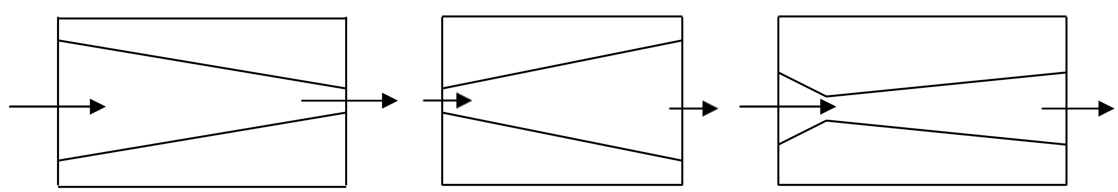
MODULE I

STEAM NOZZLES

When a fluid flows through a passage or channel of varying cross section, its velocity varies from point to point along the passage. If the velocity increases, the passage is called a Nozzle. The steam nozzle is device designed to increase the velocityof steam. The fluid enters the nozzle at high pressure and expands to lower pressure. If the cross section of the nozzle decreases continuously from the entrance to exit, it is called **Convergent nozzle**. The maximum Mach number at the exit of the convergent nozzle is 1. If the cross section of the nozzle increases, it is called **Divergent nozzle.** If the cross section of the nozzle, first decreases and then increases, it is called **Convergent-divergent nozzle.** At the throat, i.e., at the narrowest cross section the Mach number is 1.



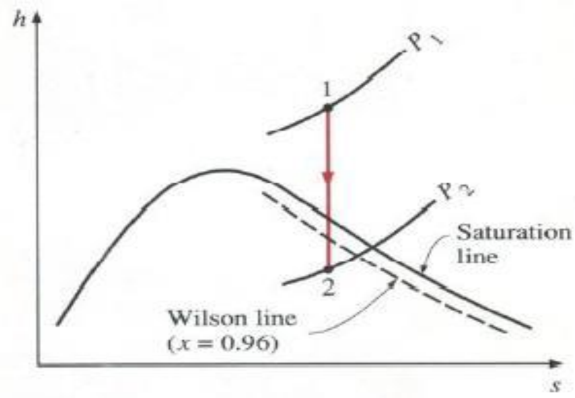
Convergent **Divergent** **Convergent-Divergent**

1. Describe about supersaturated flow or metastable flow in a nozzleand state effect of super saturation

As steam expands in the nozzle, its pressure and temperature drop, and it is expected that the Steam start condensing when it strikes the saturation line. But this is not always the case. Owing to the high velocities, the residence time of the steam in the nozzle is small, and there may not Sufficient time for the necessary heat transfer and the formation of liquid droplets. Consequently, the condensation of steam is delayed for a little while. This phenomenon is known as Super saturation, and the steam that exists in the wet region without containing any liquid is Known as supersaturated steam.

The locus of points where condensation will take place regardless of the initial temperature and Pressure at the nozzle entrance is called the Wilson line. The Wilson line lies between 4 and 5 percent moisture curves in the saturation region on the h-s diagram for steam, and is often

Approximated by the 4 percent moisture line. The super saturation phenomenon is shown on the h-s chart below:



The *h-s* diagram for the isentropic expansion of steam in a nozzle.

Effects of Supersaturation:

The following are the effects of supersaturation in a nozzle.

(a) The temperature at which the supersaturation occurs will be less than the saturation temperature corresponding to that pressure. Therefore, the density of supersaturated steam will be more than that of equilibrium condition which gives the increase in the mass of steam discharged.

(b) Supersaturation increases the specific volume and entropy of the steam.

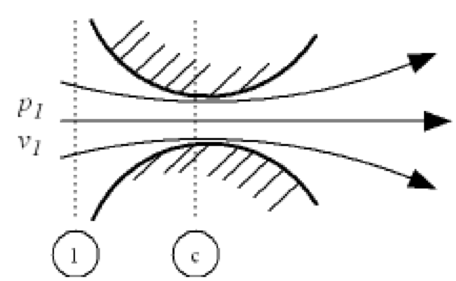
(c) Supersaturation reduces the heat drop. Thus the exit velocity of steam is reduced.

(d) Supersaturation increases the dryness fraction of the steam.

Critical Pressure Ratio:

The critical pressure ratio is the pressure ratio which will accelerate the flow to a velocity equal to the local velocity of sound in the fluid.

Critical flow nozzles are also called **sonic chokes**. By establishing a shock wave the sonic choke establish a fixed flow rate unaffected by the differential pressure, any fluctuations or changes in downstream pressure. A sonic choke may provide a simple way to regulate a gas flow.



The ratio between the critical pressure and the initial pressure for a nozzle can expressed as

$p_c / p_1 = (2 / (n + 1))^{n / (n - 1)}$

where

p_c = critical pressure (Pa)

p_1 = inlet pressure (Pa)

n = index of isentropic expansion or compression - or polytropic constant

For a perfect gas undergoing an adiabatic process the index - n - is the ratio of specific heats - k = c_p / c_v. There is no unique value for - n. Values for some common gases are

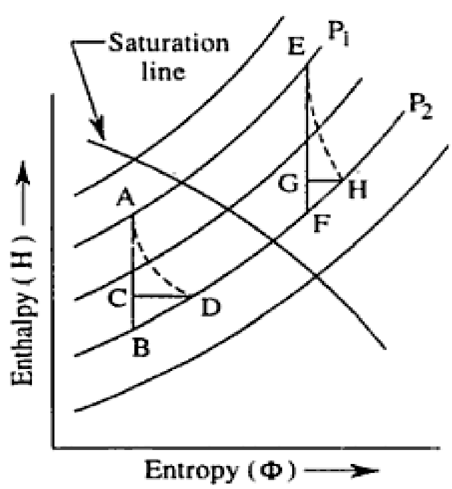
- Steam where most of the process occurs in the wet region : n = 1.135
- Steam superheated: n = 1.30
- Air: n = 1.4
- Methane: n = 1.31
- Helium: n = 1.667

2. Describe the Effect of Friction on Nozzles.

1) Entropy is increased.
2) Available energy is decreased.
3) Velocity of flow at throat is decreased.
4) Volume of flowing steam is decreased.
5) Throat area necessary to discharge a given mass of steam is increased.

Most of the friction occurs in the diverging part of a convergent-divergent nozzle as the length of the converging part is very small. The effect of friction is to reduce the available enthalpy drop by about 10 to 15 per cent. The velocity of steam will be then $V_2 = 44.72\sqrt{K(H_1 - H_2)}$ where K is the coefficient which allows for friction loss. It is also known as nozzle efficiency (η_n)

$$\therefore \quad V_2 = 44.72\sqrt{(H_1 - H_2)\eta_n}$$



Velocity of steam at nozzle exit:

$$V_2^2 = 2000(H_1 - H_2) + V_1^2 \quad \therefore \quad V_2 = \sqrt{2000(H_1 - H_2) + V_1^2}$$

As the velocity of steam entering the nozzle is very small, V_1 can be neglected.

$$\therefore \qquad V_2 = \sqrt{2000(H_1 - H_2)} = 44.72\sqrt{(H_1 - H_2)} \text{ m/s}$$

If frictional losses are taken into account then

$$V_2 = 44.72\sqrt{(H_1 - H_2)\eta_n} \text{ m/s}$$

3. Derive the expression for maximum discharge through a nozzle.

Mass of steam discharged through a nozzle:

$$m = A\sqrt{2000\frac{n}{n-1} \times \frac{P_1}{v_1}\left[\left(\frac{P_2}{P_1}\right)^{\frac{2}{n}} - \left(\frac{P_2}{P_1}\right)^{\frac{n+1}{n}}\right]}$$

Condition for maximum discharge through nozzle:

The nozzle is always designed for maximum discharge

$$\frac{m}{A} = \sqrt{2000\frac{n}{n-1} \times \frac{P_1}{v_1}\left[\left(\frac{P_2}{P_1}\right)^{\frac{2}{n}} - \left(\frac{P_2}{P_1}\right)^{\frac{n+1}{n}}\right]}$$

The mass flow per unit area will be maximum at the throat because the throat area is minimum.

It is seen from the above equation that the discharge through a nozzle is a function of $\frac{P_2}{P_1}$ only, as the expansion index is fixed according to the steam supplied to the nozzle.

Therefore, $\frac{m}{A}$ is maximum when

$$\left[\left(\frac{P_2}{P_1}\right)^{\frac{2}{n}} - \left(\frac{P_2}{P_1}\right)^{\frac{n+1}{n}}\right] \text{ is minimum}$$

Values for maximum discharge:

$$m = A\sqrt{2000\frac{n}{n-1}\times\frac{P_1}{v_1}\left[\left(\frac{P_2}{P_1}\right)^{\frac{2}{n}}-\left(\frac{P_2}{P_1}\right)^{\frac{n+1}{n}}\right]}$$

we know $\frac{P_2}{P_1}=\left(\frac{2}{n+1}\right)^{\frac{n}{n-1}}$

Putting the value of $\frac{P_2}{P_1}$ in the above equation

$$m_{max} = A\sqrt{2000\frac{n}{n-1}\times\frac{P_1}{v_1}\left[\left(\frac{2}{n+1}\right)^{\frac{2}{n-1}}-\left(\frac{2}{n+1}\right)^{\frac{n+1}{n-1}}\right]}$$

$$m_{max} = A\sqrt{2000\frac{n}{n-1}\times\frac{P_1}{v_1}\times\left(\frac{2}{n+1}\right)^{\frac{n+1}{n-1}}\left[\left(\frac{2}{n+1}\right)^{\frac{2}{n-1}-\frac{n+1}{n-1}}-1\right]}$$

$$= A\sqrt{2000\frac{n}{n-1}\times\frac{P_1}{v_1}\times\left(\frac{2}{n+1}\right)^{\frac{n+1}{n-1}}\left[\left(\frac{2}{n+1}\right)^{\frac{1-n}{n-1}}-1\right]}$$

$$= A\sqrt{2000\frac{n}{n-1}\times\frac{P_1}{v_1}\times\left(\frac{2}{n+1}\right)^{\frac{n+1}{n-1}}\left[\left(\frac{2}{n+1}\right)^{-1}-1\right]}$$

$$= A\sqrt{2000\frac{n}{n-1}\times\frac{P_1}{v_1}\times\left(\frac{2}{n+1}\right)^{\frac{n+1}{n-1}}\left[\frac{n+1}{2}-1\right]}$$

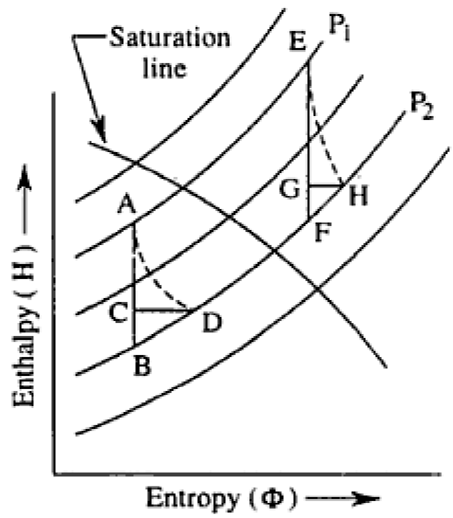
$$= A\sqrt{2000\frac{n}{n-1}\times\frac{P_1}{v_1}\times\left(\frac{2}{n+1}\right)^{\frac{n+1}{n-1}}\left(\frac{n-1}{2}\right)}$$

$$m_{max} = A\sqrt{1000n\times\frac{P_1}{v_1}\times\left(\frac{2}{n+1}\right)^{\frac{n+1}{n-1}}}$$

W3here P_1 is the initial pressure of the steam in kpa and v_1 is the specific volume of the steam

Metastable expansion of steam in a nozzle with help of h-s diagram.

Most of the friction occurs in the diverging part of a convergent-divergent nozzle as the length of the converging part is very small. The effect of friction is to reduce the available enthalpy drop by about 10 to 15 per cent. The velocity of steam will be then $V_2 = 44.72\sqrt{K(H_1 - H_2)}$ where K is the coefficient which allows for friction loss. It is also known as nozzle efficiency (η_n)



$$\therefore \quad V_2 = 44.72\sqrt{(H_1 - H_2)\eta_n}$$

1) Velocity of steam at exit from the stage is 85 m/sat an angle of 80° from the tangential direction. Blade velocity coefficient is 0.82 and the rate of steam flowing through the stage is 2.5 kg/s. If the blades are equiangular, determine i) Blade angles and ii) Axial thrust. (MAY/JUNE 2016)

(a) Blade inlet angle

By measurement from the velocity diagram, we find that the blade angle at inlet,

$$\theta = 29^0$$

(b) During force on the wheel

We know that driving force on the wheel,

$$F_x = m(V_w + V_{w1}) = 0.5\ (1130 + 190) = 660\ N$$

(c) Arial thrust on the wheel

We know that axial thrust on the wheel,

$$F_\gamma = m(V_f - V_{f1}) = 0.5(410 - 310) = 50N$$

(d) Power development by the turbine

We know that power development by the turbine,

$$P = m(V_w + V_{w1})\ V_b$$
$$= 0.5(1130 + 190)\ 375 = 247\ 500\ W$$
$$= 247.5\ kW$$