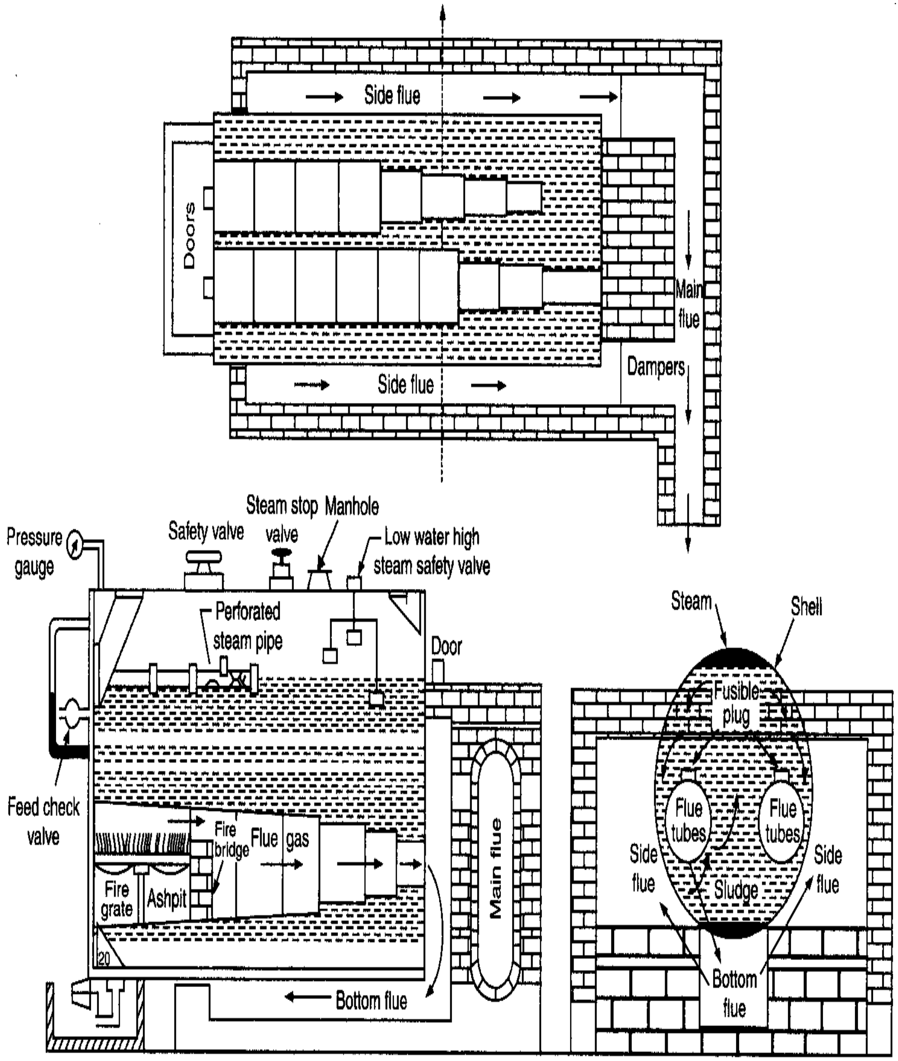
FIRE TUBE BOILER



- **Cochran Boiler**
- Simple vertical boiler
- Suitable for small plants require small quantity of steam.
- Size = 1 m Dia. x 2 m high *(evaporation 20kg/hr.)*
- Size = 3 m Dia. x 6 m high *(evaporation 3000kg/hr.)*
- Heating surface= 10 to 25 times of grate area
- Steam pressure= upto 20 bar
- Efficiency = 70 to 75%

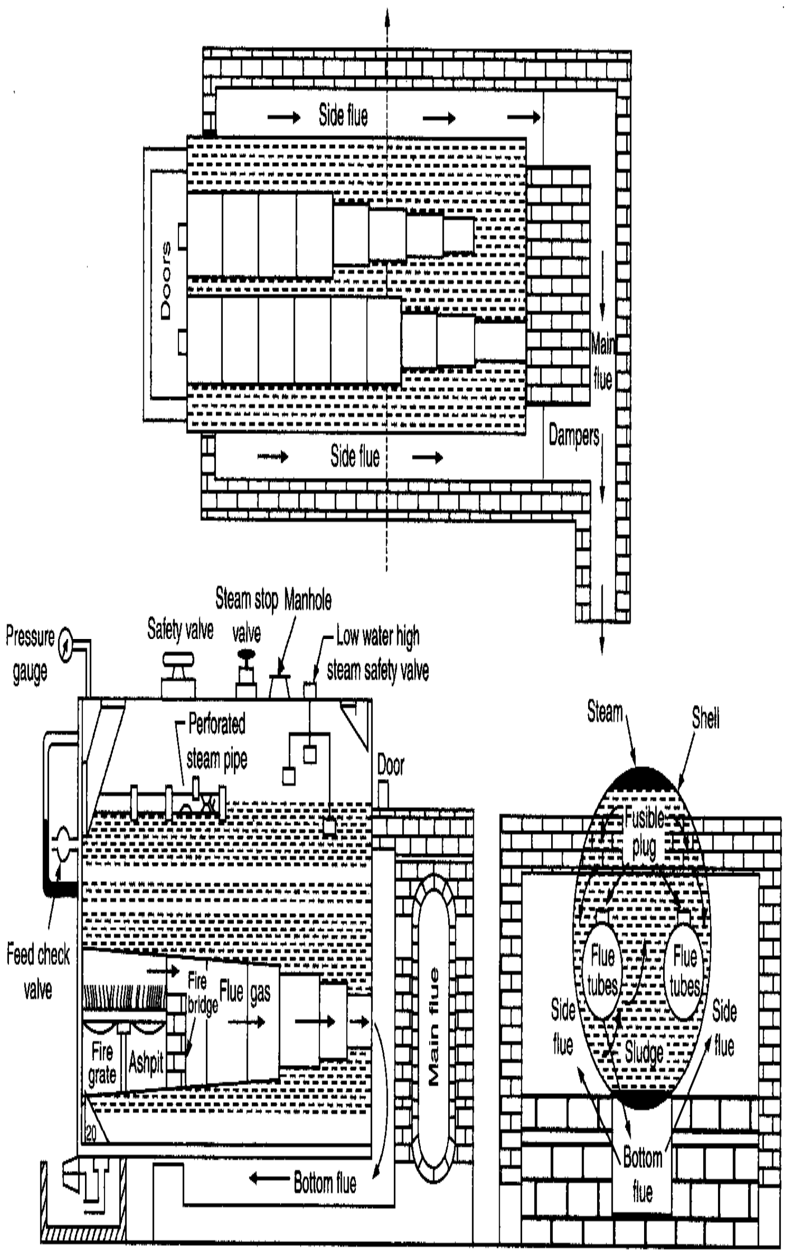
LANCASHIRE BOILER





LANCASHIRE BOILER

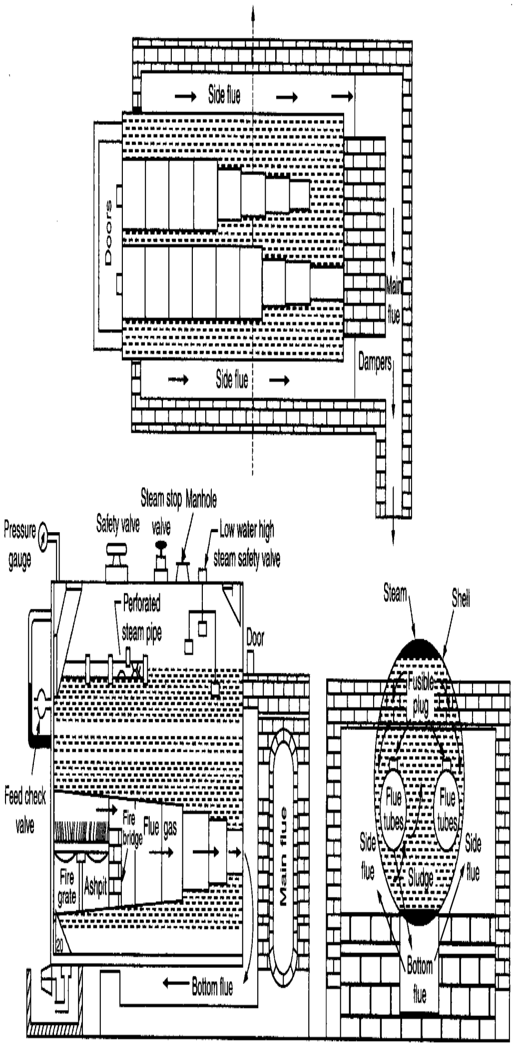
- Internally fired, horizontal, natural draft and natural circulation type boiler.
- Diameter of tubes is 0.4 times the diameter of shell.
- Each flue tube has its own furnace with grate of about 2 met. Length.
- Dampers are placed in the path of the flue gases to regulate gas flow and air inflow.
- Openings are made in the boiler for inspection.



LANCASHIRE BOILER

(Working)

- Flue gases traverse along the horizontal path.
- To the rear end → bottom common flue → travel back to front of the boiler → bifurcate→ pass into the two sides→ discharge to the atmosphere through chimney.
- Perforated feed pipe controls the feed water→ boiler strongly heated→ steam generates→ generated steam contains water particles→ water particles remove by passing through antipriming pipe→ steam taken to stop valve to supplied to steam engine.



LANCASHIRE BOILER

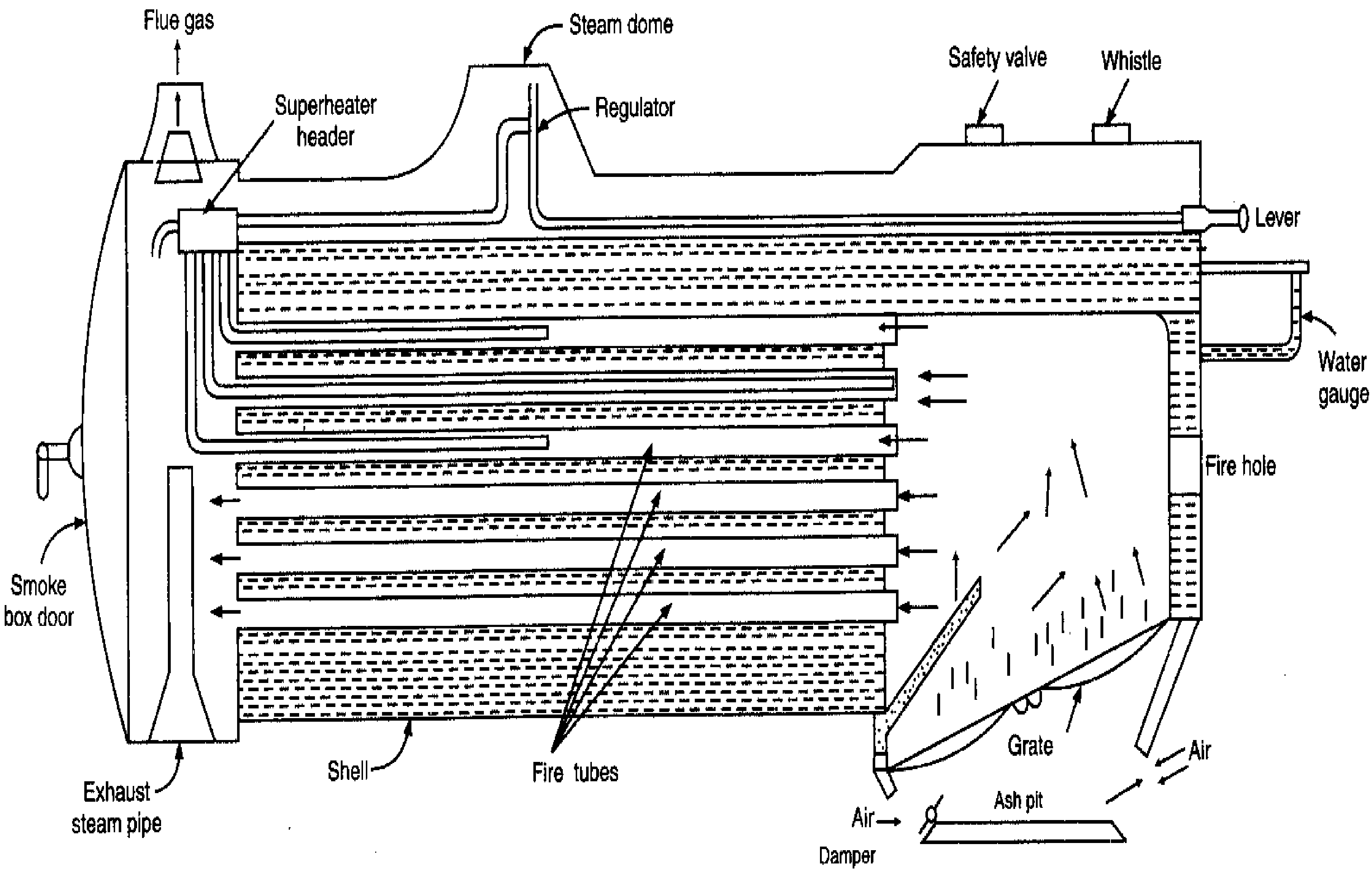
(Capacity and Utility)

- Made to withstand working pressure up to 20bar.
- Evaporative capacity 8000 kg/hr.
- Heating surface: grate area 24:30
- Shell size ranges from (2m diameter x 6m length) to (3m diameter x 10m length)
- Widely used in sugar mills, chemical plants, power systems, process works.

LANCASHIRE BOILER

S.No	Advantages	Disadvantages
1	Simplicity of design	Maximum working pressure is limited to 20 bar.
2	Good steaming quality	More floor area is required due to brick work setting.
3	Can burn coal of inferior quality	Cracks in setting due to large temperature difference inside and out side.
4	Easy to clean and inspect	Restricted grate area due to furnace being inside
5	Less maintenance and operating cost	More time taken for developing steam pressure due to large water capacity.
6	Stand against sudden heavy demand for considerable time without appreciable pressure drop.	

LOCOMOTIVE BOILER



LOCOMOTIVE BOILER

- Internally fired, horizontal, multitubular, natural circulation, artificial draft fire tube type portable boiler.

- **Dimensions and specifications:**

Length and diameter of barrel	: 5.203m and 2.095m
Size and number of super heater tubes	: 14 cm and 38
Size and number of fire tubes	: 5.72 cm and 116
Working pressure and capacity	: 14 bar and 9000 kg/hr.
Heating surface and grate area	: 271m^2 and 4.2 m^2

LOCOMOTIVE BOILER
(Utility/ Application)

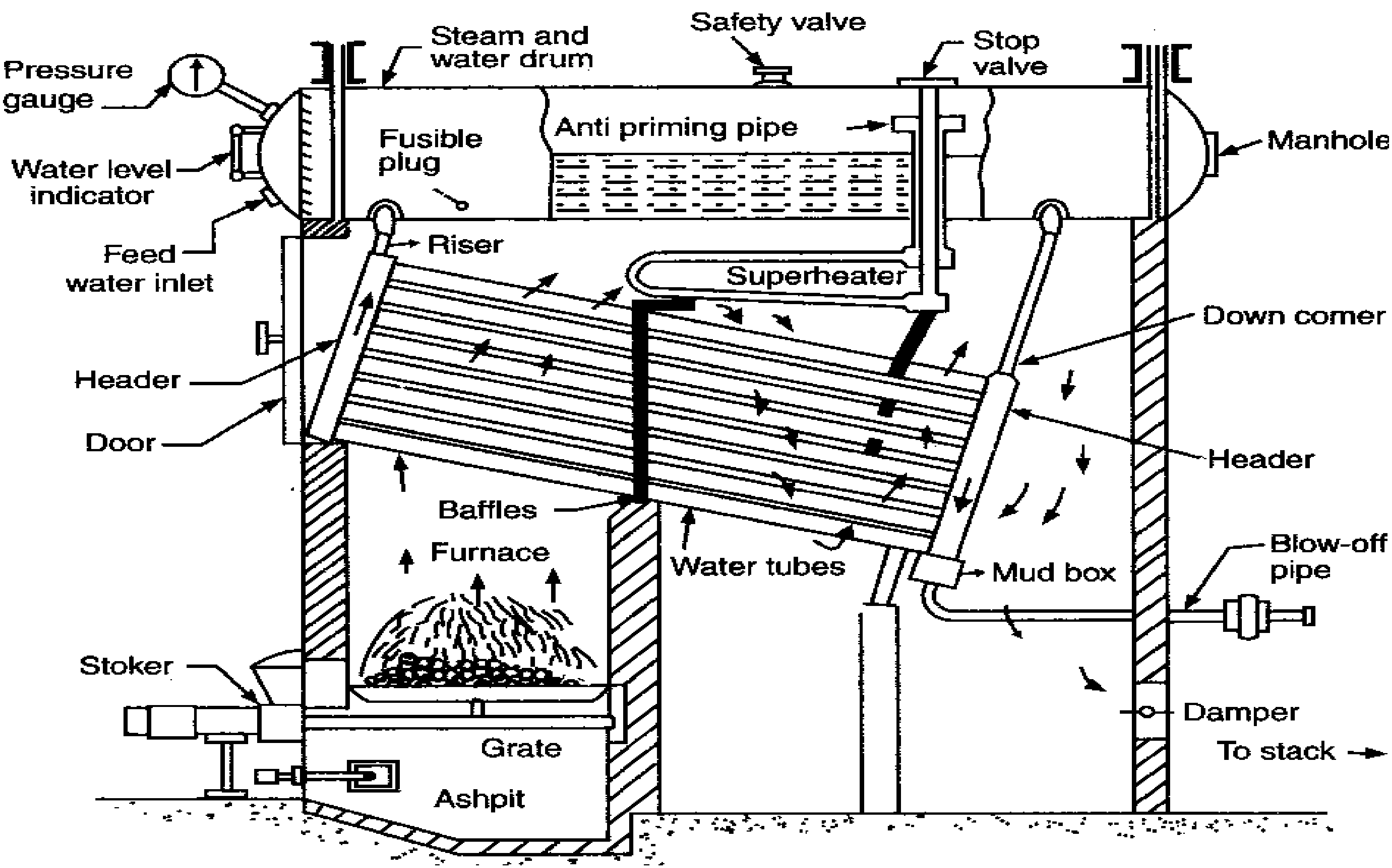
- The locomotive boiler is so designed that it is capable of meeting sudden and fluctuating demand of steam, which may be imposed due to variation in power and speed.
- Uses in railways, road rollers etc.
- Also used in agricultural fields, saw mill plants and stationary power services where semi- portability is desired.

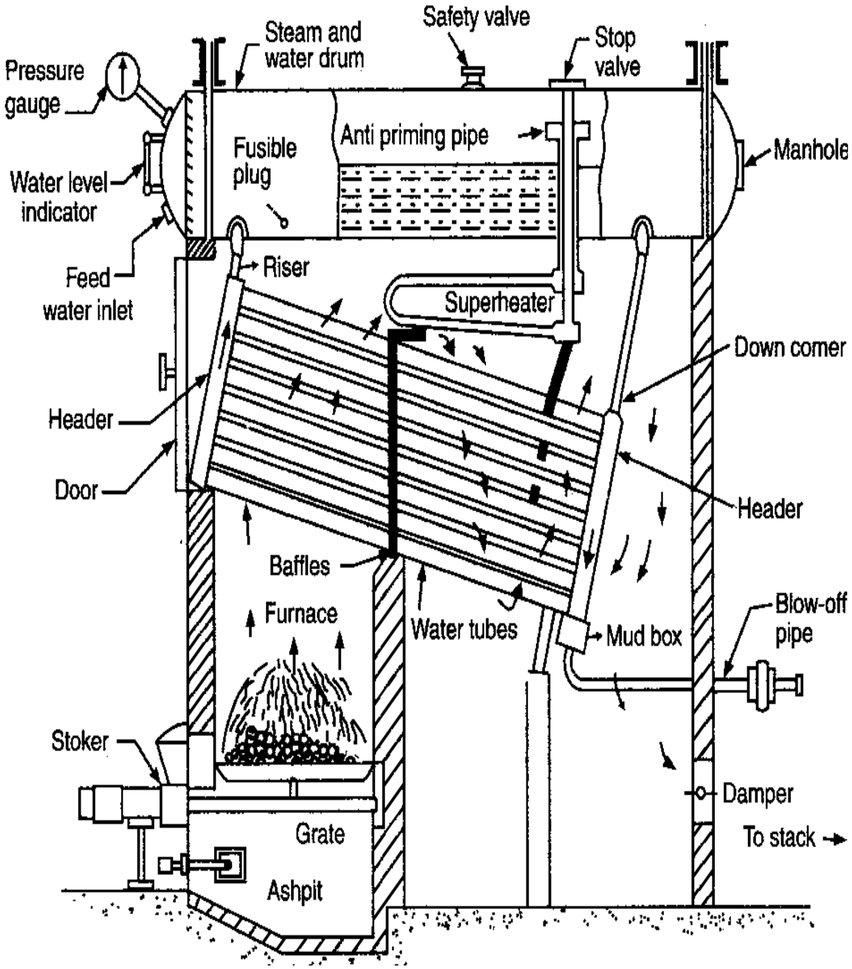
LOCOMOTIVE BOILER

Advantages	Disadvantages
Large rate of evaporation (55 to70kg/sec) per sq. met. Of heating surface.	Incapable of meeting very high overloads because of danger of being damaged due to overheat.
Freedom from brickwork, chimney and special foundations, which reduces the cost of installation.	Max. steam pressure is limited to 20 bar.
Reasonable low cost and compactness makes it ideal for portable unit.	Leakage occurs frequently at the place where the tube joins the plate.
	Large flat surface needs bracing
	Accumulation of mud particles in water lags cause scale formation.

WATER TUBE BOILERS

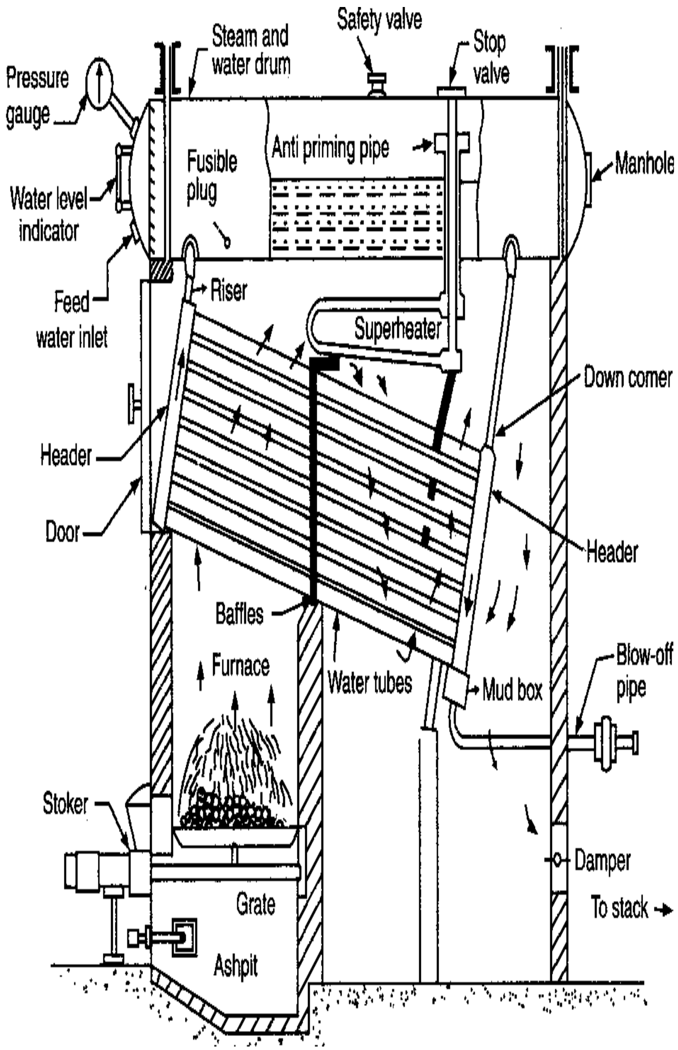
BABCOCK & WILCOX BOILERS





BABCOCK & WILCOX BOILERS
(Constructional features)

- It consist of welded steel high pressure drum mounted at the top.
- Drum is connected with uptake header and down take header.
- Water tubes connected to the headers are inclined at 15^0 to the horizontal.
- Water tubes are straight and 10cm diameter expended into the bored holes of header.
- Serpentine from of header provides complete heating surface to the flue gases.
- Furnace is arranged below the uptake header.



BABCOCK & WILCOX BOILERS
(Constructional features)

- Unit is provided with chain grate stroker.
- Speed of chain is adjusted with respect to the complete combustion of coal.
- Deflectors to flue gases are provided in the form of baffles.
- Mud Box: To collect the sedimentation in water.
- Super heater tubes: To enhance the super heated steam.
- Vents provided: safety valve, pressure gauge, water level indicator, fusible plug and feed check valve.
- Water tube and drum assembly hung on steel girder frame called slings.

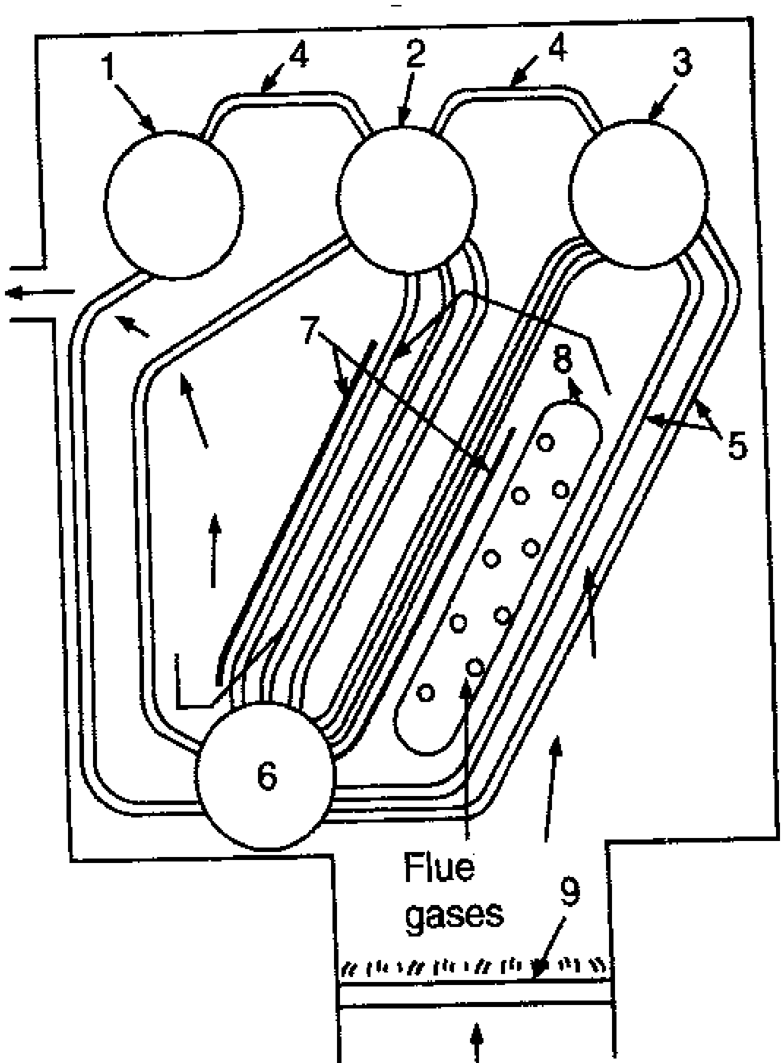
BABCOCK & WILCOX BOILERS
(Capacity and utility)

- Evaporative capacity ranges from 20000 to 40000 kg/hr
- Operative pressure ranges from 11.5 to 17.5 bar.
- Steam formed from such boilers are primarily used to run steam turbines and generate electric power.

BABCOCK & WILCOX BOILERS
(Salient Aspects)

- ✓ Capability to cope with high peak loads which are generally needed in thermal power stations.
- ✓ Inspection of the boiler can be carried even when the boiler is in operation.
- ✓ Draught loss is minimum.
- ✓ Replacement of defective tubes can be made easily.

STIRLING BENT- TUBE BOILER



1. 2 and 3 drums
5. Water tubes
7. Baffles
9. Fire grate
4. Equalising tubes
6. Mud drum
8. Superheater

STIRLING BENT- TUBE BOILER

1. Drums are interlinked to each other with bent water tubes for the following reasons:

a) To allow free expansion and contraction of the tubes.

b) Tube replacement become easier.

c) Flexibility in design with regards to location of drums.

d) Tubes can enter the drums in approximately radial direction.

2. Mud drum is usually 10 to 25cm larger in diameter than a steam drum.

3. Entire unit is independent of brick work.

4. High steam pressures (60bar and 450^{0}c).

5. Evaporation capacity up to 50000kg/hr.

COMPARISION Between WATER TUBE & FIRE TUBE BOILERS

(Dec05,Dec08)

WATER TUBE	FIRE TUBE
Water passes through water tubes.	Hot gases passes through flues.
Water content: steam capacity low (high speed)	Water content: Steam capacity high (Slow speed)
Complexity in design requires quick examination by skilled hands.	Simple & rigid construction hence greater reliability & low operating cost.
Operating pressure up to 200 bar.	Pressure ranges from 17.5 bar to 24.5 bar
Evaporation rate ranges from 20,000 to 50,000kg/hr.	Evaporation rate 900kg/hr.
Increased heating surface area.	Low heating surface area.
Low water to steam ratio	Large water to steam ratio
Bigger in size, suitable for large power plants	Smaller in size, used only for small power plants
Transportation and installation is easy due to handling of dismentaled parts	Transportation and installation is difficult due to large size of shell.
Externally fired boilers, furnace size can be varied.	Internally fired boilers, furnace size can not be varied.
Requires more floor area	Requires less floor area

ESSENTIALS OF A GOOD BOILER

?

ESSENTIALS OF A GOOD BOILER

1. **Heat generation capability should be at:**
   a) Required pressure
   b) Required quality
   c) Fast speed
   d) Minimum fuel consumption

2. **Economic :**
   a) Low initial cost
   b) Low installation cost
   c) Low operating cost
   d) Low maintenance cost

ESSENTIALS OF A GOOD BOILER

3. Construction:

a) Light in weight

b) Less amount of brick work

c) Occupy small floor area

4.Quick starting.

5.Capable to meet fluctuating demand of steam supply.

6. Easy availability of spare parts

BOILER MOUNTINGS AND ACCESSORIES

?

Boiler Mountings:

The necessary devices installed or mounted for the ***safety*** of boiler and its ***control*** are called boiler mountings.

Boiler Accessories:

The devices which are installed in the boiler for their ***efficient operation*** and ***smooth working*** are called Boiler Accessories.

Boiler Mountings for safety:

1. Two water level indicators – 2
2. Two safety valves.
3. Combined high steam and low water safety valve.
4. Fusible plug.

Boiler Mountings for control:

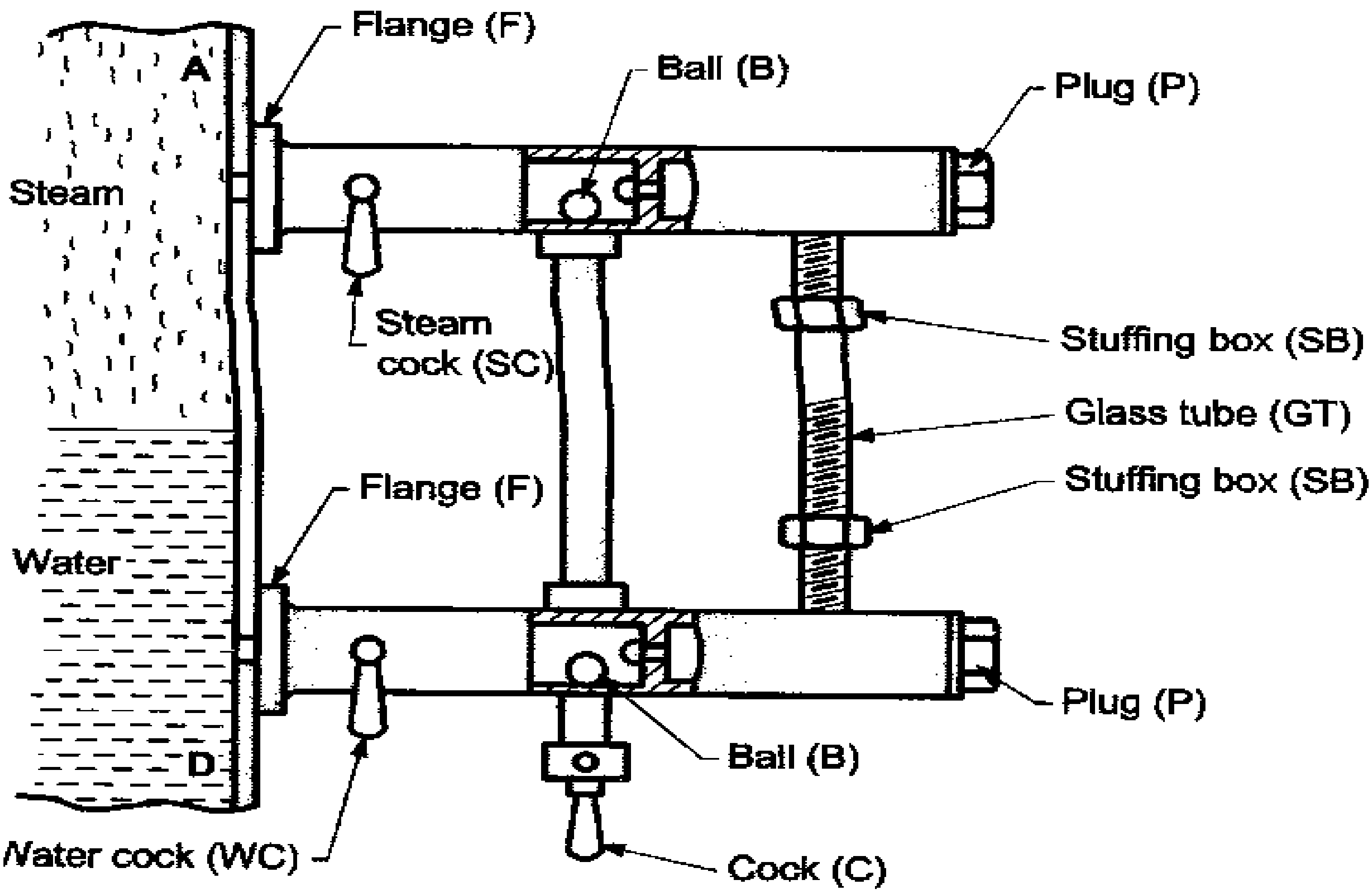
1. Pressure gauge
2. Junction or stop valve
3. Feed check valve
4. Blow-off cock
5. Man hole and mud hole

Boiler Accessories for efficient operation:

1. Water heating devices.
2. Water feeding devices.
3. Super heater
4. Economizer
5. Air preheater

BOILER MOUNTINGS

1. WATER LEVEL INDICATOR (Dec 05, Dec 08)



2. PRESSURE GAUGE

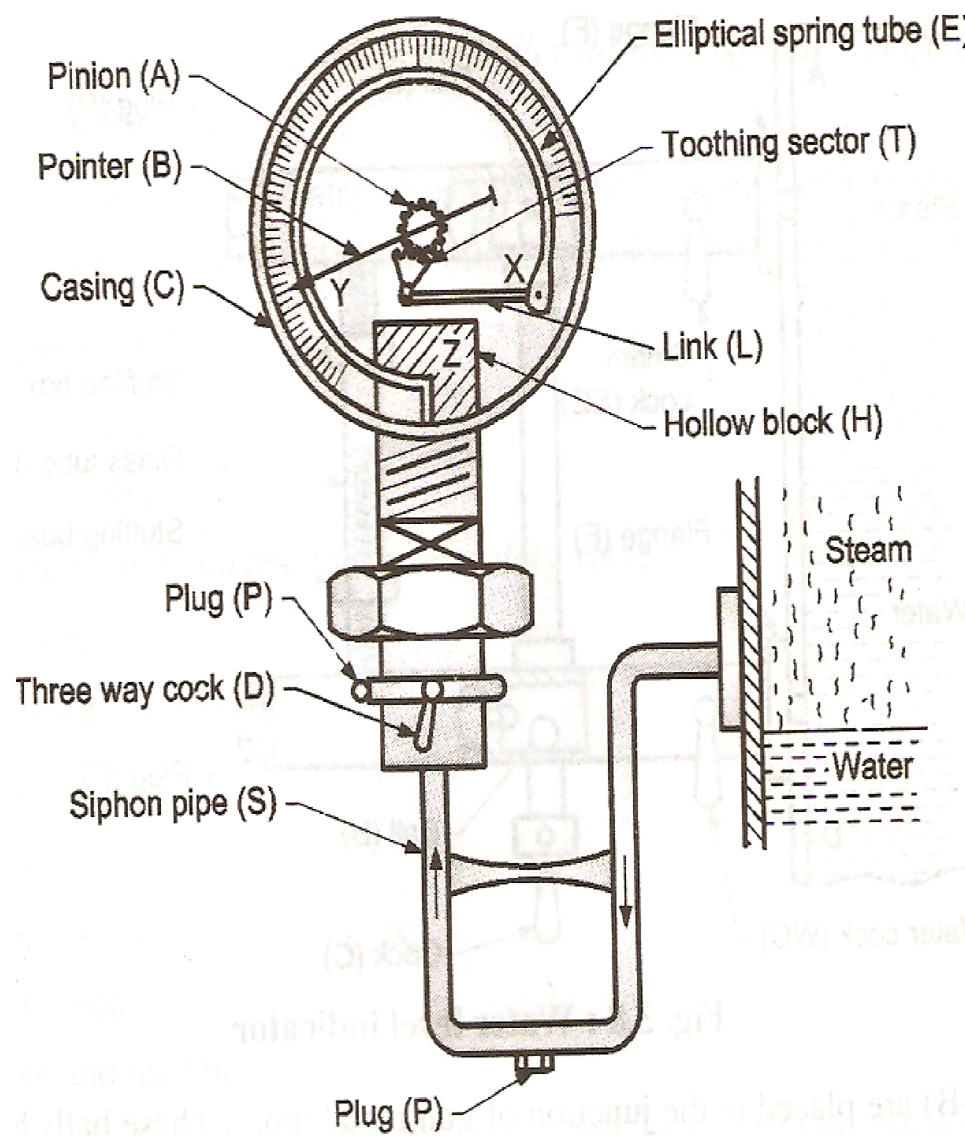
(*Bourdon's*) (Dec 05)

a) Records gauge pressure

b) Elliptical spring tube is also called Bourdon tube and is made up of special quality Bronze.

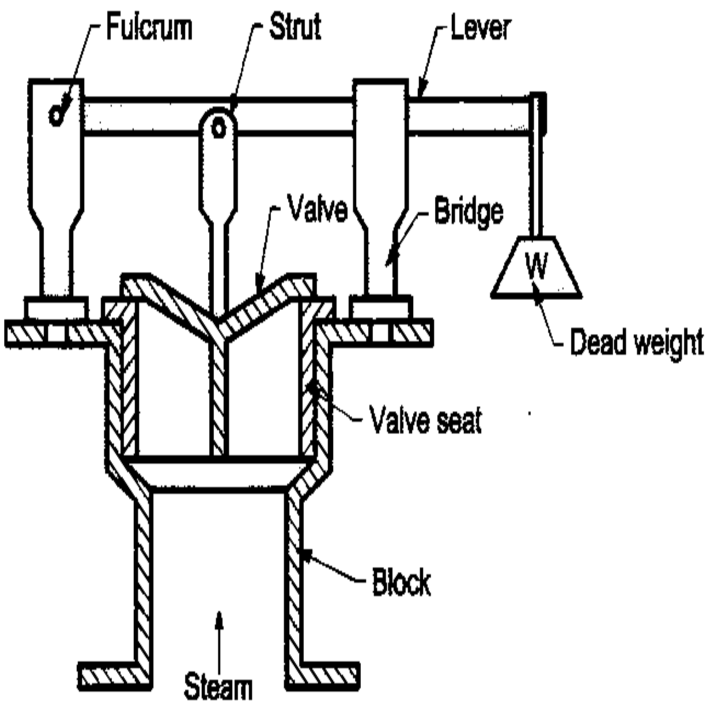
c) Plug (P) is provided for cleaning the siphon tube.

d) Siphon is filled with cold water to prevent the hot steam entering into the bourdon tube and spring tube remains comparatively cool.

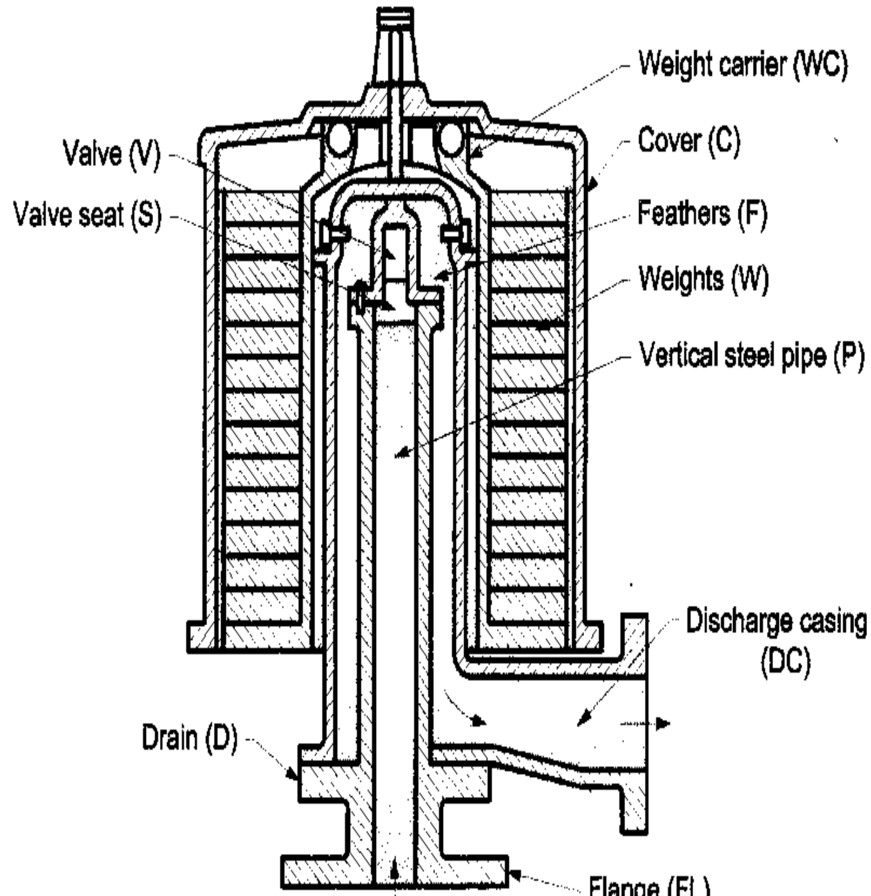


SAFETY VALVES

LEVER SAFETY VALVE

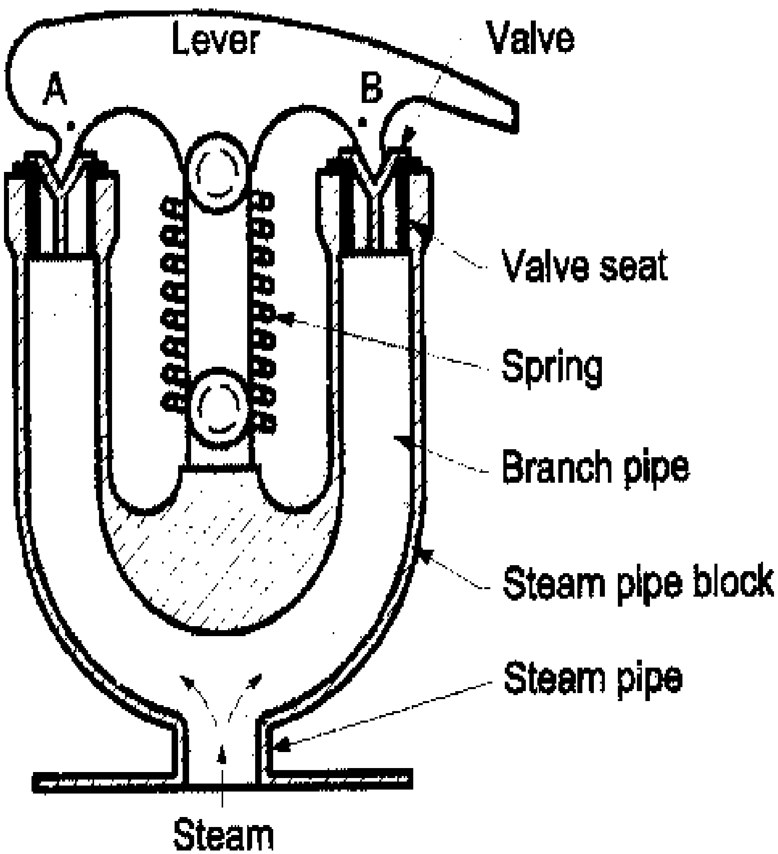


Dead Weight safety valve

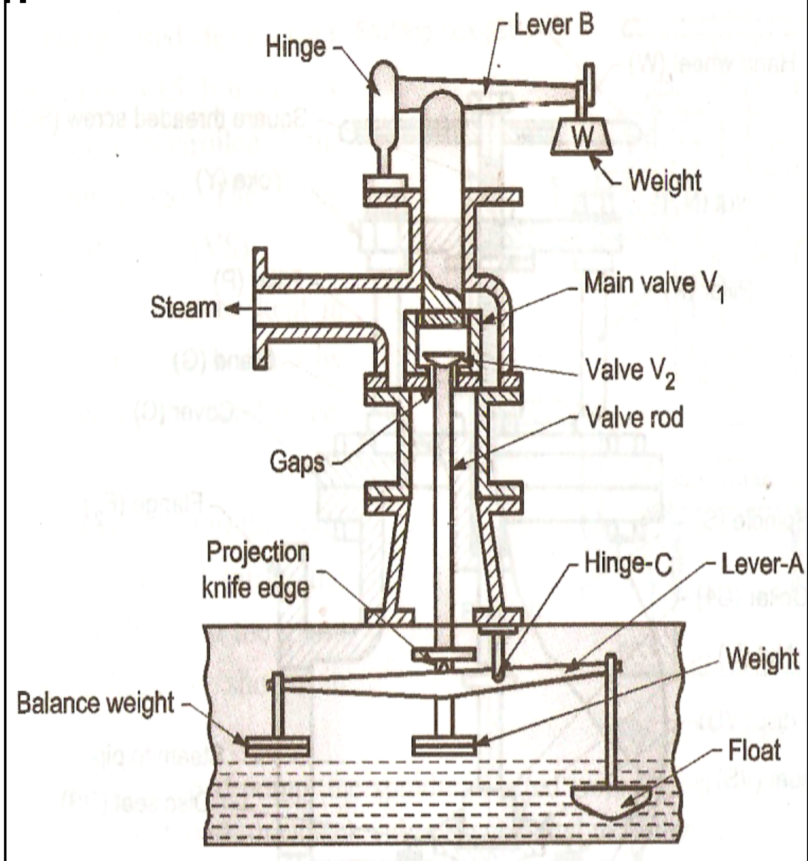


SAFETY VALVES

SPRING LOADED SAFETY VALVE



HIGH STEAM AND LOW WATER SAFETY VALVE



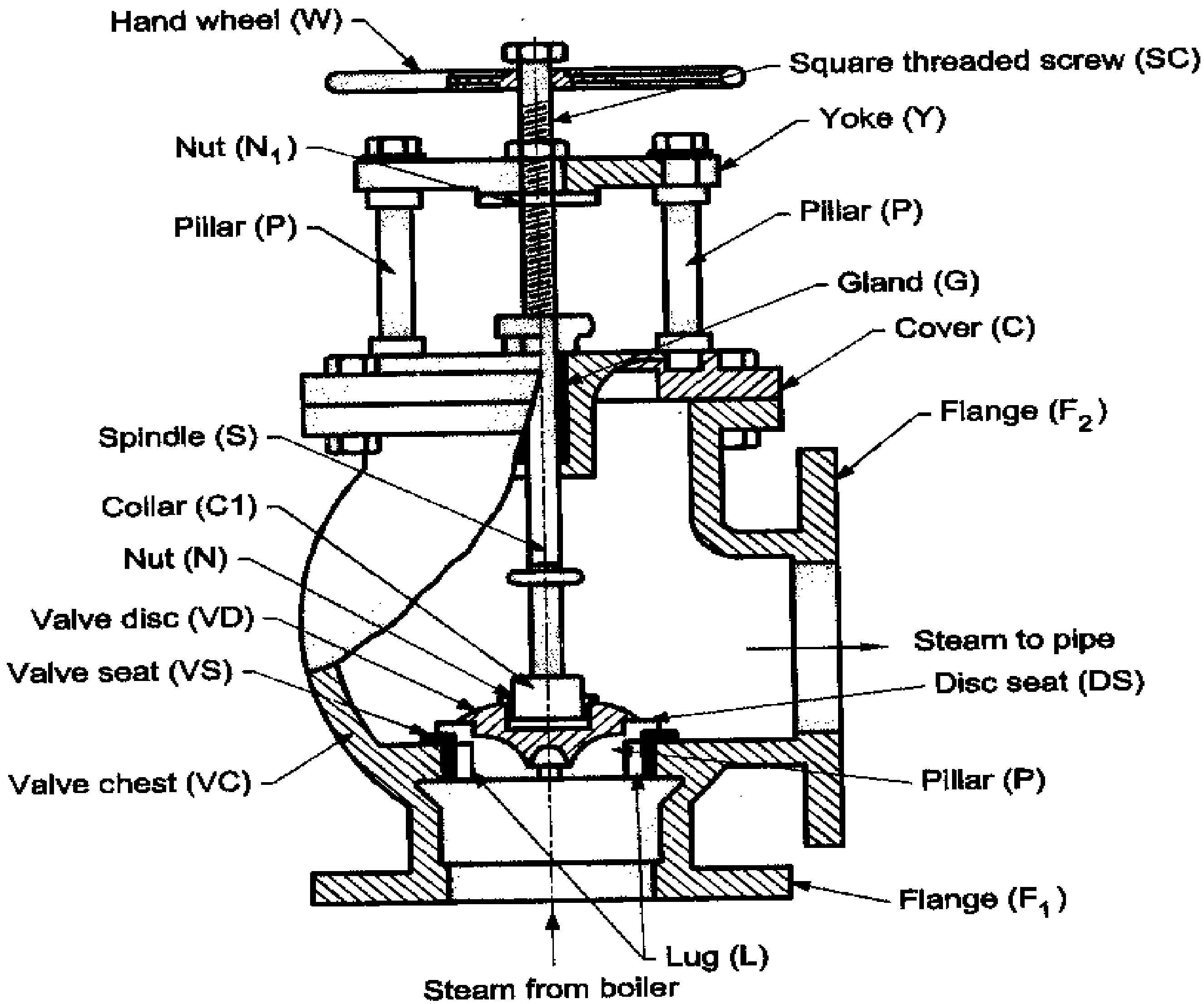
JUNCTION VALVE:

The valve placed directly on a boiler in order to regulate the steam supply from boiler to steam pipe is called the *Junction Valve*.

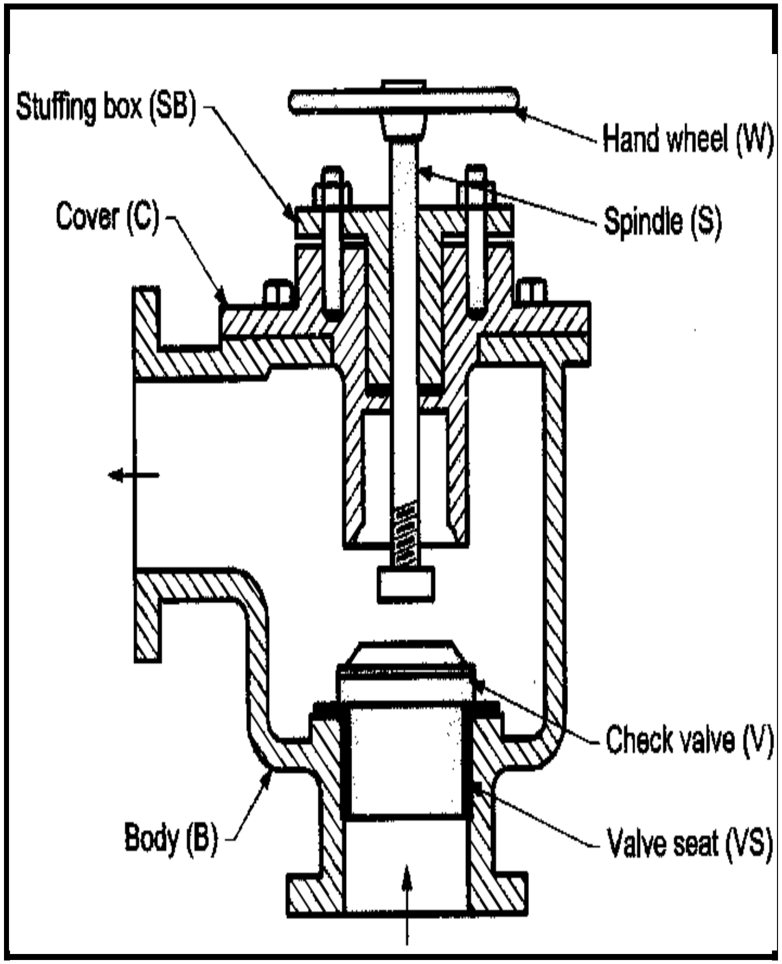
STOP VALVE:

The valve used to regulate the steam supply from the steam pipe to the prime mover (steam engine or steam turbine) is called *Stop Valve*.

JUNCTION VALVE

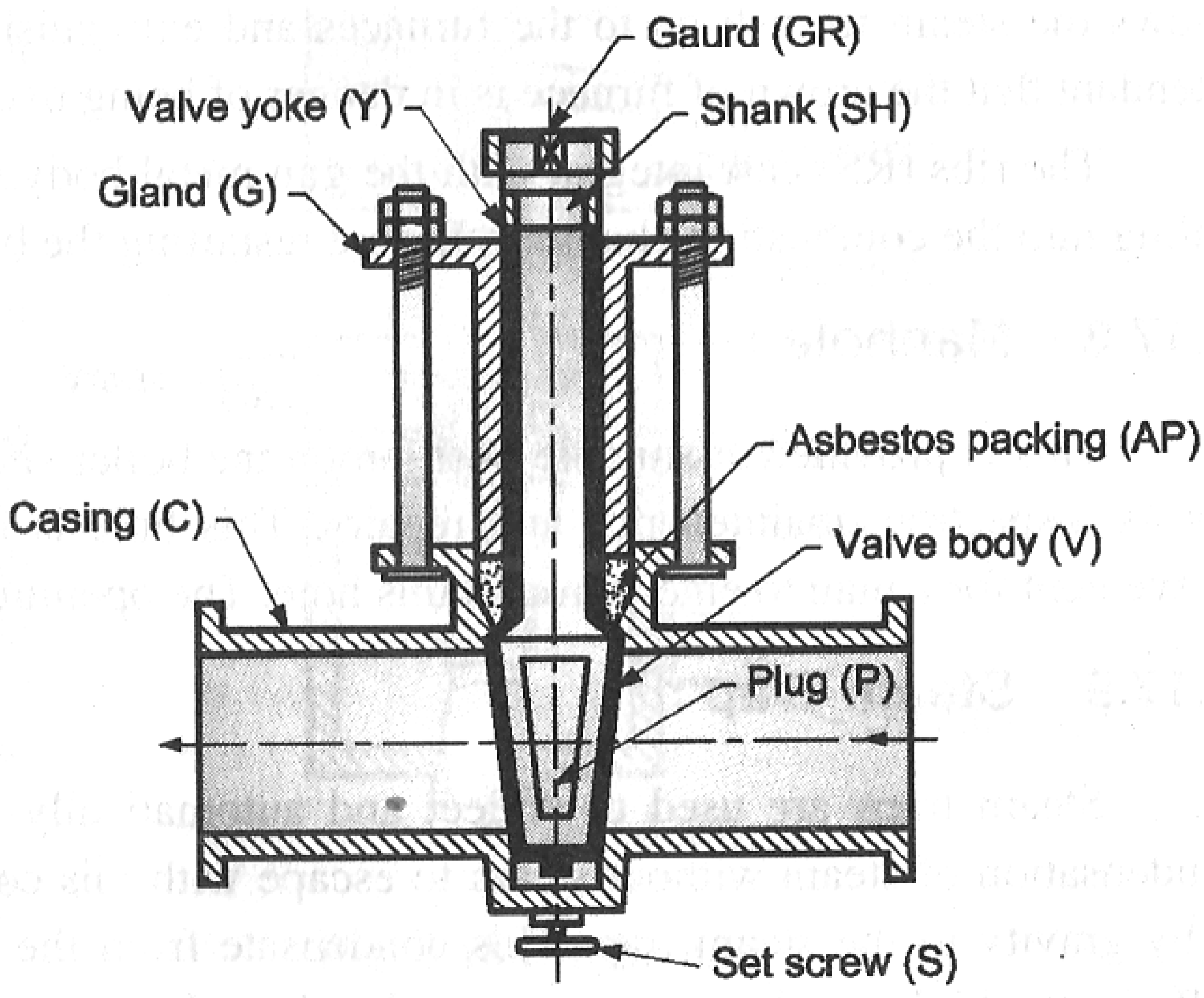


FEED CHECK VALVE

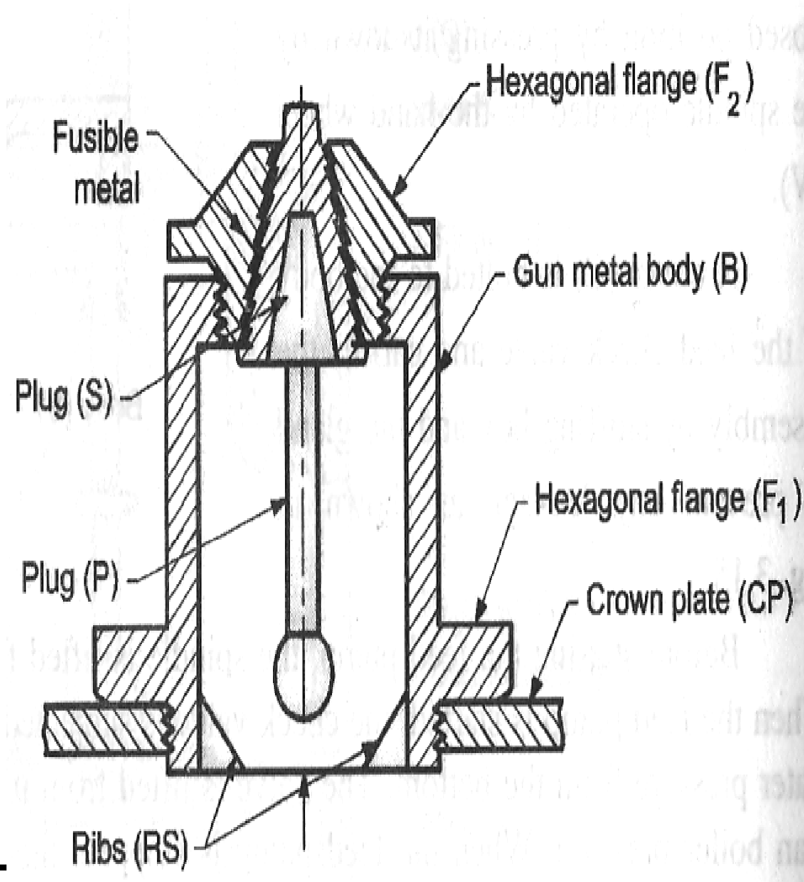


1. Feed check valve works as NRV (Non- return valve).
2. Prevents the back flow of water from the boiler when the feed water pump is either not working or in case of its failure.

BLOW-OFF COCK



FUSIBLE PLUG



- Plugs P and R are made up of Gun Metal.
- Plug S is made up of Copper.
- Plug R is screwed to the plug P.
- Plug S is locked into plug R by a metal like tin or lead.

MANHOLE

This is provided at suitable position on the boiler shell so that the man can enter into boiler shell for inspection, maintenance and repairs. This hole is usually made in elliptical shape of the size convenient for a man to enter through this hole. The opening is closed by steam tight cover.

STEAM TRAP

Steam trap is used to collect and automatically drain away the water resulted from partial condensation of steam without steam to escape with this condensate through a valve. The valve after draining the condensate is closed. Is presses the leakage of steam from the trap.

ANTIPRIMING PIPE

It is attached below the stop valve to avoid the water particles being carried away along with steam. It has closed pipe with closed ends of 1m and 2m length. The top side of the pipe has perforations. When the steam passes through it, due to inertia effect, the moisture of steam falls into the pipe and the steam with reduced moisture passes into the stop valve.

BOILER ACESSORIES

The devices used to improve the performance and operation of the boilers are called boiler accessories. Main accessories used are:

(UPTU-Dec 04,Dec 05)

BOILER ACCESSORIES

- **WATER HEATING DEVICES**

(UPTU- Dec 05)

Used to heat the feed water before it is fed to boiler with the help of steam of a steam engine.

Heating of feed water can be carried out either by:

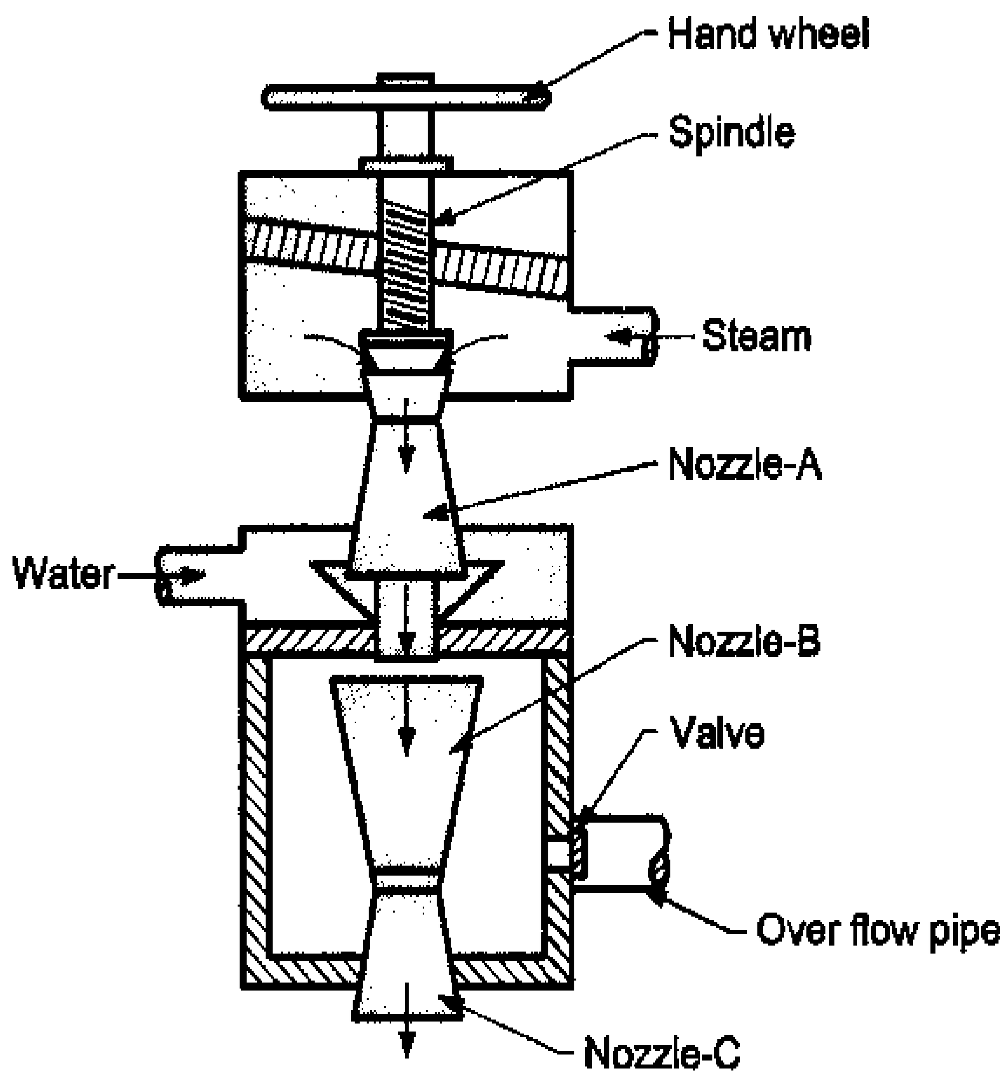
1. Open Heater- Direct mixing
2. Closed heater- Indirect convection

WATER FEEDING DEVICES

Used to supply water while the boiler is in operation. These devices include the use of feed pumps either reciprocating type or centrifugal type.

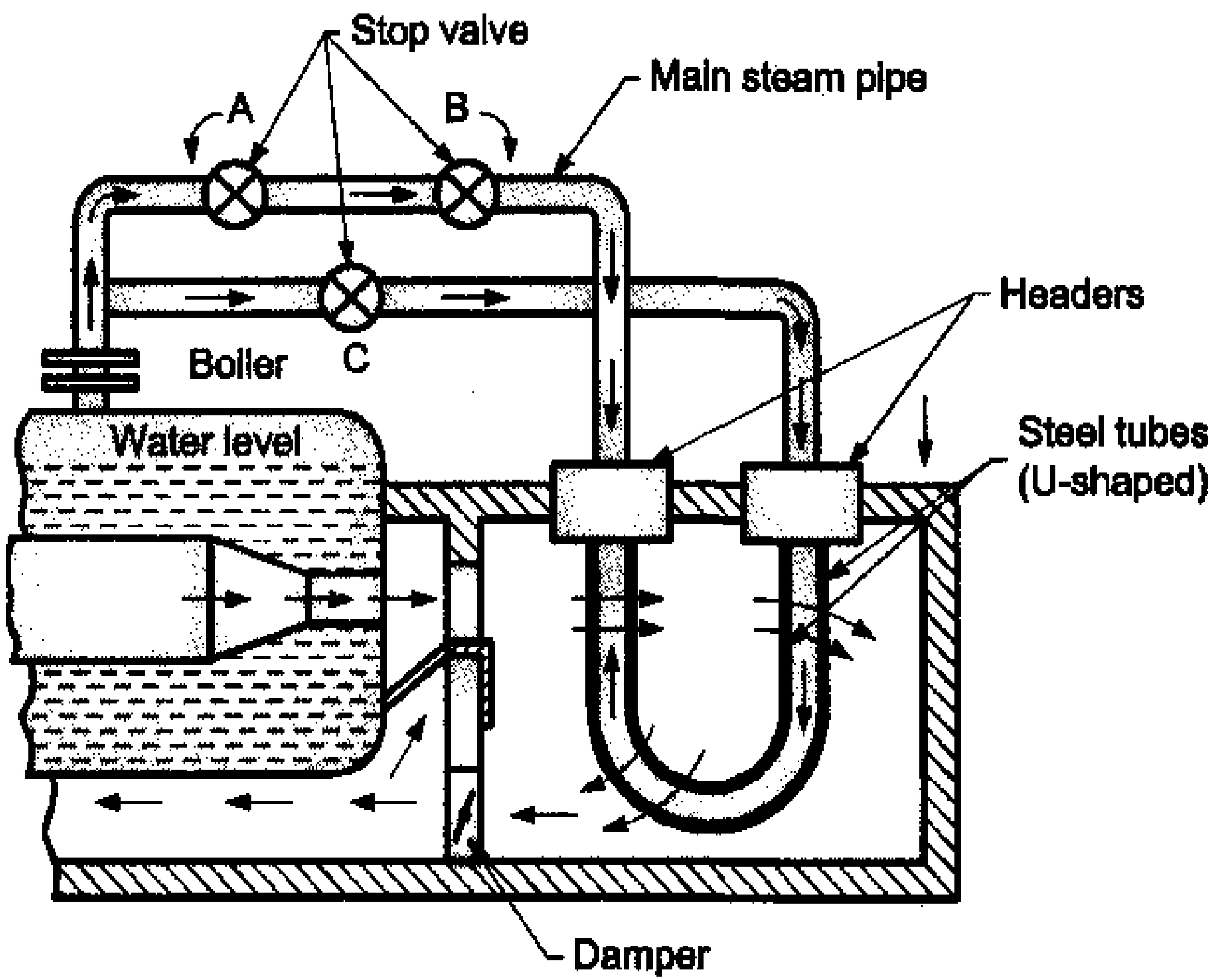
INJECTOR

(UPTU-Dec 04, Dec 05, Dec o6)

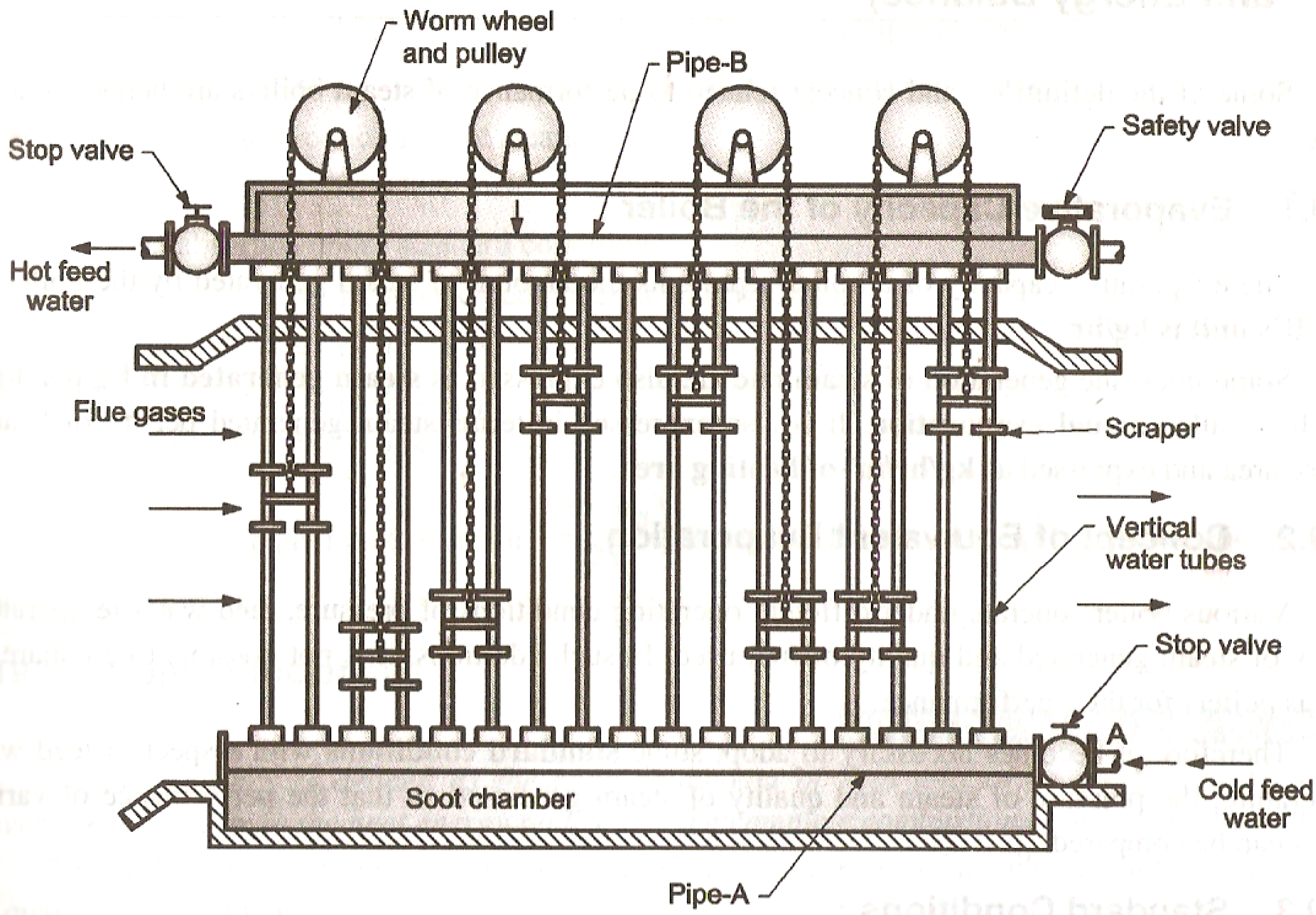


SUPER HEATERS

(UPTU-Dec 04, Dec 05, Dec 06)



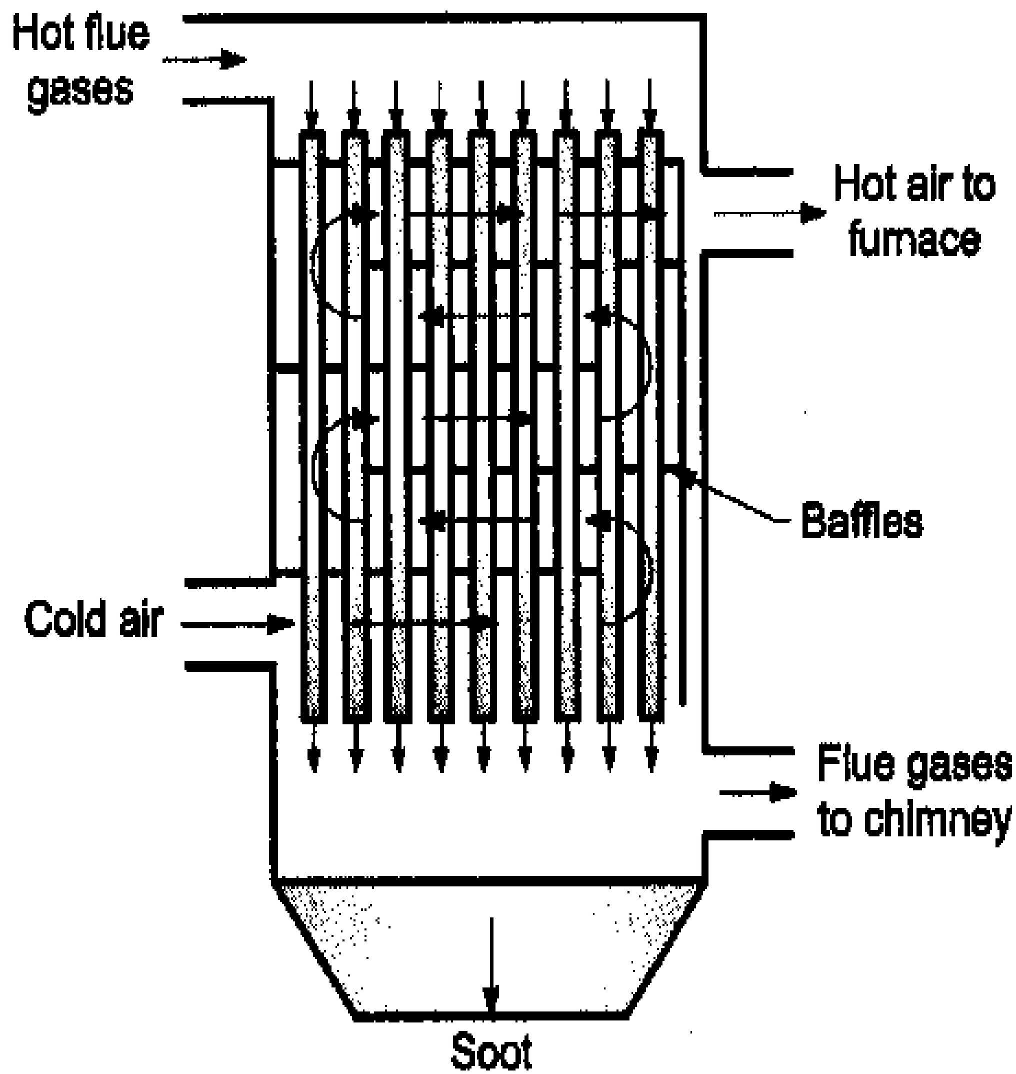
ECONOMISER



Worm wheel
and pulley
Pipe-B
Stop valve
Safety valve
Hot feed
water
Flue gases
Scraper
Vertical
water tubes
Stop valve
A
Cold feed
water
Soot chamber
Pipe-A

AIR PREHEATER

(UPTU- Dec 05)



STELLA MARYS COLLEGE OF ENGINEERING

ME8595

THERMAL ENGINEERING – II

UNIT III

STEAM TURBINES

Types, Impulse and reaction principles, Velocity diagrams, Work done and efficiency – optimal operating conditions. Multi-staging, compounding and governing.

Steam turbine

✓ **Definition:**

A turbine may be defined as, "*the turbine is a prime mover in which a rotary motion is obtained by centrifugal force brought into action by changing the direction of a jet or a fluid escaping from a nozzle at high velocity.*"

Classification of Steam Turbine :

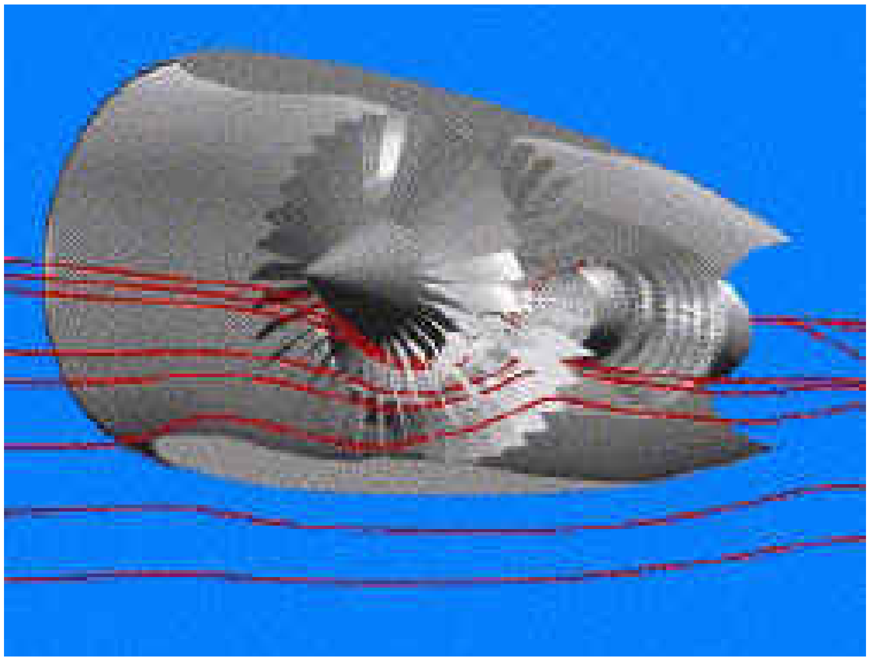
- **Classification of Steam Turbine :**
- Steam turbines are classified according to :

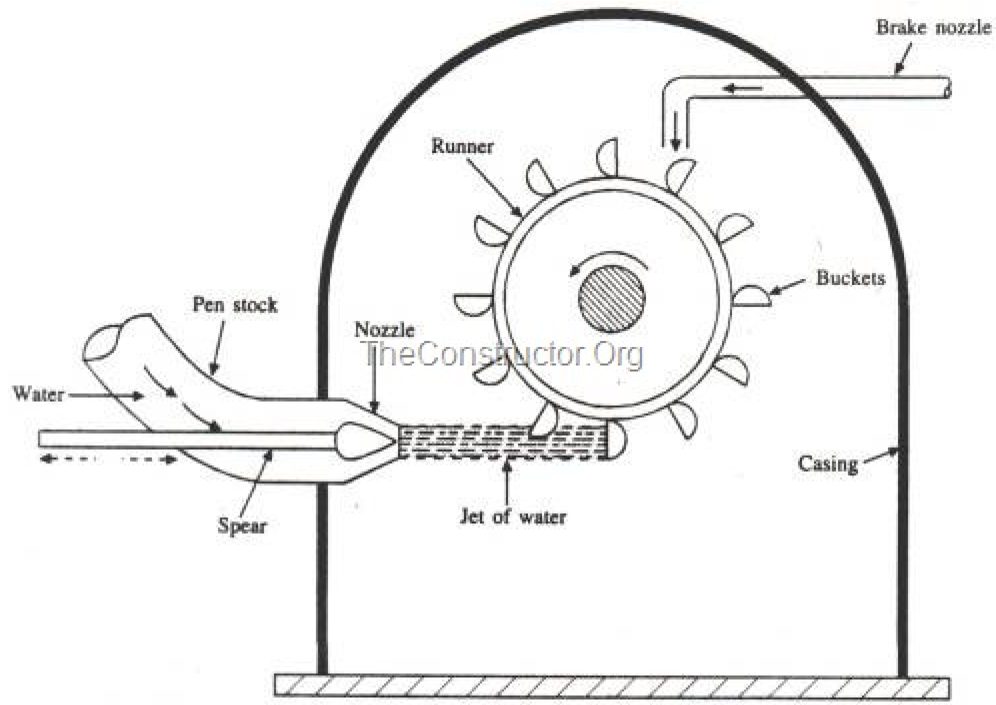
Principle of action of steam
a. Impulse turbine
b. Reaction turbine

Direction of steam flow
a. Axial
b. Radial
c. Tangential

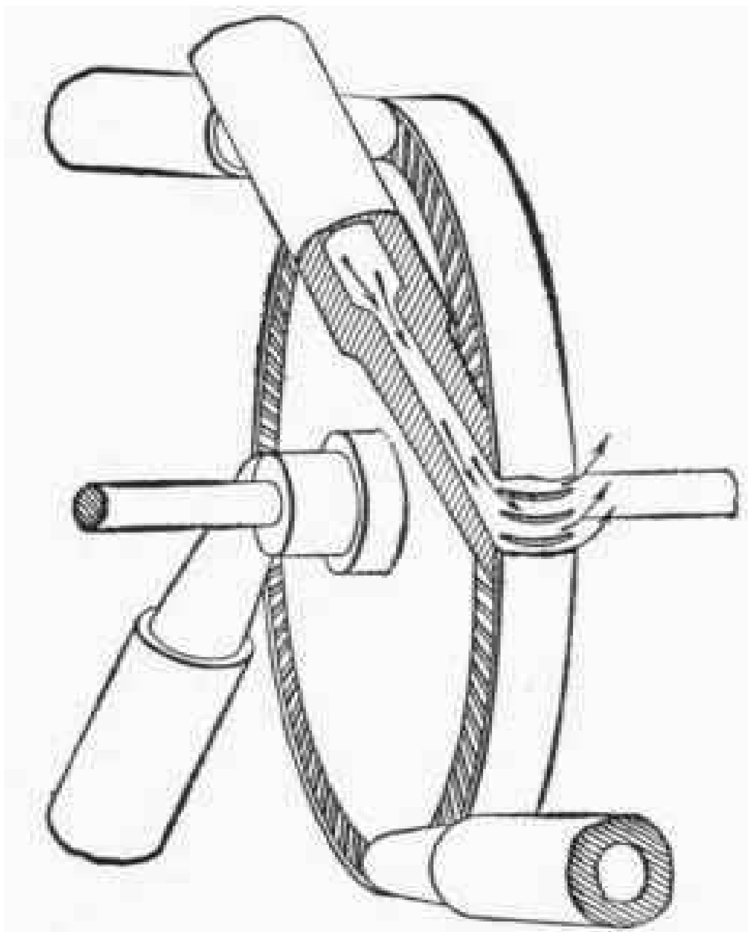
Number of pressure stages
a. Single stage
b. Multi stage

Method of governing
a. Throttle
b. Nozzle
c. By-pass
d. Combination of throttle , nozzle by pass



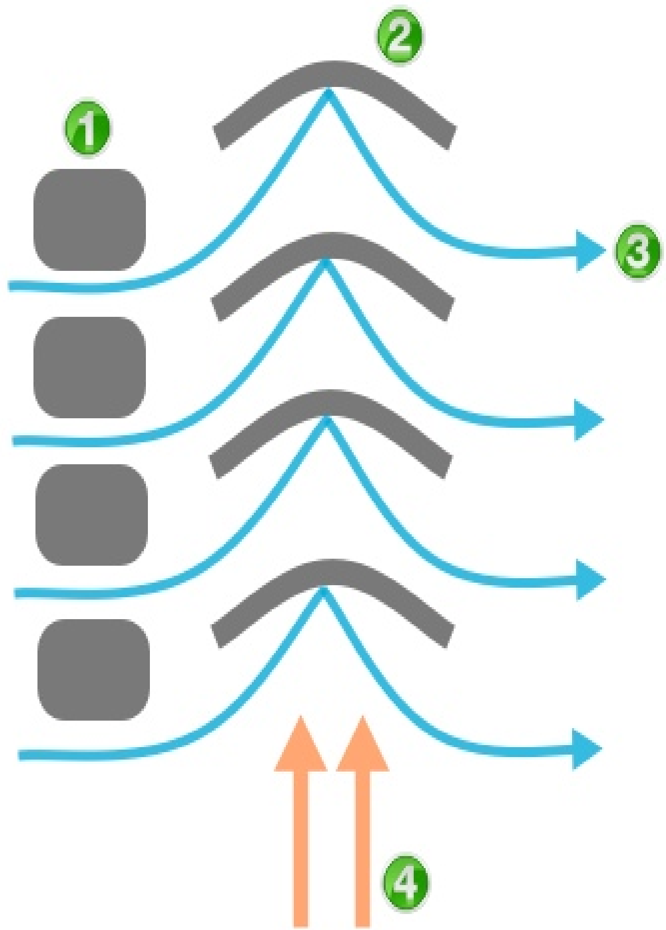

Brake nozzle
Runner
Buckets
Pen stock
Nozzle
TheConstructor.Org
Water
Casing
Spear
Jet of water

Impulse turbine



impulse turbine

- **impulse turbine** is a type of steam turbine where the rotor derives its rotational force from the impact force, or the direct push of steam on the blades.
- The impulse turbine was first built in 1883 by the Swedish engineer De Laval.
- The impulse turbine consists of a rotor mounted on a shaft that is free to rotate.
- Attached to the rotor are a set of curved blades. Nozzles then direct the high pressure and high temperature steam towards the blades of the turbines.
- The blades catch the impact force of the rapidly moving steam and rotate from this force.
- Below is a simple diagram of impulse turbine blades:

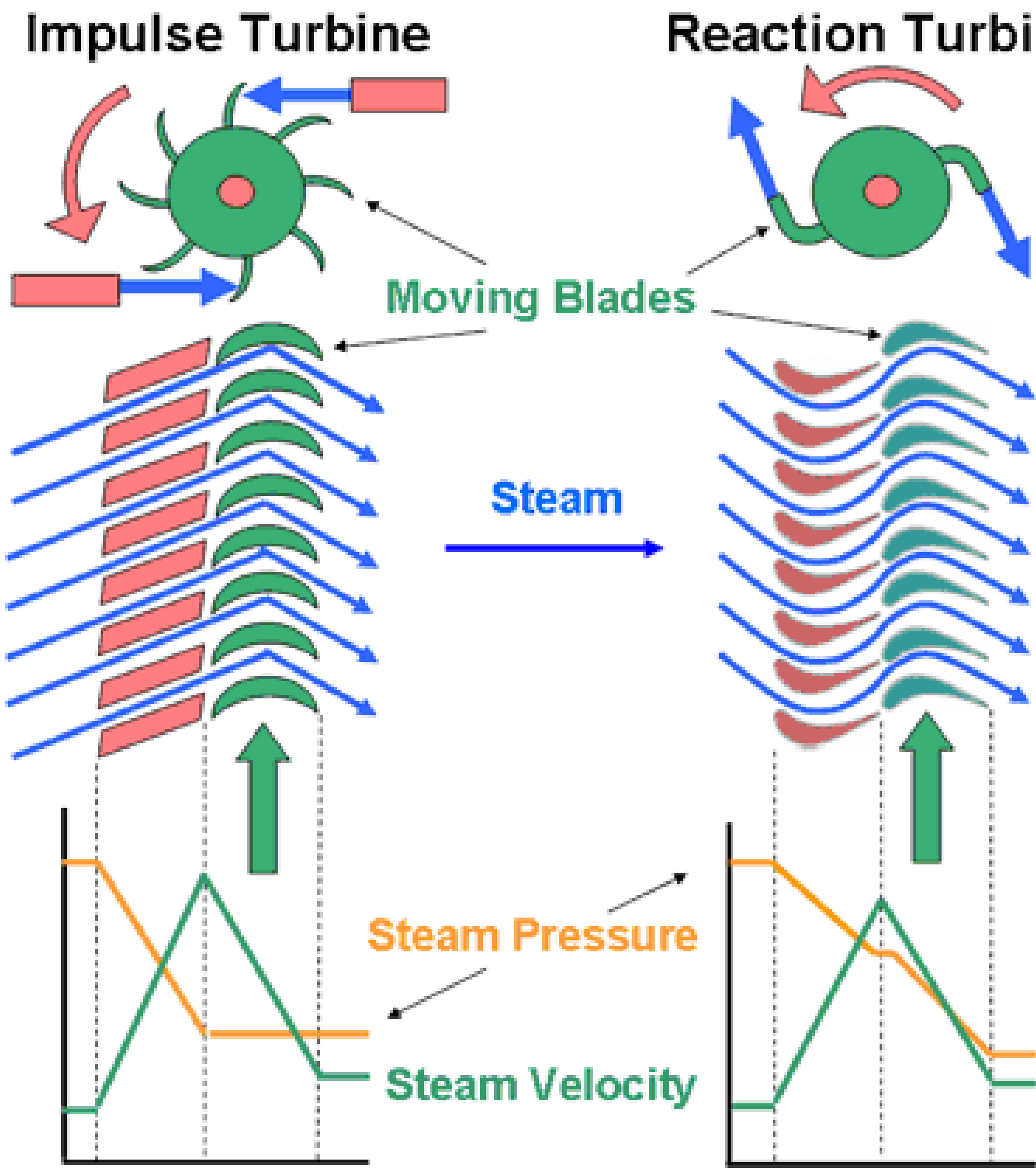


(1) The steam first enters the impulse turbine through a fixed Nozzle.

(2) The steam strikes the blades that are free to rotate with a strong enough force to move the blades.

(3) The steam exits the blade towards the condensing system of the steam turbine generator system.

(4) The direction of the blades due to the force of steam.



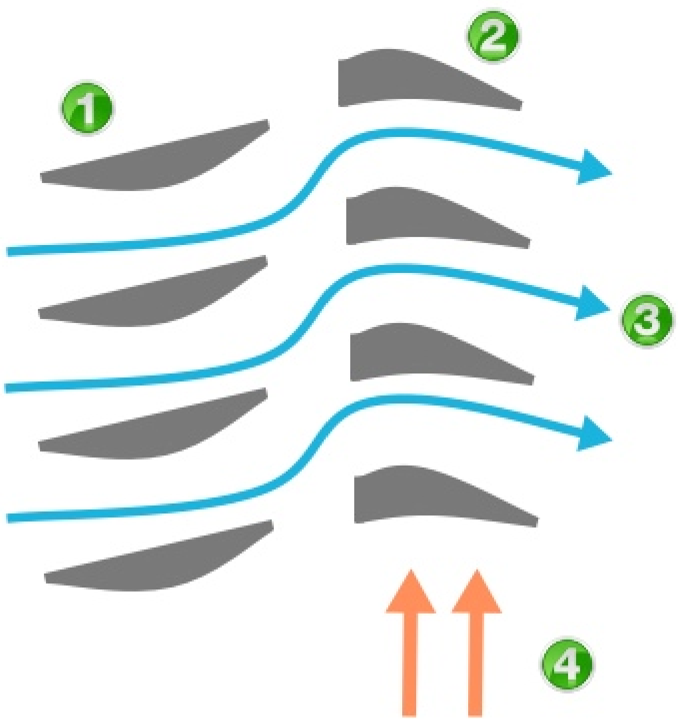
Impulse Turbine
Reaction Turbine
Moving Blades
Steam
Steam Pressure
Steam Velocity

Reaction turbine

- A **reaction turbine** is a type of steam turbine that works on the principle that the rotor spins, as the name suggests, from a reaction force rather than an impact or impulse force.
- In a reaction turbine there are no nozzles to direct the steam like in the impulse turbine.
- Instead, the blades that project radially from the outer edge of the rotor are shaped and mounted so that the shape between the blades, created by the cross-section, create the shape of a nozzle. These blades are mounted on the revolving part of the rotor and are called the moving blades.

Reaction turbine

- The fixed blades, which are the same shape as the moving blades, are mounted to the outer casing where the rotor revolves and are set to guide the steam into the moving blades.
- Below is a simple diagram of reaction turbine blades:



- (1) The steam enters through a section of curved blades in a fixed position.
- (2) The steam then enters the set of moving blades and creates enough reactive force to rotate them,
- (3) The steam exits the section of rotating blades.
- (4) The direction of rotation.

Reaction turbine

- There are three main forces that act to move a reaction turbine.
- First, from the reactive force that is created on the moving blades as it expands and increases in velocity as it moves through the nozzle shaped spaces between the blades.
- Second, from the reactive force produced on the moving blades as the steam passes through and changes directions.
- Third, and to a lesser extent, from the impact force of the steam on the blades helps rotate the reaction turbine.

Difference between Impulse and Reaction Turbine

1. In impulse turbine, there are nozzle and moving blades are in series while there are fixed blades and moving blades are present in Reaction turbine (No nozzle is present in reaction turbine).
2. In impulse turbine pressure falls in nozzle while in reaction turbine in fixed blade boiler pressure falls.
3. In impulse turbine velocity (or kinetic energy) of steam increases in nozzle while this work is to be done by fixed blades in the reaction turbine.
4. Compounding is to be done for impulse turbines to increase their efficiency while no compounding is necessary in reaction turbine.
5. In impulse turbine pressure drop per stage is more than reaction turbine.

Difference between Impulse and Reaction Turbine

6) Not much power can be developed in impulse turbine than reaction turbine.

7) Efficiency of impulse turbine is lower than reaction turbine.

8) Impulse turbine requires less space than reaction turbine.

9) Blade manufacturing of impulse turbine is not difficult as in reaction turbine it is difficult.

Compounding of steam turbines

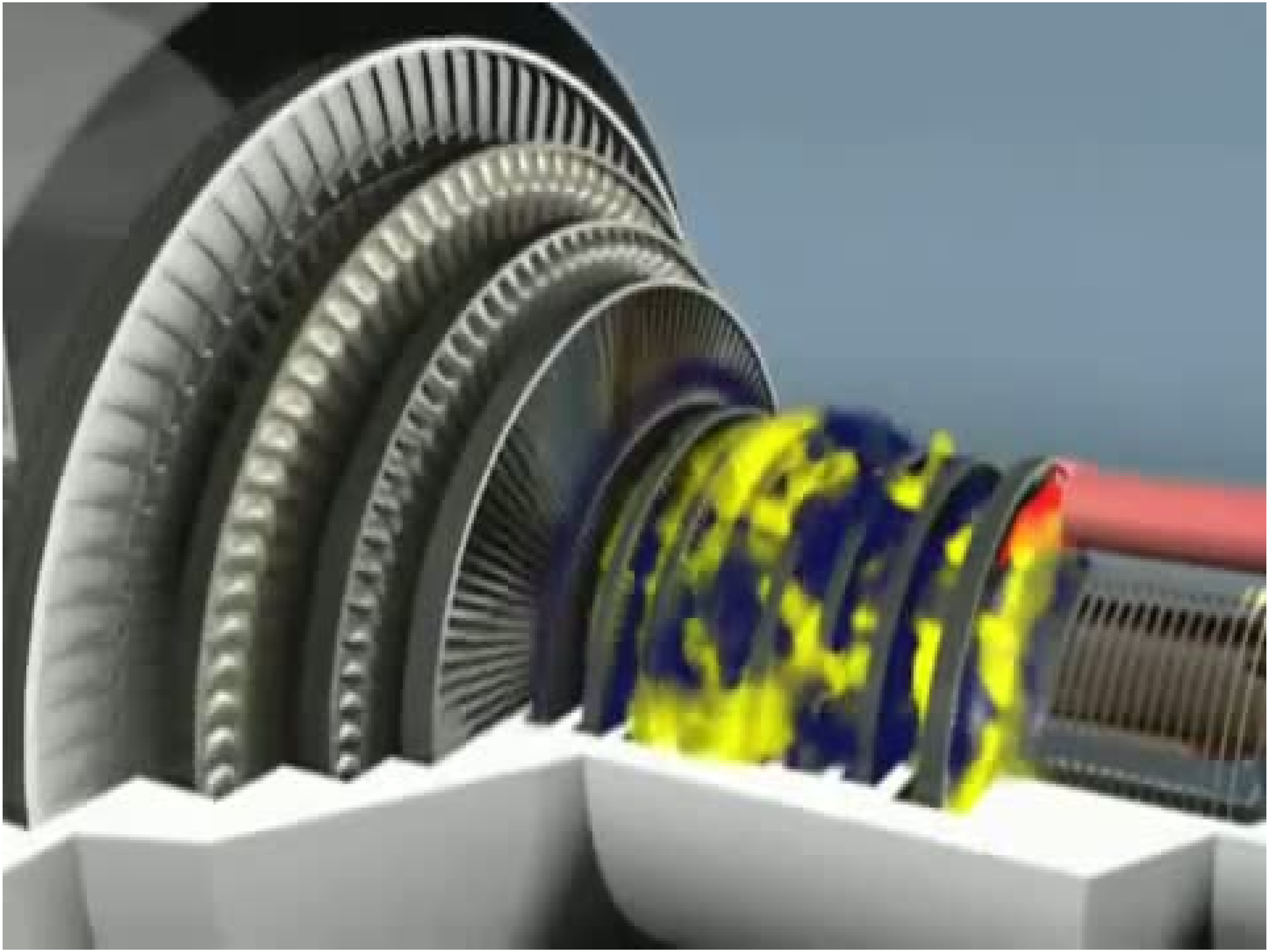
- **Compounding of steam turbines** is the method in which energy from the steam is extracted in a number of stages rather than a single stage in a turbine.
- A compounded steam turbine has multiple stages i.e. it has more than one set of nozzles and rotors, in series, keyed to the shaft or fixed to the casing, so that either the steam pressure or the jet velocity is absorbed by the turbine in number of stages.

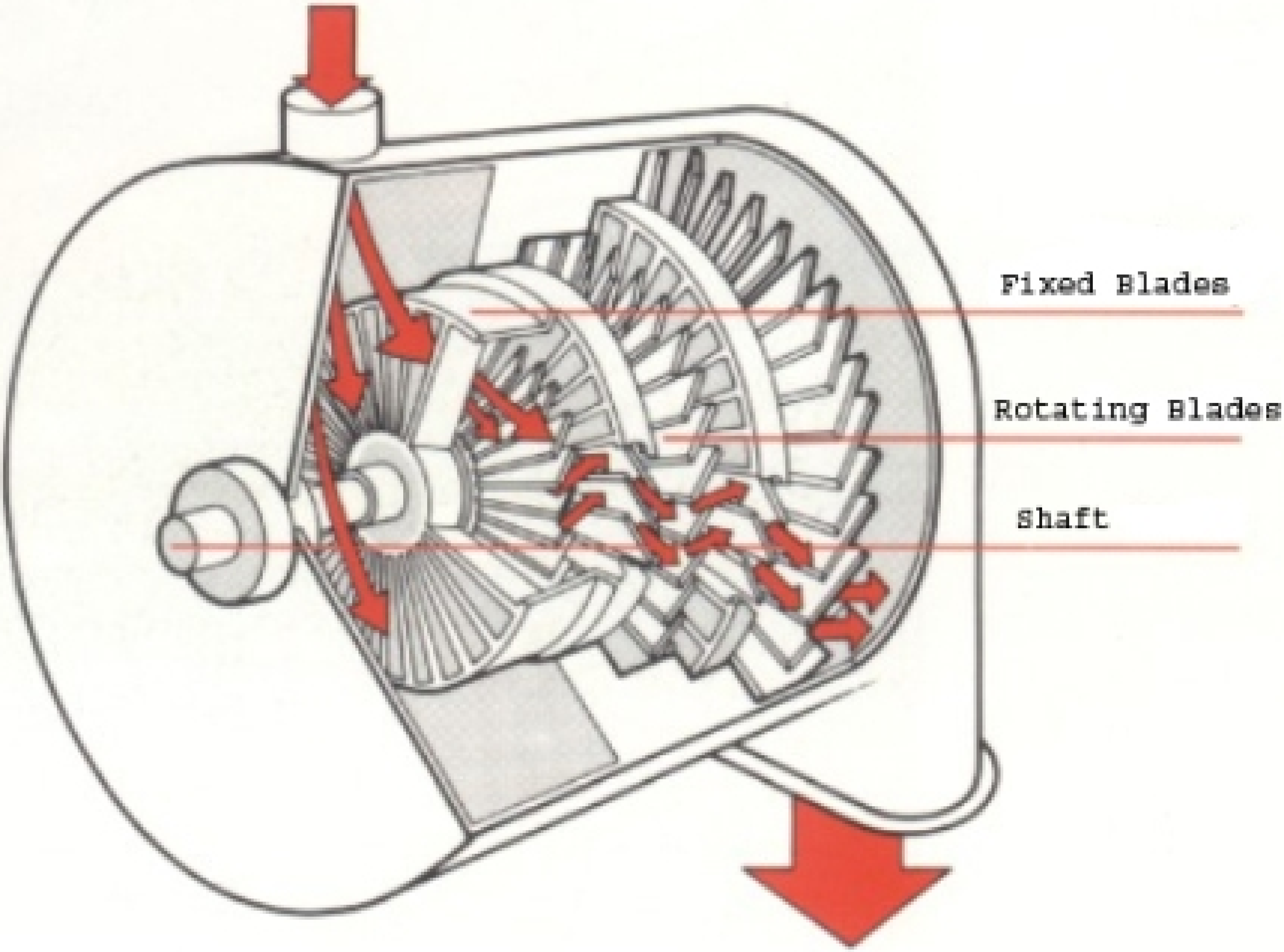
Compounding of steam turbines

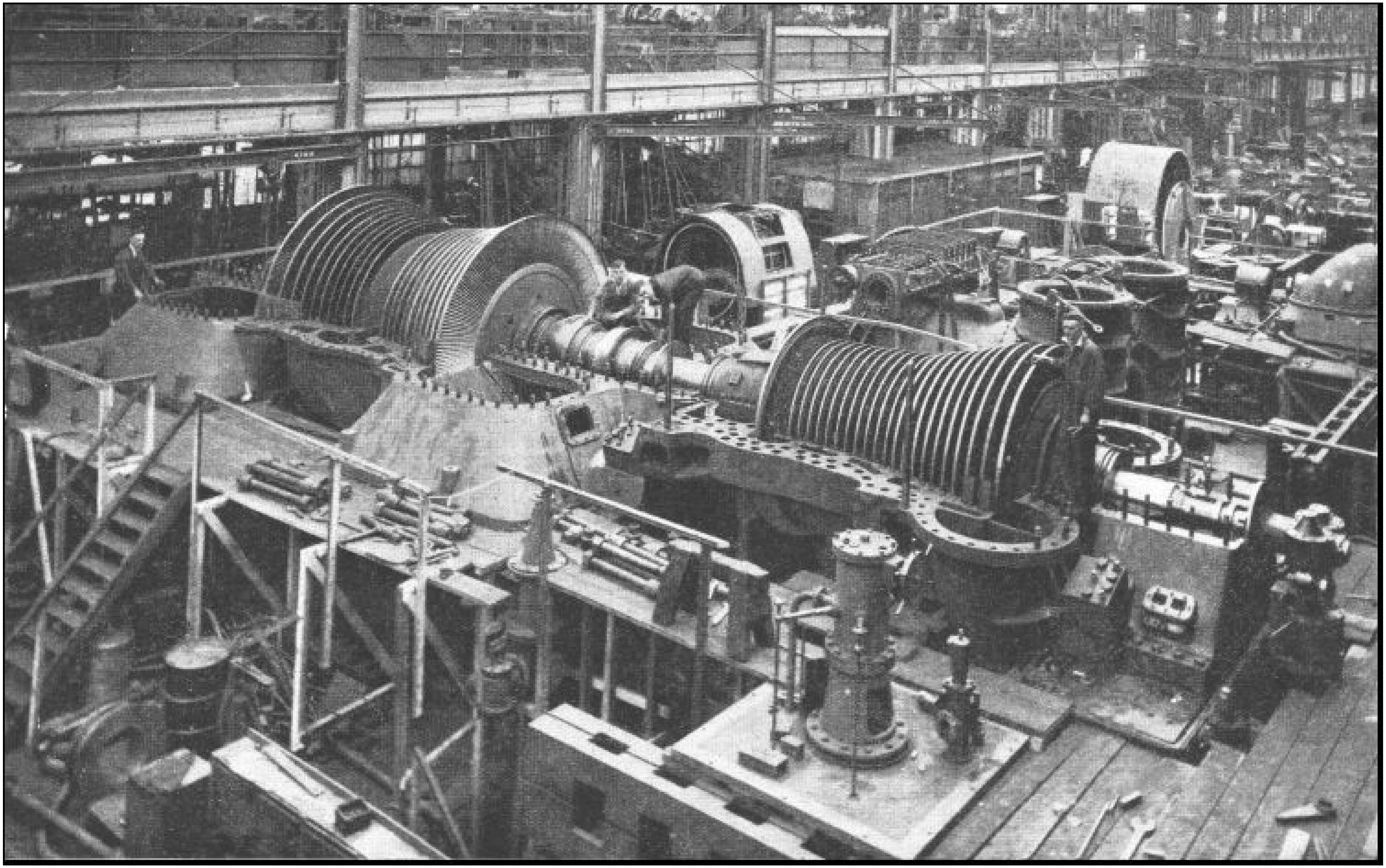
- As we have seen , if the high velocity steam is allowed to flow through one row of moving blades, it produces a rotor speed of about 30000 r.p.m. which is too high for practical use.
- Not only this, the leaving loss is also very high.
- It is therefore essential to incorporate some improvements in the simple impulse turbine for practical use and also to achieve high performance.
- This is possible by making use of more than one set of nozzles, blades, rotors, in a series, keyed to a common shaft.

Compounding of steam turbines

- So that either the steam pressure or the jet velocity is absorbed by the turbine in stages.
- The leaving loss also will be less.
- This process is called compounding of steam turbine.




Fixed Blades
Rotating Blades
Shaft

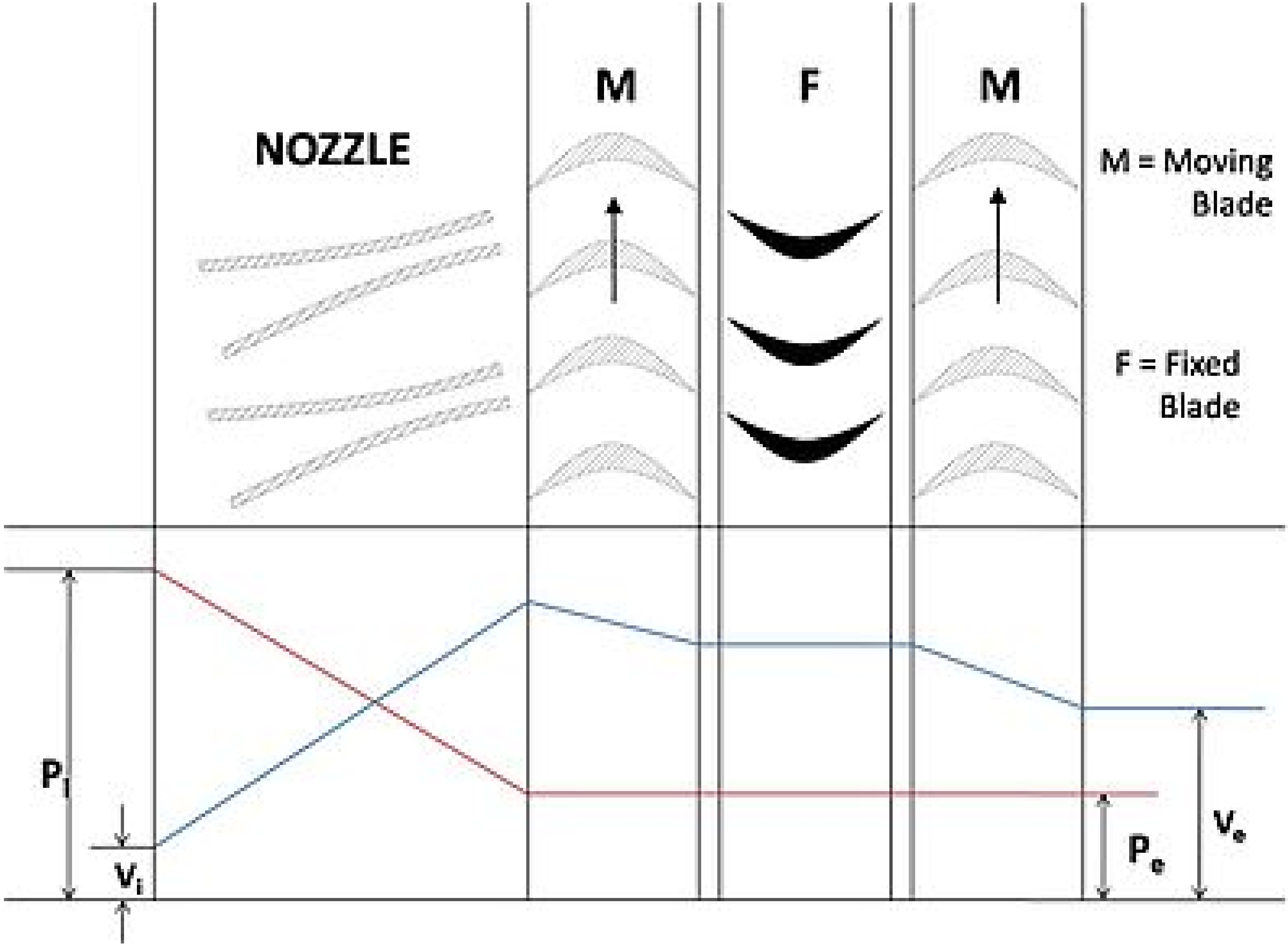


Types of compounding

- In an Impulse steam turbine compounding can be achieved in the following three ways: -
- 1. Velocity compounding
- 2. Pressure compounding
- 3. Pressure-Velocity Compounding

velocity compounded

- The velocity compounded Impulse turbine was first proposed by C G Curtis to solve the problem of single stage Impulse turbine for use of high pressure and temperature steam.
- The rings of moving blades are separated by rings of fixed blades. The moving blades are keyed to the turbine shaft and the fixed blades are fixed to the casing.
- The high pressure steam coming from the boiler is expanded in the nozzle first. The Nozzle converts the pressure energy of the steam into kinetic energy
- It is interesting to note that the total enthalpy drop and hence the pressure drop occurs in the nozzle. Hence, the pressure thereafter remains constant.
- This high velocity steam is directed on to the first set (ring) of moving blades. As the steam flows over the blades, due the shape of the blades, it imparts some of its momentum to the blades and losses some velocity.



NOZZLE
M
F
M
M = Moving Blade
F = Fixed Blade
P
V
P
V

velocity compounded

- Only a part of the high kinetic energy is absorbed by these blades. The remainder is exhausted on to the next ring of fixed blade.
- The function of the fixed blades is to redirect the steam leaving from the first ring moving blades to the second ring of moving blades. There is no change in the velocity of the steam as it passes through the fixed blades.
- The steam then enters the next ring of moving blades; this process is repeated until practically all the energy of the steam has been absorbed.
- A schematic diagram of the Curtis stage impulse turbine, with two rings of moving blades one ring of fixed blades is shown in **figure 1**. The figure also shows the changes in the pressure and the absolute steam velocity as it passes through the stages.

velocity compounded

- where,
- P_i = pressure of steam at inlet
- V_i = velocity of steam at inlet
- P_o = pressure of steam at outlet
- V_o = velocity of steam at outlet
- In the above figure there are two rings of moving blades separated by a single of ring of fixed blades.
- As discussed earlier the entire pressure drop occurs in the nozzle, and there are no subsequent pressure losses in any of the following stages. Velocity drop occurs in the moving blades and not in fixed blades.

advantages

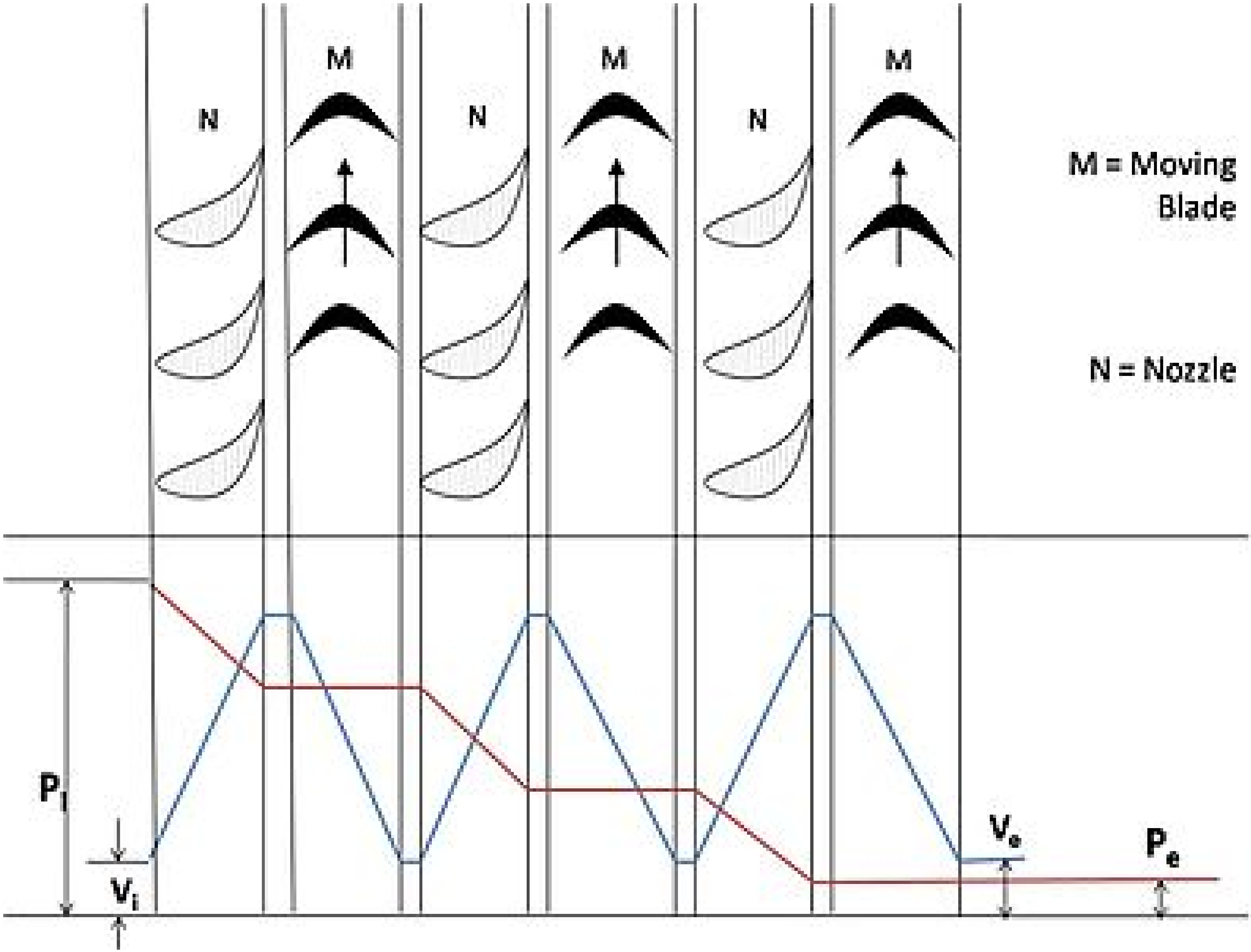
- Velocity compounded impulse turbine requires a comparatively small number of stages due to relatively large heat drop per stage.
- Due to small number of stages the initial cost is less.
- In two or three row wheel, the steam temperature is sufficiently lo, hence a cast iron cylinder may be used , thus saving material cost.

disadvantages

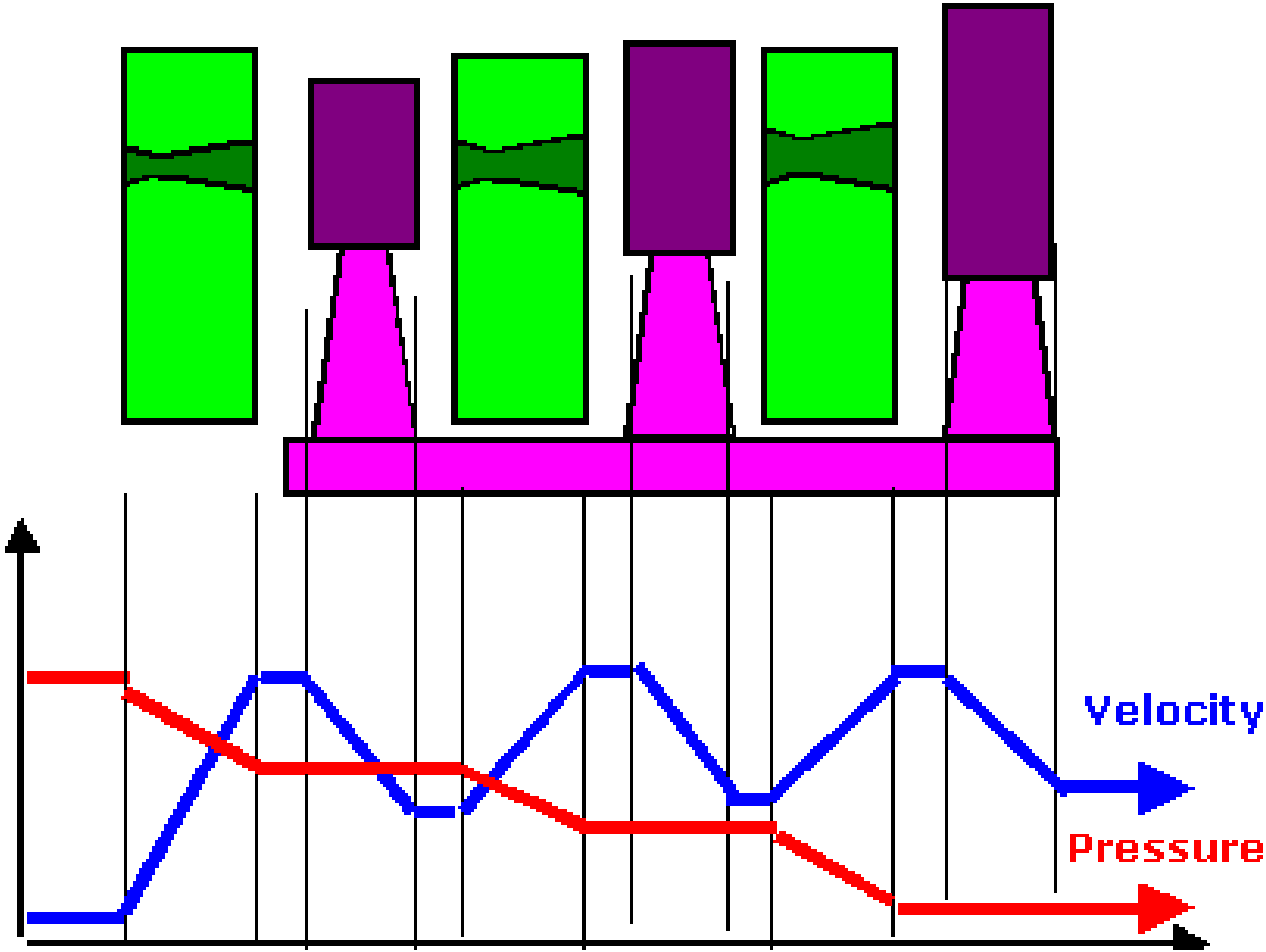
- The velocity compounded impulse turbine has low efficiency and high steam consumption.

pressure compounded

- The pressure compounded Impulse turbine is also called as Rateau turbine, after its inventor. This is used to solve the problem of high blade velocity in the single-stage impulse turbine.
- It consists of alternate rings of nozzles and turbine blades. The nozzles are fitted to the casing and the blades are keyed to the turbine shaft.
- In this type of compounding the steam is expanded in a number of stages, instead of just one (nozzle) in the velocity compounding.
- It is done by the fixed blades which act as nozzles. The steam expands equally in all rows of fixed blade. The steam coming from the boiler is fed to the first set of fixed blades i.e. the nozzle ring. The steam is partially expanded in the nozzle ring.
- Hence, there is a partial decrease in pressure of the incoming steam. This leads to an increase in the velocity of the steam. Therefore the pressure decreases and velocity increases partially in the nozzle.



M
M
M
N
N
N
M = Moving Blade
N = Nozzle
P_i
V_i
V_e
P_e


Velocity
Pressure

pressure compounded

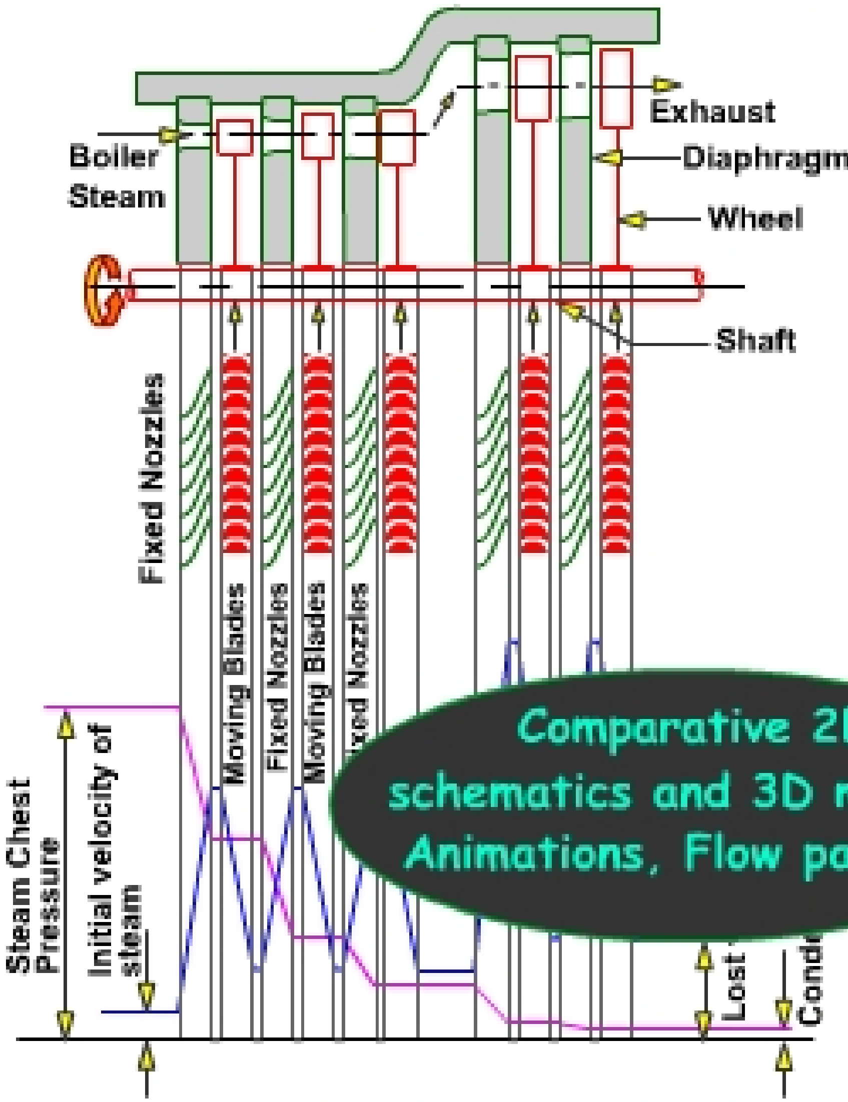
- This is then passed over the set of moving blades. As the steam flows over the moving blades nearly all its velocity is absorbed. However, the pressure remains constant during this process.
- After this it is passed into the nozzle ring and is again partially expanded. Then it is fed into the next set of moving blades, and this process is repeated until the condenser pressure is reached.
- This process has been illustrated in **figure 3**.
- where, the symbols have the same meaning as given above.
- It is a three stage pressure compounded impulse turbine. Each stage consists of one ring of fixed blades, which act as nozzles, and one ring of moving blades. As shown in the figure pressure drop takes place in the nozzles and is distributed in many stages.

Disadvantages of Pressure Compounding

- The disadvantage is that since there is pressure drop in the nozzles, it has to be made air-tight.
- They are bigger and bulkier in size

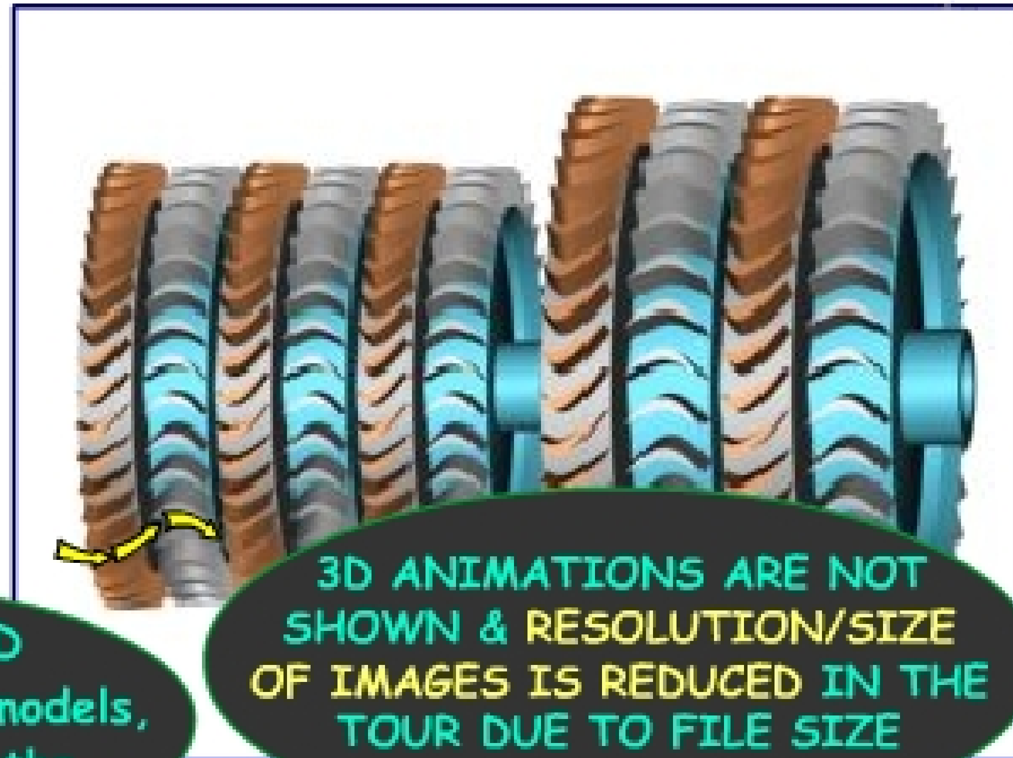
STEAM TURBINES

INTRODUCTION



Diagrammatic Arrangement of Pressure-compounded Impulse Turbine

Pressure-compounded Impulse Turbine:



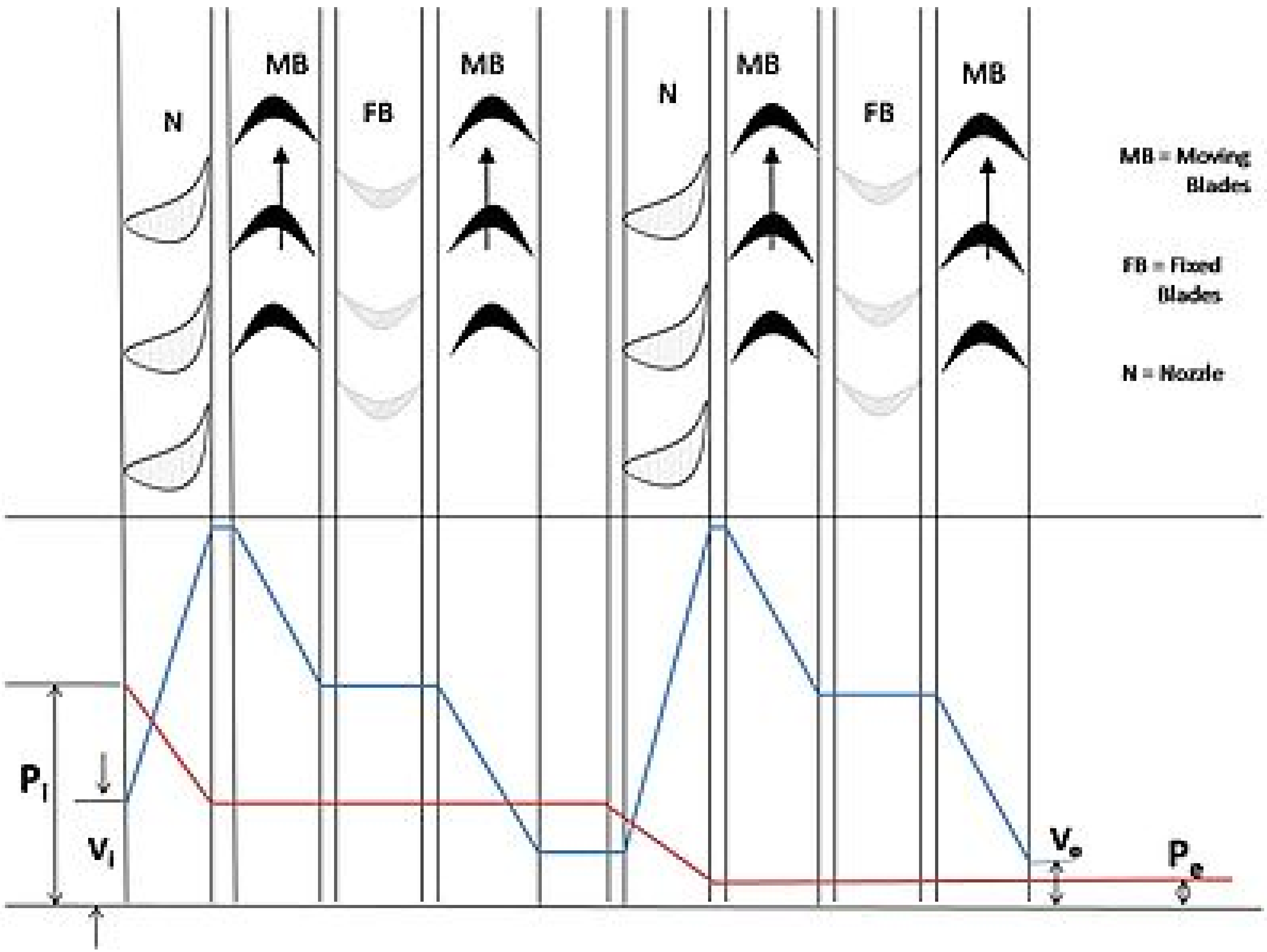
Comparative 2D schematics and 3D models, Animations, Flow paths...

3D ANIMATIONS ARE NOT SHOWN & RESOLUTION/SIZE OF IMAGES IS REDUCED IN THE TOUR DUE TO FILE SIZE CONSTRAINTS!

…low path across a … …sented.

Pressure-Velocity compounded Impulse Turbine

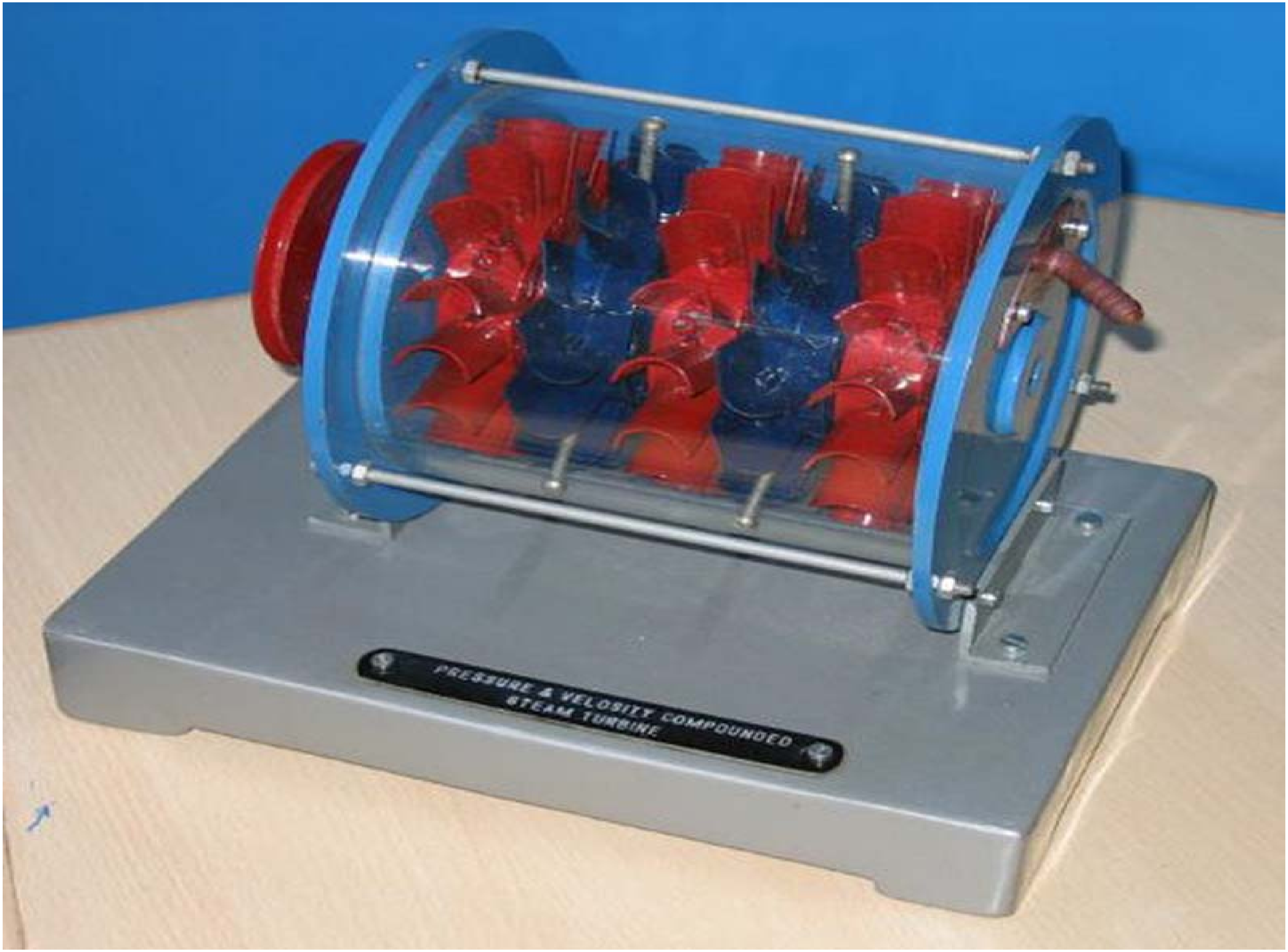
- It is a combination of the above two types of compounding. The total pressure drop of the steam is divided into a number of stages.
- Each stage consists of rings of fixed and moving blades. Each set of rings of moving blades is separated by a single ring of fixed blades.
- In each stage there is one ring of fixed blades and 3-4 rings of moving blades. Each stage acts as a velocity compounded impulse turbine.
- The fixed blades act as nozzles. The steam coming from the boiler is passed to the first ring of fixed blades, where it gets partially expanded.



N
MB
FB
MB
N
MB
FB
MB
MB = Moving Blades
FB = Fixed Blades
N = Nozzle
P_i
V_i
V_e
P_e

Pressure-Velocity compounded Impulse Turbine

- The pressure partially decreases and the velocity rises correspondingly. The velocity is absorbed by the following rings of moving blades until it reaches the next ring of fixed blades and the whole process is repeated once again.
- This process is shown diagrammatically in **figure 5**.
- where, symbols have their usual meaning.


PRESSURE & VELOSITY COMPOUNDED
STEAM TURBINE

Regenerative feed heating

- The dry saturated steam , from boiler, enters the turbine at a high temperature, and then expands isentropically to a lower temperature in the same way as that of Rankine and Carnot cycle.
- Now the condensate from condenser, is pumped back and circulated around the turbine casing.
- The direction opposite to the steam flow in the turbine.
- The steam is thus heated before entering in to the boiler, such a system of heating is known as regenerative heating.

Regenerative feed heating

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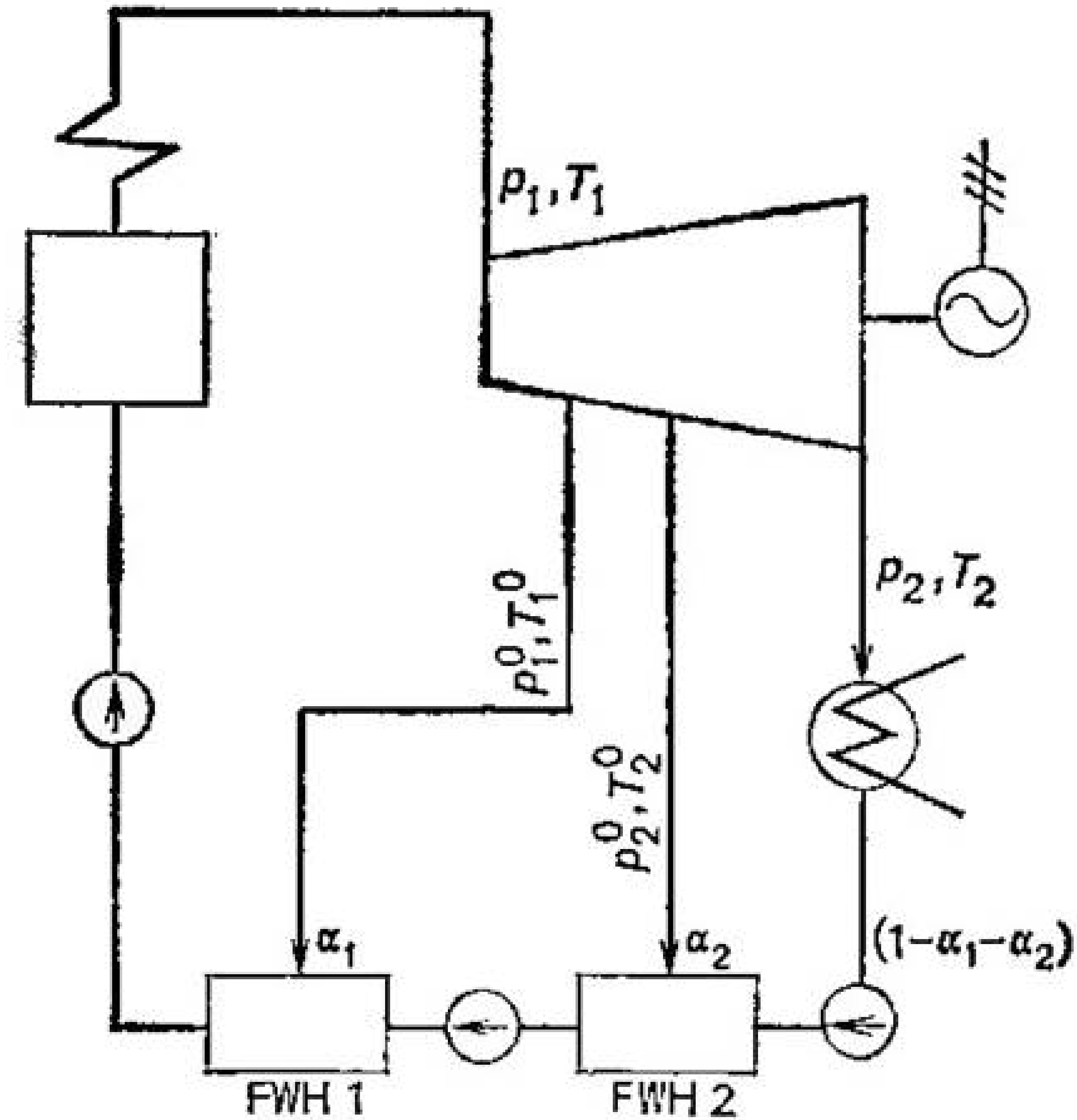
Regenerative feed heating

- Advantages
- Thermodynamic efficiency increases.
- Thermal stresses in the boiler reduces as hot feed water is supplied.
- Small size of condenser is required.
- Disadvantages
- Cost of plant is increased
- Work done per kg of steam is reduced.
- Complication of the plant increases.

Bleeding of steam turbine

- The process of draining steam from turbine, at certain points during its expansion and using this steam for heating the feed water and then supplying it to the boiler is known as bleeding.



p_1, T_1
p_2, T_2
p_1^0, T_1^0
p_2^0, T_2^0
α_1
α_2
$(1-\alpha_1-\alpha_2)$
FWH 1
FWH 2

Bleeding of steam turbine

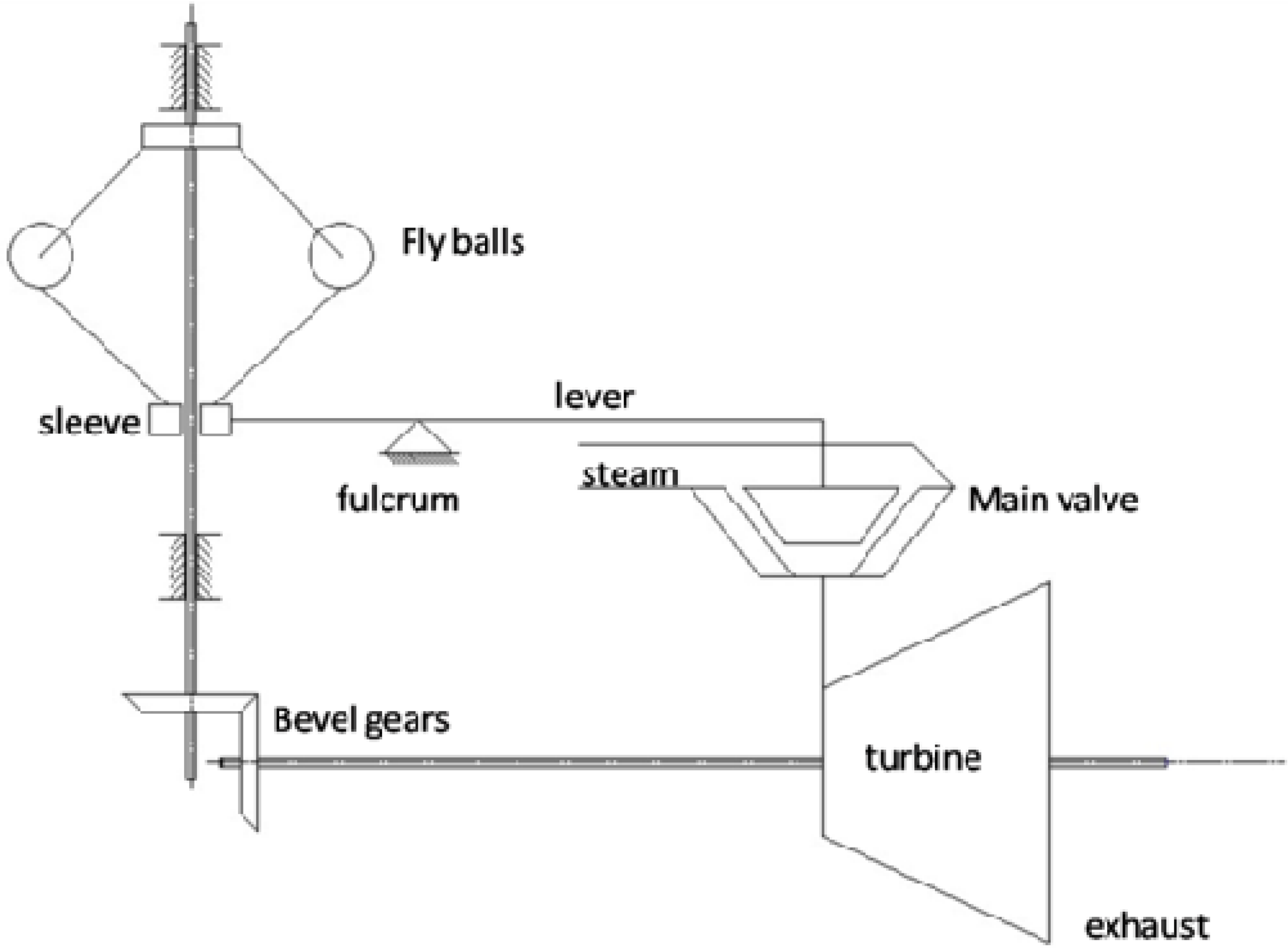
- At certain stages of turbine , some wet steam is drained out .
- This bleed steam is then circulated around the pipe leading the feed water to the boiler , where feed water is heated by using steam.
- Due to the process , the boiler is supplied with hot feed water while small amount of work is lost by the turbine.

Governing

- **Steam turbine governing** is the procedure of controlling the flow rate of steam into a steam turbine so as to maintain its speed of rotation as constant.
- The variation in load during the operation of a steam turbine can have a significant impact on its performance.
- In a practical situation the load frequently varies from the designed or economic load and thus there always exists a considerable deviation from the desired performance of the turbine.
- The primary objective in the steam turbine operation is to maintain a constant speed of rotation irrespective of the varying load. This can be achieved by means of governing in a steam turbine.

Throttle governing

- In throttle governing the pressure of steam is reduced at the turbine entry thereby decreasing the availability of energy.
- In this method steam is allowed to pass through a restricted passage thereby reducing its pressure across the governing valve.[
- The flow rate is controlled using a partially opened steam control valve. The reduction in pressure leads to a throttling process in which the enthalpy of steam remains constant,
- Low initial cost and simple mechanism makes throttle governing the most apt method for small steam turbines. The mechanism is illustrated in figure 1.
- The valve is actuated by using a centrifugal governor which consists of flying balls attached to the arm of the sleeve.


Fly balls
lever
sleeve
steam
fulcrum
Main valve
Bevel gears
turbine
exhaust

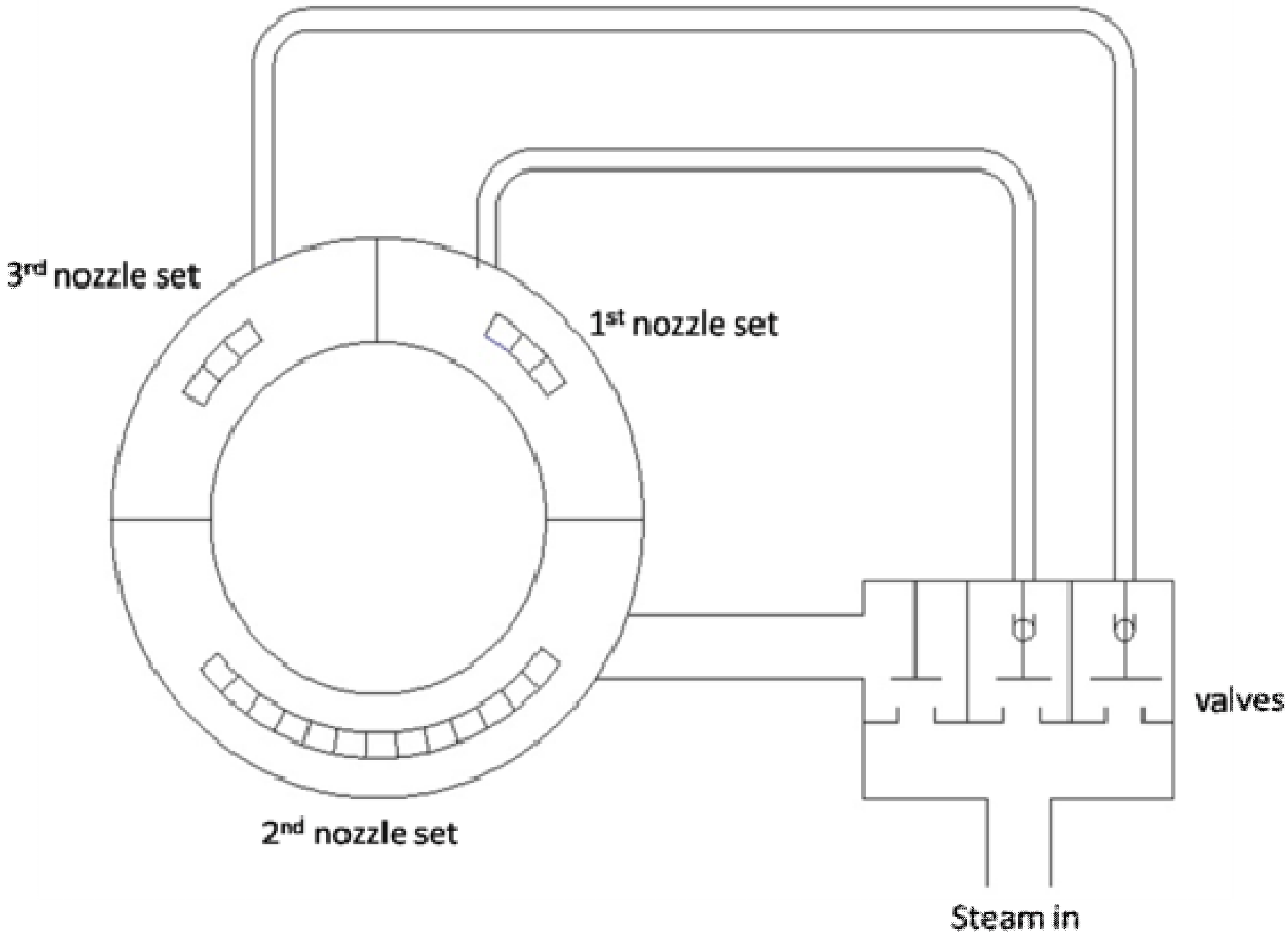
Throttle governing

- A geared mechanism connects the turbine shaft to the rotating shaft on which the sleeve reciprocates axially.
- With a reduction in the load the turbine shaft speed increases and brings about the movement of the flying balls away from the sleeve axis.
- This result in an axial movement of the sleeve followed by the activation of a lever, which in turn actuates the main stop valve to a partially opened position to control the flow rate.

Nozzle governing

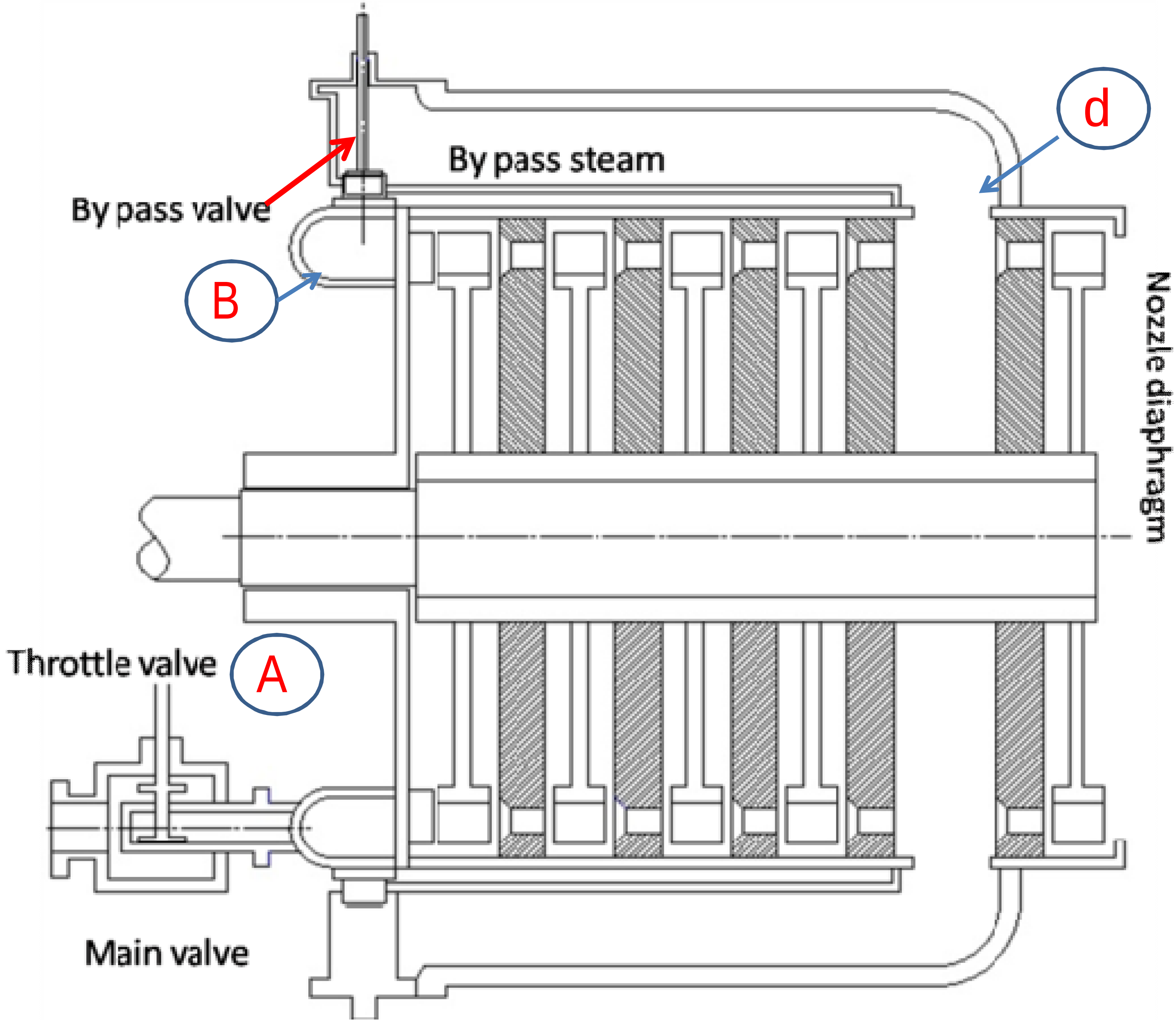
In nozzle governing the flow rate of steam is regulated by opening and shutting of sets of nozzles rather than regulating its pressure.

- In this method groups of two, three or more nozzles form a set and each set is controlled by a separate valve.
- The actuation of individual valve closes the corresponding set of nozzle thereby controlling the flow rate.
- In actual turbine, nozzle governing is applied only to the first stage whereas the subsequent stages remain unaffected. Since no regulation to the pressure is applied.
- Figure 2 shows the mechanism of nozzle governing applied to steam turbines. As shown in the figure the three sets of nozzles are controlled by means of three separate valves.


3rd nozzle set
1st nozzle set
valves
2nd nozzle set
Steam in

By pass governing

- Occasionally the turbine is overloaded for short durations.
- During such operation, bypass valves are opened and fresh steam is introduced into the later stages of the turbine.
- This generates more energy to satisfy the increased load.
- The schematic of bypass governing is as shown in figure3.



By pass valve
By pass steam
d
B
Nozzle diaphragm
Throttle valve
A
Main valve

By pass governing

- The total amount of steam entering the turbine passes through the valve A which is under the control of speed governor.
- B is a nozzle box or steam chest .
- For all loads greater than the economic load , a by pass valve c is opened, allowing steam to pass from the first stage nozzle box in to the steam belt D and so in to the nozzle of downstream stage.
- The valve c is designed such that it is not opened until the lift of the valve a diminishes.
- The by pass valve c remains under control of a speed governor for all loads within its range.

Losses in turbine

1) Nozzle loss

It is important loss in impulse turbine , which occurs when the steam flows through the nozzle.

This loss takes place due to friction in the nozzle.

2) Blade friction loss

It is important loss in both the impulse and reaction turbines, which occurs hen steam glides over the blades.

This loss takes place due to friction of surface of blades.

As a result of blade friction, the relative velocity of steam is reduced while gliding over the blade.

Losses in turbine

3) wheel friction loss

It occurs when the turbine wheel rotates in steam.

This loss takes place due to resistance offered by the steam to the moving turbine wheel or disc.

As a result of this loss, the turbine wheel rotates at a lower speed.

Losses in turbine

4) Mechanical friction loss

It is loss in both turbine, which occurs due to friction between the shaft and wheel bearing as well as regulating the valves.

This loss can be reduced by lubricating the moving parts of turbine.

5) Leakage loss

It is loss in both turbines, which occurs due to leakage of steam at each stage to the turbine, blade tips.

Losses in turbine

6) Moisture loss

It is loss in both the turbines, which takes place due to moisture present in the steam.

This loss occurs when the steam, passing through lower stages, becomes wet.

The velocity of water particles is less than steam.

As a result of this , the steam has to drag the water particles, which reduces the kinetic energy of the steam.

Losses in turbine

7) Radiation losses

It is a loss in both the turbines, which takes place due to difference of the temperature between the turbine casing and the surrounding atmosphere.

This is reduces by properly insulating the turbine.

8) Governing loss

It is loss in both the turbines, which occurs due to throttling of the steam at main stop valve of the governor.

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THERMAL ENGINEERING – II

UNIT IV

CO-GENERATION

DEFINATION:

- ➢Cogeneration or Combined Heat and Power (CHP) is defined as the sequential generation of two different forms of useful energy from a single primary energy source, typically mechanical energy and thermal energy.
- ➢Mechanical energy may be used either to drive an alternator for producing electricity, or rotating equipment such as motor, compressor, pump or fan for delivering various services

- Thermal energy can be used either for direct process applications or for indirectly producing steam, hot water, hot air for dryer or chilled water for process cooling.

NEED FOR COGENERATION

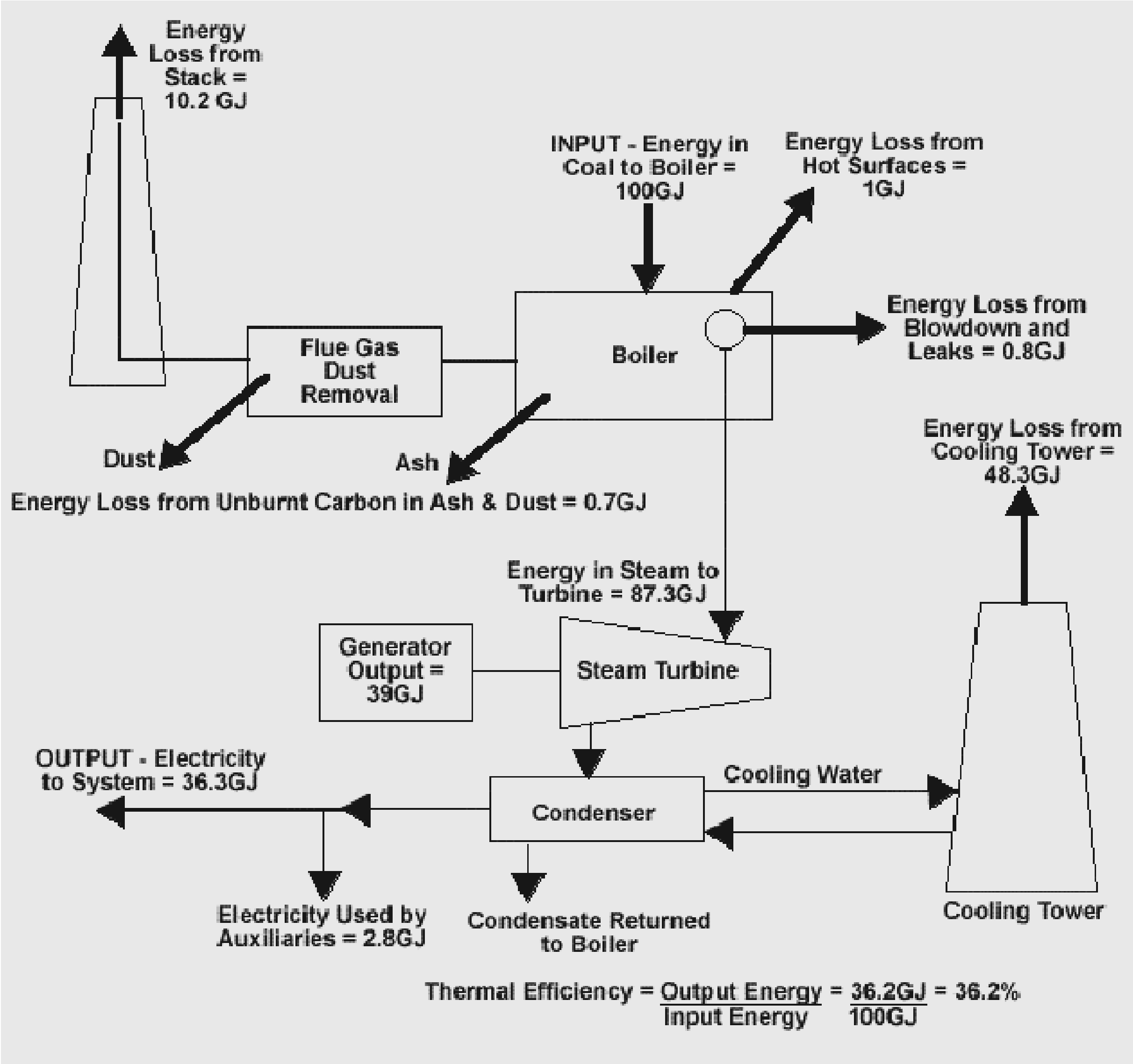
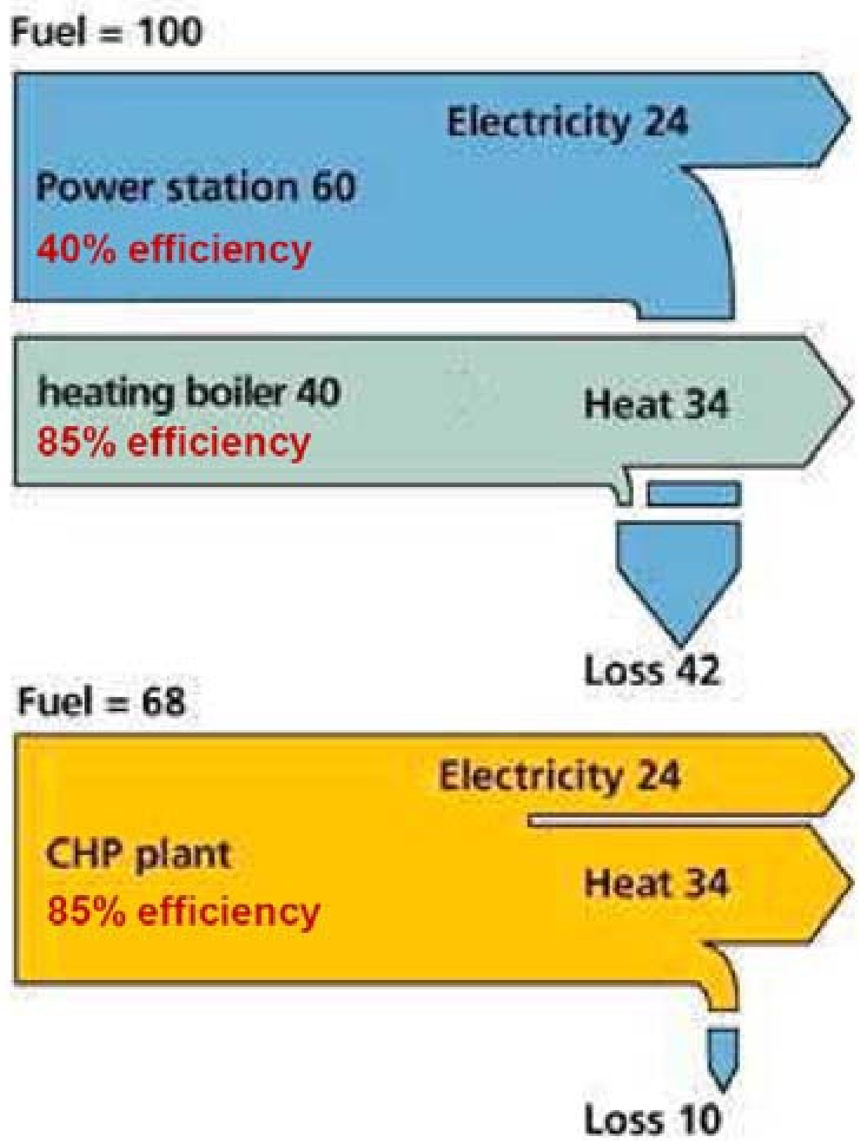


Figure 7.1 BALANCE IN A TYPICAL COAL FIRED POWER STATION
For an Input Energy of 100 Giga Joules (GJ)

- The conventional method of power generation and supply to the customer is wasteful in the sense that only about a third of the primary energy fed into the power plant is actually made available to the user in the form of electricity.
- In conventional power plant, efficiency is only 35% and remaining 65% of energy is lost.
- The overall efficiency of energy use in cogeneration mode can be up to 85 per cent and above in some cases.

EXAMPLE


Fuel = 100
Electricity 24
Power station 60
40% efficiency
heating boiler 40
85% efficiency
Heat 34
Loss 42
Fuel = 68
Electricity 24
CHP plant
85% efficiency
Heat 34
Loss 10

- For example in the scheme shown in Figure 7.2, an industry requires 24 units of electrical energy and 34 units of heat energy
- Through separate heat and power route the primary energy input in power plant will be 60 units (24/0.40).
- If a separate boiler is used for steam generation then the fuel input to boiler will be 40 units (34/0.85).
- If the plant had cogeneration then the fuel input will be only 68 units (24+34)/0.85 to meet both electrical and thermal energy requirements

- It can be observed that the losses, which were 42 units in the case of, separate heat and power has reduced to 10 units in cogeneration mode.
- Along with the saving of fossil fuels, cogeneration also allows to reduce the emission of greenhouse gases (particularly CO2 emission).
- The production of electricity being on-site, the burden on the utility network is reduced and the transmission line losses eliminated

ADVANTAGES

- High fuel efficiency rating
- Well-suited to low quality fuels
- Less impact on environment
- Low relative capital cost
- Quick start up & stoppage
- Optimum fuel efficiency rating

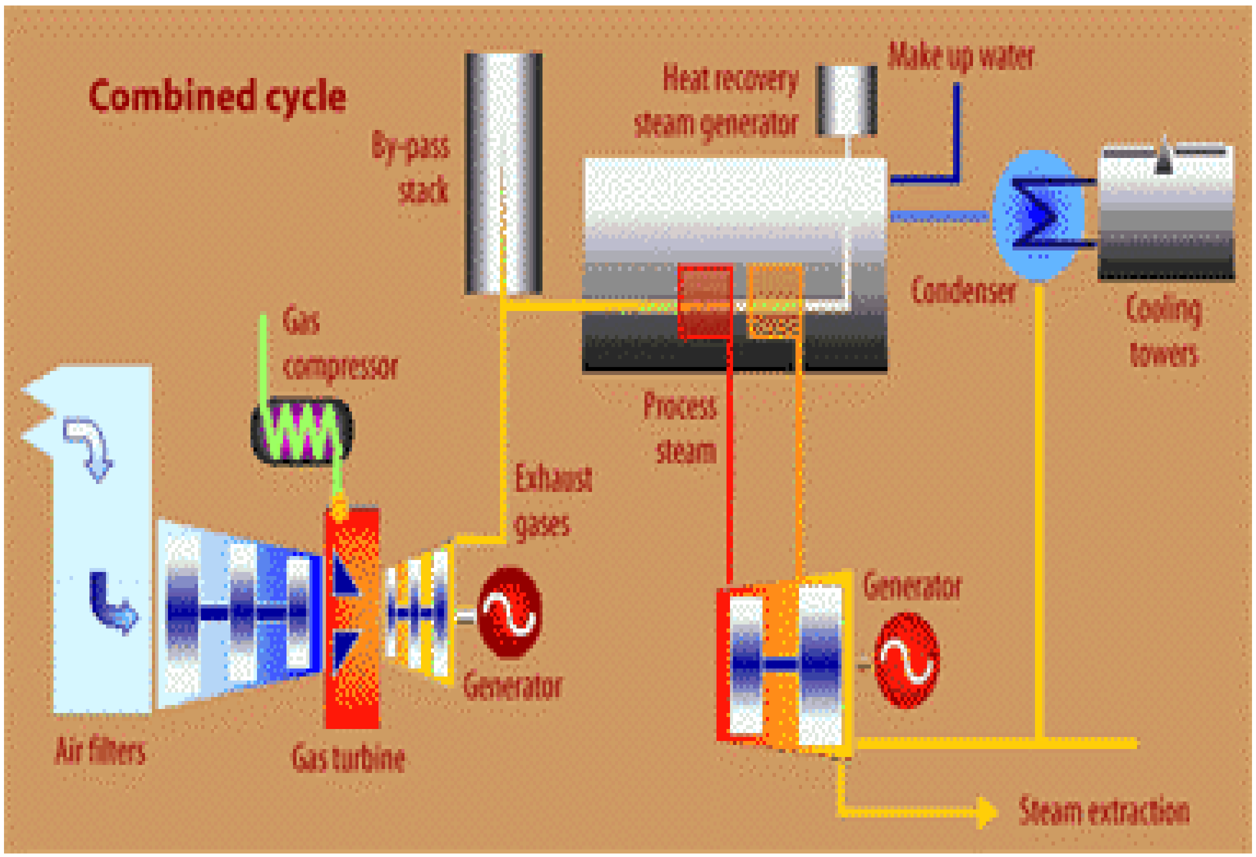
CLASSIFICATION OF CO-GENERATION SYSTEM

- Cogeneration systems are normally classified according to the sequence of energy use and the operating schemes adopted.
- A cogeneration system can be classified as either a **topping** or a **bottoming** cycle on the basis of the sequence of energy use.
- In a topping cycle, the fuel supplied is used to first produce power and then thermal energy, which is the by-product of the cycle and is used to satisfy process heat or other thermal requirements.

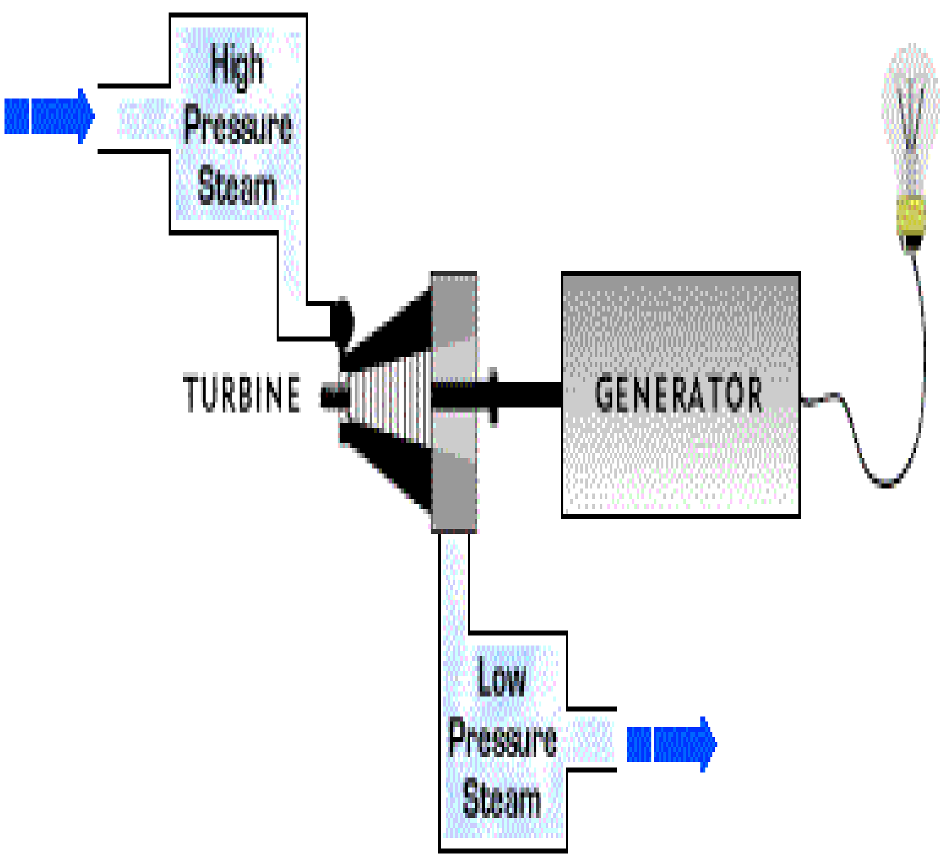
- In a bottoming cycle, the primary fuel produces high temperature thermal energy and the heat rejected from the process is used to generate power through a recovery boiler and a turbine generator. Typical areas of application include cement, steel, ceramic, gas and petrochemical industries
- Topping cycle cogeneration is widely used and is the most popular method of cogeneration.

TOPPING CYCLE

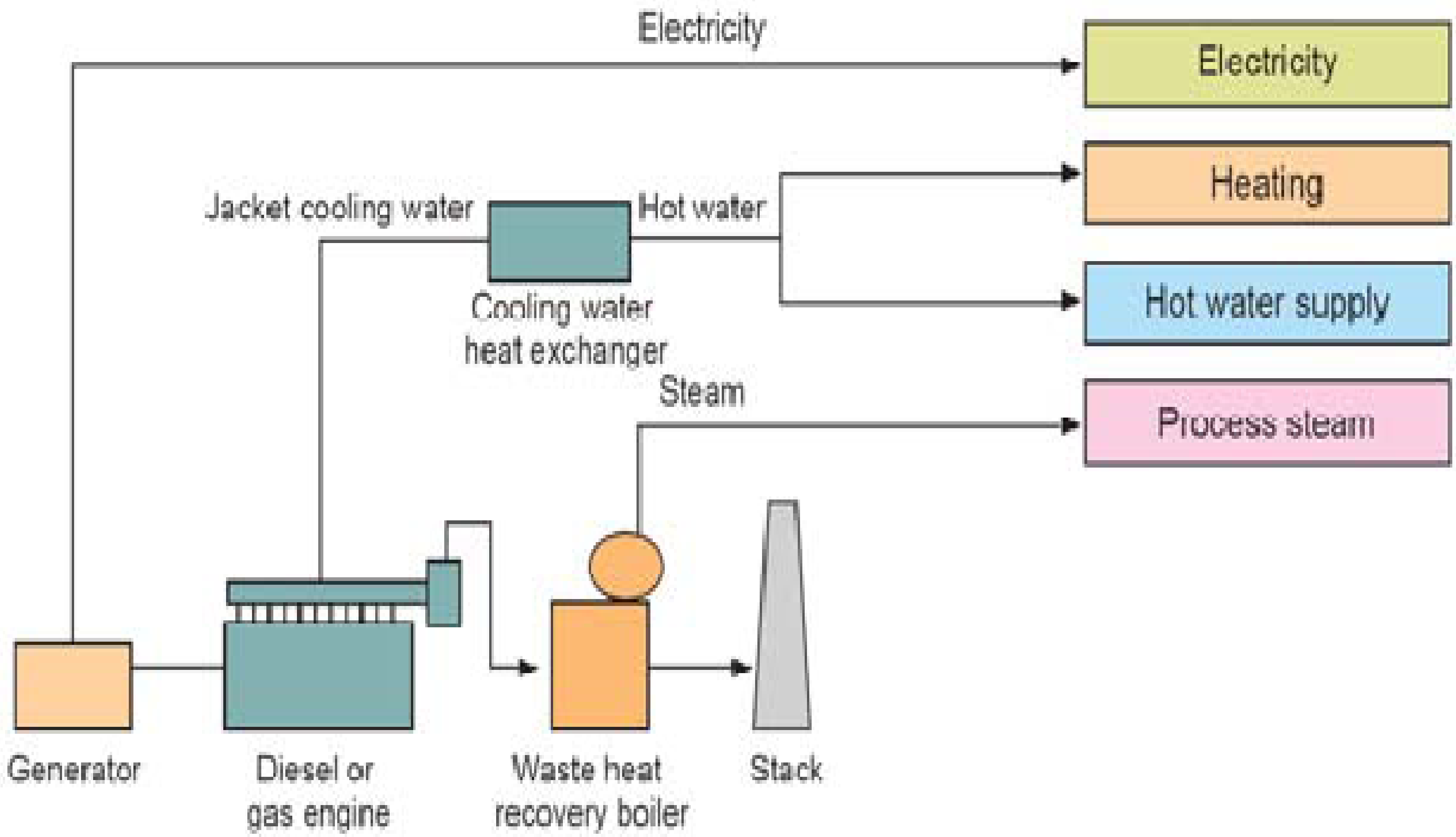
- The four types of topping cycle cogeneration systems are briefly explained



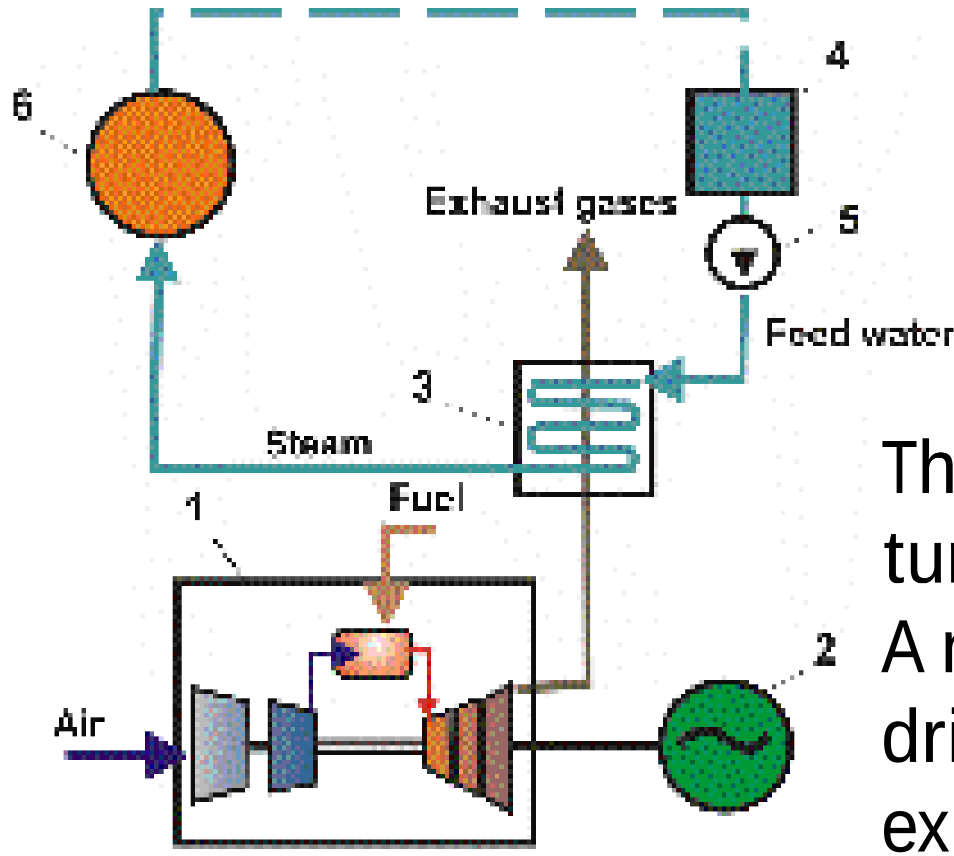
A gas turbine or diesel engine producing electrical or mechanical power followed by a heat recovery boiler to create steam to drive a secondary steam turbine. This is called a combined-cycle topping system.



The second type of system burns fuel (any type) to produce high-pressure steam that then passes through a steam turbine to produce power with the exhaust provides low-pressure process steam. This is a steam-turbine topping system.



A third type employs heat recovery from an engine exhaust and/or jacket cooling system flowing to a heat recovery boiler, where it is converted to process steam / hot water for further use.

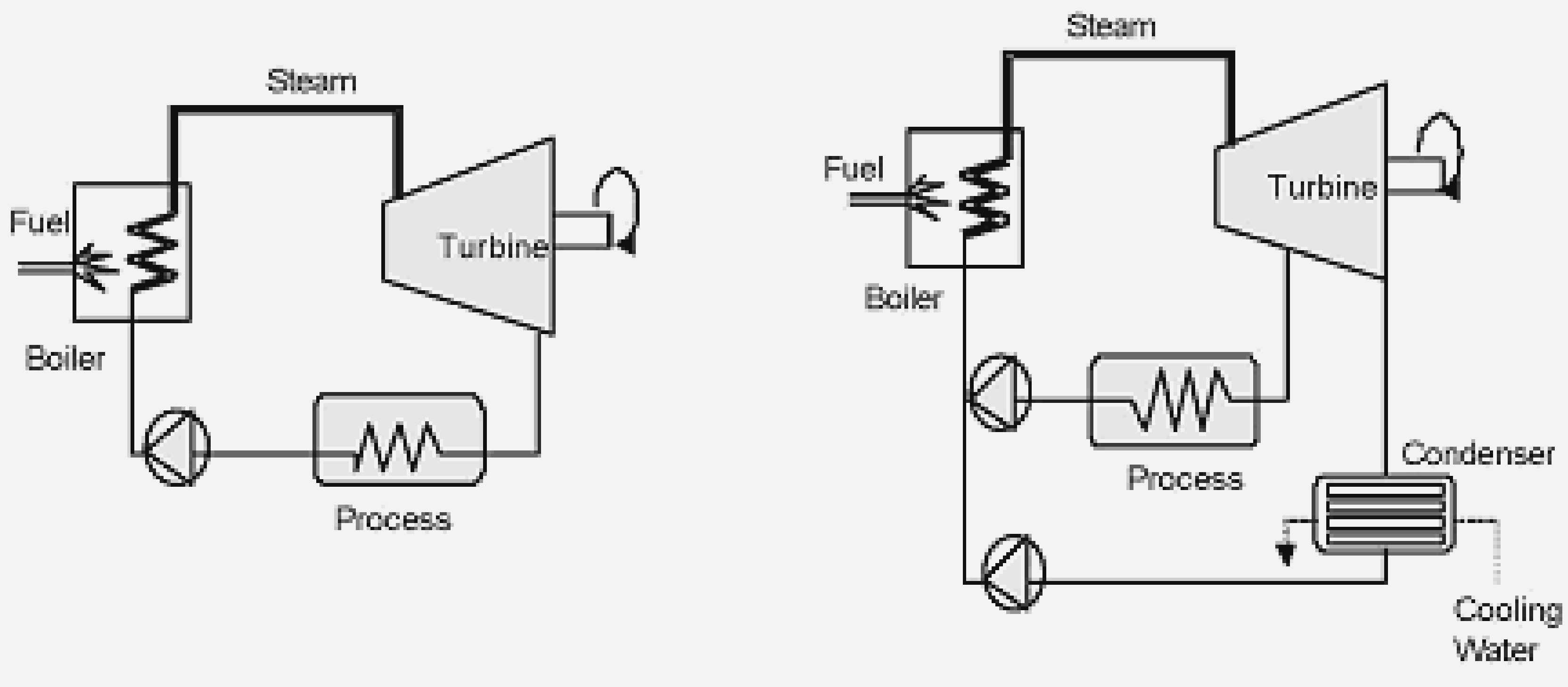


The fourth type is a gas-turbine topping system. A natural gas turbine drives a generator. The exhaust gas goes to a heat recovery boiler that makes process steam and process heat

TYPES OF CO-GENERATION SYSTEMS

- Steam turbine Co-Generation systems
- Gas turbine Co-Generation systems
- Reciprocating engine Co-Generation systems

Steam Turbine Co-Generation System



(i) Back-Pressure Turbine **(ii) Extraction-Condensing Turbine**

Figure 7.3 Schematic diagrams of steam turbine cogeneration systems

- The two types of steam turbines most widely used are the backpressure and the extraction-condensing types.

- The choice between backpressure turbine and extraction-condensing turbine depends mainly on the quantities of power and heat, quality of heat, and economic factors.

- The extraction points of steam from the turbine could be more than one, depending on the temperature levels of heat required by the processes.

- The specific advantage of using steam turbines in comparison with the other prime movers is the option for using a wide variety of conventional as well as alternative fuels such as coal, natural gas, fuel oil and biomass.

- The power generation efficiency of the cycle may be sacrificed to some extent in order to optimize heat supply

Back Pressure Steam Turbine

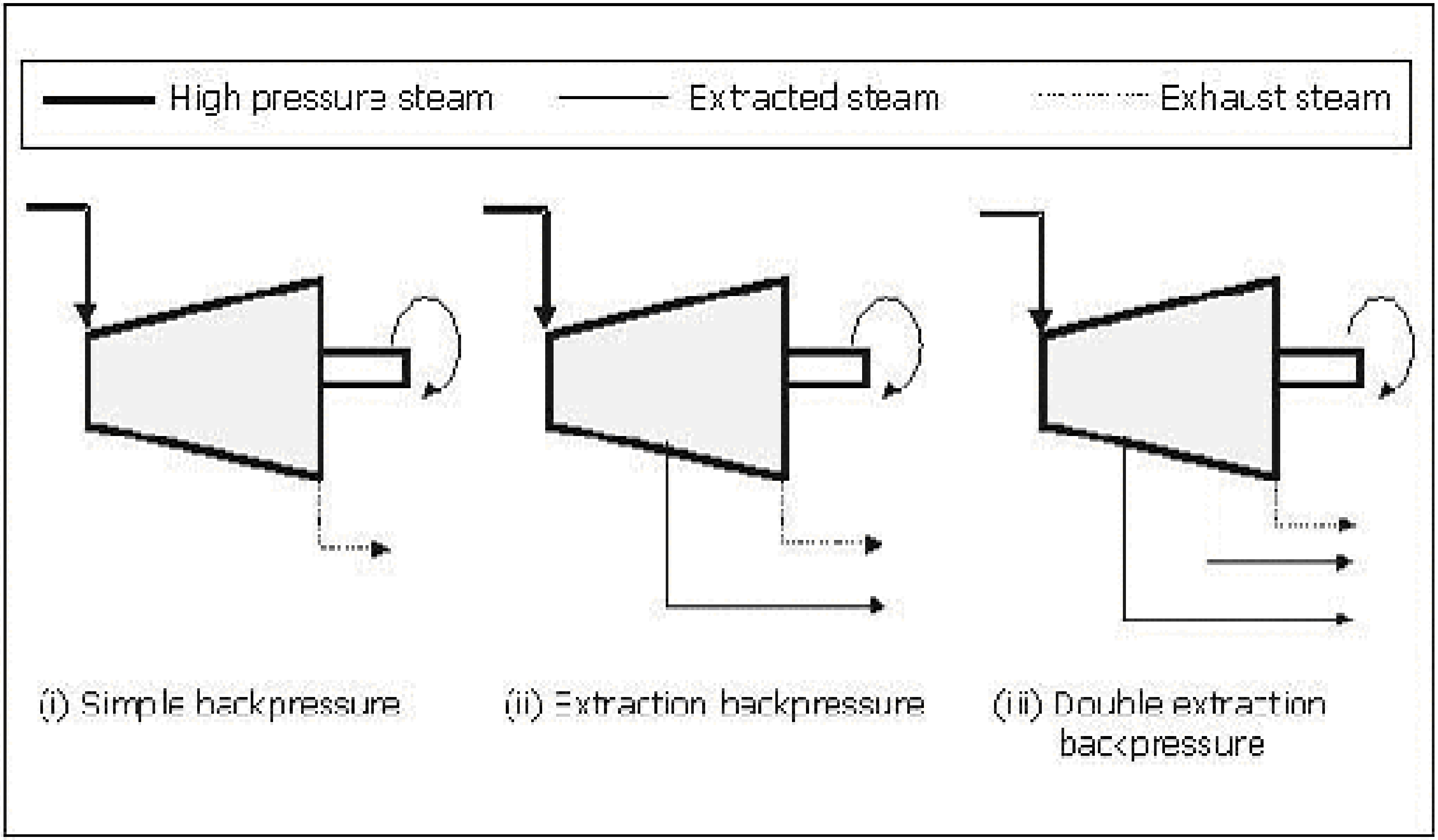
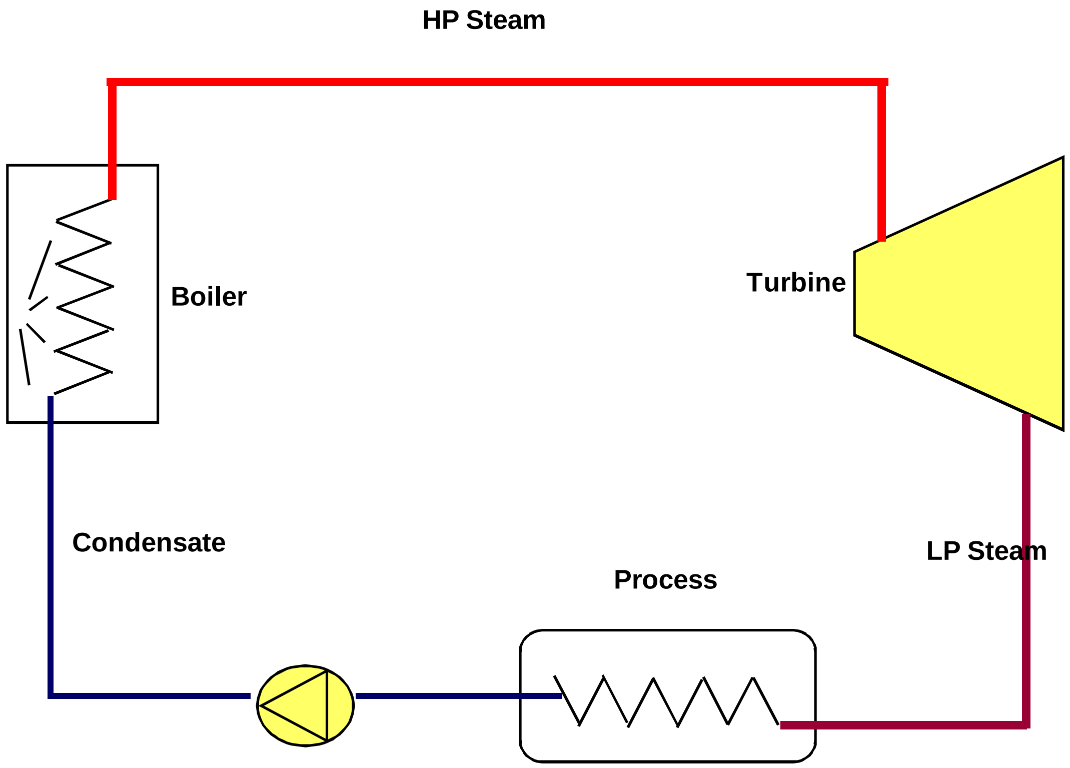


Figure 7.9 Different configurations for back pressure steam turbines

Simple back pressure



- In this type steam enters the turbine chamber at High Pressure and expands to Low or Medium Pressure. Enthalpy difference is used for generating power / work.

- Depending on the pressure (or temperature) levels at which process steam is required, backpressure steam turbines can have different configurations .

- In extraction and double extraction backpressure turbines, some amount of steam is extracted from the turbine after being expanded to a certain pressure level.

- Back pressure steam turbine is the most simple configuration.

- Steam exits the turbine at a pressure higher or at least equal to the atmospheric pressure. This is why the term back- pressure is used.

- After the steam exits the turbine, it is fed to the load where it releases heat and is condensed. The condensate then returns to the system

- The efficiency of a backpressure steam turbine cogeneration system is the highest.

- In cases where 100 per cent backpressure exhaust steam is used, the only inefficiencies are gear drive and electric generator losses, and the inefficiency of steam generation.

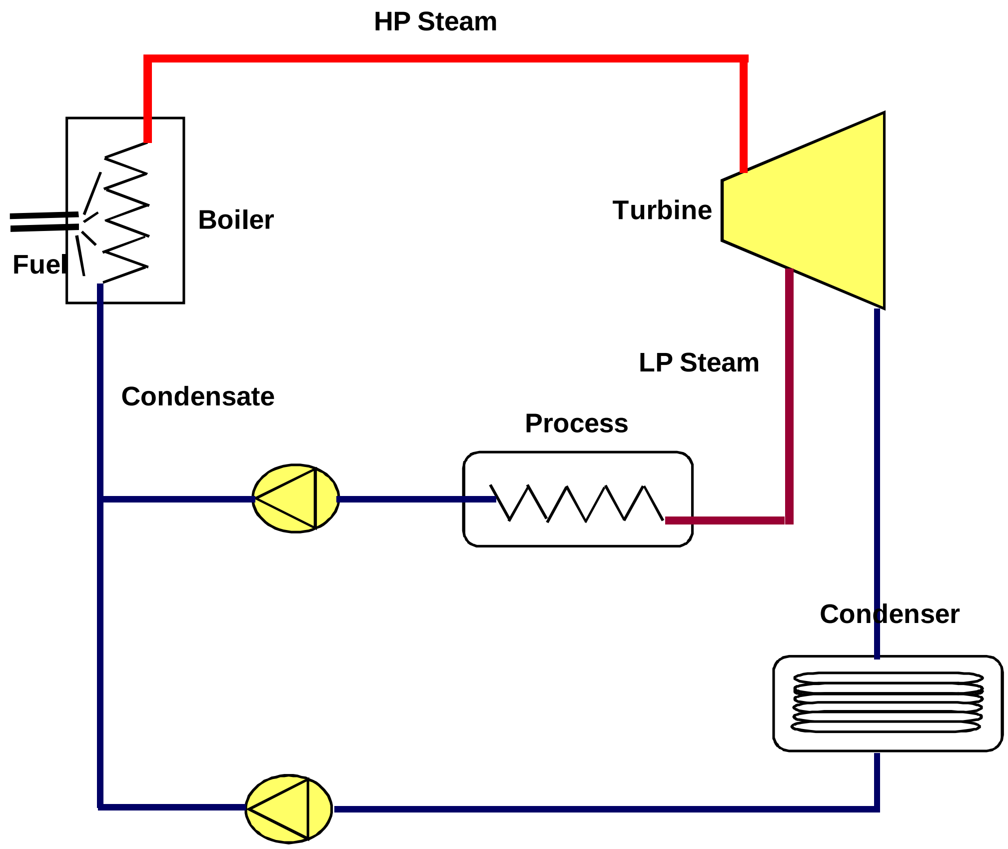
- Therefore, with an efficient boiler, the overall thermal efficiency of the system could reach as much as 90 per cent.

- **Advantages:**
  - ➢ Simple configuration
  - ➢ Low capital cost
  - ➢ Low need of cooling water
  - ➢ High total efficiency

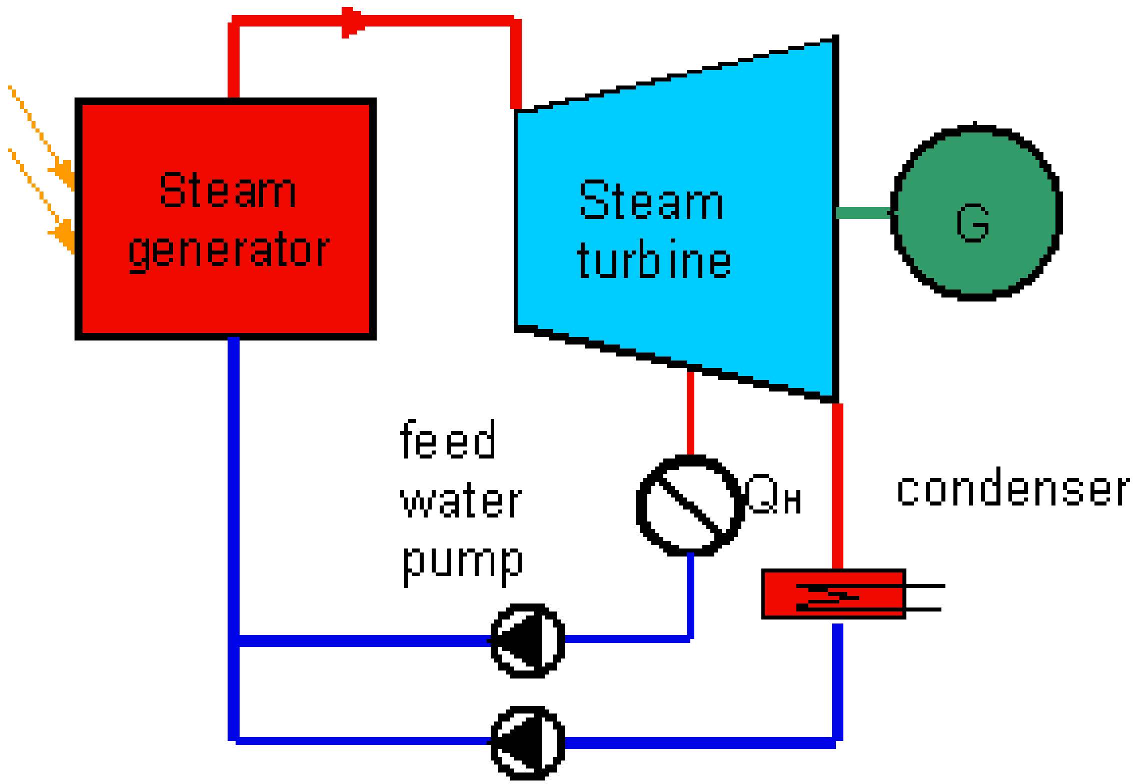
- **Disadvantages:**
  - ➢ Larger steam turbine
  - ➢ Electrical load and output can not be matched

Extraction Condensing Steam Turbine

- Steam turbine



- **Extraction Condensing Steam Turbine**



- In this type, steam entering at High / Medium Pressure is extracted at an intermediate pressure in the turbine for process use while the remaining steam continues to expand and condenses in a surface condenser and work is done till it reaches the Condensing pressure.(vacuum).

- In Extraction cum Condensing steam turbine as shown in Figure, high Pressure steam enters the turbine and passes out from the turbine chamber in stages.

- In a two stage extraction cum condensing turbine MP steam and LP steam pass out to meet the process needs.

- In an extraction condensing steam turbine system, the steam for the thermal load is obtained through extraction from one or more intermediate stages at appropriate pressure and temperature. The remaining steam is exhausted to the pressure of the condenser
- The extraction condensing turbines have higher power to heat ratio in comparison with backpressure turbines

- Although condensing systems need more auxiliary equipment such as the condenser and cooling towers, better matching of electrical power and heat demand can be obtained where electricity demand is much higher than the steam demand and the load patterns are highly fluctuating.

- The overall thermal efficiency of an extraction condensing turbine cogeneration system is lower than that of back pressure turbine system

- basically because the exhaust heat cannot be utilized (it is normally lost in the cooling water circuit). However, extraction condensing cogeneration systems have higher electricity generation efficiencies .
- Advantage is that the extraction condensing steam turbine can control the electrical power independent of the thermal load by proper regulation of the steam flow rate through the turbine to a certain extent.
- Disadvantage the condensing type turbine has a higher capital cost and generally a lower total efficiency.

Gas Turbine Co-Generation System

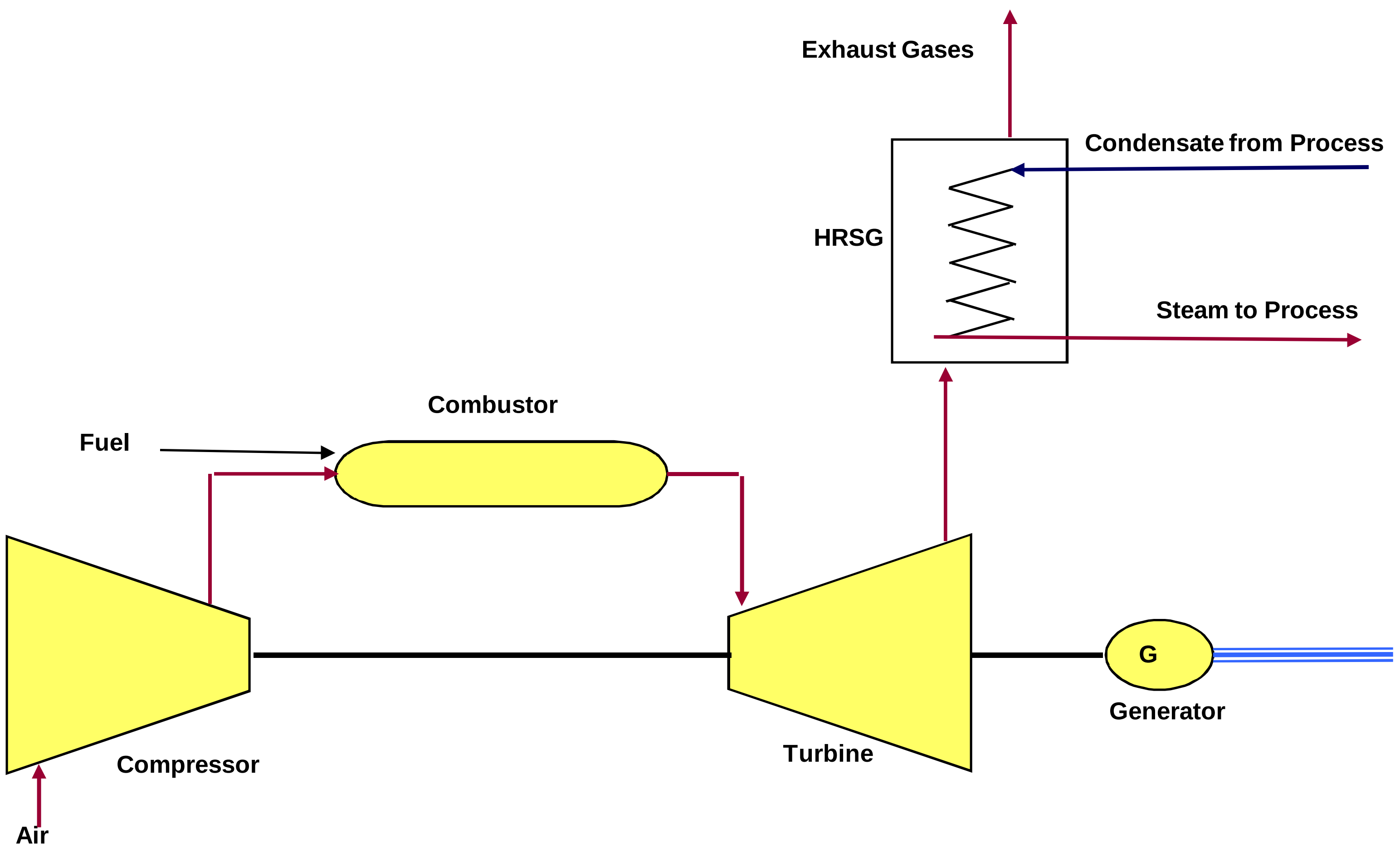


Figure: Open cycle gas turbine co-generation

- Gas turbine cogeneration systems can produce all or a part of the energy requirement of the site, and the energy released at high temperature in the exhaust stack can be recovered for various heating and cooling applications

- Though natural gas is most commonly used, other fuels such as light fuel oil or diesel can also be employed

- The typical range of gas turbines varies from a fraction of a MW to around 100 MW.

- Gas turbine cogeneration has probably experienced the most rapid development in the recent years due to the greater availability of natural gas, rapid progress in the technology, significant reduction in installation costs, and better environmental performance

- Gas turbine has a short start-up time and provides the flexibility of intermittent operation.

- Though it has a low heat to power conversion efficiency, more heat can be recovered at higher temperatures.

- If the heat output is less than that required by the user, it is possible to have supplementary natural gas firing by mixing additional fuel to the oxygen-rich exhaust gas to boost the thermal output more efficiently.
- On the other hand, if more power is required at the site, it is possible to adopt a combined cycle that is a combination of gas turbine and steam turbine cogeneration
- Steam generated from the exhaust gas of the gas turbine is passed through a backpressure or extraction-condensing steam turbine to generate additional power.

- The exhaust or the extracted steam from the steam turbine provides the required thermal energy.

- Most of the currently available gas turbine systems operate on the open Brayton cycle where a compressor takes in air from the atmosphere and derives it at increased pressure to the combustor.

- The air temperature is also increased due to compression.

- Older and smaller units operate at a pressure ratio in the range of 15:1, while the newer and larger units operate at pressure ratios approaching 30:1.

- The air is delivered through a diffuser to a constant-pressure combustion chamber, where fuel is injected and burned.

- Combustion takes place with high excess air and the exhaust gases exit the combustor at high temperature and with oxygen concentrations of up to 15-16%.

- The highest temperature of the cycle appears at this point; with current technology this is about 1300°C.

- The high pressure and high temperature exhaust gases enter the gas turbine and produce mechanical work to drive the compressor and the load.

- The exhaust gases leave the turbine at a considerable temperature (450-600°C), which makes high-temperature heat recovery ideal.

- This makes it appropriate not only for thermal processes but also for driving a steam turbine thus producing additional power.

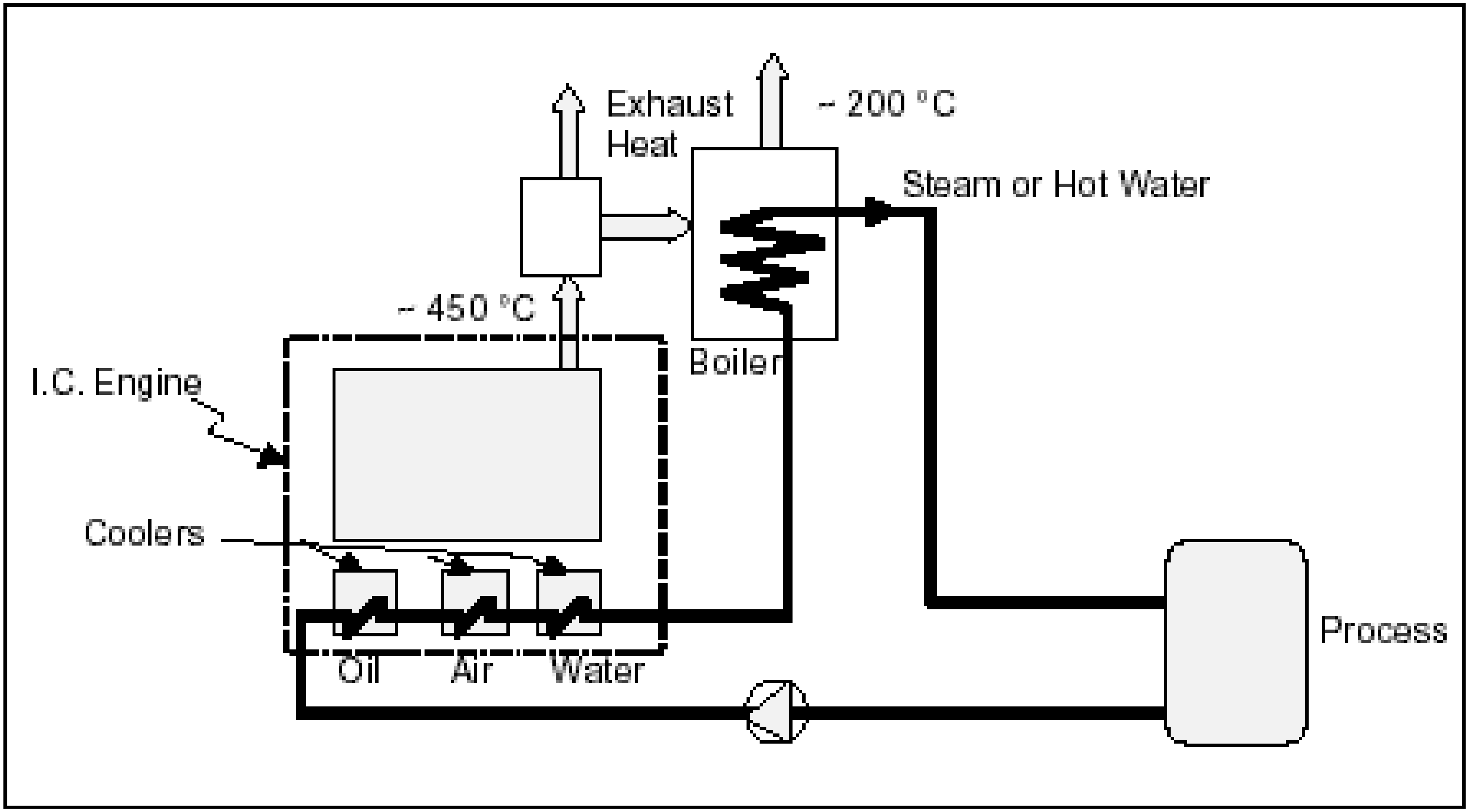
- A gas turbine operates under exacting conditions of high speed and high temperature.

- A gas turbine operates under exacting conditions of high speed and high temperature. The hot gases supplied to it must therefore be clean (i.e. free of particulates which would erode the blades) and must contain not more than minimal amounts of contaminants, which would cause corrosion under operating conditions

- High-premium fuels are therefore most often used, particularly natural gas. Distillate oils such as gas oil are also suitable, and sets capable of using both are often installed to take advantage of cheaper interruptible gas tariffs.

- LPGs and Naphtha are also suitable, LPG being a possible fuel in either gaseous or liquid form.

Reciprocating Engine CoGeneration systems



Reciprocating Engine CoGeneration systems

- It is also known as internal combustion (I. C.) engines

- These cogeneration systems have high power generation efficiencies in comparison with other prime movers.

- There are two sources of heat for recovery: exhaust gas at high temperature and engine jacket cooling water system at low temperature as shown in the fig

- As heat recovery can be quite efficient for smaller systems, these systems are more popular with smaller energy consuming facilities, particularly those having a greater need for electricity than thermal energy and where the quality of heat required is not high, e.g. low pressure steam or hot water.
- These machines are ideal for intermittent operation and their performance is not as sensitive to the changes in ambient temperatures as the gas turbines.
- Though the initial investment on these machines is low, their operating and maintenance costs are high due to high wear and tear.

- Turbine Efficiency is the ratio of actual work output of the turbine to the net input energy supplied in the form of fuel.

- For stand alone Gas Turbines, without any heat recovery system the efficiency will be as low as 35 to 40%.

- Since Exhaust gas from the Gas Turbine is high, it is possible to recover energy from the hot gas by a Heat Recovery Steam Generator and use the steam for process.

- This system provides process heat or steam from engine exhaust.
- The engine jacket cooling water heat exchanger and lube oil cooler may also be used to provide hot water or hot air.
- There are, however, limited applications for this.

- **Advantages:**

- Reciprocating engines start quickly.
- It has good part-load efficiencies.
- Generally have high reliabilities.
- In many cases, multiple reciprocating engine units further increase overall plant capacity and availability.
- Reciprocating engines have higher electrical efficiencies than gas turbines of comparable size, and therefore lower fuel-related operating costs.

- Reciprocating engines are also used extensively as direct mechanical drives in applications such as water pumping, air and gas compression and chilling/refrigeration.

- There are various sources of usable waste heat from a reciprocating engine: exhaust gas, engine jacket cooling water and lube oil cooling water.

- **Disadvantages:**

- ➢ As these engines can use only fuels like HSD, distillate, residual oils, natural gas, LPG etc. and as they are not economically better than steam/gas turbine, their use is not widespread for co-generation.
- ➢ One more reason for this is the engine maintenance requirement.

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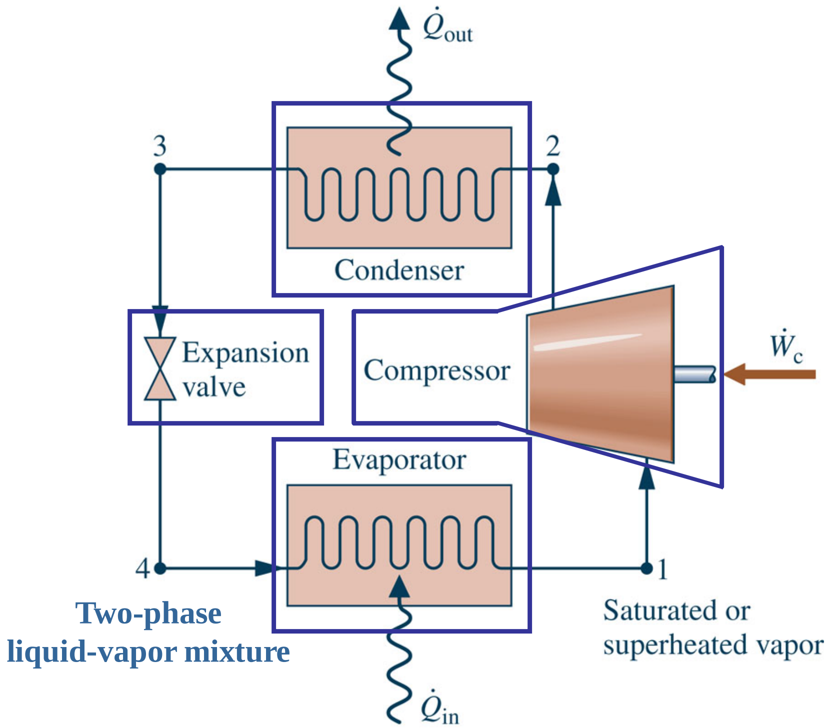
THERMAL ENGINEERING – II

UNITV

Refrigeration and Heat Pump Systems

Vapor-Compression Refrigeration Cycle

- Most common refrigeration cycle in use today
- There are four principal control volumes involving these components:
  - Evaporator
  - Compressor
  - Condenser
  - Expansion valve



All energy transfers by work and heat are taken as positive in the directions of the arrows on the schematic and energy balances are written accordingly.

The Vapor-Compression Refrigeration Cycle

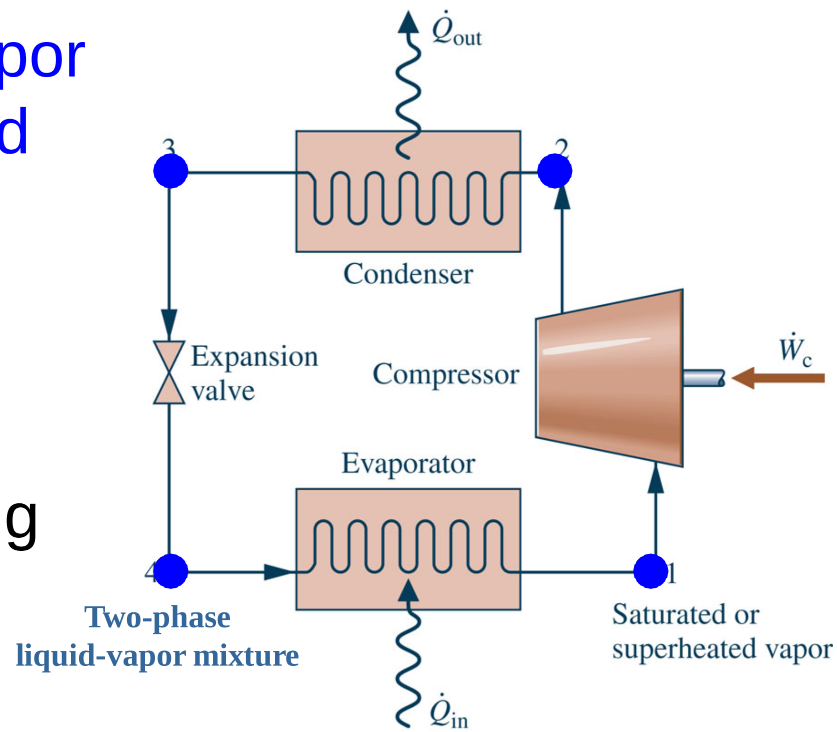
► The processes of this cycle are

Process 4-1: two-phase liquid-vapor mixture of refrigerant is evaporated through heat transfer from the refrigerated space.

Process 1-2: vapor refrigerant is compressed to a relatively high temperature and pressure requiring work input.

Process 2-3: vapor refrigerant condenses to liquid through heat transfer to the cooler surroundings.

Process 3-4: liquid refrigerant expands to the evaporator pressure.



The Vapor-Compression Refrigeration Cycle

- ►Engineering model:
  - ►Each component is analyzed as a control volume at steady state.
  - ►Dry compression is presumed: the refrigerant is a vapor.
  - ►The compressor operates adiabatically.
  - ►The refrigerant expanding through the valve undergoes a throttling process.
  - ►Kinetic and potential energy changes are ignored.

The Vapor-Compression Refrigeration Cycle

► Applying mass and energy rate balances

Evaporator

$$\frac{\dot{Q}_{\text{in}}}{\dot{m}} = h_1 - h_4 \qquad \textbf{(Eq. 10.3)}$$

► The term $\dot{Q}_{\text{in}}$ is referred to as the refrigeration capacity, expressed in kW in the SI unit system or Btu/h in the English unit system.

► A common alternate unit is the ton of refrigeration which equals **200 Btu/min** or about **211 kJ/min**.

The Vapor-Compression Refrigeration Cycle

► Applying mass and energy rate balances

Compressor

Assuming adiabatic compression

$$\frac{\dot{W}_c}{\dot{m}} = h_2 - h_1 \qquad \text{(Eq. 10.4)}$$

Condenser

$$\frac{\dot{Q}_{out}}{\dot{m}} = h_2 - h_3 \qquad \text{(Eq. 10.5)}$$

Expansion valve

Assuming a throttling process

$$h_4 = h_3 \qquad \text{(Eq. 10.6)}$$

The Vapor-Compression Refrigeration Cycle

- Performance parameters

Coefficient of Performance (COP)

$$\text{C.O.P} = \frac{Q_{in}/\dot{m}}{\dot{W}_c/\dot{m}} = \frac{h_1 - h_4}{h_2 - h_1}$$

Carnot Coefficient of Performance

$$\text{C.O.P} = \frac{T_c}{T_H - T_C}$$

This equation represents the maximum theoretical coefficient of performance of any refrigeration cycle operating between cold and hot regions at T_C and T_H, respectively.

Example 11-1

Refrigerant-134a is the working fluid in an ideal compression refrigeration cycle. The refrigerant leaves the evaporator at -20°C and has a condenser pressure of 0.9 MPa. The mass flow rate is 3 kg/min. Find COP_R and $COP_{R,\ Carnot}$ for the same T_{max} and T_{min} , and the tons of refrigeration.

Using the Refrigerant-134a Tables, we have

$$\left.\begin{array}{l} State\,1 \\ Compressor\ inlet \\ T_1 = -20^o C \\ x_1 = 1.0 \end{array}\right\} \left\{\begin{array}{l} h_1 = 238.41\dfrac{kJ}{kg} \\ s_1 = 0.9456\dfrac{kJ}{kg \cdot K} \end{array}\right.$$

$$\left.\begin{array}{l} State\,2 \\ Compressor\ exit \\ P_{2s} = P_2 = 900\,kPa \\ s_{2s} = s_1 = 0.9456\dfrac{kJ}{kg \cdot K} \end{array}\right\} \left\{\begin{array}{l} h_{2s} = 278.23\dfrac{kJ}{kg} \\ T_{2s} = 43.79^o C \end{array}\right.$$

$$\left.\begin{array}{l} State\,3 \\ Condenser\ exit \\ P_3 = 900\,kPa \\ x_3 = 0.0 \end{array}\right\} \left\{\begin{array}{l} h_3 = 101.61\dfrac{kJ}{kg} \\ s_3 = 0.3738\dfrac{kJ}{kg \cdot K} \end{array}\right.$$

$$\left.\begin{array}{l} State\,4 \\ Throttle\ exit \\ T_4 = T_1 = -20^o C \\ h_4 = h_3 \end{array}\right\} \left\{\begin{array}{l} x_4 = 0.358 \\ s_4 = 0.4053\dfrac{kJ}{kg \cdot K} \end{array}\right.$$

$$COP_R = \frac{\dot{Q}_L}{\dot{W}_{net,in}} = \frac{\dot{m}(h_1 - h_4)}{\dot{m}(h_2 - h_1)} = \frac{h_1 - h_4}{h_2 - h_1}$$

$$= \frac{(238.41 - 101.61)\dfrac{kJ}{kg}}{(278.23 - 238.41)\dfrac{kJ}{kg}}$$

$$= 3.44$$

The tons of refrigeration, often called the cooling load or refrigeration effect, are

$$\dot{Q}_L = \dot{m}(h_1 - h_4)$$

$$= 3\frac{kg}{\min}(238.41 - 101.61)\frac{kJ}{kg}\frac{1Ton}{211\dfrac{kJ}{\min}}$$

$$= 1.94\,Ton$$

$$COP_{R,\,Carnot} = \frac{T_L}{T_H - T_L}$$

$$= \frac{(-20 + 273)K}{(43.79 - (-20))K}$$

$$= 3.97$$

Another measure of the effectiveness of the refrigeration cycle is how much input power to the compressor, in horsepower, is required for each ton of cooling.

The unit conversion is 4.715 hp per ton of cooling.

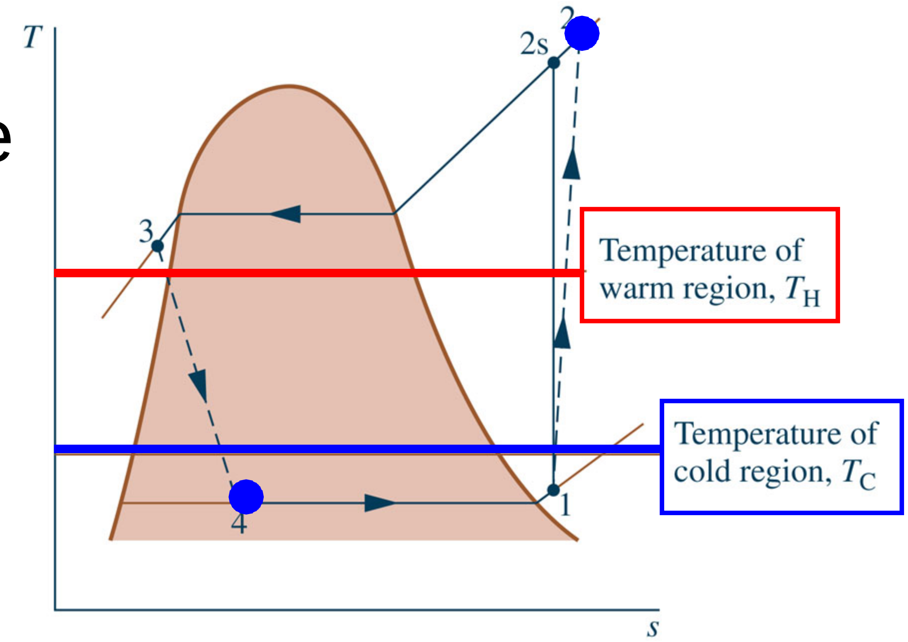
$$\frac{\dot{W}_{net,\,in}}{\dot{Q}_L} = \frac{4.715}{COP_R}$$

$$= \frac{4.715}{3.44}\frac{hp}{Ton}$$

$$= 1.37\frac{hp}{Ton}$$

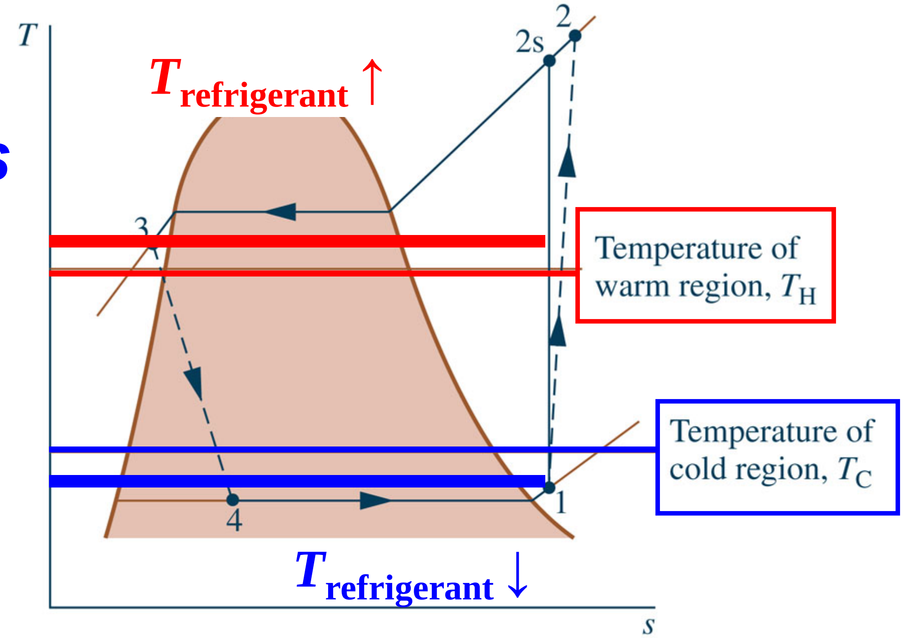
Features of Actual Vapor-Compression Cycle

- Heat transfers between refrigerant and cold and warm regions are not reversible.
  - Refrigerant temperature in evaporator is less than T_C.
  - Refrigerant temperature in condenser is greater than T_H.
  - Irreversible heat transfers have negative effect on performance.



Features of Actual Vapor-Compression Cycle

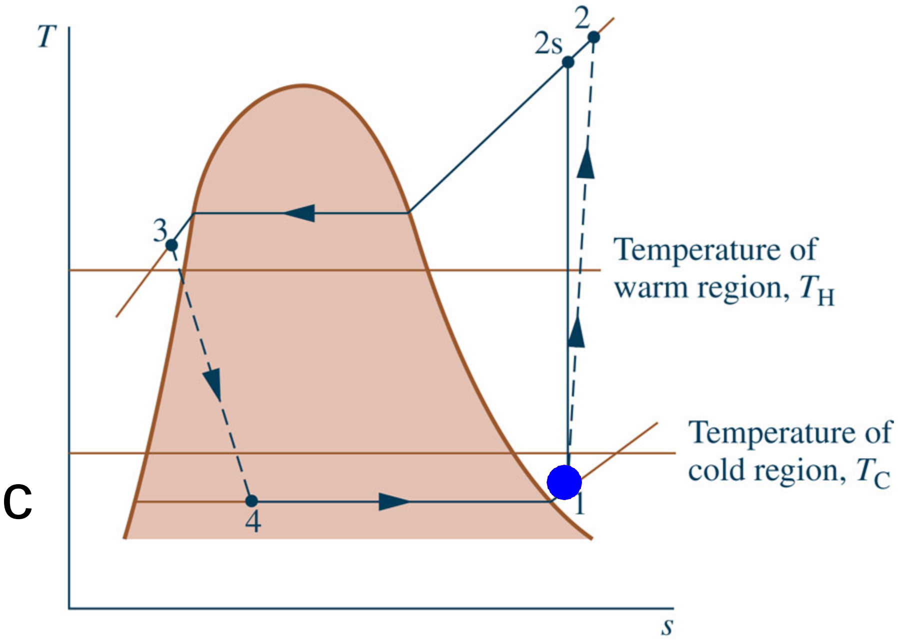
- The COP decreases – primarily due to increasing compressor work input – as the
  - temperature of the refrigerant passing through the evaporator ***is reduced*** relative to the temperature of the cold region, T_C.
  - temperature of the refrigerant passing through the condenser ***is increased*** relative to the temperature of the warm region, T_H.



Features of Actual Vapor-Compression Cycle

► Irreversibilities during the compression process are suggested by dashed line from state **1** to state **2**.

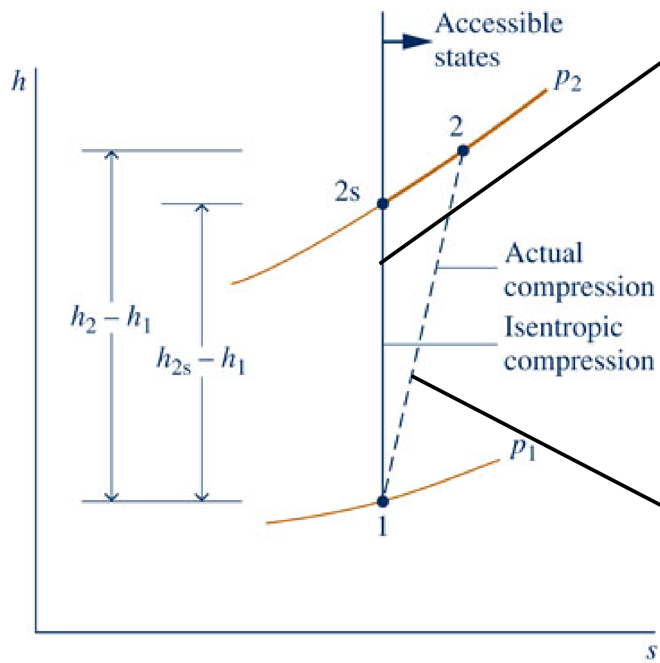
► An increase in specific entropy accompanies an adiabatic irreversible compression process. The work input for compression process **1-2** is greater than for the counterpart isentropic compression process **1-2s**.



► Since process **4-1**, and thus the refrigeration capacity, is the same for cycles **1-2-3-4-1** and **1-2s-3-4-1**, cycle **1-2-3-4-1** has the lower COP.

Isentropic Compressor Efficiency

► The isentropic compressor efficiency is the ratio of the minimum theoretical work input to the actual work input, each per unit of mass flowing:



work required in an isentropic compression from compressor inlet state to the exit pressure

$$\eta_c = \frac{(-\dot{W}_{cv}/\dot{m})_s}{(-\dot{W}_{cv}/\dot{m})} = \frac{h_{2s} - h_1}{h_2 - h_1}$$

(Eq. 6.48)

work required in an actual compression from compressor inlet state to exit pressure

Actual Vapor-Compression Cycle

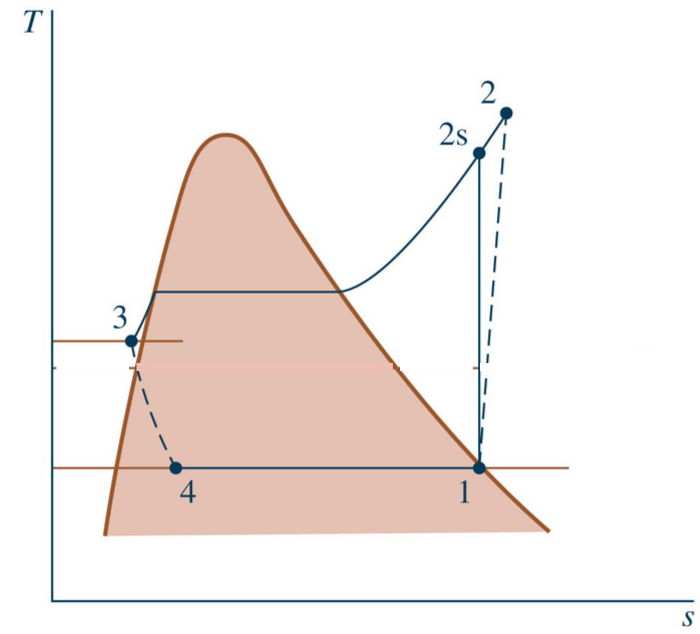
Example: The table provides steady-state operating data for a vapor-compression refrigeration cycle using **R-134a** as the working fluid. For a refrigerant mass flow rate of **0.08 kg/s**, determine the

(a) compressor power, in **kW**,

(b) refrigeration capacity, in **tons**,

(c) coefficient of performance,

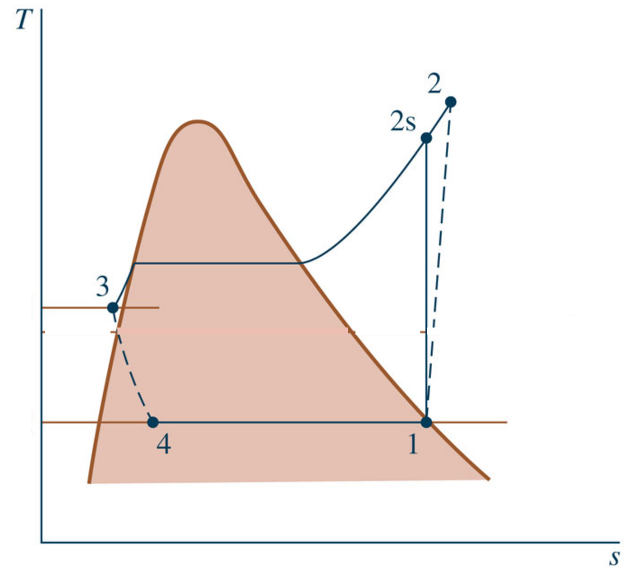
(d) isentropic compressor efficiency.



State	1	2s	2	3	4
h (kJ/kg)	241.35	272.39	280.15	91.49	91.49

Actual Vapor-Compression Cycle

State	1	2s	2	3	4
h (kJ/kg)	241.35	272.39	280.15	91.49	91.49



(a) The **compressor power** is

$$\dot{W}_c = \dot{m}(h_2 - h_1)$$

$$\dot{W}_c = \left(0.08\frac{\text{kg}}{\text{s}}\right)(280.15-241.35)\frac{\text{kJ}}{\text{kg}}\left|\frac{1\,\text{kW}}{1\,\text{kJ/s}}\right| = \mathbf{3.1\ kW}$$

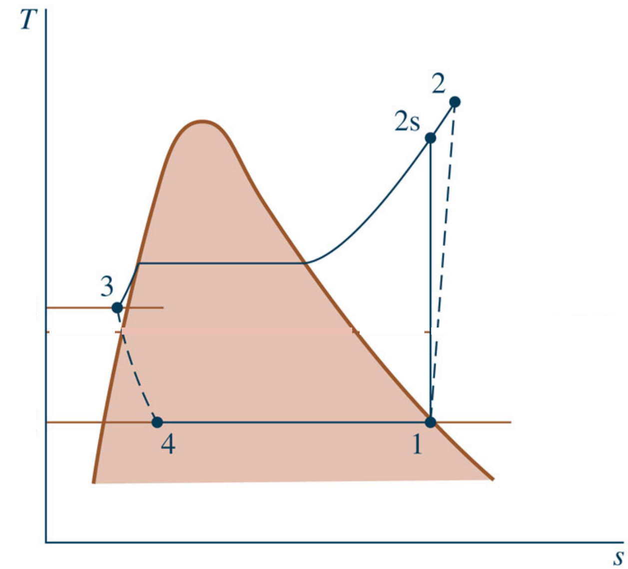
(b) The **refrigeration capacity** is

$$\dot{Q}_{in} = \dot{m}(h_1 - h_4)$$

$$\dot{Q}_{in} = \left(0.08\frac{\text{kg}}{\text{s}}\right)(241.35-91.49)\frac{\text{kJ}}{\text{kg}}\left|\frac{1\,\text{ton}}{211\,\text{kJ/min}}\right|\left|\frac{60\,\text{s}}{\text{min}}\right| = \mathbf{3.41\ tons}$$

Actual Vapor-Compression Cycle

State	1	2s	2	3	4
h (kJ/kg)	241.35	272.39	280.15	91.49	91.49



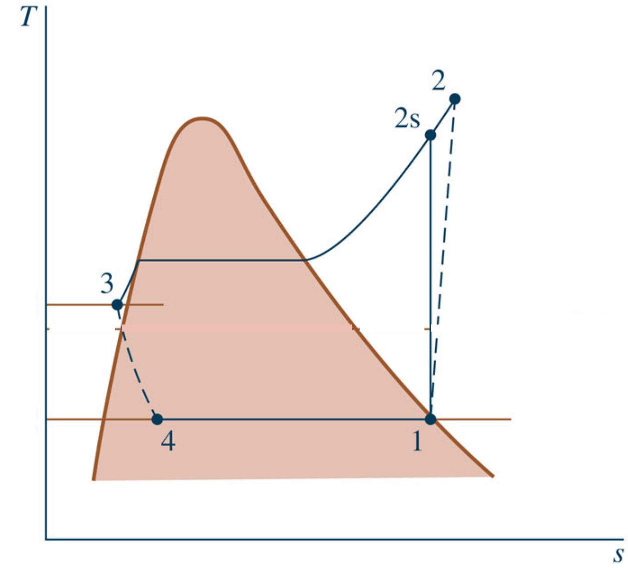
(c) The **coefficient of performance** is

$$C.O.P = \frac{(h_1 - h_4)}{(h_2 - h_1)}$$

$$C.O.P = \frac{(241.35 - 91.49)\text{kJ/kg}}{(280.15 - 241.35)\text{kJ/kg}} = \mathbf{3.86}$$

Actual Vapor-Compression Cycle

State	1	2s	2	3	4
h (kJ/kg)	241.35	272.39	280.15	91.49	91.49



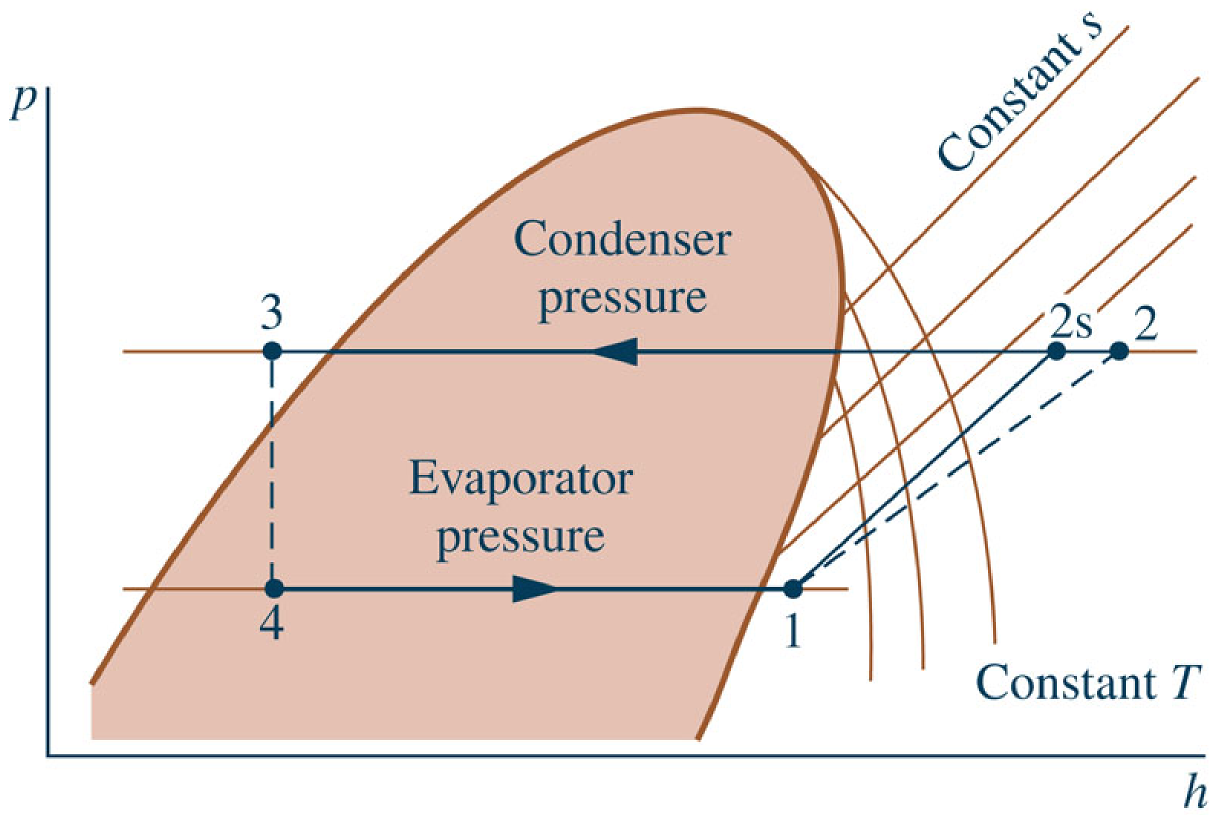
(d) The **isentropic compressor efficiency** is

$$\eta_c = \frac{(\dot{W}_c / \dot{m})_s}{\dot{W}_c / \dot{m}} = \frac{(h_{2s} - h_1)}{(h_2 - h_1)}$$

$$\eta_c = \frac{(272.39 - 241.35)\text{kJ/kg}}{(280.15 - 241.35)\text{kJ/kg}} = \mathbf{0.8 = 80\%}$$

p-h **Diagram**

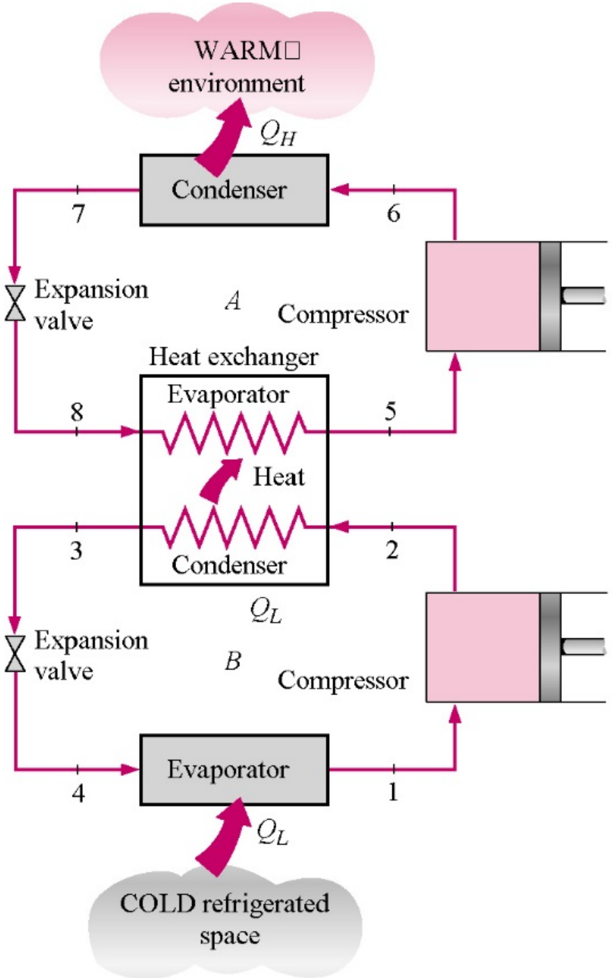
► The pressure-enthalpy (***p-h***) diagram is a thermodynamic property diagram commonly used in the refrigeration field.

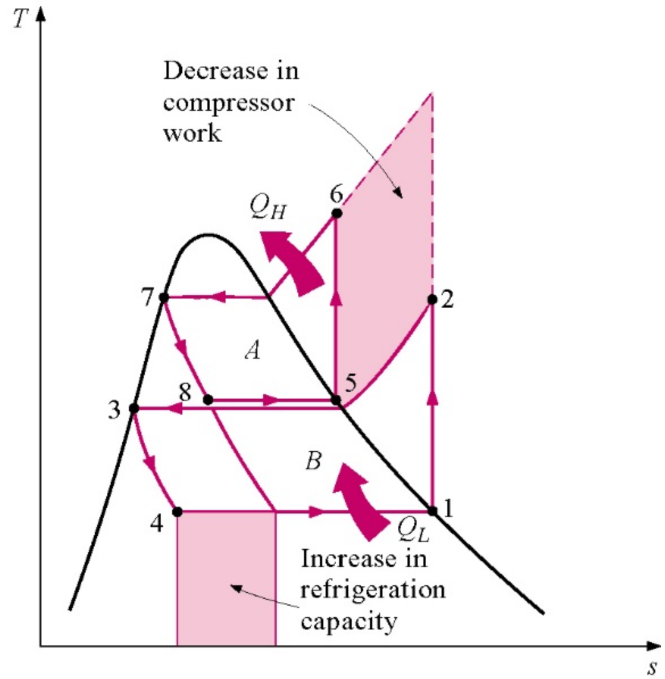


Other Refrigeration Cycles

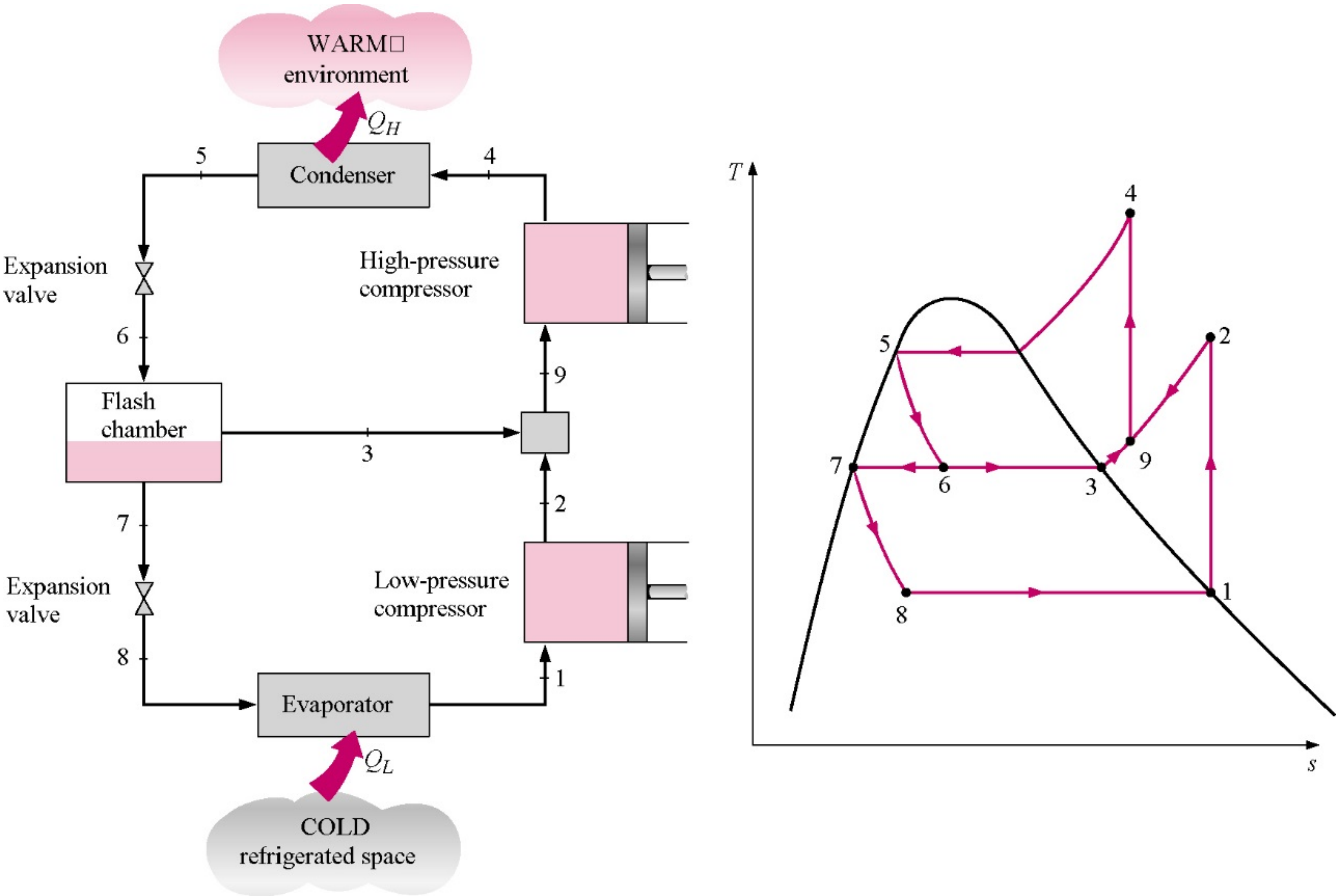
Cascade refrigeration systems

Very low temperatures can be achieved by operating two or more vapor-compression systems in series, called *cascading.* The COP of a refrigeration system also increases as a result of cascading.



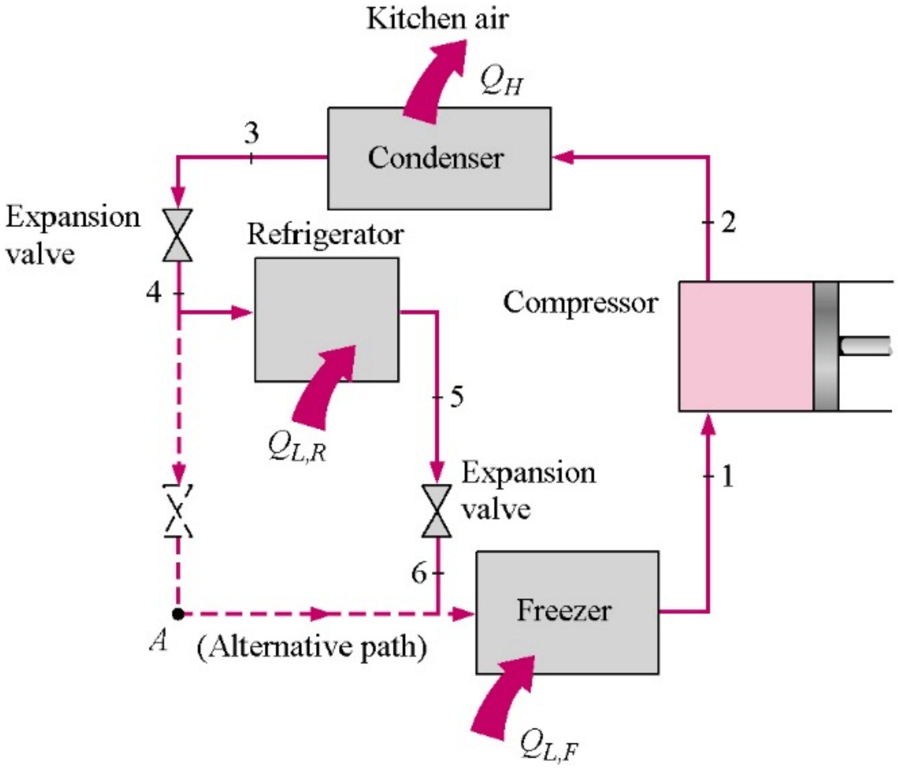


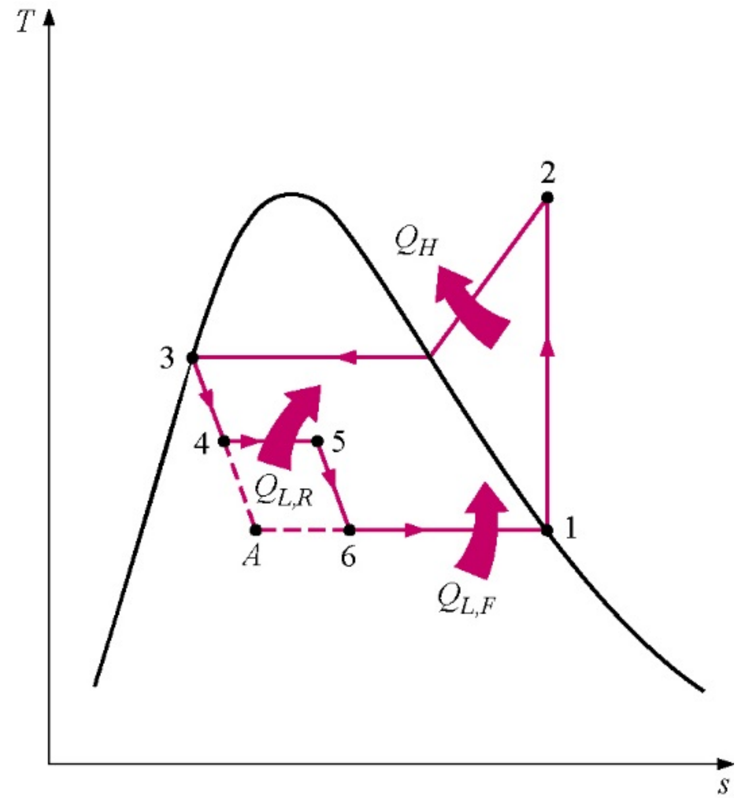
Multistage compression refrigeration systems



Multipurpose refrigeration systems

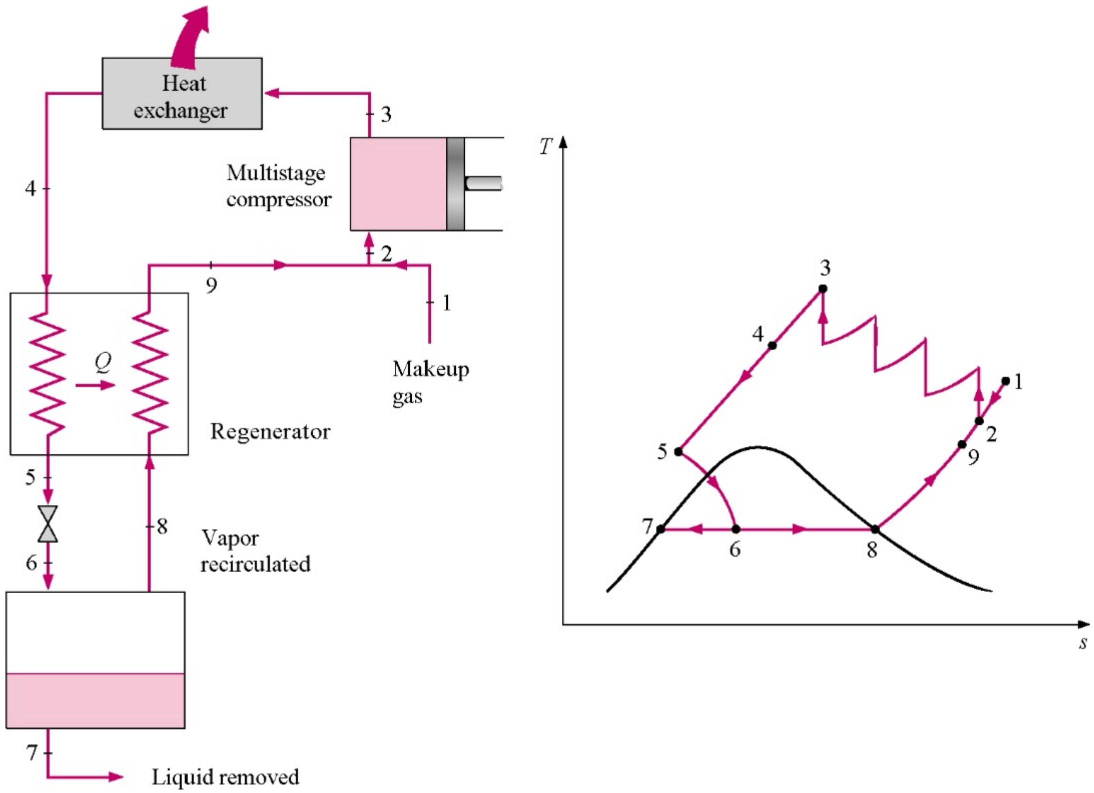
A refrigerator with a single compressor can provide refrigeration at several temperatures by throttling the refrigerant in stages.





Liquefaction of gases

Another way of improving the performance of a vapor-compression refrigeration system is by using *multi-stage compression with regenerative cooling.* The vapor-compression refrigeration cycle can also be used to liquefy gases after some modifications.



Selecting Refrigerants

- ►Refrigerant selection is based on several factors:
  - ►Performance: provides adequate cooling capacity cost-effectively.
  - ►Safety: avoids hazards (i.e., toxicity).
  - ►Environmental impact: minimizes harm to stratospheric ozone layer and reduces negative impact to global climate change.

Refrigerant Types and Characteristics

Refrigerant Data Including Global Warming Potential (GWP)

Refrigerant Number	Type	Chemical Formula	Approx. GWP
R-12	CFC	CCl_2F_2	10900
R-11	CFC	CCl_3F	4750
R-114	CFC	$CClF_2CClF_2$	10000
R-113	CFC	CCl_2FCClF_2	6130
R-22	HCFC	$CHClF_2$	1810
R-134a	HFC	CH_2FCF_3	1430
R-1234yf	HFC	$CF_3CF=CH_2$	4
R-410A	HFC blend	R-32, R-125 (50/50 Weight %)	1725
R-407C	HFC blend	R-32, R-125, R-134a (23/25/52 Weight %)	1526
R-744 (carbon dioxide)	Natural	CO_2	1
R-717 (ammonia)	Natural	NH_3	0
R-290 (propane)	Natural	C_3H_8	10
R-50 (methane)	Natural	CH_4	25
R-600 (butane)	Natural	C_4H_{10}	10

Global Warming Potential (GWP) is a simplified index that estimates the ***potential future influence on global warming*** associated with different gases when released to the atmosphere.

Refrigerant Types and Characteristics

►**Chlorofluorocarbons (CFCs) and Hydrochlorofluorocarbons (HCFCs)** are early synthetic refrigerants each containing chlorine. Because of the adverse effect of chlorine on Earth's stratospheric ozone layer, use of these refrigerants is regulated by international agreement.

►**Hydrofluorocarbons (HFCs) and HFC blends** are chlorine-free refrigerants. Blends combine two or more HFCs. While these chlorine-free refrigerants do not contribute to ozone depletion, with the exception of R-1234yf, they have high GWP levels.

►**Natural refrigerants** are nonsynthetic, naturally occurring substances which serve as refrigerants. These include carbon dioxide, ammonia, and hydrocarbons. These refrigerants feature low GWP values; still, concerns have been raised over the toxicity of NH_3 and the safety of the hydrocarbons.

Eco-friendly Refrigerants

History Of Refrigeration

- Refrigeration relates to the cooling of air or liquids, thus providing lower temperature to preserve food, cool beverages, make ice and for many other .
- Most evidence indicate that the Chinese were the first to store natural ice and snow to cool wine and other delicacies.
- Ancient people of India and Egypt cooled liquids in porous earthen jars.
- In 1834, Jacob Perkins, an American, developed a closed refrigeration system using liquid expansion and then compression to produce cooling. He used Ether as refrigerant, in a hand- operated compressor, a water-cooled condenser and an evaporator in liquid cooler.

Refrigerantion Principle

- Modern refrigeration and air-conditioning equipment is dominated by vapour compression refrigeration technology built upon the thermodynamic principles of the reverse Carnot cycle.
- Refrigerant Changes phases during cooling and used again and again.

What is a Refrigerant

- Refrigerants are used as working substances in a Refrigeration systems.
- Fluids suitable for refrigeration purposes can be classified into primary and secondary refrigerants.
- Primary refrigerants are those fluids, which are used directly as working fluids, for example in vapour compression and vapour absorption refrigeration systems.
- These fluids provide refrigeration by undergoing a phase change process in the evaporator.
- Secondary refrigerants are those liquids, which are used for transporting thermal energy from one location to other. Secondary refrigerants are also known under the name brines or antifreezes

What is ChloroFloroCarcons

- Today’s refrigerants are predominantly from a group of compounds called halocarbons (halogenated hydrocarbons) or specifically fluorocarbons.
- Chlorofluorocarbons were first developed by General Motor’s researchers in the 1920’s and commercialized by Dupont as “Freons”.

Halocarbon Refrigerants

- Halocarbon Refrigerant are all synthetically produced and were developed as the Freon family of refrigerants.

Examples :

- CFC's : R11, R12, R113, R114, R115

Freon Group Refrigerants Application and ODP Values

Refrigerant	Areas of Application	ODP
CFC 11(R11)	Air-conditioning Systems ranging from 200 to 2000 tons in capacity. It is used where low freezing point and non-corrosive properties are important.	1.0
CFC 12 (R 12)	It is used for most of the applications. Air-conditioning plants, refrigerators, freezers, ice-cream cabinets, water coolers, window air-conditioners, automobile air conditioners.	1.0
CFC 13 (R 13)	For low temp refrigeration up to – 90 °C in cascade system	1.0
CFC113 (R113)	Small to medium air-conditioning system and industrial cooling	1.07
CFC114 (R114)	In household refrigerators and in large industrial cooling	0.8 0.34
Blend of R22 and R115 (R502)	Frozen food ice-cream display cases and warehouses and food freezing plants. An excellent general low temp refrigerant	

What is Ozone Layer

- Ozone is an isotope of oxygen with three atoms instead of normal two. It is naturally occurring gas which is created by high energy radiation from the Sun.
- The greatest concentration of ozone are found from 12 km to 50 km above the earth forming a layer in the stratosphere which is called the ozone layer.
- This layer, which forms a semi-permeable blanket, protects the earth by reducing the intensity of harmful ultra-violet (UV) radiation from the sun.

Ozone Layer Depletion

- In the early70's,scientists Sherwood Roland and Mario Molina at the University of California at Irvine were the first to discover the loss of ozone in stratosphere while investigating the ozone layer from highflying aircraft and spacecraft.
- They postulated the theory that exceptionally stable chlorine containing fluorocarbons could, overtime, migrate to the upper reaches of the atmosphere and be broken by the intense radiation and release chlorine atoms responsible for catalytic ozone depletion.

OZONE LAYER DEPLETION

- N0RMAL REACTION
- $O_2 \quad = \quad O + O$
- $O_2 + O = O_3$
- But CFC refrigerants leaked during the manufacturing and normal operation or at the time of servicing or repair, mix with surrounding air and rise to troposphere and then into stratosphere due to normal wind or storm. The Ultraviolet rays act on CFC releasing Cl atom, which retards the normal reaction:
- RETARDED REACTION
- $O_3 \quad = \quad O_2 + O$
- $CCL_2F_2 \quad = \quad CCLF_2 + CL$
- $O_3 + CL = CLO + O_2$
- $O + CLO = CL + O_2$

Harmful consequences of ozone depletion

- ***For Humans*** Increase in
- skin cancer
- snow blindness
- cataracts
- **Less immunity to**
- infectious diseases
- malaria
- herpes
- ***For plants***
- smaller size
- lower yield
- increased toxicity
- altered form
-
- ***For marine life***
- Reduced
- plankton
- juvenile fish
- larval crabs and shrimps

MONTREAL PROTOCOL

- **SIGNED IN 1987 UNDER THE 'UNEP', AFTER MUCH DISCUSSIONS**
- **MORE THAN 170 COUNTRIES HAVE RATIFIED**
- **INDIA RATIFIED ON SEPT 17,1992**
- **ONE OF MOST SUCCESSFUL EXAMPLE OF INTERNATIONAL COOPERATION IN UN HISTORY**

Montreal protocol - Control Schedule

Montréal Protocol - Control Schedule

ozone depleting substance	developed countries	developing countries
CFCs	phased out end of 1995	total phase out by 2010
halons	phased out end of 1993	total phase out by 2010
HCFCs	total phase out by 2020	total phase out by 2040

CFC Phase-out in India

- **What is to be phased out?**
- CFC-11, CFC-12 & CFC-113a.
- **How much and when?**

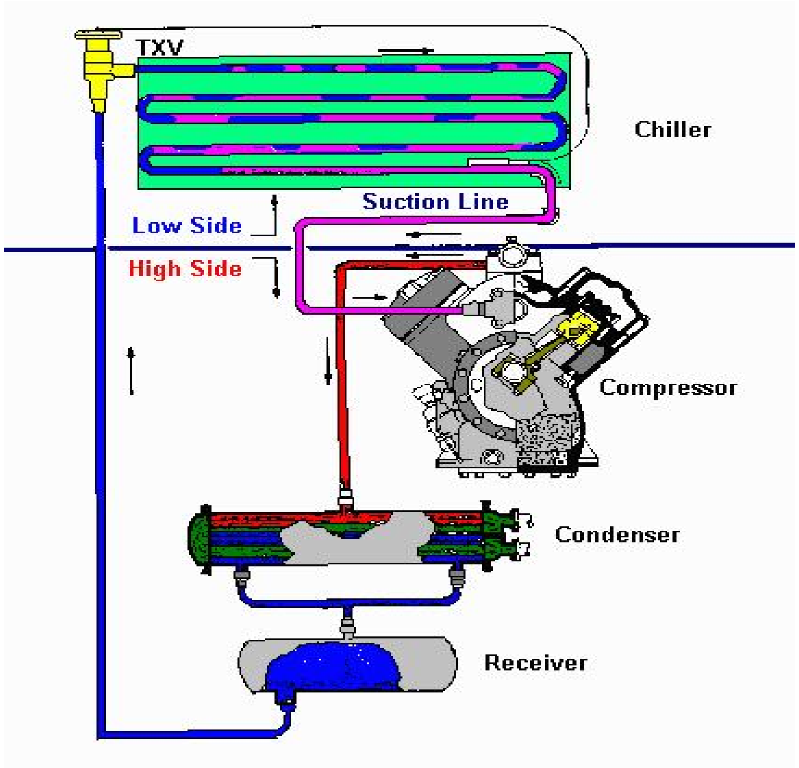
- **Year 1999** 22,588 MT
- 2005 11,294 MT
- 2010 o MT
- **How to achieve the target?**
- Production is controlled through a production quota allocated to each producer every year. The Ozone Cell conducts audits twice a year to monitor the production.
- **How much has been Phaseout?** CFC has been completely phased out as on 1st August, 2008

Vapor compression refrigeration System

- In 1834 an American inventor named Jacob Perkins obtained the first patent for a vapor-compression refrigeration system, it used ether in a vapor compression cycle.
- Joule-Thomson (Kelvin) expansion
- Low pressure (1.5 atm) low temperature (-10 to +15 ℃) inside
- High pressure (7.5 atm) high temperature (+15 to +40 ℃) outside

Components

- Refrigerant
- Evaporator/Chiller
- Compressor
- Condenser
- Receiver
- Thermostatic expansion valve (TXV)



Circulation of Refrigerant

- Compressor
  cold vapor from the evaporator is compressed, raising it temperature and boiling point
  adiabatic compression
  T, b.p. ~ P
  work done on the gas
- Condenser
  hot vapor from the compressor condenses outside the cold box, releasing latent heat
  isothermal, isobaric condensation (horizontal line on PV diagram)
  high temperature
  T (hot)
  latent heat of vaporization *Q* (hot)
- Expansion valve (throttling valve)
  hot liquid from the condenser is depressurized, lowering its temperature and boiling point
  adiabatic, isochoric expansion (vertical line on PV diagram)
  T, b.p. ~ P
  no work done $W = 0$
- Evaporator
  cold liquid from the expansion valve boils inside the cold box, absorbing latent heat
  isothermal, isobaric boiling (horizontal line on PV diagram)
  low temperature
  T (cold)
  latent heat of vaporization *Q* (cold)

Importance of Refrigerant

- The thermodynamic efficiency of a refrigeration system depends mainly on its operating temperatures.
- However, important practical issues such as the system design, size, initial and operating costs, safety, reliability, and serviceability etc. depend very much on the type of refrigerant selected for a given application.
- Due to several environmental issues such as ozone layer depletion and global warming and their relation to the various refrigerants used, the selection of suitable refrigerant has become one of the most important issues in recent times.

Refrigerant selection criteria

- Selection of refrigerant for a particular application is based on the following requirements:
  - i. Thermodynamic and thermo-physical properties
  - ii. Environmental and safety properties
  - Iii. Economics

Thermodynamic and thermo-physical properties

- The requirements are:
- a) Suction pressure: At a given evaporator temperature, the saturation pressure should be above atmospheric for prevention of air or moisture ingress into the system and ease of leak detection. Higher suction pressure is better as it leads to smaller compressor displacement
- b) Discharge pressure: At a given condenser temperature, the discharge pressure should be as small as possible to allow light-weight construction of compressor, condenser etc.
- c) Pressure ratio: Should be as small as possible for high volumetric efficiency and low power consumption
- d) Latent heat of vaporization: Should be as large as possible so that the required mass flow rate per unit cooling capacity will be small

Thermodynamic and thermo-physical properties

- In addition to the above properties; the following properties are also important:
- e) Isentropic index of compression: Should be as small as possible so that the temperature rise during compression will be small
- f) Liquid specific heat: Should be small so that degree of subcooling will be large leading to smaller amount of flash gas at evaporator inlet
- g) Vapour specific heat: Should be large so that the degree of superheating will be small
- h) Thermal conductivity: Thermal conductivity in both liquid as well as vapour phase should be high for higher heat transfer coefficients
- i) Viscosity: Viscosity should be small in both liquid and vapour phases for smaller frictional pressure drops
- The thermodynamic properties are interrelated and mainly depend on normal boiling point, critical temperature, molecular weight and structure.

Environmental and safety properties

- At present the environment friendliness of the refrigerant is a major factor in deciding the usefulness of a particular refrigerant. The important environmental and safety properties are:
- <u>a) Ozone Depletion Potential (ODP):</u> According to the Montreal protocol, the ODP of refrigerants should be zero, i.e., they should be non-ozone depleting substances. Refrigerants having non-zero ODP have either already been phased-out (e.g. R 11, R 12) or will be phased-out in near-future(e.g. R22). Since ODP depends mainly on the presence of chlorine or bromine in the molecules, refrigerants having either chlorine (i.e., CFCs and HCFCs) or bromine cannot be used under the new regulations

Environmental Effects of Refrigerants

Global warming :

Refrigerants directly contributing to global warming when released to the atmosphere

Indirect contribution based on the energy consumption of among others the compressors (CO_2 produced by power stations)

Environmental and safety properties

- <u>b) Global Warming Potential (GWP):</u> Refrigerants should have as low a GWP value as possible to minimize the problem of global warming. Refrigerants with zero ODP but a high value of GWP (e.g. R134a) are likely to be regulated in future.
- <u>c) Total Equivalent Warming Index (TEWI):</u> The factor TEWI considers both direct (due to release into atmosphere) and indirect (through energy consumption) contributions of refrigerants to global warming. Naturally, refrigerants with as a low a value of TEWI are preferable from global warming point of view.

Environmental and safety properties

- d) Toxicity: Ideally, refrigerants used in a refrigeration system should be non-toxic. Toxicity is a relative term, which becomes meaningful only when the degree of concentration and time of exposure required to produce harmful effects are specified. Some fluids are toxic even in small concentrations. Some fluids are mildly toxic, i.e., they are dangerous only when the concentration is large and duration of exposure is long. In general the degree of hazard depends on:
  - - Amount of refrigerant used vs total space
  - - Type of occupancy
  - - Presence of open flames
  - - Odor of refrigerant, and
  - - Maintenance condition

Environmental and safety properties

- e) Flammability: The refrigerants should preferably be non-flammable and non-explosive. For flammable refrigerants special precautions should be taken to avoid accidents.
- f) Chemical stability: The refrigerants should be chemically stable as long as they are inside the refrigeration system.
- g) Compatibility with common materials of construction (both metals and non-metals)
- h) Miscibility with lubricating oils: Oil separators have to be used if the refrigerant is not miscible with lubricating oil (e.g. ammonia). Refrigerants that are completely miscible with oils are easier to handle(R12).

Environmental and safety properties

- Ease of leak detection: In the event of leakage of refrigerant from the system, it should be easy to detect the leaks.

Economic properties:

- The refrigerant used should preferably be inexpensive and easily available.

ECO-FRIENDLY REFRIGERANTS

CFC ALTERNATIVES.

- **HCFC**
  R22,R124
- **HFC**
  R134a,R152a
- **NATURAL REFRIGERANT**
  NH_3, HC's

Halocarbon Refrigerants

- Halocarbon Refrigerant are all synthetically produced and were developed as the Freon family of refrigerants.

Examples :

- CFC's : R11, R12, R113, R114, R115
- HCFC's : R22, R123
- HFC's : R134a, R404a, R407C, R410a

HFCs

- Remain a popular choice
  – especially for R22 phase out
- Good efforts at improving leakage performance
  – e.g. Real Zero project
- Interest in R407A to replace R404A
  – 50% reduction in GWP

Inorganic Refrigerants

- Carbon Dioxide
- Water
- Ammonia
- Air
- Sulphur dioxide

Table 1: Environmental Effects of Some Refrigerants (UNEP, 2002)

Refrigerants		ODP	GWP (Time horizons of 100 yrs)
HCFC's	R-22	0.055	1,700
HFC's	R-134a	0	1,300
	R-404A (R125/143a/134a)	0	3,800
	R-410A (R32/125)	0	2,000
Natural Refrigerants	Carbon dioxide (R-744)	0	1
	Ammonia (R-717)	0	<1
	Propane (R-290)	0	20
	Isobutane (R-600a)	0	20
	Cyclopropane (RC-270)	0	n/a

HCFC

- Transitional compounds with low ODP
- Partially halogenated compounds of hydrocarbon
- Remaining hydrogen atom allows Hydrolysis and can be absorbed.
- R22, R123

HCFC

- Production frozen at 1996 level
- 35% cut by 2005,65% by 2010
- 90% by 2015,100 % by 2030
- 10 year grace period for developing countries.

R22

- ODP-0.05, GWP-1700
- R22 has 40% more refrigerating capacity
- Higher pressure and discharge temp and not suitable for low temp application
- Extensively used in commercial air-conditioning and frozen food storage and display cases

HFC

- Zero ODP as no chlorine atom contains only Hydrogen and Flurodine
- Very small GWP values
- No phase out date in Montreal Protocol
- R134a and R152 a – Very popular refrigerants
- HFC refrigerants are costly refrigerants

R134a

- ODP-0, GWP-1300
- Used as a substitute for R12 and to a limited range for R22
- Good performance in medium and high temp application
- Toxicity is very low
- Not miscible with mineral oil

Hydrocarbon

- Very promising non-halogenated organic compounds
- With no ODP and very small GWP values
- Their efficiency is slightly better than other leading alternative refrigerants
- They are fully compatible with lubricating oils conventionally used with CFC12.

Hydrocarbon Refrigerants

- Extraordinary reliability- The most convincing argument is the reliability of the hydrocarbon system because of fewer compressor failures.
- But most of the hydrocarbons are highly flammable and require additional safety precaution during its use as refrigerants.
- Virtually no refrigerant losses
- Hydrocarbons have been used since the beginning of the century and now being considered as long term solutions to environmental problems,

Hydrocarbons

- Dominant in domestic market like household refrigerators and freezers
- Growing use in very small commercial systems like car air-conditioning system
- Examples: R170, Ethane, C_2H_6
  R290 , Propane C_3H_3
  R600, Butane, C_4H_{10}
  R600a, Isobutane, C_4H_{10}
  Blends of the above Gases

R 600a

- ODP-0,GWP-3
- Higher boiling point hence lower evaporator pressure
- Discharge temp is lowest
- Very good compatibility with mineral oil

Flammability

- Approximate auto ignition temperatures
- R22 630 ºC
- R12 750 ºC
- R134a 740 ºC
- R290 465 ºC
- R600a 470 ºC
-

Modifications of Electrical Equipment

- Replaced with solid state equivalents
- Sealed to ensure that any sparks do not come into contact with leaking gas
- Relocated to a position where the component would not come into contact with leaking gas

Modifications of Electrical Equipment

- Faulty components.
- Poor, corroded, loose, or dirty electrical connections.
- Missing or broken insulation which could cause arcing/sparks.
- Friction sparks, like a metal fan blade hitting a metal enclosure.

Blends & Mixtures

- Limited no of pure refrigerants with low ODP & GWP values
- To try a mixture of pure refrigerants to meet specific requirement

Azeotropic Refrigerants

- A stable mixture of two or several refrigerants whose vapour and liquid phases retain identical compositions over a wide range of temperatures.

- Examples : R-500 : 73.8% R12 and 26.2% R152
  R-502 : 8.8% R22 and 51.2% R115
  R-503 : 40.1% R23 and 59.9% R13

Zeotropic Refrigerants

- A zeotropic mixture is one whose composition in liquid phase differs to that in vapour phase. Zeotropic refrigerants therefore do not boil at constant temperatures unlike azeotropic refrigerants.
- Examples :R404a : R125/143a/134a (44%,52%,4%)

  R407c : R32/125/134a (23%, 25%, 52%)

  R410a : R32/125 (50%, 50%)

  R413a : R600a/218/134a (3%, 9%, 88%)

Inorganic Refrigerants

- Carbon Dioxide
- Water
- Ammonia
- Air
- Sulphur dioxide

Carbon Dioxide

- Zero ODP & GWP
- Non Flammable, Non toxic
- Inexpensive and widely available
- Its high operating pressure provides potential for system size and weight reducing potential.
- ***<u>Drawbacks:</u>***
- Operating pressure (high side) : 80 bars
- Low efficiency

Ammonia –A Natural Refrigerant

Ammonia is produced in a natural way by human beings and animals; 17 grams/day for humans.

Natural production	3000 million tons/year
Production in factories	120 million tons/year
Used in refrigeration	6 million tons/year

Ammonia as Refrigerant

- ODP = 0
- GWP = 0
- Excellent thermodynamic characteristics: small molecular mass, large latent heat, large vapour density and excellent heat transfer characteristics
- High critical temperature (132C) : highly efficient cycles at high condensing temperatures
- Its smell causes leaks to be detected and fixed before reaching dangerous concentration
- Relatively Low price

Some Drawbacks of Ammonia as Refrigerant

- Toxic
- Flammable (16 – 28% concentration)
- Not compatible with copper
- Temperature on discharge side of compressor is higher compared to other refrigerants

Water

- Zero ODP & GWP
- Water as refrigerant is used in absorption system .New developing technology has created space for it for use in compression cycles also.
- But higher than normal working pressure in the system can be a factor in restricted use of water as refrigerant

Application of New Eco-friendly Refrigerants

Application	**HFCs used**	**Possible Eco-friendly refrigerant**
Domestic refrigeration	R134a,R152a	HC600a and blends
Commercial refrigeration	R134a,R404A,R407C	HC blends,NH_3 ,CO_2 **
Cold storage ,food processing		
And industrial refrigeration	R134a,R404A,R507A	NH_3 ,HCs,CO_2 **
Unitary air conditioners	R410A,R407C	CO_2 , HC s
Centralized AC (chillers)	R134a,R410A,R407C	NH_3 ,HCs,CO_2, water **
Transport refrigeration	R134a,R404A	CO_2,
Mobile air conditioner	R134a	CO_2 ,HCs
Heat pumps	R134a,R152a,R404A	NH_3 ,HCs,CO_2, water **
	R407C,R410A	

General Safety measures for refrigerating plants

- **Reduction of refrigerant contents:**
  - Components with reduced contents
  - Indirect systems with secondary refrigerant: distinction between generation and transport of cold

- **Scheduled maintenance and leak testing**

- **Governmental surveillance –** Refrigerant Audits for

  systems operating with HFC's. Recovery, Stock of used refrigerants, Recycling of refrigerants.

- For the Netherlands, the combined measures resulted in a leak rate reduction of 35% (1995) to 8% (2001) for R22-systems

Survey Of Refrigerants

Refrigerant	Group	Atmospheric life	ODP	GWP
R11	CFC	130	1	4000
R12	CFC	130	1	8500
R22	HCFC	15	.05	1500
R134a	HFC	16	0	1300
R404a	HFC	16	0	3260
R410a	HFC	16	0	1720
R507	HFC	130	1	3300
R717	NH3	-	0	0
R744	CO_2	-	0	1
R290	HC	< 1	0	8
R600a	HC	< 1	0	8

Comparison of Alternatives

F-GAS SUPPORT
Promoting Compliance with F-Gas and Ozone Regulations

Refrigerant	HFCs	HCs	Ammonia	CO_2	Low GWP FCs
GWP	✗✗	✓	✓✓	✓✓	✓
Toxicity	✓✓	✓✓	✗✗	✓	✓✓
Flammability	✓✓	✗✗	✗	✓✓	? ✗
Efficiency	✓	✓	✓	✓	✓
Materials	✓	✓	✗	✓	✓
Pressure	✓	✓	✓	✗✗	✓
Cost	✓	✓✓	✓✓	✓✓	?
Availability	✓✓	✓	✓	✓	✗✗
Familiarity	✓✓	✓	✓	✗	✗

Very poor ✗✗ Poor ✗ Good ✓ Very Good ✓✓

Environmental Effects of Refrigerants

Global warming :

Refrigerants directly contributing to global warming when released to the atmosphere

Indirect contribution based on the energy consumption of among others the compressors (CO_2 produced by power stations)

Conclusions

- In the aftermath of the Montreal protocole HFC's have predominantly replaced CFC's and HCFC's in RAC equipment.
- Due to their high GWP, HFC's are not a good replacement solution.
- The solution are the natural refrigerants :

  Ammonia, Hydrocarbons and Carbon dioxide
- System need to have low TEWI factor
- High efficiency with ammonia and lower power consumption with hydrocarbons

AIR CONDITIONING

Air conditioning

- **Definition**
- A system for controlling the humidity ,ventilation and temperature in a building or vehicle typically to maintain comfortable conditions.
- **History and development**
- In 1820,Micheal Faraday discovered that compressing and liquefying ammonia could chill air if allowed to evaporate.
- In 1842,Physician John Gorrie used compressor technology to cool air.
- First modern electrical air conditioning unit was invented by Willis Carrier in 1902 at Buffalo,NewYork .

REFRIGERANT

A refrigerant is a substance or mixture, usually a fluid, used in a heat pump and refrigeration cycle. In most cycles it undergoes phase transitions from a liquid to a gas and vice-versa.

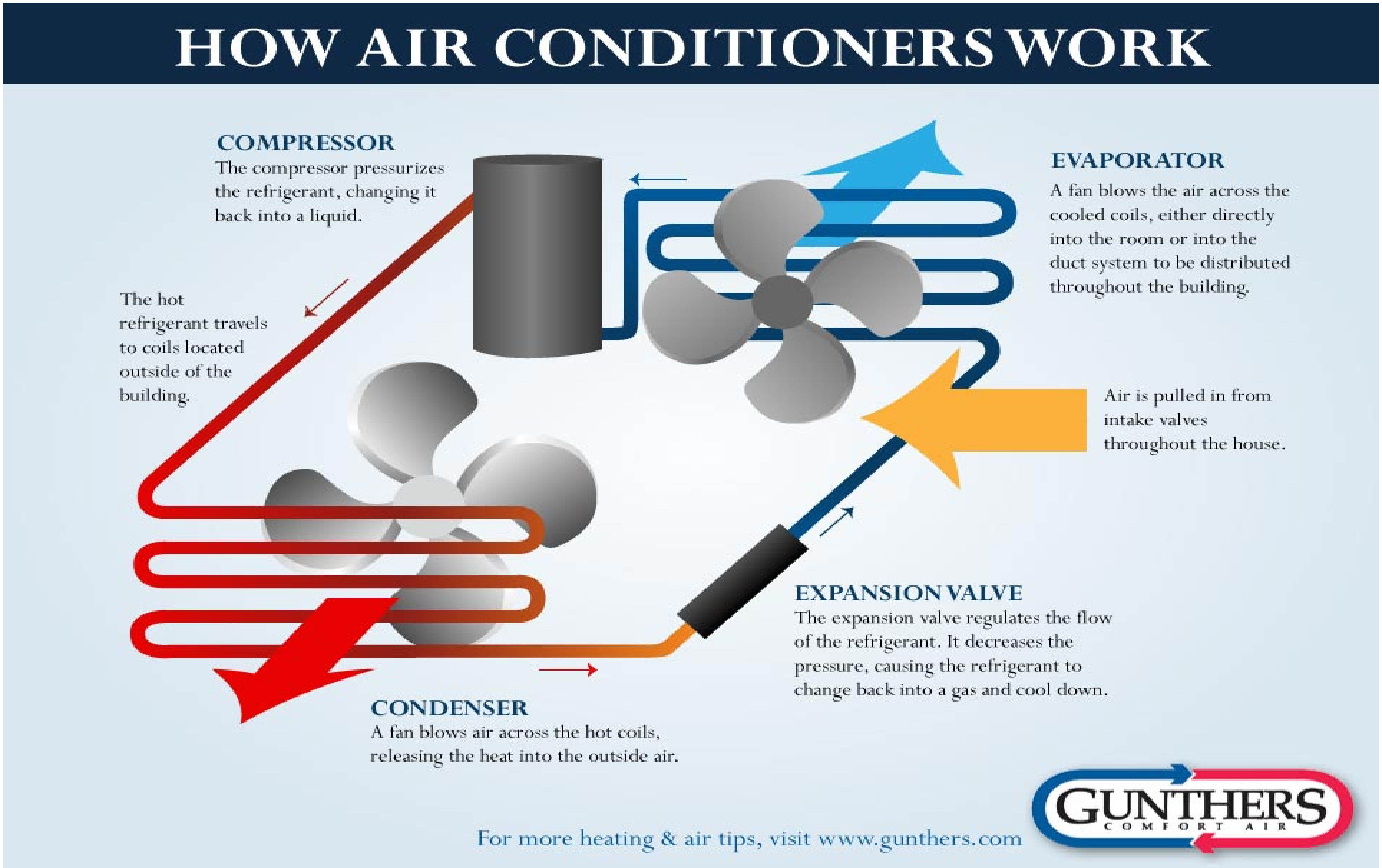
Ex.- Freon(R-22),Puron(R-410A).

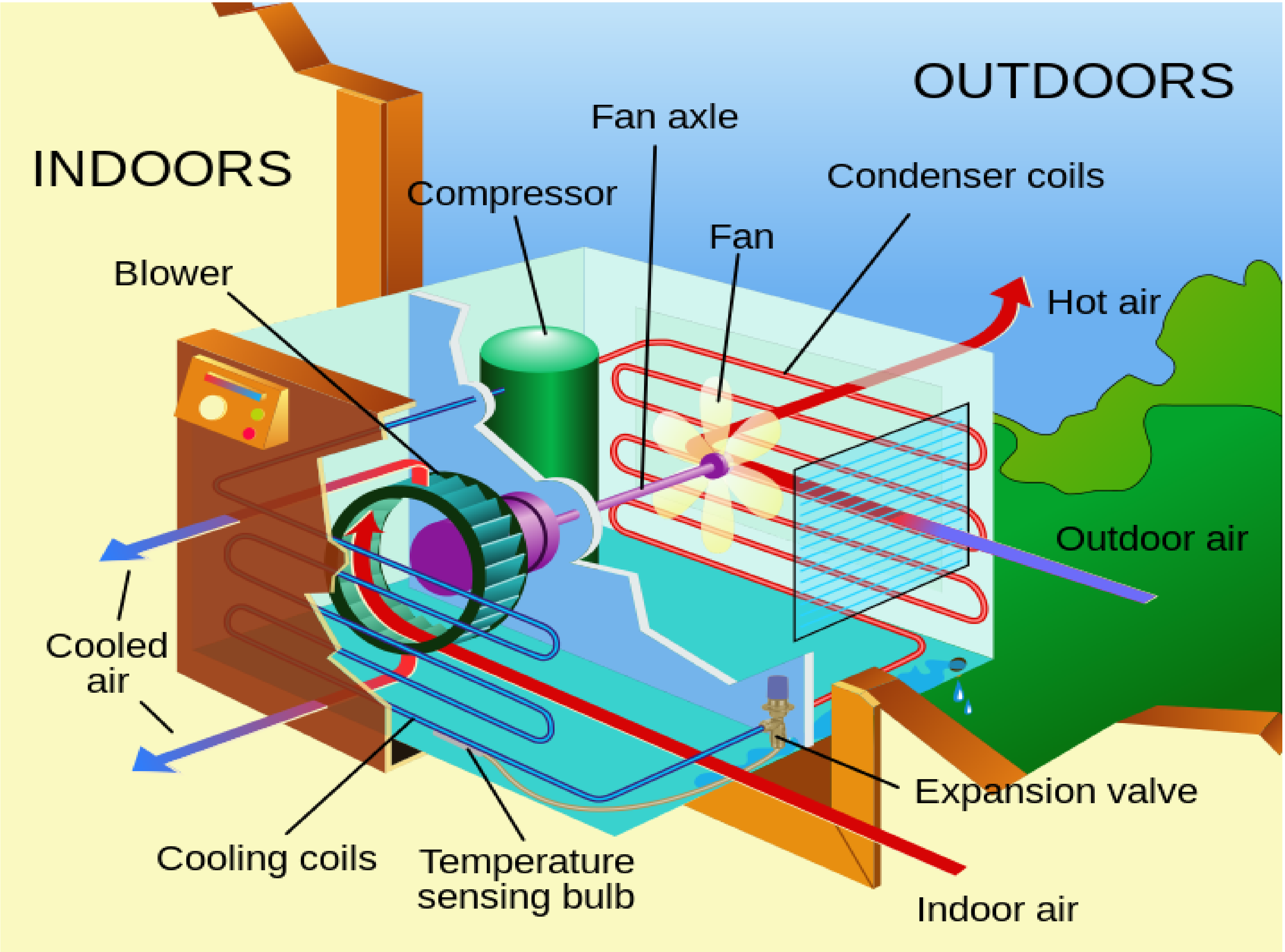
A refrigerant should be non-flammable, non-toxic ,should have dense vapour ,lower boiling point.

MAJOR PARTS OF THE AC

- Evaporator
- Compressor
- Condenser
- Expansion Valve

Working of an AC



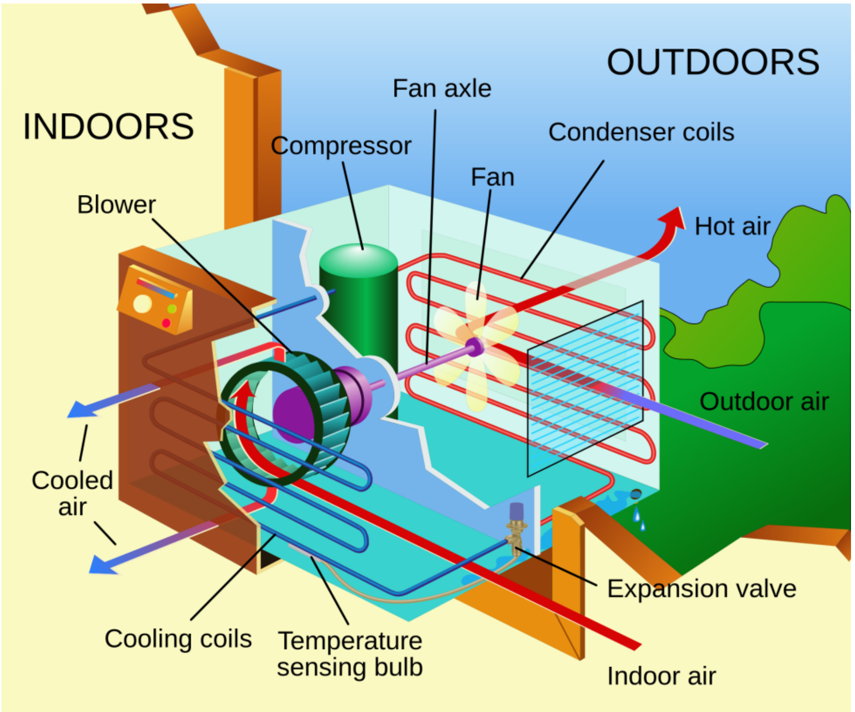

OUTDOORS
INDOORS
Fan axle
Condenser coils
Compressor
Fan
Blower
Hot air
Outdoor air
Cooled
air
Expansion valve
Cooling coils
Temperature
sensing bulb
Indoor air

Types of AC

- Window AC
- Split AC
- Central AC plant
- Packaged AC

Window air-conditioning system

- In this air conditioner all the components namely the compressor, condenser ,expansion valves or coil, evaporator and cooling coil are enclosed in a single box
- Window air-conditioning system are one of the most commonly used and cheapest type of air conditioners.
- Window air conditioner units are reliable and simple-to-install solution to keep a room cool while avoiding the costly construction of a



OUTDOORS
INDOORS
Fan axle
Compressor
Condenser coils
Fan
Blower
Hot air
Outdoor air
Cooled air
Expansion valve
Cooling coils
Temperature sensing bulb
Indoor air

Split air-conditioning system

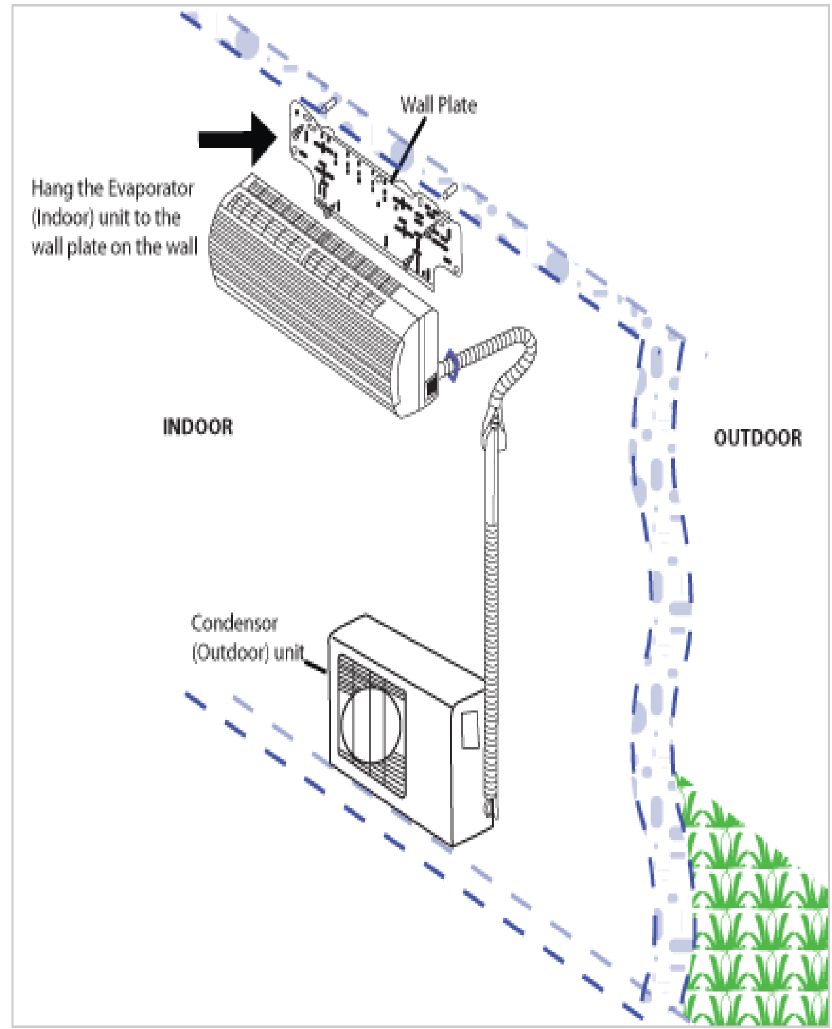
The split air conditioner comprises of two parts the outdoor unit and the indoor unit.

Outdoor unit consists of compressor, condenser and expansion valve.

Indoor unit consists of evaporator or cooling coil and cooling fan.

Indoor Unit

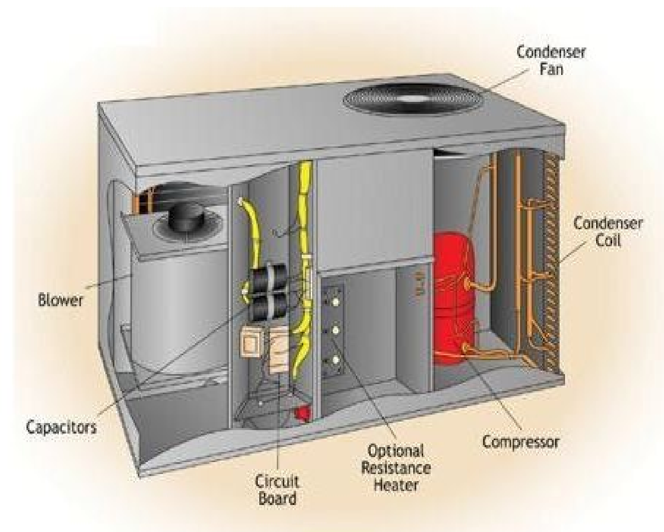
Outdoor Unit



Packaged terminal air-conditioning system

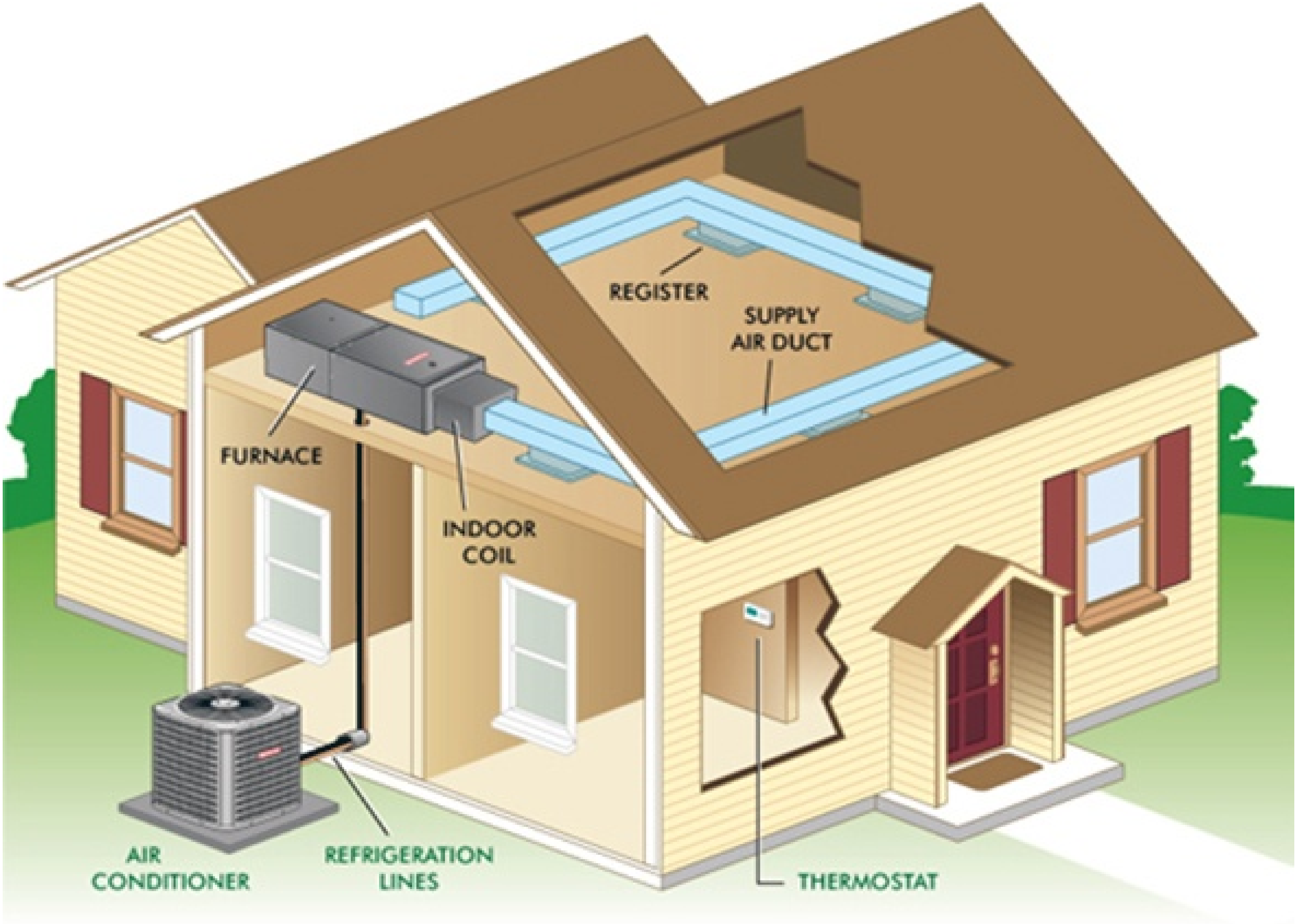
- They are used where the cooling loads extend beyond 20 tons.
- All the components are housed in a same box.
- Cooled air is thrown by the high capacity blower, and it flows through the duct laid through various rooms.
- They are of two types PACS

  i) air cooled ii) water cooled


Condenser
Fan
Condenser
Coil
Blower
Capacitors
Circuit
Board
Optional
Resistance
Heater
Compressor

Centralised air-conditioning system

- Used for cooling big buildings, offices, hotels, movie theatre etc.
- It consists of a huge compressor that has the capacity to produce hundred of tons of air conditioning.
- Same as PTAC cooled air is flows through duct.


REGISTER
SUPPLY
AIR DUCT
FURNACE
INDOOR
COIL
AIR
CONDITIONER
REFRIGERATION
LINES
THERMOSTAT

TEMPERATURE CONTROL IN AIR CONDITIONERS

The main purpose of the air-conditioning system is to create comfort conditions by controlling the temperature, humidity and flow of air inside the rooms.

To provide the comfort conditions throughout the year, the air-conditioning systems are fitted with three controls:
temperature controls, humidistats and airstats that control the temperature, relative humidity and flow of air inside the room respectively.

Temperature Control:

One of the most commonly used devise for controlling the room temperature is the room thermostat.

The basic operation principle of air conditioning thermostat is it relies on random air current that passing thought it to determine the room temperature.

- There are various types of thermostats, but the most commonly used is the bimetal room thermostat.
- It comprises of two metals which at particular temperature are of same length, but when their temperature is increased one metal increases in length more while the other increases less due to their different coefficients of expansions.
- When the bimetal is heated it tends to get bent which helps in opening or closing of the electrical supply to the compressor.

Types of air conditioning thermostat:

- Regular old AC thermostat (mercury)
- Digital thermostats
- System zoning thermostat (for individual room)
- Heat Pump thermostats – thermostat for heat pump only.
- Electronic thermostat

Motor Protection of Air Conditioner

Motor Instantaneous Over-current Protection:

Instantaneous over-current is usually the result of fault conditions (phase to phase, phase to ground), in which current flow will greatly exceed normal values. Damage due to winding overheating and burning damage associated with large fault currents can occur without this type of protection.

In these situations, fast acting electromagnetic relays will be used to trip the affected motor.

TIMED OVERLOAD PROTECTION:

A common type of relay used for timed overload protection is a thermal overload relay. In this type of relay, the motor current or a fraction of the current through a current transformer is connected to an in-line heater.

The heater (heated by I^2R action) is used to heat a bimetallic strip, which causes the displacement of a relay contact. A bimetallic strip consists of two different materials bonded together, each having different thermal expansion properties.

As the materials are heated, one side will lengthen more than the other, causing bending. This bending causes tripping.

Motor Ground Fault Protection

In the detection of ground faults, as with the detection of instantaneous over-currents, it is extremely important that the fault be detected and cleared quickly to prevent equipment damage. Insulation damaged by heat , brittleness of insulation (due to aging), wet insulation or mechanically damaged insulation can cause ground faults.

Ground fault protection schemes use differential protection to detect and clear the faulted equipment. For motors, the common method is to use a Core-Balance CT. The output of the core-balance CT will be the difference or imbalance of current between the three phases.
If no ground fault is present, no current imbalance is present; hence no current will flow in the protection circuit.

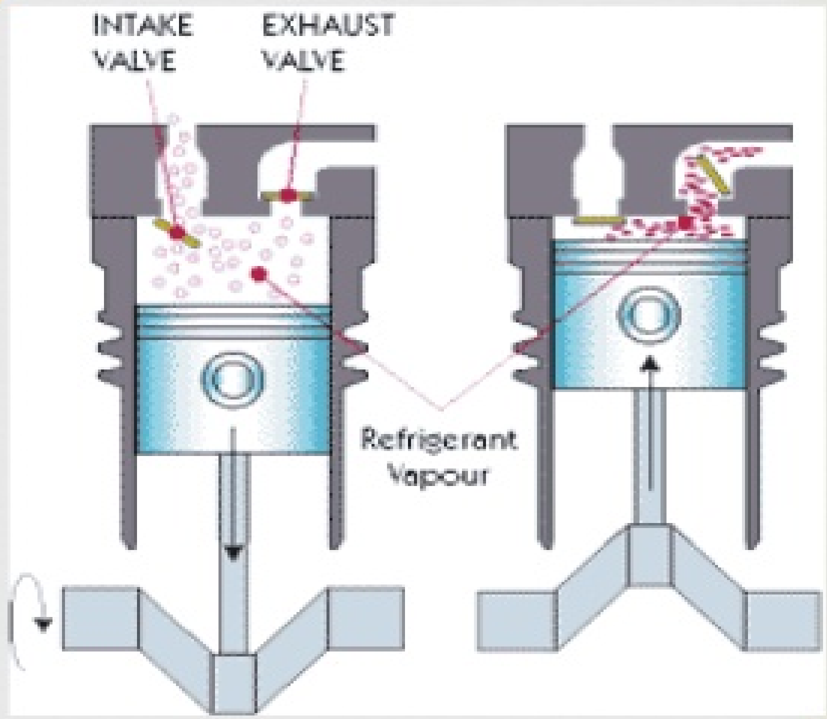
Types of Compressors

- Reciprocating Compressor
- Rotary Compressor
- Screw Compressor
- Centrifugal Compressor
- Scroll Compressor

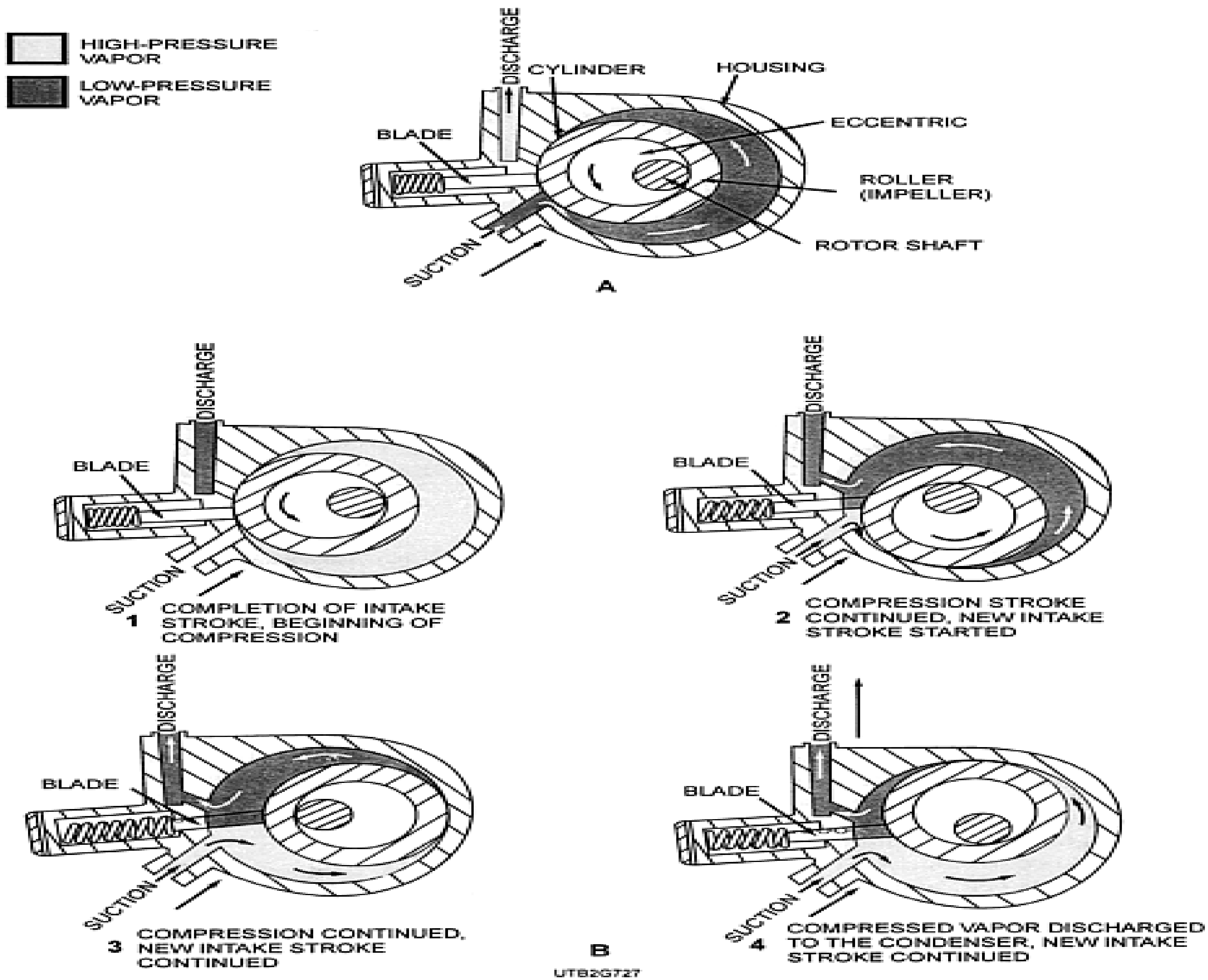
Reciprocating Compressor

Principle of Operation

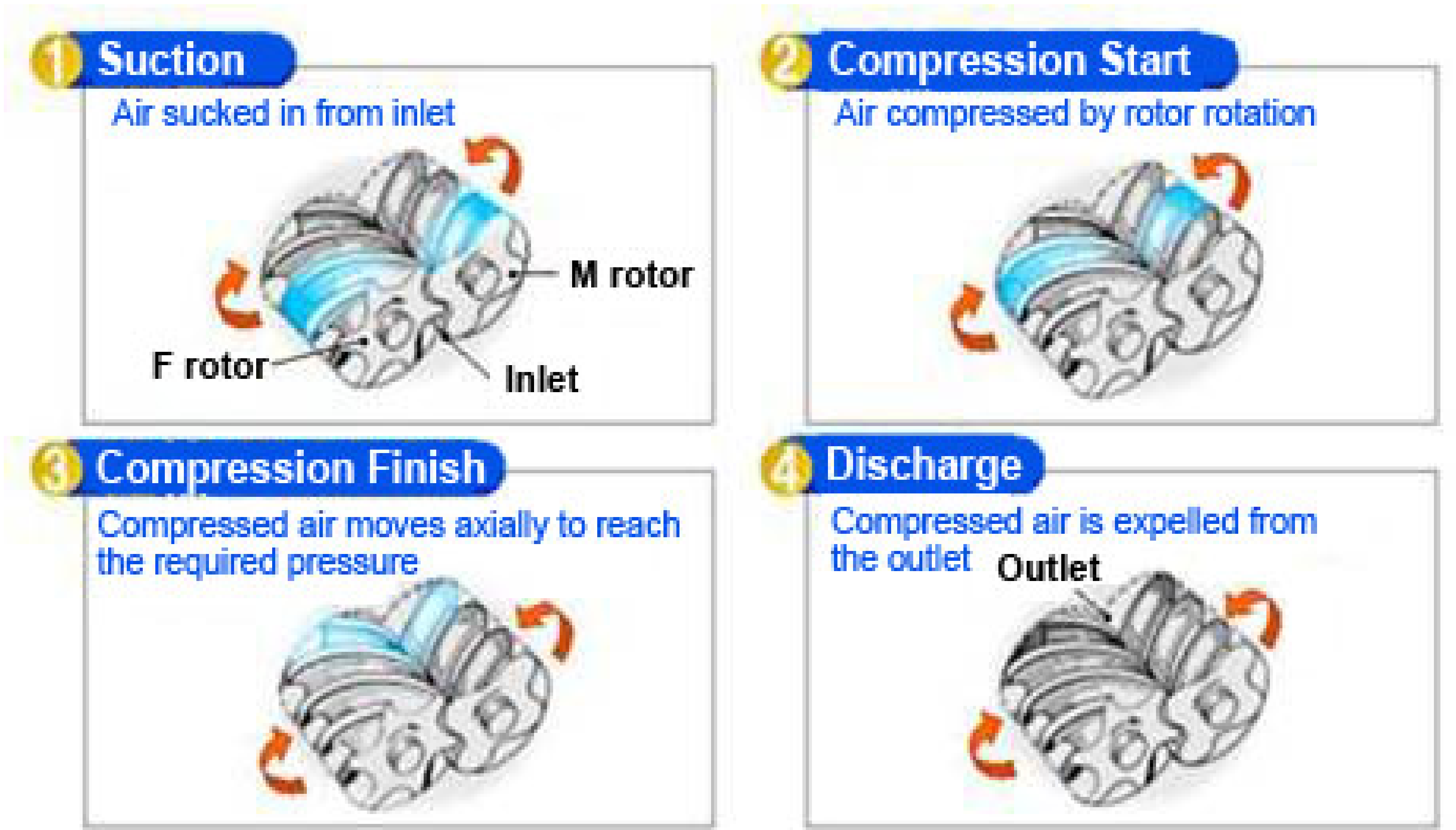
- Fig shows single-acting piston actions in the cylinder of a reciprocating compressor.
- The piston is driven by a crank shaft via a connecting rod.
- At the top of the cylinder are a suction valve and a discharge valve.
- A reciprocating compressor usually has two, three, four, or six cylinders in it.



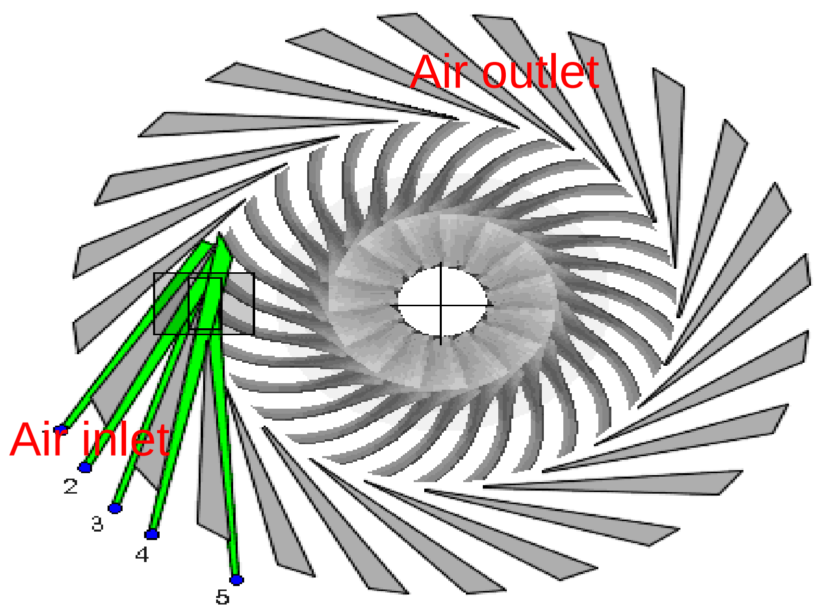
Rotary Compressor



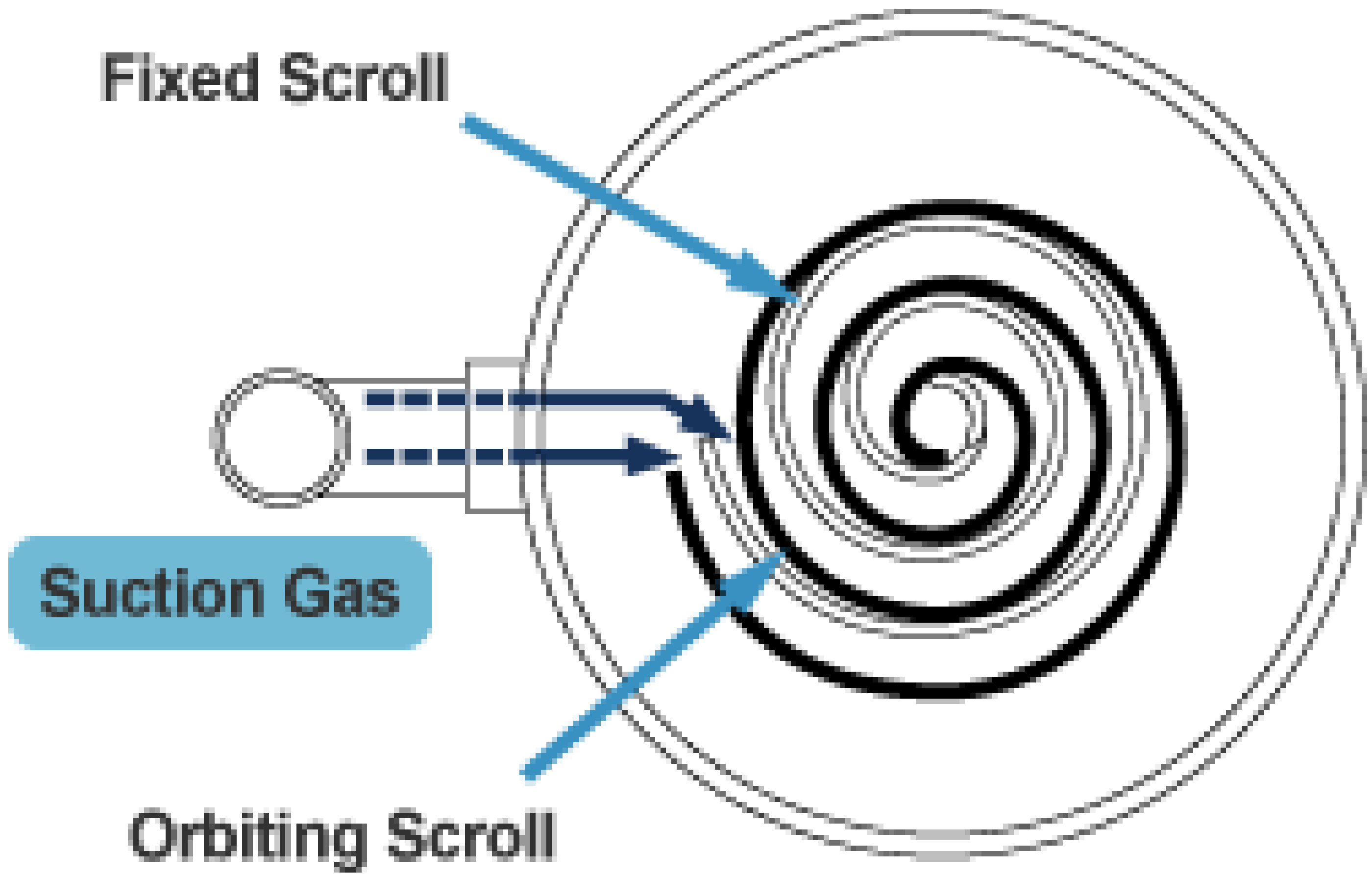
Screw Compressor



Centrifugal Compressor



Scroll Compressor



ENERGY CONSUMPTION AND EFFICIENCY

Energy Consumption

- Air conditioners are rated by the number of British Thermal Units (Btu) of heat they can remove per hour. Another common rating term for air conditioning size is the "ton," which is 12,000 Btu per hour.
- Room air conditioners range from 5,500 Btu per hour to 14,000 Btu per hour.
- A 12,000 Btu air conditioner can cool between 450 and 550 square feet of floor space. The rule of thumb is that it takes around 25 Btu to cool 1 square foot of room floor area.

Energy Efficiency

Rating is based on how many Btu per hour are removed for each watt of power it draws .

For room air conditioners, this efficiency rating is the Energy Efficiency Ratio or EER .

For central air conditioners, it is the Seasonal Energy Efficiency Ratio or SEER

EER &SEER

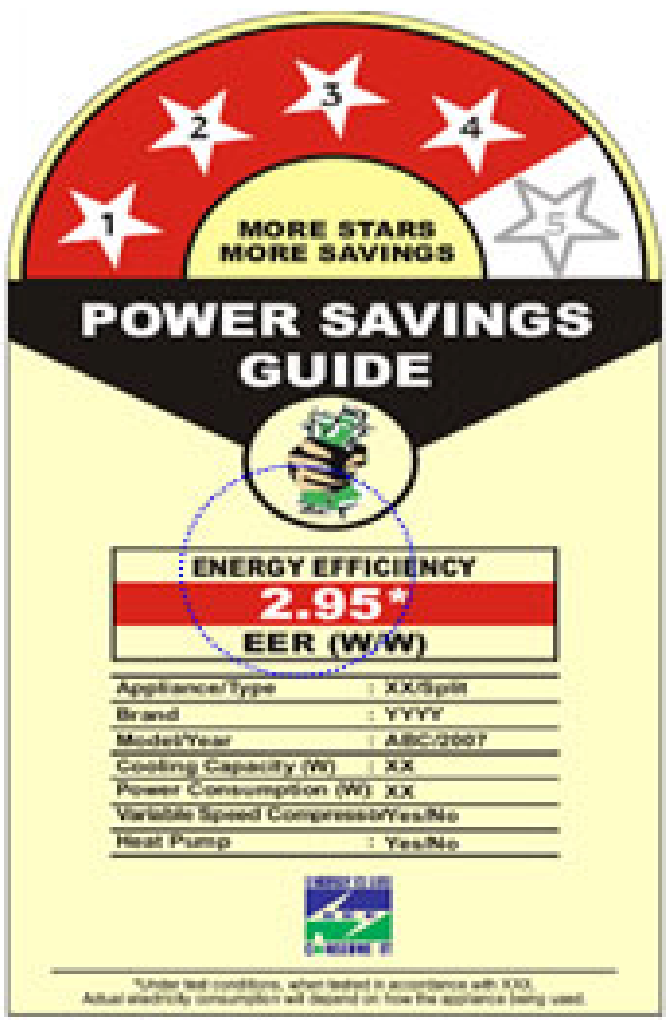
Energy efficiency ratio (EER) is the ratio between the cooling capacity and the power input of the Air conditioners. For example, if a 1 TR (3500 W) AC consumes 1000 watts, then the EER of the Air conditioners is 3.5 W/W. ACs with high EER consume less power.

Cooling capacity is the amount of heat energy removed by the Air conditioner from a space for a given time. It is generally measured in British Thermal Unit (BTU) per hour (BTU/Hr). In SI units it is measured by KJ / Sec= KW.

- Seasonal Energy Efficiency Ratio (SEER) is also expressed in (BTU/W·hr) but instead of being evaluated at a single operating condition, it represents the expected overall performance for a typical year's weather in a given location. The SEER is thus calculated with the same indoor temperature, but over a range of outside temperatures from 65 °F (18 °C) to 104 °F (40 °C).

- Typical EER for residential central cooling units = 0.875 × SEER. SEER is a higher value than EER for the same equipment

Star Rating



- At the time of Initial Purchase of **AC**, customers want to know the electrical consumption of an **AC**.
- This star rating is provided for customer awareness by **BEE** (**Bureau of Energy Efficiency**.)
- This Sticker is provided by **Bureau of Energy Efficiency** (BEE) Department of Energy Saving, Govt. of India.

TABLE 2.1: Star Rating Band valid from 01 May 2011 to 31 December 2011.

	EER (W/W)	
Star Rating	**Min**	**Max**
1 Star *	2.30	2.49
2 Star **	2.50	2.69
3 Star ***	2.70	2.89
4 Star ****	2.90	3.09
5 Star *****	3.10	

TABLE 2.4: Star Rating Band valid from 01 January 2016 to 31 December 2017.

	EER (W/W)	
Star Rating	**Min**	**Max**
1 Star *	2.70	2.89
2 Star **	2.90	3.09
3 Star ***	3.10	3.29
4 Star ****	3.30	3.49
5 Star *****	3.50	

- The sticker showed EER of 2.95. Therefore it had star rating of 4 in 2011 and now it has star rating of 2.