Power Plants: Ch 3 Steam Power Plants

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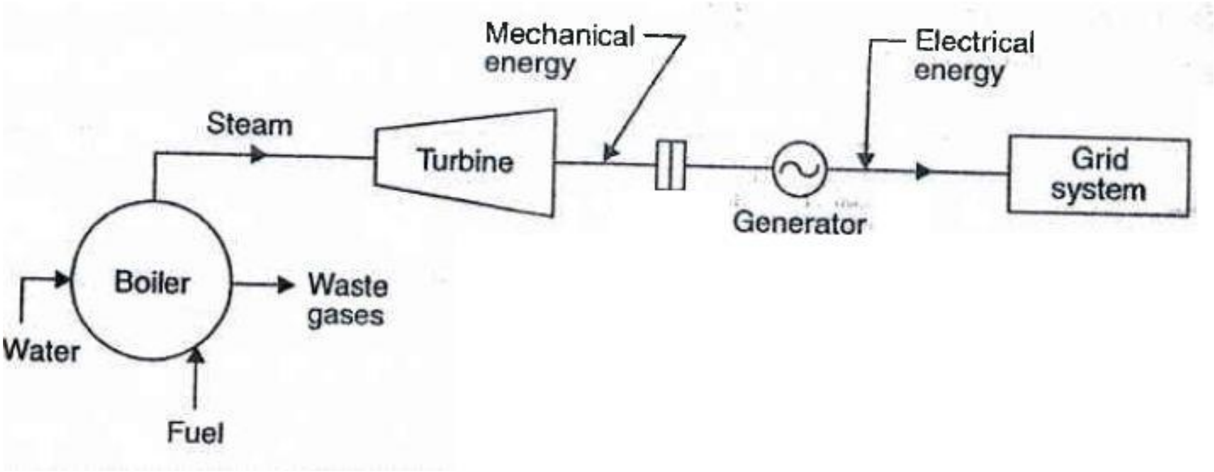
Chapter Three: Steam Power Plants

1. Introduction

A steam power plant converts the chemical energy of the fossil fuel (Coal, Oil and Gas) into mechanical-electrical energy. This is achieved by raising the steam in the boiler, expanding it through the turbines and coupling the turbines to the generators that convert the mechanical energy to electrical energy.

The main purpose of the steam power plant are:

1. To produce the electric power.
2. To produce steam for industrial & residential purposes.



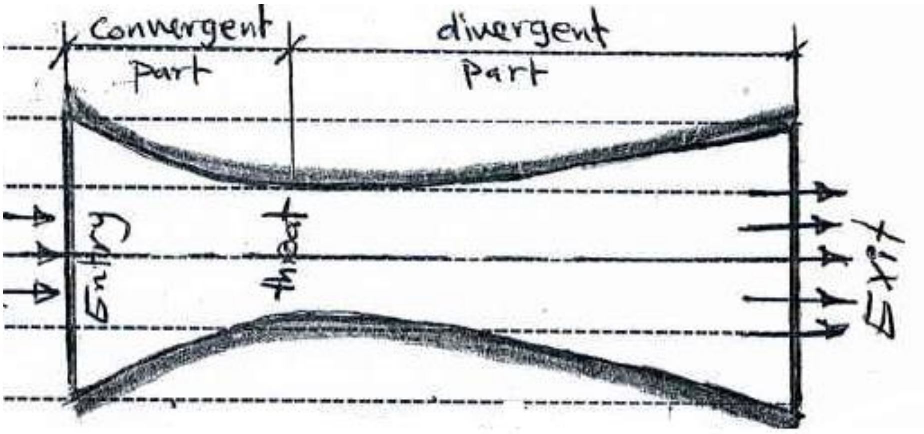
2. The Selection of Sit for Steam Power Plant

It needs the following points to be into consideration:

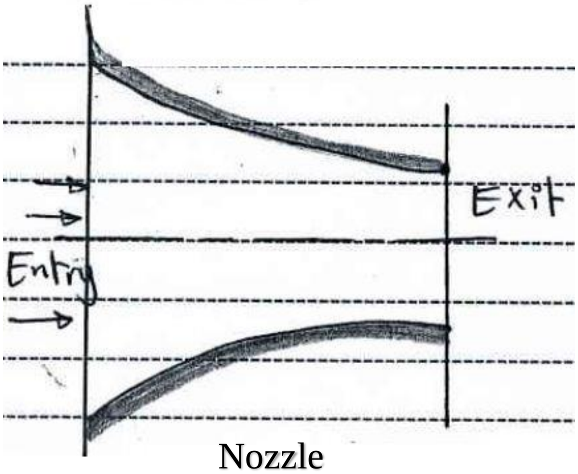
1. Availability of raw material
2. Availability of water
3. Cost of land
4. Nature of land
5. Transport of facilities
6. Ash disposal facilities
7. Availability of labour
8. Size of plant
9. Load centre
10. Future extensions

3. Steam Nozzle

A nozzle is a flow passage of varying cross-sectional area in which the velocity of fluid increases and pressure reduces in the direction of flow. Thus in the nozzle, the fluid enters the variable cross-section area duct with small velocity and high pressure and leaves it with high velocity and a small pressure. During flow through the nozzle, the enthalpy drops and heat drop in the expansion is spent in increasing the velocity of the fluid. Similar to nozzle a duct with variable cross-section area will be called a diffuser if the fluid is decelerated, causing a rise in pressure along the direction of flow. Nozzles are generally used in turbines, jet engines, rockets, injectors etc.



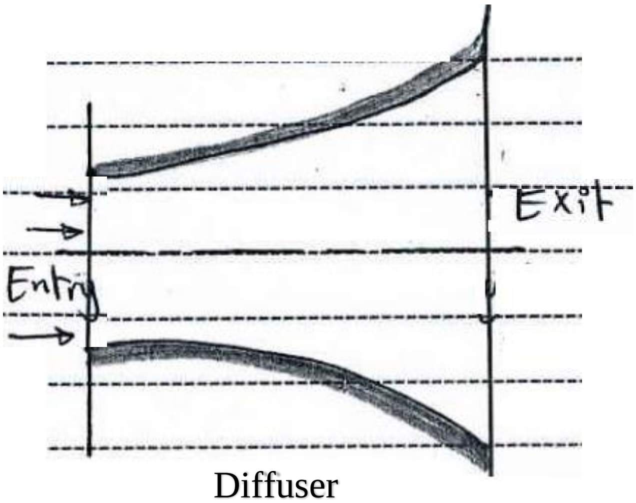
Convergent-Divergent Nozzle



Nozzle

$P_2 < P_1$

$V_2 = C_2 > V_1 = C_1$



Diffuser

$P_2 > P_1$

$V_2 = C_2 < V_1 = C_1$

The Exit Velocity of The Nozzle

By applying steady flow energy equation to the nozzle as a stream of fluid at a pressure (P_1), enthalpy (h_1) and with a low velocity (C_1 or V_1):

$$\frac{dE_{cv}}{dt} = Q - W + m_{in}\left(h_{in} + \frac{V_{in}^2}{2} + g.z_{in}\right) - m_{out}\left(h_{out} + \frac{V_{out}^2}{2} + g.z_{out}\right)$$

Assumptions:

Steady state: $\frac{dE_{cv}}{dt} = 0$

No change in the elevation: $g.z_{in} = g.z_{out} = 0$

No work added or obtained: $W = 0$

No heat added or obtained (adiabatic flow): $Q = 0$

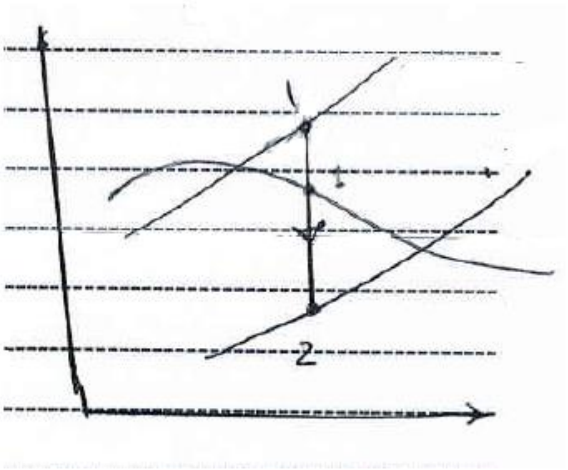
Mass conservation: $m_{in} = m_{out}$

$$0 = m_{in}(h_{in} + \frac{V_{in}^2}{2}) - m_{out}(h_{out} + \frac{V_{out}^2}{2})$$

$$V_{out}^2 = 2(h_{in} - h_{out}) + V_{in}^2$$

$$V_2^2 = 2(h_1 - h_2) + V_1^2$$

$$\left[V_2 \ = \sqrt{2(h_1 - h_2) + V_1^2}\right] \text{................(1)}$$



In most problems, the inlet velocity (V_1=C_1) can be neglected.

$$\left[V_2 = \sqrt{2(h_1 - h_2)}\right] \text{..................... (2)}$$

For Gases, Find The Exit Velocity of The Nozzle:

$$\Delta \boldsymbol{h} = \boldsymbol{h_1} - \boldsymbol{h_2} = \boldsymbol{C_p}(\boldsymbol{T_1} - \boldsymbol{T_2})$$

But, $\boldsymbol{C_p} = \frac{\gamma R}{\gamma - 1}$

$$\boldsymbol{V_2} = \sqrt{\frac{2\gamma}{\gamma - 1} \boldsymbol{R}(\boldsymbol{T_1} - \boldsymbol{T_2})}$$

$$\boldsymbol{V_2} = \sqrt{\frac{2\gamma}{\gamma - 1} (\boldsymbol{p_1 v_1} - \boldsymbol{p_2 v_2})}$$

$$\left[\boldsymbol{V_2} = \sqrt{\frac{2\gamma}{\gamma - 1} \boldsymbol{p_1 v_1}(1 - \frac{\boldsymbol{p_2 v_2}}{\boldsymbol{p_1 v_1}})}\right] \dots\dots\dots\dots\dots\dots\dots\dots..(3)$$

For Adiabatic Expansion, The Exit Velocity of The Nozzle

$$\boldsymbol{p_1 v_1}^{\gamma} = \boldsymbol{p_2 v_2}^{\gamma}$$

$\frac{\boldsymbol{v_2}}{\boldsymbol{v_1}} = \left(\frac{\boldsymbol{p_1}}{\boldsymbol{p_2}}\right)^{1/\gamma}$ substitute in (3) $\Rightarrow$

$$\boldsymbol{V_2} = \sqrt{\frac{2\gamma}{\gamma - 1} \boldsymbol{p_1 v_1} \left(1 - \frac{\boldsymbol{p_2}}{\boldsymbol{p_1}} . \left(\frac{\boldsymbol{p_1}}{\boldsymbol{p_2}}\right)^{1/\gamma}\right)}$$

$$\boldsymbol{V_2} = \sqrt{\frac{2\gamma}{\gamma - 1} \boldsymbol{p_1 v_1} \left(1 - \frac{\boldsymbol{p_2}}{\boldsymbol{p_1}} . \left(\frac{\boldsymbol{p_2}}{\boldsymbol{p_1}}\right)^{-1/\gamma}\right)}$$

$$\left[\boldsymbol{V_2} = \sqrt{\frac{2\gamma}{\gamma - 1} \boldsymbol{p_1 v_1} \left(1 - \left(\frac{\boldsymbol{p_2}}{\boldsymbol{p_1}}\right)^{\gamma - 1/\gamma}\right)}\right] \dots\dots\dots\dots\dots\dots\dots(4)$$

For The Throat Section, The Throat Velocity (V_t) & Mass Flow Rate ($\dot{m}$) Can Be Written As:

Now, and at any section in the nozzle

$$\dot{m}v = AV$$

where m = mass flow rate (kg/s)

v = specific volume (m$_3$/kg)

A = cross section area (m^2)

V = velocity (m/s)

$$\left[V_t = \sqrt{\frac{2\gamma}{\gamma-1}p_1v_1\left(1-\left(\frac{p_t}{p_1}\right)^{\gamma-1/\gamma}\right)}\right] \ldots\ldots\ldots\ldots.\ldots\ldots.(5)$$

$\dot{m}v_t = A_tV_t$ substitute (5) in this equation $\Rightarrow$

$$\left[\dot{m} = \frac{A_t}{v_t}\sqrt{\frac{2\gamma}{\gamma-1}p_1v_1\left(1-\left(\frac{p_t}{p_1}\right)^{\gamma-1/\gamma}\right)}\right] \ldots\ldots\ldots\ldots\ldots.(6)$$

For Adiabatic Expansion, Mass Flow Rate ($\dot{m}$) Can Be Written As:

$$p_1{v_1}^{\gamma} = p_t{v_t}^{\gamma}$$

$$\left[\frac{v_t}{v_1} = \left(\frac{p_1}{p_t}\right)^{1/\gamma}\right] \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.\ldots\ldots.(7)$$

substitute (7) in (6) $\Rightarrow$

$$\dot{m} = \frac{A_t}{v_1\left(\frac{p_1}{p_t}\right)^{1/\gamma}}\sqrt{\frac{2\gamma}{\gamma-1}p_1v_1\left(1-\left(\frac{p_t}{p_1}\right)^{\gamma-1/\gamma}\right)}$$

$$\dot{m} = \frac{A_t}{v_t}\left(\frac{p_t}{p_1}\right)^{1/\gamma}\sqrt{\frac{2\gamma}{\gamma-1}p_1v_1\left(1-\left(\frac{p_t}{p_1}\right)^{\gamma-1/\gamma}\right)}$$

$$\dot{m} = \frac{A_t}{v_t}\sqrt{\frac{2\gamma}{\gamma-1}p_1v_1\left(\frac{p_t}{p_1}\right)^{2/\gamma}\left(1-\left(\frac{p_t}{p_1}\right)^{\gamma-1/\gamma}\right)}$$

$$\left[\dot{m} = \frac{A_t}{v_t}\sqrt{\frac{2\gamma}{\gamma-1}p_1v_1\left(\left(\frac{p_t}{p_1}\right)^{2/\gamma}-\left(\frac{p_t}{p_1}\right)^{\gamma+1/\gamma}\right)}\right] \dots\dots\dots\dots\dots\dots\dots\dots (\mathbf{8})$$

For Maximum Discharge, Find The Critical Pressure (p_t/p_1):

let $X = \frac{p_t}{p_1}$ where $v_1, \mathbf{p_1}$ and $\boldsymbol{\gamma}$ are constant

$$\dot{m} = \frac{A_t}{v_t}\sqrt{\frac{2\gamma}{\gamma-1}p_1v_1\left(X^{2/\gamma}-X^{\gamma+1/\gamma}\right)}$$

For a maximum value of $\frac{\dot{m}}{A_t}$

$$\frac{d}{dx}\left(X^{2/\gamma}-X^{\gamma+1/\gamma}\right) = 0$$

$$\frac{2}{\gamma}\left(X^{2-\gamma/\gamma}\right) - \frac{\gamma+1}{\gamma}\left(X^{1/\gamma}\right) = 0$$

$$\frac{X^{1/\gamma}}{X^{2-\gamma/\gamma}} = \frac{2}{\gamma+1}$$

$$X^{\frac{\gamma-1}{\gamma}} = \frac{2}{\gamma+1}$$

$$X = \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma}{\gamma-1}}$$

$$\left[\frac{p_t}{p_1} = \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma-1}{\gamma}}\right] \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots.. (\mathbf{9})$$

Where (**p_t/p_1**) is called **The Critical Pressure**. γ=1.4 for air

For Maximum Discharge, Find The Critical Temperature (T_t/T_1):

$$\frac{T_t}{T_1} = \left(\frac{p_1}{p_t}\right)^{\frac{\gamma-1}{\gamma}} = \left[\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma}{\gamma-1}}\right]^{\frac{\gamma-1}{\gamma}} = \left(\frac{2}{\gamma+1}\right)$$

$$\frac{T_t}{T_1} = \left(\frac{2}{\gamma+1}\right) \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots.. (10)$$

For Steam Nozzle

n=1.135, for saturated & wet steam

n=1.3, for superheated steam

$$pv^n = constant$$

The steam velocity at the throat section can be evaluated by:

$$\left[V_t = \sqrt{2(h_1 - h_2) + V_1^2}\right] \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad \ldots\ldots\ldots\ldots..(11)$$

In most problems, the inlet velocity (V_1=C_1) can be neglected.

$$\left[V_t = \sqrt{2(h_1 - h_2)}\right] \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad ..(12)$$

And **The Critical Pressure (p_t/p_1):**

$$\left[\frac{p_t}{p_1} = \left(\frac{2}{\gamma + 1}\right)^{\frac{n-1}{n}}\right] \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..(13)$$

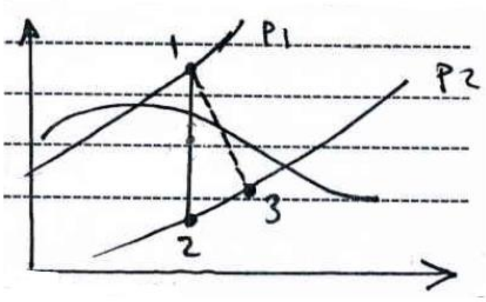
The steam velocity at the exit:

$$\left[V_2 = \sqrt{2(h_1 - h_2)}\right] \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad ..(14)$$

$$\left[V_2 = \sqrt{\frac{2n}{n-1} p_1 v_1 \left(1 - \left(\frac{p_2}{p_1}\right)^{n-1/n}\right)}\right] \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.\ldots\ldots(15)$$

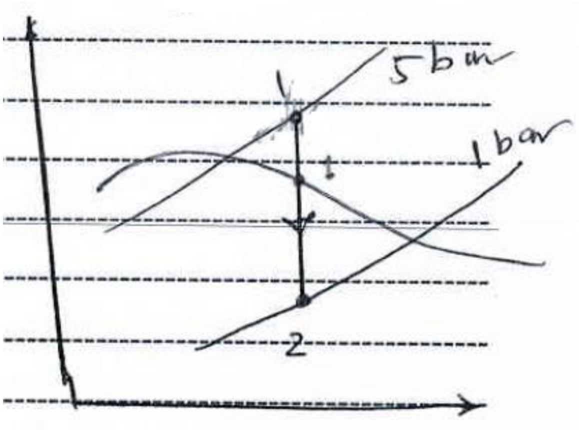
Nozzle Efficiency

$$\eta_{Nozzle} = \frac{h_1 - h_3}{h_1 - h_2}$$

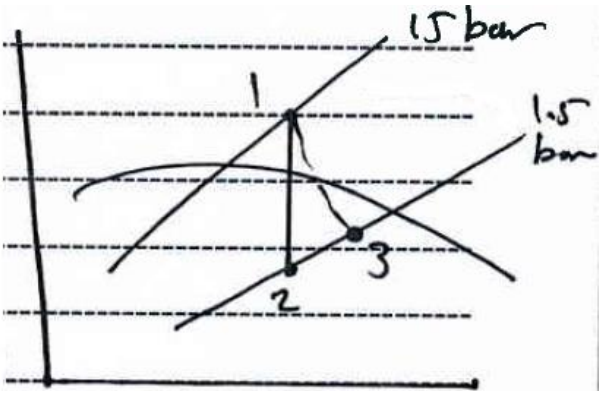


Ex. Dry saturated steam at 5 bar with negligible velocity expands isentropically in a convergent nozzle to 1 bar & dryness fraction 94%. **Find** the velocity of steam leaving the nozzle.

Sol.



Ex. Dry saturation at a pressure of 15 bar enters in a nozzle & is discharged at a pressure of 1.5 bar. Find the final velocity of the steam as 10% of enthalpy is lost in friction. **Find** the percentage of decrease in the final velocity.



Ex. Steam at 8 bar & 250°C flows without friction through a nozzle. The outlet pressure is 2 bar. **Estimate** the exit velocity & the exit area required to discharge 1 kg.

Sol.

Ex. Air enters a nozzle at a pressure of 3.5MPa & a temperature of 500°C. It leaves the nozzle at a pressure of 0.7MPa. The airflow rate is 1.3 kg/s, the expansion may be considered adiabatic & obey the law pv^{γ} = constant. Take γ=1.4, R 0.287 kJ/kg.°K. **Evaluate** the throat area & the exit area.

Sol.

4. Steam Turbines

It is a prime part mover. The potential energy of the steam is transformed into kinetic energy and the latter is transformed into mechanical energy of rotation of the turbine shaft by using a steam turbine.

Generally, it essentially consists of:

1. Nozzles: the potential energy of the higher-pressure steam is converted into kinetic energy by using nozzles.
2. Blades: mounted on the rotor of the turbine, which changes the direction of steam supplying from the nozzle. Thus, a force acts on the blades due to the change in momentum.

Turbines may be classified according to several ways. The most important and common division being with respect to the action of the steam as:

1. Impulse turbine **2.** Reaction turbine **3.** Combination of impulse & reaction

4.1 Energy losses in steam turbine

The losses in the actual turbine are divided into two groups:

I. Internal Losses: losses directly connected to the steam conditions while its flow through the turbine. It includes the following losses:

1. Losses in regulating valves.
2. Losses in nozzles.
3. Losses in moving blades such as vorticities, impingement losses, frictional losses, turning the steam jet in the blades, steam leakage.
4. Leaving velocity losses.
5. Losses of clearance between the rotor & guide blade discs.
6. Losses of steam wetness.
7. Losses in exhaust pipes.

II. External Losses: which can be classified into:

1. Mechanical losses.
2. Losses of steam from problem gland seals.

4.2 Velocity Diagram for Moving Blade Impulse Turbine

U: linear mean velocity of blades. (m/s)

C_1: absolute velocity of steam at the inlet to blade (outlet from the nozzle). (m/s)

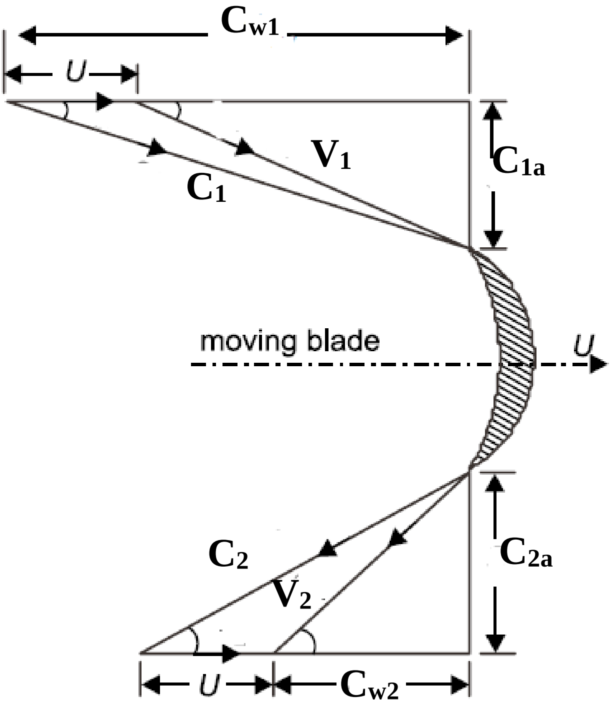
C_2: absolute velocity of steam at the outlet from the blade. (m/s)

V_1: relative velocity of steam to blade at the inlet. (m/s)

V_2: relative velocity of steam to blade at the outlet. (m/s)

C_{1ax}: axial component at the inlet. (N)

C_{2ax}: axial component at the outlet. (N)



Inlet and outlet velocity diagrams.

C_{1w}: tangent component at the inlet, (whirl component). (N)

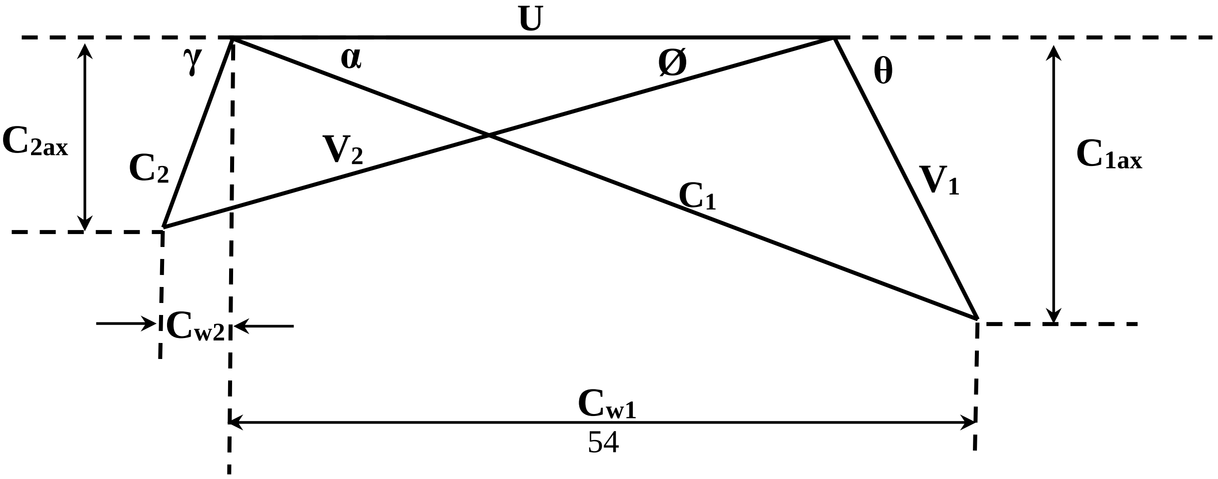
C_{2w}: tangent component at the outlet, (whirl component). (N)

α: jet angle (nozzle outlet angle).

Ø: outlet angle of blades.

θ: inlet angle of blades

γ: the absolute direction of steam leaving blades.



Linear mean velocity:

$$U = \frac{\pi d N}{60},$$

d: mean diameter of the wheel (m) and N: rotational speed (rpm)

Axial Force Thrust:

$$F_a = \dot{m}(C_{1ax} - C_{2ax}), \qquad N$$

Driving Force (Work Done on Blades):

$$W = U(C_{w1} \mp C_{w2}), \qquad J/kg$$

Power Outlet:

$$P = \dot{m}W, \qquad W$$

Blade Efficiency (Efficiency of velocity diagram):

$$\eta = \frac{2W}{{C_1}^2} = \frac{2U(C_{w1} \mp C_{w2})}{{C_1}^2}$$

Friction Factor (Blade Velocity Coefficient):

$$k = \frac{V_2}{V_1}$$

$$k = 100\% - \text{loss friction}$$

Notes:

1. In the case of the blades are given symmetrical. It means that **Ø= θ.**
2. If the friction of the blades is negligible, $V_1=V_2$.
3. Absolute velocity is the velocity of an object relative to the earth.

Ex. The velocity of steam at the inlet to a simple impulse turbine is 1000m/s and the nozzle angle is 20^o. The blade speed is 400m/s and the blades are symmetrical. The mass flow rate of the steam is 45kg/min. **Find 1.** The angles of velocity diagram. **2.** The tangential force on the blades. **3.** The diagram power **4.** The axial thrust of the blade **5.** The blade efficiency.

Sol.

Ex. In the previous example, if the relative velocity at the exit is reduced by friction to 80% of that at the inlet, what is **1.** The power of the diagram. **2.** The axial thrust of the blade. **3.** The blade efficiency in this case.

Sol.

Ex. Two rows of velocity compounded impulse turbine have a mean blade speed of 170m/s. The inlet & exit angles of the first moving row of blades are 30° & 25°, respectively. The inlet & exit angles of the second moving row of blades are 44° & 30°, respectively. The absolute discharge from the second row of moving blades is axial. The loss of velocity in all blades is 15 per cent due to friction. **Estimate:**

1. The inlet & exit angles of the fixed blades.

2. The inlet nozzle angle & velocity.

3. The power output of the two rows of blades if the turbine uses 5400 kg of steam per hour.

Sol.