Chapter 1
Steam turbines Design

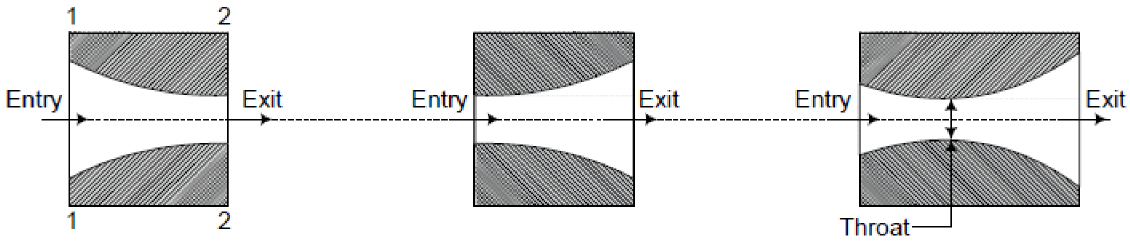
1. INTRODUCTION

Steam turbine is a type of turbomachine which is an assembly of nozzles and blades. It converts a part of the energy of high temperature and high pressure steam into mechanical energy (or shaft work). The operation of steam turbine completely depends on the dynamic action of the steam expanding in nozzles. The steam turbines are used for the generation of electricity in steam power plants varying from 1 MW to 1500 MW capacity. These are also used for marine propulsion. The steam turbines operate at very high speed (up to about 40,000 rpm) and are able to give efficiency about 40% which is higher than the other power producing devices.

2. STEAM NOZZLE AND ITS GENERAL FLOW ANALYSIS

A nozzle is a duct of smoothly varying cross section by means of which pressure energy of steadily flowing fluid is converted into kinetic energy. The fluid enters the nozzle with a relatively small velocity and high pressure. As it flows through the nozzle, its pressure falls and a part of the enthalpy of steam gets converted into kinetic energy. The amount of energy which converts into kinetic energy depends on the pressure ratio and the type of expansion. Generally, nozzles are designed to obtain isentropic expansion which imparts maximum conversion. The velocity increases from entrance to the exit of the nozzle.

The applications of nozzles are: (i) In steam and gas turbines for power generation, (ii) In aviation purposes such as propulsion of jet engines and rocket, (iii) In injectors and ejectors, and (v) For flow measurements, etc.



(a) (b) (c)

Fig. 2.1 Types of Nozzles

The nozzles are of three types:

(i) Convergent Nozzle If the cross section of the nozzle decreases continuously from the entrance to the exit, it is called convergent nozzle shown in Figure 2.1 (a).

(ii) Divergent Nozzle If the cross section of the nozzle increases continuously from the entrance to the exit, it is called divergent nozzle shown in Figure 2.1 (b).

(iii) Convergent-divergent Nozzle If the cross section of the nozzle first decreases and then increases, it is called convergent-divergent nozzle shown in Figure 2.1 (c).

In nozzles the flow is considered adiabatic (i.e., $q = 0$) and no work is done on or by the fluid (i.e., $w = 0$). Consider a nozzle (Figure 2.1a) in which section 1-1 is the entrance of the nozzle and section 2-2 is the exit of the nozzle. Let the flow of fluid be initially at pressure p_1, velocity V_1, and enthalpy h_1 expands through the nozzle. Applying steady flow energy equation, we have,

$$h_1 + \frac{V_1^2}{2} = h_2 + \frac{V_2^2}{2} \qquad (\because q = 0 \text{ and } w = 0)$$

The entering velocity of steam V_1 is small as compared with velocity V_2. Thus, neglecting V_1, we have,

$$h_1 = h_2 + \frac{V_2^2}{2}$$

$$V_2 = \sqrt{2 \times (h_1 - h_2)}$$

Generally, enthalpy is expressed in kJ/kg, then the exit velocity in m/s is given by,

$$V_2 = \sqrt{2 \times 1000 \times (h_1 - h_2)}$$

$$= 44.72 \times \sqrt{(h_1 - h_2)} \text{ m/s} \qquad (2.1)$$

When the nozzle efficiency (η_{nozzle}) is also considered, then the exit velocity is given by,

$$V_2 = 44.72 \times \sqrt{\eta_{nozzle} \times (h_1 - h_2)} \text{ m/s} \qquad (2.2)$$

The general thermodynamic relation for flow of gas through a duct is given by,

$$\frac{dA}{A} = \frac{dV}{V}(M^2 - 1) \qquad (2.3)$$

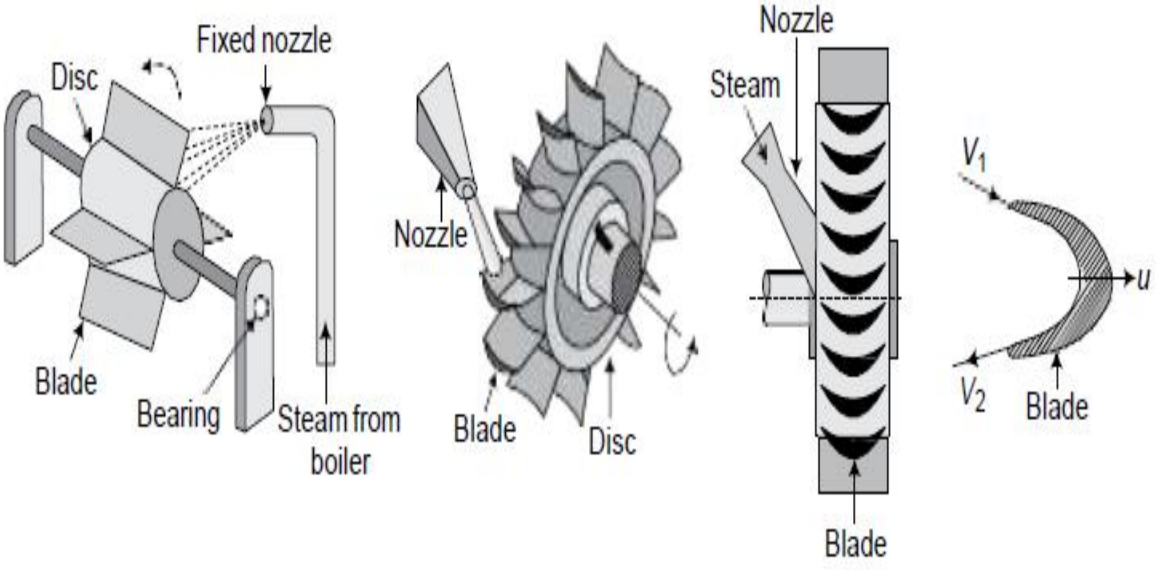


Fig. 2.2 Principle of Impulse Turbine

(i) Impulse Turbine In impulse turbines the steam expands only in the nozzles. It means the pressure drop (enthalpy drop) takes place only in nozzles and not in moving blades. The moving blades only deflect the steam through an angle. An impulse turbine works on the principle of impulse, means the kinetic energy of steam is used to exert a force on the moving blades. This is achieved by having the symmetrical blades, means the cross sectional area of blades is constant as shown in Figure 2.5. Thus, steam pressure remains constant while it flows through the moving blades.

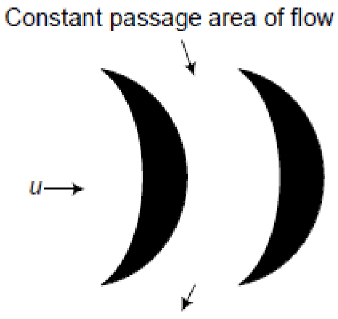


Fig. 2.5 Impulse Blade

A simple impulse turbine consists of a nozzle or a set of nozzles, a rotor (or runner) mounted on a shaft, one set of moving blades fixed to the runner, and a casing. A set (or row) of nozzles and moving blades makes a stage. The schematic view and the flow of steam through a simple impulse turbine are shown in Figure 2.6 in which the pressure and velocity variation have also been illustrated. It can be seen from the figure that the pressure drop takes place only in nozzles. So, the complete expansion of steam from the steam chest pressure to the condenser pressure takes place only in one set of nozzles and it leaves with a high

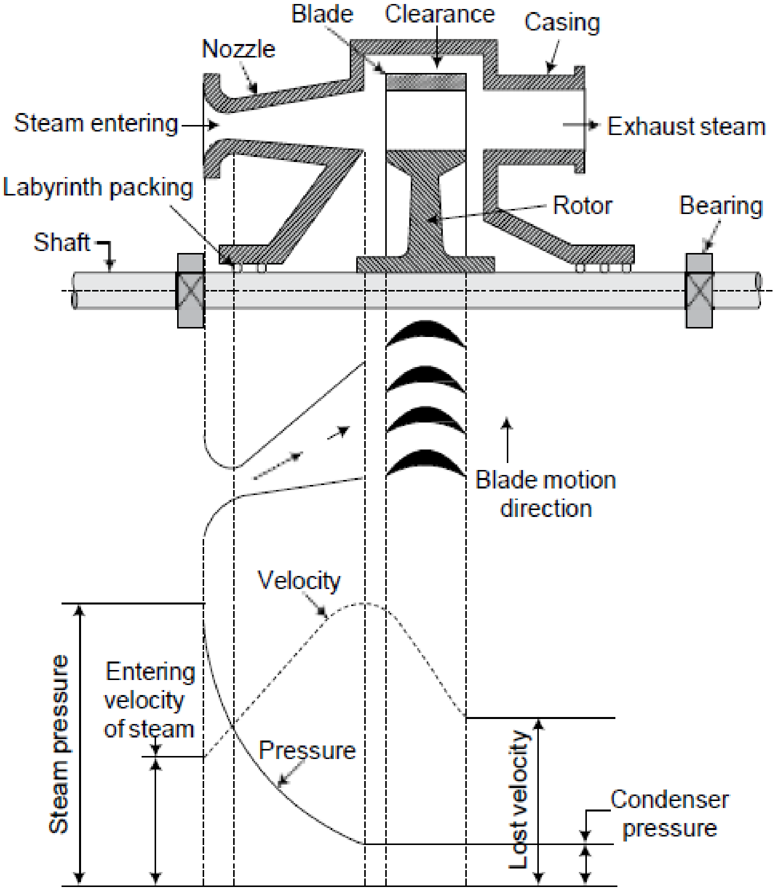


Fig. 2.6 Schematic View of Simple Impulse Turbine

2.8 VELOCITY DIAGRAMS FOR IMPULSE TURBINE

To evaluate the force on the blades and the power developed by a turbine, it is necessary to determine the rate of change of momentum of steam across the moving blades. The steam should enter and leave the blade without any shock for which the inlet and outlet angles of the moving blades should be evaluated. In order to fulfil these objectives, it is essential to draw the vector diagrams at the inlet and outlet of the moving blades showing the variations of velocity of steam during its flow through the blade passage.

The following notations are used for the velocity diagrams:

Suffixes 1 and 2 denote the inlet and outlet conditions respectively, for moving blades as shown in Figure 2.12 and Figure 2.13.

u = Tangential or circumferential velocity of blades which remains constant at inlet and outlet of moving blades because of small blades height, i.e., $u_1 = u_2 = u$

V_1 and V_2 = Absolute velocity of steam at the inlet and outlet respectively

V_{w1} and V_{w2} = Velocity of whirl at the inlet and outlet respectively, (i.e., tangential component of V_1)

V_{f1} and V_{f2} = Velocity of flow at the inlet and outlet respectively, (i.e., axial component of V_1 and V_2 respectively)

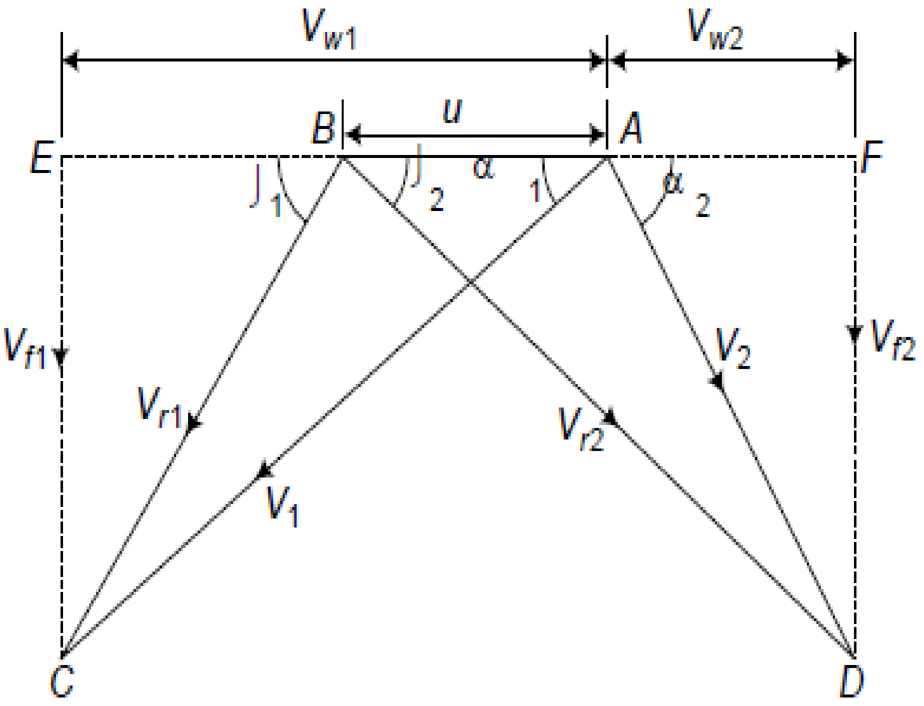


Fig. 2.13 Combined Velocity Diagram for Impulse Turbine

The value of K varies from 0.85 to 0.9 and for smooth blades $K = 1$, means $V_{r1} = V_{r2}$.

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

1. Draw horizontal line AB equal to blade velocity u to some suitable scale.
2. Draw a line AC at an angle a_1 with AB. Cut $AC = V_1$.
3. Join B and C which represents the relative velocity V_{r1} at inlet. The blade inlet angle b_1 is measured and its value is evaluated.
4. From point C draw a perpendicular CE on AB produced. CE represents flow velocity (axial velocity) at inlet and AE represents whirl velocity (tangential velocity) at inlet.
5. From point B draw a line BD at an angle b_2 (blade outlet angle).

   Cut $BD = V_{r2} = KV_{r1}$. Join A and D which represents the absolute velocity (V_2) at outlet. The angle a_2 is measured.
6. From point D draw a perpendicular DF on BA produced. DF represents flow velocity (axial velocity) at outlet and AF represents whirl velocity (tangential velocity) at outlet.

   Thus, velocity triangles get completed.

1. Force and Work Done on Turbine Blades and Efficiency

1. Force in the tangential direction (F_t).

$$F_t = \text{mass} \times \text{acceleration in tangential direction}$$

$$= \text{mass per second} \times \text{change in velocity in tangential direction}$$

$$F_t = m \times (V_{w1} - V_{w2}) \text{ N}$$

(when V_{w1} and V_{w2} are in opposite direction)

$$F_t = m \times (V_{w1} + V_{w2}) \text{ N}$$

(when V_{w1} and V_{w2} are in same direction)

Thus general expression for tangential force becomes,

$$F_t = m \times (V_{w1} \pm V_{w2}) \text{ N} \tag{2.6}$$

4. 3 .1 Velocity Diagram for Impulse Turbine

The velocity diagram for a single-stage impulse has been shown in Fig. 4.5. Figure 4.5 shows the velocity diagram indicating the flow through the turbine blades.

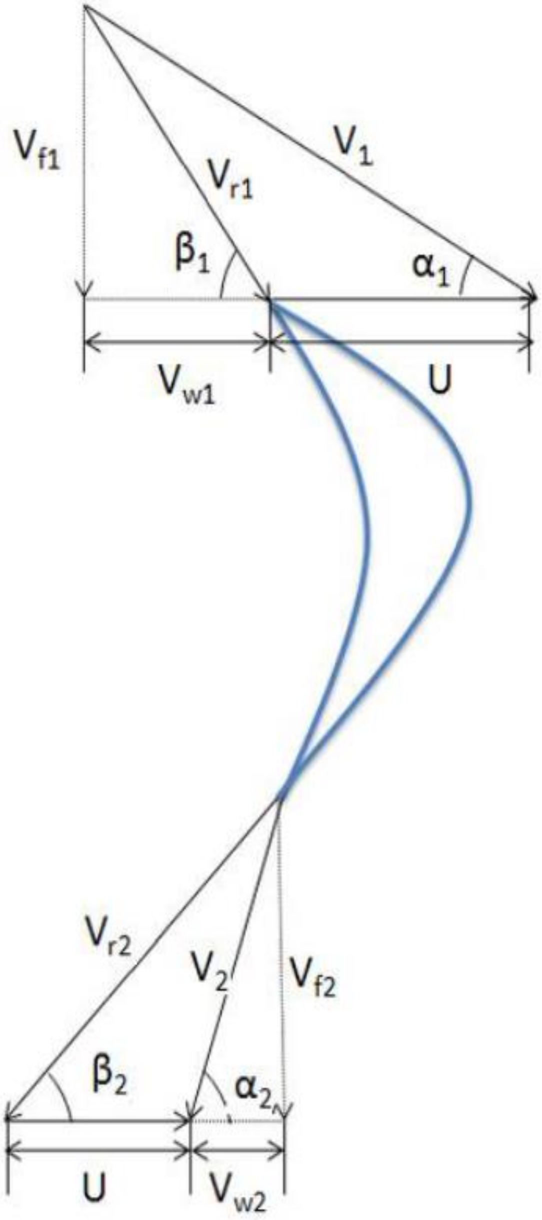


Figure 4.5: Single– Stage velocity diagram Impulse Turbine (De-Laval)

Illustrative Example 6.6: The velocity of steam leaving a nozzle is 925 m/s and the nozzle angle is 20°. The blade speed is 250 m/s. The mass flow through the turbine nozzles and blading is 0.182 kg/s and the blade velocity coefficient is 0.7. Calculate the following:

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

Assume that the inlet and outlet blade angles are equal.

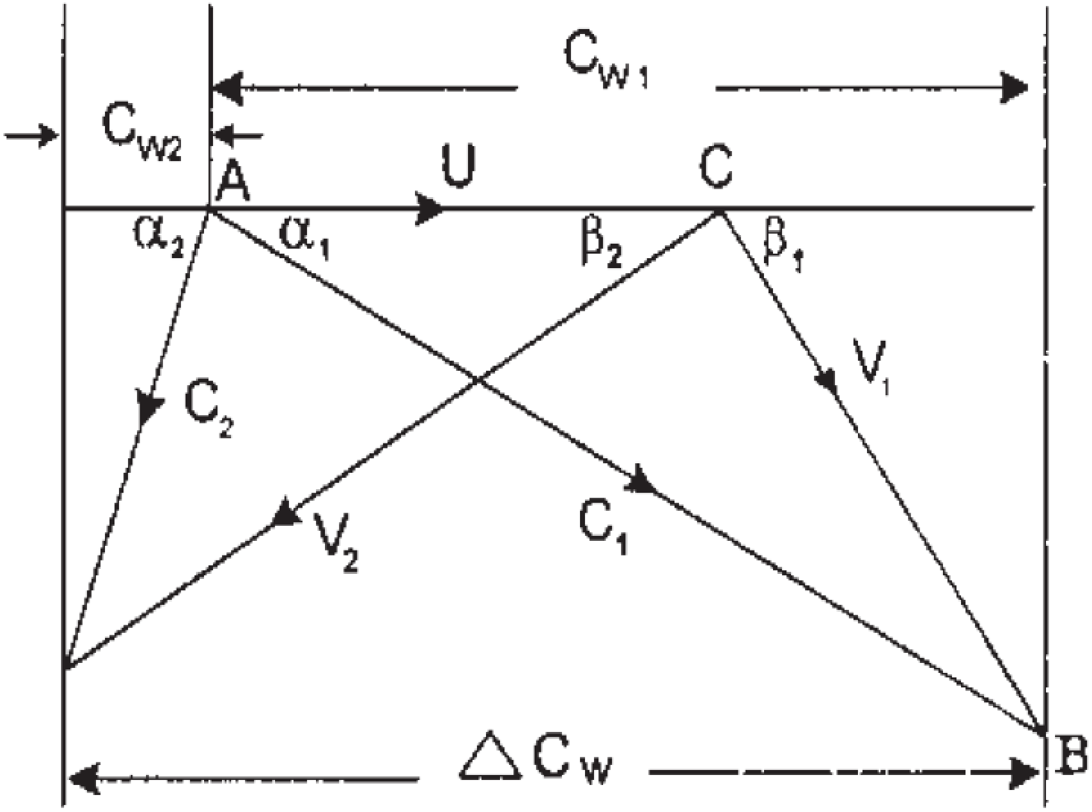


Figure 6.23 Velocity triangles for Example 6.6.

Applying the cosine rule to the $\triangle$ABC,

$$V_1^2 = U^2 + C_1^2 - 2UC_1\cos\alpha_1$$
$$= 250^2 + 925^2 - (2) \times (250) \times (925) \times \cos 20^\circ$$

so: $V_1 = 695.35$ m/s

But,

$$k = \frac{V_2}{V_1}, \text{or} V_2 = (0.70) \times (695.35) = 487 \text{m/s}.$$

Velocity of whirl at inlet:

$$C_{w1} = C_1 cos\alpha_1 = 925\cos 20^\circ = 869.22 \text{m/s}$$

Axial component at inlet:

$$C_{a1} = \text{BD} = C_1 \sin\alpha_1 = 925\sin 20^\circ = 316.37 \text{m/s}$$

Blade angle at inlet:

$$\tan\beta_1 = \frac{C_{a1}}{C_{w1} - U} = \frac{316.37}{619.22} = 0.511$$

Therefore, $\beta_1 = 27.06^\circ = \beta_2 =$ outlet blade angle.

$$\cos\beta_2 = \frac{C_{w2} + U}{V_2},$$

or: $$C_{w2} = V_2 \cos\beta_2 - U = 487 \times \cos 27.06^\circ - 250$$
$$= 433.69 - 250 = 183.69 \text{ m/s}$$

and: $C_{a2} = \text{FE} = (U + C_{w2}) \tan\beta_2 = 433.69 \tan 27.06^\circ = 221.548$ m/s

1. Velocity of whirl at inlet, $C_{w1} = 869.22$ m/s;

   Velocity of whirl at outlet, $C_{w2} = 183.69$ m/s

2. Tangential force on blades

$$= \dot{m}\,(C_{w1} + C_{w2}) = (0.182)\,(1052.9) = 191.63\text{ N.}$$

3. Axial force on blades

$$= \dot{m}(C_{a1} - C_{a2}) = (0.182)(316.37 - 221.548) = 17.26\text{N}$$

4. Work done on blades

$$= \text{tangential force on blades} \times \text{blade velocity}$$

$$= (191.63) \times (250)/1000 = 47.91\text{ kW.}$$

5. Efficiency of blading $= \dfrac{\text{Work done on blades}}{\text{Kinetic energy supplied}}$

$$= \frac{47.91}{\frac{1}{2}mC_1^2} = \frac{(47.91)(2)(10^3)}{(0.182)(925^2)}$$

$$= 0.6153 \text{ or } 61.53\%$$

6. Inlet angle of blades $\beta_1 = 27.06° = \beta_2$.