Course Material

Name of the Course : **Applied Thermodynamics**

Name of the Unit : **Refrigeration**

Name of the Topic : **Vapour Compression Refrigeration System**

(Domestic Refrigerator)

1. Objectives: To understand the basics and as well as construction & working principle of Vapour Compression Refrigeration (VCR) system – Domestic refrigeration system

Outcomes: Upon successful completion, the student should be able to understand the basics and working principle of domestic refrigeration system

2. Pre-Test: (Students should be able to answer the following)

1. State II law of thermodynamics-Clausius statement
2. What do you mean by perpetual motion machine of II kind-PMM-II?
3. State the difference between refrigerator and heat pump.
4. Explain with neat P-V and T-S diagram, about the theoretical cycle of refrigeration.

3. Pre-requisites: To have a basic knowledge of second law of thermodynamics

4. Theory Behind:

Introduction: A vapour compression refrigeration system is an improved type of air refrigeration system in which a suitable working substance, termed as refrigerant, is used. It condenses and evaporates at temperatures and pressures close to the atmospheric conditions. The refrigerants, usually, used for this purpose are ammonia (NH_3), carbon dioxide (CO_2) and sulphur dioxide (SO_2) and freon. The refrigerant used, does not leave the system, but is circulated throughout the system alternately condensing and evaporating. In evaporating, the refrigerant absorbs its latent heat from the brine (salt water) which is used for circulating it around the cold chamber. While condensing, it gives out its latent heat to the circulating water of the cooler. The vapour compression refrigeration system is, therefore a latent heat pump, as it pumps its latent heat from the brine and delivers it to the cooler. The vapour compression refrigeration system is now-a-days used for all purpose refrigeration. It is generally used for all industrial purposes from a small domestic refrigerator to a big air conditioning plant.

Construction & Working Principle:

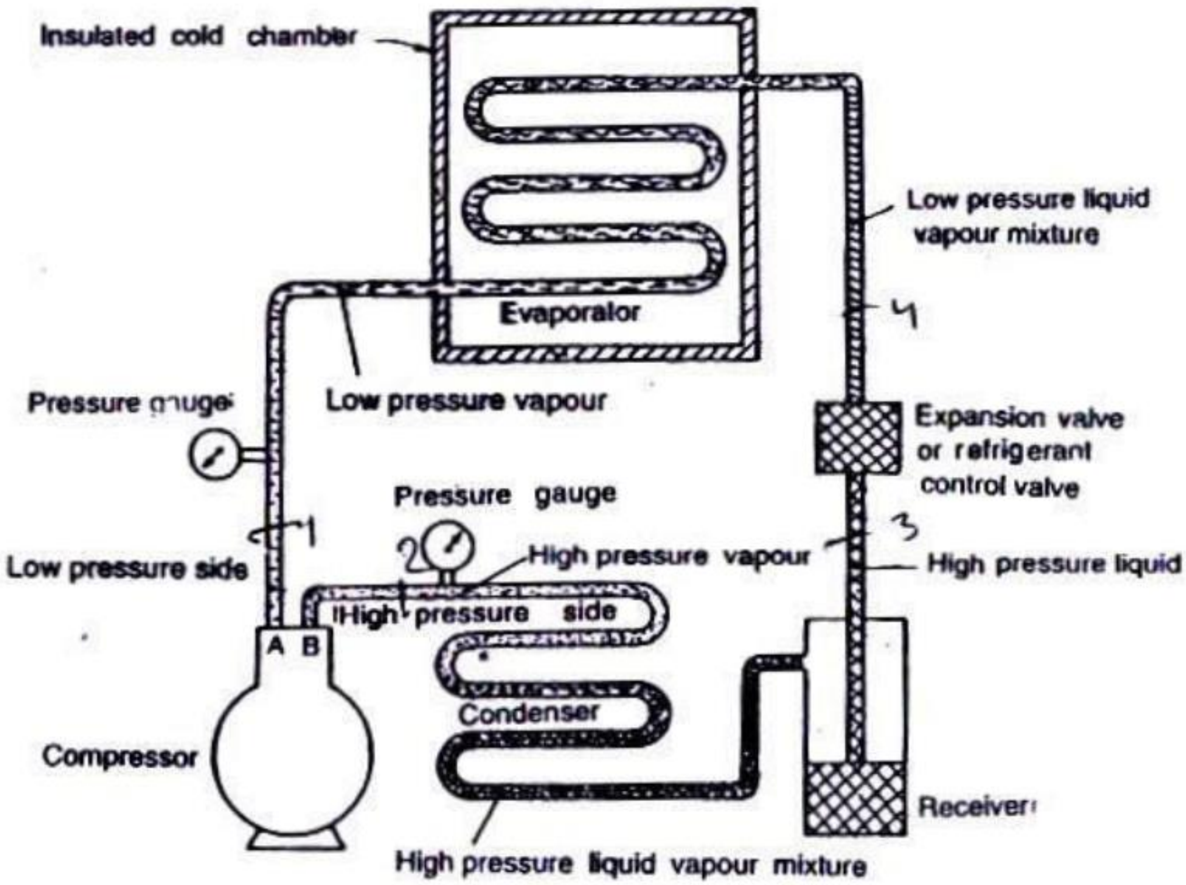


Fig. shows the schematic diagram of a simple vapour compression refrigeration system. It consists of the following five essential parts:

1. Compressor. The low pressure and temperature vapour refrigerant from evaporator is drawn into the compressor through the inlet or suction valve A, where it is compresses to a high pressure and temperature. This high pressure and temperature vapour refrigerant is discharge the condenser through the delivery or discharge valve B.

2. Condenser. The condenser or cooler consists of coils of pipe in which the high pressure and temperature vapour refrigerant is cooled and condensed. The refrigerant, while

passing through the condenser, gives up its latent heat to the surrounding condensing medium which is normally air or water.

3. *Receiver*. The condensed liquid refrigerant from the condenser is stored in a vessel known as receiver from where it is supplied to the evaporator through the expansion valve or refrigerant control valve.

4. *Expansion valve*. It is also called throttle valve or refrigerant control valve. The function of the expansion valve is to allow the liquid refrigerant under high pressure and temperature to pass at a controlled rate after reducing its pressure and temperature. Some of the liquid refrigerant evaporates as it passes through the expansion valve, but the greater portion is vaporised in the evaporator at the low pressure and temperature.

5. *Evaporator*. An evaporator consists of coils of pipe in which the liquid vapour refrigerant at low pressure and temperature is evaporated and changed into vapour refrigerant at low pressure and temperature. In evaporating, the liquid vapour refrigerant absorbs its latent heat of vaporisation from the medium (air, water or brine) which is to be cooled.

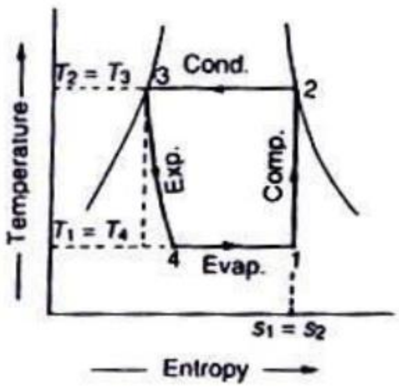
Note: In any compression refrigeration system, there are two different pressure conditions. One is called the high-pressure side and other is known as low pressure side. The high-pressure side includes the discharge line (i.e. piping from the evaporator to the suction valve A).

Types of Vapour Compression Cycles

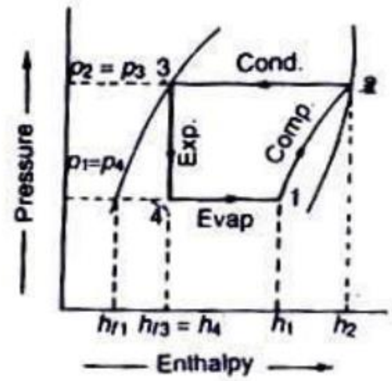
1. Cycle with dry saturated vapour after compression,
2. Cycle with wet vapour after compression,
3. Cycle with superheated vapour after compression,

Theoretical Vapour Compression Cycle with Dry Saturated Vapour after Compression

A vapour compression cycle with dry saturated vapour after compression is shown on T-s and p-h diagrams in Fig. (a) and (b) respectively. At point 1, let T1, p1 and s1 be the temperature, pressure and entropy of the vapour refrigerant respectively. The four process of the cycle are as follows:



(*a*) *T-s* diagram.



(*b*) *p-h* diagram.

1. *Compression process*. The vapour refrigerant at low pressure p1 and temperature T1 is compressed isentropically to dry saturated vapour as shown by the vertical line 1-2 on T-s diagram and by the curve 1-2 on p-h diagram. The pressure and temperature rises from p1 to p2 and T1 to T2 respectively. The work done during isentropic compression per kg of refrigerant is given by

w = h2 - h1

where h1 = Enthalpy of vapour refrigerant at temperature T1, i.e. at suction of the compressor, and h2 = Enthalpy of the vapour refrigerant at temperature T2, i.e. at discharge of the compressor.

2. *Condensing process*. The high pressure and temperature vapour refrigerant from the compressor is passed through the condenser where it is completely condensed at constant pressure p2 and temperature T2, as shown by the horizontal line 2-3 on T-s and p-h diagrams. The vapour refrigerant is changed into liquid refrigerant. The refrigerant, while passing through the condenser, gives its latent heat to the surrounding condensing medium.

3. *Expansion process*. the liquid refrigerant at pressure p3 = p2 and temperature T3 = T2 is expanded by *throttling process through the expansion valve to a low pressure p4 = p1 and temperature T4 = T1, as shown by the curve 3-4 on T-s diagram and by the vertical line 3-4 on p-h diagram. We have already discussed that some of the liquid refrigerant evaporates as it passes through the expansion valve, but the greater portion is vaporised

in the evaporator. We know that during the throttling process, no heat is absorbed or rejected by the liquid refrigerant.

4. *Vaporising process*. The liquid-vapour mixture of the refrigerant at pressure p4 = p1 and temperature T4 = T1 is evaporated and changed into vapour refrigerant at constant pressure and temperature, as shown by the horizontal line 4-1 on T-s and p-h diagrams. During evaporation, the liquid-vapour refrigerant absorbs its latent heat of vaporisation from the medium (air, water or brine) which is to be cooled. This heat which is absorbed by the refrigerant is called refrigerating effect and it is briefly written as RE. The process of vaporisation continues upto point 1 which is the starting point and thus the cycle is completed. We know that the refrigerating effect or the heat absorbed or extracted by the liquid-vapour refrigerant during evaporation per kg of refrigerant is given by

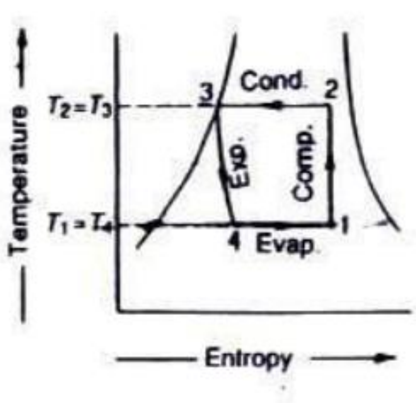
Refrigerating effect = h1-h4 = h1-hf3

where hf3 = Sensible heat at temperature T3, i.e. enthalpy of liquid refrigerant leaving the condenser.

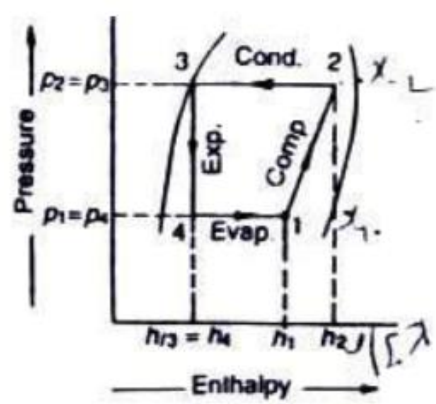
It may be noticed from the cycle that the liquid-vapour refrigerant has extracted heat during evaporation and the work will be done by the compressor for isentropic compression of the high pressure and temperature vapour refrigerant.

Coefficient of performance (COP) = $\frac{\text{Refrigerating effect}}{\text{workdone}} = \frac{\text{h1}-\text{hf3}}{\text{h2}-\text{h1}}$

Theoretical Vapour Compression Cycle with Wet Vapour after Compression



(*a*) *T-s* diagram.



(*b*) *p-h* diagram.

A vapour compression cycle with wet vapour after compression is shown on T-s and p-h diagrams in Fig. (a) and (b) respectively. In this cycle, the enthalpy at point 2 is found out with the help of dryness fraction at this point. The dryness fraction at points 1 and 2 may be obtained by equating entropies at points 1 and 2. Now the coefficient of performance may be found out as usual from the relation.

Advantages of vapour Compression Refrigeration System over Air Refrigeration System:

1. It has smaller size for the given capacity of refrigeration.
2. It has less running cost.
3. It can be employed over a large range of temperatures.
4. The coefficient of performance is quite high.

Disadvantages

1. The initial cost is high
2. The prevention of leakage of the refrigerant is the major problem in vapour compression system

5. Related Laboratories

Conduct performance test on vapour compression (domestic) refrigeration system and calculate the refrigerating effect, workdone and coefficient of performance.

6. Post Test:

1. Define: COP
2. Define: Refrigerating effect
3. Explain the construction and working principle of VCR or domestic refrigeration system?
4. Write down the advantages and disadvantages of VCR system?

7. Conclusions:

The air-cycle refrigeration systems, as originally designed and installed, are now practically obsolete because of their low COP and high-power requirements. The above difficulties are overcome by the introduction of vapour compression refrigeration system.

8. References:

Arora.C.P, ”Refrigeration and Air Conditioning ,” Tata McGraw-Hill Publishers, 2008.

9. Demo Video: https://www.youtube.com/watch?v=h5wQoA15OnQ

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Name of the Course : **Applied Thermodynamics**

Name of the Unit : **Refrigeration**

Name of the Topic : **Vapour Absorption Refrigeration System (Industrial Chiller)**

1. Objectives: To understand the basics and as well as construction & working principle of Vapour absorption Refrigeration (VAR) system – Industrial Chiller system

Outcomes: Upon successful completion, the student should be able to understand the basics and working principle of industrial chiller system

2. Pre-Test: (Students should be able to answer the following)

1. State II law of thermodynamics-Clausius statement
2. State the difference between refrigerator and heat pump.
3. Explain with neat P-V and T-S diagram, about the theoretical cycle of refrigeration.

3. Pre-requisites: To have a basic knowledge of vapour compression refrigeration system & refrigeration cycle

4. Theory Behind:

Introduction:

An absorption refrigerator is a refrigerator that uses a heat source (e.g., solar energy, a fossil-fuel flame, waste heat from factories, or district heating systems) to provide the energy needed for the cooling process.

◉ In this system mechanical compression process of vapor compression cycle is replaced by a thermal compression process.

◉ The thermal compression is achieved by the following process:

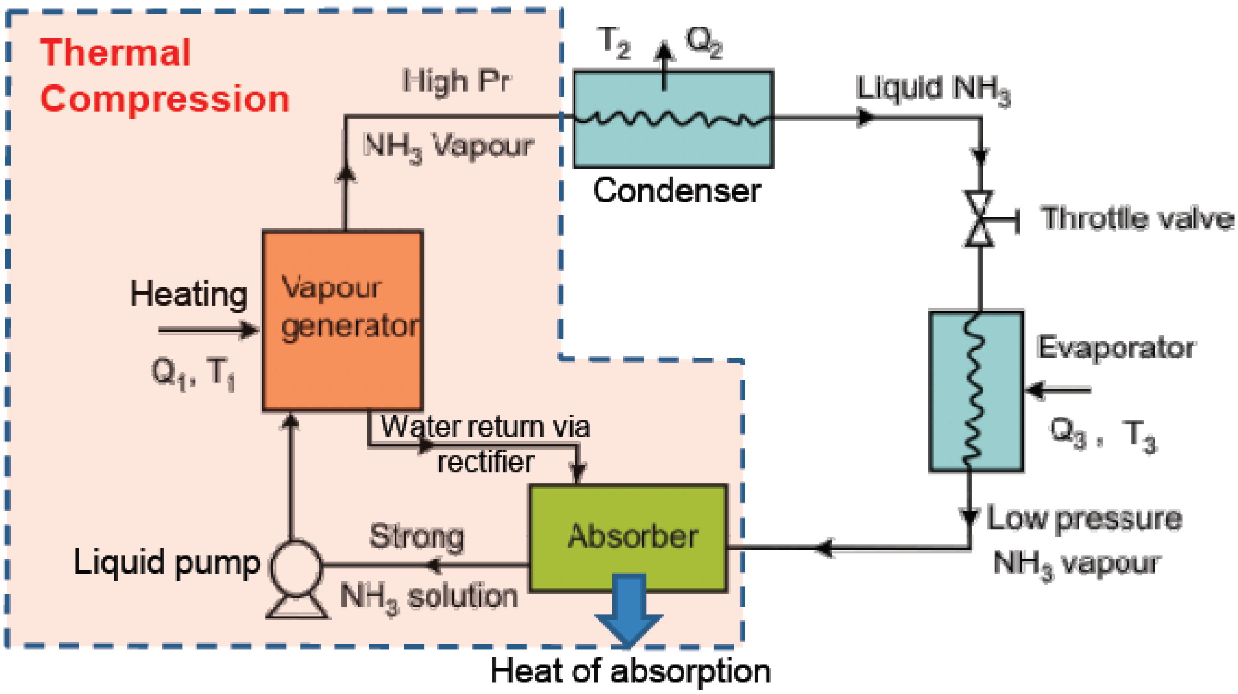
- Absorbing a fluid vapor (e.g., say: ammonia) into another carrier liquid (e.g., say water).
- Pumping this solution to a high-pressure cycle by a simple pump.
- Producing vapor from the solution by heating (thus, cooling).

Features

◉ The principle can be used to air-condition buildings using available waste heat from a source. ARS are primarily used in large commercial, industrial installations or for storage in recreational vehicles.

◉ Some examples include geothermal energy, solar energy, and waste heat from cogeneration or process steam plants, and even natural gas when it is at a relatively low price.

◉ For example, using waste heat from a gas turbine makes it very efficient because it first produces electricity, then hot water, and finally, air conditioning
(called cogeneration/trigeneration).



Operational steps:

Remember that in NH_3-H_2O – ammonia is the refrigerant and water is the absorber but the LiBr-H_2O water is the refrigerant and LiBr is the absorber. In this case, we are demonstrating the Aqua-Ammonia Vapor absorption system. Here NH_3 is the refrigerant and H_2O is the absorbent. In VA refrigeration system the requirement of the compressor is fulfilled by using an arrangement consisting of an absorber, a pump, and a generator. However, more elements are added to improve the performance of the system. The elements condenser, evaporator and expansion valve are all same for VC and VA cycles.

First, evaporator passes the refrigerant vapor to the absorber (In this case ammonia vapor). NH_3 has a property of mixing with the cool water promptly. So, in absorber ammonia mixed with water is known as strong NH_3-Water solution. With the help of a pump, this strong solution moves towards the generator where the solution is heated and NH_3 is liberated from the water and collected on the top of the generator with high pressure. In the VC system, the function of the compressor is to compress the refrigerant vapor and increase its pressure. Here in VARS, the generator is doing the same. Hence, the function of the compressor is already achieved. Likewise, the refrigerant vapor with high pressure goes to condenser and liberates heat and ultimately becomes liquid. The liquid is collected in a receiver tank and then moves through the expansion valve. Here it is expanded, moves towards the evaporator and collects heat and becomes vapor and the cycle continues. The solution exchange in generator and absorber also runs in a cycle. Now, what happens in the absorber and generator. With the help of a pump, the strong solution is transferred to the generator. In the generator, heat is supplied and separated ammonia is ready for the next step. The solution in the generator is thus called a weak solution. This weak solution comes back to the generator with the help of a return duct. For example, the heat exchanger is used to cool the weak solution, otherwise, the water of the absorber will be heated.

This type of refrigeration cycle is used where exhaust heat is available. Extra or unused heat can be used to run the generator. For developing solar refrigeration system this type of arrangement is very useful. But you might be thinking that here electrical is used to run the pump. But still, the running the cost is less in Vapor absorption system than Vapor compression cycle because the energy used in pumps is very less in comparison to that of a compressor.

Function of other elements used in the Vapor Absorption Refrigeration system:

Heat Exchanger: The heat exchanger is placed between the generator and the absorber. The strong solution pumped to the generator must be heated and the weak solution coming back from the generator to the absorber must be cooled. This heat exchanger facilitates both and thus reduce the cost of heating and cooling the solution.

Analyzer: The analyzer is a series of plated situated at the top of the generator. It traps the water vapor from entering the condenser. Ultimately it helps the pure ammonia vapor to enter the condenser. Actually, it helps to remove some unwanted water vapor particles to enter the condenser with NH_3 vapor. If these water vapors are permitted in the condenser, they might freeze in the expansion valve and the pipe may get choked.

Rectifier: The rectifier is nothing but a water-cooled condenser. It condenses the water vapor and some of the ammonia vapor and sends back to the generator. Elimination of the water vapor takes place in the condenser.

Calculating the COP of vapor Absorption System:

The actual formula for calculating the COP of Vapor absorption Refrigeration system is COP = R.E/(Win+Qg)

Here- R.E – refrigeration effect, Win – the work done in the pump, Qin – The heat supplied in the generator. But for ideal case, the pump work is negligible so the formula becomes COP = R.E/Qg

And if you know the different ranges you can just use this formula to calculate the COP of vapor absorption refrigeration system COP = $T_E(T_G-T_1)/TG(T_1-TE)$

Here- TE – The temperature at which evaporator extracts heat

T_G – The temperature at which heat is added to the generator

T_1 – Cooling water temperature/ room temperature.

Where Vapour Absorption Refrigeration system is used?

- Electricity is unreliable or load shedding is very frequent.
- The places where noise from the compressor can create disturbances. In VARS there is no compressor so very less noise.
- Where extra or exhaust heat is easily available. For example, the surplus heat from the power plants can be used or solar energy can be used.

Comparison: Vapor compression and absorption systems

- Compared with vapor-compression systems, ARS have one major advantage: A liquid is compressed instead of a vapor and as a result the work input is very small (on the order of one percent of the heat supplied to the generator) and often neglected in the cycle analysis.
- ARS are much more expensive than the vapor-compression refrigeration systems.
- They are more complex and occupy more space, they are much less efficient thus requiring much larger cooling towers to reject the waste heat, and they are more difficult to service since they are less common.

- Therefore, ARS should be considered only when the unit cost of thermal energy is low and is projected to remain low relative to electricity.

Comparison: Vapor compression and absorption systems

S. No.	Vapor Compression System	Vapor Absorption System
1.	This system has more wear and tear and produces more noise due to the moving parts of the compressor.	Only moving part in this system is an aqua pump. Hence the quieter in operation and less wear and tear
2.	Electric power is needed to drive the system	Waste, Low grade heat/Solar power can be used. No need of electric power
3.	COP is more	COP is less
4.	At partial loads performance is poor.	At partial loads performance is not affected.
5.	Mechanical energy is supplied through a compressor	Heat energy is utilized

Electrolux ammonia refrigerator

Front view
(1933 Model)

Rear view

Old advert of domestic Electrolux fridge (Introduced in 1925)

4. Related Laboratories

Conduct performance test on vapour absorption (Industrial chiller) refrigeration system and calculate the refrigerating effect, workdone and coefficient of performance.

5. Post Test:

1. Define: COP & Refrigerating effect
2. Explain the construction and working principle of aqua-NH_3 vapour absorption refrigeration system?
3. Explain the construction and working principle of Li-Br vapour absorption refrigeration system?
4. Write down the advantages and disadvantages of VAR system over VCR system?

5. Conclusions:

Vapour absorption refrigeration system

◉ Ideally fits into the concept of Integrated Energy Systems such as Cogeneration involving combined generation, heat, refrigeration and power (CHRP Plants) on various fuels like bio-mas, coal, Natural Gas, Heavy Oil, Solar, geothermal, etc.

◉ Excellent for waste heat utilization

◉ Earns carbon credits, reduces taxes, promotes sustainable development.

◉ Uses best eco-friendly refrigerant – ammonia

◉ Wide operational range + 5 ˚C to – 55 ˚C

◉ Low maintenance cost – no moving parts & an operate well for over 25 years.

6. References:

Arora.C.P, "Refrigeration and Air Conditioning ," Tata McGraw-Hill Publishers, 2008.

7. Demo Video https://www.youtube.com/watch?v=1p6dgGVnS2w

https://www.youtube.com/watch?v=qgf6vvksR54

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Name of the Course : **Applied Thermodynamics**

Name of the Unit : **Refrigeration**

Name of the Topic : **Ejector or Steam jet Refrigeration System**

1. Objectives: To understand the basics and as well as construction & working principle of ejector or steam jet Refrigeration system

Outcomes: Upon successful completion, the student should be able to understand the basics and working principle of ejector or steam jet Refrigeration system

2. Pre-Test: (Students should be able to answer the following)

1. State II law of thermodynamics-Clausius statement
2. State the difference between refrigerator and heat pump.
3. Explain with neat P-V and T-S diagram, about the theoretical cycle of refrigeration.

3. Pre-requisites: To have a basic knowledge of vapour compression refrigeration system & refrigeration cycle

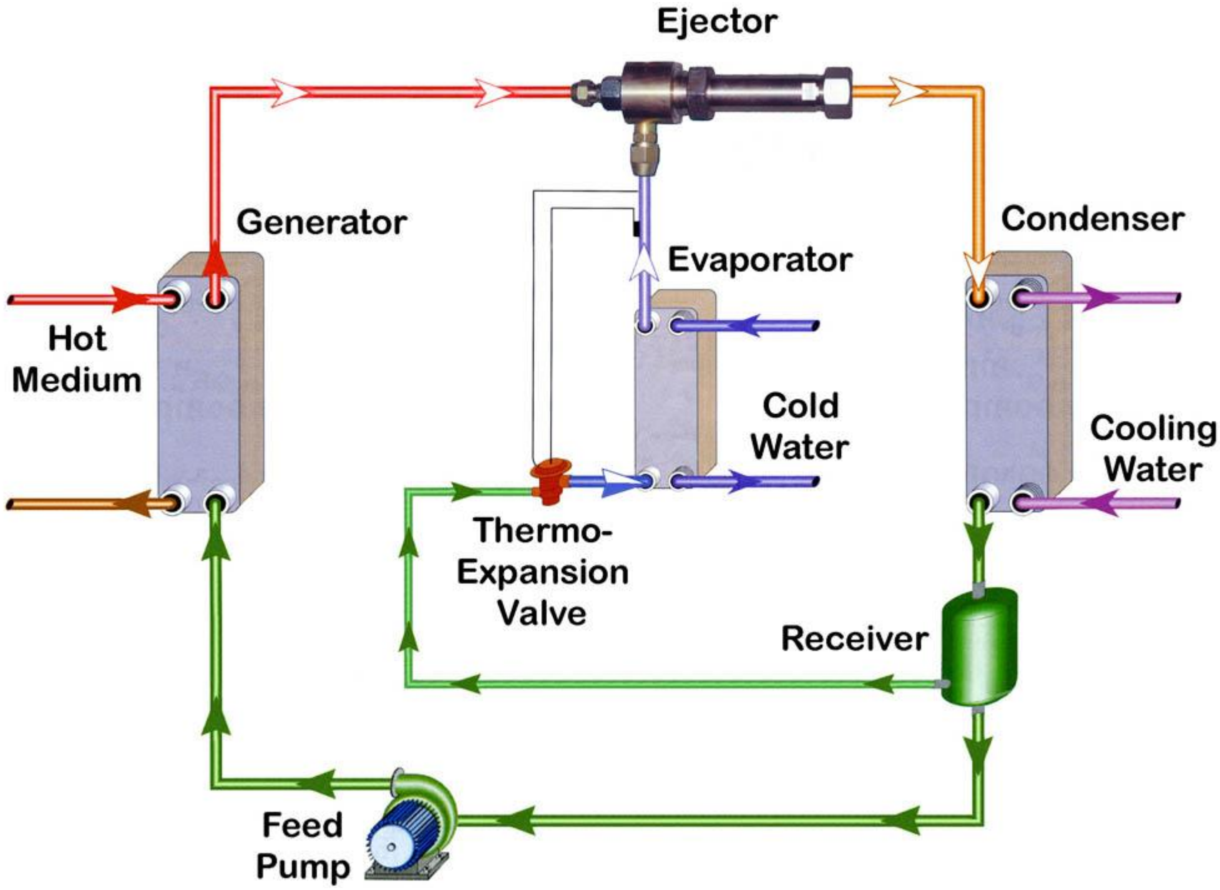
4. Theory Behind:

Introduction:

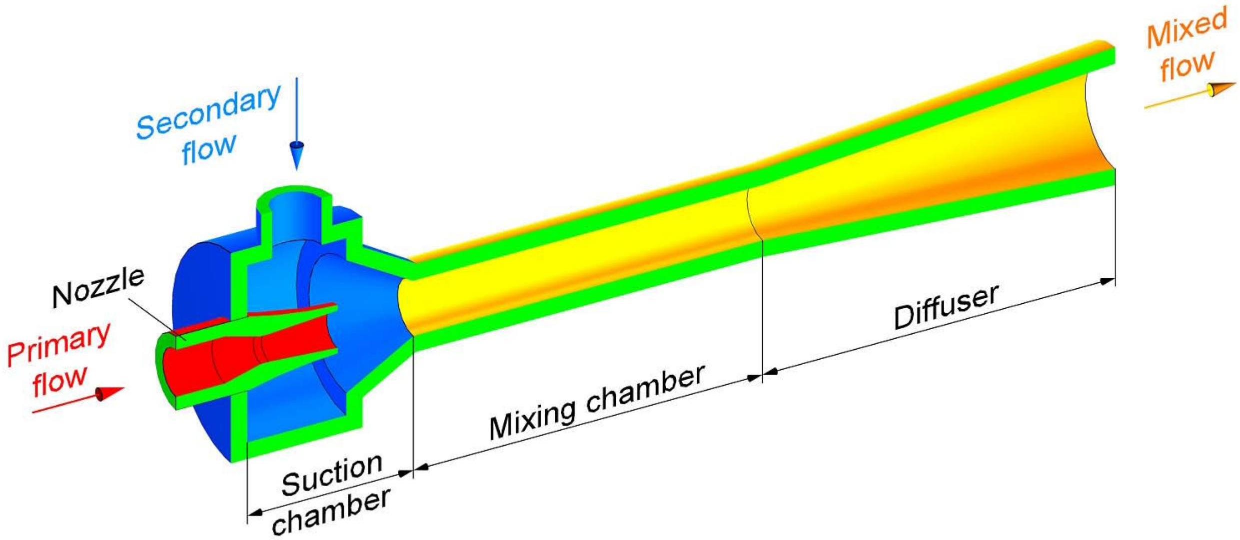
The earliest ejector refrigerators dating from the early 1900s used water as their working fluid. Because they have few moving parts ejector systems can be very reliable. In the early systems high temperature sources were needed to power them and the ejector used in some cases were physically large, with a scale similar to ejector used today in chemical plant. The need for physically large ejector in the past confined their application to air-conditioning large buildings and ships. Therefore, after their first wave of popularity in the 1930s, steam ejector refrigeration units were supplanted by more compact electricity powered vapour compression machines.

Many attempts have been made to make ejector refrigeration systems viable by using more suitable low-boiling (halocarbon compound) refrigerants. Although the ejector cycle, using halocarbon compounds have several important advantages over steam-jet refrigeration systems, most halocarbon refrigerants damage the ozone layer. Therefore, one important area of research at this time aims to find the most suitable environmentally friendly (preferably natural) low boiling refrigerants for ejector refrigeration machine in terms of thermal efficiency, economic viability and environmental safety.

The basic components of an ejector refrigeration machine include an ejector, a generator, an evaporator, a condenser, a thermo-expansion valve and a feed pump. The below Figure shows the arrangement of these components.



The working principles are as follows: Liquid refrigerant is heated in the generator by low-grade heat energy Q_g to produce vapour at relatively high pressure P_g. This vapour with a mass flow rate m_p accelerates through the primary convergent-divergent nozzle of the ejector so that at its exit it creates low-pressure region due to its supersonic velocity. This low pressure region causes vapour at low pressure P_e and with a mass flow rate m_s is drawn from the evaporator into the ejector. The primary and secondary fluids combine within the mixing section from where they undergo a pressure recovery process in the diffuser. The combined stream flows to the condenser where it condenses at an intermediate pressure P_c. The heat of condensation Q_c is rejected to the environment. Some of the condensate is pumped back to the generator via the feed-pump whilst the remainder returns to the evaporator via an expansion valve. The liquid that returns to the evaporator where it absorbs heat from a low temperature source to produce the necessary cooling effect Q_e by generating low pressure vapour, which flows to the ejector.



The ejector is the key component in the ejector refrigeration machine. Ejector is a jet compressor, using gas-dynamic compression effect, intended to suck the refrigerant vapor from the evaporator and then to compress it and to force up to the condenser. The ejector executes simultaneously the turbine and the compressor functions, but being much simpler in structure and having no moving parts.

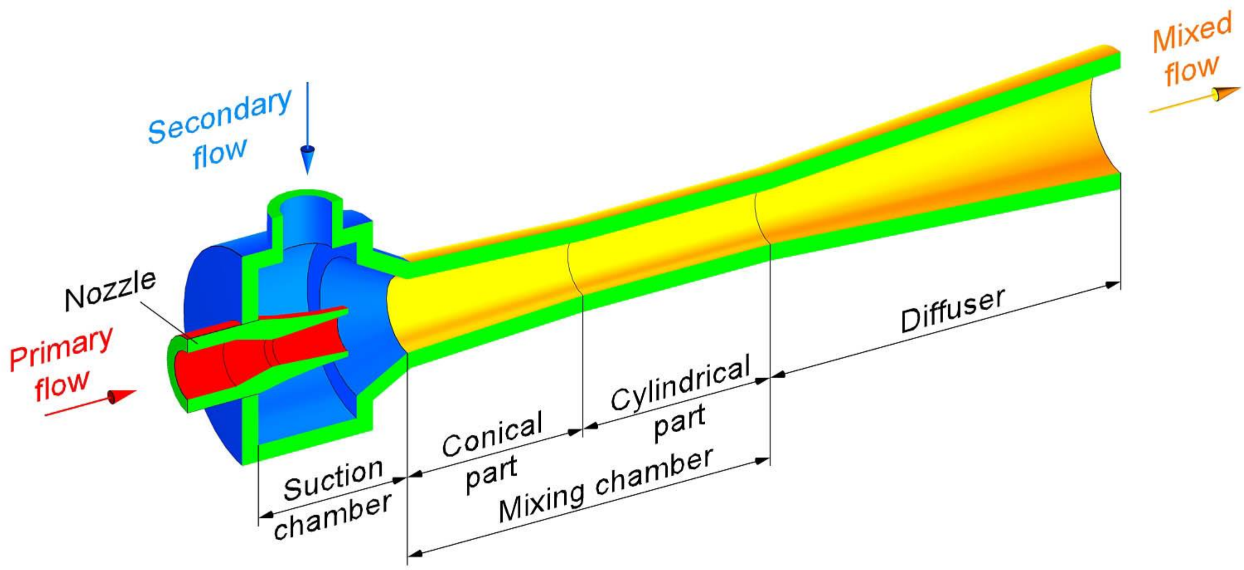


Figure shows classical structures of supersonic ejector: constant area ejector (a) and constant pressure ejector (b). The ejector assembly can be divided into four parts: a supersonic nozzle (de Laval nozzle), suction chamber for the secondary fluid flow, a constant area or constant pressure mixing chamber and a sub-sonic diffuser. Supersonic ejectors are simple mechanical device in which mechanical energy transfer from higher to lower level of two fluid streams to perform the thermal compression action within the jet-pump refrigeration system. The fluid with higher energy is the primary stream that flows through the primary nozzle to reach supersonic velocity at the nozzle exit. A secondary stream is drawn into the mixing chamber by an entrainment effect; it is accelerated to sonic velocity and then is mixed with the primary stream in the mixing chamber. The mixing process ended by a normal shock system at the end of mixing chamber, where the mixed stream pressure increases and velocity decreases to subsonic value. Within the diffuser more pressure is recovered to reach the condenser pressure.

Advantages:

a) It is flexible in operation; cooling capacity can be easily and quickly changed.

b) It has no moving parts as such it is vibration free.

c) It can be installed out of doors.

d) The weight of the system per ton of refrigerating capacity is less.

e) The system is very reliable and maintenance cost is less.

f) The system is particularly adapted to the processing of cold water used in rubber mills, distilleries, paper mills, food processing plants, etc.

g) This system is particularly used in air-conditioning installations, because of the complete safety of water as refrigerant and ability to adjust quickly to load variations and no hazard from the leakage of the refrigerant.

Disadvantages:

a) The use of direct evaporation to produce chilled water is usually limited as tremendous volume of vapor is to be handled.

b) About twice as much heat must be removed in the condenser of steam jet per ton of refrigeration compared with the vapor compression system.

c) The system is useful for comfort air-conditioning, but it is not practically feasible for water temperature below 4˚C.

5. Related Laboratories: ---

6. Post Test:

1. Define: COP & Refrigerating effect
2. Explain the construction and working principle of steam jet or ejector refrigeration system?
3. Write down the advantages and disadvantages of ejector system?

7. Conclusions:

Applications in the food sector Applications:

In the food sector will be primarily in areas where waste heat is available to drive the ejector system. Such applications can be found in food processing factories where the ejector refrigeration system can be used for product and process cooling and transport refrigeration. Other possible application is in tri-generation where the ejector refrigeration system can be used in conjunction with combined heat and power systems to provide cooling.

8. References:

Arora.C.P, ”Refrigeration and Air Conditioning ,” Tata McGraw-Hill Publishers, 2008.

9. Demo Video: https://www.youtube.com/watch?v=JB5JuO3pXuU

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Name of the Course : **Applied Thermodynamics**

Name of the Unit : **Air conditioning**

Name of the Topic : **Room or Window Air conditioner**

1. Objectives: To understand the basics and as well as construction & working principle of Room or window air conditioner.

Outcomes: Upon successful completion, the student should be able to understand the basics and working principle of Room or window air conditioner.

2. Pre-Test: (Students should be able to answer the following)

1. State the difference between sensible heat and latent heat.
2. State the difference between refrigerator and air conditioner.
3. Explain with various properties of psychrometry.

3. Pre-requisites: To have a basic knowledge of Psychrometry and Psychrometric properties of air.

4. Theory Behind:

Meaning of Air conditioning: Air conditioning refers to the treatment of air simultaneously controlling its temperature, moisture content, cleanliness, odour and circulation, as required by the occupants, process or products in the space. The subject of refrigeration and air conditioning has evolved out of the human need for food and comfort. There are two basic types of air conditioning systems as far as their functions are concerned.

(a) Comfort air conditioning system: The purpose of this system is to create atmospheric conditions conducive for human health, comfort, and efficiency. Air conditioning systems at homes, offices, stores, restaurants, theatre, hospitals, schools, and churches are of this type.

(b) Industrial air conditioning system: The purpose of this system is to control atmospheric conditions primarily for the proper conduct of research and manufacturing operations. The essential feature of comfort air conditioning system is to provide a comfortable environment for the occupants.

Factors Affecting Comfort Air Conditioning:

1. **Temperature of air:** In air conditioning, the control of temperature means maintenance of any desired temperature within an enclosed space, even though the temperature of the outside air is above or below the desired room temperature. This is accomplished either, by addition or removal of heat from the enclosed space as and when required. It may be noted that a human being feels comfortable when the air is at 21- 24 °C with 56% relative humidity.

2. **Humidity of air:** The control of humidity of air means decreasing or increasing the moisture content of air during summer or winter respectively in order to produce comfortable healthy conditions. The control of humidity is not only necessary for the human comfort but also increases the efficiency of the workers. In general, for summer air conditioning, the relative humidity should not be less than 60%, whereas for winter air conditioning it should not be less than 40%.

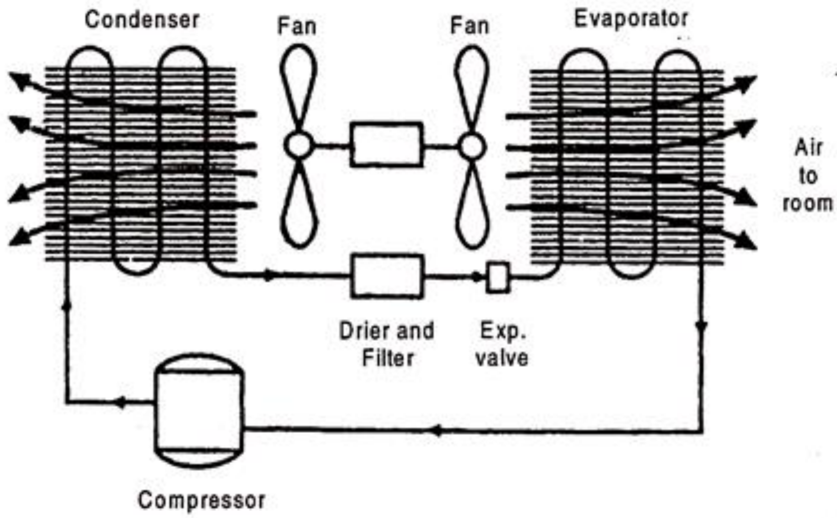
3. Purity of air: It is an important factor for the comfort of human body. It has been noticed that people do not feel comfortable on breathing contaminated air, even if it is within the acceptable temperature and humidity range. It is thus obvious that proper filtration, cleaning, and purification of air is essential to keep it free from dust and other impurities.

4. Motion of air: The motion or circulation of air should be controlled, in order to maintain constant temperature throughout the conditioned space. Hence, there should be equi-distribution of air throughout the space to be air conditioned.

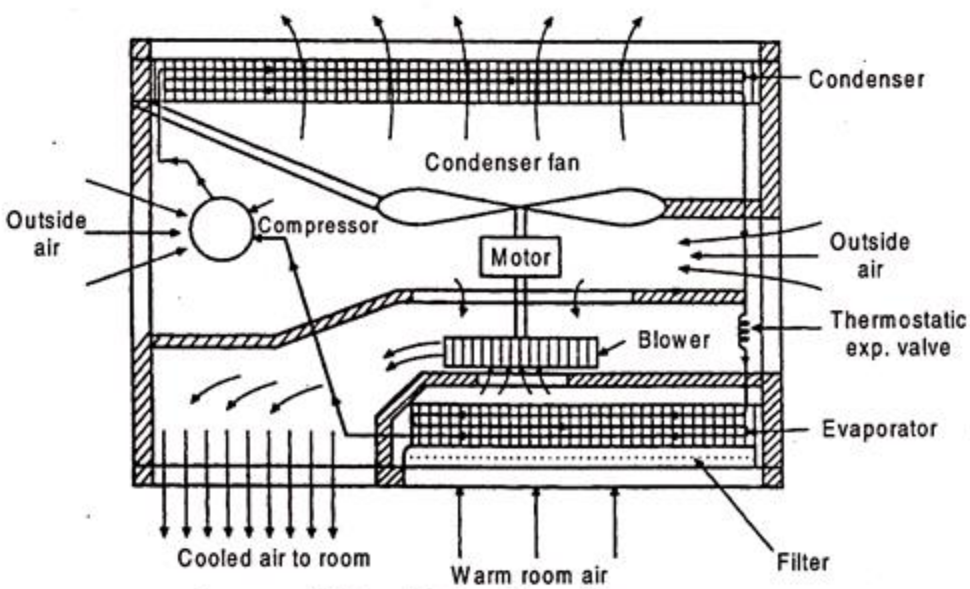
Room Air Conditioner (Window Air Conditioner):

A room air conditioner is an encased assembly designed as a unit primarily for mounting in a window or through a wall. These units are made to deliver cool or warm conditioned air to the room, generally without ducts. This unit includes the main source of refrigeration, dehumidification and means of circulating and cleaning air and also may include means of heating. The basic function of any air conditioning plant is to provide comfort by cooling or heating, dehumidifying or humidifying, filtering or cleaning and recirculating the space air. All these functions are present in a room air conditioner or window air conditioner. It may provide ventilation by introducing outside air into the room and/or exhausting the room air to the outside. Room temperature can be controlled by providing a thermostatic setting in the window air conditioner. The conditioner may provide heating by heat pump operation, electric resistance elements or by a combination of both.

Figure (a) shows the schematic diagram of a typical room air conditioner or window air conditioner. Working or operation of this air conditioner is illustrated in Fig. (b).



(a) Schematic diagram of refrigeration unit for room air conditioner



(b) Room/window air conditioner

Warm room air (for recirculation) passes over the cooling or evaporator coil and in the process, gives up its sensible and latent heat also (in case of dehumidification is required). This conditioned air along with the fresh air (ventilation air) is then re-circulated in the room by a fan or blower. The heat from the warm air-vaporises the cold liquid refrigerant flowing through the evaporator. The vapour then carries heat to the compressor, which compresses the vapour and increase its temperature to a value higher than temperature of the outdoor air. In the condenser, the hot refrigerant vapour liquefies and gives up the heat from the room air to the outdoor air. The high-pressure liquid refrigerant then passes through a restrictor—thermostatic expansion valve or capillary tube—which reduces its pressure and temperature. The cold and low-pressure liquid refrigerant then re-enters the evaporator to repeat this refrigeration cycle. The cooling capacities or commercially available window conditioners range from 0.75 to 10 kW. Most room air conditioners are designed for bringing in outside air, exhausting room air or both. Controls usually permit these features to function independently.

Shortly,

(a) Temperature is controlled by an adjustable built-in thermostat.

(b) One control operates the unit electrically.

(c) Additional knobs or levers operate louvers, deflectors, ventilation system, etc.

(d) Some air conditioners are of slide-out chassis design or integral chassis design.

(e) Filter replacement is the essential service requirement.

(f) Sound level, particularly in bed-room, is to be minimised.

Lastly, the room unit serves a definite need; spot cooling at a minimum installed cost and mobility of location, both of which preclude the consideration of central system cooling units.

5. Related Laboratories: Conduct performance test on room air conditioner test set up and calculate the refrigerating effect, workdone and coefficient of performance.

6. Post Test:

1. State the difference between room and central A/C system?
2. Explain the construction and working principle of room air conditioner system?
3. Write down the advantages and disadvantages of room air conditioner?

7. Conclusions:

Benefits of Using a Window Air Conditioner:

- Low Cost. The first major advantage that window air conditioners have is their low and affordable cost.

- Extremely Energy Efficient.
- Easy to Install.
- Doesn't Take Up Floor Space.
- Great for Supplemental Cooling.
- Multi-Functional for Year-Round Use.
- Portable
- Can Be Used in Many Places.

8. Reference:

Arora.C.P, ”Refrigeration and Air Conditioning ,” Tata McGraw-Hill Publishers, 2008.

9. Demo Video: https://www.youtube.com/watch?v=IRuuF3xZTwM

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Name of the Course : **Applied Thermodynamics**

Name of the Unit : **Air conditioning**

Name of the Topic : **Centralized Air conditioner**

1. Objectives: To understand the basics and as well as construction & working principle of Centralized air conditioner.

Outcomes: Upon successful completion, the student should be able to understand the basics and working principle of Centralized air conditioner.

2. Pre-Test: (Students should be able to answer the following)

1. State the difference between sensible heat and latent heat.
2. State the difference between refrigerator and air conditioner.
3. Explain with various properties of psychrometry.

3. Pre-requisites: To have a basic knowledge of Psychrometry and Psychrometric properties of air.

4. Theory Behind:

Meaning of Air conditioning: Air conditioning refers to the treatment of air simultaneously controlling its temperature, moisture content, cleanliness, odour and circulation, as required by the occupants, process or products in the space. The subject of refrigeration and air conditioning has evolved out of the human need for food and comfort.

There are two basic types of air conditioning systems as far as their functions are concerned.

(a) Comfort air conditioning system: The purpose of this system is to create atmospheric conditions conducive for human health, comfort, and efficiency. Air conditioning systems at homes, offices, stores, restaurants, theatre, hospitals, schools, and churches are of this type.

(b) Industrial air conditioning system: The purpose of this system is to control atmospheric conditions primarily for the proper conduct of research and manufacturing operations. The essential feature of comfort air conditioning system is to provide a comfortable environment for the occupants.

Factors Affecting Comfort Air Conditioning:

1. **Temperature of air:** In air conditioning, the control of temperature means maintenance of any desired temperature within an enclosed space, even though the temperature of the outside air is above or below the desired room temperature. This is accomplished either, by addition or removal of heat from the enclosed space as and when required. It may be noted that a human being feels comfortable when the air is at 21- 24 °C with 56% relative humidity.

2. **Humidity of air:** The control of humidity of air means decreasing or increasing the moisture content of air during summer or winter respectively in order to produce comfortable healthy conditions. The control of humidity is not only necessary for the human comfort but also increases the efficiency of the workers. In general, for summer air conditioning, the relative humidity should not be less than 60%, whereas for winter air conditioning it should not be less than 40%.

3. Purity of air: It is an important factor for the comfort of human body. It has been noticed that people do not feel comfortable on breathing contaminated air, even if it is within the acceptable temperature and humidity range. It is thus obvious that proper filtration, cleaning, and purification of air is essential to keep it free from dust and other impurities.

4. Motion of air: The motion or circulation of air should be controlled, in order to maintain constant temperature throughout the conditioned space. Hence, there should be equi-distribution of air throughout the space to be air conditioned.

Central Air Conditioning System:

The name central station system or equipment is also commonly called as applied system or applied machinery. Central station equipment is associated with installations where the cooling plant is located in the basement or in a penthouse on the roof of multistorey buildings.

It serves air handling equipment and air distribution systems throughout the building. Although size is not necessarily the crossover point between unitary and central station, it is usually acknowledged that central station equipment starts at 25 to 50 tonnes and extends upward to the multi-thousand- tonne systems.

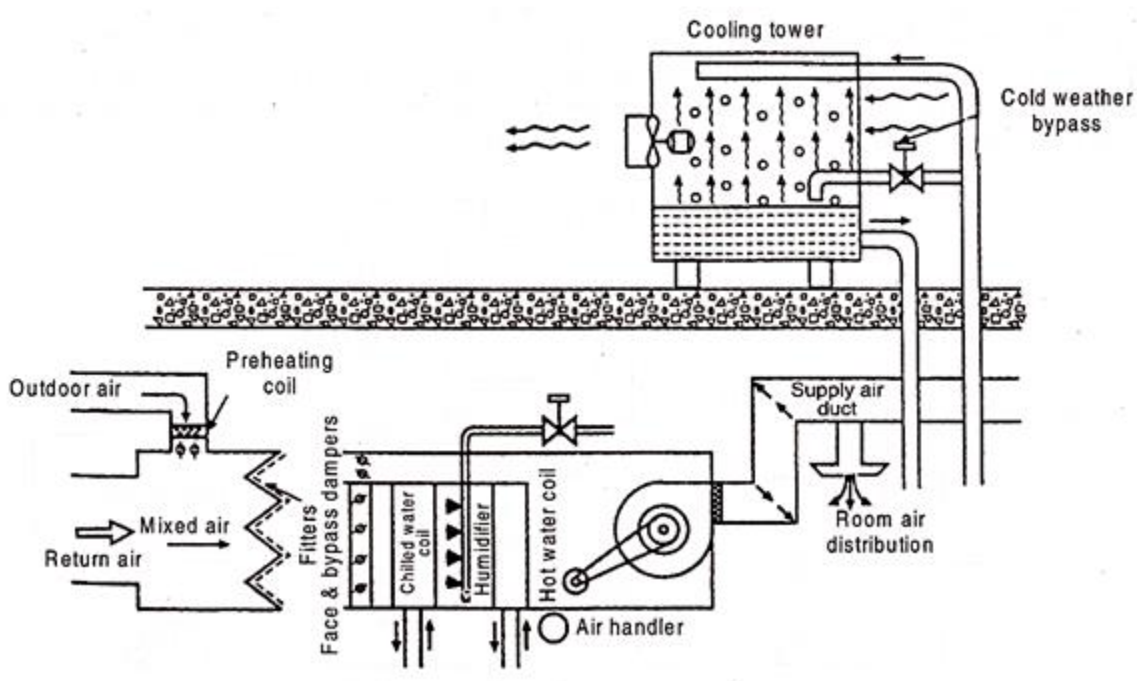
Another distinguishing difference is that central station systems use the medium of liquid—mostly water— to transfer heating and cooling to a space air terminal, while unitary systems are based on distributing conditioned air directly to the conditioned space. Unitary equipment makes use of factory packaged, balanced and tested equipment which requires a minimum of onsite labour and. material to be operational. Central station systems are made up of separate components such as chillers, air-handlers, water towers, controls, etc. which can become quite complex in terms of on-site installations and labour and related trades and crafts. Central station equipment is closely associated with the plan put on by engineering firms. Equipment is then selected and/or built in order to compliance with these specifications.

Conventional Central Station System:

Conventional Central Station System is shown in Fig.

The major components are:

1. Water chiller
2. Boiler
3. Air handling unit
4. Water cooling tower
5. Control system



The water chiller will produce 4°C – 7°C cold water, and by means of a pump, circulate it to the cold-water coil in the air handler. Water off the coil will generally return at a 6°C rise. Similarly, in winter, the boiler will produce hot water at 80°C to 90°C and pump it to the hot water coil. Note that it is possible to have the boiler and chiller operating at the same time, because in large buildings, there may be need for cooling and heating in different zones. Condenser water off the chiller (36 – 37°C) is pumped to cooling tower spray nozzles where it is cooled within the tower to around 30°C and then is returned to the condenser.

The air handling unit or units, depending on the number of floors or zones, generally contain:

(a) Chilled water coils

(b) Main hot water coils (can be steam)

(c) Humidifier

(d) Filters

(e) Dampers for mixing return air and outside air

(f) Blower and motor.

A pre-heat coil is frequently required where large amounts of outside air at or below 0°C are needed. The face and by-pass dampers either permit all the air to go through the humidifiers and the heating and cooling coils or allow some of it to be by-passed, depending on the particular situation. All air to be conditioned is always filtered and cleaned.

Water Chilling Equipment may be:

1. Packaged chillers – Lower capacity.
2. Centrifugal chillers (Hermetic) – Very large capacities upto 1300 tonnes.
3. Screw compressor chillers.
4. Absorption chillers.

Cooling coils in central air conditioning station may use either chilled water circulating through the coils or there may be chilled water evaporators (chilled water sprays) or air-washers. In this case, chilled water works as a secondary refrigerant.

DX System (Direct Expansion) for Central Air Conditioning Plant:

The process of heat removal from the substance to be cooled or refrigerated is done in the evaporator. The liquid refrigerant is vapourised inside the evaporator (coil and shell) in order to remove heat from a fluid such as air, water or brine. The fluid to be cooled can be made to pass over the evaporator surface inside which the refrigerant is boiling, such a system is called the Direct Expansion System (DX System).

In certain cases, such as in large air conditioning systems or in industrial processing, water or brine is chilled in the evaporator and the chilled fluid is circulated through copper or steel coils over which the air is passed. Such a system is called the indirect system. The coil, generally called cooling coil, acts as heat exchangers.

In cases, where condensing unit and evaporator are comparatively near to each other. Direct expansion (DX) system can be used.

5. Related Laboratories: ---

6. Post Test:

1. State the difference between room and central A/C system?
2. Explain the construction and working principle of centralized air conditioner system?
3. Write down the advantages and disadvantages of centralized air conditioner?

7. Conclusions: Using air-conditioner is common in food cooking and processing areas. Used in hospital operating theatres to provide comfortable conditions to patients. And many more industries like Textile, Printing, Photographic and much more. Air-conditioning system used as the commercial purpose for a human being. Example, in Theatres, Departmental store-room, etc. Many transport vehicles use air-conditioning systems such as cars, trains, aircraft, ships, etc. This provides a comfortable condition for the passengers. The air-conditioning system used in Television-centre. Computer centers, and museums for a special purpose.

8. Reference:

Arora.C.P, "Refrigeration and Air Conditioning ," Tata McGraw-Hill Publishers, 2008.

9. Demo Video: https://www.youtube.com/watch?v=OvYIyQ_whXE

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Name of the Course	:	**Applied Thermodynamics**
Name of the Unit	:	**Air conditioning**
Name of the Topic	:	**Winter Air conditioning System**

1. Objectives: To understand the basics and as well as construction & working principle of Winter air conditioning system.

Outcomes: Upon successful completion, the student should be able to understand the basics and working principle of Winter air conditioning system.

2. Pre-Test: (Students should be able to answer the following)

1. State the difference between sensible heat and latent heat.
2. State the difference between refrigerator and air conditioner.
3. Explain with various properties of psychrometry.

3. Pre-requisites: To have a basic knowledge of Psychrometry and Psychrometric properties of air.

4. Theory Behind:

Meaning of Air conditioning: Air conditioning refers to the treatment of air simultaneously controlling its temperature, moisture content, cleanliness, odour and circulation, as required by the occupants, process or products in the space. The subject of refrigeration and air conditioning has evolved out of the human need for food and comfort.

There are two basic types of air conditioning systems as far as their functions are concerned.

(a) Comfort air conditioning system: The purpose of this system is to create atmospheric conditions conducive for human health, comfort, and efficiency. Air conditioning systems at homes, offices, stores, restaurants, theatre, hospitals, schools, and churches are of this type.

(b) Industrial air conditioning system: The purpose of this system is to control atmospheric conditions primarily for the proper conduct of research and manufacturing operations. The essential feature of comfort air conditioning system is to provide a comfortable environment for the occupants.

Factors Affecting Comfort Air Conditioning:

1. **Temperature of air:** In air conditioning, the control of temperature means maintenance of any desired temperature within an enclosed space, even though the temperature of the outside air is above or below the desired room temperature. This is accomplished either, by addition or removal of heat from the enclosed space as and when required. It may be noted that a human being feels comfortable when the air is at 21- 24 °C with 56% relative humidity.

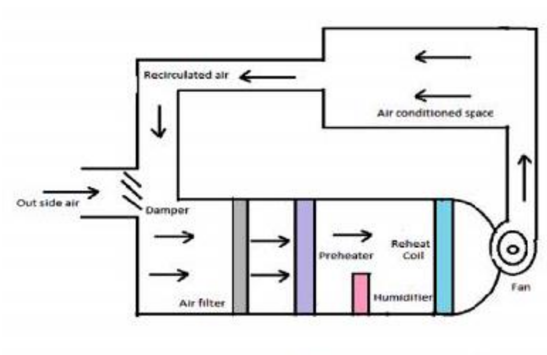
2. **Humidity of air:** The control of humidity of air means decreasing or increasing the moisture content of air during summer or winter respectively in order to produce comfortable healthy conditions. The control of humidity is not only necessary for the human comfort but also increases the efficiency of the workers. In general, for summer air conditioning, the relative humidity should not be less than 60%, whereas for winter air conditioning it should not be less than 40%.

3**. Purity of air:** It is an important factor for the comfort of human body. It has been noticed that people do not feel comfortable on breathing contaminated air, even if it is within the acceptable temperature and humidity range. It is thus obvious that proper filtration, cleaning, and purification of air is essential to keep it free from dust and other impurities.

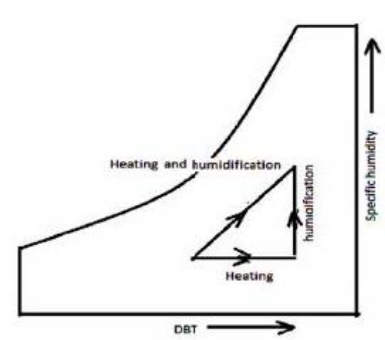
4. **Motion of air:** The motion or circulation of air should be controlled, in order to maintain constant temperature throughout the conditioned space. Hence, there should be equi-distribution of air throughout the space to be air conditioned.

Winter air conditioning system

It is the most important type of air conditioning, in which the air is heated and humidified. The schematic arrangement of a typical winter air conditioning system is as shown in the figure. The outside air flows through the damper, and mixes up with re-circulated air (which is obtained from the conditioned space). The mixed air passes through a filter to remove the dirt, dust and other impurities. The air now passes through a pre-heat coil. The outside air flows through the damper, and mixes up with re-circulated air which is obtained from the conditioned space. After that, the air is made to pass through a reheat coil to bring the air to the designed dry bulb temperature. Now the conditioned air is supplied to the conditioned space by a fan. From the conditioned space, a part of the used air is exhausted to the atmosphere by the exhaust fans or ventilators. The remaining part of the used air (known as re-circulated air) is again conditioned. The psychrometric process involved in winter air conditioning system is heating and humidification and the psychrometric chart represented by winter air-conditioning system is as follows



Winter Air Conditioning System



Winter a c system - psychrometric processes

5. Related Laboratories: ---

6. Post Test:

1. State the difference between room and central A/C system?
2. Explain the construction and working principle of winter air conditioner system?
3. Write down the advantages and disadvantages of winter air conditioner?

7. Conclusions: Winter air conditioning systems is mainly use to convert cold air into hot air. They are used to maintain warmness temperature in the room during winter season. They are especially suited to that region where there is winter season throughout the year.

8. References:

Arora.C.P, "Refrigeration and Air Conditioning ," Tata McGraw-Hill Publishers, 2008.

9. Demo Video: https://www.youtube.com/watch?v=OvYIyQ_whXE

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Name of the Course : **Applied Thermodynamics**

Name of the Unit : **Air conditioning**

Name of the Topic : **Summer Air conditioning System**

1. Objectives: To understand the basics and as well as construction & working principle of Summer air conditioning system.

Outcomes: Upon successful completion, the student should be able to understand the basics and working principle of Summer air conditioning system.

2. Pre-Test: (Students should be able to answer the following)

1. State the difference between sensible heat and latent heat.
2. State the difference between refrigerator and air conditioner.
3. Explain with various properties of psychrometry.

3. Pre-requisites: To have a basic knowledge of Psychrometry and Psychrometric properties of air.

4. Theory Behind:

Meaning of Air conditioning: Air conditioning refers to the treatment of air simultaneously controlling its temperature, moisture content, cleanliness, odour and circulation, as required by the occupants, process or products in the space. The subject of refrigeration and air conditioning has evolved out of the human need for food and comfort.

There are two basic types of air conditioning systems as far as their functions are concerned.

(a) Comfort air conditioning system: The purpose of this system is to create atmospheric conditions conducive for human health, comfort, and efficiency. Air conditioning systems at homes, offices, stores, restaurants, theatre, hospitals, schools, and churches are of this type.

(b) Industrial air conditioning system: The purpose of this system is to control atmospheric conditions primarily for the proper conduct of research and manufacturing operations. The essential feature of comfort air conditioning system is to provide a comfortable environment for the occupants.

Factors Affecting Comfort Air Conditioning:

1. **Temperature of air:** In air conditioning, the control of temperature means maintenance of any desired temperature within an enclosed space, even though the temperature of the outside air is above or below the desired room temperature. This is accomplished either, by addition or removal of heat from the enclosed space as and when required. It may be noted that a human being feels comfortable when the air is at 21- 24 °C with 56% relative humidity.

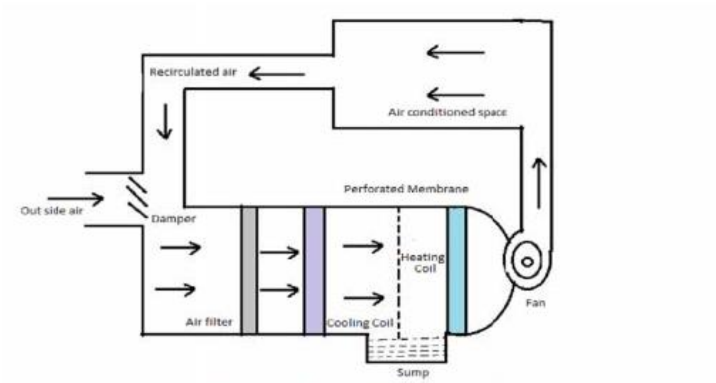
2. **Humidity of air:** The control of humidity of air means decreasing or increasing the moisture content of air during summer or winter respectively in order to produce comfortable healthy conditions. The control of humidity is not only necessary for the human comfort but also increases the efficiency of the workers. In general, for summer air conditioning, the relative humidity should not be less than 60%, whereas for winter air conditioning it should not be less than 40%.

3. Purity of air: It is an important factor for the comfort of human body. It has been noticed that people do not feel comfortable on breathing contaminated air, even if it is within the acceptable temperature and humidity range. It is thus obvious that proper filtration, cleaning, and purification of air is essential to keep it free from dust and other impurities.

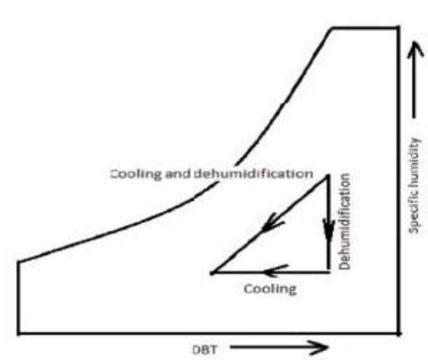
4. Motion of air: The motion or circulation of air should be controlled, in order to maintain constant temperature throughout the conditioned space. Hence, there should be equi-distribution of air throughout the space to be air conditioned.

Summer air conditioning system

It is the most important type of air-conditioning, in which the air is cooled and dehumidified. The schematic arrangement of a typical summer air conditioning system shown in the figure. The outside air flows through the damper, and mixes up with re-circulated air (which is obtained from the conditioned space). The mixed air passes through a filter to remove the dirt, dust and other impurities. The air now passes through a cooling coil. The coil has a temperature much below the required dry bulb temperature of the air in the conditioned space. The cooled air passes through a perforated membrane and loses its moisture in the condensed form which is collected in a sump. After that, the air is made to pass through a heating coil which heats up the air slightly. This is done to bring the air to the designed dry bulb temperature and relative humidity. Now the conditioned air is supplied to the conditioned space by a fan. From the conditioned space, a part of the used air is exhausted to the atmosphere by the exhaust fans or ventilators. The remaining part of the used air (known as re-circulated air) is again conditioned. The psychrometric process involved in summer air conditioning system is cooling and dehumidification and psychrometric chart represented by summer air-conditioning system is as follows.



Summer Air conditioning System



Summer a c system - psychrometric processes

5. Related Laboratories: ---

6. Post Test:

1. State the difference between room and central A/C system?
2. Explain the construction and working principle of summer air conditioner system?
3. Write down the advantages and disadvantages of summer air conditioner?

7. **Conclusions:** In most of the places the summer season is hot and humid. Hence, in order to provide comfortable conditions to the occupants during summer, it is required to supply cold and dry air to the occupied space. This requires systems wherein the hot and humid air can be cooled to temperatures lower than the dew point temperature, so that the water vapour in air can be removed by condensation, and the resulting cold and dehumidified air supplied to the conditioned space in required quantity for providing

thermal comfort. Thus, it can be seen that a typical summer air conditioning system requires a refrigeration system that reduces the temperature of the air to temperatures much lower than the surroundings. Of course, in some areas such as deserts, the summer is hot and dry. Air conditioning systems for these hot and dry climates also require cooling of air below the ambient temperatures, however, instead of removing water vapour it may be required to add water to the air supplied to the conditioned space.

8. **Reference:** Arora.C.P, "Refrigeration and Air Conditioning ,"Tata McGraw-Hill Publishers, 2008.
9. **Demo Video**: https://www.youtube.com/watch?v=1KdQtWyvKpE

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Name of the Course	:	**Applied Thermodynamics**
Name of the Unit	:	**Air conditioning**
Name of the Topic	:	**Year-Round Air conditioning System**

1. Objectives: To understand the basics and as well as construction & working principle of Year-round air conditioning system.

Outcomes: Upon successful completion, the student should be able to understand the basics and working principle of Year-round air conditioning system.

2. Pre-Test: (Students should be able to answer the following)

1. State the difference between sensible heat and latent heat.
2. State the difference between refrigerator and air conditioner.
3. Explain with various properties of psychrometry.

3. Pre-requisites: To have a basic knowledge of Psychrometry and Psychrometric properties of air.

4. Theory Behind:

Meaning of Air conditioning: Air conditioning refers to the treatment of air simultaneously controlling its temperature, moisture content, cleanliness, odour and circulation, as required by the occupants, process or products in the space. The subject of refrigeration and air conditioning has evolved out of the human need for food and comfort.

There are two basic types of air conditioning systems as far as their functions are concerned.

(a) Comfort air conditioning system: The purpose of this system is to create atmospheric conditions conducive for human health, comfort, and efficiency. Air conditioning systems at homes, offices, stores, restaurants, theatre, hospitals, schools, and churches are of this type.

(b) Industrial air conditioning system: The purpose of this system is to control atmospheric conditions primarily for the proper conduct of research and manufacturing operations. The essential feature of comfort air conditioning system is to provide a comfortable environment for the occupants.

Factors Affecting Comfort Air Conditioning:

1. **Temperature of air:** In air conditioning, the control of temperature means maintenance of any desired temperature within an enclosed space, even though the temperature of the outside air is above or below the desired room temperature. This is accomplished either, by addition or removal of heat from the enclosed space as and when required. It may be noted that a human being feels comfortable when the air is at 21- 24 °C with 56% relative humidity.

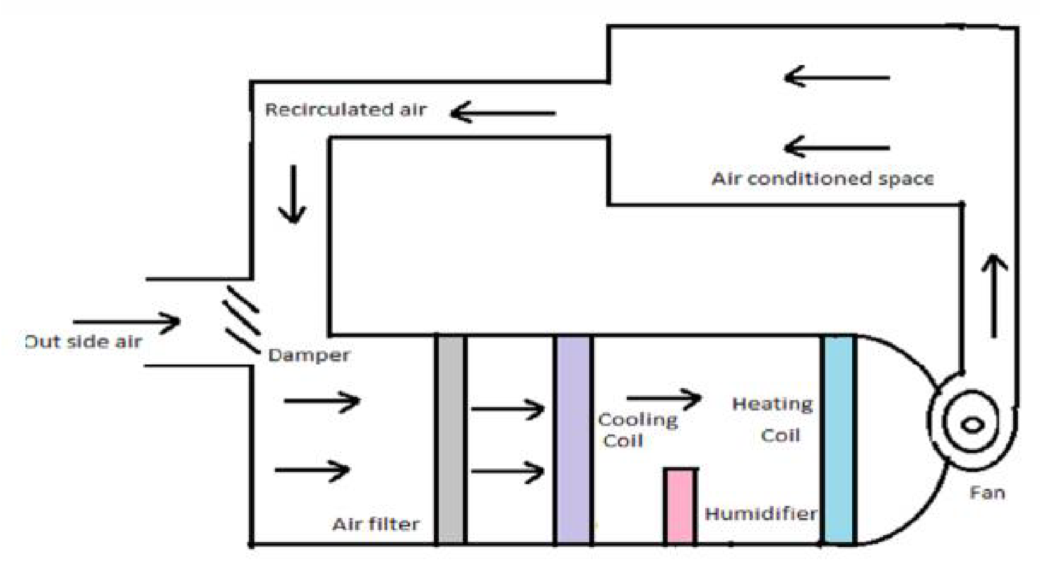
2. **Humidity of air:** The control of humidity of air means decreasing or increasing the moisture content of air during summer or winter respectively in order to produce comfortable healthy conditions. The control of humidity is not only necessary for the human comfort but also increases the efficiency of the workers. In general, for summer air conditioning, the relative humidity should not be less than 60%, whereas for winter air conditioning it should not be less than 40%.

3. Purity of air: It is an important factor for the comfort of human body. It has been noticed that people do not feel comfortable on breathing contaminated air, even if it is within the acceptable temperature and humidity range. It is thus obvious that proper filtration, cleaning, and purification of air is essential to keep it free from dust and other impurities.

4. Motion of air: The motion or circulation of air should be controlled, in order to maintain constant temperature throughout the conditioned space. Hence, there should be equi-distribution of air throughout the space to be air conditioned.

Year -Round air conditioning system

The year-round air conditioning system should have equipment for both the summer and winter air conditioning. The schematic arrangement of a modern year-round air-conditioning system is shown in the figure. The outside air flows through the damper, and mixes up with re-circulated air (which is obtained from the conditioned space). The mixed air passes through a filter to remove the dirt, dust and other impurities. In summer air conditioning, the cooling coil operates to cool the air to the desired value. The dehumidification is obtained by operating the cooling coil at a temperature lower than the dew point temperature. In winter, the cooling coil is made inoperative and the heating coil operates to heat the air. The spray type humidifier is also made use of in the dry season to humidify the air.



Year Round Air Conditioning System

5. Related Laboratories: ---

6. Post Test:

1. State the difference between room and central A/C system?
2. Explain the construction and working principle of Year-round air conditioner system?
3. Write down the advantages and disadvantages of Year-round air conditioner?

7. Conclusions: Year-round air conditioner is suitable for both summer and winter climatic conditions.

8. Reference:

Arora.C.P, "Refrigeration and Air Conditioning ,"Tata McGraw-Hill Publishers, 2008.

9. Demo Video: https://www.youtube.com/watch?v=1KdQtWyvKpE

Name of the Course : **Applied Thermodynamics**

Name of the Unit : **Air compressor**

Name of the Topic : **Single acting Single stage Reciprocating Air Compressor**

1. Objectives: To understand the basics and as well as construction & working principle of single acting single stage reciprocating air compressor.

Outcomes: Upon successful completion, the student should be able to understand the basics and working principle of single acting single stage reciprocating air compressor.

2. Pre-Test: (Students should be able to answer the following)

1. State the application of air compressor & compressed air.
2. State the difference between various thermodynamic compression process.

3. Pre-requisites: To have a basic knowledge of thermodynamic compression process.

4. Theory Behind:

INTRODUCTION

Compressors are work absorbing devices which are used for increasing pressure of fluid at the expense or work done on fluid. The compressors used for compressing air are called air compressors. Compressors are invariably used for all applications requiring high pressure air. Some of popular applications of compressor are, for driving pneumatic tools and air operated equipments, spray painting, compressed air engine, supercharging surface cleaning, refrigeration and air conditioning, chemical industry etc. compressors are supplied with low pressure air (or any fluid) at inlet which comes out as high-pressure air (or any fluid) at outlet. Work required for increasing pressure of air is available from the prime mover driving the compressor. Generally, electric motor, internal combustion engine or steam engine, turbine etc. are used as prime movers. Compressors are similar to fans and blowers but differ in terms of pressure ratios. Fan is said to have pressure ratio up to 1.1 and blowers have pressure ratio between 1.1 to 4 while compressors have pressure ratios more than 4.

Compressors can be classified in the following different ways.

(a) **Based on principle of operation:** Based on the principle of operation compressors can be classified as.

(i) Positive displacement compressor.

(ii) Non-positive displacement compressors.

In positive displacement compressors the compression is realized by displacement of solid boundary and preventing fluid by solid boundary from flowing back in the direction of pressure gradient. Due to solid wall displacement these are capable of providing quite large pressure ratios. Positive displacement compressors can be further classified based on the type of mechanism used for compression. These can be

(i) Reciprocating type positive displacement compressors

(ii) Rotary type positive displacement compressors.

Reciprocating compressors generally, employ piston-cylinder arrangement where displacement of piston in cylinder causes rise in pressure. Reciprocating compressors are capable of giving large pressure ratios but the mass handling capacity is limited or small. Reciprocating compressors may also be single acting compressor or double acting compressor. Single acting compressor has one delivery stroke per revolution while in double acting there are two delivery strokes per revolution of crank shaft. Rotary compressors employing positive displacement have a rotary part whose boundary causes positive displacement of fluid and thereby compression. Rotary compressors of this type are available in the names as given below;

(i) Roots blower

(ii) Vane type compressors

Rotary compressors of above type are capable of running at higher speed and can handle large mass flow rate than reciprocating compressors of positive displacement type.

Non-positive displacement compressors, also called as steady flow compressors use dynamic action of solid boundary for realizing pressure rise. Here fluid is not contained in definite volume and subsequent volume reduction does not occur as in case of positive displacement compressors. Non-positive displacement compressor may be of ‘axial flow type’ or centrifugal type’ depending upon type of flow in compressor.

(b) **Based on number of stages:** Compressors may also be classified on the basis of number of stages. Generally, the number of stages depend upon the maximum delivery pressure. Compressors can be single stage or multistage. Normally maximum compression ratio of 5 is realized in single stage compressors. For compression ratio more than 5 the multistage compressors are used. Type values of maximum delivery pressures generally available from different type of compressor are,

(i) Single stage Compressor, for delivery pressure upto 5 bar.

(ii) Two stage Compressor, for delivery pressure between 5 to 35 bar

(iii) Three stage Compressor, for delivery pressure between 35 to 85 bar.

(iv) Four stage compressor, for delivery pressure more than 85 bar

(c) **Based on Capacity of compressors:** Compressors can also be classified depending upon the capacity of Compressor or air delivered per unit time. Typical values of capacity for different compressors are given as;

(i) Low capacity compressors, having air delivery capacity of 0.15 m^3/s or less

(ii) Medium capacity compressors, having air delivery capacity between 0.15 to 5 m^3/s.

(iii) High capacity compressors, having air delivery capacity more than 5 m^3/s

(d) Based on highest pressure developed: Depending upon the maximum pressure available from compressor they can be classified as low pressure, medium pressure, high pressure and super high-pressure compressors. Typical values of maximum pressure developed for different compressors are as under:

(i) Low pressure compressor, having maximum pressure upto 1 bar

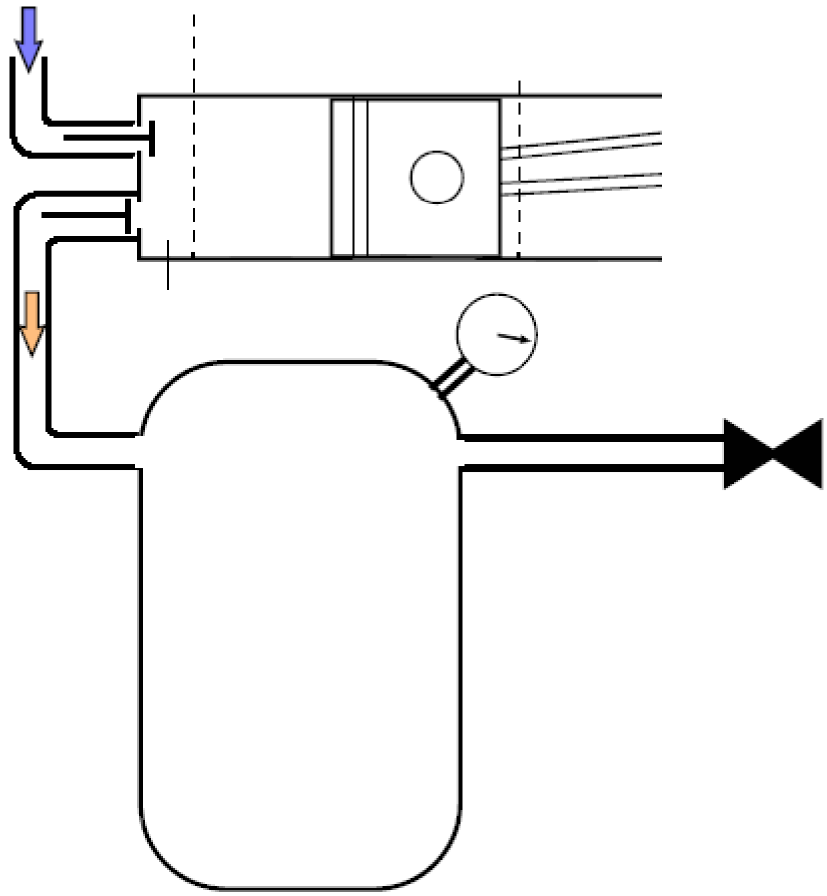
(ii) Medium pressure compressor, having maximum pressure from 1 bar to 8 bar

(iii) High pressure compressor, having maximum pressure from 8 to 10 bar

(iv) Super high-pressure compressor, having maximum pressure more than 10 bar.

Reciprocating Compressors

Reciprocating Compressor has piston cylinder arrangement as shown Fig.



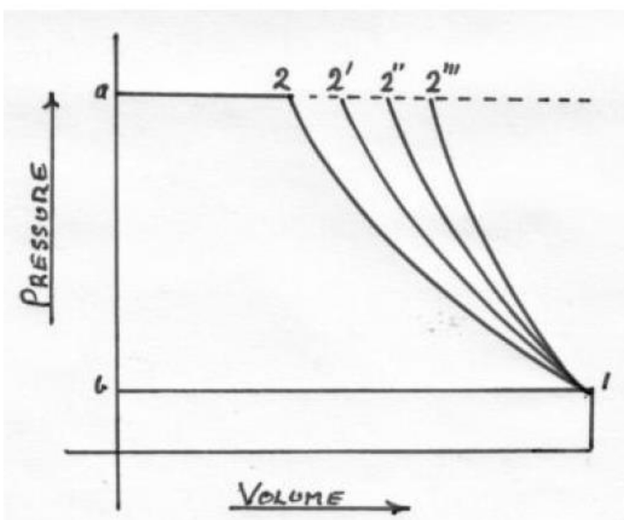
Single stage reciprocating air compressor:

Reciprocating Compressor has piston, cylinder, inlet valve, exit valve, connecting rod, crank, piston pin, crank pin and crank shaft. Inlet valve and exit valves may be of spring loaded type which get opened and closed due to pressure differential across them. Let us consider piston to be at top dead centre (TDC) and move towards bottom dead centre (BDC). Due to this piston movement from TDC to BDC suction pressure is created causing opening of inlet valve. With this opening of inlet valve and suction pressure the atmospheric air enters the cylinder.

Air gets into cylinder during this stroke and is subsequently compressed in next stroke with both inlet valve and exit valve closed. Both inlet valve and exit valves are of plate type and spring loaded so as to operate automatically as and when sufficient pressure difference is available to cause deflection in spring of valve plates to open them. After piston reaching BDC it reverses its motion and compresses the air inducted in previous stroke. Compression is continued till the pressure of air inside becomes sufficient to cause deflection in exit valve. At the moment when exit valve plate gets lifted the exhaust of compressed air takes place. This piston again reaches TDC from where downward piston movement is again accompanied by suction. This is how reciprocating compressor. Keeps on working as flow device. In order to counter for the heating of piston-cylinder arrangement during compression the provision of cooling the cylinder is there in the form of cooling jackets in the body. Reciprocating compressor described above has suction, compression and discharge as three prominent processes getting completed in two strokes of piston or one revolution of crank shaft.

Thermodynamic Analysis

Compression of air in compressor may be carried out following number of thermodynamic processes such as isothermal compression, polytropic compressor or adiabatic compressor. Fig. shows the thermodynamic cycle involved in compressor. Theoretical cycle is shown neglecting clearance volume but in actual cycle clearance volume can not be negligible. Clearance volume is necessary in order to prevent collision of piston with cylinder head, accommodating valve mechanism etc., Compression process is shown by process1-2, 1-2', 1-2'' and 1-2''' following isothermal, polytropic and adiabatic processes.



P-V diagram (Without clearance volume)

On P-V diagram process 4-1 shows the suction process followed by compression during 1-2 and discharge through compressor is shown by process 2-3. Air enters compressor at pressure p1 and is compressed upto p2. Compression work requirement can be estimated from the area below each compression process. Area on p-V diagram shows that work requirement shall be minimum with isothermal process 1-2”. Work requirement is maximum with process 1-2 ie., adiabatic process. As a designer one shall be interested in a compressor having minimum compression work requirement. Therefore, ideally compression should occur isothermally for minimum work input. In practice it is not possible to have isothermal compression because constancy of temperature during compression can not be realized. Generally, compressors run at substantially high speed while isothermal compression requires compressor to run at very slow speed so that heat evolved during compression is dissipated out and temperature remains constant. Actually due to high speed running of compressor the compression process may be assumed to be near adiabatic or polytropic process following law of compression as $pV^n=C$ with of ‘n’ varying between 1.25 to 1.35 for air. Compression process following three processes is also shown on T-s diagram in Fig.16.4. it is thus obvious that actual compression process should be compared with isothermal compression process. A mathematical parameter called isothermal efficiency is defined for quantifying the degree of deviation of actual compression process from ideal compression process. Isothermal efficiency is defined by the ratio is isothermal work and actual indicated work in reciprocating compressor.

$$\text{Isothermal efficiency} = \frac{\text{Isothermal work}}{\text{Actual indicated Work}}$$

Practically, compression process is attempted to be closed to isothermal process by air/water cooling, spraying cold water during compression process. In case of multistage compression process the compression in different stages is accompanied by intercooling in between the stages. P_2 V_2 Mathematically, for the compression work following polytropic process, $PV^n=C$. Assuming negligible clearance volume the cycle work done.

Wc = Area on p-V diagram

$$\text{Wc} = \left[p_2V_2 + \left(\frac{p_2V_2 - p_1V_1}{n-1} \right) \right] - p_1V_1$$

$$= \left[\left(\frac{n}{n-1} \right) [p_2V_2 - p_1V_1] \right]$$

$$= \left(\frac{n}{n-1} \right) (p_1V_1) \left[\frac{p_2V_2}{p_1V_1} - 1 \right]$$

$$= \left(\frac{n}{n-1} \right) (p_1V_1) \left[\left(\frac{p_2}{p_1} \right)^{\left(\frac{n-1}{n} \right)} - 1 \right]$$

$$= \left(\frac{n}{n-1} \right) (mRT_1) \left[\left(\frac{p_2}{p_1} \right)^{\left(\frac{n-1}{n} \right)} - 1 \right]$$

$$= \left(\frac{n}{n-1} \right) (mR)(T_2 - T_1)$$

In case of compressor having isothermal compression process, n = 1, ie., $p_1V_1 = p_2V_2$

$$W_{iso} = p_2V_2 + p_1V_1 \ln r - p_1V_1$$

$$W_{iso} = p_1V_1 \ln r, \qquad where, r = \frac{V_1}{V_2}$$

In case of compressor having adiabatic compression process,

$$W_{adiabatic} = \left(\frac{\gamma}{\gamma - 1} \right) (mR)(T_2 - T_1)$$

Or

$$W_{adiabatic} = (mC_p)(T_2 - T_1)$$

$$W_{adiabatic} = (m)(h_2 - h_1)$$

$$\eta_{iso} = \frac{p_1 V_1 \ln r}{\left(\frac{n}{n-1}\right)(p_1 V_1)\left[\left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}} - 1\right]}$$

The isothermal efficiency of a compressor should be close to 100% which means that actual compression should occur following a process close to isothermal process. For this the mechanism be derived to maintain constant temperature during compression process. Different arrangements which can be used are:

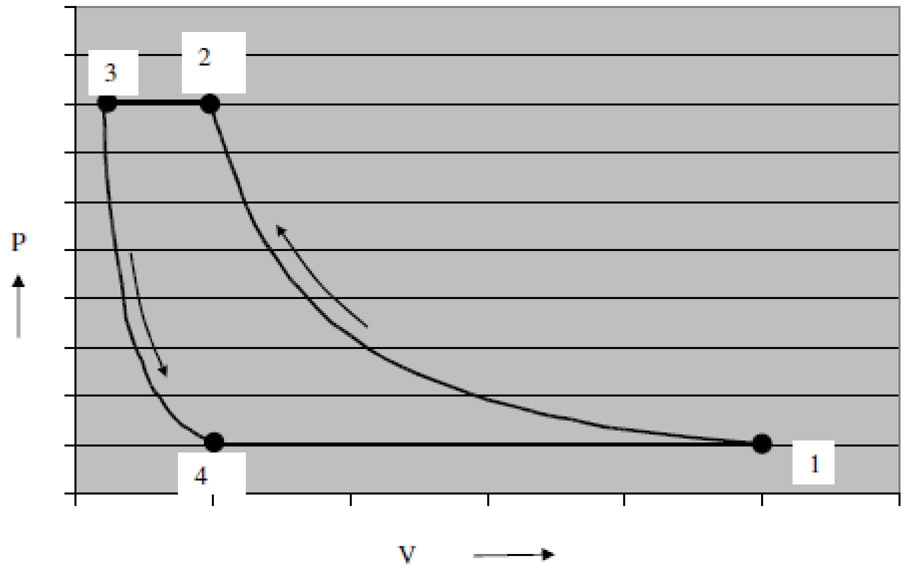
(i) Faster heat dissipation from inside of compressor to outside by use of fins over cylinder. Fins facilitate quick heat transfer from air being compressed to atmosphere so that temperature rise during compression can be minimized.

(ii) Water jacket may be provided around compressor cylinder so that heat can be picked by cooling water circulating through water jacket. Cooling water circulation around compressor regulates rise in temperature to great extent.

(iii) The water may also be injected at the end of compression process in order to cool the air being compressed. This water injection near the end of compression process requires special arrangement in compressor and also the air gets mixed with water and needs to be separated out before being used. Water injection also contaminates the lubricant film inner surface of cylinder and may initiate corrosion etc, the water injection is not popularly used.

(iv) In case of multistage compression in different compressors operating serially, the air leaving one compressor may be cooled upto ambient state or somewhat high temperature before being injected into subsequent compressor. This cooling of fluid being compressed between two consecutive compressors is called intercooling and is frequently used in case of multistage compressors. Considering clearance volume: With clearance volume the cycle is represented on Fig.

The work done for compression of air polytropically can be given by the are a enclosed in cycle 1-2-3-4. Clearance volume in compressors varies from 1.5% to 35% depending upon type of compressor.



P-V diagram (With clearance volume)

$W_{c,with\ CV}$ = Area 1234

$$= \left(\frac{n}{n-1}\right)(p_1V_1)\left[\left(\frac{p_2}{p_1}\right)^{\left(\frac{n-1}{n}\right)} - 1\right] - \left(\frac{n}{n-1}\right)(p_4V_4)\left[\left(\frac{p_3}{p_4}\right)^{\frac{n-1}{n}} - 1\right]$$

Here $P_1 = P_4$, $P_2 = P_3$

$$= \left(\frac{n}{n-1}\right)(p_1V_1)\left[\left(\frac{p_2}{p_1}\right)^{\left(\frac{n-1}{n}\right)} - 1\right] - \left(\frac{n}{n-1}\right)(p_1V_4)\left[\left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}} - 1\right]$$

$$= \left(\frac{n}{n-1}\right)(p_1)\left[\left(\frac{p_2}{p_1}\right)^{\left(\frac{n-1}{n}\right)} - 1\right](V_1 - V_4)$$

In the cylinder of reciprocating compressor (V_1-V_4) shall be the actual volume of air delivered per cycle. $V_d = V_1 - V_4$. This ($V_1 - V_4$) is actually the volume of air in hated in the cycle and delivered subsequently.

$$W_{c,withCV} = \left(\frac{n}{n-1}\right)(p_1V_d)\left[\left(\frac{p_2}{p_1}\right)^{\left(\frac{n-1}{n}\right)} - 1\right]$$

If air is considered to behave as perfect gas then pressure, temperature, volume and mass can be inter related using perfect gas equation. The mass at state 1 may be given as m_1 mass at state 2 shall be m1, but at state 3 after delivery mass reduces to m_2 and at state 4 it shall be m_2.

So, at state 1, $p_1V_1 = m_1RT_1$

at state 2, $p_2V_2 = m_1RT_2$

at state 3, $p_3V_3 = m_2RT_3$ or $p_2V_3 = m_2RT_3$

at state 4, $p_4V_4 = m_2RT_4$ or $p_1V_4 = m_2RT_4$

Ideally there shall be no change in temperature during suction and delivery
i.e., $T_4 = T_1$ and $T_2 = T_3$ from earlier equation

$$W_{c,withCV} = \left(\frac{n}{n-1}\right)(p_1)\left[\left(\frac{p_2}{p_1}\right)^{\left(\frac{n-1}{n}\right)} - 1\right](V_1 - V_4)$$

Temperature and pressure can be related as,

$$\left(\frac{p_2}{p_1}\right)^{\frac{(n-1)}{n}} = \frac{T_2}{T_1} \quad \text{and} \quad \left(\frac{p_4}{p_3}\right)^{\frac{(n-1)}{n}} = \frac{T_4}{T_3} \quad \Longrightarrow \quad \left(\frac{p_1}{p_2}\right)^{\frac{(n-1)}{n}} = \frac{T_4}{T_3}$$

Substiuting

$$W_{c,withCV} = \left(\frac{n}{n-1}\right)(m_1RT_1 - m_2RT_4)\left[\frac{T_2}{T_1} - 1\right]$$

Substituting for constancy of temperature during suction and delivery.

$$W_{c,withCV} = \left(\frac{n}{n-1}\right)(m_1RT_1 - m_2RT_1)\left[\frac{T_2 - T_1}{T_1}\right]$$

Or

$$W_{c,withCV} = \left(\frac{n}{n-1}\right)(m_1 - m_2)R(T_2 - T_1)$$

Thus (m_1-m_2) denotes the mass of air sucked or delivered. For unit mass of air delivered the work done per kg of air can be given as,

Thus, from above expressions it is obvious that the clearance volume reduces the effective swept volume i.e., the mass of air handled but the work done per kg of air delivered remains unaffected. From the cycle work estimated as above the theoretical power required for running compressor shall be, For single acting compressor running with N rpm, power input required, assuming clearance volume.

$$Power required = \left[\left(\frac{n}{n-1} \right) \left[\left(\frac{p_2}{p_1} \right)^{\left(\frac{n-1}{n} \right)} - 1 \right] p_1 (V_1 - V_4) \right] (N)$$

For double acting compressor, Power

$$Power required = \left[\left(\frac{n}{n-1} \right) \left[\left(\frac{p_2}{p_1} \right)^{\left(\frac{n-1}{n} \right)} - 1 \right] p_1 (V_1 - V_4) \right] (2N)$$

Volumetric efficiency: Volumetric efficiency of compressor is the measure of the deviation from volume handling capacity of compressor. Mathematically, the volumetric efficiency is given by the ratio of actual volume of air sucked and swept volume of cylinder. Ideally the volume of air sucked should be equal to the swept volume of cylinder, but it is not so in actual case. Practically the volumetric efficiency lies between 60 to 90%. Volumetric efficiency can be overall volumetric efficiency and absolute volumetric efficiency as given below.

$$\text{Overall volumetric efficiency} = \frac{\text{Volume of free air sucked in cylinder}}{\text{Swept volume of LP cylinder}}$$

$$(\text{Volumetric efficiency})_{\text{freeaircondition}} = \frac{\text{Volume of free air sucked in cylinder}}{(\text{Swept volume of LP cylinder})_{freeaircondition}}$$

Here free air condition refers to the standard conditions. Free air condition may be taken as 1 atm or 1.01325 bar and 15oC or 288K. consideration for free air is necessary as otherwise the different compressors can not be compared using volumetric efficiency because specific volume or density of air varies with altitude. It may be seen that a compressor at datum level (sea level) shall deliver large mass than the same compressor at high altitude. This concept is used for giving the capacity of compressor in terms of ‘free air delivery’ (FAD). “Free air delivery is the volume of air delivered being reduced to free air conditions”. In case of air the free air delivery can be obtained using perfect gas equation as,

$$\frac{p_a V_a}{T_a} = \frac{p_1(V_1 - V_4)}{T_1} = \frac{p_2(V_2 - V_3)}{T_2}$$

Where subscript a or p_a, V_a, T_a denote properties at free air conditions

$$V_a = \frac{p_1 T_a}{p_a}\frac{p_1(V_1 - V_4)}{T_1} = \text{FAD per cycle}$$

This volume V_a gives 'free air delivered' per cycle by the compressor.

Absolute volumetric efficiency can be defined, using NTP conditions in place of free air conditions.

$$\eta_{vol} = \frac{FAD}{Sweptvolume} = \frac{V_a}{(V_1 - V_2)} = \frac{p_1 T_a (V_1 - V_4)}{p_a T_1 (V_1 - V_3)}$$

$$\eta_{vol} = \left(\frac{p_1 T_a}{p_a T_1}\right)\left\{\frac{(V_s + V_c) - V_4}{V_s}\right\}$$

Here V_s is the swept volume = $V_1 - V_3$

V_c is the clearance volume = V_3

$$\eta_{vol} = \left(\frac{p_1 T_a}{p_a T_1}\right)\left\{1 + \left(\frac{V_c}{V_s}\right) - \left(\frac{V_4}{V_s}\right)\right\}$$

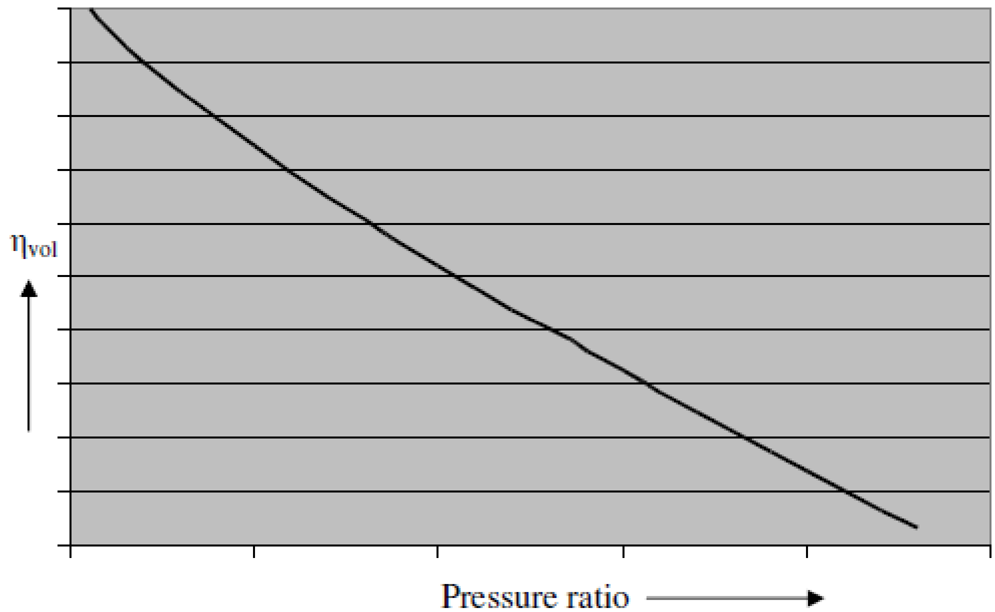
Here $\frac{V_4}{V_s} = \frac{V_4}{V_c} \cdot \frac{V_c}{V_s} = \left(\frac{V_4}{V_3} \cdot \frac{V_c}{V_s}\right)$

Let the ratio of clearance volume to swept volume be given by C. = $\frac{V_c}{V_s}$

$$\eta_{vol} = \left(\frac{p_1 T_a}{p_a T_1}\right)\left\{1 + C - C\left(\frac{V_4}{V_3}\right)\right\}$$

$$\eta_{vol} = \left(\frac{p_1 T_a}{p_a T_1}\right)\left\{1 + C - C\left(\frac{p_2}{p_1}\right)^{1/n}\right\}$$

Volumetric efficiency depends on ambient pressure and temperature, suction pressure and temperature, ratio of clearance to swept volume, and pressure limits. Volumetric efficiency increases with decrease in pressure ratio in compressor.



5. Related Laboratories: Conduct the performance test on single stage reciprocating air compressor and determine the isothermal and volumetric efficiency.

6. Post Test:

1. Explain the construction and working principle of single stage reciprocating air compressor?
2. Derive the expression for workdone of single stage reciprocating air compressor with & without clearance volume.
3. Define: Volumetric efficiency and derive the expression for the same.

7. Conclusions: The Single Stage Air Compressors provide power to pneumatic tools such as spray guns, ratchet wrenches and air nailer. They can be used in gas stations and various manufacturing plants. Single Stage Air Compressors are typically immobile and can be used to provide power to a range of tools for a long duration.

8. Reference: R.K. Rajput, Thermal Engineering, 6^{th} Edition, Laxmi Publications (P) Ltd.,

9. Demo Video: https://www.youtube.com/watch?v=e402VfVE7VE

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Name of the Course : **Applied Thermodynamics**

Name of the Unit : **Air compressor**

Name of the Topic : **Multi-stage Reciprocating Air Compressor**

1. Objectives: To understand the basics and as well as construction & working principle of multi-stage reciprocating air compressor.

Outcomes: Upon successful completion, the student should be able to understand the basics and working principle of multi-stage reciprocating air compressor.

2. Pre-Test: (Students should be able to answer the following)

1. State the application of air compressor & compressed air.
2. State the difference between various thermodynamic compression process.

3. Pre-requisites: To have a basic knowledge of thermodynamic compression process.

4. Theory Behind:

INTRODUCTION

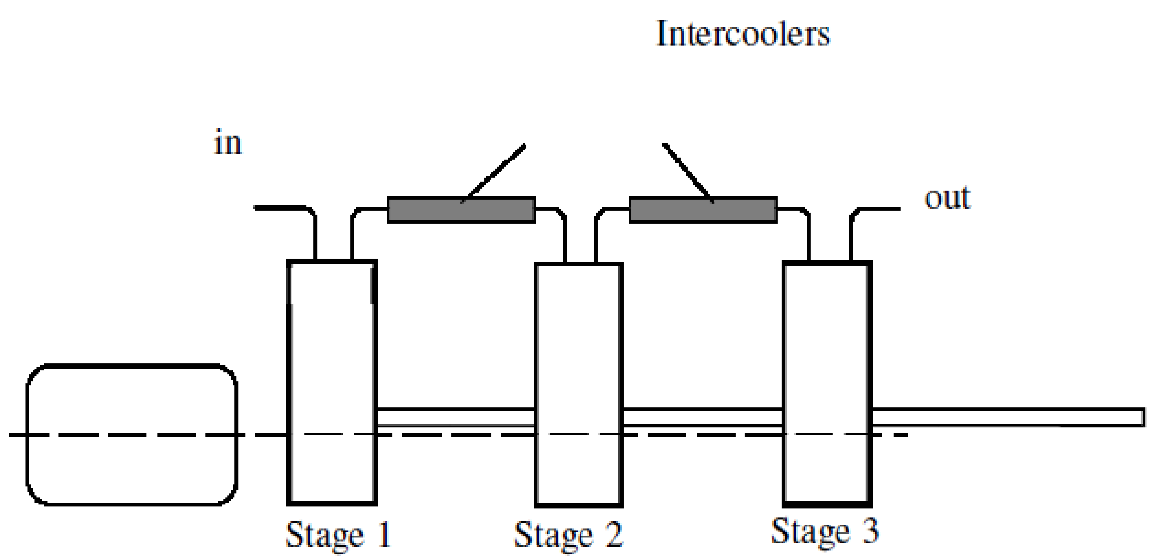

Fig. Multi-stage compressor with intercooler

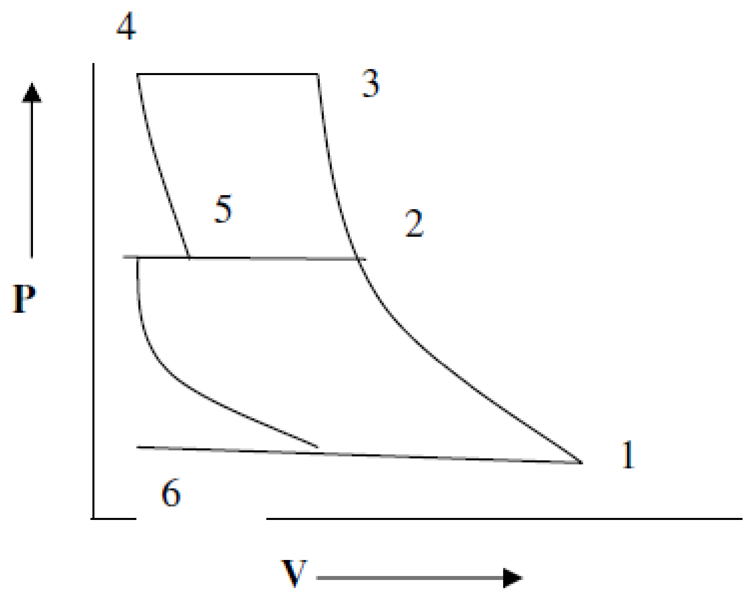

Fig. P-V diagram for Multi-stage compressor

Multistage compression refers to the compression process completed in more than one stage i.e., a part of compression occurs in one cylinder and subsequently compressed air is sent to subsequent cylinders for further compression. In case it is desired to increase the compression ratio of compressor then multi-stage compression becomes inevitable. If we look at the expression for volumetric efficiency then it shows that the volumetric efficiency decreases with increase in pressure ratio. This aspect can also be explained using p-V representation shown in Fig.

Therefore, the volumetric efficiency reduces with increasing pressure ratio in compressor with single stage compression. Also, for getting the same amount of free air delivery the size of cylinder is to be increased with increasing pressure ratio. The increase in pressure ratio also requires sturdy structure from mechanical strength point of view fro withstanding large pressure difference.

The solution to number of difficulties discussed above lies in using the multistage compression where compression occurs in parts in different cylinders one after the other. Fig., shows the multistage compression occurring in two stages. Here first stage of compression occurs in cycle 12671 and after first stage compression partly compressed enters second stage of compression and occurs in cycle 2345. In case of multistage compression, the compression in first stage occurs at low temperature and subsequent compression in following stages occurs at higher temperature. The compression work requirement depends largely upon the average temperature during compression. Higher average temperature during compression has larger work requirement compared to low temperature so it is always desired to keep the low average temperature during compression. Apart from the cooling during compression the temperature of air at inlet o compressor can be reduced so as to reduce compression work. In multistage compression the partly compressed air leaving first stage is cooled upto ambient air temperature in intercooler and then sent to subsequent cylinder (stage) for compression. Thus, intercoolers when put between the stages reduce the compression work and compression is called intercooled compression. Intercooling is called perfect when temperature at inlet to subsequent stages of compression is reduced to ambient temperature. Intercooling between two stages causes temperature drop from 2 to 2' i.e discharge from first stage (at 2) is cooled upto the ambient temperature stage (at2') which lies on isothermal compression process 1-2'-3". In the absence of intercooling the discharge from first stage shall enter at 2. Final discharge from second stage occurs at 3' in case of intercooled compression compared to discharge at 3 in case of non-intercooled compression. Thus, intercooling offers reduced work requirement by the amount shown by area 22'3'3 on p-V diagram. If the intercooling is not perfect then the inlet state to second/subsequent stage shall not lie on the isothermal compression process line and this stage shall lie between actual discharge state from first stage and isothermal compression line.

Fig. shows the schematic of multi stage compressor (double stage) with inter cooler between stage T-s representation is shown in Fig.5.6. The total work requirement for running this shall be algebraic summation of work required for low pressure (LP) and high pressure (HP) stages. The size of HP cylinder is smaller than LP cylinder as HP cylinder handles high pressure air having smaller specific volume.

Mathematical analysis of multistage compressor is done with following assumptions:

(i) Compression in all the stages is done following same index of compression and there is no pressure drop in suction and delivery pressures in each stage. Suction and delivery pressure remains constant in the stages.

(ii) There is perfect intercooling between compression stages.

(iii) Mass handled in different stages is same i.e, mass of air in LP and HP stages are same.

(iv) Air behaves as perfect gas during compression.

From combined p-V diagram the compressor work requirement can be given as,

$$\text{Work requirement in LP cylinder, } W_{LP} = \left(\frac{n}{n-1}\right) P_1 V_1 \left\{ \left(\frac{P_2}{P_1}\right)^{\frac{(n-1)}{n}} - 1 \right\}$$

$$\text{Work requirement in HP cylinder, } W_{HP} = \left(\frac{n}{n-1}\right) P_2 V_2 \left\{ \left(\frac{P_2}{P_1}\right)^{\frac{(n-1)}{n}} - 1 \right\}$$

For perfect intercooling, $p_1V_1 = p_2V_2'$ and

$$W_{HP} = \left(\frac{n}{n-1}\right) P_2 V_{2'} \left\{ \left(\frac{P_2}{P_1}\right)^{\frac{(n-1)}{n}} - 1 \right\}$$

Therefore, total work requirement, $W_c = W_{LP} + W_{HP}$, for perfect inter cooling

$$W_C = \left(\frac{n}{n-1}\right) \left[P_1 V_1 \left\{ \left(\frac{P_2}{P_1}\right)^{\frac{(n-1)}{n}} - 1 \right\} + P_2 V_{2'} \left\{ \left(\frac{P_{2'}}{P_2}\right)^{\frac{n-1}{n}} - 1 \right\} \right]$$

$$= \left(\frac{n}{n-1}\right) \left[P_1 V_1 \left\{ \left(\frac{P_2}{P_1}\right)^{\frac{(n-1)}{n}} - 1 \right\} + P_1 V_1 \left\{ \left(\frac{P_{2'}}{P_2}\right)^{\frac{n-1}{n}} - 1 \right\} \right]$$

$$W_C = \left(\frac{n}{n-1}\right) P_1 V_1 \left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} + \left(\frac{P_{2'}}{P_1}\right)^{\frac{n-1}{n}} - 2 \right]$$

Power $= W_c \times N$ - Watts

If we look at compressor work then it shows that with the initial and final pressures p_1 and P_2 remaining same the intermediate pressure p2 may have value floating between p_1 and

P_2 and change the work requirement Wc. Thus, the compressor work can be optimized with respect to intermediate pressure P

3. Mathematically, it can be differentiated with respect to P_2.

$$\frac{dW_C}{dP_2} = \frac{d}{dP_2}\left[\left(\frac{n}{n-1}\right)P_1V_1\left\{\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} + \left(\frac{P_{2'}}{P_2}\right)^{\frac{n-1}{n}} - 2\right\}\right]$$

$$\frac{dW_C}{dP_2} = \left[\left(\frac{n}{n-1}\right)P_1V_1\frac{d}{dP_2}\left\{\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} + \left(\frac{P_{2'}}{P_2}\right)^{\frac{n-1}{n}} - 2\right\}\right]$$

$$\frac{dW_C}{dP_2} = \left(\frac{n}{n-1}\right)P_1V\left\{\left(\frac{n-1}{n}\right)P_1^{\frac{1-n}{n}} \cdot P_2^{\frac{-1}{n}} - \left(\frac{n-1}{n}\right) \cdot P_{2'}^{\frac{1-n}{n}} \cdot P_2^{\frac{1-2n}{n}}\right\}$$

Equating to zero yields

$$P_1^{\frac{1-n}{n}} \cdot P_2^{\frac{-1}{n}} = \cdot P_{2'}^{\frac{1-n}{n}} \cdot P_2^{\frac{1-2n}{n}}$$

$$P_2^{\frac{-2+2n}{n}} = \cdot P_{2'}^{\frac{1-n}{n}} \cdot P_1^{\frac{n-1}{n}}$$

$$P_2^{2\left(\frac{n-1}{n}\right)} = \left(P_1 \cdot P_{2'}\right)^{\left(\frac{n-1}{n}\right)}$$

$$P_2^{2} = \left(P_1 \cdot P_{2'}\right), P_2 = \sqrt{P_1 \cdot P_{2'}}$$

Pressure ratio in Ist stage = Pressure ratio in IInd stage

Thus, it is established that the compressor work requirement shall be minimum when the pressure ratio in each stage is equal. In case of multiple stages, say *i* number of stages, for the delivery and suction pressures of P_{i+1} and P_1 the optimum stage pressure ratio shall be

Optimum stage pressure ratio = $\left(\frac{P_{i+1}}{P_1}\right)^{\frac{1}{i}}$ for pressure at stages being P_1, P_2, P_3,……P_{i-1}, P_i, P_{i+1}

Minimum work required in two stage compressor can be given by

$$W_{C,\min} = \left(\frac{n}{n-1}\right)P_1V_1 \cdot 2\left\{\left(\frac{P_2}{P_1}\right)^{\frac{(n-1)}{n}} - 1\right\}$$

For *i* number of stages, minimum work,

$$W_{C,\min} = i \cdot \left(\frac{n}{n-1}\right)P_1V_1\left\{\left(\frac{P_{i+1}}{P_i}\right)^{\frac{(n-1)}{n \cdot i}} - 1\right\}$$

5. Related Laboratories: Conduct the performance test on, multi stage reciprocating air compressor and determine the isothermal and volumetric efficiency.

6. Post Test:

1. Explain the construction and working principle of single stage reciprocating air compressor?
2. Derive the expression for workdone of multi-stage reciprocating air compressor.

7. Conclusions: Multistage compressors are used when high pressures are required, because better cooling between stages can effectively increase the efficiency and reduce the input power requirements. ... Discharge pressures in the range of 250 bars can be obtained with high pressure reciprocating compressor of three and four stages.

8. References: R.K. Rajput, Thermal Engineering, 6^{th} Edition, Laxmi Publications (P) Ltd.,

9. Demo Video: https://www.youtube.com/watch?v=0B8K1ZCJl9A

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Name of the Course : **Applied Thermodynamics**

Name of the Unit : **Air compressor**

Name of the Topic : **Rotary Compressor**

1. Objectives: To understand the basics and as well as construction & working principle of various rotary air compressor.

Outcomes: Upon successful completion, the student should be able to understand the basics and working principle of rotary air compressor.

2. Pre-Test: (Students should be able to answer the following)

1. State the application of air compressor & compressed air.
2. State the difference between various thermodynamic compression process.

3. Pre-requisites: To have a basic knowledge of thermodynamic compression process.

4. Theory Behind:

4.1 AXIAL FLOW COMPRESSOR:

Axial flow compressor also works on the same principle on which centrifugal compressor works i.e. energy will be supplied from outside to the rotor of the compressor and this energy will be further imparted to the working fluid i.e. air in terms of static pressure energy and kinetic energy. Further, working fluid i.e. air will flow finally through the diffuser where kinetic energy will also be converted in to static pressure energy. Hence, at the outlet of compressor, there will be air with relatively lower velocity and with high static pressure energy.

Axial flow compressor will also have similar basic parts such as the rotor and the stator like centrifugal compressor. Rotor is the rotating component of the axial flow compressor which will have the number of blades attached over its surface. Mechanical energy will be supplied to the rotor of the compressor from outside in the terms of external torque. Working fluid i.e. air will gain the energy from the rotor of the compressor in terms of static pressure and kinetic energy. Stator of the axial flow compressor will be basically the diffuser which will be the responsible for the diffusion process where kinetic energy of the working fluid coming out from the rotor will be converted in to pressure energy and therefore working fluid coming out from the diffuser will have high static pressure with

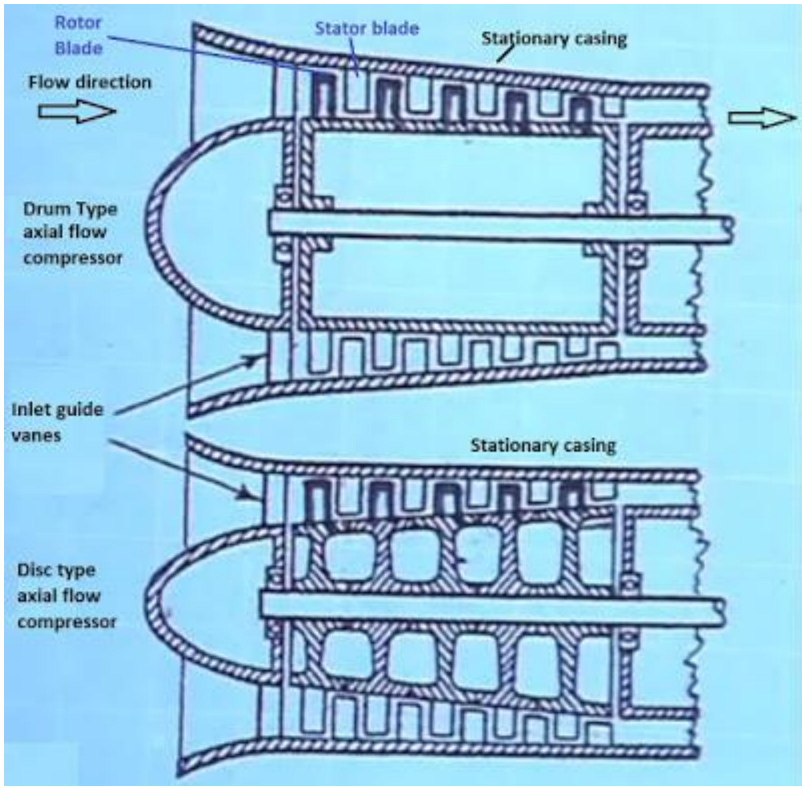
relatively lower velocity. Hence, the working principle of axial flow compressor is similar with the working principle of centrifugal compressor.
In case of axial flow compressor, flow will take place in axial direction and in case of centrifugal compressor flow will take place in radially outward direction. In case of axial flow compressor, there will be number of stages and each stage consist a rotor and a stator. Axial flow compressor can handle a large amount of air as compared to centrifugal compressor or we can say that flow rate in case of axial flow compressor will be higher as compared to the centrifugal compressor. Axial flow compressor will run more efficiently with higher flow rate as compared to centrifugal compressor. Weight of the axial flow compressor will be less as compared to the weight of the respective centrifugal compressor.

Axial flow compressor: Construction:

There are basically two types of axial flow compressors and these are as mentioned here in following figure.

1. Drum type axial flow compressor
2. Disc type axial flow compressor

Disc type axial flow compressor will be used where lower weight will be quite important.
There will be a rotating drum in case of drum type axial flow compressor. Rotor blades will be fixed over the surface of this rotating drum along its circumference. Similarly, in case of disc type axial flow compressor, there will be one disc and rotor blades will be mounted over the surface of the disc. There will be stationary casing, as displayed in following figure, stator blades will be mounted with this stationary casing of axial flow compressor. For an axial flow compressor, a row of rotor blades followed by a row of stator blades will be termed as a stage.



There will be one row of inlet guide vanes which will be upstream to the first row of rotor. Working fluid will be directed by these inlet guide vanes in the axial direction. Working fluid will flow through the number of rotor blades and stator blades in a direction parallel to the axis of rotation of the drum or disc of the axial flow compressor i.e. flow will take place in axial direction and that's why this compressor is termed as axial flow compressor. There is very important point that we must know about the designing of the axial flow compressor and that is the flow annulus area. Annulus area will be decreasing along the direction of flow or from lower to higher pressure end of the axial flow compressor. You might have one question that why it is important to have decreasing annulus area along the direction of flow.

Let us recall the continuity equation

Mass flow rate (m) = Density (ρ) x Flow annulus area (A) x Velocity of flow (V_f)

When fluid flow will take place, pressure will be increasing along the direction of flow and therefore density of fluid will be increased. Mass flow rate i.e. m will also be constant for steady state flow and therefore if we want to keep axial velocity of flow constant, we will have to decrease the flow annulus area.

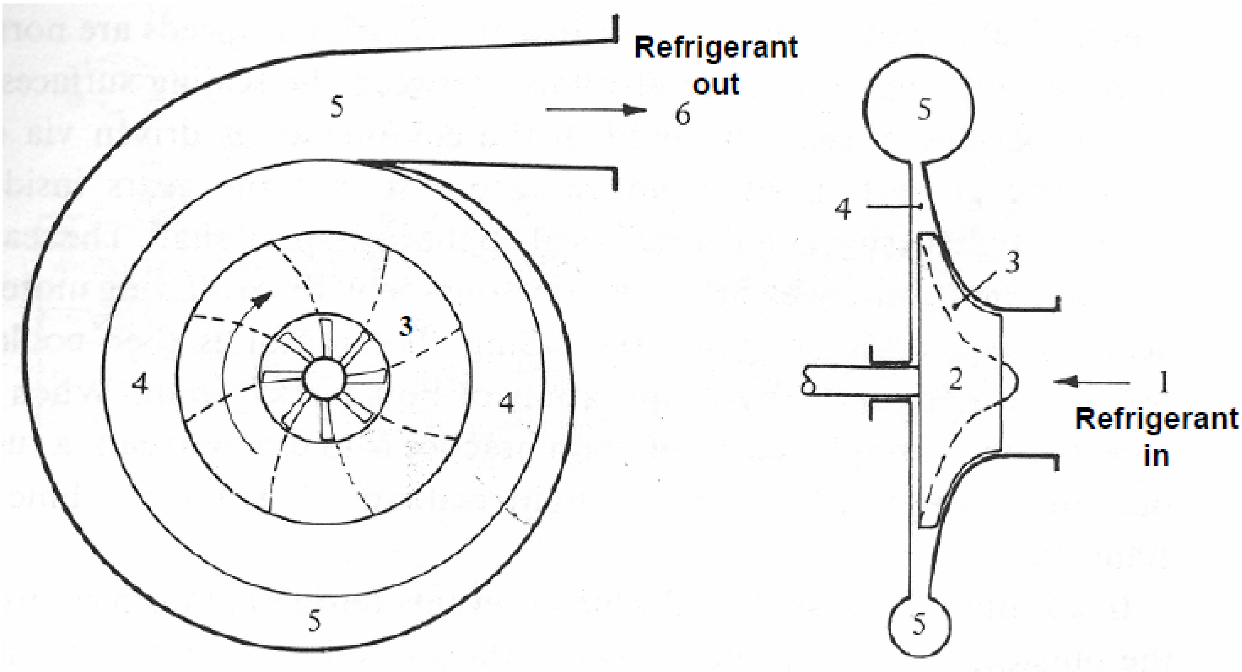
a. **Centrifugal Compressor:**

Centrifugal compressors; also known as turbo-compressors belong to the roto-dynamic type of compressors. In these compressors the required pressure rise takes place due to the continuous conversion of angular momentum imparted to the air by a high-speed impeller into static pressure. Unlike reciprocating compressors, centrifugal compressors are steady-flow devices hence they are subjected to less vibration and noise. Figure shows the working principle of a centrifugal compressor. As shown in the figure, low-pressure air enters the compressor through the eye of the impeller (1). The impeller (2) consists of a number of blades, which form flow passages (3) for air. From the eye, the air enters the flow passages formed by the impeller blades, which rotate at very high speed. As the air flows through the blade passages towards the tip of the impeller, it gains momentum and its static pressure also increases. From the tip of the impeller, the air flows into a stationary diffuser (4). In the diffuser, the air is decelerated and as a result the dynamic pressure drop is converted into static pressure rise, thus increasing the static pressure further. The air from the diffuser enters the volute casing (5) where further conversion of velocity into static pressure takes place due to the divergent shape of the volute. Finally, the pressurized air leaves the compressor from the volute casing (6). The gain in momentum is due to the transfer of momentum from the highspeed impeller blades to the refrigerant confined between the blade passages. The increase in static pressure is due to the self-compression caused by the centrifugal action. This is analogous to the gravitational effect, which causes the fluid at a higher level to press the fluid below it due to gravity (or its weight). The static pressure produced in the impeller is equal to the static head, which would be produced by an equivalent gravitational column. If we assume the impeller blades to be radial and the inlet diameter of the impeller to be small, then the static head, h developed in the impeller passage for a single stage is given by:

$$h=V^2/g$$

where h = static head developed, m V = peripheral velocity of the impeller wheel or tip speed, m/s g = acceleration due to gravity, m/s^2, Hence, increase in total pressure, ΔP as the refrigerant flows through the passage is given by:

$$\Delta P=\rho gh=\rho V^2$$



***21.1**. Centrifugal Compressor*
1: Refrigerant inlet (eye); 2: Impeller; 3: Refrigerant passages
4: Vaneless diffuser; 5: Volute casing; 6: Refrigerant discharge

Thus, it can be seen that for a given air with a fixed density, the pressure rise depends only on the peripheral velocity or tip speed of the blade. The tip speed of the blade is proportional to the rotational speed (RPM) of the impeller and the impeller diameter. The maximum permissible tip speed is limited by the strength of the structural materials of the blade (usually made of high-speed chrome-nickel steel) and the sonic velocity of the refrigerant. Under these limitations, the maximum achievable pressure rise (hence maximum achievable temperature lift) of single stage centrifugal compressor is limited for a given refrigerant. Hence, multistage centrifugal compressors are used for large temperature lift applications. In multistage centrifugal compressors, the discharge of the lower stage compressor is fed to the inlet of the next stage compressor and so on. In multistage centrifugal compressors, the impeller diameter of all stages remains same, but the width of the impeller becomes progressively narrower in the direction of flow as air density increases progressively.

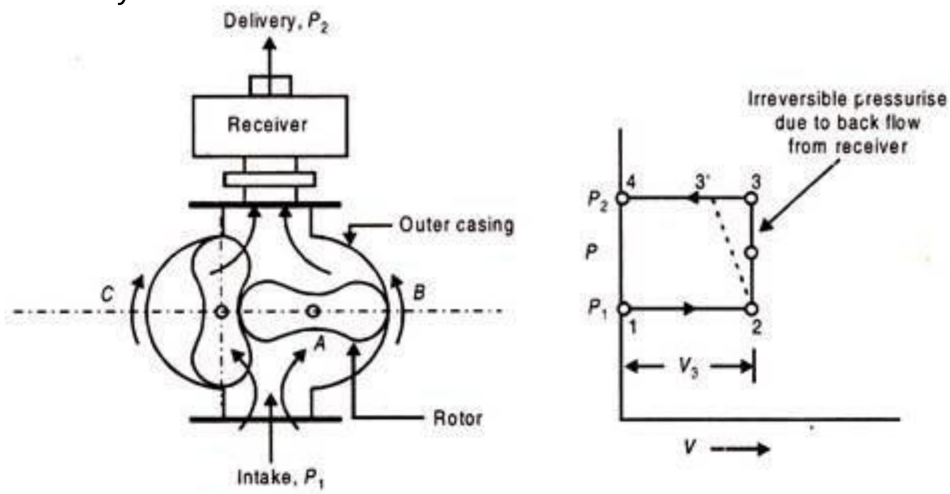
The blades of the compressor or either forward curved or backward curved or radial. Backward curved blades were used in the older compressors, whereas the modern centrifugal compressors use mostly radial blades. The stationary diffuser can be vaned or vaneless. As the name implies, in vaned diffuser vanes are used in the diffuser to form flow passages. The vanes can be fixed or adjustable. Vaned diffusers are compact compared to the vaneless diffusers and are commonly used for high discharge pressure applications. However, the presence of vanes in the diffusers can give rise to shocks, as the refrigerant velocities at the tip of the impeller blade could reach sonic velocities in large, high-speed centrifugal compressors. In vaneless diffusers the velocity of air in the diffuser decreases and static pressure increases as the radius increases. As a result, for a required pressure rise, the required size of the vaneless diffuser could be large compared to vaned diffuser. However, the problem of shock due to supersonic velocities at the tip does not arise with vaneless diffusers as the velocity can be diffused smoothly.

Rotary Vane Compressor:

Rotary Vane compressor is also called as 'sliding vane compressor'. It consists of a rotor eccentrically housed in the casing. Rotor has several radial slots in it, each housing a spring-loaded vane. These vanes are made of steel or synthetic fibrous material. Larger the number of vanes, internal leakage of air decreases due to small pressure difference prevailing between the adjacent spaces around the rotor. High pressure ratio requires large number of vanes (20 – 30). The casing has intake and delivery openings. These compressors are often used for capacities upto 150 m^3/min and for pressure ratios upto 8.5. For a given pressure ratio and FAD, vane compressor requires less work input than that for roots blower. When the rotor rotates, vanes are driven out of the rotor towards the casing due to centrifugal force. The space between the two adjacent vanes, rotor and the casing increases creating vacuum. Thus, the gas is drawn in, from the suction opening. When the rotor crosses the point just opposite to its eccentricity, suction starts. As the rotor continues to rotate, the entrapped gas is compressed due to reduction in volume. The high-pressure gas is then discharged through delivery opening. Usually, half of the total pressure rise is developed during the internal reversible compression and the remaining pressure rise occurs irreversibly when the entrapped gas is released to the delivery side, due to back flow of high-pressure air from the receiver.

Roots Blower (Lose Type) Compressor:

Figure (a) shows a twin lobe roots blower. It has two lobes each mounted on separate shaft. One of these shafts is connected to the external prime mover (electric motor) while the other is gear driven from the first. The lobes of the rotor are of cycloidal or involute profile. Throughout all angular positions, the high-pressure delivery side remains sealed from the low-pressure suction side by the closely mating lobes. The wear between the lobes is avoided by a small clearance of 0.1 – 0.2 mm. The clearance results in leakage of air thereby reducing volumetric efficiency of the blower.



(a) Twin lobe roots blower (b) p-V diagram

Suction takes place through the intake port. The entrapped air between the lobes and casing is carried forward during the rotation and is finally discharged to the delivery port. There is no change in the flow area and no reduction of volume of air. However, when the delivery port is open, blower discharges air into the high-pressure reservoir causing irreversible pressurise as shown in the p-V diagram [Fig. (b)]. The dotted line in p-V diagram shows compression process of a reciprocating compressor. The area represents excess work required due to irreversible pressurise.

5. Related Laboratories: Conduct the performance test on axial/centrifugal air compressor and draw its performance characteristics.

6. Post Test:

1. Explain the construction and working principle of axial flow compressor?
2. Explain the construction and working principle of vane blower compressor?
3. Explain the construction and working principle of root blower compressor?

7. Conclusions: A rotary compressor is a type of gas compressor which uses a rotary type positive displacement mechanism. They are commonly used to replace piston compressors where large volumes of high-pressure air are needed, either for large industrial applications or to operate high-power air tools such as jackhammers.

8. **References:** R.K. Rajput, Thermal Engineering, 6th Edition, Laxmi Publications (P) Ltd.,

9. **Demo Video:**

https://www.youtube.com/watch?v=Il27VvHu-s0

https://www.youtube.com/watch?v=s-bbAoxZmBg

https://www.youtube.com/watch?v=b93GSe-xgqI

https://www.youtube.com/watch?v=v3gE4cA5_gg

Name of the Course : **Applied Thermodynamics**

Name of the Unit : **Air Standard Cycles**

Name of the Topic : **Otto/Diesel/Dual/Brayton Cycle**

1. Objectives: To understand the basics and as well as air standard efficiency of Otto/Diesel/Dual/Brayton cycle.

Outcomes: Upon successful completion, the student should be able to understand the basics, practical applications and air standard efficiency of Otto/Diesel/Dual/Brayton cycle.

2. Pre-Test: (Students should be able to answer the following)

1. State and explain the various process involved in Ideal Carnot cycle?

3. Pre-requisites: To have a basic knowledge of ideal Carnot cycle.

4. Theory Behind:

Air-standard assumptions:

1.The working fluid is air, which continuously circulates in a closed loop and always behaves as an ideal gas.

2. All the processes that make up the cycle are internally reversible.

3.The combustion process is replaced by a heat-addition process from an external source.

4.The exhaust process is replaced by a heat-rejection process that restores the working fluid to its initial state.

OTTO CYCLE:

The air-standard-Otto cycle is the idealized cycle for the spark-ignition internal combustion engines. This cycle is shown above on p-v and T-s diagrams. The Otto cycle 1-2-3-4 consists of following four process:

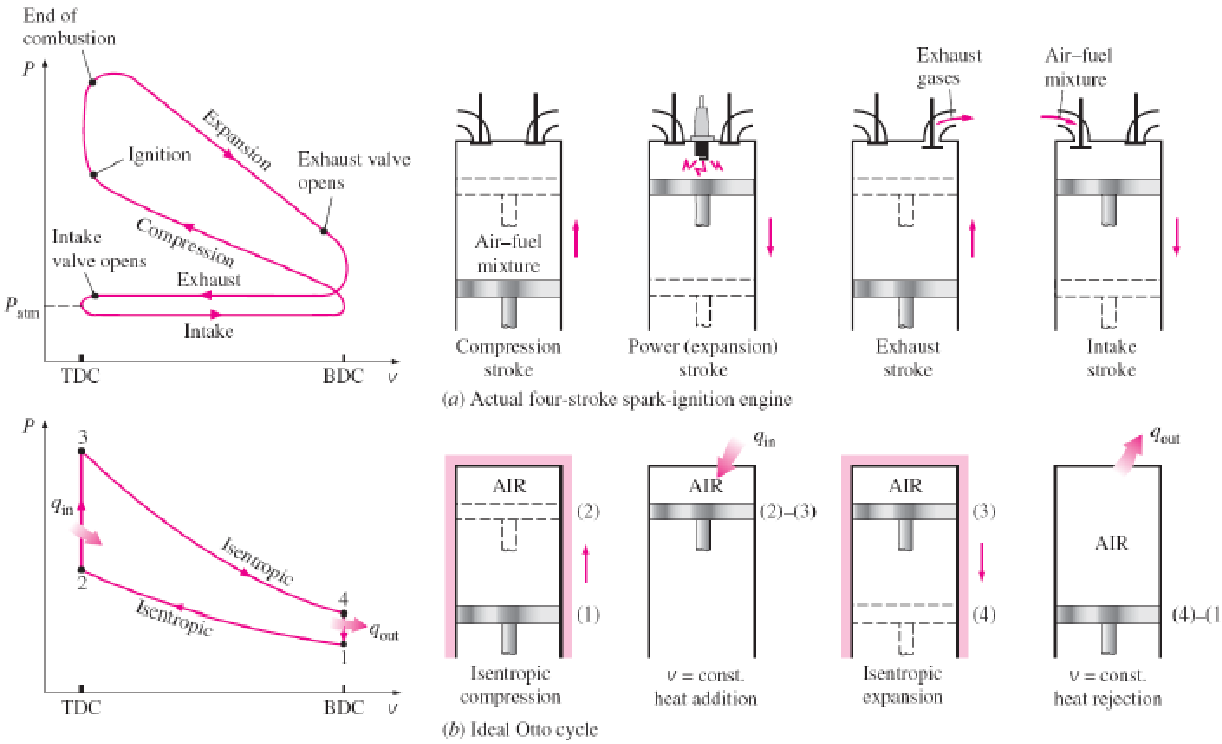
Process 1-2: Reversible adiabatic compression of air.

Process 2-3: Heat addition at constant volume.

Process 3-4: Reversible adiabatic expansion of air.

Process 4-1: Heat rejection at constant volume.

OTTO CYCLE: THE IDEAL CYCLE FOR SPARK-IGNITION ENGINES



Actual and ideal cycles in spark-ignition engines and their *P*-*v* diagrams.

Air Standard Efficiency:

$$\eta_{th} = \frac{\text{Net workdone}}{\text{Net heat added}}$$

Since processes 1-2 and 3-4 are adiabatic processes, the heat transfer during the cycle takes place only during processes 2-3 and 4-1 respectively. Therefore, thermal efficiency can be written as,

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

Consider 'm' kg of working fluid,

$$\text{Heat added} = mC_V(T_3 - T_2)$$
$$\text{Heat Rejected} = mC_V(T_4 - T_1)$$

$$\eta_{th} = \frac{mC_V(T_3 - T_2) - mC_V(T_4 - T_1)}{mC_V(T_3 - T_2)} = 1 - \frac{T_4 - T_1}{T_3 - T_2}$$

For the reversible adiabatic processes 3-4 and 1-2, we can write,

$$\frac{T_4}{T_3} = \left(\frac{v_3}{v_4}\right)^{\gamma - 1} \text{ and } \frac{T_1}{T_2} = \left(\frac{V_2}{V_1}\right)^{\gamma - 1}$$

$$v_2 = v_3 \text{ and } v_4 = v_1$$

$$\frac{T_4}{T_3} = \frac{T_1}{T_2} = \frac{T_4 - T_1}{T_3 - T_2} = \left(\frac{V_2}{V_1}\right)^{\gamma - 1}$$

$$\eta_{th} = 1 - \frac{T_1}{T_2} = 1 - \left(\frac{V_2}{V_1}\right)^{\gamma - 1}$$

The ratio $\frac{V_1}{V_2}$ is called as compression ratio, r.

$$\eta_{th} = 1 - \left(\frac{1}{r}\right)^{\gamma - 1}$$

From the above equation, it can be observed that the efficiency of the Otto cycle is mainly the function of compression ratio for the given ratio of Cp and Cv. If we plot the variations of the thermal efficiency with increase in compression ratio for different gases, the curves are obtained as shown in Fig. Beyond certain values of compression ratios, the increase in the thermal efficiency is very small, because the curve tends to be asymptotic. However, practically the compression ratio of petrol engines is restricted to maximum of 9 or 10 due to the phenomenon of knocking at high compression ratios.

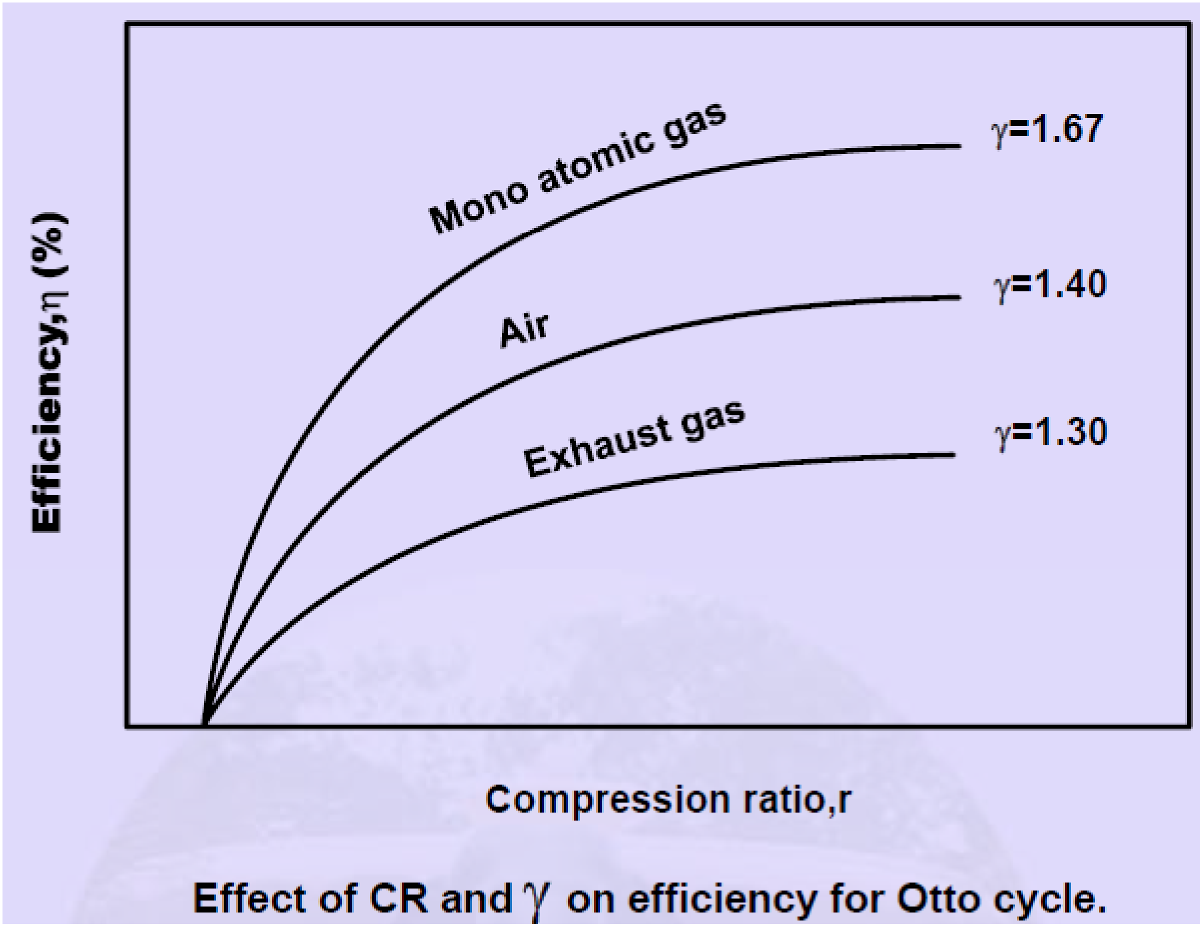


Fig. Variation of thermal efficiency with compression ratio

Mean Effective Pressure:

Generally, it is defined as the ratio of the net workdone to the displacement volume of the piston.

Let us consider 'm' kg of working substance.

$$\text{Net work done} = m\,C_v\left\{(T_3 - T_2) - (T_4 - T_1)\right\}$$

$$\text{Displacement Volume} = (V_1 - V_2)$$

$$= V_1\left(1 - \frac{1}{r}\right) = \frac{m\,R\,T_1}{P_1}\left(\frac{r - 1}{r}\right)$$

$$= \frac{m\,C_v\,(\gamma - 1)\,T_1}{P_1}\left\{\frac{r - 1}{r}\right\}$$

since, $R = C_v(\gamma - 1)$

$$\text{mep} = \frac{m\, C_v\left[(T_3 - T_2) - (T_4 - T_1)\right]}{\dfrac{m\, C_v(\gamma - 1)\, T_1}{P_1}\left\{\left(\dfrac{r - 1}{r}\right)\right\}}$$

$$= \left(\frac{1}{\gamma - 1}\right)\left(\frac{p_1}{T_1}\right)\left(\frac{r}{r - 1}\right)\left\{(T_3 - T_2) - (T_4 - T_1)\right\}$$

Now, $T_2 = T_1 (r)^{\gamma - 1}$

Let, $r_p = \dfrac{P_3}{P_2} = \dfrac{T_3}{T_2} = \text{Pressure ratio}$

$$T_3 = \frac{P_3}{P_2} T_2 = r_p T_2 = r_p\, r^{\gamma-1}\, T_1 \qquad \text{(for V = C)}$$

So, $T_4 = T_3 \left(\dfrac{1}{r}\right)^{\gamma-1} = r_p\, r^{\gamma-1}\, T_1 \left(\dfrac{1}{r}\right)^{\gamma-1} = r_p T_1$

$$\text{mep} = \frac{P_1\, r}{(r - 1)\,(\gamma - 1)}\left\{\left(r_p\, r^{\gamma-1} - r^{\gamma-1}\right) - \left(r_p - 1\right)\right\}$$

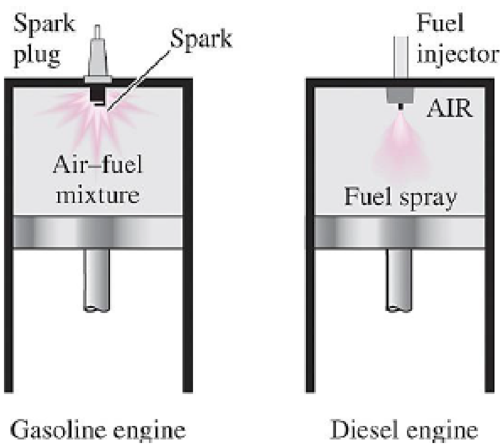
$$= P_1\, r \left\{\left(\frac{r^{\gamma-1}\left(r_p - 1\right) - \left(r_p - 1\right)}{(\gamma - 1)\,(r - 1)}\right)\right\}$$

$$\text{mep} = P_1\, r \left\{\frac{\left(r^{\gamma-1} - 1\right)\left(r_p - 1\right)}{(r - 1)\,(\gamma - 1)}\right\}$$

DIESEL CYCLE:

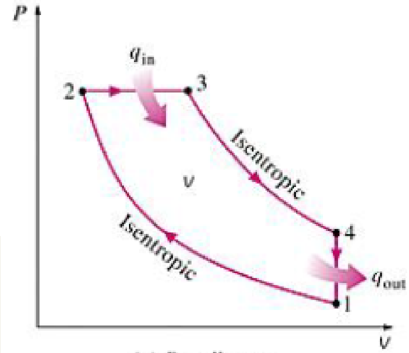
DIESEL CYCLE: THE IDEAL CYCLE FOR COMPRESSION-IGNITION ENGINES

In diesel engines, only air is compressed during the compression stroke, eliminating the possibility of autoignition (engine knock). Therefore, diesel engines can be designed to operate at much higher compression ratios than SI engines, typically between 12 and 24.

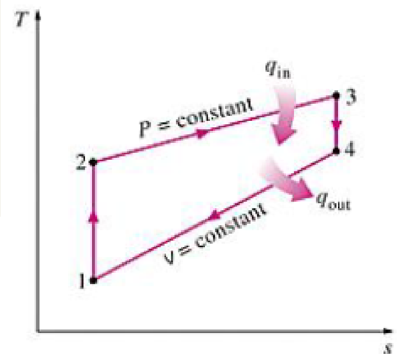


- 1-2 isentropic compression
- 2-3 constant-pressure heat addition
- 3-4 isentropic expansion
- 4-1 constant-volume heat rejection.

In diesel engines, the spark plug is replaced by a fuel injector, and only air is compressed during the compression process.



(a) P-v diagram



(b) T-s diagram

Process 1-2: Reversible adiabatic Compression.
Process 2-3: Constant pressure heat addition.
Process 3-5: Reversible adiabatic Compression.
Process 4-1: Constant volume heat rejection.
Consider ‘m’ kg of working fluid. Since the compression and expansion processes are reversible adiabatic processes, we can write,

$$\text{Heat supplied} = m\,C_p\left(T_3 - T_2\right) = \left(h_3 - h_2\right)$$

$$\text{Heat rejected} = m\,C_v\left(T_4 - T_1\right) = \left(u_4 - u_1\right)$$

$$\text{Workdone} = m\,C_p\left(T_3 - T_2\right) - m\,C_v\left(T_4 - T_1\right)$$

Now, we can write, thermal efficiency as,

$$\eta_{th} = \frac{m\,C_p\left(T_3 - T_2\right) - m\,C_v\left(T_4 - T_1\right)}{m\,C_p\left(T_3 - T_2\right)}$$

$$= 1 - \frac{1}{\gamma}\left(\frac{T_4 - T_1}{T_3 - T_2}\right)$$

$$T_2 = T_1\,r^{\gamma-1} \;;\quad r = \frac{v_1}{v_2} = \frac{v_4}{v_2}$$

$$\frac{T_3}{T_2} = \frac{v_3}{v_2} = r_c = \text{cutoff ratio}$$

$$T_3 = r_c\,T_2 = r_c\,T_1\,r^{\gamma-1}$$

$$T_4 = T_3\left(\frac{v_3}{v_4}\right)^{\gamma-1} = T_3\left(\frac{v_4}{v_3}\right)^{\gamma-1}$$

$$= T_3\left(\frac{v_4}{v_2}.\frac{v_2}{v_3}\right)^{1-\gamma} = T_3\left(\frac{r}{r_c}\right)^{1-\gamma}$$

$$= r_c\ T_1\ r^{\gamma-1}\left(\frac{r}{r_c}\right)^{1-\gamma} \quad ; \quad T_4 = r_c^{\gamma}\ T_1$$

Hence,

$$\eta_{th} = 1 - \frac{1}{\gamma}\left\{\frac{r_c^{\gamma}\ T_1 - T_1}{r_c\ r^{\gamma-1}\ T_1 - r^{\gamma-1}\ T_1}\right\}$$

$$= 1 - r^{1-\gamma}\left\{\frac{r_c^{\gamma} - 1}{\gamma(r_c - 1)}\right\}$$

From the above equation, it is observed that, the thermal efficiency of the diesel engine can be increased by increasing the compression ratio, r, by decreasing the cut-off ratio, α_2, or by using a gas with large value of γ. Since the quantity $(r^{\gamma}-1)/\gamma(r_p-1)$ in above equation is always greater than unity, the efficiency of a Diesel cycle is always lower than that of an Otto cycle having the same compression ratio. However, practical Diesel engines uses higher compression ratios compared to petrol engines.

Mean effective Pressure:

$$mep = \frac{\text{Net workdone}}{\text{Displacement volume}}$$

$$= \frac{m\,C_p\,(T_3 - T_2) - m\,C_v\,(T_4 - T_1)}{v_1 - v_2}$$

$$v_1 - v_2 = v_1\left(1 - \frac{v_2}{v_1}\right) = v_1\left(1 - \frac{1}{r}\right)$$

$$= m\,R\,T_1\left(\frac{r - 1}{r}\right)$$

$$= \frac{m\,C_v\,(\gamma - 1)\,T_1}{P_1}\left(\frac{r - 1}{r}\right)$$

$$mep = \frac{m\,C_p\,(T_3 - T_2) - m\,C_v\,(T_4 - T_1)}{m\,C_v T_1\left(\frac{\gamma - 1}{P_1}\right)\left(\frac{r - 1}{r}\right)}$$

$$\left(\frac{P_1\,r}{r - 1}\right)\left(\frac{1}{\gamma - 1}\right)\left\{\gamma\left(\frac{T_3 - T_2}{T_1}\right) - \left(\frac{T_4 - T_1}{T_1}\right)\right\}$$

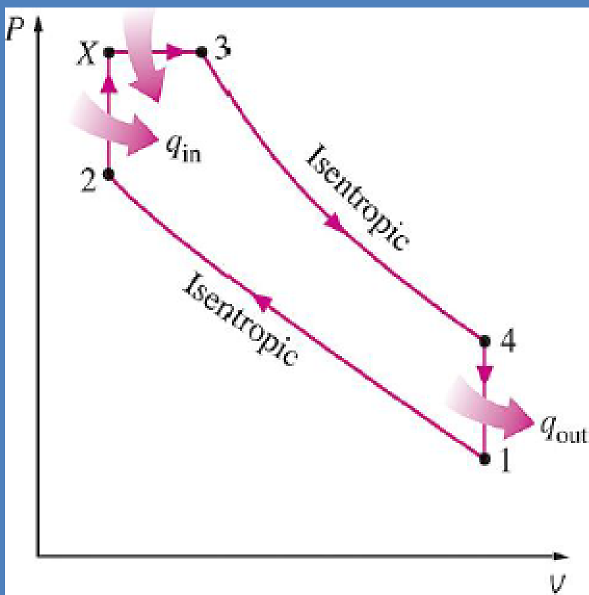
$$= P_1\,r\left\{\frac{\gamma\,r^{\gamma-1}\,(r_c - 1) - \left(r_c^{\gamma} - 1\right)}{(r - 1)(\gamma - 1)}\right\}$$

Difference between Actual Diesel and the Otto Engines:

Otto Engine	Diesel Engine
1. Homogenous mixture of fuel and air formed in the carburetor is supplied to engine cylinder.	1. No carburetor is used. Air alone is supplied to the engine cylinder. Fuel is injected directly into the engine cylinder at the end of compression stroke by means of a fuel injector. Fuel-air mixture is heterogeneous.
2. Ignition is initiated by means of an electric spark plug.	2. No spark plug is used. Compression ratio is high and the high temperature of air ignites fuel.
3. Power output is controlled by varying the mass of fuel-air mixture by means of a throttle valve in the carburetor.	3. No throttle value is used. Power output is controlled only by means of the mass of fuel injected by the fuel injector.

DUAL CYCLE:

Dual cycle: A more realistic ideal cycle model for modern, high-speed compression ignition engine.



P-v diagram of an ideal dual cycle.

QUESTIONS

Diesel engines operate at higher air-fuel ratios than gasoline engines. Why?

Despite higher power to weight ratios, two-stroke engines are not used in automobiles. Why?

The stationary diesel engines are among the most efficient power producing devices (about 50%). Why?

What is a turbocharger? Why are they mostly used in diesel engines compared to gasoline engines.

Limited Pressure Cycle:

This cycle is also called as the dual cycle, which is shown in Fig. Here the heat addition occurs partly at constant volume and partly at constant pressure. This cycle is a closer approximation to the behavior of the actual Otto and Diesel engines because in the actual engines, the combustion process does not occur exactly at constant volume or at constant pressure but rather as in the dual cycle.

Process 1-2: Reversible adiabatic compression.

Process 2-3: Constant volume heat addition.

Process 3-4: Constant pressure heat addition.

Process 4-5: Reversible adiabatic expansion.

Process 5-1: Constant volume heat rejection.

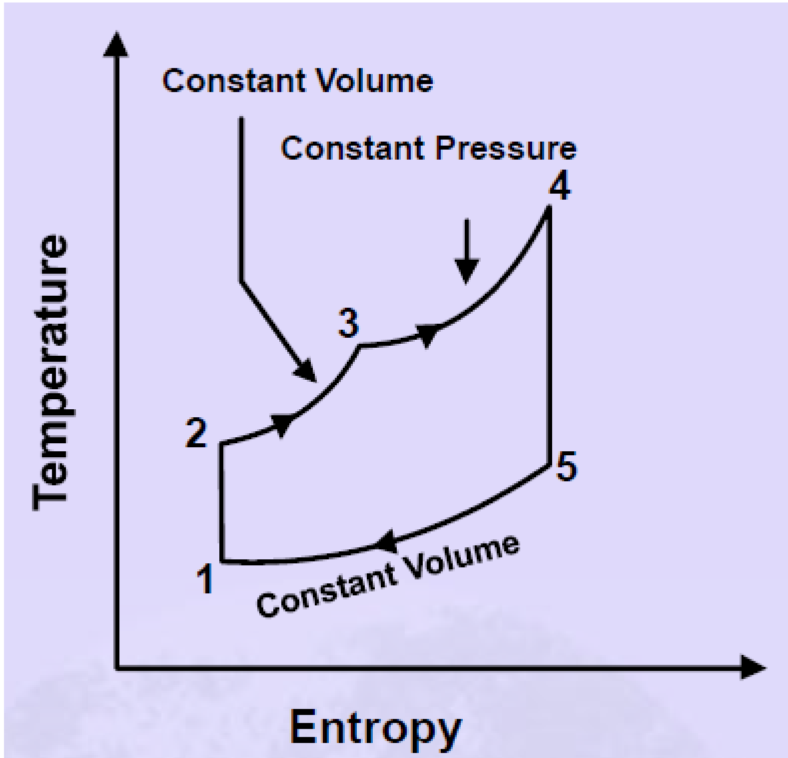


Fig. Dual cycle on T-S diagram

Air Standard Efficiency:

$$\text{Heat supplied} = m\,C_v\left(T_3 - T_2\right) + m\,C_p\left(T_4 - T_3\right)$$

$$\text{Heat rejected} = m\,C_v\left(T_5 - T_1\right)$$

$$\text{Net work done} = m\,C_v\left(T_3 - T_2\right) + m\,C_p\left(T_4 - T_3\right) - m\,C_V\left(T_5 - T_1\right)$$

$$\eta_{th} = \frac{m\,C_v\left(T_3 - T_2\right) + m\,C_p\left(T_4 - T_3\right) - m\,C_v\left(T_5 - T_1\right)}{m\,C_v\left(T_3 - T_2\right) + m\,C_p\left(T_4 - T_3\right)}$$

$$\eta_{th} = 1 - \frac{T_5 - T_1}{\left(T_3 - T_2\right) + \gamma\left(T_4 - T_3\right)}$$

$$\text{Let, } \frac{P_3}{P_2} = r_p \;;\; \frac{v_4}{v_3} = r_c \;;\; \frac{v_1}{v_2} = r$$

$$T_2 = T_1\,r^{\gamma - 1}$$

$$T_3 = T_2\,r_p = T_1\,r^{\gamma - 1}\,r_p$$

$$T_4 = T_3\,r_c = T_1\,r^{\gamma - 1}\,r_p\,r_c$$

$$\frac{T_5}{T_4} = \left(\frac{v_4}{v_5}\right)^{\gamma - 1} = \left(\frac{v_4}{v_2} \cdot \frac{v_2}{v_5}\right)^{\gamma - 1} = \left(\frac{r_c}{r}\right)^{\gamma - 1}$$

$$T_5 = T_4 \left(\frac{r_c}{r}\right)^{\gamma - 1} = T_1 \; r_p \; r_c^{\gamma}$$

$$\eta_{th} = 1 - \frac{T_1 \; r_p \; r_c^{\gamma} - T_1}{\left\{\left(T_1 \; r^{\gamma - 1} \; r_p - T_1 \; r^{\gamma - 1}\right) + \gamma\left(T_1 \; r^{\gamma - 1} \; r_p \; r_c - T_1 \; r^{\gamma - 1} \; r_p\right)\right\}}$$

$$= 1 - \frac{\left(r_p \; r_c^{\gamma} - 1\right)}{\left\{\left(r_p \; r^{\gamma - 1} - r^{\gamma - 1}\right) + \gamma\left(r_p \; r_c \; r^{\gamma - 1} - r_p \; r^{\gamma - 1}\right)\right\}}$$

$$\eta_{th} \; 1 - \frac{1}{r^{\gamma - 1}} \left\{\frac{r_p \; r_c^{\gamma} - 1}{\left(r_p - 1\right) + \gamma r_p \left(r_c - 1\right)}\right\}$$

From the above equation, it is observed that, a value of rp > 1 results in an increased efficiency for a given value of rc and γ. Thus, the efficiency of the dual cycle lies between that of the Otto cycle and the Diesel cycle having the same compression ratio.

Mean Effective Pressure:

$$\text{mep} = \frac{\text{Workdone}}{\text{Displacement volume}}$$

$$= \frac{m\,C_v\left(T_3 - T_2\right) + m\,C_p\left(T_4 - T_3\right) - m\,C_v\left(T_5 - T_1\right)}{v_1 - v_2}$$

$$v_1 - v_2 = \frac{m\,C_v(\gamma - 1)T_1}{p_1}\left(\frac{r - 1}{r}\right)$$

$$mep = \frac{p_1 r}{(r-1)(\gamma-1)}\left\{\frac{T_3 - T_2}{T_1} + \frac{\gamma(T_4 - T_3)}{T_1} - \frac{T_5 - T_1}{T_1}\right\}$$

$$= \frac{p_1 r}{(r-1)(\gamma-1)}\left\{r^{\gamma-1}(r_p - 1) + \gamma r^{\gamma-1} r_p (r_c - 1) - (r_p r_c^{\gamma} - 1)\right\}$$

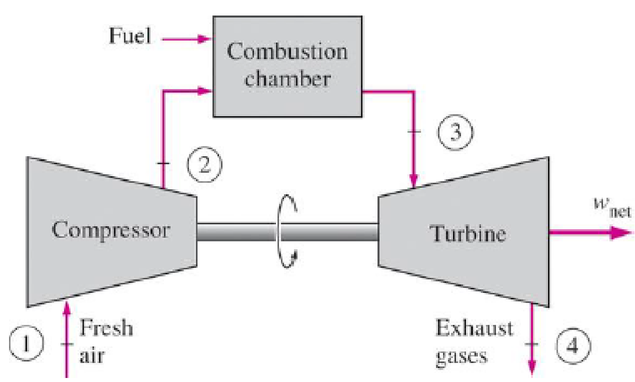
$$= \frac{p_1 r}{(r-1)(\gamma-1)}\left\{r^{\gamma-1}\{(r_p - 1) + \gamma r_p (r_c - 1)\} - (r_p r_c^{\gamma} - 1)\right\}$$

BRAYTON CYCLE:

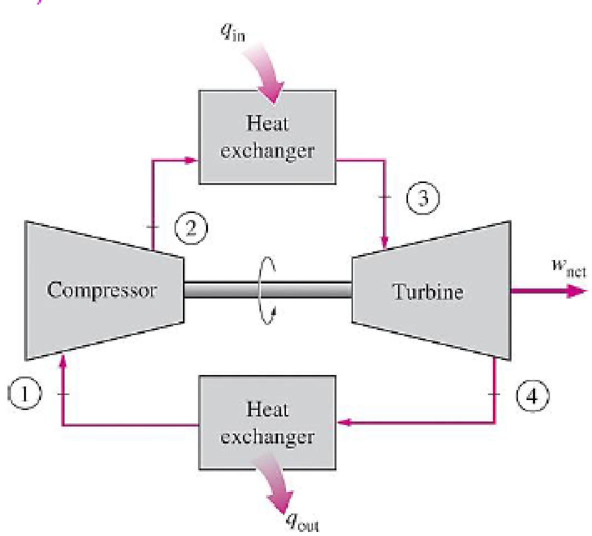
BRAYTON CYCLE: THE IDEAL CYCLE FOR GAS-TURBINE ENGINES

The combustion process is replaced by a constant-pressure heat-addition process from an external source, and the exhaust process is replaced by a constant-pressure heat-rejection process to the ambient air.

1-2 Isentropic compression (in a compressor)
2-3 Constant-pressure heat addition
3-4 Isentropic expansion (in a turbine)
4-1 Constant-pressure heat rejection



An open-cycle gas-turbine engine.



A closed-cycle gas-turbine engine.

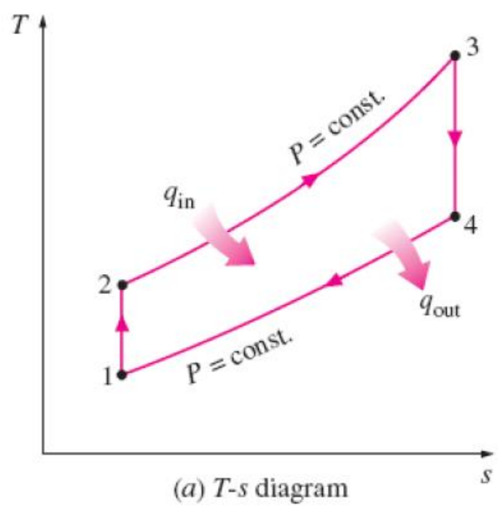
The Brayton cycle was first proposed by George Brayton for use in the reciprocating oil-burning engine that he developed around 1870. Today, it is used for gas turbines only where both the compression and expansion processes take place in rotating machinery. Gas turbines usually operate on an *open cycle,* as shown in Fig. Fresh air at ambient conditions is drawn into the compressor, where its temperature and pressure are raised. The high-pressure air proceeds into the combustion chamber, where the fuel is burned at constant pressure. The resulting high temperature gases then enter the turbine, where they expand to the atmospheric pressure while producing power. The exhaust gases leaving the turbine are thrown out (not recirculated), causing the cycle to be classified as an open cycle. The open gas-turbine cycle described above can be modelled as a *closed cycle,* as shown in Fig., by utilizing the air-standard assumptions. Here the compression and expansion processes remain the same, but the combustion process is replaced by a constant-pressure heat-addition process from an external source, and the exhaust process is replaced by a constant pressure heat-rejection process to the ambient air. The ideal cycle that the working fluid undergoes in this closed loop is the **Brayton cycle,** which is made up of four internally reversible processes:

1-2 Isentropic compression (in a compressor)

2-3 Constant-pressure heat addition

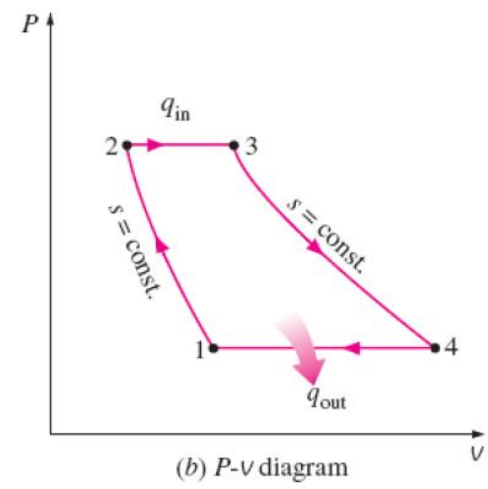
3-4 Isentropic expansion (in a turbine)

4-1 Constant-pressure heat rejection



(a) T-s diagram

Figure: T-s diagram of the Ideal Brayton Cycle



(b) P-v diagram

Figure: P-v diagram of the Ideal Brayton Cycle

The highest temperature in the cycle occurs at the end of the combustion process (state 3), and it is limited by the maximum temperature that the turbine blades can withstand. This also limits the pressure ratios that can be used in the cycle. There should be a compromise between the pressure ratio (thus the thermal efficiency) and the net work output. With less work output per cycle, a larger mass flow rate (thus a larger system) is needed to maintain the same power output, which may not be economical. In most common designs, the pressure ratio of gas turbines ranges from about 11 to 16.

The air in gas turbines performs two important functions: It supplies the necessary oxidant for the combustion of the fuel, and it serves as a coolant to keep the temperature of various components within safe limits. The second function is accomplished by drawing in more air than is needed for the complete combustion of the fuel. In gas turbines, an air–fuel mass ratio of 50 or above is not uncommon. Therefore, in a cycle analysis, treating the combustion gases as air does not cause any appreciable error. Also, the mass flow rate through the turbine is greater than that through the compressor, the difference being equal to the mass flow rate of the fuel. Thus, assuming a constant mass flow rate throughout the cycle yields conservative results for open-loop gas-turbine engines.

The two major application areas of gas-turbine engines are *aircraft propulsion* and *electric power generation.* When it is used for aircraft propulsion, the gas turbine produces just enough power to drive the compressor and a small generator to power the auxiliary equipment. The high-velocity exhaust gases are responsible for producing the necessary thrust to propel the aircraft. Gas turbines are also used as stationary power plants to generate electricity as stand-alone units or in conjunction with steam power plants on the high-temperature side. In these plants, the exhaust gases of the gas turbine serve as the heat source for the steam. The gas-turbine cycle can also be executed as a closed cycle for use in nuclear power plants. This time the working fluid is not limited to air, and a gas with more desirable characteristics (such as helium) can be used. The majority of the Western world's naval fleets already use gas-turbine engines for propulsion and electric power generation. The General Electric LM2500 gas turbines used to power ships have a simple-cycle thermal efficiency of 37 percent. The General Electric WR-21 gas turbines equipped with intercooling and regeneration have a thermal efficiency of 43 percent and produce 21.6 MW (29040 hp). The regeneration also reduces the exhaust temperature from 600°C to 350°C. Air is compressed to 3 atm before it enters the intercooler. Compared to steam-turbine and diesel propulsion systems, the gas turbine offers greater power for a given size and weight, high reliability, long life, and more convenient operation. The engine start-up time has been reduced from 4 h required for a typical steam propulsion system to less than 2 min for a gas turbine. Many modern marine propulsion systems use gas turbines together with diesel engines because of the high fuel consumption of simple-cycle gas-turbine engines. In combined diesel and gas-turbine systems, diesel is used to provide for efficient low-power and cruise operation, and gas turbine is used when high speeds are needed. In gas-turbine power plants, the ratio of the compressor work to the turbine work, called the back-work ratio**,** is very high. Usually more than one-half of the turbine work output is used to drive the compressor. The situation is even worse when the isentropic efficiencies of the compressor and the turbine are low. This is quite in contrast to steam power plants, where the back-work ratio is only a few percent. This is not surprising, however, since a liquid is compressed in steam power plants instead of a gas, and the steady-flow work is proportional to the specific volume of the working fluid. A power plant with a high back work ratio requires a larger turbine to provide the additional power requirements of the compressor. Therefore, the turbines used in gas-turbine power plants are larger than those used in steam power plants of the same net power output.

Energy added, $Q_{in} = C_p (T_3 - T_2)$

Energy rejected, $Q_{out} = C_p (T_4 - T_1)$

Thermal efficiency for the Brayton cycle is:

$$\eta_{th,Brayton} = 1 - \frac{q_{out}}{q_{in}} = 1 - \frac{(T_4 - T_1)}{(T_3 - T_2)} = 1 - \frac{T_1(T_4 / T_1 - 1)}{T_2(T_3 / T_2 - 1)}$$

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

thus

$$\eta_{th,Brayton} = 1 - \frac{1}{r_P^{(k-1)/k}}$$

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

where r_P is called the pressure ration and $k = c_p / c_v$ is the specific heat ratio.

Actual Brayton Cycle

Irreversibilities exist in actual cycle. Most important differences are deviations of actual compressor and turbine from idealized isentropic compression/expansion, and pressure drop in combustion chamber.

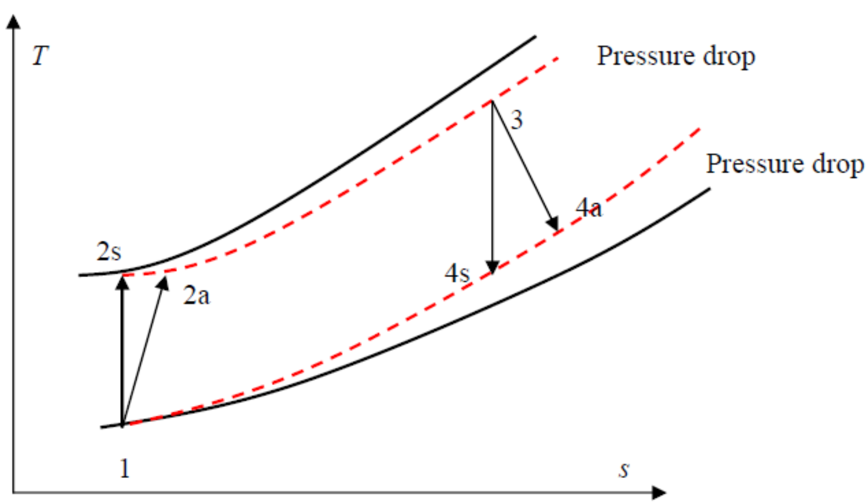


Fig. 4: Actual Brayton cycle.

$$\eta_c = \frac{w_s}{w_a} \cong \frac{h_{2s} - h_1}{h_{2a} - h_1} \qquad \eta_T = \frac{w_a}{w_s} \cong \frac{h_3 - h_{4a}}{h_3 - h_{4s}}$$

THE BRAYTON CYCLE WITH REGENERATION:

In gas-turbine engines, the temperature of the exhaust gas leaving the turbine is often considerably higher than the temperature of the air leaving the compressor. Therefore, the high-pressure air leaving the compressor can be heated by transferring heat to it from the hot exhaust gases in a counter-flow heat exchanger, which is also known as a *regenerator* or a *recuperator.* A sketch of the gas-turbine engine utilizing a regenerator and the *T*-*s* diagram of the new cycle are shown in Figs. The thermal efficiency of the Brayton cycle increases as a result of regeneration since the portion of energy of the exhaust gases that is normally rejected to the surroundings is now used to preheat the air entering the combustion chamber. This, in turn, decreases the heat input (thus fuel) requirements for the same net work output. Note, however, that the use of a regenerator is recommended only when the turbine exhaust temperature is higher than the compressor exit temperature. Otherwise, heat will flow in the reverse direction (*to* the exhaust gases), decreasing the efficiency. This situation is encountered in gas-turbine engines operating at very high-pressure ratios.

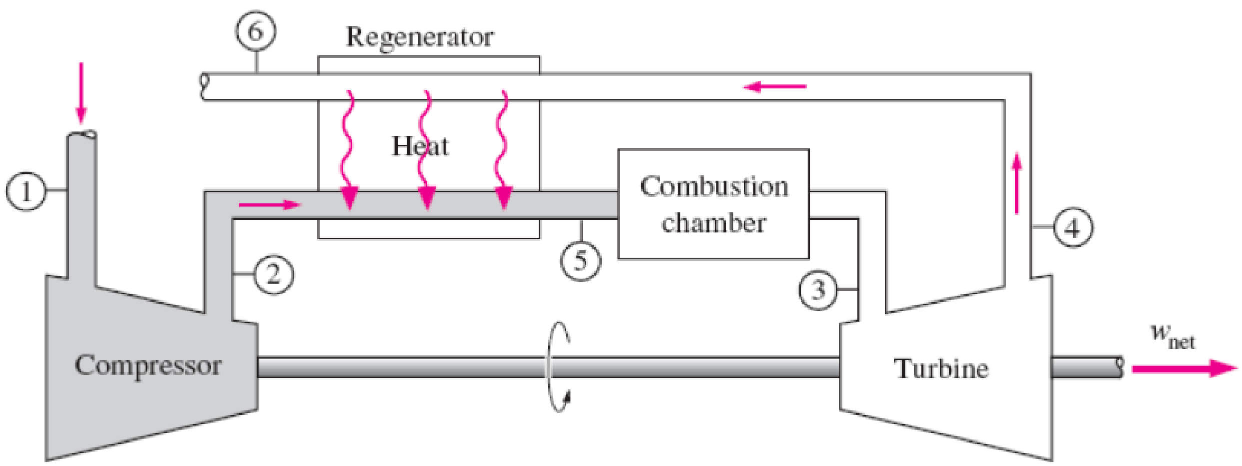
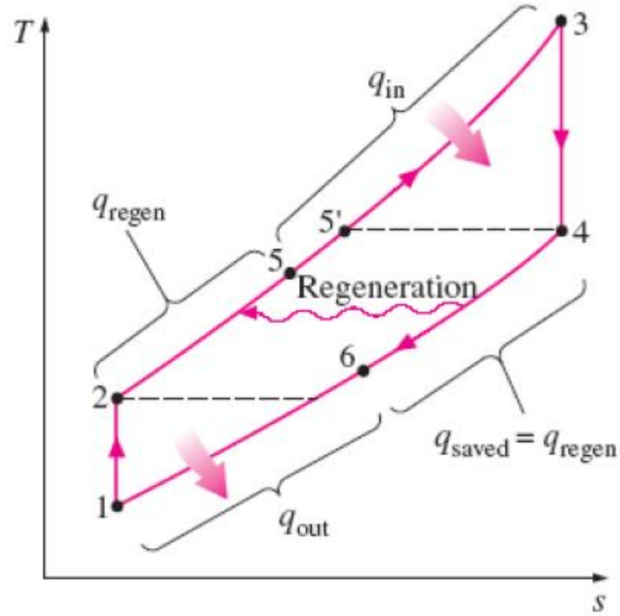


Figure: A gas-turbine engine with regenerator.

The highest temperature occurring within the regenerator is *T*4, the temperature of the exhaust gases leaving the turbine and entering the regenerator. Under no conditions can the air be preheated in the regenerator to a temperature above this value. Air normally leaves the regenerator at a lower temperature, *T*5. In the limiting (ideal) case, the air exits the regenerator at the inlet temperature of the exhaust gases *T*4.



T-S diagram on Brayton cycle with regeneration

In the ideal case, the air exits the regenerator at the inlet temperature of the exhaust gases, T_4. One can write:

$q_{regen,\ actual} = h_5 - h_2$

$q_{regen,\ max} = h_{5'} - h_2 = h_4 - h_2$

The effectiveness of regenerator is defined as:

$$\varepsilon = \frac{q_{regen,act}}{q_{regen,\max}} = \frac{h_5 - h_2}{h_4 - h_2} = \frac{T_5 - T_2}{T_4 - T_2} \text{(assuming cold - air - standard conditions)}$$

Thermal efficiency of an ideal Brayton cycle with regenerator can be found from:

$$\eta_{th,regen} = 1 - \left(\frac{T_1}{T_3}\right)(r_p)^{(k-1)/k}$$

GAS TURBINE CYCLE WITH REHEAT:

A common method of increasing the mean temperature of heat reception is to reheat the gas after it has expanded in a part of the gas turbine. By doing so the mean temperature of heat rejection is also increased, resulting in a decrease in the thermal efficiency of the plant. However, the specific output of the plant increases due to reheat. A reheat cycle gas turbine plant is shown in Figure,

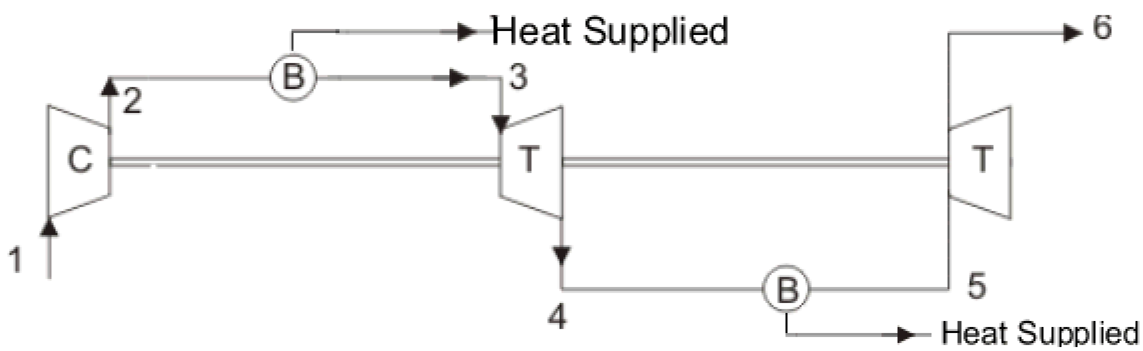


Figure: Brayton cycle with Reheater

The specific work output is given by,

$$= C_p(T_3 - T_4) + C_p(T_5 - T_6) - C_p(T_2 - T_1)$$

The heat supplied to the cycle is

$$= C_p(T_3 - T_2) + C_p(T_5 - T_4)$$

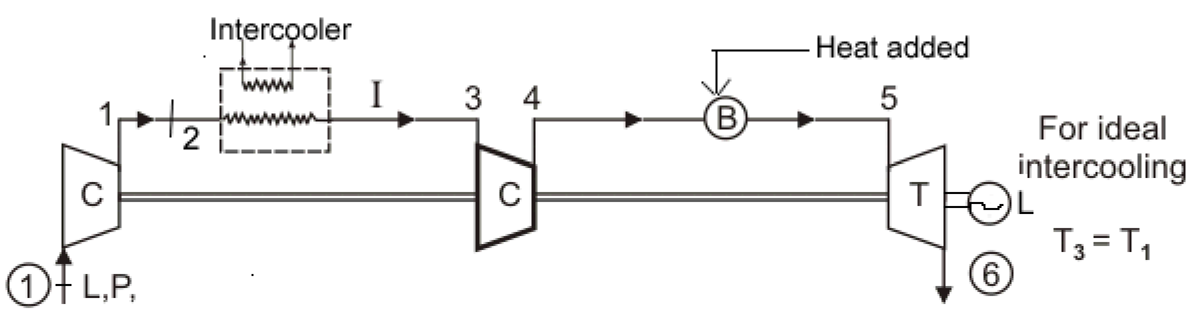
Thus, the cycle efficiency,

$$\eta = \frac{(T_3 - T_4) + (T_5 - T_6) - (T_2 - T_1)}{(T_3 - T_2) + (T_5 - T_4)}$$

Therefore, a reheat cycle is used to increase the work output while a regenerative cycle is used to enhance the efficiency.

GAS TURBINE CYCLE WITH INTER-COOLING:

The cooling of air between two stages of compression is known as intercooling. This reduces the work of compression and increases the specific output of the plant with a decrease in the thermal efficiency. The loss in efficiency due to intercooling can be remedied by employing exhaust heat exchange as in the reheat cycle.



Specific work output $= C_p(T_5 - T_6) - C_p(T_2 - T_1) - C_p(T_4 - T_3)$

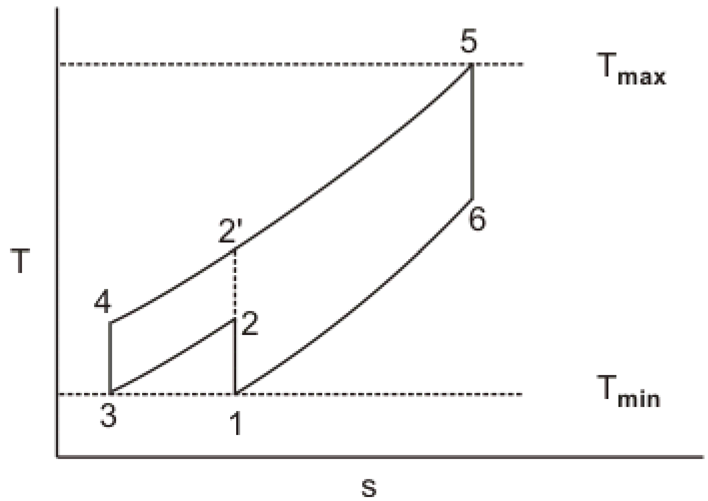


Figure: Brayton Cycle with intercooling

Heat supplied = $C_p(T_5 - T_4)$

If C_p is constant and not dependent on temperature, we can write:

$$\eta = \frac{(T_5 - T_6) - (T_2 - T_1) - (T_4 - T_3)}{(T_5 - T_4)}$$

Note $C_p(T_4 - T_3) < C_p(T_2' - T_2)$

Here heat supply and output both increases as compared to simple cycle. Because the increase in heat supply is proportionally more, η decreases.

With multiple inter-cooling and multiple reheat, the compression and expansion processes tend to be isothermal as shown in Figure.

BRAYTON CYCLE WITH INTERCOOLING, REHEATING, AND REGENERATION:

The net work output of the cycle can be increased by reducing the work input to the compressor and/or by increasing the work output from turbine (or both). Using multi-stage compression with intercooling reduces the work input the compressor. As the number of stages is increased, the compression process becomes nearly isothermal at the compressor inlet temperature, and the compression work decreases. Likewise utilizing multistage expansion with reheat (in a multi-turbine arrangement) will increase the work produced by turbines.

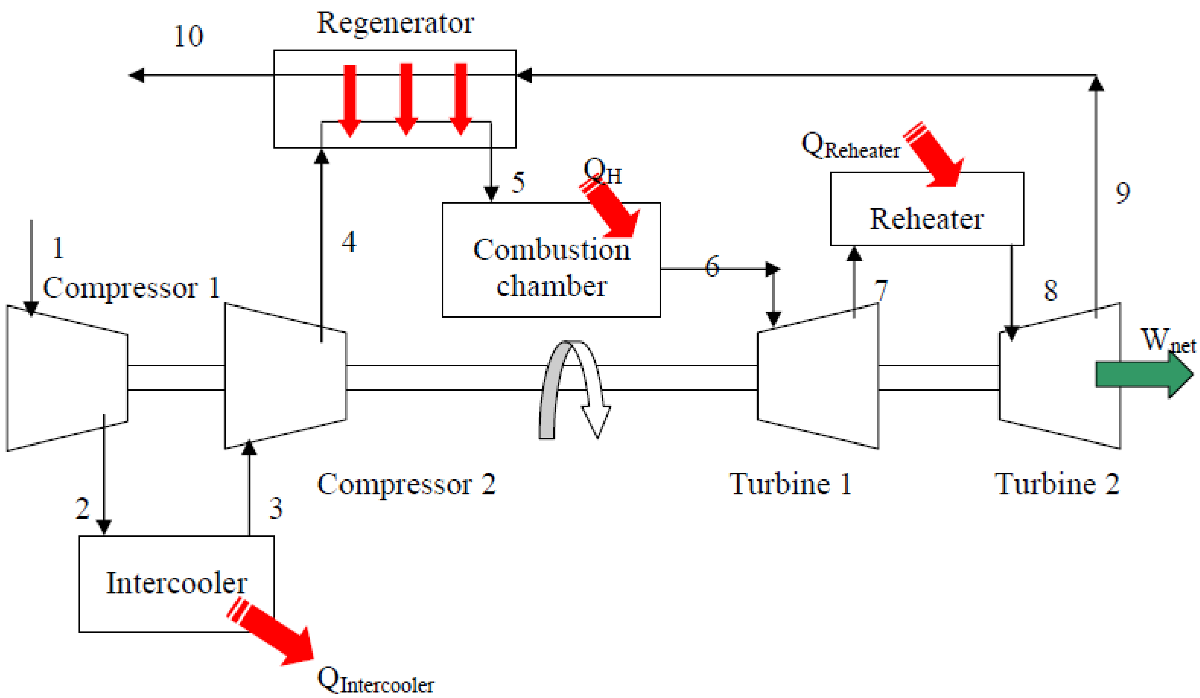


Fig. A gas-turbine engine with two-stage compression with intercooling, two-stage expansion with reheating, and regeneration.

When intercooling and reheating are used, regeneration becomes more attractive since a greater potential for regeneration exists. The back work ratio of a gas-turbine improves as a result of intercooling and reheating. However; intercooling and reheating *decreases thermal efficiency* unless they are accompanied with regeneration.

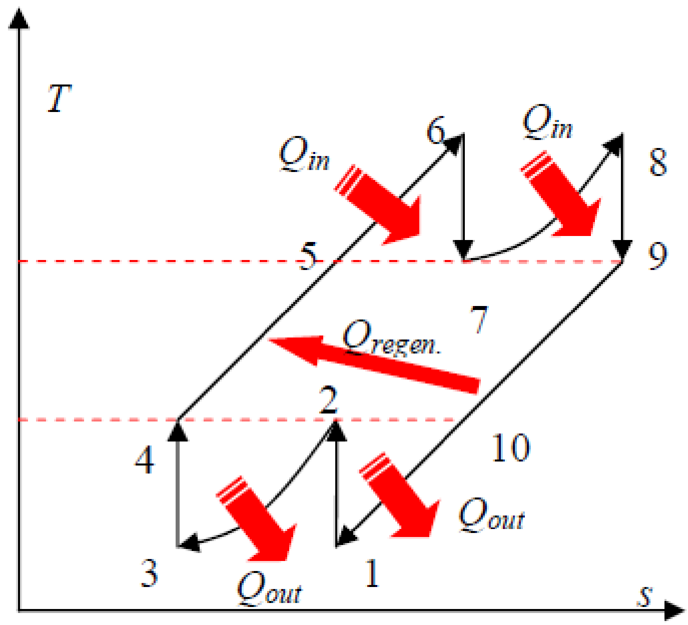


Fig. T-S diagram on Brayton cycle with intercooler, reheater & regenerator

As shown in Fig. 8:

$T_1 = T_3$, $T_2 = T_4$

In an ideal regenerator, $T_5 = T_9$. In practice (actual regenerator), $T_5 < T_9$.

$T_8 = T_6$, $T_7 = T_9$

The net work input to a two-stage compressor is minimized when equal pressure ratios are maintained across each stage. That is:

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

This procedure also maximizes the turbine work output.

$$\frac{P_6}{P_7} = \frac{P_8}{P_9}$$

5. Related Laboratories: Conduct the performance test on axial/centrifugal air compressor and draw its performance characteristics.

6. Post Test:

1. Explain the principle of operation of Brayton cycle?
2. Explain the principle of operation of Brayton cycle with regeneration?
3. Explain the principle of operation of Brayton cycle with reheater?

4. Explain the principle of operation of Brayton cycle with regenerator, reheater & intercooling?

7. Conclusions:

- Gas-turbine is used in aircraft propulsion and electric power generation.
- High thermal efficiencies up to 44%.
- Suitable for combined cycles (with steam power plant)
- High power to weight ratio, high reliability, long life
- Fast start up time, about 2 min, compared to 4 hr for steam-propulsion systems
- High back work ratio (ratio of compressor work to the turbine work), up to 50%, compared to few percent in steam power plants.

8. Reference: R.K. Rajput, Thermal Engineering, 6th Edition, Laxmi Publications (P) Ltd.,

9. Demo Video:

https://www.youtube.com/watch?v=kuvq-X9sdr0
https://www.youtube.com/watch?v=boqulC62Hsk
https://www.youtube.com/watch?v=t5IQ2TyiG5w
https://www.youtube.com/watch?v=eIwGBVG0Srk

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Name of the Course : **Applied Thermodynamics**

Name of the Unit : **Steam Nozzle**

Name of the Topic : **Steam Nozzle**

1. Objectives: To understand the basics and flow of steam through steam nozzle.

Outcomes: Upon successful completion, the student should be able to understand the basics, and flow of steam through steam nozzle.

2. Pre-Test: (Students should be able to answer the following)

1. State and explain the various types of steam?
2. Show the various process of Rankine cycle on T-S diagram.

3. Pre-requisites: To have a basic knowledge of pure substances.

4. Theory Behind: STEAM NOZZLES: TECHNICAL TERMS:

- **Wet steam:** The steam which contains some water particles in superposition.
- **Dry steam / dry saturated steam:** When whole mass of steam is converted into steam then it is called as dry steam.
- **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.
- **Degree of super heat:** The difference between the temperature of saturated steam and saturated temperature is called degree of superheat.
- **Nozzle:** It is a duct of varying cross-sectional area in which the velocity increases with the corresponding drop in pressure.
- **Coefficient of nozzle:** It is the ratio of actual enthalpy drop to isentropic enthalpy drop.
- **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.

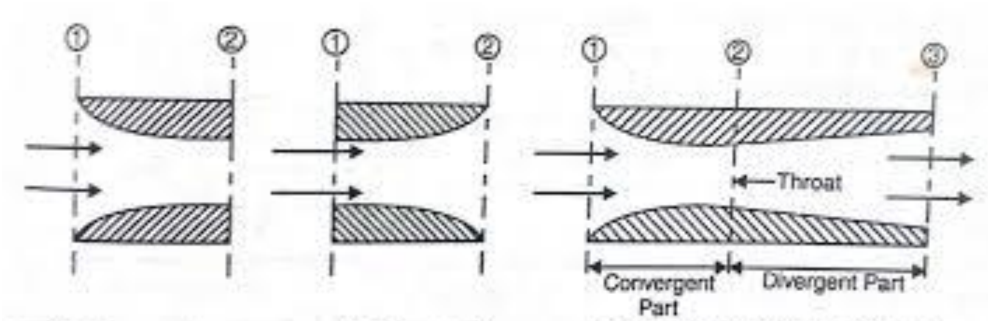
Introduction:

A steam nozzle is a passage of varying cross-section, which converts heat energy of steam into kinetic energy. During the first part of the nozzle, the steam increases its velocity. But in its later part, the steam gains more in volume than in velocity. Since the mass of steam, passing through any section of the nozzle remains constant, the variation of steam pressure in the nozzle depends upon the velocity, specific volume and dryness fraction of steam. A well-designed nozzle converts the heat energy of steam into kinetic energy with a minimum loss. The main use of steam nozzle in steam turbines, is to produce a jet of steam with a high velocity. The smallest section of the nozzle is called throat.

Types of Steam Nozzles:

Following three types of nozzles are important from the subject point of view:

1. Convergent nozzle: When the cross-section of a nozzle decreases continuously from entrance to exit, it is called a convergent nozzle as shown in Fig. (a).



(a) Convergent Nozzle (b) Divergent Nozzle (c) Convergent-Divergent Nozzle

2. Divergent nozzle. When the cross-section of a nozzle increases continuously from entrance to exit, it is called a divergent nozzle, as shown in Fig. (b).

3. Convergent-divergent nozzle. When the cross-section of a nozzle first decreases from its entrance to throat, and then increases from its throat to exit, it is called a convergent-divergent nozzle as shown in Fig. (c). This type of nozzle is widely used these days in various types of steam turbines.

Flow of Steam through Convergent-divergent Nozzle:

The steam enters the nozzle with a high pressure, but with a negligible velocity. in he converging portion (i.e. from the inlet to the throat), there is a drop in the steam pressure with a rise in its velocity. There is also a drop in the enthalpy or total heat of the steam. This drop of heat.is not utilized in doing some external work, but is converted into kinetic energy. In the divergent portion (i.e. from the throat to outlet), there is further drop of steam pressure with a further rise in its velocity. Again, there is a drop in the enthalpy or total heat of steam, which is converted into kinetic energy. It will be interesting to know that the steam enters, the nozzle with a high pressure and negligible velocity. But leaves the nozzle with a high velocity and small pressure. The pressure, at which the steam leaves the nozzle, is known as backpressure. Moreover, no heat is supplied or rejected by the steam during flow through a nozzle. Therefore, it is considered as isentropic flow, and the corresponding expansion is considered as an isentropic expansion.

Velocity of Steam Flowing through a Nozzle:

Consider a unit mass flow of steam through a nozzle.

Let V_1 = Velocity of steam at the entrance *of* nozzle in m/s

V_2 = Velocity *of* steam at any section considered in m/s,

h_1 = Enthalpy or total heat *of* steam entering the nozzle in kJ/kg, and

h_2 = Enthalpy or total heat *of* steam leaving the nozzle in kJ/kg,

We know that for a steady flow process in a nozzle,

$h_1+(v_1^2/2000) = h_2+(V_2^2/2000)$ + Losses

$V_2=[V_1^2+2000(h_1-h_2)]^{½}$

$V_2=[V_1^2+2000(h_d)]^{½}$

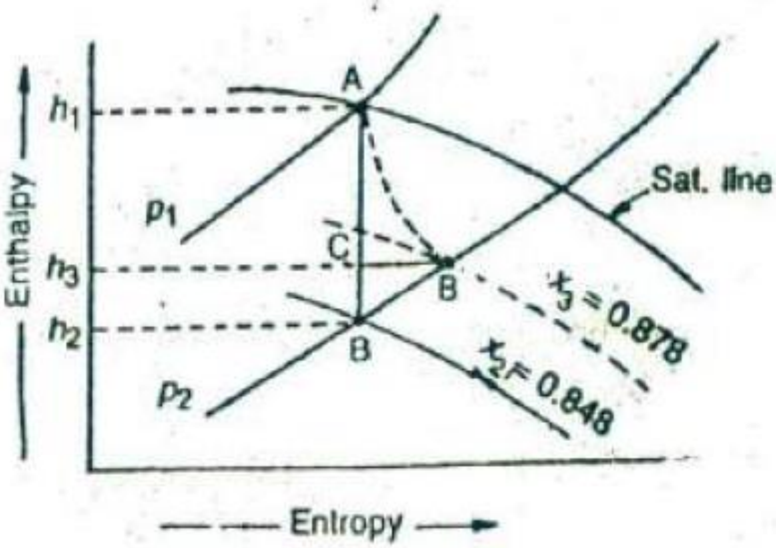
Where h_d= heat drop or enthalpy drop during expansion of steam in nozzle, Since, inlet velocity V_1 is negligible; Exit velocity $V_2=44.72(h_d)^{½}$

In actual practice, there is always a certain amount of friction present between the steam and nozzle surfaces. This reduces the heat drop by to 15 percent and thus the exit velocity of steam is also reduced correspondingly. Thus, the above relation may be written as: $V_2=44.72(Kh_d)^{½}$

Where K is nozzle co-efficient or nozzle efficiency

Friction in a Nozzle or Nozzle Efficiency:

As a matter fact, when the steam flows through a nozzle, some loss in its enthalpy or total heat takes place due to friction between the nozzle surface and the flowing steam. This can be best understood with the help of *h-s* diagram or Mollier chart, as shown in Fig.



coefficient of nozzle or nozzle efficiency (usually denoted by K) is defined as the ratio of useful heat drop to the isentropic heat drop. Mathematically,

K = Useful heat drop/Isentropic heat drop = AC/AB = $(h_1\text{-}h_3)/(h_1\text{-}h_2)$

In general, if 15% of the heat drop is Iost in friction, then efficiency of the nozzle is equal to 100- 15 = 85%= 0.85.

Mass of Steam Discharged through Nozzle:

18.2.2. Discharge through the Nozzle and Conditions for its Maximum Value :

Let p_1 = Initial pressure of steam,

v_1 = Initial volume of 1 kg of steam at pressure p_1 (m^3),

p_2 = Steam pressure at the throat,

v_2 = Volume of 1 kg of steam at pressure p_2 (m^3),

A = Cross-sectional area of nozzle at throat (m^2), and

C = Velocity of steam (m/s).

The steam flowing through the nozzle follows approximately the equation given below :

$$pv^n = \text{Constant}$$

where, $n = 1.135$ for **saturated steam**

and $= 1.3$ for **superheated steam.**

[For **wet steam,** the value of n can be calculated by Dr. *Zenner's equation,*

$n = 1.035 + 0.1x$, where x is the initial dryness fraction of steam]

Work done per kg of steam during the cycle (Rankine area)

$$= \frac{n}{n-1}(p_1v_1 - p_2v_2)$$

and, Gain in kinetic energy = Adiabatic heat drop

= Work done during Rakine cycle

or
$$\frac{C^2}{2} = \frac{n}{n-1}(p_1v_1 - p_2v_2)$$

$$= \frac{n}{n-1}p_1v_1\left(1 - \frac{p_2v_2}{p_1v_1}\right) \quad ...(18.3)$$

Also
$$p_1v_1^n = p_2v_2^n$$

or
$$\frac{v_2}{v_1} = \left(\frac{p_1}{p_2}\right)^{1/n} \quad ...(18.4)$$

or
$$v_2 = v_1\left(\frac{p_1}{p_2}\right)^{1/n} \quad ...(18.5)$$

Putting the value of v_2/v_1 from eqn. (18.4) in eqn. (18.3), we get

$$\frac{C^2}{2} = \frac{n}{n-1}p_1v_1\left[1 - \frac{p_2}{p_1}\left(\frac{p_1}{p_2}\right)^{1/n}\right] = \frac{n}{n-1}p_1v_1\left[1 - \left(\frac{p_2}{p_1}\right)^{1-\frac{1}{n}}\right]$$

$$= \frac{n}{n-1}p_1v_1\left[1 - \left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}}\right]$$

$$C^2 = 2\left(\frac{n}{n-1}\right)p_1v_1\left[1 - \left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}}\right]$$

$$C = \sqrt{2\left(\frac{n}{n-1}\right) p_1 v_1 \left\{1-\left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}}\right\}} \qquad ...(18.6)$$

If m is the mass of steam discharged in kg/sec.,

Then $$m = \frac{AC}{v_2} \qquad ...(18.7)$$

Substituting the value of v_2 from eqn. (18.5) in eqn. (18.7),

$$m = \frac{AC}{v_1\left(\frac{p_1}{p_2}\right)^{1/n}}$$

or

$$m = \frac{A}{v_1\left(\frac{p_1}{p_2}\right)^{1/n}} \sqrt{2\left(\frac{n}{n-1}\right) p_1 v_1 \left[1-\left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}}\right]}$$

$$= \frac{A}{v_1} \sqrt{\left[2\left(\frac{n}{n-1}\right) p_1 v_1 \left\{\left(\frac{p_2}{p_1}\right)^{2/n} - \left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}} \left(\frac{p_2}{p_1}\right)^{2/n}\right\}\right]}$$

$$= \frac{A}{v_1} \sqrt{\left[2\left(\frac{n}{n-1}\right) p_1 v_1 \left\{\left(\frac{p_2}{p_1}\right)^{2/n} - \left(\frac{p_2}{p_1}\right)^{\frac{n+1}{n}}\right\}\right]} \qquad ...(18.8)$$

Condition for Maximum Discharge through a Nozzle (Critical Pressure Ratio):

A nozzle is, normally, designed for maximum discharge by designing a certain throat pressure which produces this condition.

Let p_1 = Initial pressure of steam in N/rn^2.

p_2 = Pressure of steam at throat in N/rn^2,

v_1 = Volume of I kg of steam at pressure (P_1) in m^3,

v_2 = Volume of I kg of steam at pressure (p_2) in m^3 and

A = Cross-sectional area of nozzle at throat, in.

We have derived an equation in the previous article that the mass of steam discharged through nozzle,

$$m = A\sqrt{\frac{2n}{n-1}\times\frac{p_1}{v_1}\left[\left(\frac{p_2}{p_1}\right)^{\frac{2}{n}}-\left(\frac{p_2}{p_1}\right)^{\frac{n+1}{n}}\right]} \qquad \ldots(i)$$

There is only one value of the ratio p_2/p_1, which produces maximum discharge from the nozzle. This ratio p_2/p_1, is obtained by differentiating the right hand side of the equation. We see from this equation that except p_2/p_1, all other values are constant. Therefore, only that portion of the equation which contains p_2/p_1, is differentiated and equated to zero for maximum discharge.

$$\therefore \qquad \frac{d}{d\left(\frac{p_2}{p_1}\right)}\left[\left(\frac{p_2}{p_1}\right)^{\frac{2}{n}}-\left(\frac{p_2}{p_1}\right)^{\frac{n+1}{n}}\right] = 0$$

or

$$\frac{2}{n}\left(\frac{p_2}{p_1}\right)^{\frac{2}{n}-1} - \frac{n+1}{n}\left(\frac{p_2}{p_1}\right)^{\frac{n+1}{n}-1} = 0$$

$$\frac{2}{n}\left(\frac{p_2}{p_1}\right)^{\frac{2-n}{n}} = \frac{n+1}{n}\left(\frac{p_2}{p_1}\right)^{\frac{1}{n}}$$

$$\left(\frac{p_2}{p_1}\right)^{\frac{2-n}{n}}\times\left(\frac{p_2}{p_1}\right)^{-\frac{1}{n}} = \frac{n+1}{n}\times\frac{n}{2}$$

$$\left(\frac{p_2}{p_1}\right)^{\frac{2-n}{n}-\frac{1}{n}} = \frac{n+1}{2}$$

$$\left(\frac{p_2}{p_1}\right)^{\frac{1-n}{n}} = \frac{n+1}{2}$$

$$\frac{p_2}{p_1} = \left(\frac{n+1}{2}\right)^{\frac{n}{1-n}} = \left(\frac{n+1}{2}\right)^{\frac{-n}{-(1-n)}}$$

$$= \left(\frac{2}{n+1}\right)^{\frac{n}{n-1}} \qquad \ldots (ii)$$

Notes : 1. The ratio p_2 / p_1 is known as *critical pressure ratio,* and the pressure p_2 at the throat is known as *critical pressure.*

2. The maximum value of the discharge per second is obtained by substituting the value of p_2 / p_1 in equation (*i*).

$$\therefore \text{ Maximum discharge, } m_{max} = A\sqrt{\frac{2n}{n-1}\times\frac{p_1}{v_1}\left[\left(\frac{2}{n+1}\right)^{\frac{2}{n-1}} - \left(\frac{2}{n+1}\right)^{\frac{n+1}{n-1}}\right]}$$

$$= A\sqrt{\frac{2n}{n-1}\times\frac{p_1}{v_1}\left(\frac{2}{n+1}\right)^{\frac{2}{n-1}}\left[1-\left(\frac{2}{n+1}\right)^{\frac{n+1}{n-1}-\frac{2}{n-1}}\right]}$$

$$= A\sqrt{\frac{2n}{n-1}\times\frac{p_1}{v_1}\left(\frac{2}{n+1}\right)^{\frac{2}{n-1}}\left[1-\left(\frac{2}{n+1}\right)\right]}$$

$$= A\sqrt{\frac{2n}{n-1}\times\frac{p_1}{v_1}\left(\frac{2}{n+1}\right)^{\frac{2}{n-1}}\left[\frac{n-1}{n+1}\right]}$$

$$= A\sqrt{\frac{2n}{n+1}\times\frac{p_1}{v_1}\left(\frac{2}{n+1}\right)^{\frac{2}{n-1}}} \qquad \ldots (iii)$$

Values for Maximum Discharge through a Nozzle:

The maximum discharge through a nozzle,

$$m_{max} = A\sqrt{\frac{2n}{n+1} \times \frac{p_1}{v_1}\left(\frac{2}{n+1}\right)^{\frac{2}{n-1}}}$$

Now we shall discuss the values of maximum discharge for the following three conditions :

1. When the steam is dry saturated steam,

We know that for dry saturated steam. ***n =*** 1.135. Therefore, substituting the value of *n* relation for maximum discharge, we have

$$m_{max} = 0.637\, A\sqrt{\frac{p_1}{v_1}}$$

2. When the steam is initially superheated

We know that for superheated steam, ***n =*** 1.3. Therefore, substituting the value of *n* in the relation for maximum discharge, we have

$$m_{max} = 0.666\, A\sqrt{\frac{p_1}{v_1}}$$

3. For gases

We know that for gases, *n = 1.4.* Therefore, substituting the value of *n* in the relation for maximum discharge, we have

$$m_{max} = 0.685\, A\sqrt{\frac{p_1}{v_1}}$$

Values for critical pressure ratio:

The critical pressure ratio

$$\frac{p_2}{p_1} = \left(\frac{2}{n+1}\right)^{\frac{n}{n-1}}$$

p_2/p_1 = Critical pressure ratio.

We shall now discuss the values of critical pressure ratio for the following conditions:

1. *When the Steam is initially saturated:*

We know that for dry saturated steam, n = 1.135.

$$\frac{p_2}{p_1} = \left(\frac{2}{1.135+1}\right)^{\frac{1.135}{1.135-1}} = 0.577 \quad \text{or} \quad p_2 = 0.577\,p_1$$

2. *When the steam Is initially superheated*

   We know that for superheated steam, *is* = 1.3.

$$\frac{p_2}{p_1} = \left(\frac{2}{1.3+1}\right)^{\frac{1.3}{1.3-1}} = 0.546 \quad \text{or} \quad p_2 = 0.546\,p_1$$

3. *When the steam is initially wet*

   It has been experimentally found that the critical pressure ratio for wet steam.

$$\frac{p_2}{p_1} = 0.582 \quad \text{or} \quad p_2 = 0.582\,p_1$$

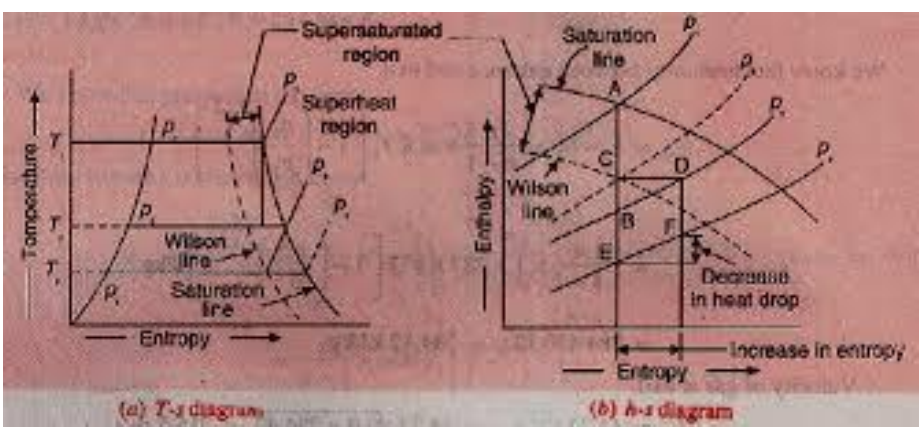
4. *For gases*

   We know that for gases, n = 1.4.

$$\frac{p_2}{p_1} = \left(\frac{2}{1.4+1}\right)^{\frac{1.4}{1.4-1}} = 0.528 \quad \text{or} \quad p_2 = 0.528\,p_1$$

Supersaturated Flow or Metastable Flow through Nozzle:

When dry saturated steam is expanded adiabatically or isentropically, it becomes wet and is shown by a vertical line on Mollier diagram.



We have already discussed that expansion of steam in an ideal nozzle is isentropic, which is accompanied by condensation process. If the steam is initially superheated, the condensation should start after it has become dry saturated. This is possible when the steam has proceeded through some distance in the nozzle and in a short interval of time. But from practical point of view, the steam has a great velocity (sometimes sonic and even supersonic). Thus, the phenomenon of condensation does not take place at the expected rate. As a result of this, equilibrium between the liquid and vapour phase is delayed and the steam Continues to expand in a dry state. The steam in such a set of conditions, is said to be *supersaturated* or in *metastable state.* It is also called *supercooled steam,* as its temperature at any pressure is less than the saturation temperature corresponding to the pressure. The flow of supersaturated steam, through the nozzle is called *supersaturated flow* or *metastable flow.* Experiments or supersaturated flow of steam have shown that there is a limit to which the supersaturated *flow is* possible. This limit is represented by Wilson line on *T-* sand *h-s* diagram as shown in Fig. *(a)* and *(b)* respectively. It may be noted that the Wilson line closely follows the 0.97 dryness fraction line. Beyond this Wilson line, there is no supersaturation. The steam suddenly condenses and restores its normal equilibrium state. In Fig. *(b) is* shown the isentropic expansion *of* steam in a nozzle. The point A represents the position *of* initial dry saturated steam at pressure p_1. The line *AC* represents the isentropic expansion *of* steam in the supersaturated region. The metastable slate (point *C)* is obtained by drawing a vertical line through *A* to meet the Wilson line. At *C.* the steam condenses suddenly. The line *CD* represents the condensation *of* steam at constant enthalpy. The point *D* is obtained by drawing a horizontal line through *C* to meet the throat pressure (p_2) *of* the nozzle. The line *DF* represents the isentropic expansion *of* steam in the divergent portion.

Effects *of* Supersaturation:

The following effects in a nozzle, in which supersaturation occurs, are important from the subject point *of* view;

1. Since the condensation does not take place during supersaturated expansion. so the temperature at which the supersaturation occurs will be *less* than the saturation temperature corresponding to the pressure. Therefore, the density of supersaturated

steam will be more than for the equilibrium conditions, which gives the increase in the mass *of* steam discharged.

2. The supersaturation increases the entropy and specific volume *of* the steam.

3. The supersaturation reduces the heat drop (for the same pressure limits) below that for thermal equilibrium. Hence the exit velocity *of* the steam is reduced.

4. The supersaturation increases dryness fraction *of* steam.

5. Related Laboratories: Conduct the performance test on axial/centrifugal air compressor and draw its performance characteristics.

6. Post Test:

1. Mention various types of nozzles and distinguish their features.

2. Define nozzle velocity coefficient and how it is related to nozzle efficiency and discharge coefficient as applied to nozzles.

3. Derive an expression for maximum mass flow per unit area of flow through a convergent- divergent nozzle when steam expands isentropically from rest.

4. Discuss the process of super-saturation in steam nozzles with the help of enthalpy entropy diagram.

5. Define degree of super-saturation and degree of under-cooling. Explain in detail the physical significance of abrupt change at Wilson`s line.

7. Conclusions: Nozzle is used in

- Steam and Gas turbine
- Jet Engine
- Rocket Motors-
- It is used to measure the discharge of fluid.- e.g. Venturimeter
- Injectors for pumping feed water to boilers.
- The supersonic gas turbine engine: for the air intake when the air requirement of the engine is high.
- Rockets: for providing sufficient thrust to move upwards.
- For removing air from the condenser using the injector.
- Spray painting
- Steam jet refrigeration system

8 **Reference:** R.K. Rajput, Thermal Engineering, 6th Edition, Laxmi Publications (P) Ltd.,

10. **Demo Video:**

https://www.youtube.com/watch?v=cYaoBCfHLdo

https://www.youtube.com/watch?v=3AWQRixSe5c

Name of the Course	:	**Applied Thermodynamics**
Name of the Unit	:	**Steam Turbines**
Name of the Topic	:	**Impulse & Reaction Turbines**

1. Objectives: To understand the basics and flow of steam through impulse and reaction turbine.

Outcomes: Upon successful completion, the student should be able to understand the basics, and flow of steam through impulse & reaction turbine.

2. Pre-Test: (Students should be able to answer the following)

1. State and explain the various types of steam?
2. Show and explain the various process of Rankine cycle on T-S diagram.

3. Pre-requisites: To have a basic knowledge of pure substances.

4. Theory Behind: STEAM TURBINE: Introduction

A steam turbine is a prime mover in which rotary motion is obtained by the gradual change of momentum of the steam. In a reciprocating steam engine, the steam acts on the piston, as a load or weight, i.e., the action of steam is *static.* The statical pressure of steam gives to and fro motion to the piston, and conversion of energy takes place through crank and connecting rod. In a steam turbine, the force exerted on the blades is due to the velocity of steam. This is due to the fact that the curved blades by changing the direction of steam receive a force or impulse. The action of steam in this case is said to be *dynamic. Thus,* the dynamical pressure of steam rotates the vanes, buckets or blades directly. The turbine blades are curved in such a way that the steam directed upon them enters without shock, though there is always some loss of energy by the friction upon the surface of blades. In general, a steam turbine, essentially, consists of the following two pasts:

I. The nozzle in which the heat energy of high-pressure steam is converted into kinetic energy, so that the steam issues from the nozzle with a very high velocity.

2. The blades which change the direction of steam issuing from the nozzle, so that force acts on the blades due to change of momentum and propel them.

Thus, the basic principle of operation of a steam turbine is the generation of high velocity.

Steam jet by the expansion of high-pressure steam and then conversion of kinetic energy, so obtained into mechanical work on rotor blades.

Advantages of Steam Turbines over Reciprocating Steam Engines

Following are the important advantages of steam turbines over reciprocating steam engines:

I. A steam turbine may develop higher speeds and a greater steam range is possible.

2. The efficiency of a steam turbine is higher.

3. The steam consumption is less.

4. Since all the moving pails are enclosed in a casing, the steam turbine is comparatively safe.

5. A steam turbine requires less space and lighter foundations, as there are little vibrations.

6. There is less frictional loss due to fewer sliding parts.

Classification of Steam Turbines

The steam turbines may be classified into the following types:

1. According to the mode of steam action

(i) Impulse turbine, and (ii) Reaction turbine.

2. According to the direction of steam flow

(i) Axial flow turbine, and *(ii)* Radial flow turbine.

3. According to the exhaust condition of steam

(i) Condensing turbine, and (ii) Non-condensing turbine.

4. According to the pressure of steam

(I) High pressure turbine, *(ii)* Medium pressure turbine, and *(iii)* Low pressure turbine.

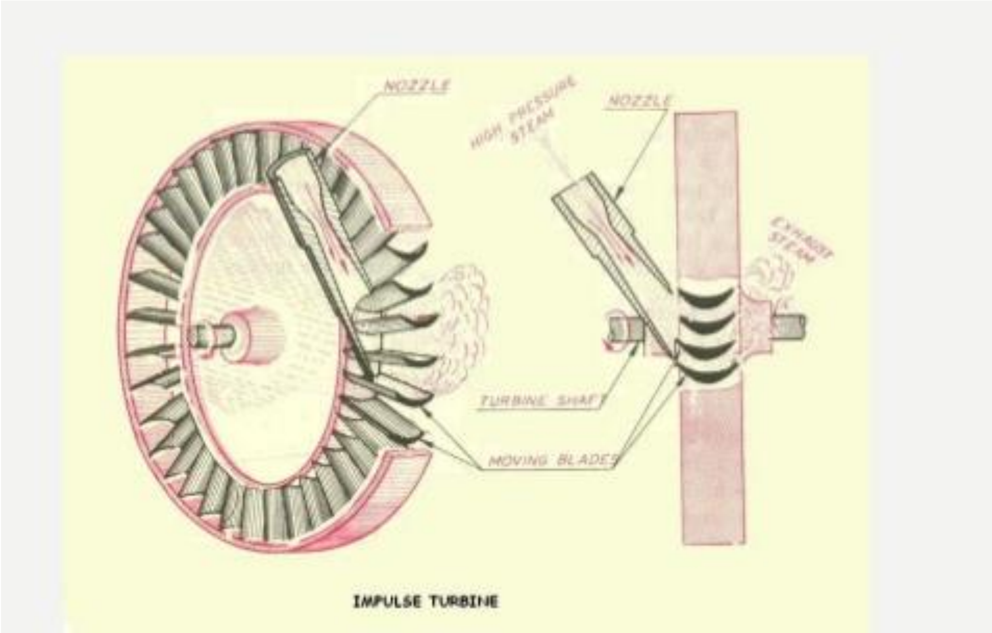
5. According to the number of stages

(i) Single stage turbine, and *(ii)* Multi-stage turbine.

Impulse Turbine:

An impulse turbine, as the name indicates, is a turbine which runs by the impulse of steam Jet. In this turbine, the steam is first made to flow through a nozzle. Then the steam jet impinges on the turbine blades (which are curved like buckets) and are mounted on the circumference of the wheel. The steam jet after impinging glides over the concave surface of the blades and finally leave the turbine.

Nole: The action of the jet of steam, impinging on the blades, is said to be an *impulse* and the rotation of the rotor is due to the impulsive forces of the steam jets.



De-Level Impulse Turbine:

A De Level turbine is the simplest type of impulse steam turbine, and is commonly used. It has the following main components:

1. *Nozzle.* It is a circular guide mechanism, which guides the steam to flow at the designed direction and velocity. It also regulates the flow of steam. The nozzle is kept very close to the blades, in order to minimize the losses due to windage.

2. *Runner and blades.* The runner of a De-Laval impulse turbine essentially consists of a circular disc fixed to a horizontal shaft. On the periphery of the runner, a number of blades are fixed uniformly. The steam jet impinges on the buckets, which move in the direction of the jet. This movement of the blades makes the runner to rotate. The surface of the blades is made very smooth to minimize the frictional losses. The blades are generally made of special steel alloys. In most of the cases, the blades are bolted to the runner disc. But sometimes the blades and disc are cast as a single Unit. It has been experienced that all the blades do not wear Out equally with the time. A few of them get worn out and

damaged early and need replacement. This can be done only if the blades are bolted to the disc.

3. *Casing.* It is an air-tight metallic case, which contains the turbine runner and blades. It controls the movement of steam from the blade to the condenser, and does not permit it to move into the space. Moreover, it is essential to safeguard the runner against any accident.

Pressure and Velocity of Steam in an Impulse Turbine:

The pressure of steam jet is reduced in the nozzle and remains constant while passing through the moving blade. The velocity of steam is increased in the nozzle, and is reduced while passing through the moving blades.

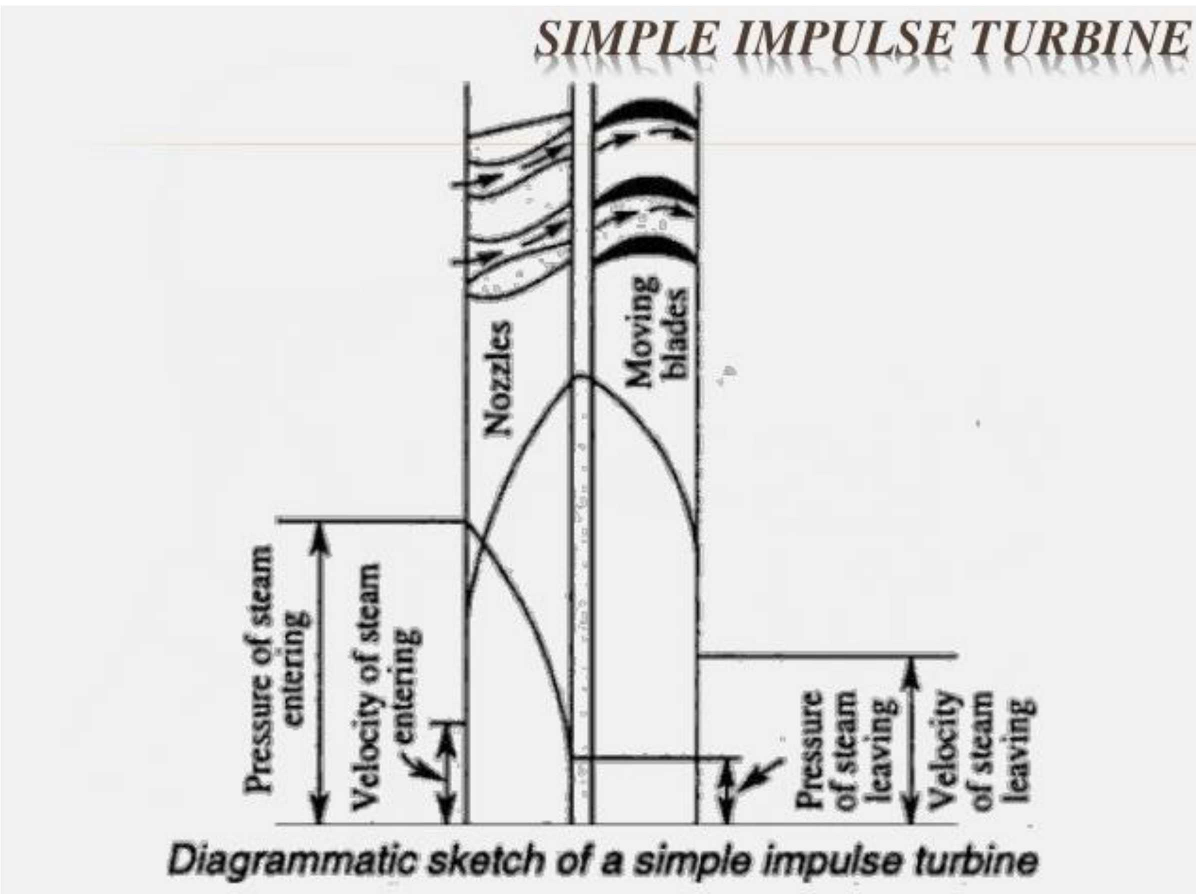
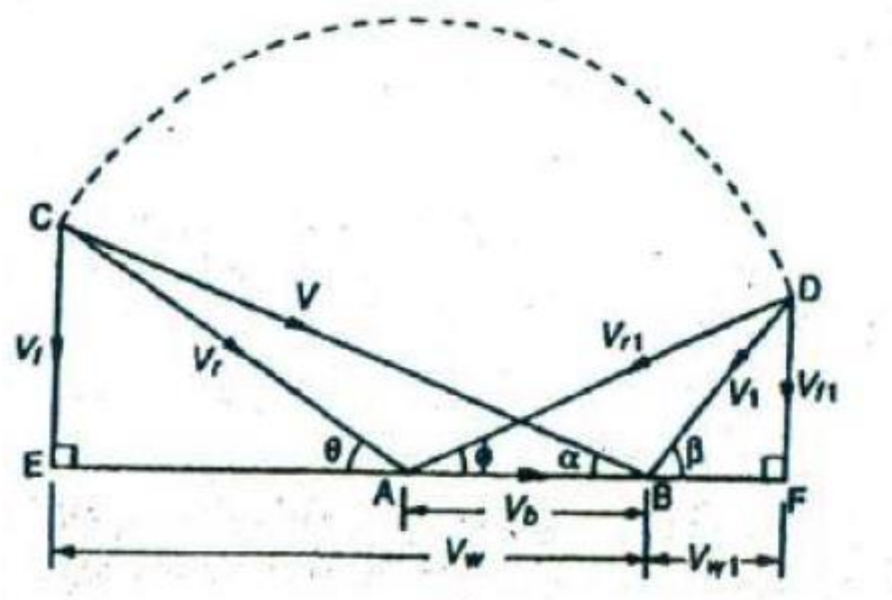


Fig. shows the pressure and velocity graphs of the steam in a simple impulse turbine while it flows in the nozzle and blades. The pressure graph represents steam pressure at entrance of the nozzle, exit of the nozzle, entrance of the blades and exit of the blades respectively. Similarly, velocity graph represents the velocity of steam at entrance of the nozzle, exit of the nozzle, entrance of the blades and exit of the blades respectively.

Velocity Triangle for Moving Blades:

For the sake of simplification, a combined velocity triangle for the moving blade is drawn, for solving problems on steam turbines, as shown in Fig, and as discussed below:



I. First of all, draw a horizontal line, and cut off *AB* equal to velocity of blade *(V_b)* to some suitable scale.

2. Now at *B,* draw a line *BC* at an angle a with *AB.* Cut off BC equal to *V (i.e.* velocity of steam jet at inlet of the blade) to the scale.

3. Join *AC,* which represents the relative velocity at inlet (V_r). Now at *A,* draw a line *AD* at an angle Q with *AB.*

4. Now with *A as* centre and radius equal to *AC,* draw an arc meeting the line through *A* at *D,* such that *AC = AD or* $V_r = V_{r1}$

5. Join *BD,* which represents velocity of jet at exit *(V_1)* to the scale.

6. From C and *D,* draw perpendiculars meeting the line *AB* produced at E and F respectively.

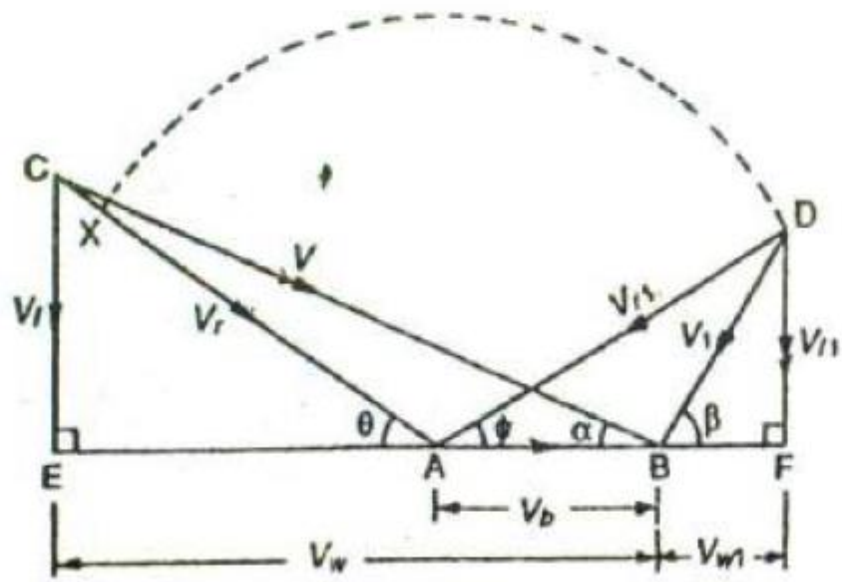
7. Now *EB* and *CE* represents the velocity of whirl and velocity of flow at inlet *(V_w* and *V_f)* to the scale. Similarly, *BF* and *DF* represents the velocity of whirl and velocity of flow at outlet *(V_{w1}* and *V_{f1})* to the scale.

Effect of Friction on the Combined Velocity Triangle:

In the last article, we have discussed that the relative velocity of steam jet is the same at the inlet and outlet tips of the blade. In other words, we have assumed that the inner side of the curved blade offers no resistance to the steam jet. But in actual practice, some resistance is always offered by the blade surface to the gliding steam jet, whose effect is to reduce the relative velocity of the jet. *i.e.* to make V_{r1} less than V_r. The ratio of V_{r1} to V_r is known as *blade velocity coefficient* or coefficient of velocity or friction factor, (usually denoted by K). Mathematically, blade velocity coefficient

$$K = \frac{V_{r1}}{V_r}$$

It *may* be noted that the effect of friction on the combined velocity triangle will be to reduce the relative velocity at outlet *(V_{r1})* as shown in Fig.



Notes: I. Since V_{r1} is decreased due to friction, therefore work done per kg *of* steam is also reduced.

2. The value *of K* varies from 0.75 to 0.85 depending upon the shape *of* the blades.

Reaction Turbine:

In a reaction turbine, the steam enters the wheel under pressure and flows over the blades. The steam, while gliding, propels the blades and make them to move. As a matter of fact, the turbine runner is rotated by the reactive forces of steam jets. The backward motion of the blades is similar to the recoil of a gun. It may be noted that an absolute reaction turbine is rarely used in actual practice.

Parson's Reaction Turbine:

A parson's turbine is the simplest type of reaction steam turbine, and is commonly used. It has the following main components:

1. Casing: It is an air-tight metallic case, in which the steam from the boiler, under a high pressure and temperature, is distributed around the fixed blades (guide mechanism) in the casing. The casing is designed in such a way that the steam enters the fixed blades with a uniform velocity.

2. *Guide mechanism:* It is a mechanism, made up with the help of gui.4e blades, in the form of a wheel. This wheel is, generally, fixed to the casing; that is why these guide blades are also called fixed blades. The guide blades are properly designed in order to:

(a) allow the steam to enter the runner without shock. This is done by keeping the relative velocity at inlet of the runner tangential to the blade angle.

(b) allow the required quantity of steam to enter the turbine. This is done by adjusting the openings of the blades. The guide blades may be opened or closed by rotating the regulating shaft, thus allowing the steam to flow according to the need. The regulating shaft is operated by means of a governor whose function is to govern the turbine (i.e. to keep to speed constant at varying loads).

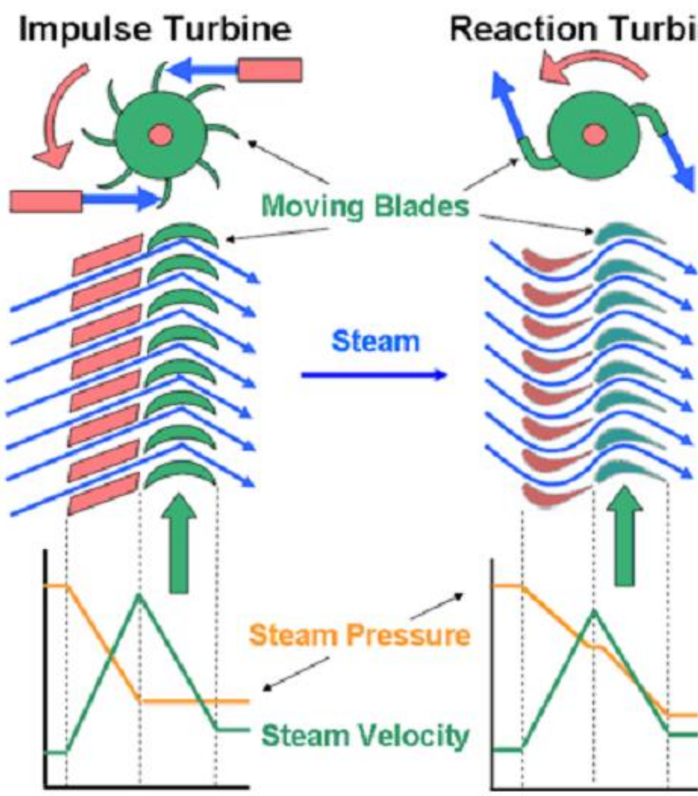
3. *Turbine runner.* The turbine runner of a Parson's reaction turbine essentially consists of runner blades fixed to a shaft or rings, depending upon the type of turbine. The blades, fixed to the runner, are properly designed in order to allow the steam to enter and leave the runner without shock, as shown in Fig. The surface of the turbine runner is made very smooth to minimize the frictional losses. The turbine runner is, generally, cast in one piece. But sometimes, it is made up of separate steel plates welded together.

4. *Draft tube.* The steam, after passing through the runner, flows into the condenser through a tube called draft tube. It may be noted that if this tube is not provided in the turbine, then the steam will move freely and will cause steam eddies.

Pressure and Velocity of Steam in a Reaction Turbine:

It will be interesting to know that the pressure in a reaction turbine is reduced in the fixed blades as well as in moving blades. The velocity of steam is increased in the fixed blades, and is reduced whi1e passing through the moving blades. Fig. shows the pressure and velocity graph of the steam while it 'flows in the fixed and moving blades of a reaction turbine. The pressure graph 1-2-3-4 represents steam pressure at entrance of the fixed blades, exit of the fixed blades, entrance of Fig. Pressure and velocity the moving blades and exit of the moving blades respectively. graphs of a reaction turbine.

Similarly, velocity graph *5-6-7-8* represents the velocity of steam at entrance of the fixed blades, exit of the fixed blades, entrance of the moving blades and exit of the moving blades respectively.



Comparison between impulse & reaction turbine:

S. No.	Impulse turbine	Reaction turbine
1.	The steam flows through the nozzles and impinges on the moving blades.	The steam flows first through guide mechanism and then through the moving blades.
2.	The steam impinges on the buckets with kinetic energy.	The steam glides over the moving vanes with pressure and kinetic energy.
3.	The steam may or may not be admitted over the whole circumference.	The steam must be admitted over the whole circumference.
4.	The steam pressure remains constant during its flow through the moving blades.	The steam pressure is reduced during its flow through the moving blades.
5.	The relative velocity of steam while gliding over the blades remains constant (assuming no friction).	The relative velocity of steam while gliding over the moving blades increases (assuming no friction).
6.	The blades are symmetrical.	The blades are not symmetrical.
7.	The number of stages required are less for the same power developed.	The number of stages required are more for the same power developed.

Combined Velocity Triangle for Moving Blades of reaction turbine:

For the sake of simplification, a combined velocity triangle for the moving blade is drawn, for solving problems on steam turbines, as shown in Fig. as discussed below:

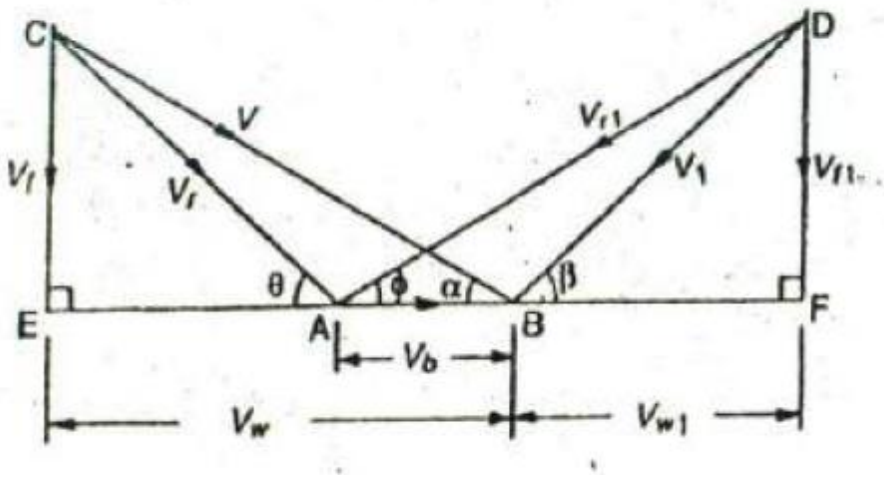
I. First of all, draw a horizontal line and cut off *AB* equal to the velocity of blade *(V_b),* to some suitable scale.

2 *Now* at *B,* draw a line *BC* at angle α with *AB.* Similarly, at *A,* draw a line *AC* at angle θ with E*A* meeting the first line at *C. Now CA* and *CB* represent the relative velocity (V_r) and absolute velocity *(V) of* steam at inlet, to the scale.

3. At *A,* draw a line *AD* at an angle Φ (such that Φ=α) with *AB.* Similarly, at *B* draw a line *BD* at an angle β Parson's reaction turbine (such that β = θ) with *AB* meeting the first line at *D. Now DA* and *DB* represent the relative velocity *(V_{r1})* arid absolute velocity *(V_1)* of steam at outlet, to the scale.

4. From *C* and *D* draw perpendiculars meeting the line *AR* produced at *E* and *F.*

5. Now EB and *CE* represent the velocity *of* whirl and velocity *of* flow at inlet *(V_w and V_f)* to the scale. Similarly, *BF* and *DF* represent the velocity *of* whirl and velocity of flow at outlet (V_{w1} and *V_{f1}),* to the scale.



Compounding of Impulse Steam Turbine (Methods of Reducing *Rotor* Speeds):

In the recent years, high pressure (10) to 140 bar) and high temperature steam is used in the power plants to increase their thermal efficiency. If the entire pressure drop (from boiler pressure to *condenser pressure (say from 125 bar to I bar) is carried out in one stage only, then the velocity of* steam entering into the turbine will be extremely high. It will make the turbine rotor to run at a very *high speed (even up to 30000 r.p.m.). From practical point of view, such a high speed of the turbine rotor is bound to have a number of disadvantages.*

In order to reduce the rotor speed, various methods are employed. All of these methods consist of a multiple system of rotors, in series, keyed to a common shaft and the steam pressure or the jet *velocity is absorbed in stages as it flows overthe rotor blades. This process is known as compounding.*

The following three methods are commonly employed for reducing the rotor speed:

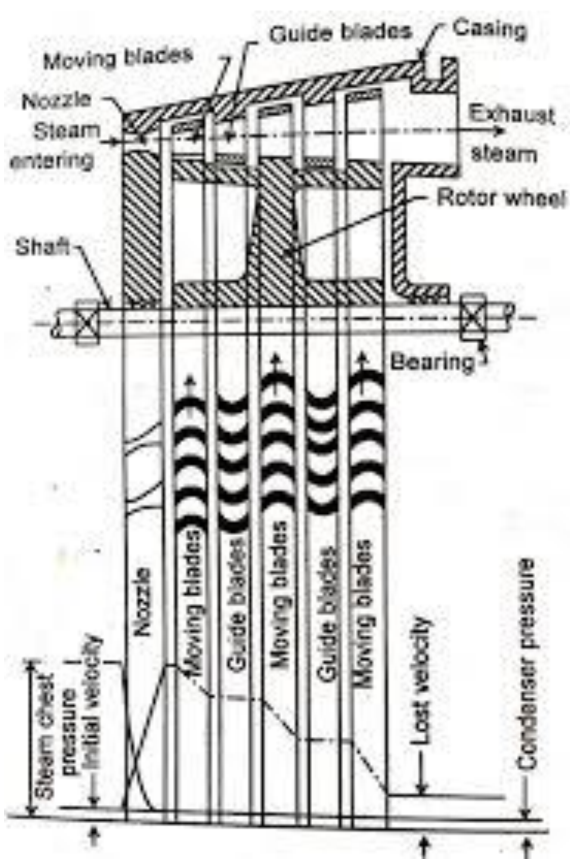
I. Velocity compounding, *2.* Pressure compounding, and *3.* Pressure-velocity compounding.

Velocity Compounding of an Impulse Turbine:

In velocity compounding of an impulse turbine, the expansion of steam takes place in a nozzle or a Set of nozzles from the boiler pressure to the condenser pressure. The impulse wheel carries two or three row of moving blades. Fig. shows the three rings of moving blades, separated by two rings of fixed or guide blades in the reverse manner.

The steam, after expanding through nozzles, enters the first ring of moving blades at a high velocity. A portion of this high velocity is absorbed by this blade ring and the remaining is passed on to the next ring of fixed blades. The fixed blades change the direction of steam and direct it to the second ring of moving blades, without altering the velocity appreciably. After passing through this second ring of moving blades, a further portion of velocity is absorbed. The steam is now directed by the second ring of fixed blades to the third ring of moving blades and then enters into the condenser.

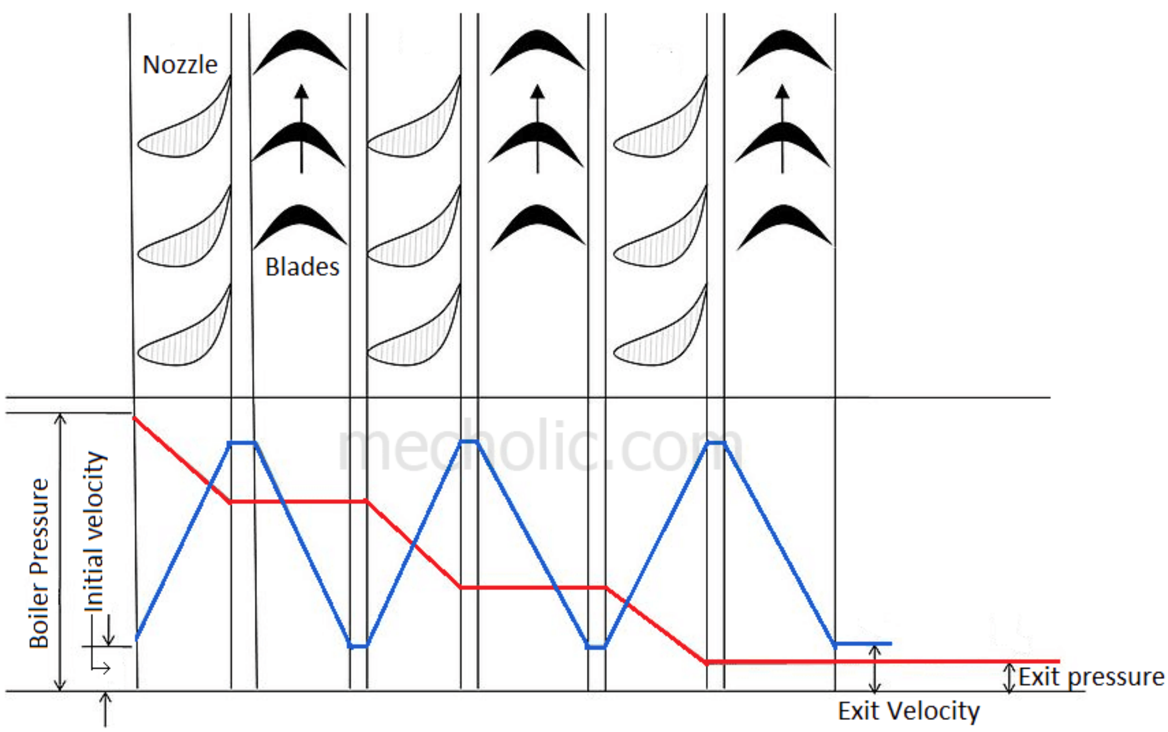
In Fig, the curves of velocity and pressure on a base representing the axis of the turbine are shown. It may be noted, from the figure, that no pressure drop occurs either in the fixed or moving blades. All the pressure drop occurs in the nozzles. This turbine can run at about one-third of the speed of De-Laval turbine, for the same pressure drop and diameter of the wheel.



Pressure Compounding of an Impulse Turbine:

In a pressure compounding of an impulse turbine, the rings of the moving blades, each having a ring of fixed nozzles, are keyed to the turbine shaft in series, as shown in Fig. The total pressure drop, of the steam, does not take place in the first nozzle ring, but is divided equally among all the nozzle rings.

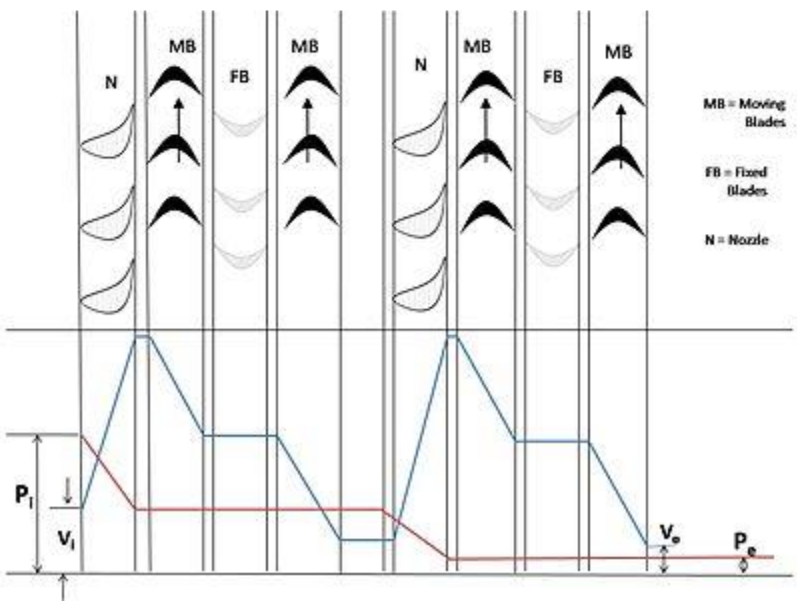
The Steam from the boiler is passed through the first nozzle ring, where only a small pressure drop occurs with an increase in velocity of steam. The steam is now directed on the first moving blade ring, where the pressure of steam does not alter, but the velocity decreases. This constitutes one stage. It may be noted that a stage consists of a fixed nozzle ring and a moving blade ring. The steam from the first moving blade ring enters the second nozzle ring, where its pressure is further reduced. A little consideration will show, that the pressure drop per stage in the nozzle rings is not the same, but the number of heat units, converted into velocity energy in each stage, is the same. The process is repeated in the remaining rings, until the condenser pressure is reached. In Fig, the curves of velocity and pressure on a base representing the axis of the turbine are also shown. It may be noted, from the figure, that by arranging a small pressure drop per stage, the velocity of steam entering the moving blades, and hence the speed of rotor is reduced. The Rateau and Zoelly turbines are the examples of pressure compounded turbines.



Pressure-velocity Compounding of an Impulse Turbine:

Ina pressure-velocity compounding of an impulse turbine, both the previous two methods are utilized. The total pressure drop of the steam is divided into stages, and velocity obtained in each stage is also compounded. A little consideration will show, that a pressure velocity compounded impulse turbine allows a bigger pressure drop, and hence less number of stages are required.

Fig. shows the curves of pressure and velocity for this type of turbine. It may be noted that the diameter of the turbine is increased at each stage, to allow the increasing volume of steam at the lower pressures. A ring of nozzles is fixed at the commencement of each stage as shown in Fig. A Curtis turbine is an example of pressure-velocity compounded impulse turbine.



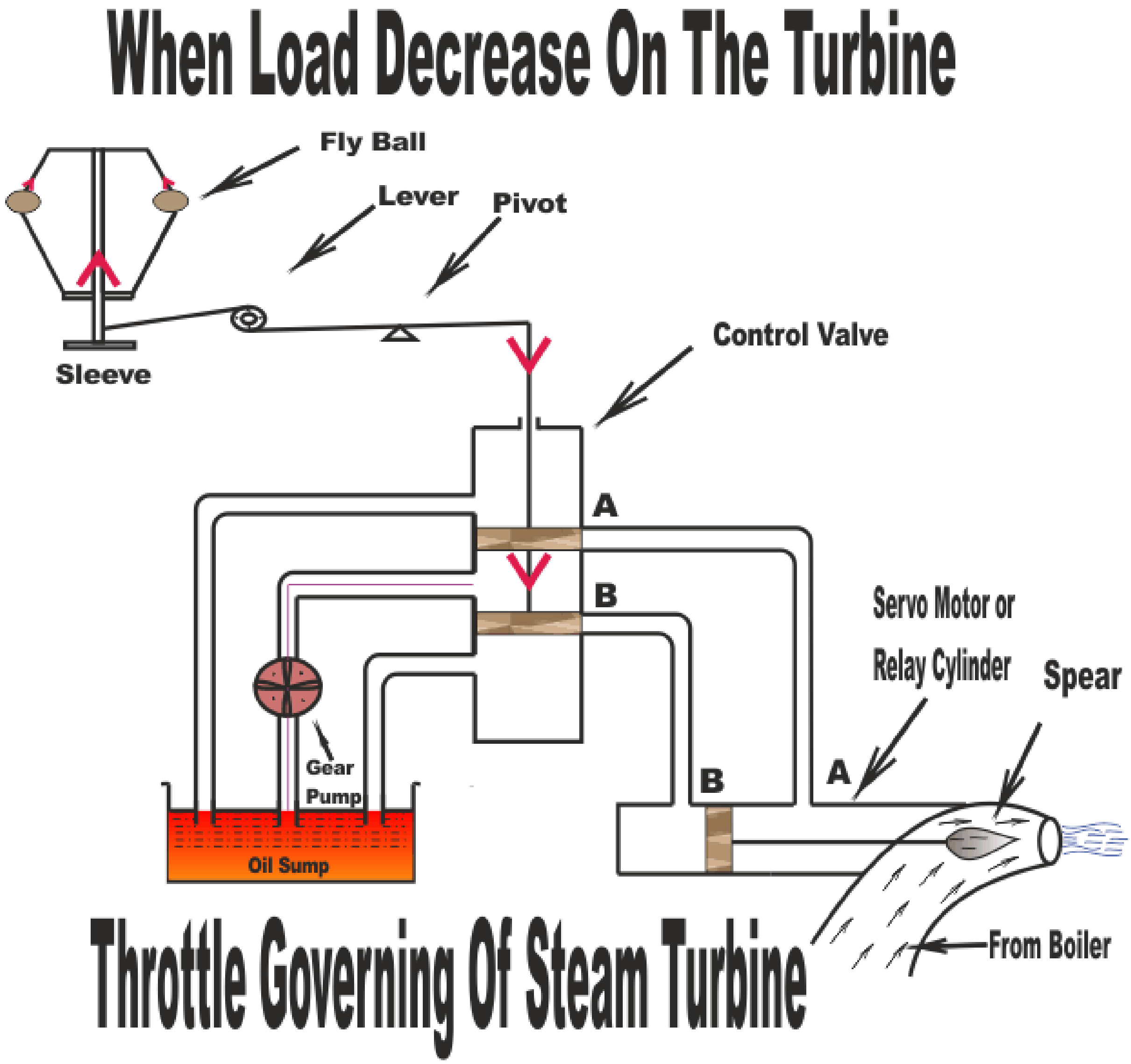
STEAM TURBINE GOVERNING SYSTEM

Steam turbine governing system is a method, used to maintain a constant steady speed of turbine. The importance of this method is, the turbine can maintain a constant steady speed irrespective of variation of its load. A turbine governor is provided for this arrangement. The purpose of the governor is to supply steam into the turbine in such a way that the turbine gives a constant speed as far as possible under varying the load. So, basically **Steam turbine governing system** is a process where turbine maintains a steady output speed irrespective of variation of load. The different types of steam turbine governor of are:

1. Throttle Governing of Steam Turbine
2. Nozzle Control Governing of Steam Turbine
3. Bypass Governing of Steam Turbine

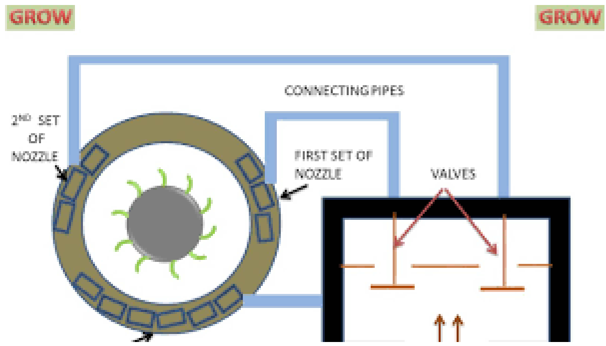
1. Throttle Governing of Steam Turbine:

Throttle Governing of steam Turbine is most popular and easiest way to control the turbine speed. When steam turbine controls its output speed by varying the quantity of steam entering the turbine is called Throttle Governing. It is also known as Servomotor methods. In this system, a centrifugal governor is driven from the main shaft of turbine by belt or gear arrangement. A control valve is used to control the direction of oil flow which supplied by the pipe AA or BB. The servomotor or relay valve has a piston which moves towards left or right depending upon the pressure of oil flow through the pipes AA or BB. This cylinder has connected a needle which moves inside the nozzle. When the turbine is running at normal speed, everything in the turbine such as such control valve, servomotor, piston position, fly balls of centrifugal governor will be in their normal position as shown in the figure. The mouth of both pipes AA or BB is closed into the control valves. Assume that the turbine's load increases. It will decrease its speed which will decrease the centrifugal force of the turbine. Now fly balls of the governor will come down thus decreasing their amplitude. These fly balls also bring down the sleeve. The sleeve is connected to a control valve rod through a lever pivoted on the fulcrum. This down word sleeve will raise the control valve rod. Now oil is coming from the from the oil sump, pumped by gear pump is just stay at the mounts of both pipes AA or BB which are closed by the two wings of control valves. So, raise of control valve rod will open the mouth of the pipe AA but BB is still closed. Now the oil pressure is coming from the pipe AA. This will rush from the control valve which will move the right side of the piston. As a result, the steams flow rate into the turbine increases which will bring the speed of the turbine to the normal range. When speed of the turbine will come to its normal range, fly balls will come into its normal position. Now, sleeve and control valve rod will back to its normal position.

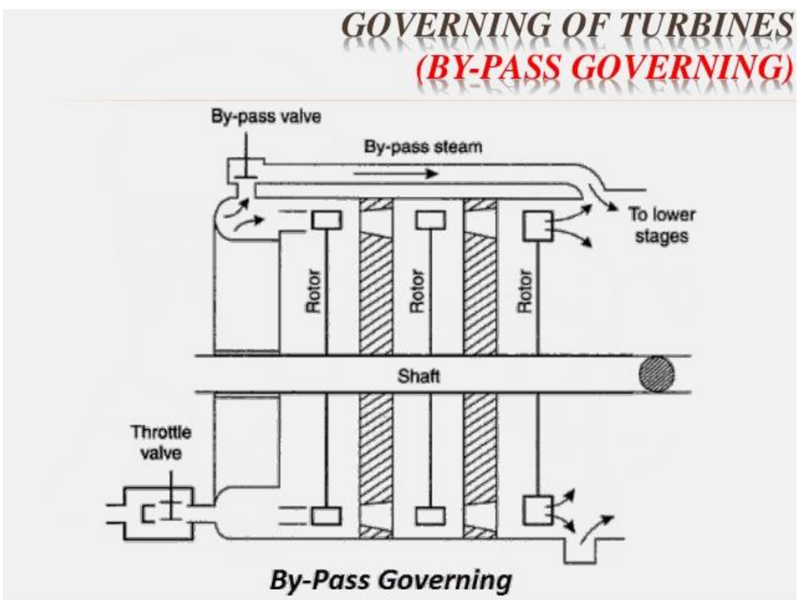


2. Nozzle Governing of Steam Turbine:

It is another interesting method by which turbine's speed can be controlled. Nozzle control governing of steam turbine is basically used for part load condition. Some set of nozzles are grouped together (may be two, three or more groups) and each group of the nozzle is supplied steam controlled by valves. Every valve is closed by the corresponding set of nozzle. Steam's flow rate is also controlled by these nozzles. Actually, nozzle control governing is restricted to the first stage of turbine whereas the subsequent nozzle area in other stage remains constant. According to the load demand, some nozzles are in active and other inactive position. Suppose turbine holds ten numbers of nozzles. If the load demand is reduced by 50% then five numbers of nozzles are in open condition and rest is closed. This method is suitable for SIMPLE IMPULSE TURBINE. It is a process where rate of steam flow is regulated depending on the opening and closing of set of nozzles rather than regulating its pressure.



2. **Bypass Governing of Steam Turbine:** Bypass governing of steam turbine is a method where a bypass line is provided for the steam. Especially this is used when turbine is running in overloaded condition. The bypass line is provided for passing the steam from first stage nozzle box into a later stage where work output increase. This bypass steam is automatically regulated by the lift of valve which is under the control of the speed of the governor for all loads within its range. Bypass valve is open to release the fresh stem into the later stage of the turbine. In the later stage output, work is increased and the efficiency is low due to the throttle effect.



5. Related Laboratories: ---

6. Post Test:

1. What is a turbine? How does it differ from a steam engine?
2. Give the classification of steam turbines.
3. Explain the principle of impulse turbine.
4. Show by graphical method, variation in the pressure and velocity of steam In an impulse turbine.
5. What do you understand by the term 'friction' in at, impulse turbine. How does it effect the combined velocity triangle.
6. Distinguish between impulse and reaction turbine.
7. Explain the functions of the blading of a reaction turbine
8. Explain the term 'Compounding of steam turbine'. What are the different methods of reducing rotor speed?
9. Discuss the method of velocity compounding of an impulse turbine for achieving rotor speed reduction.
10. Enumerate the different losses in a steam turbine.
11. What are the methods of governing a steam turbine? Describe any one method of governing steam turbines.

7. Conclusions:

Steam turbines are a part of various industries, from medium to large scale, and include dozens of institutional applications.

- Chemical Industry: Providing heat and electricity to drive different processes in the chemical and pharmaceutical industries, steam turbines are integrated in the process of producing power.
- Waste Plants: Steam turbines help generate the power needed to harness energy from wastes.
- Oil & Gas: Used as a pump drive or a compressor, steam turbines support dozens of operations in the oil and gas industry.
- Sugar Mills: Offering high levels of efficiency and sustainable operations, steam turbines are used to produce green carbon-dioxide energy from bagasse.

Some of the most popular applications of a steam turbine in different industries include the following:

- **COMBINED HEAT AND POWER**
- **DRIVING MECHANICAL EQUIPMENT**
- **DISTRICT HEATING & COOLING SYSTEMS**
- **COMBINED CYCLE POWER PLANTS**

8. **Reference:** R.K. Rajput, Thermal Engineering, 6th Edition, Laxmi Publications (P) Ltd.,

9. **Demo Video:**

https://www.youtube.com/watch?v=AzIZvvJ8BWQ
https://www.youtube.com/watch?v=04mx0PIKz4k
https://www.youtube.com/watch?v=w_DByM4qJAY
https://www.youtube.com/watch?v=FCyagN2-OBw
https://www.youtube.com/watch?v=FEHa5-P6VHs

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