# Chapter – 5
# Steam Nozzle

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# Introduction

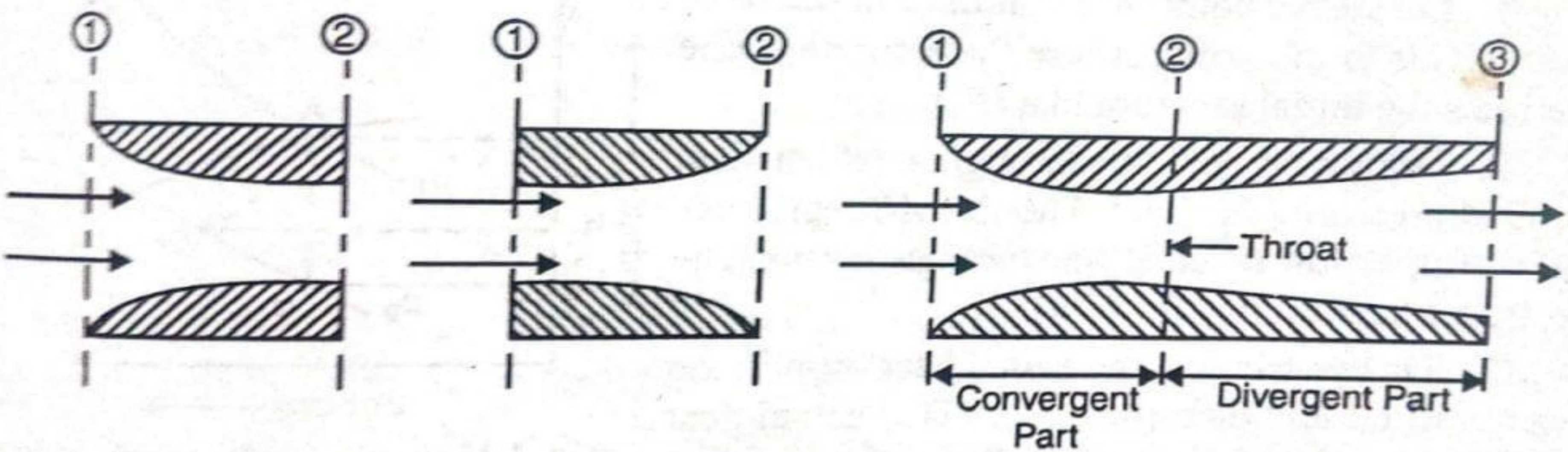
- Nozzle is a duct by flowing through which the velocity of a fluid increases at the expense of pressure drop. if the fluid is steam, then the nozzle is called as **Steam Nozzle.**
- The flow of steam through nozzles may be taken as adiabatic expansion.
- The steam possesses a very high velocity at the end of the expansion, and the enthalpy decreases as expansion occurs.
- The major function of nozzle is to produce steam jet with high velocity to drive a turbine.

# Introduction

- Friction exists between the steam and the sides of the nozzle; heat is produced as the result of the resistance to the flow.
- If a duct decreases the velocity of fluid and causes corresponding increase in pressure then it is called **Diffuser.**
- **Applications:**
- Produce high velocity jet of steam.
- Used in injector of boiler for pumping feed water.
- Cleaning of wide range of surface, for moisturization in the production of paper.

# Types of Nozzles

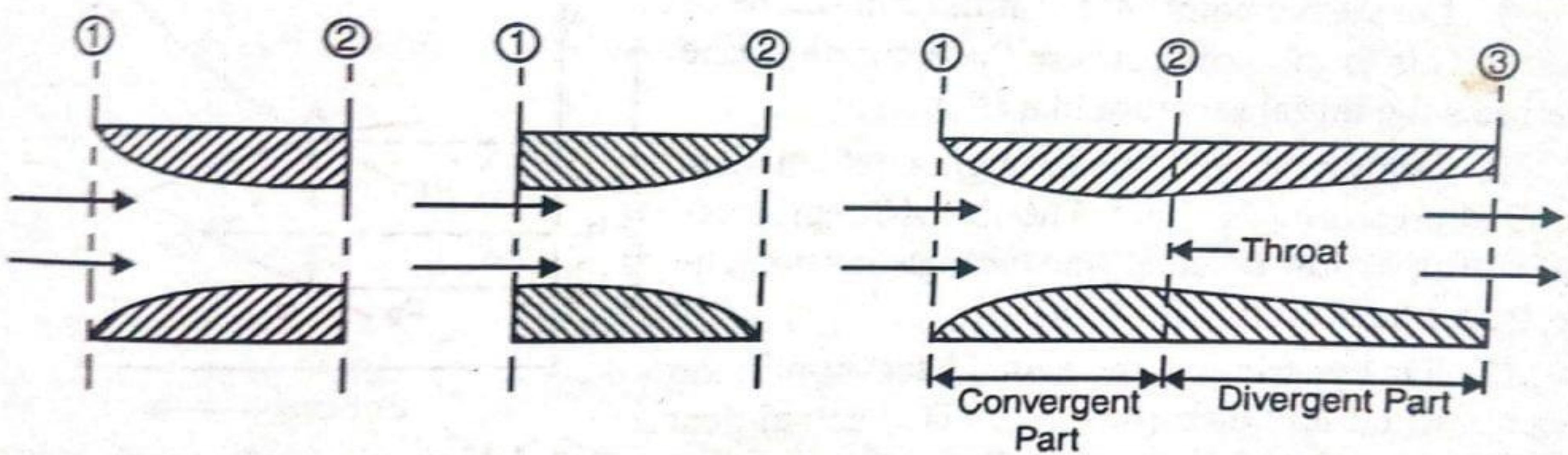
- **There are three types of nozzles:**
- 1. Convergent nozzle
- 2. Divergent nozzle
- 3. Convergent- divergent nozzle




(a) Convergent Nozzle (b) Divergent Nozzle (c) Convergent-Divergent Nozzle

# Types of Nozzles

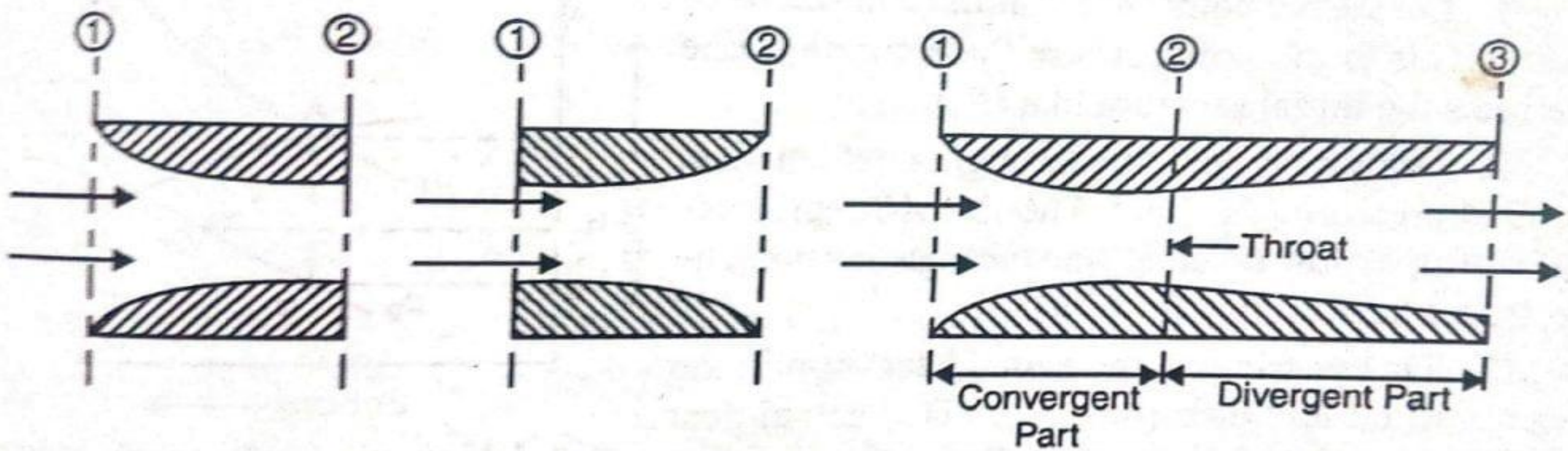
- **1. Convergent Nozzle:**
- C/S area reduces from inlet to outlet section.
- This type of nozzle is used when pressure ratio is up to 0.58 with saturated steam.
- This value is called critical pressure ratio.




(a) Convergent Nozzle (b) Divergent Nozzle (c) Convergent-Divergent Nozzle

# Types of Nozzles

- **2. Divergent Nozzle:**
- The cross sectional area of divergent nozzle increases continuously from its entrance to exit.
- It is used in a case where the back pressure is less than the critical pressure ratio.




(a) Convergent Nozzle (b) Divergent Nozzle (c) Convergent-Divergent Nozzle

# Velocity or Flow of Steam Through Nozzles

## Velocity or Flow of Steam Through Nozzle

- Consider an expansion of steam in a nozzle under steady state condition between the inlet section (1-1) to outlet section (2-2). Refer Fig. 5.3.1.

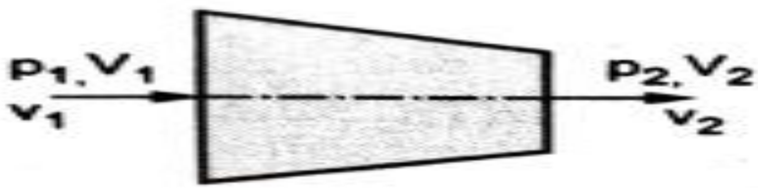



**Fig. 5.3.1 : Flow through a nozzle**

- Consider a unit mass of steam flows through a nozzle as shown in Fig. 5.3.1.
- Let,

$p_1$ and $p_2$ = Inlet and outlet pressure of steam through a nozzle.

$V_1$ and $V_2$ = Inlet and outlet velocity of steam through a nozzle.

$v_1$ and $v_2$ = Inlet and outlet specific volume of steam through a nozzle.

- The steady flow energy equation for a unit mass of steam is given as,

$$\left[h_1 + Z_1 g + \frac{V_1^2}{2}\right] + Q = \left[h_2 + Z_2 g + \frac{V_2^2}{2}\right] + W \quad \text{... (i)}$$

- But, in case of nozzles, workdone W = 0, heat transfer Q = 0 and change in potential energy $(Z_1 g - Z_2 g)$ is also negligible. Therefore, the above equation (i) becomes,

$$h_1 + \frac{V_1^2}{2} = h_2 + \frac{V_2^2}{2}$$

$$\frac{V_2^2}{2} = (h_1 - h_2) + \frac{V_1^2}{2}$$

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

$$V_2 = \sqrt{2(h_1 - h_2) + V_1^2}$$

- In the above equation (ii), if the inlet velocity of steam to the nozzle is negligible then $V_1 = 0$.

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

In the above equation enthalpy is in kJ/kg. Converting this enthalpy in J/kg,

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

$$\therefore \quad V_2 = 44.72\sqrt{(h_1 - h_2)}$$

Now, in the above equation (5.3.2), **enthalpy is in kJ/kg.**

- The steam flowing through the nozzle follows approximately the following equation :

During the process the work done/kg of steam is,

$$= \frac{n}{n-1}(p_1 v_1 - p_2 v_2)$$

But, the gain in kinetic energy must be equal to the work done during the cycle i.e.

Gain in K.E. = Work done during the process

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

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

We know that, $p_1 v_1^n = p_2 v_2^n \quad \therefore \frac{v_2}{v_1} = \left(\frac{p_1}{p_2}\right)^{\frac{1}{n}}$

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

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

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

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

where, n = Expansion index (1.13 to 1.3)

# Discharge/Mass Flow Rate/Condition for Max. Discharge Through Nozzles

- It is already discussed that, the nozzles are always designed for maximum discharge. The mass flow rate of steam through the nozzle is given by,

$$\dot{m} = \rho AV = \frac{AV}{v}, \text{ kg/sec} \quad \ldots \left(\because \rho = \frac{1}{v}\right)$$

where, A = Cross-section area of nozzle at throat

or

$$\dot{m} = \frac{AV}{v_2}$$

But,

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

$$\therefore \quad \dot{m} = \frac{A \times \sqrt{2\left(\frac{n}{n-1}\right) p_1 v_1 \left(1 - \left(\frac{p_2}{p_1}\right)^{1-\frac{1}{n}}\right)}}{v_1 \left(\frac{p_1}{p_2}\right)^{\frac{1}{n}}} \quad \ldots (5.4.1)$$

- From the above equation (5.4.1) it is clear that the flow rate or discharge through the nozzle is the function of $(p_2/p_1)$. Therefore, for maximum discharge through the nozzle, differentiate the above equation with respect to $(p_2/p_1)$ and equate to zero.

$$\frac{d(\dot{m})}{d(p_2/p_1)} = 0$$

After simplification we get,

$$\frac{p_2}{p_1} = \left(\frac{2}{n+1}\right)^{\frac{n}{n-1}} \quad \ldots (5.4.2)$$

Substituting this value of ratio of throat pressure ($p_2$) to inlet pressure ($p_1$) in equation (5.4.1) we will get the maximum value of mass flow rate through the nozzle i.e.,

$$\dot{m}_{max} = A\sqrt{n\left(\frac{p_1}{v_1}\right)\left(\frac{2}{n+1}\right)^{\frac{n+1}{n-1}}} \quad \ldots (5.4.3)$$

- From the above equation (5.4.3) it is clear that, the maximum mass flow rate depends on the initial conditions of the steam ($p_1, v_1$) and throat area (A).
- It is independent of the final pressure of steam (at the exit of nozzle). It means the addition of divergent part of nozzle after the throat does not affect the mass flow rate of steam.
- If we substitute equation (5.4.2) [Value of $p_2/p_1$] in equation (5.3.3) [value of V] then

$$V_{max} = \sqrt{2\left(\frac{n}{n+1}\right) p_1 v_1} \quad \text{... (5.4.4)}$$

- It means, the velocity of steam through the nozzle is also dependent on the initial conditions of the steam ($p_1 v_1$).

# Critical Pressure Ratio

## 5.4.1 Critical Pressure Ratio

- There is only one value of the ratio $\frac{p_2}{p_1}$ which produces maximum discharge from the nozzle.
- The ratio of $\frac{p_2}{p_1}$ is known as critical pressure ratio.
- The pressure $p_2$ at the throat is known as critical pressure.
- In other words critical pressure can be defined as the back pressure for the maximum mass flow rate through nozzle.

# Physical Significance of Critical Pressure

## 5.4.2 Physical Significance of Critical Pressure

- Consider two vessel's A and B connected with the help of convergent nozzle.
- Both the vessel A and B contains steam.
- But the pressure of steam in vessel A is high and steady which is considered as $p_1$.
- Pressure of steam in vessel B is '$p_2$' but it is not steady.
- The pressure of steam $p_2$ which is at vessel B is made equal to the pressure $p_1$.
- In this case there will be no flow of steam through the nozzle.
- But as shown in the graph, if we reduce the pressure ($p_2$) in vessel 'B', the discharge through the nozzle will get increased.
- When the pressure approaches to critical value then discharge through nozzle will also be a maximum.
- If the pressure ($p_2$) is again reduced then there will be no change in discharge, it will remains constant.
- We know velocity of steam at any section in nozzle.

$$V_2 = \sqrt{\frac{2n}{n-1} \times p_1 V_1 \left[1 - \left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}}\right]}$$

- Critical pressure ration for maximum discharge,

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

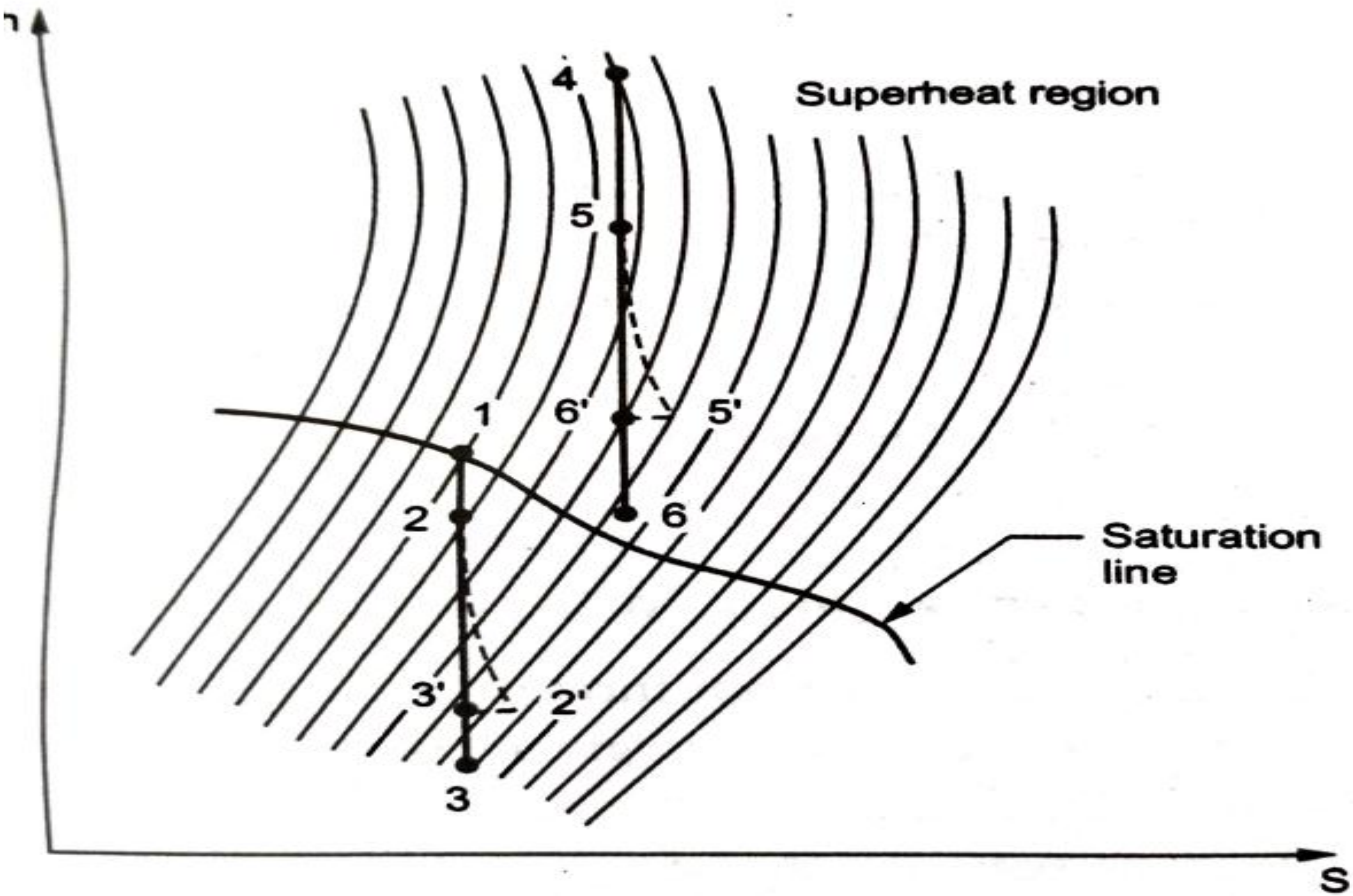
- The value of velocity of sound in medium at pressure $p_2$ is known as sonic velocity.

# Physical Significance of Critical Pressure

$$V_2 = \sqrt{2\left(\frac{n}{n+1}\right)\frac{p_2}{\rho_2}\left(\frac{n+1}{n}\right)}$$

- The critical pressure gives the velocity at throat which is equal to velocity of sound.
- The flow is subsonic from the convergent portion of nozzle.
- The flow is supersonic from divergent portion of nozzle.

# Nozzle Efficiency



# Nozzle Efficiency

- Point 1 represents the initial condition of steam i.e. dry saturated steam.
- If friction is negligible, then the expansion of steam from entry to throat is represented by vertical line 1 to 2 and from throat to exit by 2 to 3.
- If friction is considered then the heat drop takes place from 1 to 3' instead of 1 to 3.
- Now from point 3' draw horizontal line which cuts the same pressure line on which point 3 lies.
- It represents point 2', i.e. final condition of steam.
- That means dryness fraction at point 2' is greater than point 3'.

# Nozzle Efficiency

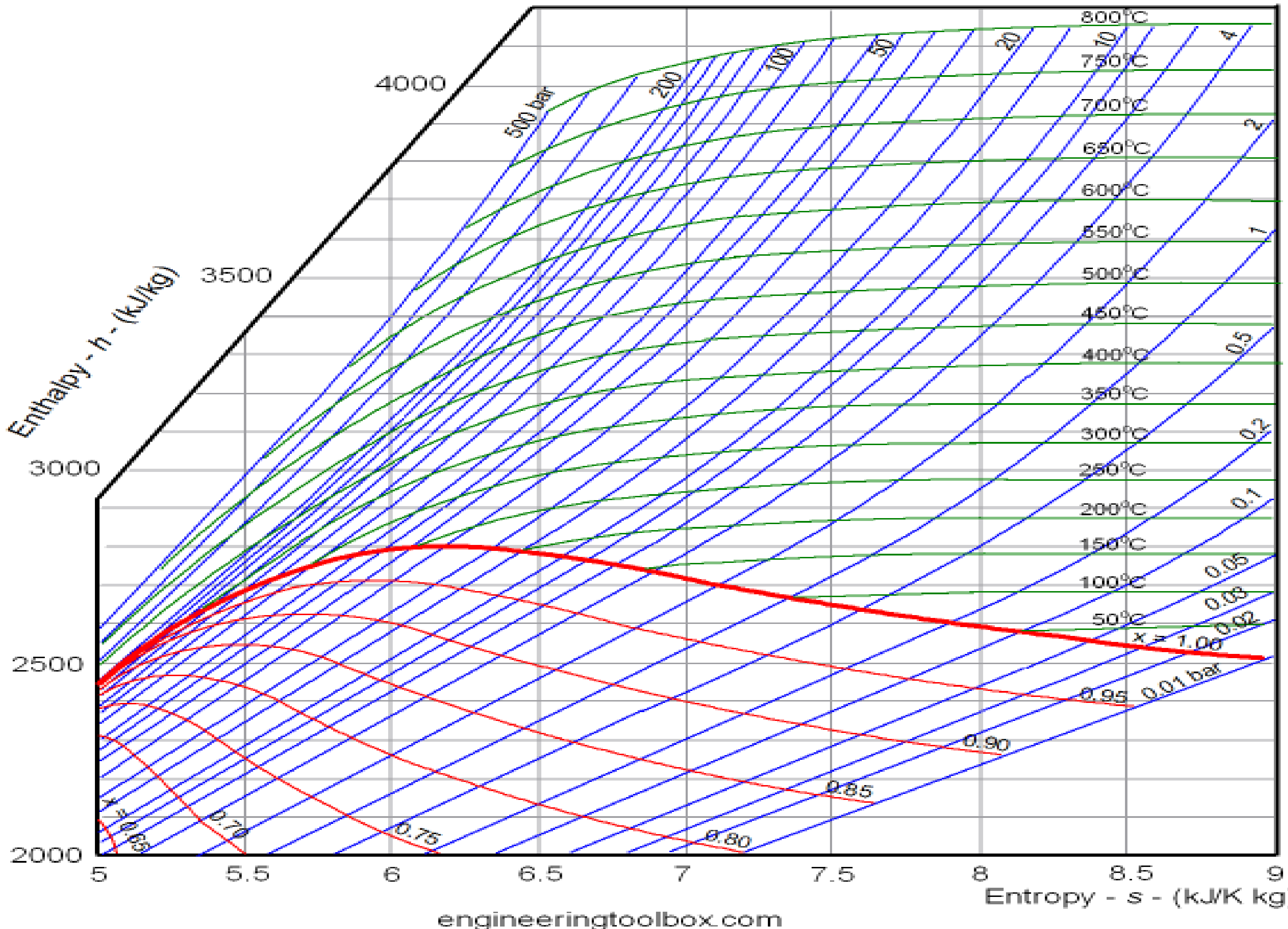
- Nozzle efficiency can be defined as ratio of actual enthalpy drop to isentropic enthalpy drop between same pressure.

$$\text{Nozzle efficiency} = \frac{h_1 - h_3'}{h_1 - h_3} \text{ or } \frac{h_4 - h_6'}{h_4 - h_6}$$

- The range of nozzle efficiency is 0.9 to 0.99.
- The nozzle efficiency can also be defined as the ratio of energy converted to kinetic energy and total potential energy which could be converted into kinetic energy.
- The total energy that can be converted is during isentropic process is,

$$E = h_o - h_{exit}$$

# Mollier's Chart



# Mollier's Chart