UNIT 61: ENGINEERING THERMODYNAMICS

Unit code: D/601/1410

QCF level: 5

Credit value: 15

OUTCOME 4
STEAM AND GAS TURBINE POWER PLANT

TUTORIAL No. 7 - TURBINE THEORY

4 **Understand the operation of steam and gas turbine power plant**

Principles of operation: impulse and reaction turbines; condensing; pass-out and back pressure steam turbines; single and double shaft gas turbines; regeneration and re-heat in gas turbines; combined heat and power plants

Circuit and property diagrams: circuit diagrams to show boiler/heat exchanger; superheater; turbine; condenser; condenser cooling water circuit; hot well; economiser/feedwater heater; condensate extraction and boiler feed pumps; temperatureentropy diagram of Rankine cycle

Performance characteristics: Carnot, Rankine and actual cycle efficiencies; turbine isentropic efficiency; power output; use of property tables and enthalpy-entropy diagram for steam

When you have completed this short tutorial, you should be able to explain the basic theory and design principles of turbines used in steam and gas turbine cycles.

1. TURBINES DESIGN

1.1 A BRIEF HISTORY

120 B.C. Hero of Alexandria constructs a simple reaction turbine.

This was constructed from a spherical vessel with two spouts as shown. Heat turned the water inside into steam that escaped through the spouts and made the vessel rotate.

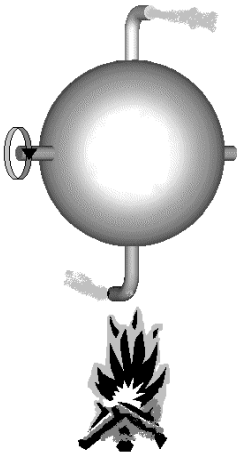

Figure 1 Hero's Turbine

1629 Branca, an Italian, created the first impulse turbine.

Steam issuing from a nozzle struck the vanes on a wheel and made it revolve.

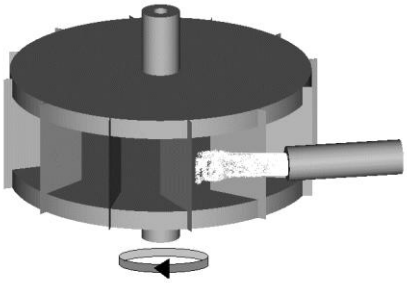

Figure 2 Branca's Turbine

Windmills, developed in medieval times formed the main source of power for centuries.

1884 Charles Parsons developed the first practical reaction turbine. This machine developed around 7 kW of power.

1889 De Laval developed the first practical impulse turbine capable of producing around 2 kW of power.

Others who developed the impulse turbine were ***Rateau*** in France and ***Curtis*** in the U.S.A.

1.2 IMPULSE THEORY

Turbines are generally classified as either impulse or reaction. This refers to the type of force acting on it and causing it to rotate.

IMPULSIVE FORCES are exerted on an object when it diverts or changes the flow of a fluid passing over it.

A very basic impulse turbine is the windmill and this converts the kinetic energy of the wind into mechanical power.

Consider a rotor with vanes arranged around the edge. Fluid is directed at the vanes by a set of nozzles.

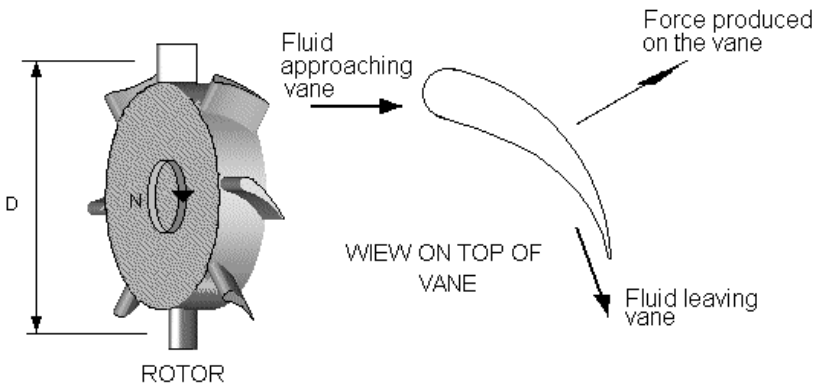

Fig. 3

If there is no pressure drop in the process, the resulting force on the vane is entirely due to the change in the momentum of the fluid and the force is entirely impulsive. It is of interest to note that the name impulsive comes from Newton's second law of motion.

Impulse = change in momentum

Impulsive force = rate of change in momentum.

$$F = m\,\Delta v$$

m is the mass flow rate in kg/s and Δv is the change in velocity of the fluid. This is a vector quantity and may be applied to any direction. If we make Δv the change in velocity in the direction of motion we obtain the force making the rotor turn. This direction is usually called the whirl direction and Δv_w means the change in velocity in the whirl direction.

$$F = m\Delta v_w$$

Suppose the vanes to be rotating on a mean circle of diameter D at N rev/s. The linear velocity of the vanes is u m/s. This is given by the following equation.

$$u = \pi DN$$

The power produced by any moving force is the product of force and velocity. The power of the ideal rotor is given by the following equation.

$$P = m\Delta v_w\, u = m\,\Delta v_w \pi ND$$

This is the fundamental way of finding the power produced by fluids passing over moving vanes. In order to find the vector quantity Δv_w, we draw vector diagrams for the velocities. For this reason, the power is called ***DIAGRAM POWER***.

$$\text{DIAGRAM POWER} = m\,\Delta v_w \pi N D$$

The construction of the vector diagrams for fluids flowing over vanes is not covered in this book and you should refer to more advanced text if you wish to study it at a deeper level.

WORKED EXAMPLE No.1

The vanes on a simple steam turbine are mounted on a rotor with a mean diameter of 0.6 m. The steam flows at a rate of 0.8 kg/s and the velocity in the whirl direction is changed by 80 m/s. The turbine rotates at 600 rev/min. Calculate the diagram power.

SOLUTION

Rotor Speed $N = 600/60 = 10$ rev/s

Velocity of the vanes $u = \pi N D = \pi \times 10 \times 0.6 = 18.85$ m/s

Diagram Power $DP = m\,u\,\Delta v_w = 0.8 \times 18.85 \times 80 = 1206.5$ W

A practical impulse turbine needs several sets of moving vanes and fixed vanes as shown in figure 4. The fixed vanes act as nozzles that convert pressure into velocity. The steam from the nozzles is deflected by the moving row. There is a pressure drop over each fixed row.

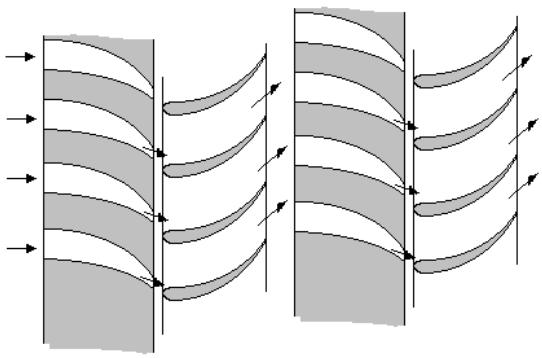

Fig.4

1.3 REACTION THEORY

REACTION FORCES are exerted on an object when it causes the velocity of the fluid to change. Consider a simple nozzle in which the fluid accelerates due to the change in the cross sectional area. The kinetic energy of the fluid increases and since energy is conserved, the pressure of the fluid drops. In other words, the pressure behind the fluid forces it through the nozzle causing it to speed up. The force required to accelerate the fluid is in the direction of the acceleration. Every force has an equal and opposite reaction so an equal and opposite force is exerted on the nozzle. This is the principle used in rockets.

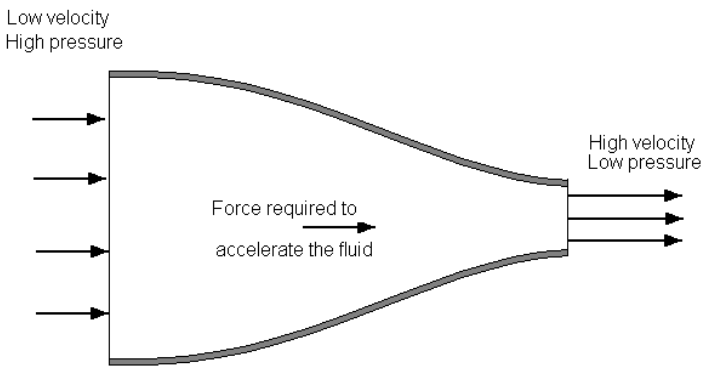

Fig. 5

It should be borne in mind that steam and gas, unlike liquids, undergoes a volume increase when the pressure falls. It is thus possible to accelerate steam and gas without narrowing the flow passage. The force required to accelerate the fluid is given by the following equation.

$$F = m \Delta v$$

The reaction force acting on the nozzle is equal and opposite in direction.

Figure 6 shows the layout of the blades for a turbine that uses both reaction and impulse. The fixed rows accelerate the steam and there is a pressure drop over the row. The moving row also accelerates the steam and there is a further pressure drop over the moving row. The moving blades are thus moved by both impulse and reaction forces. If the rows of blades are identical, the pressure drop over each is the same and there is 50% impulse and 50% reaction.

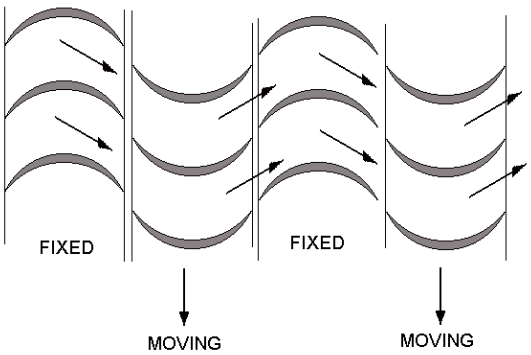

Fig.6

The moving vanes experience both reaction and impulsive forces and the two together is given by the change in momentum. The formula developed in section 1.2 applies to any kind of turbine.

$$\text{DIAGRAM POWER} = m\,\Delta v_w \pi N D$$

AXIAL FORCE

The change in momentum that produces the force on the blade is not only in the direction of rotation. There is also a change of velocity and hence momentum in the direction of the axis of rotation and this pushes the turbine rotor in that direction. This would require a large thrust bearing in the turbine design. This can be avoided by placing two identical rotors back to back so the axial thrust cancels out. Figure 7 shows the schematic for such an arrangement.

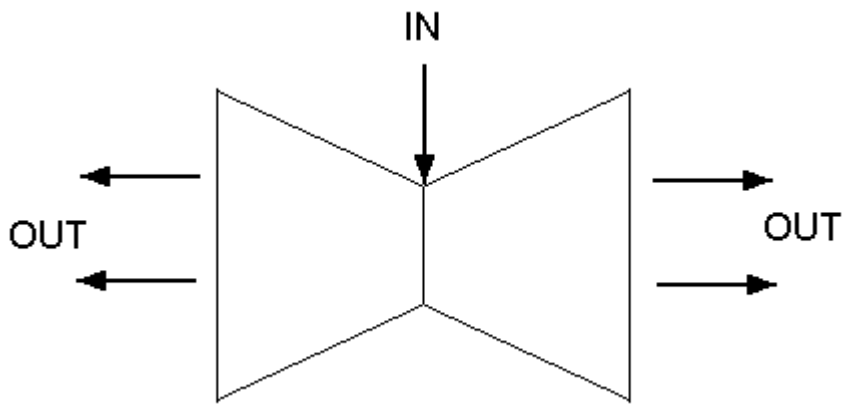

Fig. 7

Because the volume of the steam or gas increases greatly as it progresses along the axis, the height of the blades increases in order to accommodate it. Figure 8 shows a turbine with the casing removed. There are three sets or cylinders each with double flow. The exhaust steam has such a large volume that entry to the condenser is through the large passages underneath. The condenser occupies the space below the turbine hall.

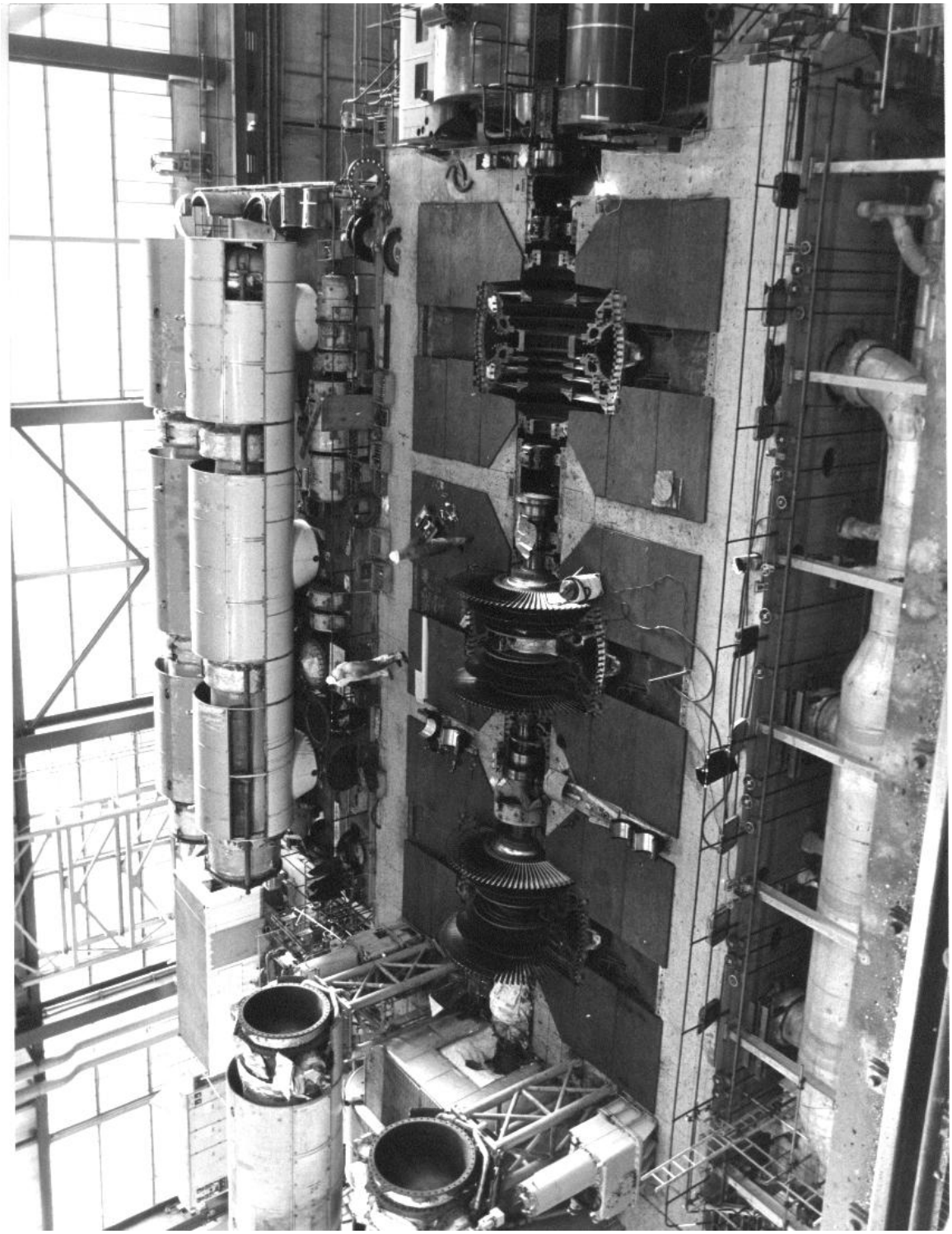

Fig. 8

Figure 9 is another picture showing the rotor of a large steam turbine.

Fig. 9

SELF ASSESSMENT EXERCISE No.1

1. A steam turbine has its vanes on a mean diameter of 1.2 m and rotates at 1500 rev/min. The change in the velocity of whirl is 65 m/s and the change in the axial velocity is 20 m/s. The flow rate is 1 kg/s. Calculate the following.

   i. The diagram power. (6.12 kW)

   ii. The axial force. (20 N)

2. A steam turbine is to be designed to rotate at 3000 rev/min and produce 5 kW of power when 1 kg/s is used. The vanes will be placed on a mean diameter of 1.4 m. Calculate the change in the velocity of whirl that will have to be produced.
   (22.7 m/s)

3. A gas turbine has rotor blades on a mean diameter of 0.5 m and the rotor turns at 2000 rev/min. The change in the whirl velocity is 220 m/s and the diagram power is 2 MW. Calculate the mass flow rate of gas.
   (173.6 kg/s)