ME8595 THERMAL ENGINEERING – II

UNIT I STEAM NOZZLE

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

UNIT II BOILERS

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

UNIT III STEAM TURBINES

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

UNIT IV COGENERATION AND RESIDUAL HEAT RECOVERY

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

UNIT V REFRIGERATION AND AIR – CONDITIONING

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

TOTAL:45 PERIODS

TEXT BOOKS:

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

REFERENCES:

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

Unit 1

STEAM NOZZLE

PREREQUISITE DISCUSSIONS

A steam turbine is basically an assembly of nozzles fixed to a stationary casing and rotating blades mounted on the wheels attached on a shaft in a row-wise manner. In 1878, a Swedish engineer, Carl G. P. de Laval developed a simple impulse turbine, using a convergent-divergent (supersonic) nozzle which ran the turbine to a maximum speed of 100,000 rpm. In 1897 he constructed a velocity-compounded impulse turbine (a two-row axial turbine with a row of guide vane stators between them.

Auguste Rateau in France started experiments with a de Laval turbine in 1894, and developed the pressure compounded impulse turbine in the year 1900.

In the USA , Charles G. Curtis patented the velocity compounded de Lavel turbine in 1896 and transferred his rights to General Electric in 1901.

In England , Charles A. Parsons developed a multi-stage axial flow reaction turbine in 1884.

Steam turbines are employed as the prime movers together with the electric generators in thermal and nuclear power plants to produce electricity. They are also used to propel large ships, ocean liners, submarines and to drive power absorbing machines like large compressors, blowers, fans and pumps.

Turbines can be condensing or non-condensing types depending on whether the back pressure is below or equal to the atmosphere pressure.

STEAM NOZZLE

Introduction

A steam turbine converts the energy of high-pressure, high temperature steam produced by a steam generator into shaft work. The energy conversion is brought about in the following ways:

1. The high-pressure, high-temperature steam first expands in the nozzles emanates as a high velocity fluid stream.

2. The high velocity steam coming out of the nozzles impinges on the blades mounted on a wheel. The fluid stream suffers a loss of momentum while flowing past the blades that is absorbed by the rotating wheel entailing production of torque.

3. The moving blades move as a result of the impulse of steam (caused by the change of momentum) and also as a result of expansion and acceleration of the steam relative to them. In other words they also act as the nozzles.

Flow Through Nozzles

➢ A *nozzle* is a duct that increases the velocity of the flowing fluid at the expense of pressure drop.

➢ A duct which decreases the velocity of a fluid and causes a corresponding increase in pressure is a *diffuser* .

➢ The same duct may be either a nozzle or a diffuser depending upon the end conditions across it. If the cross-section of a duct decreases gradually from inlet to exit, the duct is said to be convergent.

➢ Conversely if the cross section increases gradually from the inlet to exit, the duct is said to be divergent.

➢ If the cross-section initially decreases and then increases, the duct is called a convergent-divergent nozzle.

➢ The minimum cross-section of such ducts is known as throat.

➢ A fluid is said to be *compressible* if its density changes with the change in pressure brought about by the flow.

➢ If the density does not changes or changes very little, the fluid is said to be incompressible. Usually the gases and vapors are compressible, whereas liquids are *incompressible* .

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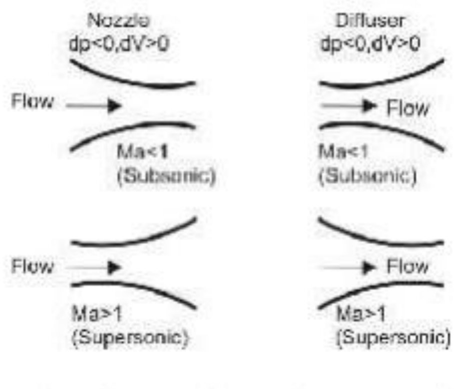
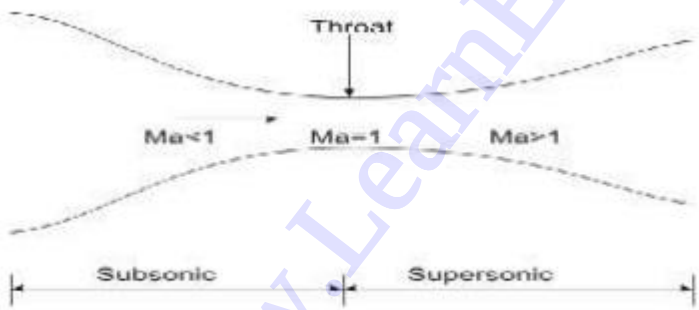
Shapes of nozzles



1. At subsonic speeds (Ma<1) a decrease in area increases the speed of flow.
2. In supersonic flows (Ma>1), the effect of area changes are different.

Convergent divergent nozzles



SIGNIFICANCE OF STEAM TURBINES

➢ Large scale electrical energy production largely depends on the use of turbines. Nearly all of the world's power that is supplied to a major grid is produced by turbines.

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- From steam turbines used at coal-burning electricity plants to liquid water turbines used at hydro-electric plants, turbines are versatile and can be used in a number of applications.

- There are also gas turbines that combust natural gas or diesel fuel for use in remote locations or where a large backup power supply is required. Most power plants use turbines to produce energy by burning coal or natural gas.

- The heat produced from combustion is used to heat water in boiler. The liquid water is converted to steam upon heating and is exhausted through a pipe which feeds the steam to the turbine.

- The pressurized steam flow imparts energy on the blades and shaft of the turbine causing it to rotate.

- The rotational mechanical energy is then converted to electrical energy using a generator.

STEAM TURBINES

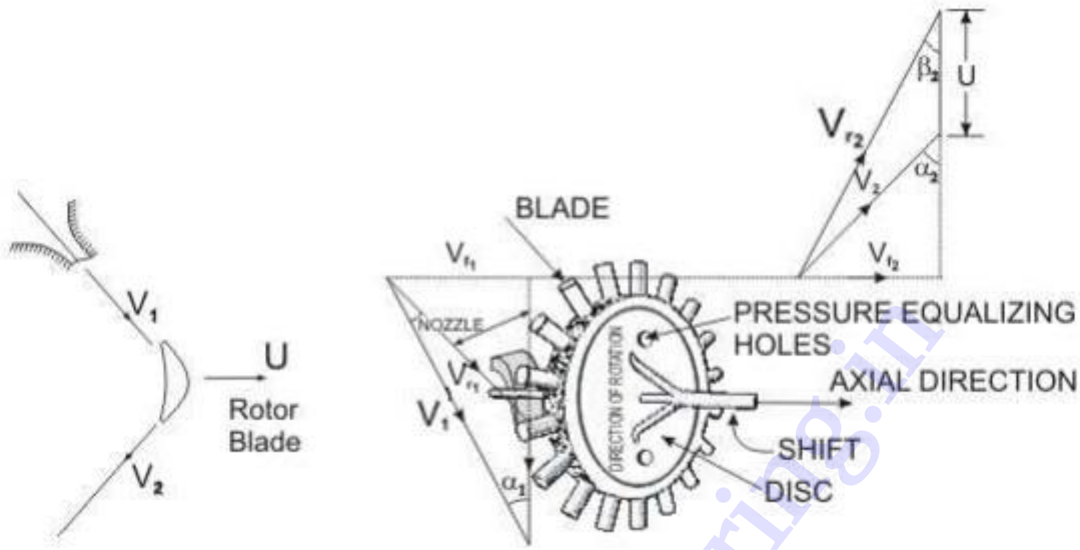
Turbines

- We shall consider steam as the working fluid
- Single stage or Multistage
- Axial or Radial turbines
- Atmospheric discharge or discharge below atmosphere in condenser
- Impulse/and Reaction turbine

Impulse Turbines

- Impulse turbines (single-rotor or multirotor) are simple stages of the turbines.
- Here the impulse blades are attached to the shaft.
- Impulse blades can be recognized by their shape.
- The impulse blades are short and have constant cross sections.

Schematic diagram of an Impulse Trubine



V_1 and V_2 = Inlet and outlet absolute velocity
V_{r1} and V_{r2} = Inlet and outlet relative velocity (Velocity relative to the rotor blades.)
U = mean blade speed
= nozzle angle,
= absolute fluid angle at outlet

It is to be mentioned that all angles are with respect to the tangential velocity (in the direction of U)

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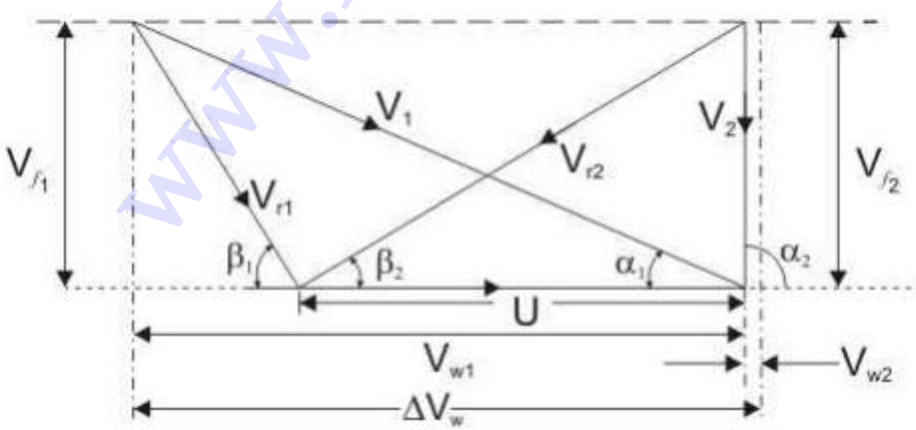

β_1 and β_2 = Inlet and outlet **blade angles**

V_{w1} and V_{w2} = Tangential or whirl component of absolute velocity at inlet and outlet

V_{f1} and V_{f2} = Axial component of velocity at inlet and outlet

Tangential force on a blade,

$$F_u = \dot{m}(V_{w1} - V_{w2}) \quad (22.1)$$

(mass flow rate X change in velocity in tangential direction)

or,

$$F_u = \dot{m}\Delta V_w \quad (22.2)$$

$$\text{Power developed} = \dot{m}U\Delta V_w \quad (22.3)$$

Blade efficiency or Diagram efficiency or Utilization factor is given by

$$\eta_b = \frac{\dot{m} \cdot U \cdot \Delta V_w}{m(V_1^2/2)} = \frac{\text{Workdone}}{\text{KE supplied}}$$

or,

$$\eta_b = \frac{2U\Delta V_w}{V_1^2} \quad (22.4)$$

The Single-Stage Impulse Turbine

- The *single-stage impulse turbine* is also called the *de Laval turbine* after its inventor.
- The turbine consists of a single rotor to which impulse blades are attached.

- The steam is fed through one or several convergent-divergent nozzles which do not extend completely around the circumference of the rotor, so that only part of the blades is impinged upon by the steam at any one time.
- The nozzles also allow governing of the turbine by shutting off one or more them.

Compounding in Impulse Turbine

- If high velocity of steam is allowed to flow through one row of moving blades, it produces a rotor speed of about 30000 rpm which is too high for practical use.

- It is essential to incorporate some improvements for practical use and also to achieve high performance.

- This is called compounding.

- Two types of compounding can be accomplished: (a) velocity compounding and (b) pressure compounding

The Velocity - Compounding of the Impulse Turbine

- The velocity-compounded impulse turbine was first proposed to solve the problems of a single-stage impulse turbine for use with high pressure and temperature steam.

- It is composed of one stage of nozzles as the single-stage turbine, followed by two rows of moving blades instead of one.

- These two rows are separated by one row of fixed blades attached to the turbine stator, which has the function of redirecting the steam leaving the first row of moving blades to the second row of moving blades.

Pressure Compounding or Rateau Staging

- To alleviate the problem of high blade velocity in the single-stage impulse turbine, the total enthalpy drop through the nozzles of that turbine are simply divided up, essentially in an equal manner, among many single-stage impulse turbines in series,Such a turbine is called a *Rateau turbine.*
- The inlet steam velocities to each stage are essentially equal and due to a reduced Δh.

Reaction Turbine

- **A *reaction turbine***, therefore, is one that is constructed of rows of fixed and rows of moving blades.
- The fixed blades act as nozzles.
- The moving blades move as a result of the impulse of steam received (caused by change in momentum) and also as a result of expansion and acceleration of the steam relative to them.
- The pressure drops will not be equal.
- They are greater for the fixed blades and greater for the high-pressure than the low-pressure stages.
- The absolute steam velocity changes within each stage as shown and repeats from stage to stage.

APPLICATIONS

- Locomotives
- Power generations
- Industrial application for producing steam

Governing of Steam Turbine: The method of maintaining the turbine speed constant irrespective of the load is known as governing of turbines. The device used for governing of turbines is called Governor. There are 3 types of governors in steam turbine,

1. Throttle governing
2. Nozzle governing
3. By-pass governing

i.Throttle Governing:

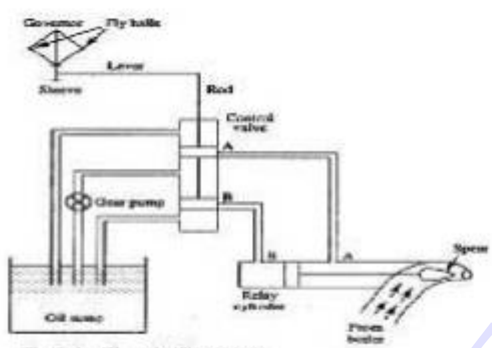

Fig 3.1: Throttle Governing

Let us consider an instant when the load on the turbine increases, as a result the speed of the turbine decreases. The fly balls of the governor will come down. The fly balls bring down the sleeve. The downward movement of the sleeve will raise the control valve rod. The mouth of the pipe AA will open. Now the oil under pressure will rush from the control valve to right side of piston in the rely cylinder through the pipe AA. This will move the piston and spear towards the left which will open more area of nozzle. As a result steam flow rate into the turbine increases, which in turn brings the speed of the turbine to the normal range.

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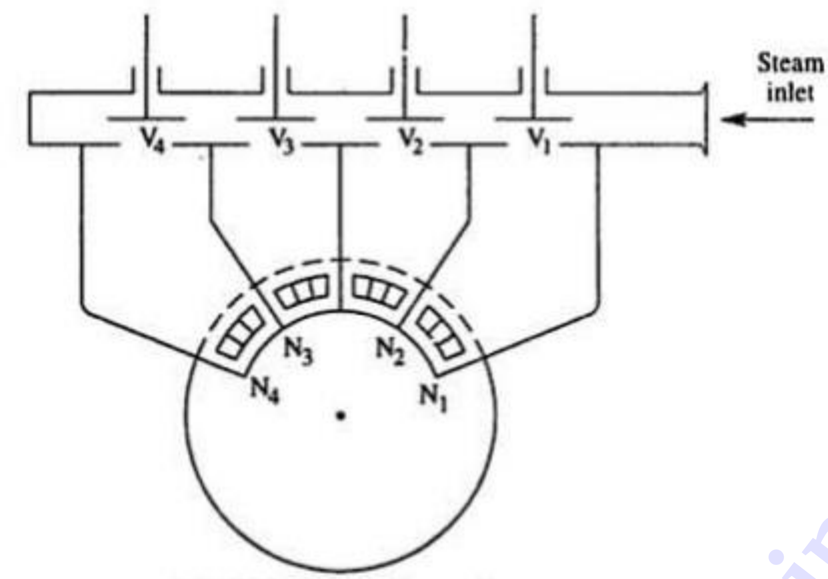

Fig 3.15 Nozzle Governing

A dynamic arrangement of nozzle control governing is shown in fig.

In this nozzles are grouped in 3 to 5 or more groups and each group of nozzle is supplied steam controlled by valves. The arc of admission is limited to 180º or less. The nozzle controlled governing is restricted to the first stage of the turbine, the nozzle area in other stages remaining constant. It is suitable for the simple turbine and for larger units which have an impulse stage followed by an impulse reaction turbine.

Solved Problems:

1. A convergent divergent adiabatic steam nozzle is supplied with steam at 10 bar and 250°c.the discharge pressure is 1.2 bar.assuming that the nozzle efficiency is 100% and initial velocity of steam is 50 m/s. find the discharge velocity.

Given Data:-

Initial pressure(p_1)=10bar Initial

Temperature(T_1)=250°c

Exit pressure(p_2)=1.2 bar

Nozzle efficiency(η_{nozzle})=100%

Initial velocity of steam (v_1)=50m/s

To Find:-

Discharge velocity (v_2)

Solution:-

From steam table, For 10 bar, 250°c, h_1=2943 KJ/kg s_1=6.926 KJ/kgk

From steam table, For 1.2 bar,

h_{f2} =439.3 KJ/kg ; h_{fg2}=2244.1 KJ/kg;

s_{f2}=1.3 61 KJ/kg K ; s_{fg2}=5.937 KJ/kgK.

Since s_1=s_2,

S1=sf 2+x2sfg2

6.926=1.361+x_2(5.937)

X_2=0 .9373

We know that,

h2=hf2+x2hfg2

= 439.3+(0.9373)2244.1

h_2 = 2542KJ/Kg

Exit velocity (V2) = Rt[(2000(2943) 2542) + 50^2]

= 896.91m/s.

2. Dry saturated steam at 6.5 bar with negligible velocity expands isentropically in a convergent divergent nozzle to 1.4 bar and dryness fraction 0.956. De termine the final velocity of steam from th e nozzle if 13% heat is loss in friction. Find th e % reduction in the final velocity.

Given data:

Exit pressure (P2) = 1.4 bar

Dryness fract ion (X2) = 0.956

Heat loss = 13%

To Find:

The percent reduction in final velocity

Solution:

From steam table for initial pressure P1 = 6.5bar, take values h_1 =

$$h_1 = 2758.8 KJ/Kg$$

Similarly, at 1.4 bar,

$$h_{fg2} = 2231.9 \text{ KJ/Kg}$$

$$h_{f2} = 458.4 KJ/Kg$$

$$h2 = hf2 + X2\ hfg2$$

$$= 458.4 + (0.956)\ 2231.6$$

$$h_2 = 2592.1 \text{ KJ/Kg}$$

Final velocit y (V2) = Rt (2000(h1-h2))

$$V2 = 577.39 \text{ m/s}$$

Heat drop is 13%= 0.13

Nozzle efficiency (η) = 1- 0.13 = 0.87

Velocity of s team by considering the nozzle efficiency,

y (V2) = Rt (2000(h1-h2)) x η

V2 = 538.55 m/s

= % reductio n in final velocity = 6.72%

3.A convergent divergent nozzle receives steam at 7bar and 200°c and it ex pands isentropically into a space of 3bar neglecting the inlet velocity calculat e the exit area required for a mass flow of 0.1Kg/sec . when the flow is in equilibrium through all and super saturated with $PV^{1.3}$=C.

Given Data:

Initiall pressure (P_1) = 7bar = $7\times 10^5 N/m^2$

Initiall temperature (T_1) = 200°C

Press ure (P_2) = 3bar = $3\times 10^5 N/m^2$

Mass flow rate (m) = 0.1Kg/sec

$PV^{1.3}$ =C

To Find:

Exit area

Solution:

From st eam table for P1 = 7bar and T1 = 200°C V_1 =

0.2999

h_1 = 2844.2

S1 = 6.886
Similarly for P2 = 3bar
Vf2 = 0.001074 Vg2 = 0.60553 hf2 =
561.5 hfg2 = 2163.2
Sf2 = 1.672 Sfg2 = 5.319
We know that, S1 = S2 = St
$S_1 = S_{f2} + X_2 S_{fg2}$

$$6.886 = 1.672 + X_2 (5.319) X_2 =$$

$$0.98$$

Similarly,

$$h2 = hf2 + X2\ hfg2$$

$$h_2 = 561.5 + 0.98\ (2163.2)$$

(i) <u>Flow is in equilibriu m through all:</u>

$$V_2 = 569.56$$
$$\nu_2 = X_2 \times \nu_{g2}$$

$$= 0.98 \times 0.60553 = 0.5934$$

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

$V_2 = \sqrt{2000\,(2844.2 - 2681.99)}$ $V_2 =$

569.56

$v_2 = X_2 \times v_{g2}$

$= 0.98 \times 0.60553 = 0.5934$

$$m = \frac{[(A]_2 \times V_2)}{v_2}$$

$$A_2 = \frac{[m \times V_2)}{v_2} = \frac{0.5934 \times 0.1}{569.56}$$

$$A_2 = 1.041 \times 10^{-4} m^2$$

(ii) <u>For saturated flow:</u>

$$v_2 = \sqrt{\frac{2n}{n-1}\ (P_1 v_1)(1 - (\frac{P_2}{P_1})^{\frac{n-1}{n}}}$$

$$v_2 = \sqrt{\frac{2(1.3)}{1.3-1}\ (7 \times 10^5 \times 0.2999)\ (1 - \frac{3\times10^5}{7\times10^5})^{\frac{1.2-1}{1.2}}}$$

v2 = 568.69 m/s

specific volume of steam at exit. For super saturated flow, $P_1 V_1^n = P_2$

$$\left(\frac{v_2}{v_1}\right)^n = \frac{P1}{P2}$$

$$\left(\frac{v_2}{v_1}\right)^n = \frac{P1}{P2}$$

$$v_2 = \left(\frac{7}{3}\right)^{\frac{1}{1.3}} \times 0.2999$$

$$v_2 = 0.5754$$

$$A_2 = \frac{(m \times V_2)}{v_2}$$

$$= \frac{0.1 \times 0.5754}{568.69}$$

$$A_2 = 1.011 \times 10^{-4} m^2$$

TECHNICAL TERMS

1.Diaphragm - Partitions b etween pressure stages in a turbine's casing.

2. Radial - flow turbine - st eam flows outward from the shaft to the casing.

3. Radial clearance - cleara nce at the tips of the rotor and casing.

4. Axial clearance - the fore -and-aft clearance, at the sides of the rotor and t he casing.

5. balance piston - Instead of piston, seal strips are also used to duplicate a piston's counter force.

6. steam rate - The steam rate is the pounds of steam that must be supplied per kilowatt-hour of generator output at the steam turbine inlet.

7. extraction turbine - ste am is withdrawn from one or more stages, at one or more pressures, for heating, pl ant process, or feedwater heater needs.

8. Wet steam: The steam w hich contains some water particles in superposition.

9. Dry steam / dry saturated steam: When whole mass of steam is converted into steam then it is called as dry steam.

10. Super heated steam: When the dry steam is further heated at consta nt pressure, the temperature increases the above saturation temperature. The steam has obtained is called super heated stea m.

11. Degree of super heat: The difference between the temperature of saturated steam and saturated temperature is c alled degree of superheat.

12. Nozzle:It is a duct of varying cross sectional area in which the velocity increases with the corresponding drop in pressure.

13. Coefficient of nozzle: It is the ratio of actual enthalpy drop to isentropic enthalpy drop.

14. Critical pressure ratio: There is only one value of ratio (P2/P1) which produces maximum discharge fro m the nozzle . then the ratio is called critica l pressure ratio.

15. Degree of reaction: It is defined as the ratio of isentropic heat drop in th e moving blade to isentrpic heat drop in the entire stages of the reaction turbine.

16. Compounding: It is the method of absorbing the jet velocity in stages when the steam flows over moving blades. (i)Velocity compounding (ii)Pressure compounding and (iii) Velocity-pressure compounding

17. Enthalpy: It is the combination of the internal energy and the flow energy.

18. Entropy: It is the function of quantity of heat with respective to the temperature.

19. Convergent nozzle: The crossectional area of the duct decreases from inlet to the outlet side then it is called as convergent nozzle.

20. Divergent nozzle: The crossectional area of the duct increases from inlet to the outlet then it is called as divergent nozzle.

Unit 3

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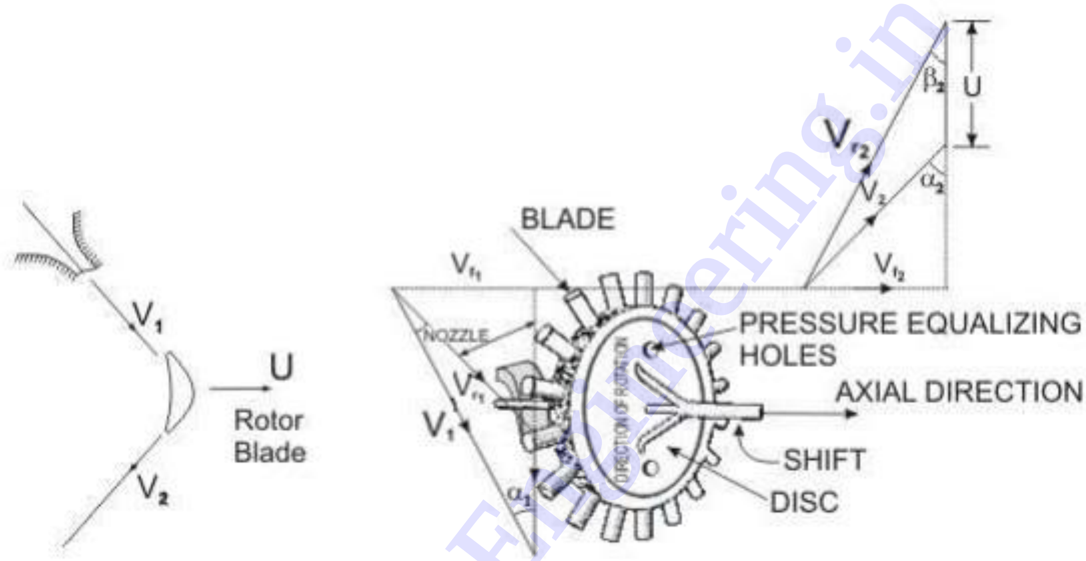

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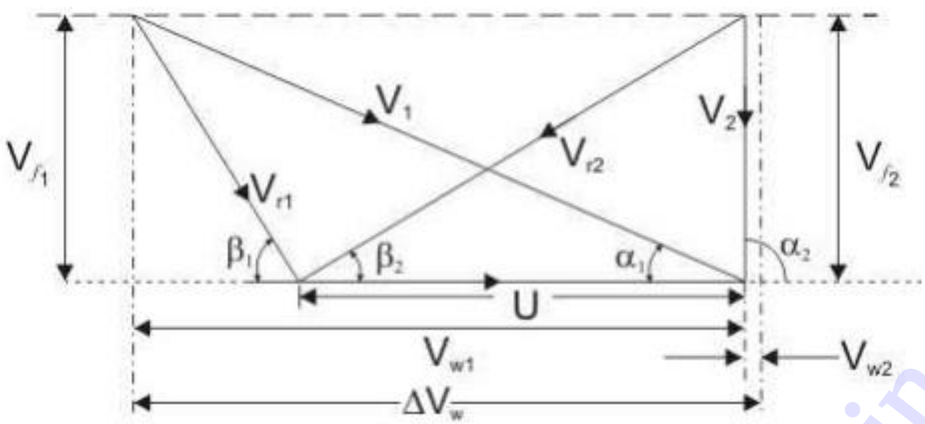

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The Single-Stage Impulse Turbine

- The *single-stage impulse turbine* is also called the *de Laval turbine* after its inventor.
- The turbine consists of a single rotor to which impulse blades are attached.
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- It is composed of one stage of nozzles as the single-stage turbine, followed by two rows of moving blades instead of one.

- These two rows are separated by one row of fixed blades attached to the turbine stator, which has the function of redirecting the steam leaving the first row of moving blades to the second row of moving blades.

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Reaction Turbine

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- Locomotives
- Power generations
- Industrial application for producing steam

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2. Nozzle governing
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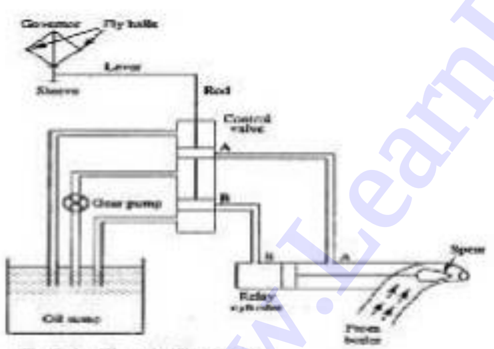

Fig 3.1- Throttle Governing

Let us consider an instant when the load on the turbine increases, as a result the speed of the turbine decreases. The fly balls of the governor will come down. The fly balls bring down the sleeve. The downward movement of the sleeve will raise the control valve rod. The mouth of the pipe AA will open. Now the oil under pressure will rush from the control valve to right side of piston in the rely cylinder through the pipe AA. This will move the piston and spear towards the left which will open more area of nozzle. As a result steam flow rate into the turbine increases, which in turn brings the speed of the turbine to the normal range.

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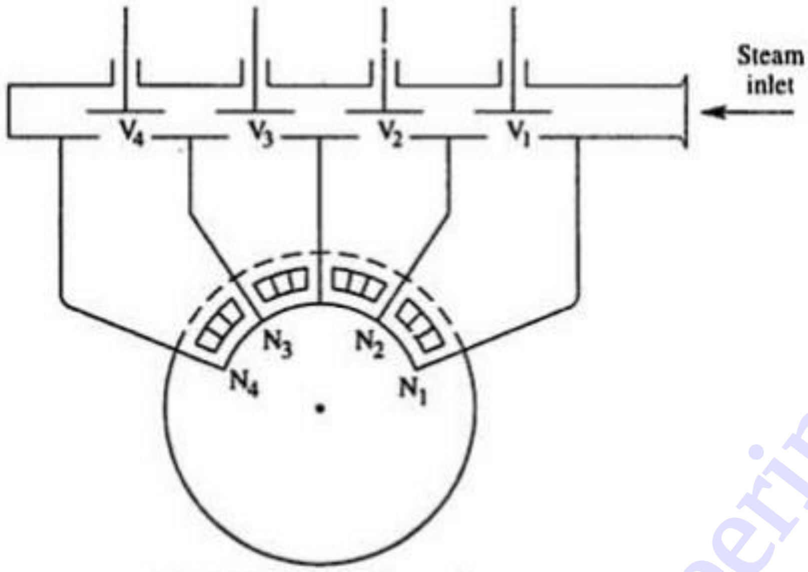

Fig 3.15 Nozzle Governing

A dynamic arrangement of nozzle control governing is shown in fig.

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UNIT – 5

REFRIGERATION AND AIR CONDITIONING

5.1 PREREQUISITE DISCUSSION

Before 1830, few Americans used ice to refrigerate foods due to a lack of ice-storehouses and iceboxes. As these two things became more widely available, individuals used axes and saws to harvest ice for their storehouses. This method proved to be difficult, dangerous, and certainly did not resemble anything that could be duplicated on a commercial scale.

Despite the difficulties of harvesting ice, Frederic Tudor thought that he could capitalize on this new commodity by harvesting ice in New England and shipping it to the Caribbean islands as well as the southern states. In the beginning, Tudor lost thousands of dollars, but eventually turned a profit as he constructed icehouses in Charleston, Virginia and in the Cuban port town of Havana. These icehouses as well as better insulated ships helped reduce ice wastage from 66% to 8%. This efficiency gain influenced Tudor to expand his ice market to other towns with icehouses such as New Orleans and Savannah. This ice market further expanded as harvesting ice became faster and cheaper after one of Tudor's suppliers, Nathaniel Wyeth, invented a horse-drawn ice cutter in 1825. This invention as well as Tudor's success inspired others to get involved in the ice trade and the ice industry grew.

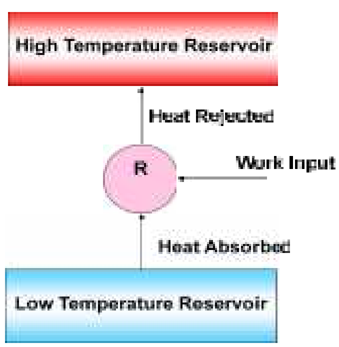
Ice became a mass-market commodity by the early 1830s with the price of ice dropping from six cents per pound to a half of a cent per pound. In New York City, ice consumption increased from 12,000 tons in 1843 to 100,000 tons in 1856. Boston's consumption leapt from 6,000 tons to 85,000 tons during that same period. Ice harvesting created a "cooling culture" as majority of people used ice and iceboxes to store their dairy products, fish, meat, and even fruits and vegetables. These early cold storage practices paved the way for many Americans to accept the refrigeration technology that would soon take over the country.

CONCEPT

5.2 CONCEPT OF REFRIGERATION

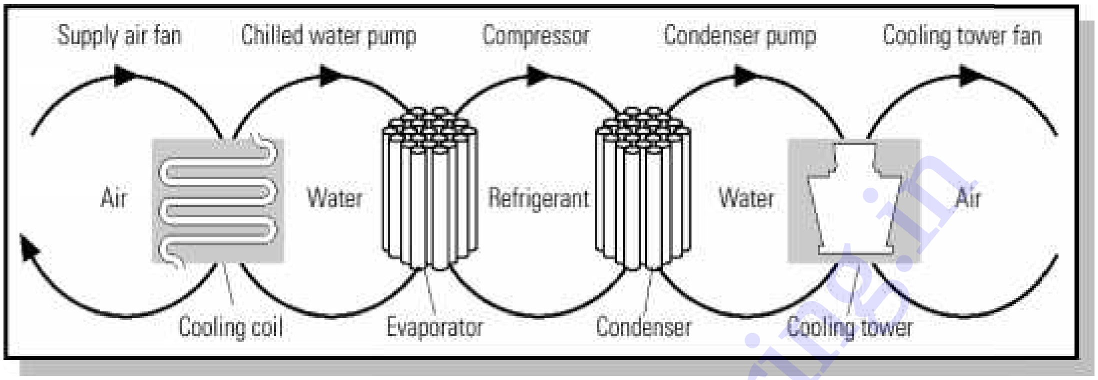
Refrigeration is a process in which work is done to move heat from one location to another. The work of heat transport is traditionally driven by mechanical work, but can also be driven by heat, magnetism, electricity, laser, or other means.

How does it work?



Thermal energy moves from left to right through five loops of heat transfer:

1) Indoor air loop
2) Chilled water loop
3) Refrigerant loop
4) Condenser water loop
5) Cooling water loop



5.3 SIGNIFICANCE

Refrigeration has had a large importance on industry, lifestyle, agriculture and settlement patterns. The idea of preserving food dates back to the ancient Roman and Chinese empires. However, refrigeration technology has rapidly evolved in the last century, from ice harvesting to temperature-controlled rail cars. In order to avoid food spoilage, refrigeration plays an important role in day to day life, similarly, Air conditioning is also an important technological system to prevent the human from the hot atmosphere during summer seasons.

5.4 CLASSIFICATION OF REFRIGERATION SYSTEM

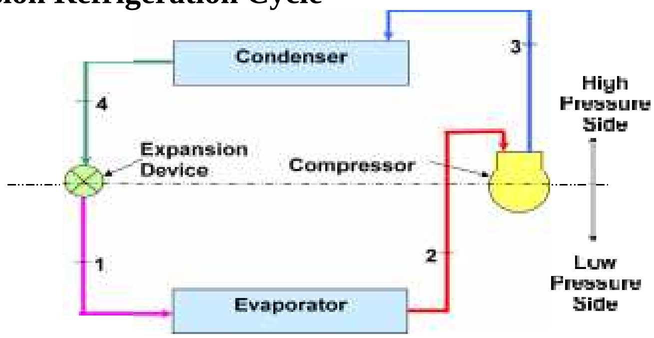
Types of Refrigeration

- Vapour Compression Refrigeration (VCR): uses mechanical energy
- Vapour Absorption Refrigeration (VAR): uses thermal energy

5.5 VAPOUR COMPRESSION REFRIGERATION

- Highly compressed fluids tend to get colder when allowed to expand
- If pressure high enough
  - Compressed air hotter than source of cooling
  - Expanded gas cooler than desired cold temperature
- Lot of heat can be removed (lot of thermal energy to change liquid to vapour)
- Heat transfer rate remains high (temperature of working fluid much lower than what is being cooled)

Vapour Compression Refrigeration Cycle



Evaporator

Low pressure liquid refrigerant in evaporator absorbs heat and changes to a gas

Compressor

The superheated vapour enters the compressor where its pressure is raised

Condenser

The high pressure superheated gas is cooled in several stages in the condenser

Expansion

Liquid passes through expansion device, which reduces its pressure and controls the flow into the evaporator

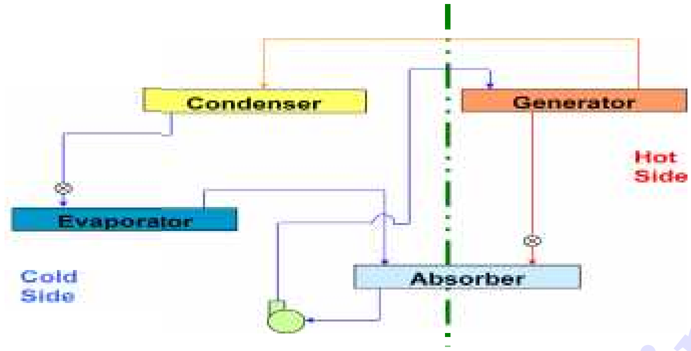
Type of refrigerant

- Refrigerant determined by the required cooling temperature
- Chlorinated fluorocarbons (CFCs) or freons: R-11, R-12, R-21, R-22 and R-502

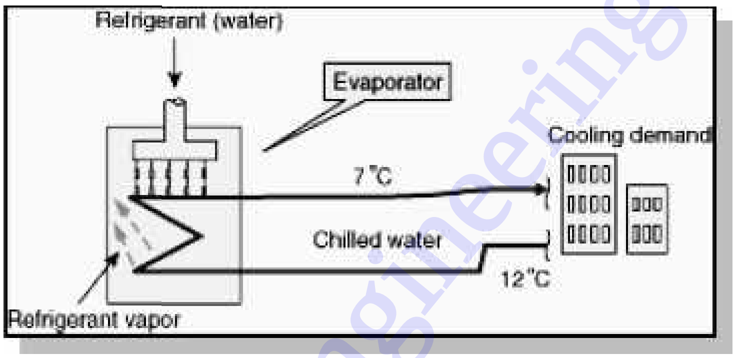
Choice of compressor, design of condenser, evaporator determined by

- Refrigerant
- Required cooling
- Load
- Ease of maintenance
- Physical space requirements
- Availability of utilities (water, power)

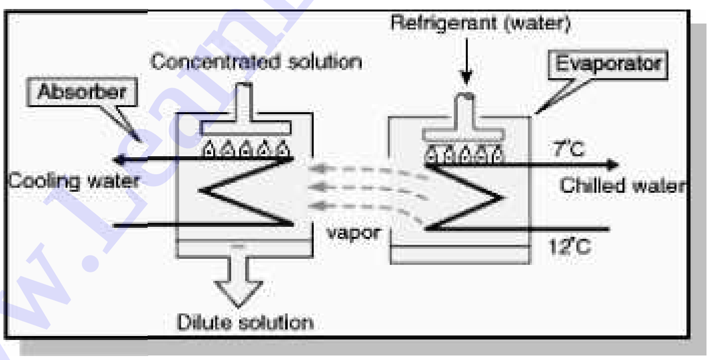
5.6 Vapour Absorption Refrigeration



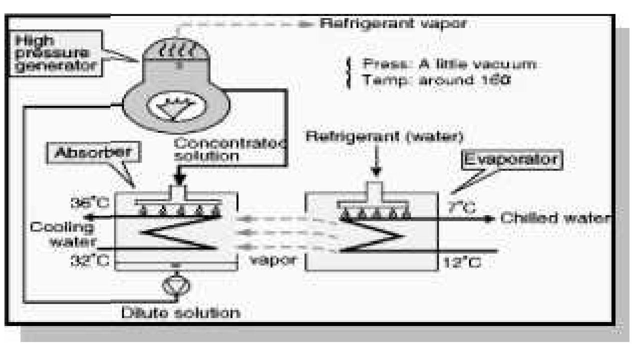
Evaporator



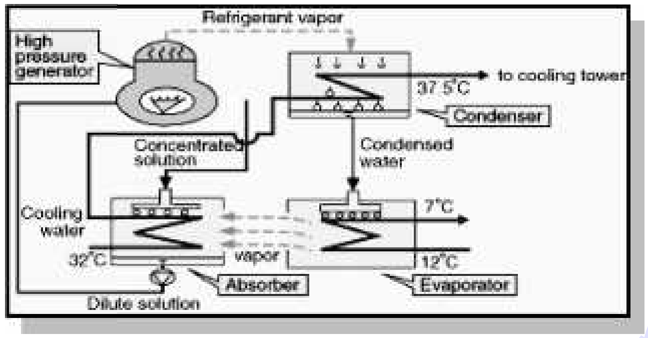
Absorber



High pressure generator



Condenser



Evaporative Cooling

- Air in contact with water to cool it close to ‘wet bulb temperature’
- Advantage: efficient cooling at low cost
- Disadvantage: air is rich in moisture

5.7 COMPARISON BETWEEN VAPOR COMPRESSION AND ABSORPTION SYSTEM

Absorption system	Compression System
a) Uses low grade energy like heat. Therefore, may be worked on exhaust systems from I.C engines, etc.	a) Using high-grade energy like mechanical work.
b) Moving parts are only in the pump, which is a small element of the system. Hence operation is smooth.	b) Moving parts are in the compressor. Therefore, more wear, tear and noise.
c) The system can work on lower evaporator pressures also without affecting the COP. d) No effect of reducing the load on performance.	c) The COP decreases considerably with decrease in evaporator pressure. d) Performance is adversely affected at partial loads.
e) Liquid traces of refrigerant present in piping at the exit of evaporator	e) Liquid traces in suction line may damage the compressor.

5.8 PERFORMANCE

Assessment of Refrigeration

- **Cooling effect: Tons of Refrigeration**

  1 TR = 3024 kCal/hr heat rejected

- **TR is assessed as:**

  $$TR = Q \times C_p \times (T_i - T_o) / 3024$$

Q = mass flow rate of coolant in kg/hr

Cp = is coolant specific heat in kCal /kg °C

Ti = inlet, temperature of coolant to evaporator (chiller) in 0°C

To = outlet temperature of coolant from evaporator (chiller) in 0°C

Specific Power Consumption (kW/TR)

- Indicator of refrigeration system's performance
- kW/TR of centralized chilled water system is sum of
    - Compressor kW/TR
    - Chilled water pump kW/TR
    - Condenser water pump kW/TR
    - Cooling tower fan kW/TR

Coefficient of Performance (COP)

- The performance of refrigerators and heat pumps is expressed in terms of coefficient of performance (COP), defined as
-

$$COP_R = \frac{\text{Desired output}}{\text{Required input}} = \frac{\text{Cooling effect}}{\text{Work input}} = \frac{Q_L}{W_{net,in}}$$

$$COP_{HP} = \frac{\text{Desired output}}{\text{Required input}} = \frac{\text{Heating effect}}{\text{Work input}} = \frac{Q_H}{W_{net,in}}$$

Measure

- Airflow Q (m3/s) at Fan Coil Units (FCU) or Air Handling Units (AHU): anemometer
- Air density ρ (kg/m3)
- Dry bulb and wet bulb temperature: psychrometer
- Enthalpy (kCal/kg) of inlet air (h_{in}) and outlet air (H_{out}): psychrometric charts

5.9 APPLICATIONS OF REFRIGERATRION

- Metal workers
- Oil refineries
- Chemical plants
- Petrochemical plants
- Transporting temperature-sensitive foodstuffs
- Dairy products

AIR CONDITIONERS

5.10 CONCEPT OF AIR CONDITIONING

Air conditioning (often referred to as aircon, AC or A/C) is the process of altering the properties of air (primarily temperatureand humidity) to more favourable conditions, typically with the aim of distributing the conditioned air to an occupied space to improve thermal comfort and indoor air quality.

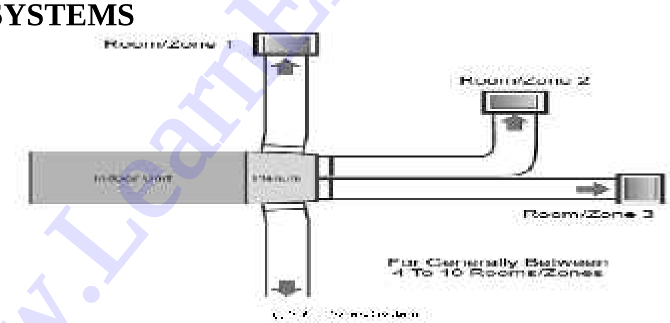
5.11 TYPES OF AIR CONDITIONERS

- Room air conditioners
- Zoned Systems
- Unitary Systems
- Window Air-conditioning System
- Split Air-conditioning System
- Central air conditioning systems

5.11.1 ROOM AIR CONDITIONER

- Room air conditioners cool rooms rather than the entire home.
- Less expensive to operate than central units
- Their efficiency is generally lower than that of central air conditioners.
- Can be plugged into any 15- or 20-amp, 115-volt household circuit that is not shared with any other major appliances

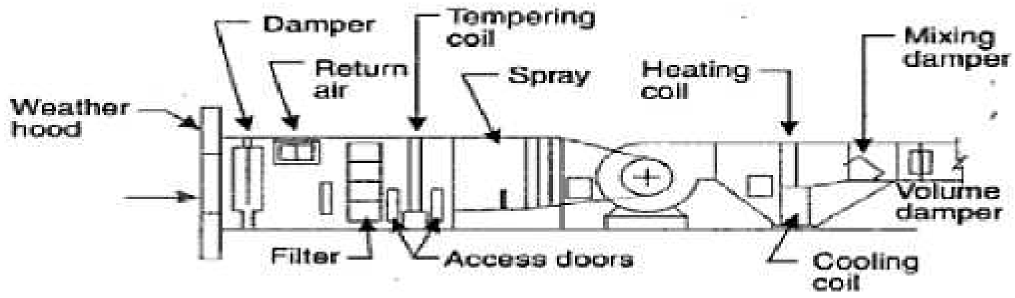
5.11.2 ZONED SYSTEMS



5.11.3 CENTRAL AIR CONDITIONING

- Circulate cool air through a system of supply and return ducts. Supply ducts and registers (i.e., openings in the walls, floors, or ceilings covered by grills) carry cooled air from the air conditioner to the home.

- This cooled air becomes warmer as it circulates through the home; then it flows back to the central air conditioner through return ducts and registers



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5.11.4 UNITARY SYSTEMS

A unitary air conditioning system comprises an outdoor unit including a compressor for compressing a refrigerant, an outdoor heat exchanger for heat exchange of the refrigerant and an expander connected to the outdoor heat exchanger, for expanding the refrigerant; a duct installed inside a zone of a building; a central blower unit having a heat exchanger connected to the outdoor unit through a first refrigerant pipe and a blower for supplying the air heat-exchanged by the heat exchanger to the duct; and an individual blower unit including a heat exchanger connected to the outdoor unit through a second refrigerant pipe and a fan for sending the air heat exchanged by the heat exchanger and disposed in a zone in the building, for individually cooling or heating the zone. Accordingly, cooling or heating operation is performed on each zone of the building, and simultaneously, additional individual heating or cooling operation can be performed on a specific space, so that a cost can be reduced and cooling or heating in the building can be efficiently performed.

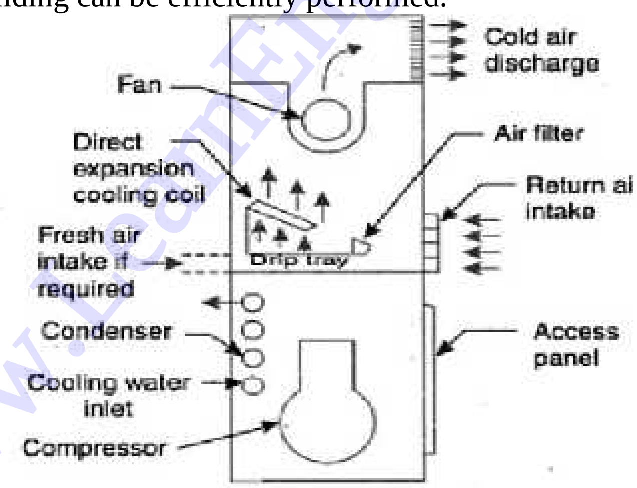
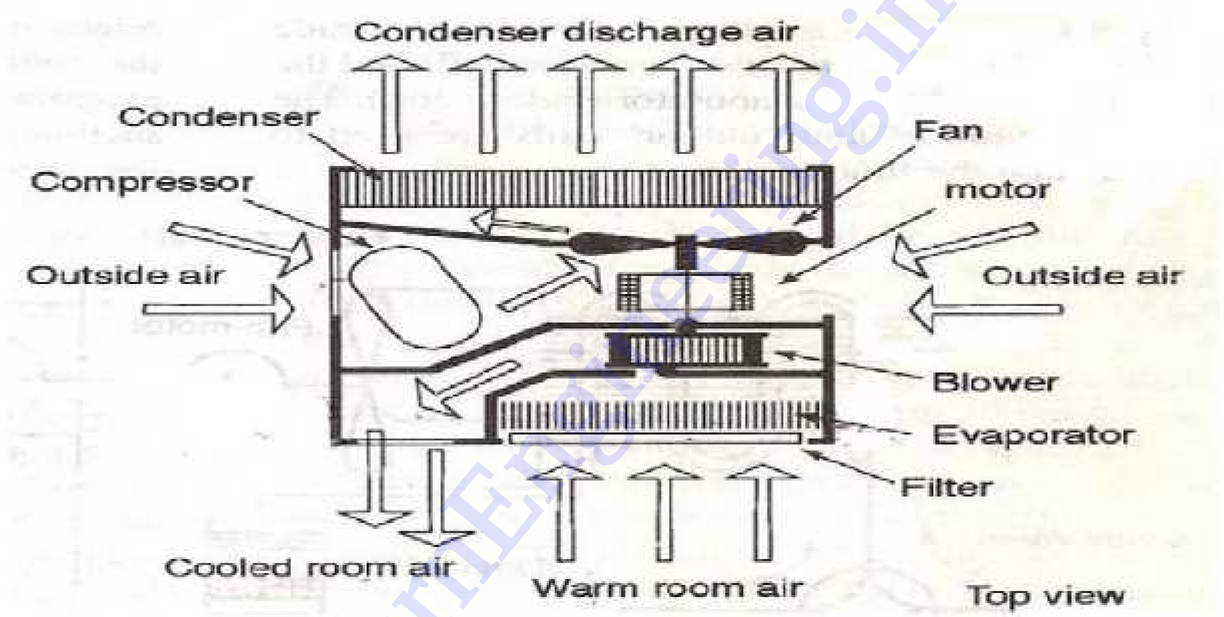


Fig.[illegible] 2 Unitary Systems

5.11.5 WINDOW AIR-CONDITIONING SYSTEM

It is the most commonly used air conditioner for single rooms. In this air conditioner all the components, namely the compressor, condenser, expansion valve or coil, evaporator and cooling coil are enclosed in a single box. This unit is fitted in a slot made in the wall of the room, or often a window sill. Windows air conditioners are one of the most widely used types of air conditioners because they are the simplest form of the air conditioning systems. Window air conditioner comprises of the rigid base on which all the parts of the window air conditioner are assembled. The base is assembled inside the casing which is fitted into the wall or the window of the room in which the air conditioner is fitted. The whole assembly of the window air conditioner can be divided into two compartments: the room side, which is also the cooling side and the outdoor side from where the heat absorbed by the room air is liberated to the atmosphere. The room side and outdoor side are separated from each other by an insulated partition enclosed inside the window air conditioner assembly. In the front of the window air conditioner on the room side there is beautifully decorated front panel on which the supply and return air grills are fitted (the whole front panel itself is commonly called as front grill). The louvers fitted in the supply air grills are adjustable so as to supply the air in desired direction. There is also one opening in the grill that allows access to the Control panel or operating panel in front of the window air conditioner.



TYPES OF CENTRAL AC

- **split-system**
    - An outdoor metal cabinet contains the condenser and compressor, and an indoor cabinet contains the evaporator

- **Packaged**
    - The evaporator, condenser, and compressor are all located in one cabinet.

5.11.6 SPLIT AIR-CONDITIONING SYSTEM:

The split air conditioner comprises of two parts: the outdoor unit and the indoor unit. The outdoor unit, fitted outside the room, houses components like the compressor, condenser and expansion valve. The indoor unit comprises the evaporator or cooling coil and the cooling fan. For this unit you don't have to make any slot in the wall of the room. Further, the present day split units have aesthetic looks and add to the beauty of the room. The split air conditioner can be used to cool one or two rooms.

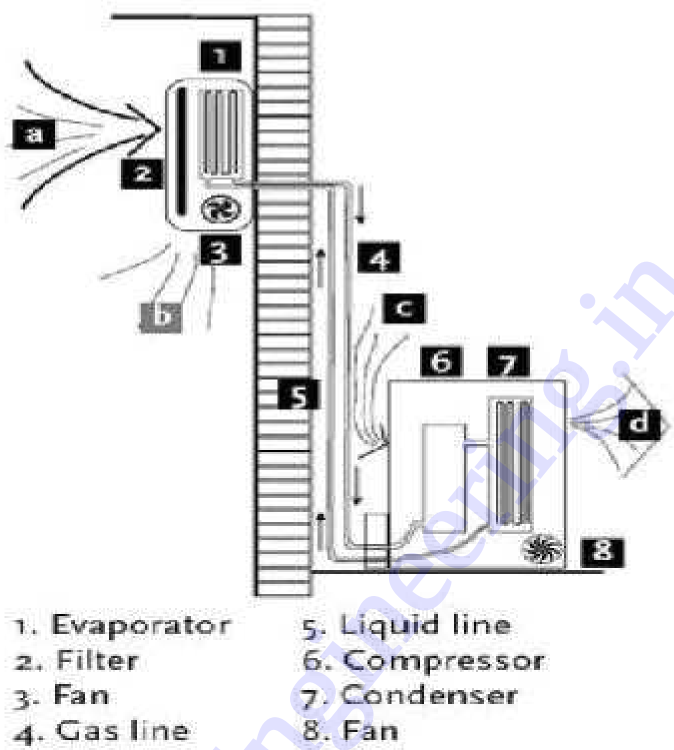


Fig.5.11 Split Air-conditioning System

Energy Consumption

- Air conditioners are rated by the number of British Thermal Units (Btu) of heat they can remove per hour. Another common rating term for air conditioning size is the "ton," which is 12,000 Btu per hour.
- Room air conditioners range from 5,500 Btu per hour to 14,000 Btu per hour.

Energy Efficiency

- Today's best air conditioners use 30% to 50% less energy than 1970s
- Even if your air conditioner is only 10 years old, you may save 20% to 40% of your cooling energy costs by replacing it with a newer, more efficient model

5.12 SOLVED PROBLEMS

1. A sling psychrometer gives reading of 25^0c dry bulb temperature 15^0c wet bulb temperature. The barometer indicates 760 mm of hg assuming partial pressure of the vapour as 10 mm of Hg. Determine 1. Specific humidity 2. Saturation ratio.

Given Data:

Dry bulb temperature t_d $=25^0$c
Wet bulb temperature $t_w=15^0$c
Barometer pressure p_b=760mm of Hg
Partial pressure p_v= 10mm of Hg

To Find:

Specific humidity

Saturation ratio.

Solution:

Specific humidity:

We know that Specific humidity

$$W = \frac{.622Pv}{Pb - Pv} = \frac{.622 \times 10}{760 - 10}$$

$= 0.0083$ kg/kg of dry air

Saturation ratio:

From steam table corresponding to dry bulb temperature t_d $=25^0$c

We find the partial pressure p_s=0.03166 bar

$$= \frac{0.03166}{0.00133}$$

=23.8 mm of Hg

We know that Saturation ratio.

$$\mu = \frac{pv(pb-ps)}{ps(pb-pv)}$$

$$= \frac{10(760-23.8)}{23.8(760-10)}$$

= 0.41

Result:

1. Specific humidity = 0.0083 kg/kg of dry air

2. Saturation ratio. = **0.41**

2. A two stages, single acting air compressor compresses air to 20bar. The air enters the

L.P cylinder at 1bar and 27^{o}c and leaves it at 4.7bar. the air enters the H.P. cylinder at

4.5bar and 27^{o}c. the size of the L.P cylinder is 400mm diameter and 500mm stroke. The clearance volume In both cylinder is 4% of the respective stroke volume. The compressor runs at 200rpm, taking index of compression and expansion in the two cylinders as 1.3, estimate 1. The indicated power required to run the compressor; and 2. The heat rejected in the intercooler per minute.

Given data:

Pressure (P4)= 20bar

Pressure (P1) = 1bar = 1×10^{5} N/m^{2}

Temperature (T1) = 27^{o}C = 27+273 = 300K Pressure (P2) = 4.7bar

Pressure (P3) = 4.5bar

Temperature (T3) = 27^{o}C = 27+273 = 300K Diameter (D1) = 400mm 0.4m

Stroke (L1) = 500mm = 0.5m

$$K = \frac{v_{c1}}{v_{s1}} = \frac{v_{c3}}{v_{s3}} = 4\% = 0.04$$

N = 200rpm ; n = 1.3

To Find:

Indicated power required to run the compressor

Solution :

We know the swept volume of the L.P cylinder

$$v_{s1} = \frac{\pi}{4}(D_1)^2 L_1 = \frac{\pi}{4}(0.4)^2\, 0.5$$

$= 0.06284\ m^3$

And volumetric efficiency,

$$\eta_v = 1 + K - K\left(\frac{P_2}{P_1}\right)^{\frac{1}{n}}$$

$$= 1 + 0.04 - 0.04\left(\frac{4.7}{1}\right)^{\frac{1}{1.3}}$$

= 0.9085 or 90.85% Volume of air sucked by air pressure compressor,

$$v_1 = v_{s1} \times \eta_v = 0.06284 \times 0.9085 = 0.0571\frac{m^3}{stroke}$$

$$= 0.0571 \times N_w = 0.0571 \times 200 = 1$$

$=1.42\ m^3/min$

And volume of air sucked by H.P compressor,

$$v_3 = \frac{P_1 V_1}{P_3} = \frac{1 \times 11.42}{4.5} = 2.54\frac{m^3}{min}$$

We know that indicated work done by L.P compressor

$$W_L = \left(\frac{n}{n-1}\right) P_1 v_1 \left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} - 1\right]$$

$$= \left(\frac{1.3}{1.3-1}\right) 1 \times 10^5 \times 11.42 \left[\left(\frac{4.7}{1}\right)^{\frac{1.3-1}{1.3}} - 1\right]$$

$= 2123.3\times10^3$ J/min = 2123.3 KJ/min

And indicated workdone by H.P compressor,

$$W_H = \left(\frac{n}{n-1}\right) P_3 v_3 \left[\left(\frac{P_4}{P_3}\right)^{\frac{n-1}{n}} - 1\right]$$

$$= \left(\frac{1.3}{1.3-1}\right) 4.5 \times 10^5 \times 2.54 \left[\left(\frac{4.20}{4.5}\right)^{\frac{1.3-1}{1.3}} - 1\right]$$

$= 2043.5\times10^3$ J/min = 2034.5 KJ/min

Total indicated work done by the compressor,

$W = W_L + W_H$ = 2123.3 + 2034.5

= 4157.8 KJ/min

Indicated power required to run the compressor = 4157.8 / 60

= 69.3KW

3. In an oil gas turbine installation , air is taken as 1 bar and 30^oC . The air is compressed to 4bar and then heated by burning the oil to a temperature of 500^oC . If the air flows at the rate of 90Kg/min . Find the power developed by the plant take γ for air as 1.4 C_p as 1KJ/KgK . If 2.4Kg of oil having calorific value of 40,000 KJ/Kg if burned in the combustion chamber per minute. Find the overall efficiency of the plant.

Given Data:

Pressure (P4 = P3) = 1bar
Pressure (P1 = P2) = 4bar
Temperature (T2) = 500^oC = 500+273 = 773K
Mass flow rate of air(m_a) = 90Kg/min = 1.5Kg/sec
Mass flow rate of fuel (m_f) = 2.4Kg/min = 0.04Kg/sec
Temperature (T4) = 30^oC = 30+273 = 303K
γ = 1.4 ; C_p = 1KJ/KgK ; C_v= 40,000 KJ/Kg

To Find:

Power developed by the plant
Performance of the gas turbine
Overall efficiency of the plant

Solution:

Power developed by the plant:

Let T1,T3 = temperature of air at points 1 and3

Weknow that isentropic expansion 2-3,

$$\frac{T_3}{T_2} = \left(\frac{P_3}{P_2}\right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{1}{4}\right)^{\frac{1.4-1}{1.4}} = 0.673$$

$T_3 = T_2 \times 0.673 = 773 \times 0.673 = 520K$

Similarly for isentropic compression 4-1:

$$\frac{T_4}{T_1} = \left(\frac{P_4}{P_1}\right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{1}{4}\right)^{\frac{1.4-1}{1.4}} = 0.673$$

$T_1 = T_4 / 0.673 = 303/0.673 = 450K$

Performance of the gas turbine:

We know that work developed by the turbine,

$$W_T = mC_p(T_2 - T_3) = 1.5 \times 1(773 - 520)$$

= 379.5KJ/s

And work developed by the compressor,

$$W_c = mC_p(T_1 - T_4) = 1.5 \times 1(450 - 303)$$

= 220.5/s

Net work or power of the turbine,

$P = W_T - W_c = 379.5 – 220.5 = 159KJ/s = 159KW$

Overall efficiency of the plant:

We know that the heat supplied per second

$= m_f \times C = 0.04 \times 40{,}000 = 1600$ KJ/s

Therefore, overall efficiency of the plant,

$\eta_o = 159/1600 = 0.099$ or 9.99%

5.13 TECHNICAL TERMS

BTU - British thermal unit. A unit of heat energy - approximately the amount of energy needed to heat one pound of water by one degree Fahrenheit.

dBA – a unit for measuring sound power or pressure, deciBel on the A scale.

Capacity – the ability of a heating or cooling system to heat or cool a given amount of space. For heating, this is usually expressed in BTU's. For cooling, it is usually given in tons.

Compressor – the pump that moves the refrigerant from the indoor evaporator to the outdoor condenser and back to the evaporator again. The compressor is often called "the heart of the system" because it circulates the refrigerant through the loop.

Condenser – a device used to condense a refrigerant thereby rejecting the heat to another source, typically an air cooled or water cooled condenser.

Cassette – a fan coil unit that fits mainly in the ceiling void with only a diffuser plate visible, diffuses conditioned air in one, two, three or four directions.

HVAC – heating, ventilation and air conditioning.

Inverter system – Constantly alters fan and motor speeds. This enables faster cooling of a room, and the inverter air conditioner doesn't have to switch itself on and off to maintain a constant temperature.

kw – standard measurement of heat or power, 1kw = 1000 watts = 3412Btu/hr = 860kcal.

Load Calculation – a mathematical design tool used to determine the heat gain and heat loss in a building so that properly sized air conditioning and heating equipment may be installed.

Refrigerant – a substance that produces a refrigerating effect while expanding or vaporizing.

Reverse cycle – the reverse cycle air conditioner internally reverses its operation to provide heating or cooling, as required.

Split System – a central air conditioner consisting of two or more major components. The system usually consists of a compressor-containing unit and condenser, installed outside the building and a non-compressor – containing air handling unit installed within the building. This is the most common type of system installed in a home.

Zoning – the practice of providing independent heating and/or cooling to different areas in a structure. Zoning typically utilizes a system controller, zoning dampers controlled by a thermostat in each zone, and a bypass damper to regulate static pressure in the supply duct.