Program : **B.Tech**

Subject Name: **Turbo Machinery**

Subject Code: **ME-603**

Semester: **6^{th}**

Unit 2 - 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. They are usually symmetrical and have entrance and exit angles respectively, around 20°. Because they are usually used in the entrance high-pressure stages of a steam turbine, when the specific volume of steam is low and requires much smaller flow than at lower pressures, the impulse blades are short and have constant cross sections.

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.

The velocity diagram for a single-stage impulse has been shown in Fig. 2.1. Figure 2.2 shows the velocity diagram indicating the flow through the turbine blades.

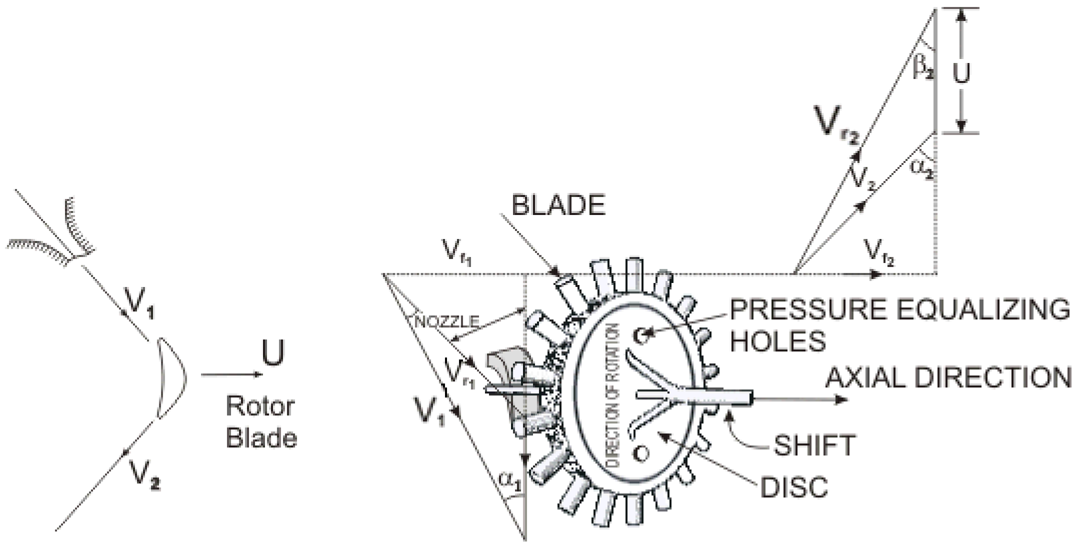


Figure 2.1 Schematic diagram of an Impulse Turbine

and V1, V2 = Inlet and outlet absolute velocity
and Vr1, Vr2 = Inlet and outlet relative velocity (Velocity relative to the rotor blades.)
U = mean blade speed
α 1 = nozzle angle, α 2= 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).

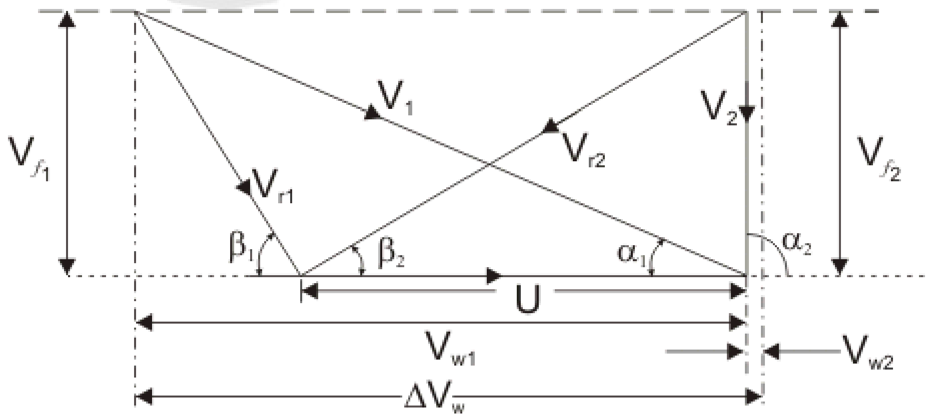


Figure 2.2 Velocity diagram of an Impulse Turbine

and β1, β2 = Inlet and outlet **blade angles**

and Vw1, Vw2 = Tangential or whirl component of absolute velocity at inlet and outlet

and Vf1, Vf2 = Axial component of velocity at inlet and outlet

Tangential force on a blade,

$$F_u = \dot{m}(V_{w1} - Vw2) \quad (2.1)$$

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

or,

$$F_u = \dot{m}\Delta V_w \quad (2.2)$$

Power developed = $F_u = \dot{m}\Delta V_w$ (2.3)

Blade efficiency or Diagram efficiency or Utilization factor is given by

$$\dot{m}U\Delta V_w \quad (2.4)$$

stage efficiency $= \eta_s = \dfrac{Work\ done\ by\ the\ rotor}{Isentropic\ enthalpy\ drop}$ (2.5)

or,

$$\eta_s = \frac{\dot{m}U\Delta V_w}{\dot{m}(\Delta H)_{isen}} = \frac{\dot{m}U\Delta V_w}{\dot{m}\left(\frac{V_1^2}{2}\right)} \cdot \frac{\dot{m}(V_1^2/2)}{\dot{m}(\Delta H)_{isen}} \quad (2.6)$$

or, $\eta_s = \eta_b \times \eta_n \qquad [\eta_n = Nozzle\ efficiency]$ (2.7)

Optimum blade speed of a single stage turbine

$$\Delta V_w = V_{r1}\cos\beta_1 + V_{r2}\cos\beta_2$$

$$= V_{r1}\cos\beta_1 + \left(1 + \frac{V_{r2}}{V_{r1}} \cdot \frac{\cos\beta_2}{\cos\beta_1}\right)$$

$$= (V_1\cos\alpha_1 - U) + (1 + kc)$$

$$k = (V_{r2}/V_{r1})$$

where, k = friction coefficient

$$c = (\cos\beta_2/\cos\beta_1) \qquad = \text{Blade speed ratio} \qquad (2.8)$$

$$\eta_b = \frac{2U\Delta V_w}{V_1^2} = 2\frac{U}{V_1}\left(\cos\alpha_1 - \frac{U}{V_1}\right)(1+kc)$$

$$\rho = \frac{U}{V_1} =$$

or,

$$\rho = \frac{\cos\alpha_1}{2} \qquad (2.9)$$

The maximum value of blade efficiency

$$= \frac{\cos^2\alpha_1}{2}(1+kc) \qquad (2.10)$$

For equiangular blades,

$$(\eta_b)_{\max} = \frac{\cos^2\alpha_1}{2}(1+k) \qquad (2.11)$$

If the friction over blade surface is neglected

$$(\eta_b)_{\max} = \cos^2\alpha_1 \qquad (2.12)$$

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 therefore essential to incorporate some improvements for practical use and also to achieve high performance. This is possible by making use of more than one set of nozzles, and rotors, in a series, keyed to the shaft so that either the steam pressure or the jet velocity is absorbed by the turbine in stages. This is called compounding. Two types of compounding can be accomplished: (a) velocity compounding and (b) pressure compounding

Either of the above methods or both in combination are used to reduce the high rotational speed of the single stage turbine.

The Velocity - Compounding of the Impulse Turbine

The velocity-compounded impulse turbine was first proposed by C.G. Curtis to solve the problems of a single-stage impulse turbine for use with high pressure and temperature steam. The *Curtis stage* turbine, as it came to be called, 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. A Curtis stage impulse turbine is shown in Fig. 2.3 with schematic pressure and absolute steam-velocity changes through the stage. In the Curtis stage, the total enthalpy drop and hence pressure drop occur in the nozzles so that the pressure remains constant in all three rows of blades.

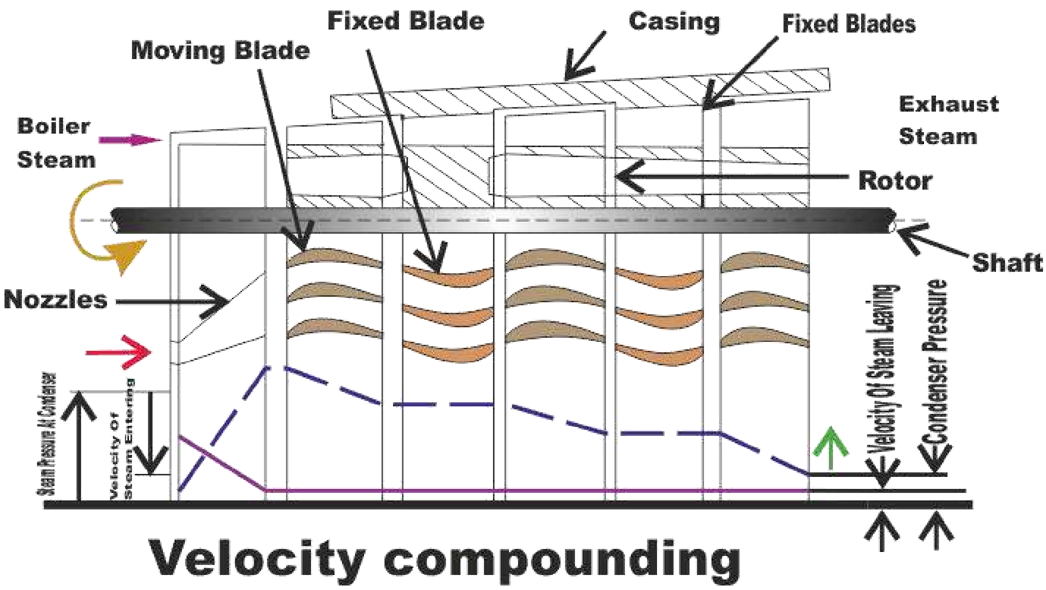


Figure 2.3 Velocity Compounding

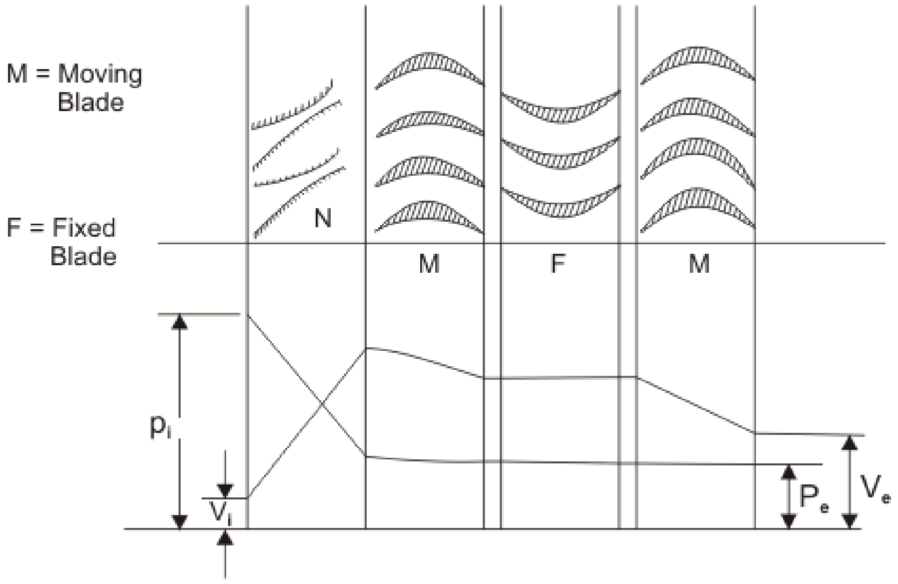
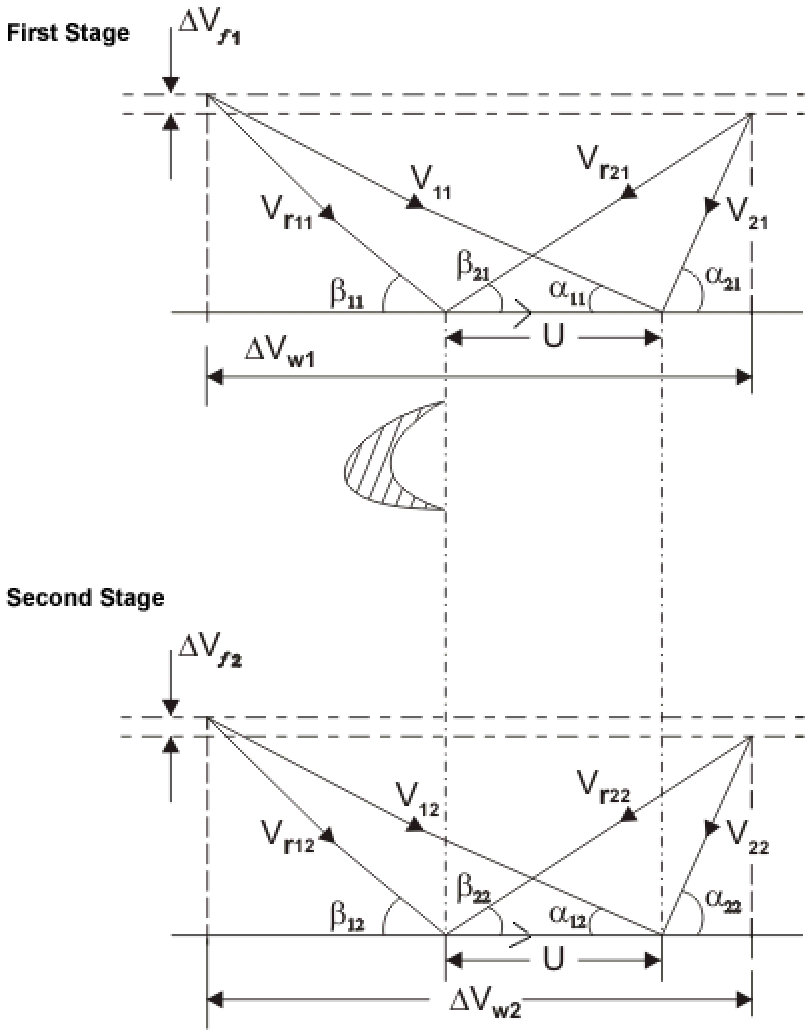


Figure 2.4 Velocity Compounding



Work done = $\dot{m}.U(\Delta V_{w1} + \Delta V_{w2})$ (2.13)

End thrust = $\dot{m}(\Delta V_{f1} + \Delta V_{f2})$ (2.14)

Velocity is absorbed in two stages. In fixed (static) blade passage both pressure and velocity remain constant. Fixed blades are also called guide vanes. Velocity compounded stage is also called **Curtis stage.** The velocity diagram of the velocity-compound Impulse turbine is shown in Figure 2.3.

The fixed blades are used to guide the outlet steam/gas from the previous stage in such a manner so as to smooth entry at the next stage is ensured.

K, the blade velocity coefficient may be different in each row of blades.

The optimum velocity ratio will depend on number of stages and is given by

- Work is not uniformly distributed (1st >2nd)

- The first stage in a large (power plant) turbine is velocity or pressure compounded impulse stage.

Pressure Compounding or Rateau Staging

The Pressure - Compounded Impulse Turbine

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 (Figure 2.4). Such a turbine is called a *Rateau turbine,* after its inventor. Thus the inlet steam velocities to each stage are essentially equal and due to a reduced Δh.

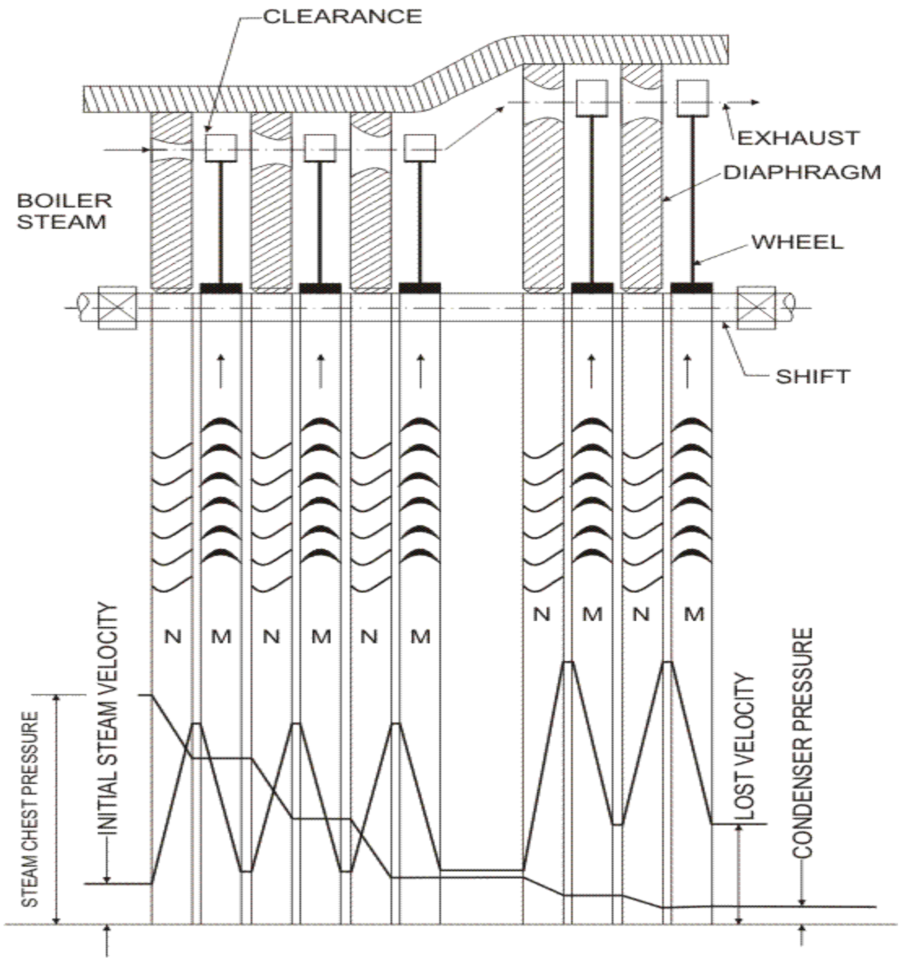


Figure 2.5 Pressure-Compounded Impulse Turbine

Pressure drop - takes place in more than one row of nozzles and the increase in kinetic energy after each nozzle is held within limits. Usually convergent nozzles are used.

We can write

$$\underbrace{\frac{V_1^2}{2} + h_1}_{exit} = \underbrace{\frac{V_2^2}{2} + h_2}_{inlet} \tag{2.15}$$

$$\eta_N = \frac{V_1^2 - \varphi V_2^2}{2(\Delta h)_{isentropic}} \tag{2.16}$$

where ϕ is carry over coefficient

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. In other words, they also act as nozzles. The enthalpy drop per stage of one row fixed and one row moving blades is divided among them, often equally. Thus a blade with a 50 percent degree of reaction, or a 50 percent reaction stage, is one in which half the enthalpy drop of the stage occurs in the fixed blades and half in the moving blades. The pressure drops will not be equal, however. They are greater for the fixed blades and greater for the high-pressure than the low-pressure stages.

The moving blades of a reaction turbine are easily distinguishable from those of an impulse turbine in that they are not symmetrical and, because they act partly as nozzles, have a shape similar to that of the fixed blades, although curved in the opposite direction. The schematic pressure line (Fig. 2.5) shows that pressure continuously drops through all rows of blades, fixed and moving. The absolute steam velocity changes within each stage as shown and repeats from stage to stage. Figure 2.5 shows a typical velocity diagram for the reaction stage.

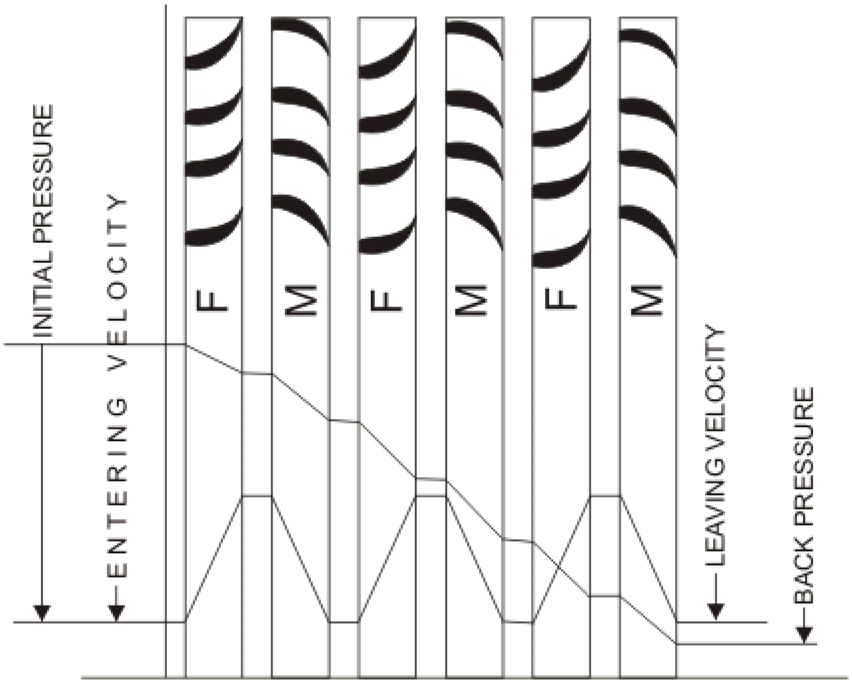


Figure 2.6 Three stages of reaction turbine indicating pressure and velocity distribution

Pressure and enthalpy drop both in the fixed blade or **stator** and in the moving blade or **Rotor**

Degree of Reaction = $\dfrac{\text{Enthalpy drop in Rotor}}{\text{Enthalpy drop in Stage}}$

or,

$$R = \frac{h_1 - h_2}{h_0 - h_1} \tag{2.17}$$

A very widely used design has half degree of reaction or 50% reaction and this is known as Parson's Turbine. This consists of symmetrical stator and rotor blades.

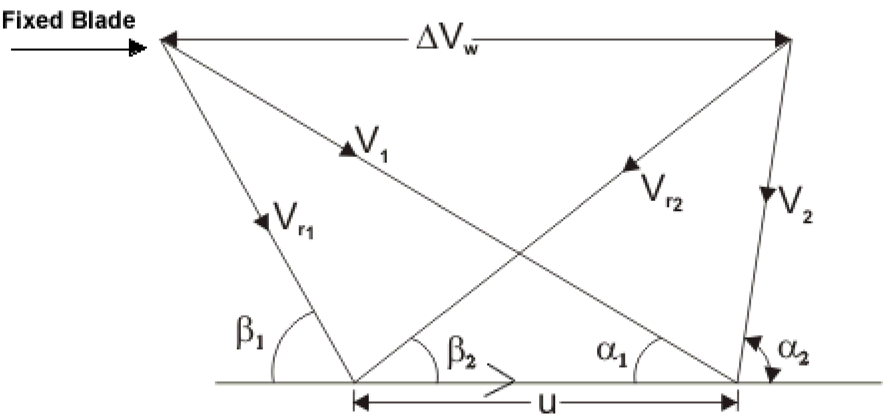


Figure 2.7 The velocity diagram of reaction blading

The velocity triangles are symmetrical and we have

$$\alpha_1 = \beta_2 \quad , \quad \beta_1 = \alpha_2$$

$$V_1 = V_{r2} \quad , \quad V_{r1} = V_2$$

Energy input per stage (unit mass flow per second)

$$E = \frac{V_1^2}{2} + \frac{V_{r2}^2 - V_{r1}^2}{2}$$

(2.18)

$$E = V_1^2 - \frac{V_{r1}^2}{2}$$

$$E = (V_1^2 - U^2 + 2V_1 U \cos\alpha_1)/2 \qquad (2.19)$$

From the inlet velocity triangle we have,

$$V_{r1}^2 = V_1^2 - U^2 - 2V_1 U \cos\alpha_1$$

Work done (for unit mass flow per second) $= W = U\Delta V_W$

$$= U(2V_1 \cos\alpha_1 - U) \qquad (2.20)$$

Therefore, the Blade efficiency

$$= \eta_b = \frac{2U(2V_1 \cos\alpha_1 - U)}{V_1^2 - U^2 + 2V_1 U \cos\alpha_1} \qquad (2.21)$$

$$\eta_b = \frac{2\rho(2\cos\alpha_1 - P)}{1 - \rho^2 + 2\rho\cos\alpha_1} \qquad (2.22)$$

For the maximum efficiency

$$-2\rho(2\cos\alpha_1 - \rho)(-2\rho + 2\cos\alpha_1) = 0 \qquad (2.23)$$

from which finally it yields

$$\rho_{opt} = \left(\frac{U}{V_1}\right)_{opt} = \cos\alpha_1 \qquad (2.24)$$

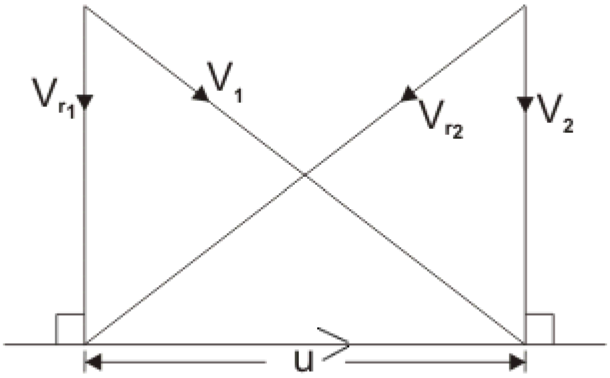


Figure 2.8 Velocity diagram for maximum efficiency

Absolute velocity of the outlet at this stage is axial (see figure 2.8). In this case, the energy transfer

$$E = U\Delta V_W = U^2 \qquad (2.25)$$

$$(\eta_b)_{max} = \frac{2\cos^2\alpha_1}{1+\cos^2\alpha_1} \qquad (2.26)$$

$$(\eta_b)_{impulse} = \cos^2\alpha_1 \qquad (2.27)$$

ηb is greater in reaction turbine. Energy input per stage is less, so there are more number of stages.

Stage Efficiency and Reheat factor

The Thermodynamic effect on the turbine efficiency can be best understood by considering a number of stages between two stages 1 and 2 as shown in Figure 2.9

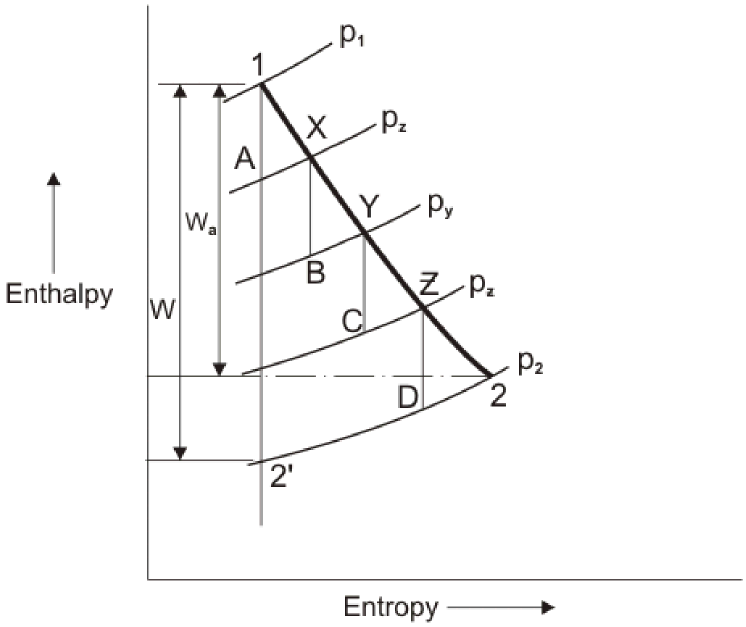


Figure 2.9 Different stage of a steam turbine

The total expansion is divided into four stages of the same efficiency η and pressure ratio.

The overall efficiency of expansion is η0. The actual work during the expansion from 1 to 2 is

or, $$\frac{P_1}{P_x} = \frac{P_x}{P_y} = \frac{P_y}{P_z} = \frac{P_z}{P_2} \qquad (2.28)$$

or, $$\eta_o = \frac{Wa}{W} = \frac{actual\ enthalpy\ drop\ (1-2)}{isentropic\ heat\ drop\ (1-2')} \qquad (2.29)$$

R.F is 1.03 to 1.04

$$R.F = \frac{\Delta h_{1A} + \Delta h_{xB} + \Delta h_{yc} + \Delta h_{zD}}{\Delta h_{12}} \qquad (2.30)$$

or, $$\eta_s = \frac{\Delta h_{1x}}{\Delta h_{1A}} = \frac{\Delta h_{xy}}{\Delta h_{xB}} = \frac{\Delta h_{yz}}{\Delta h_{yc}} = \frac{\Delta h_{z2}}{\Delta h_{zD}} \qquad (2.31)$$

We can see:

$$\eta_0 = \eta_s \times R.F \qquad (2.32)$$

This makes the overall efficiency of the turbine greater than the individual stage efficiency.

The effect depicted by Eqn (2.32) is due to the thermodynamic effect called "reheat". This does not imply any heat transfer to the stages from outside. It is merely the reappearance of stage losses an increased enthalpy during the constant pressure heating (or reheating) processes AX, BY, CZ and D2.

