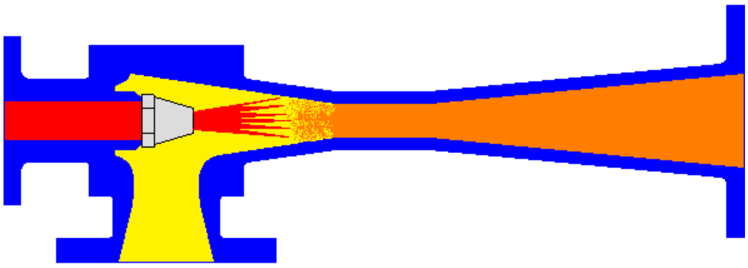
5

Steam Nozzle



Course Contents

5.1 Introduction

A nozzle is often a pipe or tube of varying cross-sectional area, and it can be used to direct or modify the flow of a fluid (liquid or gas). Nozzles are frequently used to control the rate of flow, speed, direction, mass, shape, and/or the pressure of the stream that emerges from them. In a nozzle, the velocity of fluid increases or decrease at the expense of its pressure energy

Its major function is to produce steam jet with high velocity to drive steam turbines.

5.2 Application of nozzle

- To produce high velocity jet to impinge on curved blade of driving turbine shaft.
- Jet engines to produce thrust.
- Rocket motors to produce thrust.
- Artificial Fountains.
- Flow measurements.
- Injectors for pumping feed water.
- Ejectors for removing air from condensers.
- Fire hose to produce

5.3 Types of Nozzle

There are mainly three types of nozzle.

1) Convergent nozzle
2) Divergent nozzle
3) Convergent-divergent nozzle

5.2.1 Convergent nozzle

If the c/s of the nozzle decreases continuously from the entrance to exit, it is called a convergent nozzle. It is used, when back pressure is equal to or greater than critical pressure. It is also used for non-compressible fluids.

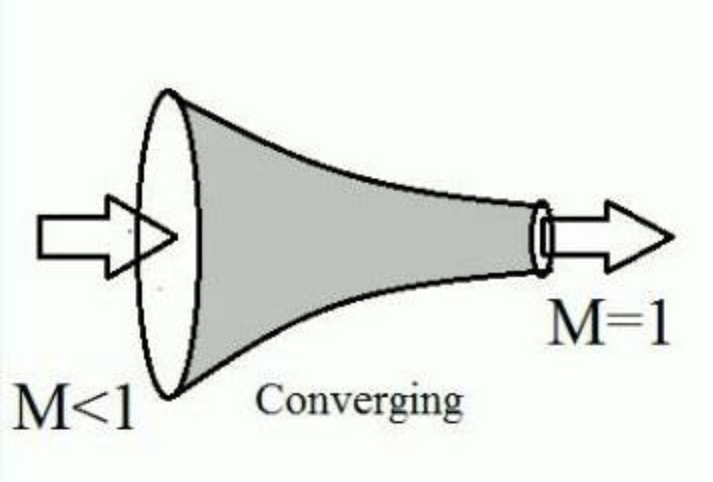


Figure 5.1 Convergent nozzle

5.2.2 Divergent nozzle

If the c/s of the nozzle increases continuously from the entrance to exit, it is called a divergent nozzle. It is used when back pressure is less than critical pressure.

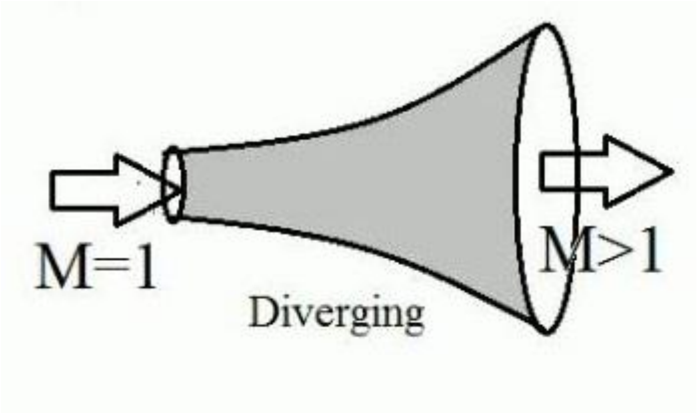


Figure 5.2 Divergent nozzle

5.2.3 Convergent-divergent nozzle

If the c/s of the nozzle first decreases and then increases, it is called convergent-divergent nozzle. The convergent-divergent nozzle is used when back pressure is less than the critical pressure. It is widely used in steam and gas turbine.

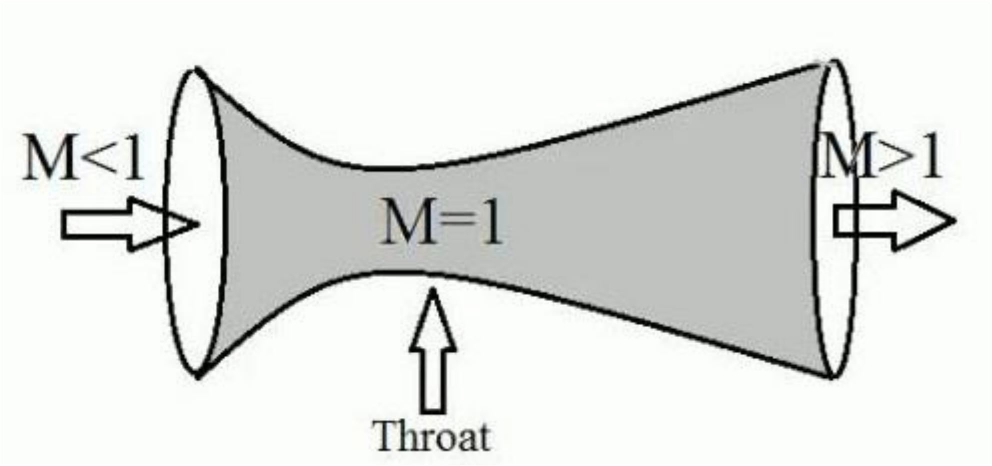


Figure 5.3 Convergent-divergent nozzle

5.4 Velocity of Steam

Steam flow through nozzle maybe assumed as adiabatic flow since during expansion of steam there is no any heat transfer. It can be calculated by following formula. Consider 1 at inlet section and 2 as outlet section.

By applying energy equation at section 1 and 2 we get

$$h_1 + \frac{{c_1}^2}{2 \times 1000} = h_2 + \frac{{c_2}^2}{2 \times 1000}$$

As the velocity of steam entering the nozzle is very small, C_1 can be neglected and finally by simplifying equation we obtain,

$$C_2 = 44.72\sqrt{((h_1 - h_2) \times \eta_n}$$

Where,
$h_1 = Enthalpy\ at\ inlet$
$h_2 = Enthalpy\ at\ outlet$
$\eta_n = Nozzle\ efficiency$

5.5 Discharge through nozzle

The steam flow through the nozzle is isentropic and is represented by $pv^{\Upsilon}=C$. Neglecting the initial velocity, gain in kinetic energy becomes $V_2^2/2$.

Heat drop = h_1-h_2. = Work done during Rankine cycle.

$$\therefore \frac{V_2{}^2}{2} = \frac{n}{n-1}(\,p_1v_1 - p_2v_2)$$

$$= \frac{n}{n-1}\,p_1v_1\left[1 - \frac{p_2v_2}{p_1v_1}\right] \underline{\qquad\qquad} 1)$$

But, $\frac{v_2}{v_1} = \left(\frac{p_2}{p_1}\right)^{-1/n}$

Substituting this value in equation 1)

$$\frac{V_2{}^2}{2} = \frac{n}{n-1}\,p_1v_1\left[1 - (\frac{p_2}{p_1})^{\frac{n-1}{n}}\right]$$

$$V_2 = \sqrt{\frac{2n}{n-1}\,p_1v_1\left[1 - (\frac{p_2}{p_1})^{\frac{n-1}{n}}\right]}$$

Mass of steam discharged through nozzle per second,

$$m = \frac{Volume\ of\ steam\ flowing\ per\ secong}{Volume\ of\ 1\ Kg\ steam\ at\ pressure\ p_2}$$

$$= \frac{AV_2}{v_2} = \frac{A}{v_2}\sqrt{\frac{2n}{n-1}\,p_1v_1\left[1 - (\frac{p_2}{p_1})^{\frac{n-1}{n}}\right]}$$

$$= \frac{A}{v_1}\left(\frac{p_2}{p_1}\right)^{1/n}\sqrt{\frac{2n}{n-1}\,p_1v_1\left[1 - (\frac{p_2}{p_1})^{\frac{n-1}{n}}\right]}$$

$$= A\sqrt{\frac{2n}{n-1} \times \frac{p_1}{v_1}\left[(\frac{p_2}{p_1})^{\frac{2}{n}} - (\frac{p_2}{p_1})^{\frac{n+1}{n}}\right]}$$

5.6 Critical pressure ratio and condition for maximum discharge

Nozzle is usually designed for maximum steam flow rate. By designing certain pressure at throat this is achieved.

Let us consider,

P_1 = Initial pressure of steam
P_2 = Pressure of steam at throat
V_1 = Specific volume of steam at pressure P_1
V_2 = Specific volume of steam at pressure P_2

Mass of steam discharged through nozzle is given by,

$$m = A\sqrt{\frac{2n}{n-1} \times \frac{p_1}{v_1}\left[(\frac{p_2}{p_1})^{\frac{2}{n}} - (\frac{p_2}{p_1})^{\frac{n+1}{n}}\right]}$$

There is only one value of the ratio P_2/P_1, which produces maximum discharge from the nozzle. In above equation except P_2/P_1, all other values are constant. Therefore only that portion of equation which contains P_2/P_1 is differentiated and equated to zero for maximum discharge.

$$\therefore \frac{d}{d\left(\frac{p_2}{p_1}\right)}\left[(\frac{p_2}{p_1})^{\frac{2}{n}} - (\frac{p_2}{p_1})^{\frac{n+1}{n}}\right] = 0$$

$$\therefore \frac{2}{n}(\frac{p_2}{p_1})^{\frac{2-n}{n}} = \frac{n+1}{n}(\frac{p_2}{p_1})^{\frac{1}{n}}$$

$$\therefore \frac{p_2}{p_1} = \left(\frac{2}{n+1}\right)^{\frac{n}{n-1}}$$

This ratio shows critical pressure ratio for maximum discharge at throat.

Sr. no.	Steam condition	n	$\frac{p_2}{p_1}$
1	Initially dry saturated steam	1.135	0.5777
2	Initially superheated steam	1.3	0.546
3	Initially wet steam	1.035+0.1x	Depend on dryness fraction
4	For air entering in nozzle	1.4	0.528

5.7 Physical significance of critical pressure ratio

Velocity of steam at any section of nozzle is given by,

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

And critical pressure ratio for maximum discharge,

$$\frac{p_2}{p_1} = \left(\frac{2}{n+1}\right)^{\frac{n}{n-1}} \underline{\qquad\qquad\qquad} 1)$$

Substituting this value in above equation,

$$V_2 = \sqrt{\frac{2n}{n-1} p_1 v_1 \left[1 - \frac{2}{n+1}\right]}$$

$$V_2 = \sqrt{\frac{2n}{n+1} p_1 v_1} \underline{\qquad\qquad\qquad} 2)$$

For isentropic expansion,

$$p_1 {v_1}^n = p_2 {v_2}^n$$

$$\frac{V_1}{V_2} = \left(\frac{p_2}{p_1}\right)^{1/n}$$

$$\therefore p_1 v_1 = p_1\ v_2 \left(\frac{p_2}{p_1}\right)^{1/n} = p_1 v_2 \frac{p_2}{p_2} \left(\frac{p_2}{p_1}\right)^{1/n} = p_2 v_2 \left(\frac{p_2}{p_1}\right)^{\frac{1-n}{n}}$$

Substituting equation 1 in above equation we get,

$$p_1 v_1 = p_2 v_2 \left(\left(\frac{2}{n+1}\right)^{\frac{n}{n-1}}\right)^{\frac{1-n}{n}} = p_2 v_2 \left(\frac{n+1}{2}\right)$$

Substituting above equation in equation 2 we get,

$$V_2 = \sqrt{n\, p_1 v_1}$$

This is the value of velocity of sound in the medium at pressure p_2 and is known as sonic velocity.

From above derivation following points are concluded,

1. The critical pressure gives the velocity of steam at the throat which is equal to the velocity of sound.
2. The steam flow in convergent portion of nozzle is subsonic and in the divergent portion it is supersonic.
3. When a nozzle operates with maximum mass flow rate, it is said to be chocked. A correctly designed convergent-divergent nozzle is always chocked.
4. To increase the velocity of steam above sonic velocity, it becomes necessary to expand steam below critical pressure. To effect this, the divergent portion for the nozzle becomes necessary.

5.8 Nozzle Efficiency

Expansion process in nozzle considered as isentropic expansion but in actual practice there is a friction loss in the nozzle, so actual flow in the nozzle is not isentropic flow.

Nozzle efficiency is defined as the ratio of actual heat drop to isentropic heat drop or heat drop due to isentropic expansion.

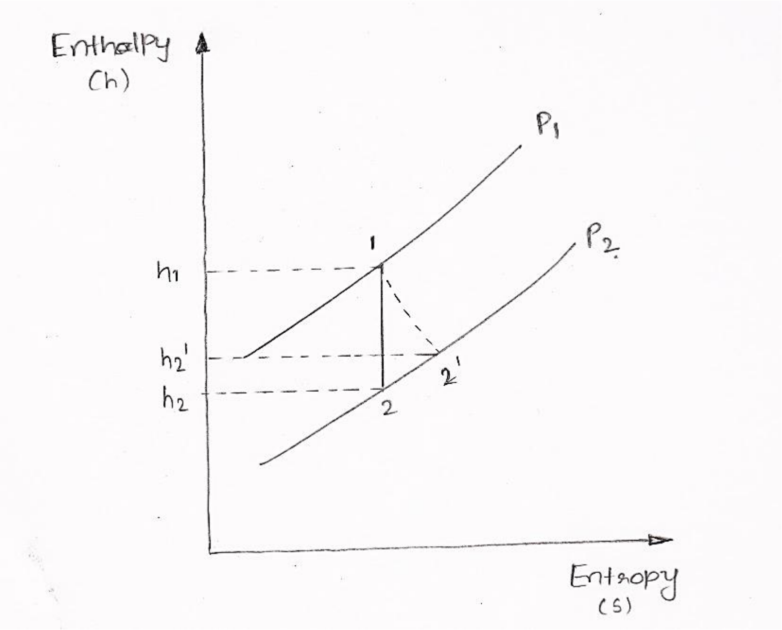


Figure 5.4 h-s diagram for nozzle

$$\eta_N = \frac{h_1 - h_2'}{h_1 - h_2}$$

Where,

$h_1 = Initial\ Enthalpy$
$h_2 = Final\ Enthalpy$
$h_2' = Actual\ final\ Enthalpy$

Effect of Friction

When steam flows through a nozzle the final velocity of steam for given pressure drop is reduced due to following reason.

- The friction between the nozzle surface and steam.
- The internal friction of steam itself.
- The shock losses.

The convergent portion of nozzle is smaller than the divergent portion. Thus, the wall friction is small in the convergent portion as compared to divergent portion.

The fluid friction is also small in convergent portion than in the divergent portion, since the fluid velocity in the convergent portion is small.

Thus, most of the friction occurs in the divergent portion of the nozzle and h-s diagram plot as shown in following figure.

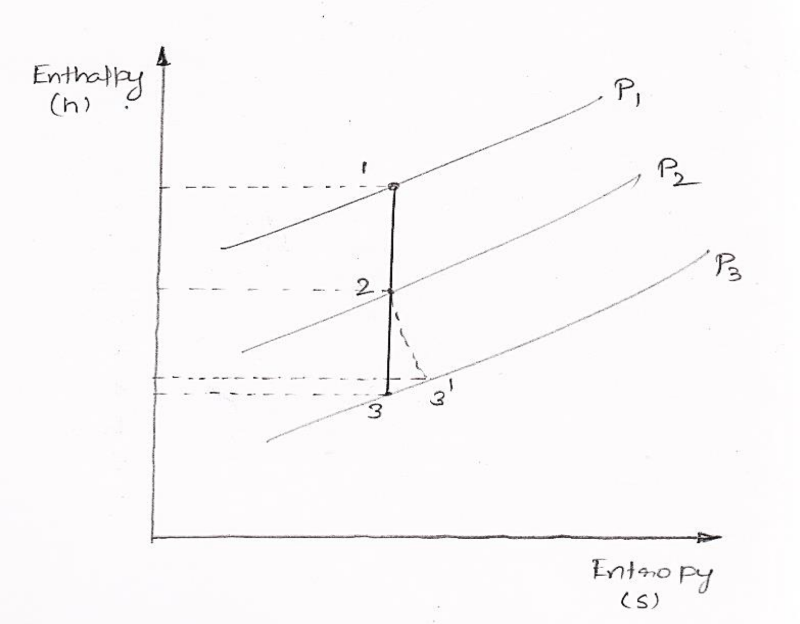


Figure 5.5 Effect of friction in divergent portion of nozzle

These frictional losses entail the following effects.

- The expansion is no more isentropic and the enthalpy and entropy of steam increasing during the process.
- The final dryness fraction of steam is increased as the kinetic energy gets converted into heat due to friction and is absorbed by steam.
- The specific volume of steam increased as the steam becomes drier due to this frictional reheating.

- Exit velocity is reduced as the kinetic energy gets converted into heat due to friction.
- Mass flow rate is decreased.