



GANESH INSTITUTE OF ENGINEERING & TECHNOLOGY,
POLYTECHNIC, BBSR

DEPARTMENT OF MECHANICAL ENGINEERING

LECTURER NOTES

**THERMAL ENGINEERING-II
(MEPC209)**

DIPLOMA in 4TH SEMESTER

[As per SCTE&VT Syllabus]

PREPARED BY

ABHIJIT DASH

SENIOR LECTURER IN MECHANICAL ENGINEERING DEPARTMENT

CHAPTER-I

1. Air-Standard Brayton Cycle

GAS TURBINE CYCLE—BRAYTON CYCLE

Brayton cycle is a constant pressure cycle for a perfect gas. It is also called Joule cycle. The heat transfers are achieved in reversible constant pressure heat exchangers. An ideal gas turbine plant would perform the processes that make up a Brayton cycle. The cycle is shown in the Fig. 1.8 (a) and it is represented on p-v and T-s diagrams as shown in Figs. 1.8 (b) and (c).

The various operations are as follows:

Operation 1-2. The air is compressed isentropically from the lower pressure p_1 to the upper pressure p_2 , the temperature rising from T_1 to T_2 . No heat flow occurs.

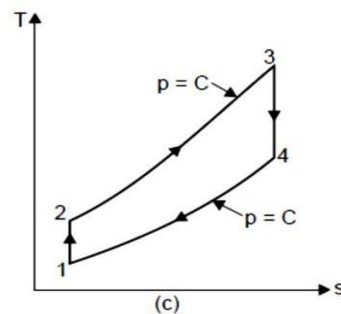
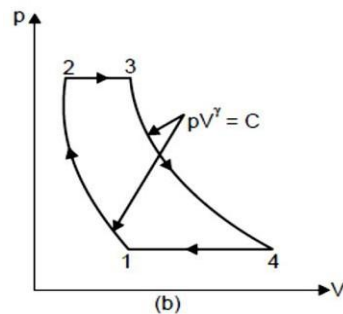
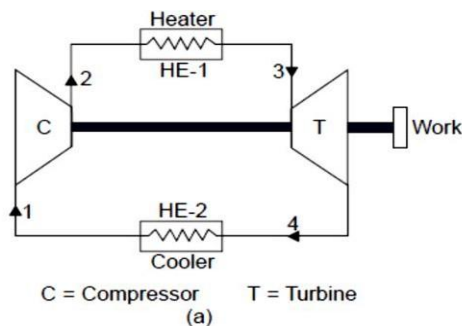
Operation 2-3. Heat flows into the system increasing the volume from V_2 to V_3 and temperature from T_2 to T_3 whilst the pressure remains constant at p_2 .

$$\text{Heat received} = mcp(T_3 - T_2).$$

Operation 3-4. The air is expanded isentropically from p_2 to p_1 , the temperature falling from T_3 to T_4 . No heat flow occurs.

Operation 4-1. Heat is rejected from the system as the volume decreases from V_4 to V_1 and the temperature from T_4 to T_1 whilst the pressure remains constant at p_1 .

$$\text{Heat rejected} = mcp(T_4 - T_1).$$



$$\begin{aligned}\eta_{\text{air-standard}} &= \frac{\text{Work done}}{\text{Heat received}} \\ &= \frac{\text{Heat received/cycle} - \text{Heat rejected/cycle}}{\text{Heat received/cycle}} \\ &= \frac{mc_p (T_3 - T_2) - mc_p (T_4 - T_1)}{mc_p (T_3 - T_2)} = 1 - \frac{T_4 - T_1}{T_3 - T_2}\end{aligned}$$

Now, from isentropic expansion,

$$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}}$$

$$T_2 = T_1 (r_p)^{\frac{\gamma-1}{\gamma}}, \text{ where } r_p = \text{pressure ratio.}$$

Similarly $\frac{T_3}{T_4} = \left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}} \text{ or } T_3 = T_4 (r_p)^{\frac{\gamma-1}{\gamma}}$

$$\therefore \eta_{\text{air-standard}} = 1 - \frac{T_4 - T_1}{T_4 (r_p)^{\frac{\gamma-1}{\gamma}} - T_1 (r_p)^{\frac{\gamma-1}{\gamma}}} = 1 - \frac{1}{(r_p)^{\frac{\gamma-1}{\gamma}}} \quad \dots(13.16)$$

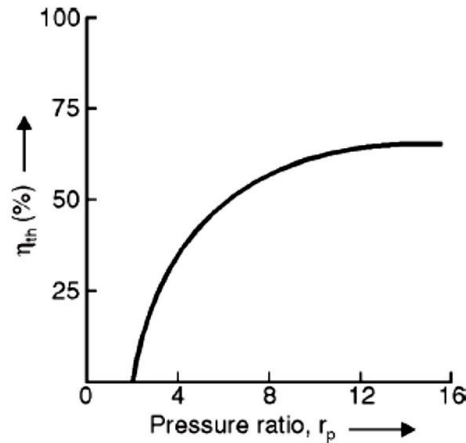


Fig.1.9. Effect of pressure ratio on the efficiency of Brayton cycle

The eqn. (13.16) shows that the efficiency of the ideal joule cycle increases with the pressure ratio. The absolute limit of upper pressure is determined by the limiting temperature of the material of the turbine at the point at which this temperature is reached by the compression process alone, no further heating of the gas in the combustion chamber would be permissible and the work of expansion would ideally just balance the work of compression so that no excess work would be available for external use.

Pressure Ratio for Maximum Work

Now we shall prove that the pressure ratio for maximum work is a function of the limiting temperature ratio.

Work output during the cycle

$$\begin{aligned}
 &= \text{Heat received/cycle} - \text{heat rejected/cycle} \\
 &= mc_p (T_3 - T_2) - mc_p (T_4 - T_1) \\
 &= mc_p (T_3 - T_4) - mc_p (T_2 - T_1) \\
 &= mc_p T_3 \left(1 - \frac{T_4}{T_3}\right) - T_1 \left(\frac{T_2}{T_1} - 1\right)
 \end{aligned}$$

In case of a given turbine the minimum temperature T_1 and the maximum temperature T_3 are prescribed, T_1 being the temperature of the atmosphere and T_3 the maximum temperature which the metals of turbine would withstand. Consider the specific heat at constant pressure c_p to be constant. Then,

Since,
$$\frac{T_3}{T_4} = (r_p)^{\frac{\gamma-1}{\gamma}} = \frac{T_2}{T_1}$$

Using the constant $z = \frac{\gamma-1}{\gamma}$,

we have, work output/cycle

$$W = K \left[T_3 \left(1 - \frac{1}{r_p^z}\right) - T_1 (r_p^z - 1) \right]$$

Differentiating with respect to r_p

$$\frac{dW}{dr_p} = K \left[T_3 \times \frac{z}{r_p^{(z+1)}} - T_1 z r_p^{(z-1)} \right] = 0 \text{ for a maximum}$$

$$\therefore \frac{zT_3}{r_p^{(z+1)}} = T_1 z (r_p)^{(z-1)}$$

$$\therefore r_p^{2z} = \frac{T_3}{T_1}$$

$$\therefore r_p = (T_3/T_1)^{1/2z} \quad \text{i.e.,} \quad r_p = (T_3/T_1)^{\frac{\gamma}{2(\gamma-1)}} \quad \dots(13.17)$$

Thus, the pressure ratio for maximum work is a function of the limiting temperature ratio.

13.10.3. Work Ratio

Work ratio is defined as the ratio of net work output to the work done by the turbine.

$$\begin{aligned} \therefore \text{Work ratio} &= \frac{W_T - W_C}{W_T} \\ &\left[\begin{array}{l} \text{where, } W_T = \text{Work obtained from this turbine,} \\ \text{and } W_C = \text{Work supplied to the compressor.} \end{array} \right] \\ &= \frac{mc_p(T_3 - T_4) - mc_p(T_2 - T_1)}{mc_p(T_3 - T_4)} = 1 - \frac{T_2 - T_1}{T_3 - T_4} \\ &= 1 - \frac{T_1}{T_3} \left[\frac{(r_p)^{\frac{\gamma-1}{\gamma}} - 1}{1 - \frac{1}{(r_p)^{\frac{\gamma-1}{\gamma}}}} \right] = 1 - \frac{T_1}{T_3} (r_p)^{\frac{\gamma-1}{\gamma}} \quad \dots(13.18) \end{aligned}$$

Open Cycle Gas Turbine

Refer Fig. 1.10. The fundamental gas turbine unit is one operating on the open cycle in which a rotary compressor and a turbine are mounted on a common shaft. Air is drawn into the compressor and after compression passes to a combustion chamber. Energy is supplied in the combustion chamber by spraying fuel into the air stream, and the resulting hot gases expand through the turbine to the atmosphere. In order to achieve net work output from the unit, the turbine must develop more gross work output than is required to drive the compressor and to overcome mechanical losses in the drive. The products of combustion coming out from the turbine are exhausted to the atmosphere as they cannot be used any more. The working fluids (air and fuel) must be replaced continuously as they are exhausted into the atmosphere.

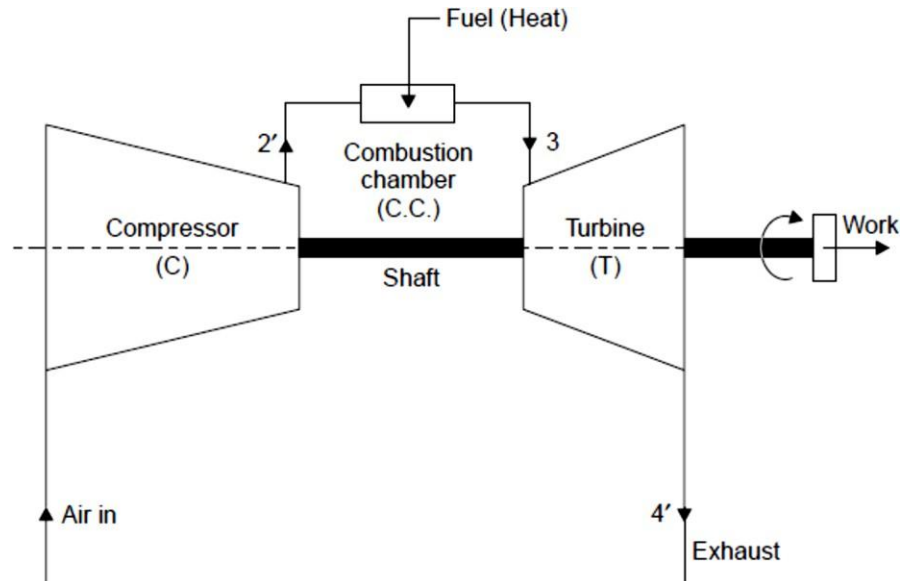


Fig.1.10.Open cycle gas turbine

If pressure loss in the combustion chamber is neglected, this cycle may be drawn on a T-s diagram as shown in Fig. 1.11.

1-2' represents: irreversible adiabatic compression.

2'-3 represents: constant pressure heat supply in the combustion chamber.

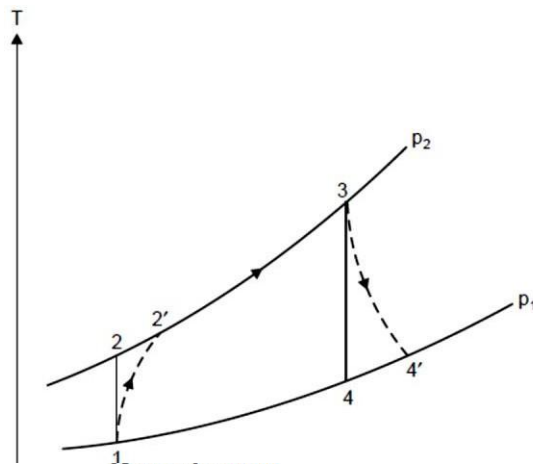
3-4' represents: irreversible adiabatic expansion.

1-2 represents: ideal isentropic compression.

3-4 represents: ideal isentropic expansion.

Assuming change in kinetic energy between the various points in the cycle to be negligibly small compared with enthalpy changes and then applying the flow equation to each part of cycle, for unit mass, we have

$$\begin{aligned} \text{Work input (compressor)} &= c_p (T_{2'} - T_1) \\ \text{Heat supplied (combustion chamber)} &= c_p (T_3 - T_{2'}) \\ \text{Work output (turbine)} &= c_p (T_3 - T_{4'}) \\ \therefore \text{Net work output} &= \text{Work output} - \text{Work input} \\ &= c_p (T_3 - T_{4'}) - c_p (T_{2'} - T_1) \end{aligned}$$



and

$$\eta_{thermal} = \frac{\text{Net work output}}{\text{Heat supplied}} = \frac{c_p (T_3 - T_{4'}) - c_p (T_{2'} - T_1)}{c_p (T_3 - T_{2'})}$$

Compressor isentropic efficiency, η_{comp}

$$\begin{aligned} &= \frac{\text{Work input required in isentropic compression}}{\text{Actual work required}} \\ &= \frac{c_p (T_2 - T_1)}{c_p (T_{2'} - T_1)} = \frac{T_2 - T_1}{T_{2'} - T_1} \end{aligned} \quad \dots(13.19)$$

Turbine isentropic efficiency, $\eta_{turbine}$

$$\begin{aligned} &= \frac{\text{Actual work output}}{\text{Isentropic work output}} \\ &= \frac{c_p (T_3 - T_{4'})}{c_p (T_3 - T_4)} = \frac{T_3 - T_{4'}}{T_3 - T_4} \end{aligned} \quad \dots(13.20)$$

Note. With the variation in temperature, the value of the specific heat of a real gas varies, and also in the open cycle, the specific heat of the gases in the combustion chamber and in turbine is different from that in the compressor because fuel has been added and a chemical change has taken place. Curves showing the variation of c_p with temperature and air/fuel ratio can be used, and a suitable mean value of c_p and hence g can be found out. It is usual in gas turbine practice to assume fixed mean value of c_p and g for the expansion process, and fixed mean values of c_p and g for the compression process. In an open cycle gas turbine unit the mass flow of gases in turbine is greater than that in compressor due to mass of fuel burned, but it is possible to neglect mass of fuel, since the air/ fuel ratios used are large. Also, in many cases, air is bled from the compressor for cooling purposes, or in the case of air-craft at high altitudes, bled air is used for de-icing and cabin air-conditioning. This amount of air bled is approximately the same as the mass of fuel injected therein.

Methods for Improvement of Thermal Efficiency of Open Cycle Gas Turbine Plant

The following methods are employed to increase the specific output and thermal efficiency of the plant :

1. Inter cooling
2. Reheating
3. Regeneration.

1. Inter cooling. A compressor in a gas turbine cycle utilises the major percentage of power developed by the gas turbine. The work required by the compressor can be reduced by compressing the air in two stages and incorporating an intercooler between the two as shown in Fig. 1.12. The corresponding T-s diagram for the unit is shown in Fig. 13.38. The actual processes take place as follows :

1-2' ...L.P.(Low pressure) compression

2'-3 ... Inter cooling

3-4' ... H.P. (High pressure) compression

4'-5...C.C.(Combustion chamber)-heating

5-6' ... T (Turbine)-expansion

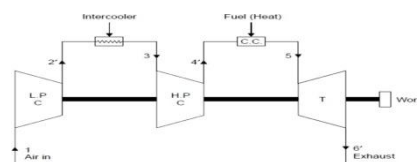


Fig.1.12.Turbineplant withintercooler

The ideal cycle for this arrangement is 1-2-3-4-5-6; the compression process without inter cooling is shown as 1-L' in the actual case, and 1-L in the ideal isentropic case. Now,

$$\begin{aligned} \text{Work input (with intercooling)} \\ = c_p(T_2' - T_1) + c_p(T_4' - T_3) \end{aligned} \quad \dots(13.21)$$

$$\begin{aligned} \text{Work input (without intercooling)} \\ = c_p(T_{L'} - T_1) = c_p(T_2' - T_1) + c_p(T_{L'} - T_2') \end{aligned} \quad \dots(13.22)$$

By comparing equation (13.22) with equation (13.21) it can be observed that the work input with inter cooling is less than the work in put with no inter cooling, when $c_p(T_4' - T_3)$ is less than $c_p(T_{L'} - T_2')$. This is so if it is assumed that isentropic efficiencies of the two compressors, operating separately, are each equal to the isentropic efficiency of the single compressor which would be required if no inter cooling were used. Then $(T_4' - T_3) < (T_{L'} - T_2')$ since the pressure lines diverge on the T-s diagram from left to the right.

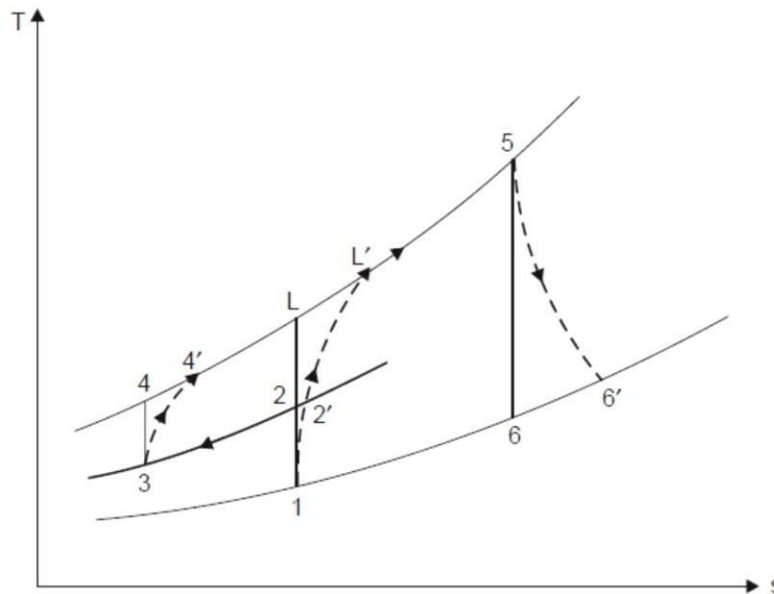


Fig.1.13. T-s diagram for the unit

$$\begin{aligned} \text{Again, work ratio} &= \frac{\text{Net work output}}{\text{Gross work output}} \\ &= \frac{\text{Work of expansion} - \text{Work of compression}}{\text{Work of expansion}} \end{aligned}$$

From this we may conclude that when the compressor work in put is reduced then the work ratio is increased.

However the heat supplied in the combustion chamber when inter cooling is used in the cycle, is given by,

$$\text{Heat supplied with inter cooling} = C_p(T_5 - T_4')$$

Also the heat supplied when inter cooling is not used, with the same maximum cycle temperature T_5 , is given by

$$\text{Heat supplied without inter cooling} = C_p(T_5 - T_{L'})$$

Thus, the heat supplied when inter cooling is used is greater than with no inter cooling. Although the net work output is increased by inter cooling it is found in general that the increase in heat to be supplied causes the thermal efficiency to decrease. When inter cooling is used a supply of cooling water must be readily available. The additional bulk of the unit may offset the advantage to be gained by increasing the work ratio.

2. Reheating: The output of a gas turbine can be amply improved by expanding the gases in two stages with a re heater between the two as shown in Fig. 1.14. The H.P. turbine drives the compressor and the L.P. turbine provides the useful power output. The corresponding T-s diagram is shown in Fig. 1.15. The line 4'-L' represents the expansion in the L.P. turbine if reheating is not employed.

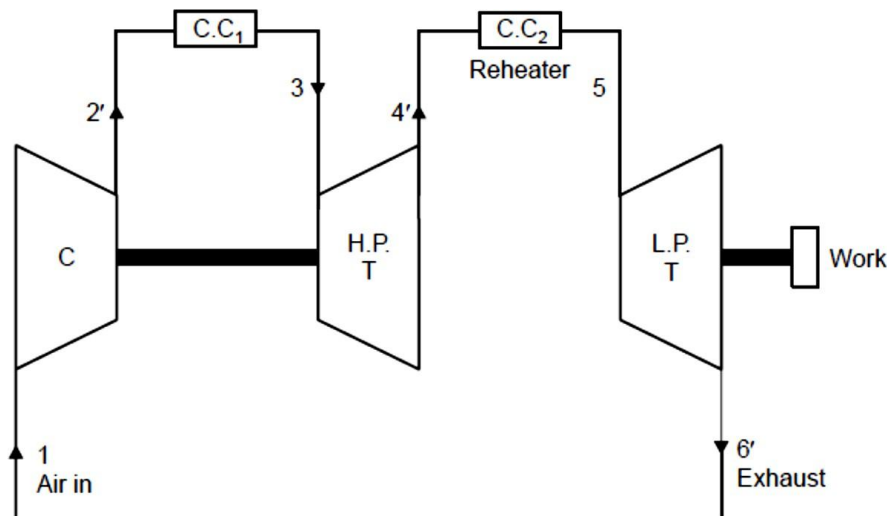


Fig.1.14. Gas turbine with reheat

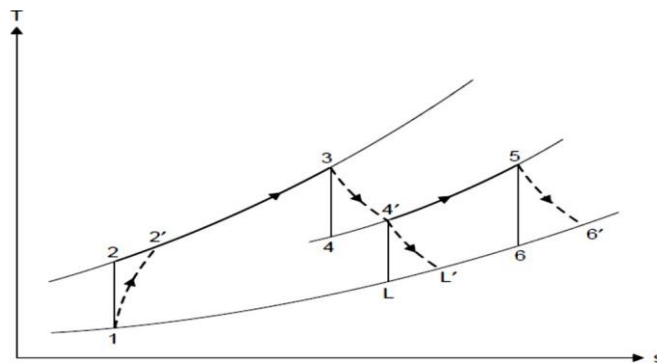


Fig.1.15. T-s diagram for the unit

Neglecting mechanical losses the work output of the H.P. turbine must be exactly equal to the work input required for the compressor i.e., $c_{pa} (T_2' - T_1) = c_{pg} (T_3 - T_4')$

The work output (net output) of L.P. turbine is given by,

$$\text{Net work output (with reheating)} = c_{pg} (T_5 - T_6')$$

and $\text{Net work output (without reheating)} = c_{pg} (T_4' - T_L')$

Since the pressure lines diverge to the right on T - s diagram it can be seen that the temperature difference $(T_5 - T_6')$ is always greater than $(T_4' - T_L')$, so that reheating increases the net work output.

Although net work is increased by reheating the heat to be supplied is also increased, and the net effect can be to reduce the thermal efficiency

$$\text{Heat supplied} = c_{pg} (T_3 - T_2') + c_{pg} (T_5 - T_4')$$

Note. c_{pa} and c_{pg} stand for specific heats of air and gas respectively at constant pressure.

2. **Regeneration:** The exhaust gases from a gas turbine carry a large quantity of heat with them since their temperature is far above the ambient temperature. They can be used to heat the air coming from the compressor thereby reducing the mass of fuel supplied in the combustion chamber. Fig. 1.16 shows a gas turbine plant with a regenerator. The corresponding T - s diagram is shown in Fig. 1.17. 2'-3 represents the heat flow into the compressed air during its passage through the heat exchanger and 3-4 represents the heat taken in from the combustion of fuel.

Point 6 represents the temperature of exhaust gases at discharge from the heat exchanger. The maximum temperature to which the air could be heated in the heat exchanger is ideally that of exhaust gases, but less than this is obtained in practice because a temperature gradient must exist for an unassisted transfer of energy. The effectiveness of the heat exchanger is given by :

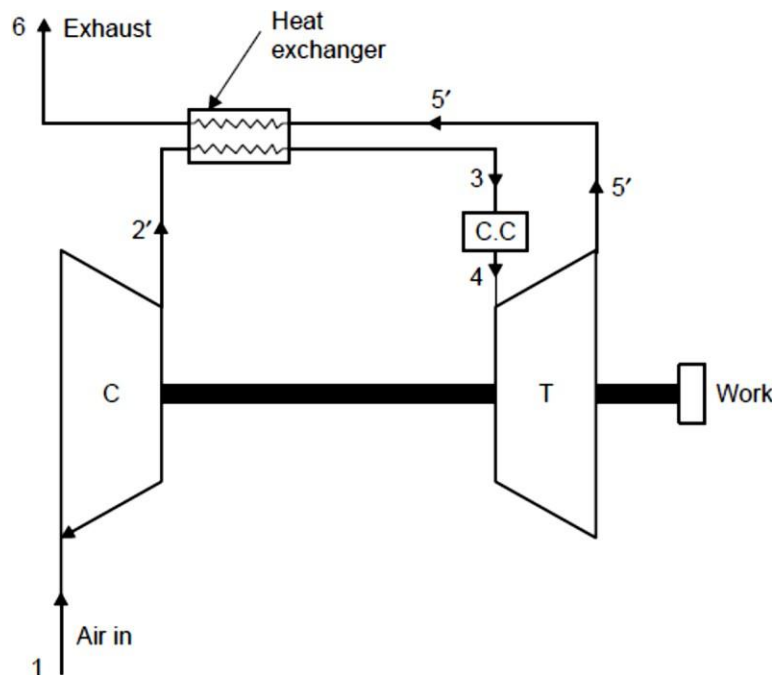


Fig.1.16. Gas turbine with regenerator

Effectiveness, $\epsilon = \frac{\text{Increase in enthalpy per kg of air}}{\text{Available increase in enthalpy per kg of air}}$

$$= \frac{(T_3 - T_2')}{(T_5' - T_2')} \quad \dots(13.23)$$

(assuming c_{pa} and c_{pg} to be equal)

A heat exchanger is usually used in large gas turbine units for marine propulsion or industrial power.

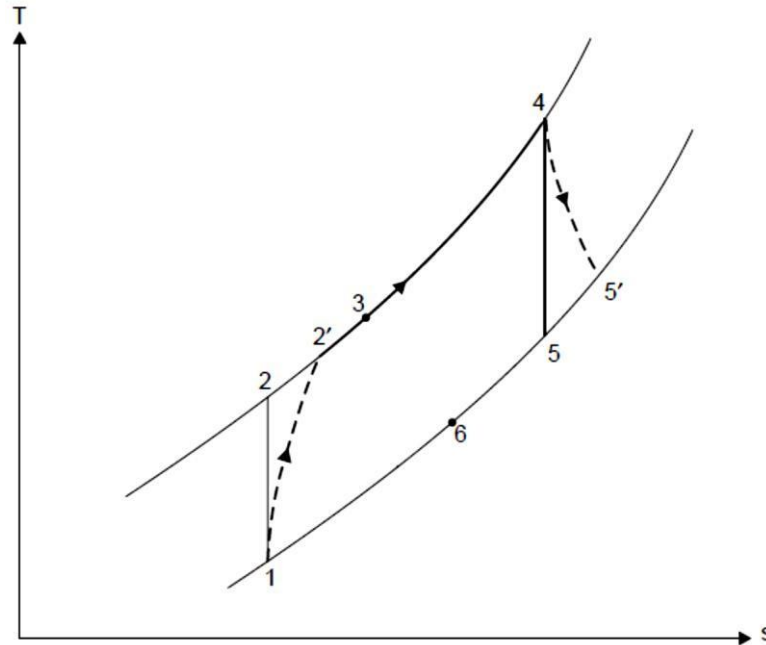


Fig.1.17. T-s diagram for the unit

Closed-Cycle Gas Turbine

In a closed-cycle gas turbine, the working fluid, typically air or another suitable medium, exits the compressor and undergoes heating at a relatively constant pressure through an external heat source. The high-pressure, high-temperature air is then directed to the turbine. Post-turbine, the fluid is cooled to its initial temperature by an external cooling agent before being recirculated to the compressor. This closed-loop process enables consistent fluid use with minimal phase change. The above figure presents the schematic of a closed-cycle gas turbine.

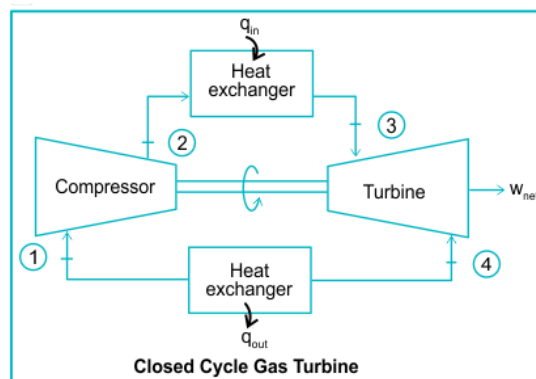


Fig 5: Closed cycle gas turbine

1. General Layout of Closed Cycle Gas Turbine

In a **closed cycle gas turbine**, the **working fluid (air, helium, or other gas)** circulates continuously in a **closed loop** and does **not mix with combustion products**.

Main Components

1. **Compressor**
2. **Heater (Heat Exchanger)**
3. **Gas Turbine**
4. **Cooler (Heat Exchanger)**
5. **Generator (Load)**

Layout Description

- The **compressor** compresses the working gas.
- The compressed gas passes through a **heater**, where it receives heat from an **external source** (coal, nuclear reactor, waste heat, etc.).
- Hot gas expands in the **turbine**, producing power.
- Exhaust gas from the turbine passes through a **cooler**, rejecting heat.
- The cooled gas returns to the **compressor**, completing the cycle.

Since combustion occurs **outside** the cycle, the same gas is reused repeatedly.

2. Working of Closed Cycle Gas Turbine

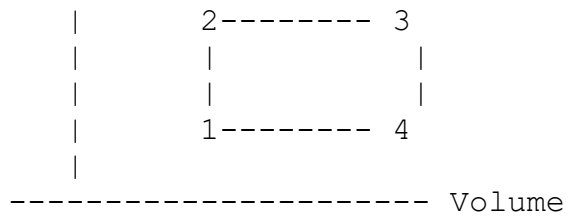
The working follows a **modified Brayton cycle**:

1. **Compression (1–2)**
 - Gas is compressed **isentropically** in the compressor.
 - Pressure and temperature increase.
2. **Heat Addition (2–3)**
 - Gas flows through the **heater**.
 - Heat is added at **constant pressure** from an external source.
3. **Expansion (3–4)**
 - Hot gas expands **isentropically** in the turbine.
 - Mechanical work is produced.
4. **Heat Rejection (4–1)**
 - Gas passes through the **cooler**.
 - Heat is rejected at **constant pressure**.
 - Gas returns to its initial state.

3. P–V Diagram of Closed Cycle Gas Turbine

Pressure

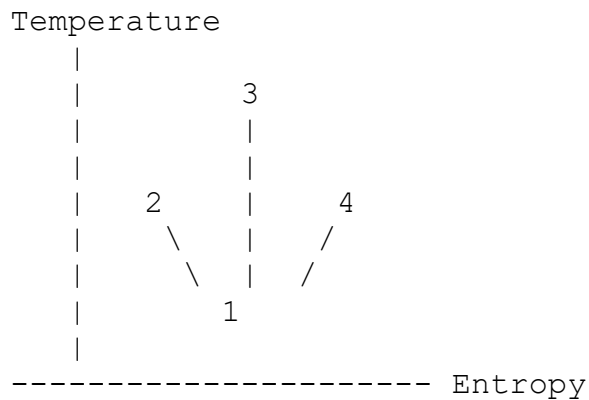
|



Process Representation

- 1–2: Isentropic compression
- 2–3: Constant pressure heat addition
- 3–4: Isentropic expansion
- 4–1: Constant pressure heat rejection

4. T-S Diagram of Closed Cycle Gas Turbine



Process Representation

- 1–2: Isentropic compression (vertical line)
- 2–3: Heat addition at constant pressure
- 3–4: Isentropic expansion (vertical line)
- 4–1: Heat rejection at constant pressure

5. Advantages of Closed Cycle Gas Turbine

- High thermal efficiency
- Can use **any heat source** (coal, nuclear, solar)
- No contamination of turbine blades
- Suitable for **nuclear power plants**

6. Disadvantages

- Complex heat exchangers
- High initial cost
- Large size

1. Comparison of Gas Turbine **with** Reciprocating I.C. Engine

Aspect	Gas Turbine	Reciprocating I.C. Engine
Working cycle	Brayton cycle	Otto / Diesel cycle
Motion	Rotary motion only	Reciprocating + rotary
Power output	Very high for given size	Lower for same size
Power-to-weight ratio	Very high	Low
Starting	Slow starting	Quick starting
Efficiency (part load)	Low	High
Efficiency (full load)	Moderate	High
Vibration	Very low	High
Maintenance	Low (fewer moving parts)	High
Fuel flexibility	Can use gas, liquid fuels	Mostly petrol or diesel
Cooling	Less critical	Critical
Initial cost	High	Lower
Application range	Large power, aircraft	Automobiles, small power plants

2. Comparison of Gas Turbine with Steam Turbine

Aspect	Gas Turbine	Steam Turbine
Working fluid	Air + combustion gases	Steam
Cycle	Brayton cycle	Rankine cycle
Boiler required	Not required	Required
Water requirement	Nil	Very high
Plant size	Compact	Bulky
Starting time	Quick	Slow
Efficiency	Lower (simple cycle)	Higher
Maintenance	Lower	Higher

Aspect	Gas Turbine	Steam Turbine
Initial cost	Lower	Higher
Load variation response	Fast	Slow
Environmental concern	NOx emissions	Water & thermal pollution
Typical output	Medium to very large	Very large

3. Applications of Gas Turbines

(A) Power Generation

- Peak load power plants
- Stand-by and emergency power stations
- Combined cycle power plants (gas + steam)

(B) Aviation

- Aircraft propulsion (jet engines, turboprop, turbofan)
- Helicopters

(C) Marine Applications

- Naval ships
- High-speed vessels

(D) Industrial Applications

- Driving compressors, pumps
- Oil and gas industries
- Pipeline pressurization

(E) Transportation

- Locomotives (limited use)
- Experimental automobiles

4. Limitations of Gas Turbines

1. Low efficiency at part load
2. High initial cost
3. Poor starting torque
4. High fuel consumption (simple cycle)
5. Performance affected by ambient temperature
6. Requires high-quality materials due to high temperatures
7. Noise problem

8. Less suitable for small power outputs

Jet propulsion:-

Jet propulsion refers to the imparting of forward motion to the object as a reaction to the exit of a high-velocity gas/liquid stream from the rear end of the object.

Jet propulsion devices are popularly used in high-speed, high-altitude aircraft/missiles/space craft, etc.

Jet propulsion is based on the principle of Newton's second law and third law of motion.

In a jet propulsion engine, the objective is to get the propelling thrust for the engine and for getting it the momentum change occurs in fluid stream such that the reaction to the impulse created by momentum change gives propelling thrust.

Thrust Equation

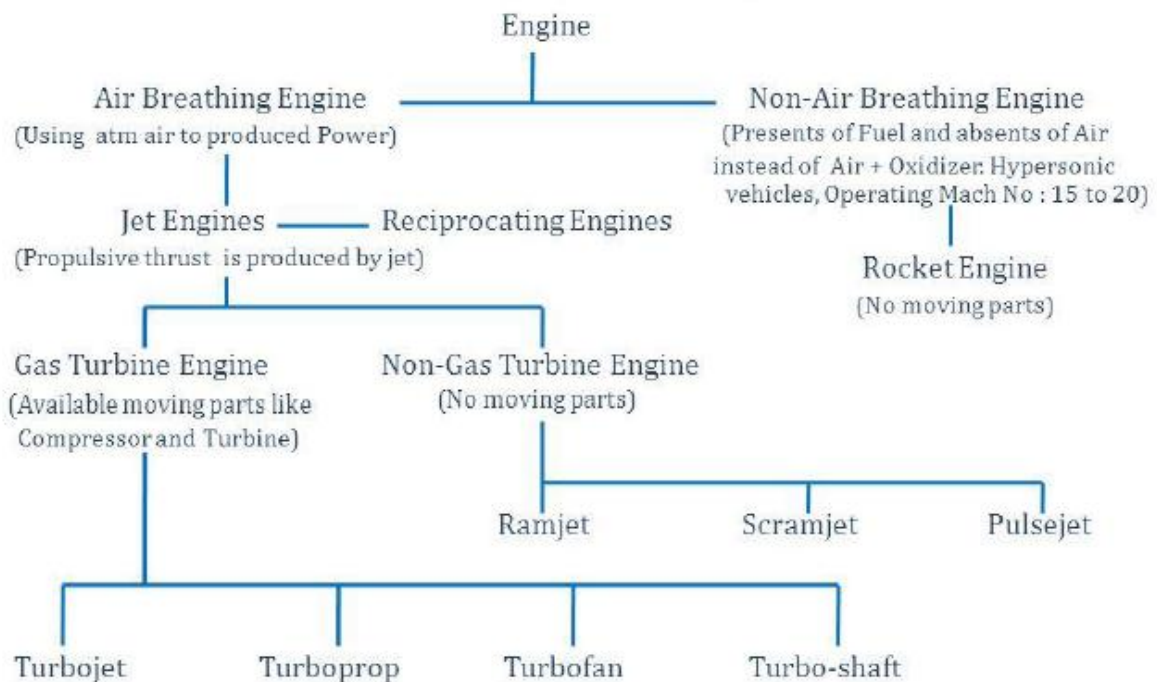
$$\text{Thrust} = \dot{m}(V_e - V_0) + (P_e - P_0)A_e$$

Where:

- \dot{m} = mass flow rate
- V_e = exit velocity
- V_0 = flight velocity
- P_e, P_0 = exit and atmospheric pressure

The change of momentum of the fluid stream flowing across engine and the reaction to the impulse due to momentum change are responsible for jet propulsion

Classification of Engine



2. Fuels Used for Jet Propulsion

Common fuels include:

1. **Aviation Turbine Fuel (ATF)**
 - Jet A
 - Jet A-1
 - Jet B
2. **Kerosene-based fuels**
3. **Hydrogen (experimental use)**

Properties Required:

- High calorific value
- Low freezing point
- Good thermal stability
- Clean combustion

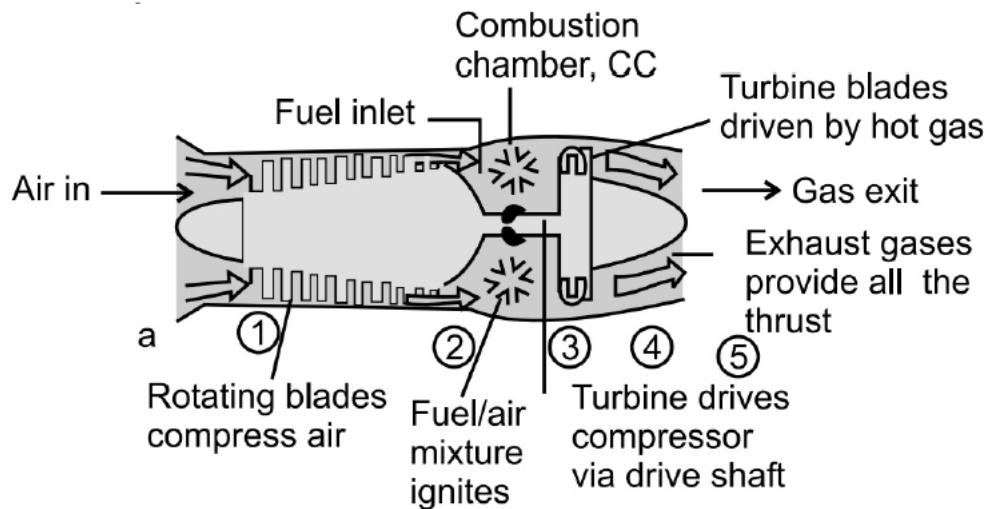
3. Applications of Jet Propulsion

- Commercial aircraft
- Military fighter aircraft
- Supersonic aircraft
- Missiles
- Unmanned aerial vehicles (UAVs)
- Space launch assistance

4. Working of Turbojet Engine

- It has a diffuser section at the inlet for realizing some compression of air passing through this section.
- Due to this air reaching the compressor section has pressure more than ambient pressure. This action of partly compressing air by passing it through the diffuser section is called “ramming action” or “ram effect”.
- Subsequently, the compressor section compresses air which is fed to the combustion chamber and fuel is added to it to cause combustion.
- Combustion products available at high pressure and temperature are then passed through the turbine and expanded there.
- Thus, the turbine yields positive work which is used for driving the compressor.
- Expanding gases leaving the turbine are passed through the exit nozzle where it is further expanded and results in the high-velocity jet at the exit.
- This high-velocity jet leaving the nozzle is responsible for getting the desired thrust for propulsion.
- These engines are used in commercial and military aircrafts.

Working of Turbojet Engine



5. Principle of Ram Effect

The **ram effect** is the **rise in pressure and temperature of air** due to **high forward speed** of the aircraft.

- At high speed, air is naturally compressed before entering the engine.
- No mechanical compressor is required.

Important: Ram effect increases with speed and is negligible at low speeds.

6. Working of a Ramjet Engine

Key Feature

- **No compressor or turbine**
- Operates efficiently only at **high speeds**

Working of Ramjet

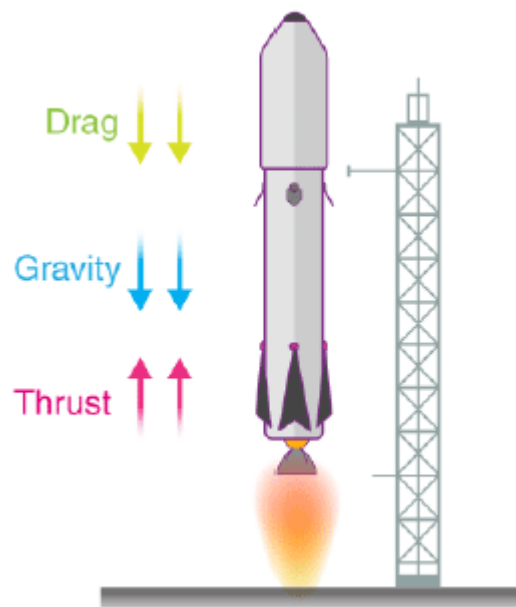
1. High-speed motion compresses incoming air (ram effect).
2. Fuel is injected into compressed air.
3. Combustion occurs at constant pressure.
4. Hot gases expand through nozzle producing thrust.

Limitations of Ramjet

- Cannot operate at rest
- Requires external acceleration
- Works efficiently at supersonic speeds

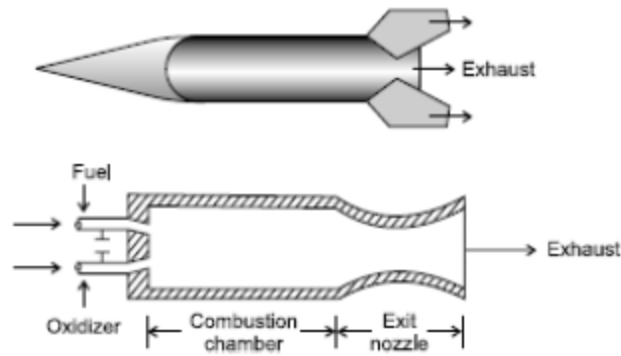
7. Principle of Rocket Propulsion

- Propulsion is a method by which an object is propelled in a particular direction.
- The word “propulsion” stems from the Latin word *propellere*, where *pro* means forward or backward and *pellere* means drive or push.
- Spacecraft must produce thrust which must be equal to the drag force caused due to the fluid motion over the body of this spacecraft and the gravitational force.
- For accelerating the spacecraft, one needs to supply higher thrust than that of drag forces and gravitational force acting on it.



8. Working Principle of a Rocket Engine

- Rocket engines are non-air-breathing engines and carry their own oxidizer for burning of fuel.
- Rocket propulsion is realized by the thrust produced by combustion products leaving the exit nozzle.
- It has an injection system for fuel and oxidizer followed by a combustion chamber and exit nozzle.
- In rocket engines the combustion products get discharged from the exit nozzle with supersonic velocity and thus have very high kinetic energy.
- Rocket gets the desired thrust by the reaction available from the nozzle stream.
- Thrust is available due to the change of momentum and pressure with which the jet comes out.



9. Applications of Rocket Propulsion

1. Space launch vehicles
2. Satellites
3. Intercontinental ballistic missiles (ICBM)
4. Space exploration missions
5. Military missiles

10. Comparison of Jet Propulsion and Rocket Propulsion

Jet engines and rocket engines operate on the **same fundamental principle of propulsion**. Both produce thrust by creating an **internal pressure difference** and by **ejecting exhaust gases at high velocity**, in accordance with **Newton's Third Law of Motion**, which states that for every action there is an equal and opposite reaction.

The **main difference** between jet engines and rocket engines lies in the **source of oxygen for combustion**. Jet engines obtain oxygen from the **surrounding atmospheric air**, whereas rocket engines **carry their own oxidizer** along with the fuel. This enables rockets to operate in **outer space**, where atmospheric oxygen is absent.

This distinction leads to another important difference in engine design. **Jet engines have two openings**—an **air intake** and an **exhaust nozzle**—to allow the entry of atmospheric air and the exit of exhaust gases. In contrast, **rocket engines have only one opening**, the **exhaust nozzle**, since all the required reactants are carried onboard.

CHAPTER-II

Properties of Steam

1. Formation of Steam under Constant Pressure

When **water is heated at constant pressure**, the following stages occur:

1. **Heating of water (sensible heating):**
Temperature rises from initial value to saturation temperature.
2. **Evaporation (latent heating):**
At saturation temperature, water changes phase to steam without rise in temperature.
3. **Dry saturated steam:**
All water is converted into vapor at saturation temperature.
4. **Superheating:**
Further heating increases temperature of steam above saturation temperature.

2. Industrial Uses of Steam

1. Power generation in steam turbines
2. Heating and drying processes
3. Chemical industries
4. Textile and paper industries
5. Food processing industries
6. Sterilization in hospitals
7. Oil refineries

3. Basic Definitions (Steam Terminology)

(a) Saturated Liquid Line

Line on phase diagram where **liquid is about to evaporate**.

(b) Saturated Vapor Line

Line where **vapor is about to condense**.

(c) Liquid Region

Region to the **left of saturated liquid line**.

(d) Vapor Region

Region to the **right of saturated vapor line**.

(e) Wet Region

Region between saturated liquid and saturated vapor lines.

(f) Superheated Region

Region beyond saturated vapor line.

(g) Critical Point

Point where **liquid and vapor phases become identical**.

(h) Saturated Liquid

Liquid at saturation temperature, ready to vaporize.

(i) Saturated Vapor

Vapor at saturation temperature, ready to condense.

(j) Saturation Temperature

Temperature at which **liquid and vapor coexist** at a given pressure.

(k) Sensible Heat

Heat required to raise temperature **without phase change**.

(l) Latent Heat

The amount of energy absorbed or released during a phase change process.

(m) Wet Steam

Both the water molecules and steam coexist to form a two phase mixture, called wet steam.

(n) Dryness Fraction (x)

$$x = \frac{\text{Mass of dry steam}}{\text{Total Mass of a wet steam}}$$

(o) Wetness Fraction

$$= 1 - x$$

(p) Saturated Steam

Both the water molecules and steam coexist to form a two phase mixture, called saturated steam.

(q) Superheated Steam

when a dry saturated steam is heated further at the given constant pressure, its temperature rise beyond its saturation vapour temperature. The steam in this state is said to be superheated

(r) Degree of Superheat

$$\text{Degree of superheat} = T_{\text{superheated}} - T_{\text{saturation}}$$

4. Properties of Steam Using Steam Tables & Mollier Chart

(A) Wet Steam

For dryness fraction (x):

- **Enthalpy**

$$h = h_f + x h_{fg}$$

- **Internal Energy**

$$u = u_f + x u_{fg}$$

- **Entropy**

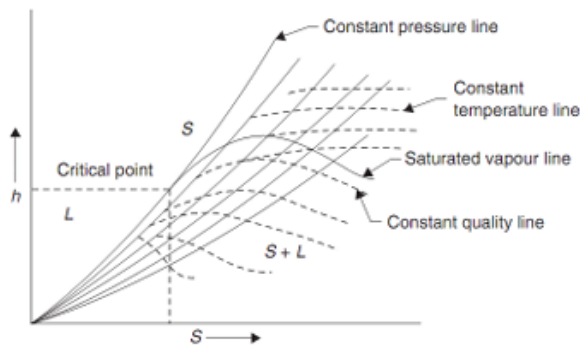
$$s = s_f + x s_{fg}$$

(B) Dry Saturated Steam (x = 1)

$$h = h_g, u = u_g, s = s_g$$

(C) Superheated Steam

Properties obtained **directly from superheated steam tables** or **Mollier (h-s) chart**.



❖ ***Enthalpy-entropy (h-s) diagram for water showing liquid and vapour saturation lines.***

❖ ***Also showing isobars (p), isotherms (T) and quality of steam (x).***

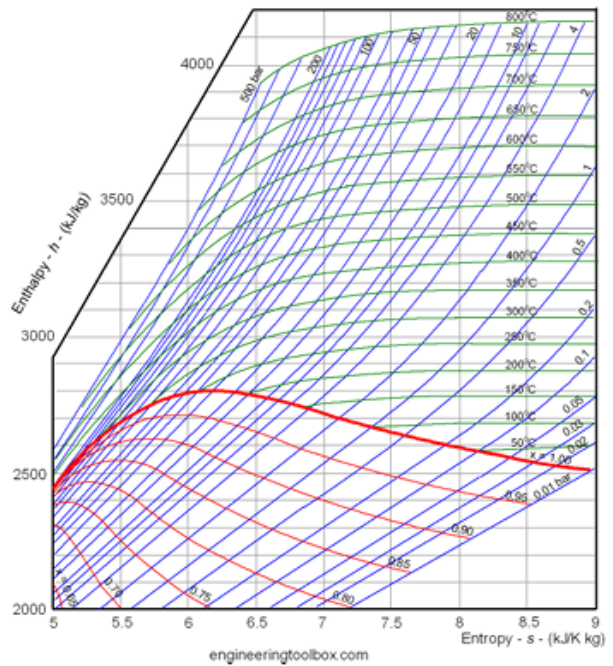


Table The property of steam tables

<u>Symbols</u>	<u>Description</u>	<u>Units</u>
p	Absolute pressure of the fluid	bar
t_s	Saturation temperature corresponding to the pressure p bar	°C
v_f	Specific volume of saturated liquid	m ³ /kg
v_g	Specific volume of saturated steam	m ³ /kg
u_f	Specific internal energy of saturated liquid	kJ/kg
u_g	Specific internal energy of saturated steam	kJ/kg
u_{fg}	Change of specific internal energy during evaporation	kJ/kg
h_f	Specific enthalpy of saturated liquid	kJ/kg
h_g	Specific enthalpy of saturated steam	kJ/kg
h_{fg}	Change of specific enthalpy during evaporation	kJ/kg
s_f	Specific entropy of saturated liquid	kJ/kg K
s_g	Specific entropy of saturated steam	kJ/kg K
s_{fg}	Change of specific entropy during evaporation	kJ/kg K

5. Thermodynamic Processes Involving Steam

1. Isochoric Process (Constant Volume)

- $v = \text{text}$
- Heat supplied changes pressure and temperature
- Used in rigid containers

2. Isobaric Process (Constant Pressure)

- $p = \text{constant}$
- Heating in boilers
- Enthalpy change used directly

3. Hyperbolic Process

- $p v = \text{constant}$
- Approximate steam expansion process

4. Isothermal Process (Constant Temperature)

- $T = \text{constant}$

- Occurs during phase change

5. Isentropic Process (Constant Entropy)

- $s = \text{constant}$
- Ideal expansion in steam turbines
- Properties found using Mollier chart

6. Throttling Process

- $h_1 = h_2$
- Pressure drops suddenly
- Used in throttling calorimeter
- No work done, no heat transfer

7. Polytropic Process

- $pv^n = \text{constant}$
- Practical expansion/compression process

6. Simple Direct Problems (Method)

Steps:

1. Identify type of steam (wet/dry/superheated)
2. Note given pressure/temperature
3. Use steam tables or Mollier chart
4. Apply appropriate formula
5. Calculate required property

7. Steam Calorimeters

Used to determine **dryness fraction of steam**.

(A) Separating Calorimeter

- Separates water droplets mechanically

- Suitable for **very wet steam**
- Not highly accurate

Dryness fraction:

$$x = \frac{m_{dry}}{m_{total}}$$

(B) Throttling Calorimeter

- Steam throttled to low pressure
- Based on **constant enthalpy**
- Suitable for **dry or slightly wet steam**

$$h_1 = h_2$$

(C) Combined Separating and Throttling Calorimeter

- Used for **very wet steam**
- Most accurate
- Combination of both methods

8. Typical Calorimeter Problems (Concept)

1. Given inlet pressure and outlet superheated condition
2. Use throttling equation
3. Find dryness fraction
4. Apply steam table values

1. Separating Calorimeter

Purpose

A separating calorimeter is used to separate entrained water droplets from wet steam. It gives an approximate dryness fraction, suitable when steam is slightly wet.

Principle

Steam is forced to change direction suddenly. Due to inertia, water droplets separate and are collected.

Formula

Let

- m_s = mass of dry steam collected
- m_w = mass of water separated

$$\text{Dryness fraction, } x = \frac{m_x}{m_s + m_w}$$

Problem 1 (Separating Calorimeter)

In a separating calorimeter experiment:

- Mass of steam collected = **9 kg**
- Mass of water separated = **1 kg**

Find the **dryness fraction** of steam.

Solution

$$x = \frac{m_x}{m_s + m_w} = \frac{9}{9+1} = \frac{9}{10}$$

$$x = 0.09$$

2. Throttling Calorimeter

Purpose

Used to determine dryness fraction of dry or slightly wet steam.

Principle

Steam is throttled (pressure reduced suddenly).

Enthalpy remains constant during throttling:

$$h_1 = h_2$$

Formula

At inlet (wet steam): $h_1 = h_f + xh_{fg}$

At outlet (superheated steam): $h_2 = h_g + C_p(T_{\text{sup}} - T_{\text{sat}})$

Equating:

$$x = \frac{h_2 - h_f}{h_{fg}}$$

Problem 2 (Throttling Calorimeter)

Steam enters a throttling calorimeter at **10 bar** and leaves at **1 bar**, where its temperature is **120°C**.

Steam table data:

At **10 bar**:

- $h_f=762$ kJ/kg
- $h_{fg}=2014$ kJ/kg

At **1 bar**:

- Saturation temperature = 100°C
- $h_g=2676$ kJ/kg
- $C_p=2.1$ kJ/kg \cdot K

Find the dryness fraction.

Solution

Superheat temperature: $T_{\text{sup}}-T_{\text{sat}}=120-100=20^\circ\text{C}$

Outlet enthalpy: $h_2=2676 + 2.1 \times 20 = 2676 + 42 = 2718$ kJ/kg

Inlet enthalpy: $h_1 = h_f + xh_{fg}$

Equating:

$$762 + 2014x = 2718$$

$$2014x = 1956$$

$$x = 0.971$$

3. Combined Separating and Throttling Calorimeter

Purpose

Used when steam is very wet (throttling alone is not suitable).

Working

1. Separating calorimeter removes some moisture
2. Remaining steam enters throttling calorimeter
3. Final dryness fraction is calculated by combining both results

Formula

Let

- m_1 = mass of water separated
- m_2 = mass of steam passing to throttling calorimeter
- x_t = dryness fraction from throttling calorimeter

$$\text{Overall dryness fraction} = \frac{m_2 x_t}{m_1 + m_2}$$

Problem 3 (Combined Calorimeter)

In a combined calorimeter test:

- Water separated = **0.5 kg**
- Steam passed to throttling calorimeter = **4.5 kg**
- Dryness fraction from throttling calorimeter = **0.95**

Find the dryness fraction of steam supplied.

Solution

$$\begin{aligned} x &= \frac{m_2 x_t}{m_1 + m_2} = \frac{4.5 \times 0.95}{0.5 + 4.5} \\ &= \frac{4.275}{5} = 0.855 \\ x &= 0.855 \end{aligned}$$

CHAPTER-III

Steam Generators

Steam is used as a working fluid in thermal (steam) power plants. Also, steam produced from water in nuclear power plants is the working fluid in nuclear power plants. In addition, steam is used for processing heating in industries like pharmaceuticals, leather, textiles, paper, tyres, distilleries, etc. The advantage of using steam in power plants and in process industries is that isothermal heat transfer (both heating and cooling) can be achieved by phase change and it is a reversible process. In addition, the exhaust steam can be condensed and recycled and hence the working fluid replenishment needs are minimum. As steam is produced from water, it is relatively cheap and the purity of water can be improved by employing simple water treatment processes which are cost effective. Due to the above reasons steam is extensively used in most of the process industries and in power plants. In western countries district heating is accomplished by extracting steam from power plants. Also in summer this steam heat is utilised to provide cooling by employing absorption refrigeration systems. Thus, steam finds immense application in most of the engineering processes.

Objectives

After studying this unit, you should be able to

Understand the process of steam generation,

Know the types of boilers,

Describe the constructional features of boilers,

Recognise the boiler mountings and accessories, and

Measure the performance of boilers.

CLASSIFICATION OF BOILER

Based on the fuels used, construction type, application, water circulation and condition of steam delivered boilers are classified as follows :

Based on Fuels

(a) Solid fuel fixed boilers

- Lignite/coal
- Charcoal/wood
- Solid waste
- Biomass

(b) Fluid fuel fired boilers

- Gas (petroleum based producer, watergas, blast furnace gas, etc.

Based on Construction Type

- Packaged

- Field erected
- Water tube
- Fire tube

Based on Application

- Utility
- Industrial
- Domestic
- Marine
- Locomotive
- Cogeneration

Based on Water Circulation

- Natural circulation
- Forced or pumped circulation

Based on Operating Condition

- Sub-critical
- Super critical

Based on Steam Delivery Condition

- Wet
- Dry saturated
- Super heated

Cochran boiler

The Cochran boiler is a vertical fire tube boiler and is commonly used for small capacity steam generation. The boiler is shown in Figure 4.2 consists of a cylindrical shell with its crown having a hemispherical shape. The upper surface of the furnace is also hemispherical in shape. The hemispherical crown of the boiler shell gives maximum strength to withstand the pressure of steam inside the boiler. The hemispherical crown of the fire box ensures excellent absorption of radiant heat from the furnace. The fuel is fed into the grate through the fire door and burnt. The hot gases thus produced pass through combustion chamber, fire tubes, smoke box and finally are released to the atmosphere through the chimney. The flow of gases through the chimney is controlled by a manually operated damper. To reduce the gas flow, the damper is closed and for maximum gas flow the damper is kept almost fully open.

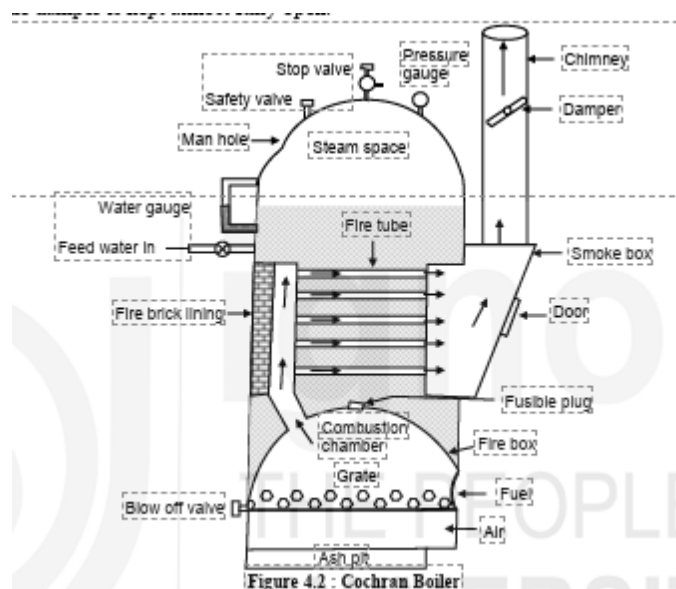
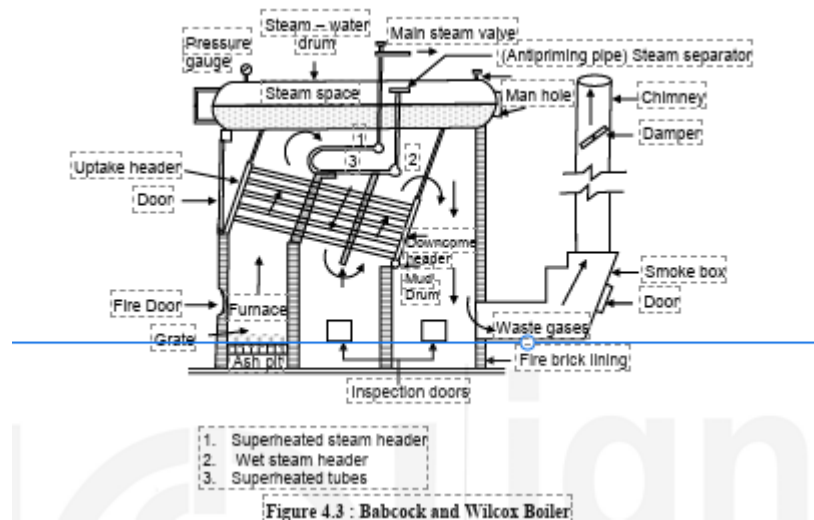


Figure 4.3 shows the constructional features of Babcock and Wilcox boiler. This is a water tube boiler and is used for high pressure steam production. Coal is fed through the fire door into the grate and is burnt. The hot gases from the furnace pass across the water Steam Generators tubes baffle, super heater and then go to the chimney through the damper. The damper controls the rate of bringing and the steam generation. Water from the steam-water drum comes down to the down header and then go to the up take header through a large number of water tubes inclined at about ‘1 ft’ to the horizontal for better circulation. At the end of the down comer header, a mud drum is provided from which the impurities are periodically remove



Like other boilers this boiler is also provided with mountings such as water gauge, pressure gauge and safety valve. Two inspection doors in the flue gas path and a man hole in the boiler drum are also provided. The steam and water get separated in the steam-water drum. Wet steam from the drum enters the wet steam header through an antipriming pipe. This pipe removes most of the moisture (liquid water) and sends the steam to the super heater tubes. The super heated steam is collected in the super heater header and is sent to the steam turbine through main steam valve.

FIRE TUBE AND WATER TUBE BOILERS: Fire Tube Boilers In the fire tube boilers, hot gases from the furnace pass through the tubes which are surrounded by water. The hot gases heat the water. Fire tube boilers are low pressure boilers and generally operate of pressures less than 1 bar. These are extensively, used in process industries like paper, leather, textile. For example : Cochram boiler, Locomotive boiler and Lancashire boiler.

Water Tube Boilers:-

In water tube boilers, water circulates inside the tube and is heated from outside by the hot gases that are produced by burning fuel in the furnace. Normally, high pressure boilers are water tube boilers.

Fire tube and water tube boilers can be compared as follows :

Sl. No.	Fire Tube Boiler	Water Tube Boiler
---------	------------------	-------------------

1	Hot gases pass through the tubes which are surrounded by water.	Water passes through the tube and hot gases surround the tube and heat it from outside.
2	Any leak of water into the tube will lead to an explosion.	Leakage of water cannot cause service damage.
3	Because smoke or fire tubes are subjected to compressive stresses, maximum pressure is restricted to about 12 bar.	Water/steam can be at very high pressures and tube failure rarely occurs as the surrounding pressure is atmospheric only.
4	Suitable for low capacity (up to 20 tone/hour).	Suitable for large– very large capacity
5	Efficiency is low.	Efficiency is high
6	Periodic tube cleaning is necessary to remove the deposits to enhance the heat transfer rate.	With the use of boiler feed water tube inside cleaning is not needed. External fouling by ash is easily overcome by 500 t blowing.

MODERN HIGH-PRESSURE BOILERS

1. Lamont Boiler

Type

- **High-pressure, water-tube boiler**
- **Forced circulation boiler**

Line Sketch Description (for drawing in exam)

In the line sketch, show and label:

- Steam drum at top
- Feed pump
- Centrifugal circulating pump
- Evaporator tubes arranged around furnace
- Superheater
- Economizer
- Furnace and flue gas path

(Water circulates continuously between drum and evaporator tubes)

Construction

The Lamont boiler consists of:

1. **Steam drum** – separates steam and water
2. **Feed pump** – supplies water to boiler

3. **Circulating pump** – forces water through tubes at high velocity
4. **Evaporator tubes** – absorb heat from furnace
5. **Superheater** – superheats steam
6. **Economizer** – preheats feed water

Working of Lamont Boiler

1. Feed water is supplied to the **steam drum** by a feed pump.
2. Water from the drum is circulated through **evaporator tubes** by a **centrifugal pump** at high speed.
3. Heat from the furnace converts part of the water into steam.
4. Steam-water mixture returns to the steam drum.
5. Steam is separated and passed through the **superheater**.
6. Superheated steam is supplied to the turbine or process.

Advantages

- High rate of heat transfer
- Suitable for high pressure (up to 100 bar)
- Compact size
- Uniform circulation prevents tube overheating

Disadvantages

- Requires power for circulation pump
- Higher initial cost

2. Benson Boiler

Type

- **High-pressure, once-through boiler**
- **Drumless boiler**
- Operates at **supercritical pressure**

Line Sketch Description (for drawing in exam)

In the line sketch, show and label:

- Feed water pump
- Economizer
- Evaporator coils
- Superheater
- Furnace
- Steam outlet

(No steam drum is shown)

Construction

The Benson boiler consists of:

1. **High-pressure feed pump**
2. **Economizer**
3. **Evaporator tubes**
4. **Superheater**
5. **Combustion chamber (furnace)**

There is **no steam drum**.

Working of Benson Boiler

1. Feed water is pumped at **supercritical pressure** (above 221 bar).
2. Water passes through the **economizer**, where it is preheated.
3. It then enters evaporator tubes placed in the furnace.
4. At supercritical pressure, **no boiling occurs**; water directly changes into steam.
5. Steam flows through the **superheater**.
6. Superheated steam is supplied directly to the turbine.

Advantages

- Very high thermal efficiency
- No steam drum → lighter and compact
- Quick start-up
- Suitable for very high pressures (up to 300 bar)

Disadvantages

- Requires very pure feed water
- Control system is complex
- High installation cost

3. Comparison: Lamont Boiler vs Benson Boiler

Aspect	Lamont Boiler	Benson Boiler
Circulation	Forced circulation	Once-through
Steam drum	Present	Not present
Pressure	High	Supercritical
Water-steam separation	In drum	Not required
Efficiency	High	Very high
Complexity	Moderate	High

BOILER MOUNTINGS

Boiler mountings are the **essential fittings provided on a boiler for safe operation and control**. They are compulsory and directly connected to the boiler.

1. Pressure Gauge

Function

Indicates the **steam pressure inside the boiler**.

Construction & Working

- Generally a **Bourdon tube pressure gauge**
- When pressure increases, the curved tube tends to straighten
- Movement is transmitted to a pointer through a link mechanism
- Pointer shows pressure on a calibrated dial

2. Water Level Indicator

Function

Shows the **level of water inside the boiler drum**.

Construction

- Consists of a **glass tube** connected between steam space and water space

- Provided with steam cock, water cock, and drain cock

Working

- Water level in glass tube is the same as boiler water level
- Ensures safe operation by preventing low or high water level

3. Fusible Plug

Function

Protects the boiler from **overheating due to low water level**.

Construction

- Made of a gunmetal body with a **fusible alloy core**
- Installed above the furnace crown

Working

- If water level falls below safe limit, fusible metal melts
- Steam and water rush into furnace
- Fire is extinguished, preventing boiler explosion

4. Blow-Down Cock

Function

Removes **mud, sediments, and impurities** from boiler water.

Working

- Located at the **lowest part of the boiler**
- Opened periodically
- Discharges dirty water along with impurities

5. Stop Valve

Function

Controls the **flow of steam from the boiler to the steam main**.

Working

- Operated manually
- Allows steam flow when open
- Stops steam supply during maintenance or emergencies

6. Safety Valve

Function

Prevents **excessive pressure build-up** inside the boiler.

(a) Dead Weight Safety Valve

Working

- Weights are placed on the valve
- When steam pressure exceeds safe limit, valve lifts
- Steam escapes and pressure reduces

Application

- Low-pressure boilers
- Mostly used in stationary boilers

(b) Spring Loaded Safety Valve

Working

- Valve is held in position by a compressed spring
- Excess pressure compresses the spring
- Valve opens and releases steam

Application

- Medium and high-pressure boilers

(c) High Pressure Safety Valve

Features

- Compact design
- Suitable for modern high-pressure boilers

- Quick response and precise control

(d) Low Water Safety Alarm

Function

Gives an **alarm or shuts down boiler** when water level falls dangerously low.

Working

- Uses float or electronic sensors
- Activates alarm or cuts fuel supply
- Prevents damage to boiler

Boiler accessories are the appliances that ensure the improved efficiency of a boiler. Boiler accessories may be installed either inside or outside a boiler. Most commonly used boiler accessories are the following:

- Economizer
- Superheater
- Air preheater
- Feed water pump
- Pressure-reducing valve
- Steam trap
- Steam separator

The function of all the accessories is briefly discussed below.

1. Economizer:

The function of the economizer is to recover a portion of heat of the exhaust gases before the flue gases enter the chimney and discharged to the atmosphere. The economizer is placed in the Steam Generator 201 path of the flue gases in between the boiler exit and entry to the chimney. Feed water coming from the feed pump when passed through the economizer tubes absorbs the heat in the exhaust gases. This increases the temperature of water entering the boiler. Due to the high temperature of feed water, fuel consumption reduces, and this increases the overall efficiency of the boiler.

2. Superheater

The function of the superheater is to increase the temperature of steam above its saturation temperature. As heat contained in unit mass of superheated steam is more than dry saturated or wet steam, it is used extensively in steam power plants. Steam from the boiler drum is passed through superheater tubes. Superheater tubes are placed in the furnace along the passage of flue gases. Temperature of steam is thus raised above the saturation temperature.

3. Air preheater

The function of the air heater is to recover the heat of a portion of exhaust flue gases before the flue gases enter the chimney. It is placed along the passage of the exhaust flue gases in between the economizer and the chimney. Air from the forced draught fan is passed over the preheater tubes that contain flue gases. Temperature of air is increased, and this high-temperature air enters the furnace. Due to higher air temperature, combustion of the fuel becomes rapid and fuel consumption becomes less. This increases the overall efficiency of the boiler. Two types of air heaters are generally used.

- (i) Tubular or recuperative air preheater This type of air preheater is composed of steel tubes through which hot flue gases flow. Air is made to circulate over these steel tubes and thus gains heat.
- (ii) Regenerative air preheater This type of air preheater consists of a rotor that turns at about 2–3 rpm. The rotor is filled with thin corrugated metal elements. Hot gases pass through one-half of the heater and air through the other half. As the rotor turns, the heat storage elements transfer the heat absorbed from the hot gases to the incoming air.

4. Feed water pump

The function of the feed pump is to pump water at high pressure to the water space of the boiler drum. Many types of feed pumps are used.

- (i) Rotary pumps They are either driven by electric motors or small steam turbines. Water is pumped due to rotary action of the impeller.
- (ii) Reciprocating pumps They are continuously run by steam from the same boiler to which the water is fed. Water is pumped by reciprocating action.

5. Pressure-reducing valve

The function of the pressure-reducing valve is to maintain constant pressure on the delivery side of the valve with the fluctuating boiler pressure. Whenever the steam demand is fluctuating, it becomes very difficult to maintain uniform pressure. In such cases, a pressure-reducing valve is connected to the steam supply line.

6. Steam trap

The function of steam trap is to drain off water resulting from the partial condensation of steam in the steam pipe lines and jackets without allowing the steam to escape through it. Water collected in the steam pipe lines results in hammering, thereby damaging the pipelines and joints. Two types of steam traps are generally used:

- (i) bucket type or float type and
- (ii) thermal expansion type.

7. Steam separator

The function of the steam separator is to separate the water particles in suspension that are carried by the steam coming from the boiler. If suspended water particles enter the turbine or engine, they cause erosion and corrosion of blades and other parts. It is always installed as close to the engine or turbine as possible on the main pipeline.

1. Actual Evaporation

Definition

Actual evaporation is the amount of water actually evaporated into steam per kg of fuel burnt in a boiler.

Formula (without proof)

$$\text{Actual evaporation} = \frac{\text{Mass of steam generated}}{\text{Mass of fuel burnt}} \text{ (kg of steam/kg of fuel)}$$

Problem 1

A boiler produces 900 kg of steam by burning 120 kg of coal.
Find the actual evaporation.

Solution

$$\text{Actual evaporation} = \frac{900}{1200} = 7.5 \text{ kg/kg fuel}$$

2. Equivalent Evaporation

Definition

Equivalent evaporation is the amount of water evaporated from and at 100°C per kg of fuel burnt.

(Used to compare boiler performance under different conditions)

Formula (without proof)

$$\text{Equivalent evaporation} = \frac{m_s(h_2 - h_1)}{2257 \times m_f}$$

Where:

- m_s = mass of steam (kg)
- m_f = mass of fuel (kg)
- h_2 = enthalpy of steam (kJ/kg)
- h_1 = enthalpy of feed water (kJ/kg)
- 2257 kJ/kg = latent heat at 100°C

Problem 2

A boiler generates **800 kg of steam** with enthalpy **2800 kJ/kg** from feed water at **100 kJ/kg**, using **100 kg of coal**.

Find the equivalent evaporation.

Solution

$$\text{Equivalent evaporation} = \frac{800(2800 - 100)}{2257 \times 100}$$

$$= \frac{800 \times 2700}{225700} = 9.57 \text{ kg/kg fuel}$$

3. Factor of Evaporation

Definition

Factor of evaporation is the ratio of equivalent evaporation to actual evaporation.

Formula (without proof)

$$\text{Factor of evaporation} = \frac{(h_2 - h_1)}{2257}$$

Problem 3

Steam enthalpy = **2800 kJ/kg**

Feed water enthalpy = **400 kJ/kg**

Find the factor of evaporation.

Solution

$$\text{Factor of evaporation} = \frac{(2800 - 400)}{2257} = \frac{2400}{2257} = 1.06$$

4. Boiler Horse Power (BHP)

Definition

Boiler horsepower is the rate of evaporation of water.

1 BHP = evaporation of 15.65 kg of water per hour from and at 100°C

Formula (without proof)

$$\text{BHP} = \frac{\text{Equivalent evaporation per hour}}{15.65}$$

Problem 4

Equivalent evaporation of a boiler is **313 kg/hr**.
Find the boiler horsepower.

Solution

$$\text{BHP} = \frac{313}{15.65} = 20$$

5. Boiler Efficiency

Definition

Boiler efficiency is the ratio of heat utilized in steam generation to heat supplied by fuel.

Formula (without proof)

$$\eta_{\text{boiler}} = \frac{m_s(h_2 - h_1)}{m_f \times cv}$$

Where:

- CV = calorific value of fuel (kJ/kg)

Problem 5

A boiler produces 1000 kg of steam at enthalpy **2800 kJ/kg** from feed water at **420 kJ/kg**, using **120 kg of coal** of CV = **30,000 kJ/kg**.
Find the boiler efficiency.

Solution

$$\eta = \frac{1000(2800 - 420)}{1200 \times 30000} = \frac{1000 \times 2380}{360000} = 0.0661$$

$$\eta = 66.1\%$$

6. Draught Systems

Draught

Draught is the **pressure difference** required to **supply air for combustion** and remove flue gases.

(a) Natural Draught

Working

Produced by a **chimney** due to **density difference** between hot flue gases and cold outside air.

Features

- No external power required
- Low cost
- Limited draught
- Used in small boilers

(b) Forced Draught

Working

Air is forced into the furnace by a **fan or blower**.

Features

- High combustion rate
- Suitable for high-capacity boilers
- Fan placed before furnace
- Furnace pressure is **positive**

(c) Induced Draught

Working

Flue gases are drawn out by a **fan placed near the chimney exit**.

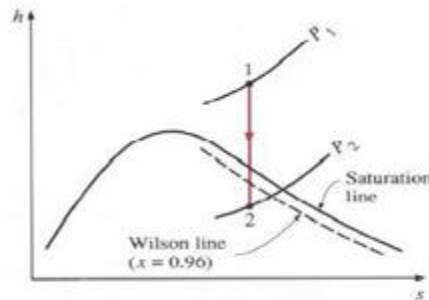
Features

- Better control of combustion
- Furnace pressure is **negative**
- Widely used in modern boilers

CHAPTER-IV

Steam Nozzles:

As steam expands in the nozzle, its pressure and temperature drop, and it is expected that the Steam start condensing when it strikes the saturation line. But this is not always the case. Owing to the high velocities, the residence time of the steam in the nozzle is small, and there may not Sufficient time for the necessary heat transfer and the formation of liquid droplets. Consequently, the condensation of steam is delayed for a little while. This phenomenon is known as Super saturation, and the steam that exists in the wet region without containing any liquid is known as supersaturated steam. The locus of points where condensation will take place regardless of the initial temperature and Pressure at the nozzle entrance is called the Wilson line. The Wilson line lies between 4 and 5 percent moisture curves in the saturation region on the h-s diagram for steam, and is often approximated by the 4 percent moisture line. The super saturation phenomenon is shown on the h-s chart below:



The h-s diagram for the isentropic expansion of steam in a nozzle.

1. Wet steam: The steam which contains some water particles in superposition.
2. Dry steam / dry saturated steam: When whole mass of steam is converted into steam then it is called as dry steam.
3. Super heated steam: When the dry steam is further heated at constant pressure, the temperature increases the above saturation temperature. The steam has obtained is called super heated steam.
4. Degree of super heat: The difference between the temperature of saturated steam and saturated temperature is called degree of superheat.
5. Nozzle: It is a duct of varying cross sectional area in which the velocity increases with the corresponding drop in pressure.
6. Coefficient of nozzle: It is the ratio of actual enthalpy drop to isentropic enthalpy drop.
7. Critical pressure ratio: There is only one value of ratio (P_2/P_1) which produces maximum discharge from the nozzle . then the ratio is called critical pressure ratio.
8. Degree of reaction: It is defined as the ratio of isentropic heat drop in the moving blade to isentropic heat drop in the entire stages of the reaction turbine.
9. Compounding: It is the method of absorbing the jet velocity in stages when the steam flows over moving blades. (i)Velocity compounding (ii)Pressure compounding and (iii) Velocity-pressure compounding

10. Enthalpy: It is the combination of the internal energy and the flow energy.
11. Entropy: It is the function of quantity of heat with respect to the temperature.
12. Convergent nozzle: The cross-sectional area of the duct decreases from inlet to the outlet side then it is called as convergent nozzle.
13. Divergent nozzle: The cross-sectional area of the duct increases from inlet to the outlet then it is called as divergent nozzle.

(i) Velocity of steam.

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

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

mass of steam discharged through the nozzle

(ii) Condition for maximum discharge

$$m = A \sqrt{\frac{2\eta}{\eta-1} \frac{P_1}{V_1} \left[\left(\frac{P_2}{P_1} \right)^{\frac{2}{\eta}} - \left(\frac{P_2}{P_1} \right)^{\frac{\eta+1}{\eta}} \right]}$$

(iii) Condition for maximum discharge

$$m_{\max} = A \sqrt{\frac{2\eta}{\eta-1} \frac{P_1}{V_1} \left[\left(\frac{2}{\eta+1} \right)^{\frac{2}{\eta-1}} - \left(\frac{2}{\eta+1} \right)^{\frac{\eta+1}{\eta-1}} \right]}$$

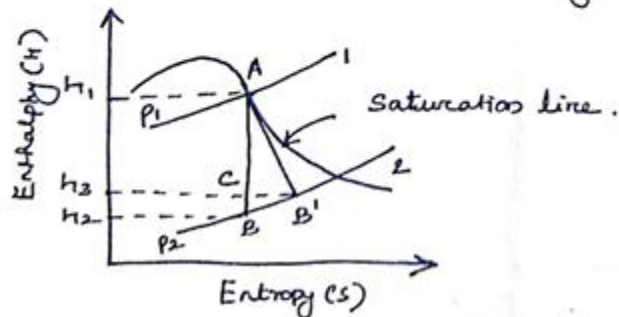
(iv) Nozzle efficiency. (or) Effect of friction in a nozzle.

When the steam flows through a nozzle the final velocity of steam for a given pressure drop is reduced due to the following reasons.

1. Due to the friction between the nozzle surface and steam.
2. Due to the internal fluid friction in the steam.
3. Due to shock losses.

These losses occur between the throat and exit in convergent-divergent nozzle.

$$\eta = \frac{\text{Actual enthalpy drop}}{\text{Isentropic drop enthalpy}} = \frac{AC}{AB} = \frac{h_1 - h_3}{h_1 - h_2}$$



1. Point A represents the initial condition of steam.
2. Where the saturation line meets the initial pressure (p_1) line.
3. If the friction is neglected the expansion of steam from entry to throat is represented by the vertical line AB.
4. The enthalpy drop ($h_1 - h_2$) isentropic enthalpy drop.
5. Due to friction in the nozzle the actual enthalpy drop in the steam will be less than ($h_1 - h_2$). The enthalpy drop is shown as AC instead of AB.
6. Actual enthalpy drop ($h_1 - h_3$)

Flow of steam through nozzles:

The flow of steam through nozzles may be regarded as adiabatic expansion. - The steam has a very high velocity at the end of the expansion, and the enthalpy decreases as expansion takes place. - Friction exists between the steam and the sides of the nozzle; heat is produced as the result of the resistance to the flow. - The phenomenon of super saturation occurs in the flow of steam through nozzles. This is due to the time lag in the condensation of the steam during the expansion.

Continuity and steady flow energy equations

Through a certain section of the nozzle: $m.v = A.C$ m is the mass flow rate, v is the specific volume, A is the cross-sectional area and C is the velocity. For steady flow of steam through a certain

Apparatus, principle of conservation of energy states:

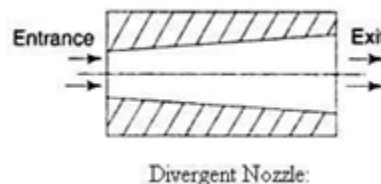
$$h_1 + C_1^2 / 2 + gz_1 + q = h_2 + C_2^2 / 2 + gz_2 + w$$

Types of Nozzles:

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

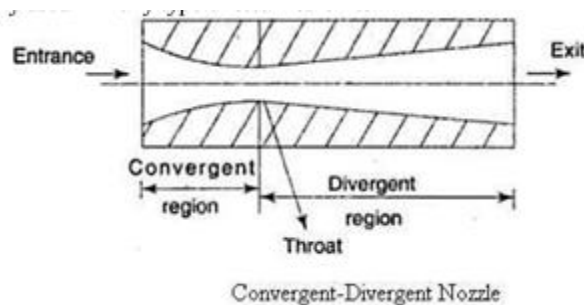
Convergent Nozzle: A typical convergent nozzle is shown in fig. in a convergent nozzle, the cross sectional area decreases continuously from its entrance to exit. It is used in a case where the back pressure is equal to or greater than the critical pressure ratio.

Divergent Nozzle: The cross sectional area of divergent nozzle increases continuously from its entrance to exit. It is used in a case, where the back pressure is less than the critical pressure ratio.



Convergent-Divergent Nozzle:

In this case, the cross sectional area first decreases from its entrance to throat, and then increases from throat to exit. it is widely used in many type of steam turbines.

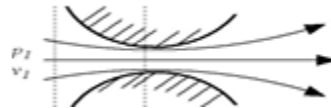


Supersaturated flow or Meta stable flow in Nozzles: As steam expands in the nozzle, its pressure and temperature drop, and it is expected that the steam start condensing when it strikes the saturation line. But this is not always the case. Owing to the high velocities, the residence time of the steam in the nozzle is small, and there may not sufficient time for the necessary heat transfer and the formation of liquid droplets. Consequently, the condensation of steam is delayed for a little while. This phenomenon is known as super saturation, and the steam that exists in the wet region without

containing any liquid is known as supersaturated steam.

Critical Pressure:

The critical pressure ratio is the pressure ratio which will accelerate the flow to a velocity equal to the local velocity of sound in the fluid. Critical flow nozzles are also called sonic chokes. By establishing a shock wave the sonic choke establish a fixed flow rate unaffected by the differential pressure, any fluctuations or changes in downstream pressure. A sonic choke may provide a simple way to regulate a gas flow.



The ratio between the critical pressure and the initial pressure for a nozzle can be expressed as

$$p_c / p_1 = (2 / (n + 1))^{n / (n - 1)}$$

Where

p_c = critical pressure (Pa)

p_1 = inlet pressure (Pa)

n = index of isentropic expansion or compression - or polytropic constant

For a perfect gas undergoing an adiabatic process the index - n - is the ratio of specific heats - $k = c_p / c_v$. There is no unique value for - n . Values for some common gases are

Steam where most of the process occurs in the wet region : $n = 1.135$

Steam superheated : $n = 1.30$

Air : $n = 1.4$

Methane : $n = 1.31$

Helium : $n = 1.667$

Effect of Friction on Nozzles:

- 1) Entropy is increased.
- 2) Available energy is decreased.
- 3) Velocity of flow at throat is decreased.
- 4) Volume of flowing steam is decreased.
- 5) Throat area necessary to discharge a given mass of steam is increased.

Most of the friction occurs in the diverging part of a convergent-divergent nozzle as the length of the converging part is very small. The effect of friction is to reduce the available enthalpy drop by about 10 to 15%. The velocity of steam will be then

$$V_2 = 44.72 \sqrt{K(H_1 - H_2)}$$

Where, k is the co-efficient which allows for friction loss. It is also known as nozzle efficiency.

Velocity of Steam at Nozzle Exit:

$$V_2^2 = 2000(H_1 - H_2) + V_1^2 \quad \therefore \quad V_2 = \sqrt{2000(H_1 - H_2) + V_1^2}$$

As the velocity of steam entering the nozzle is very small, V_1 can be neglected.

$$\therefore \quad V_2 = \sqrt{2000(H_1 - H_2)} = 44.72\sqrt{(H_1 - H_2)} \text{ m/s}$$

If frictional losses are taken into account then

$$V_2 = 44.72\sqrt{(H_1 - H_2)\eta_n} \text{ m/s}$$

3.5 Mass of steam discharged through nozzle:

$$m = A \sqrt{2000 \frac{n}{n-1} \times \frac{P_1}{v_1} \left[\left(\frac{P_2}{P_1} \right)^{\frac{2}{n}} - \left(\frac{P_2}{P_1} \right)^{\frac{n+1}{n}} \right]}$$

Condition for maximum discharge through nozzle: The nozzle is always designed for maximum discharge

$$\frac{m}{A} = \sqrt{2000 \frac{n}{n-1} \times \frac{P_1}{v_1} \left[\left(\frac{P_2}{P_1} \right)^{\frac{2}{n}} - \left(\frac{P_2}{P_1} \right)^{\frac{n+1}{n}} \right]}$$

The mass flow per unit area will be maximum at the throat because the throat area is minimum.

It is seen from the above equation that the discharge through a nozzle is a function of $\frac{P_2}{P_1}$ only, as the expansion index is fixed according to the steam supplied to the nozzle.

Therefore, $\frac{m}{A}$ is maximum when

$$\left[\left(\frac{P_2}{P_1} \right)^{\frac{2}{n}} - \left(\frac{P_2}{P_1} \right)^{\frac{n+1}{n}} \right] \text{ is minimum}$$

Values for maximum discharge:

$$m = A \sqrt{2000 \frac{n}{n-1} \times \frac{P_1}{v_1} \left[\left(\frac{P_2}{P_1} \right)^{\frac{2}{n-1}} - \left(\frac{P_2}{P_1} \right)^{\frac{n+1}{n-1}} \right]}$$

we know $\frac{P_2}{P_1} = \left(\frac{2}{n+1} \right)^{\frac{n}{n-1}}$

Putting the value of $\frac{P_2}{P_1}$ in the above equation

$$m_{\max} = A \sqrt{2000 \frac{n}{n-1} \times \frac{P_1}{v_1} \left[\left(\frac{2}{n+1} \right)^{\frac{2}{n-1}} - \left(\frac{2}{n+1} \right)^{\frac{n+1}{n-1}} \right]}$$

$$m_{\max} = A \sqrt{2000 \frac{n}{n-1} \times \frac{P_1}{v_1} \times \left(\frac{2}{n+1} \right)^{\frac{2n}{n-1}} \left[\left(\frac{2}{n+1} \right)^{\frac{2}{n-1} - \frac{n+1}{n-1}} - 1 \right]}$$

$$= A \sqrt{2000 \frac{n}{n-1} \times \frac{P_1}{v_1} \times \left(\frac{2}{n+1} \right)^{\frac{2n}{n-1}} \left[\left(\frac{2}{n+1} \right)^{\frac{1-n}{n-1}} - 1 \right]}$$

$$= A \sqrt{2000 \frac{n}{n-1} \times \frac{P_1}{v_1} \times \left(\frac{2}{n+1} \right)^{\frac{2n}{n-1}} \left[\left(\frac{2}{n+1} \right)^{-1} - 1 \right]}$$

$$= A \sqrt{2000 \frac{n}{n-1} \times \frac{P_1}{v_1} \times \left(\frac{2}{n+1} \right)^{\frac{2n}{n-1}} \left[\frac{n+1}{2} - 1 \right]}$$

$$= A \sqrt{2000 \frac{n}{n-1} \times \frac{P_1}{v_1} \times \left(\frac{2}{n+1} \right)^{\frac{2n}{n-1}} \left(\frac{n-1}{2} \right)}$$

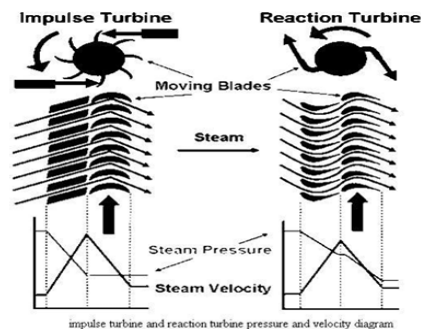
$$m_{\max} = A \sqrt{1000n \times \frac{P_1}{v_1} \times \left(\frac{2}{n+1} \right)^{\frac{2n}{n-1}}}$$

Where P1 is the initial pressure of the steam in kpa and v1 is the specific volume of the steam in m³/kg at the initial pressure.

3.6 STEAM TURBINES: Normally the turbines are classified into types,

1. Impulse Turbine
2. Reaction Turbine

Impulse and Reaction Turbines:



impulse turbine and reaction turbine pressure and velocity diagram

Steam Jet Injector

Definition

A **steam jet injector** is a **boiler accessory** used to **feed water into the boiler** using **steam from the boiler itself**, without any external power source.

Construction (Main Parts)

1. **Steam nozzle**
2. **Combining cone**
3. **Delivery cone**
4. **Overflow valve**
5. **Check (non-return) valve**

Working Principle

It works on the **principle of momentum transfer** and **condensation of steam**.

Working of Steam Jet Injector

1. **High-pressure steam** from the boiler enters the **steam nozzle**.
2. The steam expands through the nozzle, **increasing velocity** and **reducing pressure**.
3. This high-velocity steam entrains cold feed water from the feed tank in the combining cone.
4. The steam condenses while mixing with water, releasing latent heat and increasing water velocity.
5. The mixture of water passes through the delivery cone, where velocity decreases and pressure increases.
6. When the pressure becomes greater than boiler pressure, the check valve opens, allowing water to enter the boiler.
7. Excess water is discharged through the overflow valve during starting.

Advantages

- Simple construction
- No moving parts
- No external power required
- Cheap and easy maintenance

Disadvantages

- Low efficiency
- Not suitable for large boilers
- Performance affected by feed water temperature

Problem 1

A boiler evaporates 1000 kg of water per hour. Calculate the mass of feed water supplied per second.

Given:

Evaporation = 1000 kg/hr

Solution:

$$\text{Feed water per second} = \frac{1000}{3600}$$

$$= 0.278 \text{ kg/s}$$

Problem 2

If a steam jet injector supplies 900 kg of feed water in 30 minutes, find the capacity of injector in kg/hr.

Given:

Feed water = 900 kg

Time = 30 min = 0.5 hr

Solution:

$$\text{Injector capacity} = \frac{900}{0.5}$$

$$= 1800 \text{ kg/hr}$$

Problem 3

An injector uses 100 kg of steam per hour to deliver 1500 kg of water per hour. Find the injector efficiency.

Formula:

$$\text{Injector efficiency} = \frac{\text{Mass of water delivered}}{\text{Mass of steam used}}$$

Solution:

$$= \frac{1500}{100}$$

$$= 15$$

CHAPTER-V

STEAM TURBINES:

Classification Steam turbines are classified according to :

Principle of action of steam

- Impulse turbine
- Reaction turbine

Direction of steam flow

- Axial -flow occurs along the axis of rotation of the impeller- Kaplan
- Radial - flow occurs along the radius of the impeller, (i.e) in radial direction
- Tangential - flow is tangential to the circumference of the impeller - Pelton
- Mixed flow- flow occurs in both radial and axial directions – Francis

Number of pressure stages

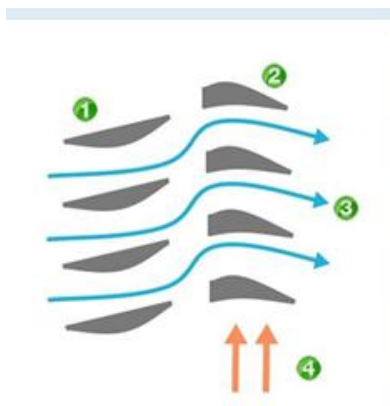
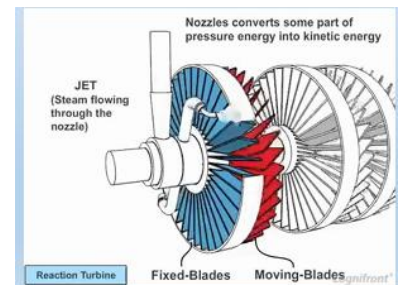
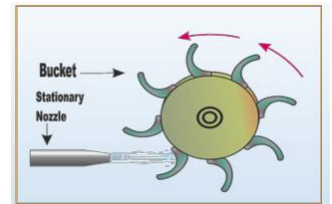
- Single stage
- Multi stage

Method of governing

- Throttle
- Nozzle
- By-pass
- Combination of throttle , nozzle by pass

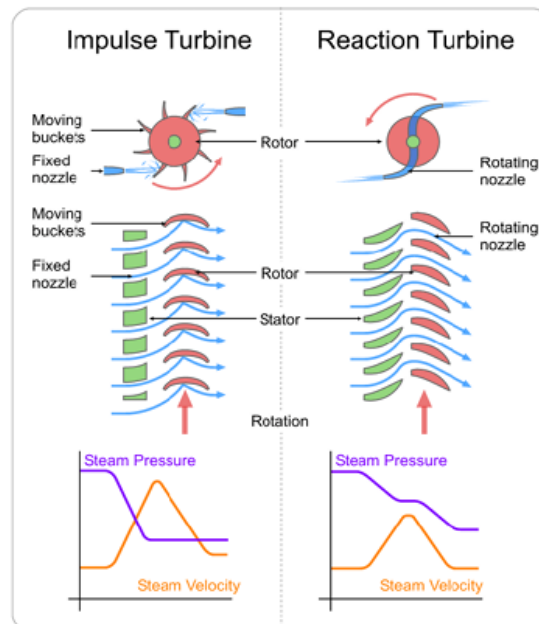
A reaction turbine is a type of steam turbine that works on the principle that the rotor spins, as the name suggests, from a reaction force rather than an impact or impulse force. Notice from the diagram of the reaction turbine above that:

- (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.

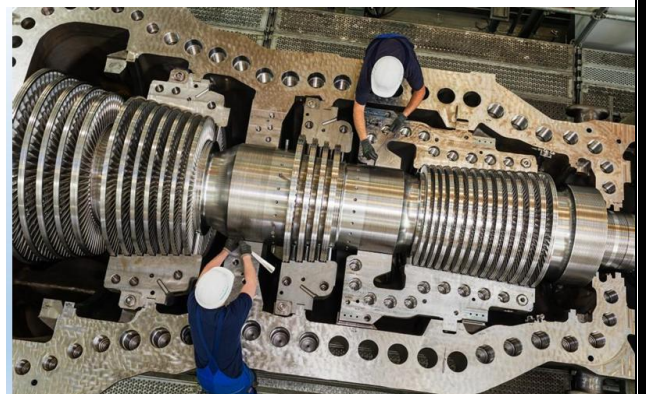
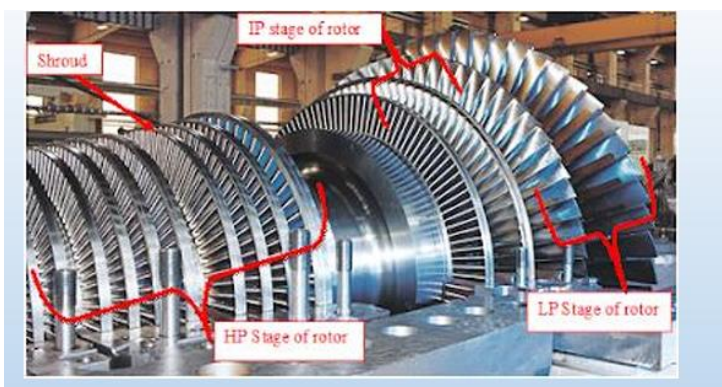


Comparison between Impulse and Reaction Turbine:

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. Not much power can be developed in impulse turbine than reaction turbine.
6. Efficiency of impulse turbine is lower than reaction turbine.
7. Impulse turbine requires less space than reaction turbine.
8. Blade manufacturing of impulse turbine is not difficult as in reaction turbine it is difficult.



Schematic diagram outlining the difference between an impulse and a reaction turbine



Simple De-Laval Turbine

Definition

A De-Laval turbine is a single-stage impulse steam turbine in which the entire pressure drop of steam occurs in a nozzle, and the high-velocity steam jet strikes the turbine blades to produce work.

Principle of Working

The De-Laval turbine works on the impulse principle.

Impulse principle:

When a high-velocity jet of steam strikes a moving blade, the change in momentum of steam produces an impulsive force, causing the rotor to rotate.

Construction (Brief)

A simple De-Laval turbine consists of:

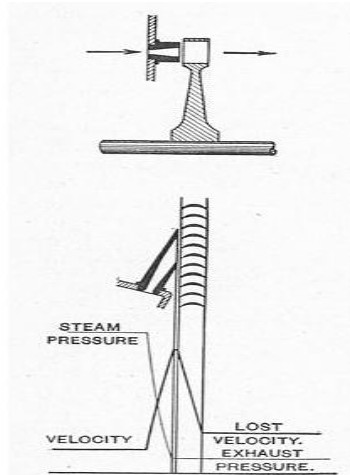
1. **Steam nozzle** (convergent–divergent type)
2. **Rotor (wheel)** mounted on a shaft
3. **Single row of moving blades**
4. **Casing**
5. **Exhaust outlet**

Working of Simple De-Laval Turbine

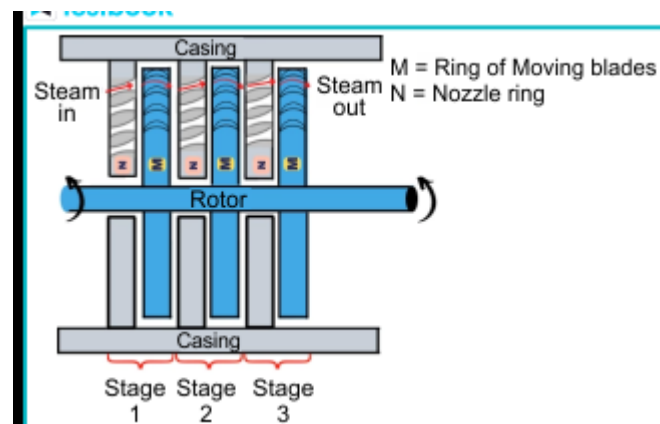
1. High-pressure steam from the boiler is expanded completely in a convergent–divergent nozzle.
2. During expansion, the pressure energy is converted into kinetic energy, producing a very high-velocity jet of steam.
3. This high-velocity steam jet impinges on the curved blades mounted on the rotor.
4. As steam flows over the blades, its direction and velocity change.
5. Due to the change in momentum, an impulse force acts on the blades.
6. This force causes the rotor to rotate, thereby producing mechanical work.
7. After passing over the blades, steam leaves the turbine at nearly atmospheric pressure.

Important:

- Pressure across the moving blades remains constant
- Only velocity changes in the moving blades



To reduce rotor speed, methods include using gearing (mechanical reduction), hydraulic couplings, braking systems, or electrical controls like Variable Frequency Drives (VFDs) for electric motors, while steam/gas turbines use compounding (pressure/velocity stages) or pitch control (for wind) to manage energy absorption and slow down rotation for efficiency and stability

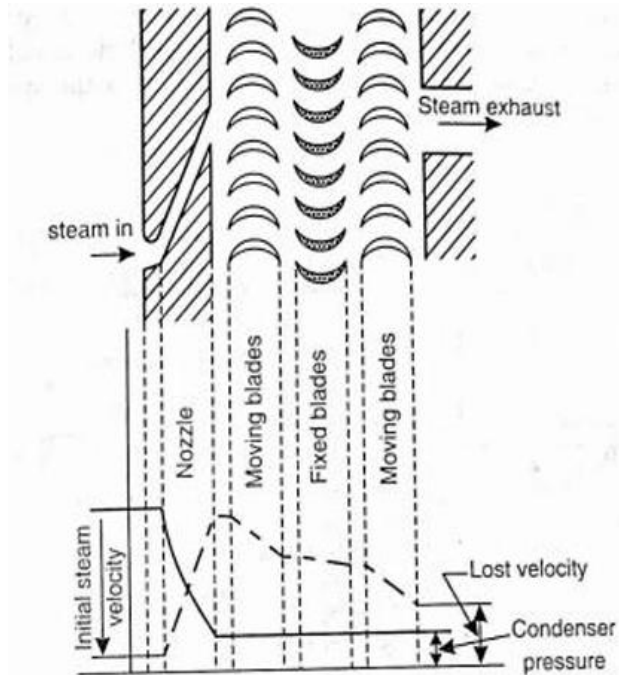


Compounding:

1. In simple impulse turbine , the steam is expanded from the boiler pr to condenser pr in one stage.
2. The speed of the rotor becomes tremendously high this leads practical complications.
3. There are several methods of reducing this speed to lower value.
4. All these methods utilize a multiple system of rotor in series
5. This is known as compounding
 - Velocity compounding
 - Pressure compounding
 - Pressure velocity compounding

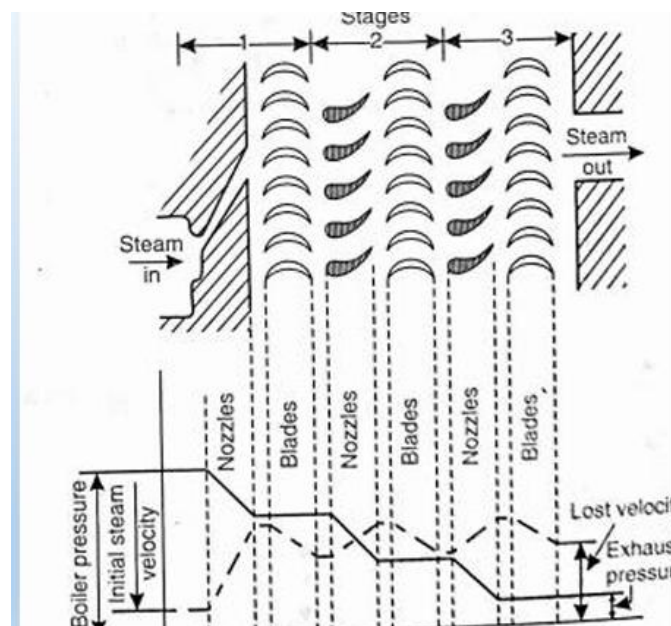
Methods of reducing rotor speed:

Method for controlling a rotor speed of a rotor of a wind turbine at rated or curtailed operation conditions the rotor being an aerodynamic rotor having one or a plurality of rotor blades, and the wind turbine further having a tower and a generator wherein a pitch control provides a pitch angle set value depending on an actual rotor speed for setting a pitch angle of the rotor blades, a main control



2. Pressure Compounding

- The fig shows rings of fixed nozzles incorporated between the rings of moving blades.
- The steam at boiler pressure enters the first set of nozzles and expands partially.
- This method of compounding is used in Rateau and Zoelly turbine.
- This is most efficient turbine since the speed ratio remains constant but it is expensive owing to a large number of stages.



3. Pressure velocity compounding

$$1) \text{ Power developed by the turbine} = \frac{m(C_{wi} + C_{we})u}{1000}$$

$$2) \text{ Blade efficiency} = \frac{2u(C_{wi} + C_{we})}{C_i^2}$$

$$3) \text{ Stage efficiency} = \frac{(C_{wi} + C_{we})}{H_d}$$

$$4) \text{ Maximum Blade efficiency} = \cos^2 \alpha_i$$

$$5) \text{ Axial force on blades} = m(C_{ai} - C_{ae})$$

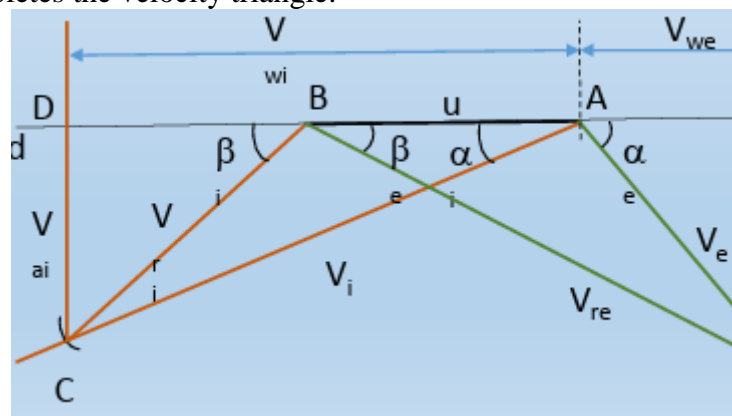
$$6) \text{ Tangential force on blades} = m(C_{wi} \pm C_{we})$$

$$7) \text{ Energy lost due to blade friction} = \frac{1}{2} m(C_{ri}^2 - C_{re}^2)$$

IMPULSE TURBINE

The procedure for drawing the combined velocity diagram is given below:

- Draw a horizontal line AB equal to blade velocity u to some suitable scale.
- Draw a line AC at an angle α_i with AB. Cut AC = V_i
- Join B and C. The line BC represents the relative velocity at inlet.
- The blade inlet angle β_i is measured and its value is noted down.
- From point C draw a perpendicular CD on AB produced.
- CD represents axial velocity at inlet and AD represents tangential velocity at inlet.
- From point B draw a line BE at an angle β_e (the blade outlet angle).
- Cut BE = $V_{re} = K V_{ri}$.
- Join A and E.
- AE represents the absolute velocity at outlet.
- The angle α_e is measured and noted down.
- From point E draw a perpendicular EF on BA.
- Then AF represents the tangential velocity of steam at outlet and EF represents the axial velocity outlet.
- This completes the velocity triangle.



Steam with absolute velocity 360 m/s enters the stage of an impulse turbine provided with a single row wheel. The nozzles are inclined at 20° to the plane of the wheel. The blade rotor with diameter 95.5 cm rotates with a speed of 3000 r.p.m. Find
 (a) suitable inlet and outlet angle for the moving blade so that there is no axial thrust on the blade.
 It may be assumed that friction in blade passages is 19% of the kinetic energy corresponding to relative velocity at inlet to blades,
 (b) Power developed in blading for a steam flow of 1 kg/s, and
 (c) Kinetic energy of steam finally leaving the stage.

Given : $V_i = 360 \text{ m/s}$ $N = 3000 \text{ rpm}$ $\alpha_i = 20^\circ$ $D = 95.5 \text{ cm}$ $m_s = 1 \text{ kg/s}$ $V_{ai} = V_{ae}$
 $u = \frac{\pi DN}{60} = \frac{\pi \times 0.955 \times 3000}{60} = 150$

For Drawing

Scale 1:30

$u = \frac{150}{30} = 5$

$V_i = \frac{360}{30} = 12$

$V_{ai} = V_{ae}$

$\frac{V_{r2}^2}{2} = (1-0.19) \frac{V_{r1}^2}{2}$

$= (1-0.19) \frac{7.5^2}{2}$

$= 6.8$

From Diagram

$V_i = 12$ $V_e = 5.6$

$V_{ri} = 7.5$ $V_{re} = 6.8$

$V_{ai} = 4$ $V_{ae} = 4$

$V_{wi} = 11.3$ $V_{we} = 0.35$

For Calculation

Multiply all the values taken from diagram by 30

$V_i = 12 \times 30 = 360 \text{ m/s}$

$V_{ri} = 7.5 \times 30 = 225 \text{ m/s}$

$V_{ai} = 4 \times 30 = 120 \text{ m/s}$

$V_{wi} = 11.3 \times 30 = 339 \text{ m/s}$

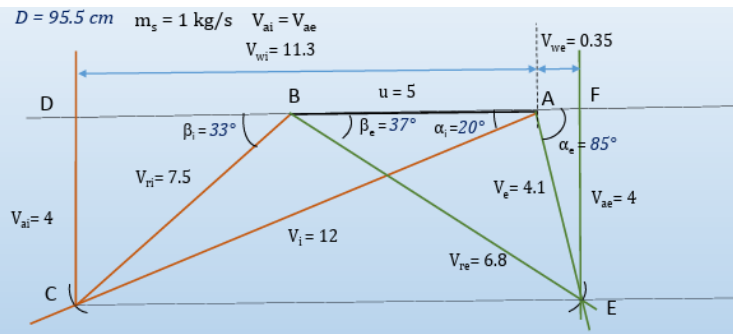
$V_e = 4.1 \times 30 = 123 \text{ m/s}$

$V_{re} = 6.8 \times 30 = 204 \text{ m/s}$

$V_{ae} = 4 \times 30 = 120 \text{ m/s}$

$V_{we} = 0.35 \times 30 = 10.5 \text{ m/s}$

$u = 5 \times 30 = 150 \text{ m/s}$



a) Inlet angle of blade $\beta_i = 33^\circ$ Outlet angle of blade $\beta_e = 37^\circ$

b) Power developed by the turbine $= \frac{m(V_{wi} \pm V_{we})u}{1000} = \frac{1(339 + 10.5)150}{1000} = 52 \text{ kW}$

c) Kinetic energy of steam finally leaving the stage $= \frac{V_e^2}{2} = \frac{123^2}{2} = 7564.5 \text{ Nm/kg}$

The velocity of steam leaving a nozzle is 925 m/s and the nozzle angle is 20° . The blade speed is 250 m/s. The mass flow through the turbine nozzles and blading is 0.182 kg/s and the blade velocity coefficient is 0.7. Calculate the following:

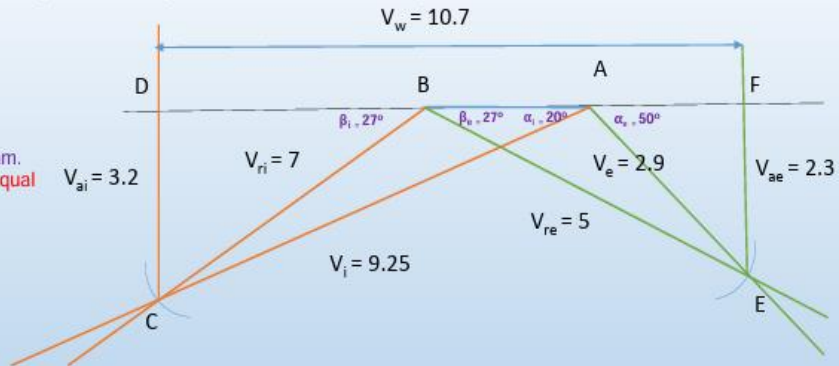
1. Velocity of whirl.
2. Tangential force on blades.
3. Axial force on blades.
4. Work done on blades.
5. Efficiency of blading.
6. Inlet angle of blades for shock less inflow of steam.

Assume that the inlet and outlet blade angles are equal

$u = 250$ After scaling
 $V_i = 925$ 1 : 100
 $\alpha_i = 20^\circ$ $u = 250 = 2.5$
 $K = 0.7$ $V_i = 925 = 9.25$
 $m = 0.18$ $\alpha_i = 20^\circ$
 $K = \frac{V_{re}}{V_{ri}} = 0.7$
 $\beta_i = \beta_e$ $m = 0.18$

$\beta_i = \beta_e$

$V_{re} = 0.7 V_{ri}$



$V_w = 1070 \text{ m/s}$
 $TF = 191.63 \text{ N.}$
 $AF = 17.26 \text{ N}$
 $WD = 47.91 \text{ kW.}$
 $\eta = 61.53\%$

Parsons' Reaction Turbine – Working Principle, Velocity Diagrams

& Numerical Problems on

- Single-stage impulse turbine (without blade friction)

- Reaction turbine (including blade height)

1. Parsons' Reaction Turbine

1.1 Definition

A Parsons' turbine is a reaction type steam turbine in which steam expands both in fixed and moving blades, and each stage consists of identical fixed and moving blades.

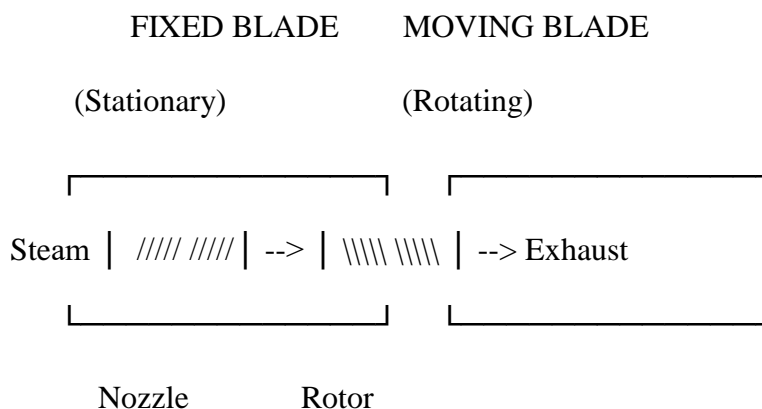
- Degree of reaction = **50%**
- Also called **50% reaction turbine**
- Fixed blades act as **nozzles**

1.2 Working Principle

The turbine works on **both impulse and reaction principles**.

1. Steam enters the **fixed blades**.
2. Pressure and velocity of steam **increase** due to nozzle action.
3. Steam strikes the **moving blades**, producing:
 - **Impulse force** (due to change in velocity)
 - **Reaction force** (due to pressure drop across moving blades)
4. Steam expands continuously while flowing over the blades.
5. Shaft rotates due to the combined effect of impulse and reaction.

1.3 Line Diagram of Parsons' Reaction Turbine



2. Velocity Diagrams of Parsons' Turbine

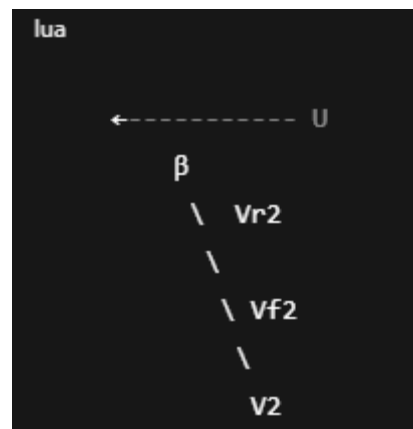
2.1 Velocity Diagram at Inlet



Where:

- V_1 = Absolute velocity at inlet
- U = Blade velocity
- V_{w1} = Whirl velocity
- V_{f1} = Flow velocity
- α = Nozzle angle

2.2 Velocity Diagram at Outlet



Degree of reaction: $R = \frac{\text{Pressure drop in moving blades}}{\text{Total pressure drop per stage}} = 0.5$

Power Developed: $P = m \cdot U (\dot{v}_{w1} - v_{w2})$

4. Numerical Problems

Problem 1: Single-Stage Impulse Turbine (Without Blade Friction)

Given:

- Steam velocity at nozzle exit, $V_1=500$ m/
- Blade speed, $U=250$ m/s
- Nozzle angle, $\alpha=20^\circ$
- Mass flow rate, $\dot{m}=10$ kg/s
- Blade friction neglected
- Steam leaves blade axially $\Rightarrow V_{w2}=0$

Solution:

Step 1: Whirl velocity at inlet

$$V_{w1} = V_1 \cos \alpha$$

$$V_{w1} = 500 \cos 20^\circ = 469.8 \text{ m/s}$$

Step 2: Power developed

$$P = \dot{m} \cdot U (V_{w1} - V_{w2})$$

$$P = 10 \times 250 \times (469.8 - 0)$$

$$P = 1.17 \times 10^6 \text{ W} = 1.17 \text{ MW}$$

Answer:

$$\boxed{Power = 1.17 \text{ MW}}$$

1. Bleeding of Steam in Steam Turbines

Definition

Bleeding of steam is the process of **withdrawing a portion of steam from intermediate stages of a steam turbine for feed water heating or other auxiliary purposes.**

Purpose of Bleeding

- To **heat feed water** in feed heaters
- To **improve thermal efficiency** of the Rankine cycle
- To **reduce moisture content** in low-pressure stages
- To reduce fuel consumption

Effects of Bleeding

Advantages

- Increases overall plant efficiency

- Reduces heat loss in condenser
- Improves turbine blade life

Disadvantages

- Slight reduction in turbine power output
- More complex plant layout

2. Re-Heating in Steam Turbines

Definition

Re-heating is the process in which steam is **expanded partially in the turbine**, then sent back to the boiler to be **reheated at constant pressure**, and finally expanded again in the remaining stages of the turbine.

Need for Re-Heating

- To **reduce moisture content** at turbine exhaust
- To **increase turbine efficiency**
- To prevent **blade erosion**
- To increase work output

Re-Heating Process

1. High-pressure steam expands in **HP turbine**
2. Partially expanded steam goes to **reheater**
3. Steam is reheated at constant pressure
4. Reheated steam enters **LP turbine** for further expansion

3. Re-Heating Factor

Definition

Re-heating factor is the ratio of **actual heat drop in turbine with re-heating** to the **isentropic heat drop** between initial and final pressures.

Expression

$$\text{Re-heating factor} = \frac{\text{Sum of actual enthalpy drops in all stages}}{\text{Isentropic enthalpy drop}}$$

Value

- Re-heating factor is **always greater than 1**
- Typical value ranges from **1.02 to 1.06**

Significance

- Accounts for **increase in enthalpy drop** due to reheating effects
- Used in **multistage turbine performance calculations**

4. Governing of Steam Turbines

Definition

Governing of steam turbines is the method of **regulating the steam flow to the turbine** so as to **maintain constant speed under varying load conditions**.

Need for Governing

- Prevents turbine overspeed
- Maintains constant frequency in power generation
- Ensures safe and efficient operation

5. Types of Governing of Steam Turbines

(A) Throttle Governing

Principle

Steam flow is controlled by **partially closing the throttle valve**, reducing **pressure of steam** entering the turbine.

Characteristics

- Steam pressure reduced
- Heat drop decreases

- Efficiency reduces at part load

Advantages

- Simple mechanism
- Used in small turbines

Disadvantages

- Loss of available energy
- Not economical at partial loads

Application

- Single-stage turbines
- Small power plants

(B) Nozzle Control Governing

Principle

Steam pressure remains constant, but **number of nozzles supplying steam is varied** according to load.

Characteristics

- No throttling loss
- High efficiency at part load
- Steam admitted through groups of nozzles

Advantages

- Better efficiency
- Suitable for large turbines

Disadvantages

- Complex mechanism
- Partial arc admission causes vibration

Application

- Impulse turbines
- Large power stations

(C) By-Pass Governing

Principle

Excess steam is **bypassed directly to condenser** when load decreases, without passing through turbine stages.

Characteristics

- Turbine speed remains constant
- Steam flow to turbine reduced indirectly

Advantages

- Simple control during sudden load changes

Disadvantages

- Wastage of steam
- Reduced plant efficiency

Application

- Large power plants for load fluctuations

