***CHAPTER1: INTRODUCTION TO TURBOMACHINES***

**1.1 Introduction:**

The turbomachine is used in several applications, the primary ones being electrical power generation, aircraft propulsion and vehicular propulsion for civilian and military use. The units used in power generation are steam, gas and hydraulic turbines, ranging in capacity from a few kilowatts to several hundred and even thousands of megawatts, depending on the application. Here, the turbomachines drives the alternator at the appropriate speed to produce power of the right frequency. In aircraft and heavy vehicular propulsion for military use, the primary driving element has been the gas turbine.

**1.2 Turbomachines and its Principal Components:**

***Question No 1.1: Define a turbomachine. With a neat sketch explain the parts of a turbomachine. (VTU, Jan-07, Dec-12, Jan-14, Jul-15)***

**Answer:** A turbomachine is a device in which energy transfer takes place between a flowing fluid and a rotating element due to the dynamic action, and results in the change of pressure and momentum of the fluid.



Fig. 1.1 Principal components of turbomachine

The following are the principal components of turbomachine: (i) Rotor, (ii) Stator and (iii) Shaft.

Rotor is a rotating element carrying the rotor blades or vanes. Rotor is also known by the names runner, impellers etc. depending upon the particular machine. Here energy transfer occurs between the flowing fluid and the rotating element due to the momentum exchange between the two.

Stator is a stationary element carrying the guide vanes or stator blades. Stator blades are also known by guide blades or nozzle depending upon the particular machine. These blades usually control the direction of fluid flow during the energy conversion process.

Housing: To keep various rotating, stationery and other passages safely under dynamic conditions.

Shaft is transmitting power into or out of the machine depending upon the particular machine. For power generating machines, it may call as output shaft and for power absorbing machines; it may called as input shaft.

**1.3 Classification of Turbomachines:**

***Question No 1.2: Explain how turbomachines are classified. Give at least one example of each. (VTU, Feb-06, Jul-13, Jun/Jul 14)***

**Answer:** Turbomachines are broadly classified into power generating, power absorbing and power transmitting turbomachines.

In power-generating turbomachines, fluid energy (decrease in enthalpy) is converted into mechanical energy which is obtained at the shaft output, whereas in power-absorbing turbomachines, mechanical energy which is supplied at the shaft input is converted to fluid energy (increase in enthalpy). The power-transmitting turbomachines are simply transmitting power from input shaft to an output shaft. That means, these devices act merely as an energy transmitter to change the speed and torque on the driven member as compared with the driver.

Again power-generating and power-absorbing turbomachines are classified by the direction of the fluid flow as: (i) axial flow, (ii) radial flow and (iii) mixed flow. In the axial flow and radial flow turbomachines, the major flow directions are approximately axial and radial respectively, while in the mixed flow machine, the flow enters axially and leaves radially or vice versa. A radial flow machine may also be classified into radial inward flow (centripetal) or radial outward flow (centrifugal) types depending on whether the flow is directed towards or away from the shaft axis.

***Question No 1.3: Explain with examples the power generating, power absorbing and power transmitting turbomachines. (VTU, Aug-02, Jul-13, Jul-14)***

**Answer:** Power generating turbomachine is one which converts fluid energy in the form of kinetic energy or pressure energy into mechanical energy in terms of rotating shaft. Turbines are the best example for this type.

Power absorbing turbomachine is one which converts mechanical energy into fluid energy. Compressors, fans, pumps and blowers are the best example for this type.

Power transmitting is one which is used to transmit power from driving shaft to driven shaft with the help of fluid. There is no mechanical connection between the two shafts. The best examples for this type are hydraulic coupling and hydraulic torque converter.

***Question No 1.4: What is an axial flow turbomachine? How is it different from a radial flow turbomachine? Give one example each.***

**Answer:** In axial flow turbomachine, the major flow direction is approximately axial, example: Kaplan turbine. Whereas in radial flow turbomachine, the major flow direction is radial, example: Francis turbine.

**1.4 Positive-Displacement Devices and Turbomachines:**

***Question No 1.5: Compare the turbomachines with positive displacement machines. (VTU, Feb-02, Feb-03, Feb-04, Jun-12, Dec-12, Jul-13, Jan-16, Jul-16, Jan-17, Jul-17)***

**Answer:** The differences between positive-displacement machines and turbomachines are given by comparing their modes of action, operation, energy transfer, mechanical features etc. in the following table.

|  |  |  |
| --- | --- | --- |
| **Modes** | **Positive-displacement Machine** | **Turbomachine** |
| ***Action*** | (a) It creates thermodynamic and mechanical action between a nearly static fluid and a relatively slowly moving surface. | (a) It creates thermodynamic and dynamic interaction between a flowing fluid and rotating element. |
| (b) It involves a change in volume or a displacement of fluid. | (b) It involves change in pressure and momentum of the fluid. |
| (c) There is a positive confinement of the fluid in the system. | (c) There is no positive confinement of the fluid at any point in the system. |
| ***Operation*** | (a) It involves a reciprocating motion of the mechanical element and unsteady flow of the fluid. But some rotary positive displacement machines are also built. Examples: Gear pump, vane pump | (a) It involves a purely rotary motion of mechanical element and steady flow of the fluid. It may also involve unsteady flow for short periods of time, especially while starting, stopping or during changes of load. |
| (b) Entrapped fluid state is different from the surroundings when the machine is stopped, if heat transfer and leakages are avoided. | (b) The fluid state will be the same as that of the surroundings when the machine is stopped. |
| ***Mechanical Features*** | (a) Because of the reciprocating masses, vibrations are more. Hence low speeds are adopted. | (a) Rotating masses can be completely balanced and vibrations eliminated. Hence high speeds can be adopted. |
| (b) Heavy foundations are required. | (b) Light foundations sufficient. |
| (c) Mechanical design is complex because of valves. | (c) Design is simple. |
| (d) Weight per unit output is more. | (d) Weight per unit output is less. |
| ***Efficiency of conversion process*** | (a) High efficiency because of static energy transfer. | (a) Efficiency is low because of dynamic energy transfer. |
| (b) The efficiencies of the compression and expansion processes are almost the same. | (b) The efficiency of the compression process is low. |
| ***Volumetric efficiency*** | (a) Much below that of a turbomachine because of valves. | (a) It is almost 100%. |
| (b) Low fluid handling capacity per unit weight of machine. | (b) High fluid handling capacity per unit weight of machine. |
| ***Fluid phase change and surging*** | No such serious problems are encountered. | (a) Causes cavitation in pumps and turbines. Therefore leads to erosion of blades. |
| (b) Surging or pulsation leads to unstable flow. And also causes vibrations and may destroy the machine. |
| (c) These factors deteriorate the performance of the machine. |

***Question No 1.6: Are vane compressors and gear pumps turbomachines? Why? (VTU, Dec-10)***

**Answer:** No, vane compressors and gear pumps are positive displacement machines and work by moving a fluid trapped in a specified volume (i.e., fluid confinement is positive).

**1.5 First and Second Laws of Thermodynamics Applied to Turbomachines:**

***Question No 1.7: Explain the applications of first and second laws of thermodynamics to turbomachines. (VTU, Jul/Aug-02) Or,***

***Starting from the first law, derive an expression for the work output of a turbomachine in terms of properties at inlet and outlet. Or,***

***Deducing an expression, explain the significance of first and second law of thermodynamics applied to a turbomachine. (VTU, Dec-12, Dec 14/Jan 15)***

**Answer:** Consider single inlet and single output steady state turbomachine, across the sections of which the velocities, pressures, temperatures and other relevant properties are uniform.

**Application of first law of thermodynamics:** The steady flow equation of the first law of thermodynamics in the unit mass basis is:

(1.1)

Here, q and w are heat transfer and work transfer per unit mass flow across the boundary of the control volume respectively.

Since, the stagnation enthalpy:.

Then, equation (1.1) becomes: (1.2)

Generally, all turbomachines are well-insulated devices, therefore q=0. Then equation (1.2) can be written as: (1.3)

The equation (1.3) represents that, *the energy transfer as work is numerically equal to the change in stagnation enthalpy of the fluid between the inlet and outlet of the turbomachine.*

In a power-generating turbomachine, w is positive as defined so that Δho is negative, i.e., the stagnation enthalpy at the exit of the machine is less than that at the inlet. The machine produces out work at the shaft. In a power-absorbing turbomachine, w is negative as defined so that Δho is positive. The stagnation enthalpy at the outlet will be greater than that at the inlet and work is done on the flowing fluid due to the rotation of the shaft.

**Application of second law of thermodynamics:** The second law equation of states, applied to stagnation properties is:

(1.4)

But equation (1.3) in differential form is, .

Then equation (1.4) can be written as:

(1.5)

In a power-generating machine, dpo is negative since the flowing fluid undergoes a pressure drop when mechanical energy output is obtained. However, the Clausius inequality for a turbomachine is given that. The sign of equality applies only to a reversible process which has a work output. In a real machine (irreversible machine),, which has a work output. So that and represents the decrease in work output due to the irreversibilities in the machine. Therefore the reversible power-generating machine exhibits the highest mechanical output of all the machines undergoing a given stagnation pressure change. A similar argument may be used to prove that the reversible power-absorbing machine needs the minimum work input of all the machines for a given stagnation pressure rise (i.e.,).

**1.6 Efficiency of Turbomachines:**

***Question No 1.8: Define: (i) adiabatic efficiency and (ii) mechanical efficiency for power generating and power absorbing turbomachines. (VTU, Dec-12)***

***Answer:*** The performance of a real machine is always inferior to that of a frictionless and loss-free ideal machine. A measure of its performance is the efficiency, defined differently for power-generating and power-absorbing machines.

For power-generating machine, the efficiency is defined as:

For power-absorbing machine, the efficiency is defined as:

Generally, losses occur in turbomachines are due to: (a) mechanical losses like bearing friction, windage, etc., (b) fluid-rotor losses like unsteady flow, friction between the blade and the fluid, leakage across blades etc. If the mechanical and fluid-rotor losses are separated, the efficiencies may be rewritten in the following forms:

For power-generating turbomachine,

Or,   
For power-absorbing turbomachines,

Or,

where ηa and ηm are adiabatic and mechanical efficiencies respectively.

For power-generating turbomachine, adiabatic or isentropic or hydraulic efficiency may be written as,

For power-absorbing turbomachine, adiabatic or isentropic or hydraulic efficiency may be written as,

*Note: (i) Hydrodynamic energy is defined as the energy possessed by the fluid in motion.*

*(ii) Windage loss is caused by fluid friction as the turbine wheel and blades rotate through the surrounding fluid.*

*(iii) Leakage loss is caused by the fluid when it passes over the blades tip without doing any useful work.*

**1.8.1 Geometric Variables:** The variables with geometric property in turbomachines are *length, diameter, thickness, height* etc.

**1.8.2 Kinematic Variables:** The variables with flow property in turbomachines are *velocity, speed, volume flow rate, acceleration, angular velocity* etc.

1**.8.3 Dynamic Variables:** The variables with fluid property in turbomachines are *mass flow rate, gas density, dynamic viscosity, bulk modulus, pressure difference, force, power, elasticity, surface tension, specific weight, stress, resistance* etc.

**Note:** (1) For power generating turbomachines, the performance of a machine is referred to the power developed (P), workdone (W), pressure ratio (P1/P2) or efficiency (η) which depend on independent variables.

(2) For power absorbing turbomachines, the performance is referred to the discharge (Q), enthalpy rise (Δh), pressure ratio (P2/P1) or efficiency (η) which depend on independent variables.

***Question No 1.10: Give the significance of the dimensionless terms (i) Flow coefficient (ii) Head coefficient (iii) Power coefficient with respect to turbomachines. (VTU, Jan-07) Or,***

***Explain capacity coefficient, head coefficient and power coefficient referring to a turbomachines. (VTU, Feb-02, Feb-03, Feb-04, Jan-16, Jul-17)***

**Answer:** The various π-terms have the very significant role in a turbomachine as explained below.

**(i) Flow Coefficient:** It is also called as capacity coefficient or specific capacity. The term is the capacity coefficient, which signifies the volume flow rate of fluid through a turbomachine of unit diameter of runner operating at unit speed. The specific capacity is constant for dynamically similar conditions. Hence for a fan or pump of certain diameter running at various speeds, the discharge is proportional to the speed. This is the *First fan law.*

**Speed ratio:** The specific capacity is related to another quantity called speed ratio and is obtained as follows:

Where is called the speed ratio, which is defined as the ratio of tangential velocity of runner to the theoretical jet velocity of fluid. For the given machine, the speed ratio is fixed.

**(ii) Head Coefficient:** The term is called the head coefficient or specific head. It is a measure of the ratio of the fluid potential energy (column height H) and the fluid kinetic energy while moving at the rotational speed of the wheel U. The term can be interpreted by noting that:

The head coefficient is constant for dynamically similar machines. For a machine of specified diameter, the head varies directly as the square of the tangential speed of wheel. This is the Second fan law.

**(iii) Power Coefficient:** The term is called the power coefficient or specific power. It represents the relation between the power, fluid density, speed and wheel diameter. For a given machine, the power is directly proportional to the cube of the tangential speed of wheel. This is the Third fan law.

***Question No 1.11: Discuss the effect of Reynolds number on turbomachine. (VTU, Jun/Jul-08)***

**Answer:** The Reynolds number defined as the ratio of the inertial force to the viscous force. It signifies the relative predominance of the inertial to the viscous force occurring in the flow system. It is an important parameter, which represents the nature of flow. If the Reynolds number is greater than 4000, the flow is termed as turbulent, in which the inertia effect is more than the viscous effects. And, if Reynolds number is less than 2000, then flow is laminar in which viscous effects are more than the inertia effect.

The values of Reynolds number in turbines are much higher than the critical values. Most of the turbines use relatively low viscosity fluids like air, water and light oil. Therefore, the Reynolds number has very little effect on the power output of the machine. But Reynolds number is an important parameter for small pumps, compressors, fans and blowers. Their performance improves with an increase in Reynolds number.

The Reynolds number for the pipe flow is expressed as

**1.10 Specific Speed:**

The specific speed is the dimensionless term and is the parameter of greatest importance in incompressible flow machines. The specific speed is only the parameter that doesn’t contain the linear dimension of the runner. Hence, while operating under the same conditions of flow and head, all geometrically similar machines have the same specific speed, irrespective of their sizes.

The specific speed can be expressed in terms of discharge (Q) for power absorbing machine or the power (P) for power generating machine.

Turbines with low specific speeds work under high head and low discharge conditions, which high specific speed turbines work under low head and high discharge conditions.

**Specific power** is referred as the ratio of Power in or out of turbomachine to its weight/Unit Mass/ Unit Volume.

**1.10.1 Specific Speed of a Pump:**

***Question No 1.12: Define specific speed of a pump. Derive an expression for specific speed of a pump from fundamentals. (VTU, Aug-05, Jun-12, Jan 15, Jul-15)***

**Answer:** Specific speed can be defined as *“a speed of geometrically similar machines discharging one cubic meter per second of water under head of one meter”*.

Head coefficient is given by

or (1.9)

Flow coefficient is given by

or

From equation (1.9)

or (1.10)

Where C is proportionality constant, from the definition of specific speed of pump:

Then equation (1.10) can be written as, (1.11)

Substitute equation (1.11) in equation (1.10), then (1.12)

The equation (1.12) gives the specific speed of a pump.

**1.10.2 Specific Speed of a Turbine:**

***Question No 1.13: Define specific speed of a turbine. Obtain an expression for the same in terms of shaft power, speed and head. (VTU, Jul-08, Jul-13, Dec 14/ Jan 1, Jan-175)***

**Answer:** Specific speed of a turbine is defined as *“a speed of a geometrically similar machine which produces one kilowatt power under a head of one meter”*.

Power coefficient is given by (1.13)

From equation (1.9) , then equation (1.13) can be written as,

or (1.14)

Where C is proportionality constant, from the definition of specific speed of turbine:

Then, equation (1.14) becomes (1.15)

Substitute equation (1.15) in equation (1.14), then (1.16)

The equation (1.16) gives the specific speed of a turbine.

**1.10.3 Significance of Specific Speed:**

***Question No 1.14: Briefly explain the significance of specific speed related to turbomachines.***

***(VTU, Jul-06, Jan-14)***

**Answer:** In incompressible flow pumps, it possible to guess the approximate rotor shape from the specific speed. Small specific speed impellers have narrow and small openings whereas large specific speed impellers have wide openings and are expected to have large flow rates. Thus, a centrifugal pump has a nearly pure radial outward flow has the small inlet area. The flow rate is small because of the small inlet area but the head against which it works is high. So for the centrifugal pumps specific speed is small. Thus, to accommodate the large flow a relatively large impeller is needed for centrifugal pumps (). A volute or mixed-flow pump has a bigger opening because of its mixed-flow characteristic though the head developed is not as large as that of the centrifugal pump. Its specific speed is higher than that of the centrifugal pump. At the extreme end is the axial-flow pump, which has a relatively large flow area and therefore a considerable volume flow rate. The head it develops is therefore small compared with that of radial-flow pumps. Its specific speed is very large.

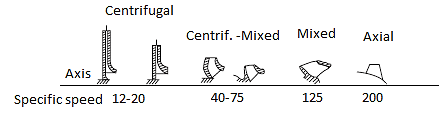


Fig. 1.2 Impeller shape variation with specific speed in pumps.

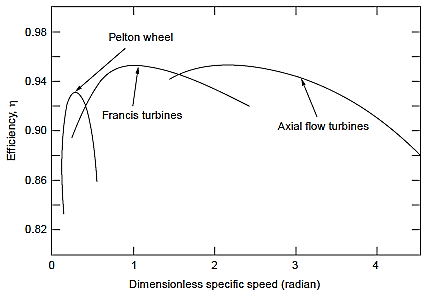


Fig. 1.3 Efficiency variation with specific speed in turbines.

Similarly, the specific speed determines the approximate shapes of the rotors as well. Consider for example the Pelton wheel which is a low specific speed, high head turbine. The volumetric flow rate is small since the turbine utilizes one or more nozzles from which the fluid emerges as jets. The Francis turbine covers a wide range of specific speeds and is suitable for intermediate heads. The Kaplan turbine operates at low heads and need large fluid flow rates to produce reasonable amounts of power. Their specific speeds are therefore high. Generally, specific speed is used as a guide to select a type of turbine under given condition of head and flow (i.e. site conditions). Therefore, such a thumb rule gives rise to a maximum efficiency. Thus, when specific speed is very high, Kaplan turbine is best selection to give rise to very high efficiency. When specific speed is very low, higher efficiencies are possible only if Pelton wheel is selected.

**1.10.4 Range of Specific Speed of Various Turbomachines:**

|  |  |  |
| --- | --- | --- |
| Specific speed in SI units | | |
| 1 | Pelton wheel | |
|  | Single jet | 3 to 30 |
|  | Double jet | 31 to 43 |
|  | Four jet | 44 to 60 |
| 2 | Francis turbine | |
|  | Radial | 61 to 102 |
|  | Mixed (Medium speed) | 103 to 188 |
|  | Mixed (Fast speed) | 189 to 368 |
| 3 | Kaplan (Propeller) turbine | 369 to 856 |
| 4 | Centrifugal pumps | |
|  | Turbine pump | 12 to 25 |
|  | Volute pump | 26 to 95 |
| 5 | Mixed flow pump | 96 to 210 |
| 6 | Axial flow pump | 211 to 320 |
| 7 | Centrifugal compressor | 32 to 74 |
| 8 | Axial compressor | 75 to 120 |
| 9 | Blowers | 121 to 1050 |

**1.11 Unit Quantities:**

***Question No 1.15: Define unit quantities. Derive expressions to each of them. (VTU, Jan-08, Jul-16)***

**Answer:** In hydraulic turbines, it is usual to define quantities as unit flow, unit speed and unit power, which are the values of the quantities under consideration per unit head.

**Unit flow (Qu):** Unit flow is the flow that occurs through the turbine while working under unit head.

Flow of fluid is given by, (1.17)

Where A is area of nozzle and Cv is coefficient of velocity.

or (1.18)

Where proportionality constant.

But, from definition,

Substitute in equation (1.18),

Then, equation (1.18) can be written as,

or

**Unit speed (Nu):** Unit speed is the speed at which the machine runs under unit head.

Head coefficient is given by

or (1.19)

Where proportionality constant.

From definition,

Substitute in equation (1.19),

Then, equation (1.19) can be written as,

or

**Unit power (Pu):** Unit power is the power developed by the hydraulic machine while working under a unit head.

Power developed by hydraulic machine is given by

But, from equation (1.18),

Then,

or (1.20)

Where proportionality constant.

From definition,

Substitute in equation (1.20),

Then, equation (1.20) can be written as,

or

**1.12 Model Studies:**

The principal of all model designs is to prepare a model, from its behaviour can produce a trustworthy, consistent and accurate prediction of the prototype performance. For this prediction the model and prototype should be geometrically, kinematically and dynamically similar. Model is a small scale replica of the actual machine and the actual machine is called prototype.

**1.12.1 Geometric Similarity:** It is the similarity of form or shape. Two systems, the model and prototype are said to be geometrically similar if the ratios of all corresponding linear dimensions of the systems are equal or homologous at all points.

For geometric similarity:

Where l, b and d are the length, width and depth respectively and m and p are the suffixes that indicate model and prototype.

**1.12.2 Kinematic Similarity:** It is the similarity of motion. Two systems are considered to be kinematically similar if they are geometrically similar and ratios of components of velocity at all homologous points are equal.

For kinematic similarity:

Where are resultant velocities at points 1, 2, and 3 in the model and are resultant velocities at the corresponding points in the prototype.

**1.12.3 Dynamic Similarity:** Two systems are considered to be dynamically similar if they are geometrically and kinematically similar and the ratios of the corresponding forces acting at the corresponding points are equal.

For dynamic similarity:

Where are forces acting at points 1, 2, and 3 in the model and are forces acting at the corresponding points in the prototype.

**1.13 Moody’s Formula:**

Machines of different sizes handling oils and other viscous fluids undergo efficiency changes under varying load conditions. For this reason, Moody has suggested an equation to determine turbine efficiencies from experiments on a geometrically similar model.

For heads smaller than 150 m, the efficiencies of model and prototype are related by the equation:

For heads larger than 150 m, the efficiencies of model and prototype are related by the equation:

Since the power outputs for the prototype and model hydraulic turbines are and, the power-ratio may be written as:

It has been assumed here that similarity equations may be applied and the power incremented in proportion to the machine efficiency.

From the flow coefficient,

But, from the head coefficient,

Then flow–ratio may be written as,

Finally the power-ratio may be written as,

From the above relation the power output-ratio can be calculated using geometric ratio, head-ratio and efficiency-ratio.

**1.14 Important Dimensionless Numbers:**

***Question No 1.16: Explain the following dimensionless numbers: (i) Froude’s number, (ii) Weber’s number, (iii) Mach’s number and (iv) Euler’s number. (VTU, Dec-07/Jan-08)***

**Answer:**

**(i) Froude’s number:** It is defined as the ratio of inertia force to gravity force. Froude’s number has considerable practical significance in free surface flow problems, like flow in orifices, flow over notches, flow over the spillways etc. The flow in these problems has predominant gravitational forces.

The Froude’s number is given by .

**(ii) Weber’s number:** It is defined as the ratio of inertia force to the surface tension force. Weber’s number has considerable practical significance in problems influenced by surface tension, like gas-liquid and liquid-liquid interfaces and contact of such interfaces with a solid boundary. These problems have predominant surface tension force.

The Weber’s number is given by.

**(iii) Mach’s number:** It is defined as the ratio of inertia force to elastic force. Mach’s number has considerable practical significance in compressible flow problems, like shells, bullets, missiles and rockets fired into air. These problems have predominant elastic force.

The Mach’s number is given by

**(iv) Euler’s number:** It is defined as the ratio of pressure force to inertia force. Euler’s number has considerable practical significance in modelling of hydraulic turbines and pumps. The flow in these machines has predominant pressure forces.

The Euler’s number is given by.