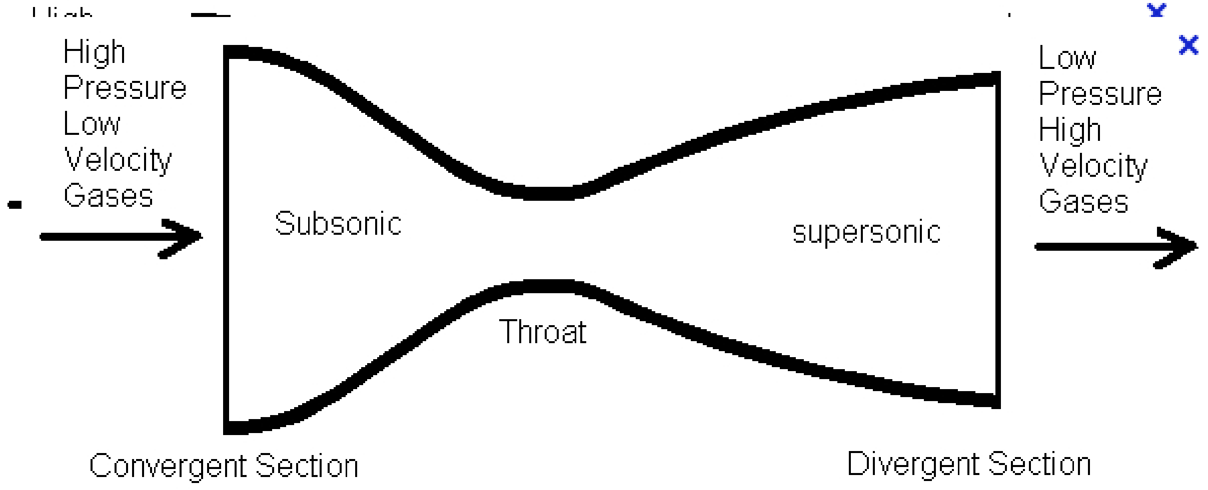
MODULE -4 STEAM NOZZLE

- ❖ One-dimensional steady flow of steam through a convergent and divergent nozzle
- ❖ Metastable flow.

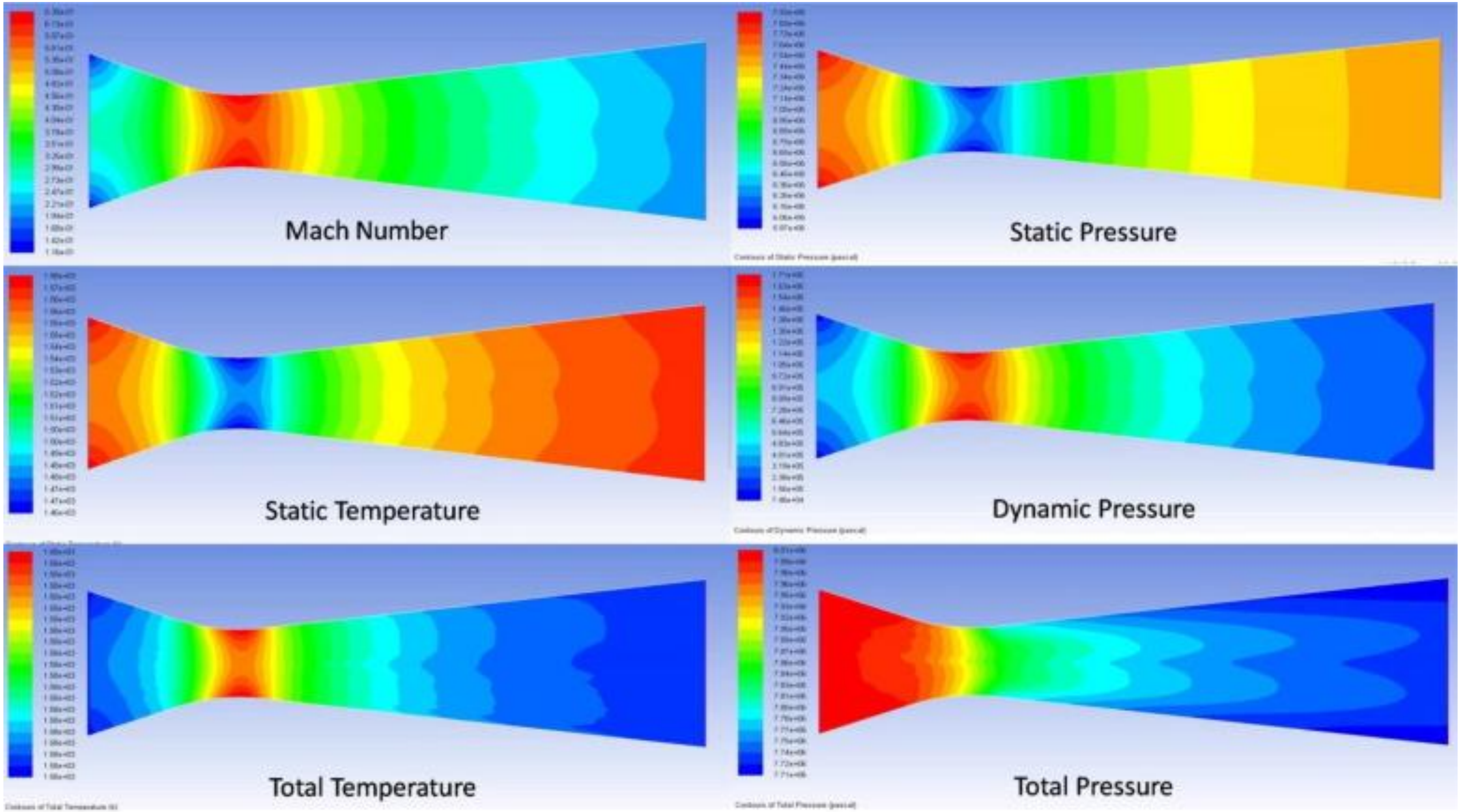
Introduction

- Steam nozzle is a device of **varied cross – sectional area** in which the heat **energy of the steam** is converted into **kinetic energy**.
- Mass flow rate is remains constant
- Types of Nozzle (a) Convergent (b) Divergent (C) Convergent-Divergent Nozzle
- Applications of Nozzle:

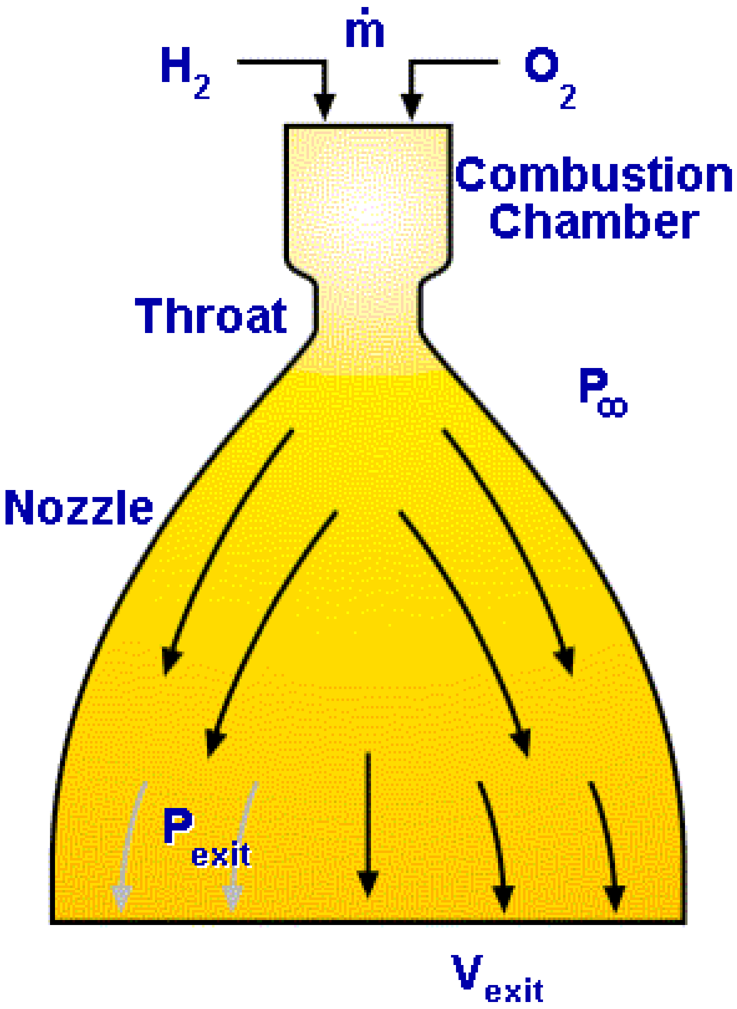
(i) Steam turbines
(ii) Gas turbines
(iii) Jet engines
(iv) Flow measuring devices
(v) Fuel injection
(vi) Spray paintings, etc.

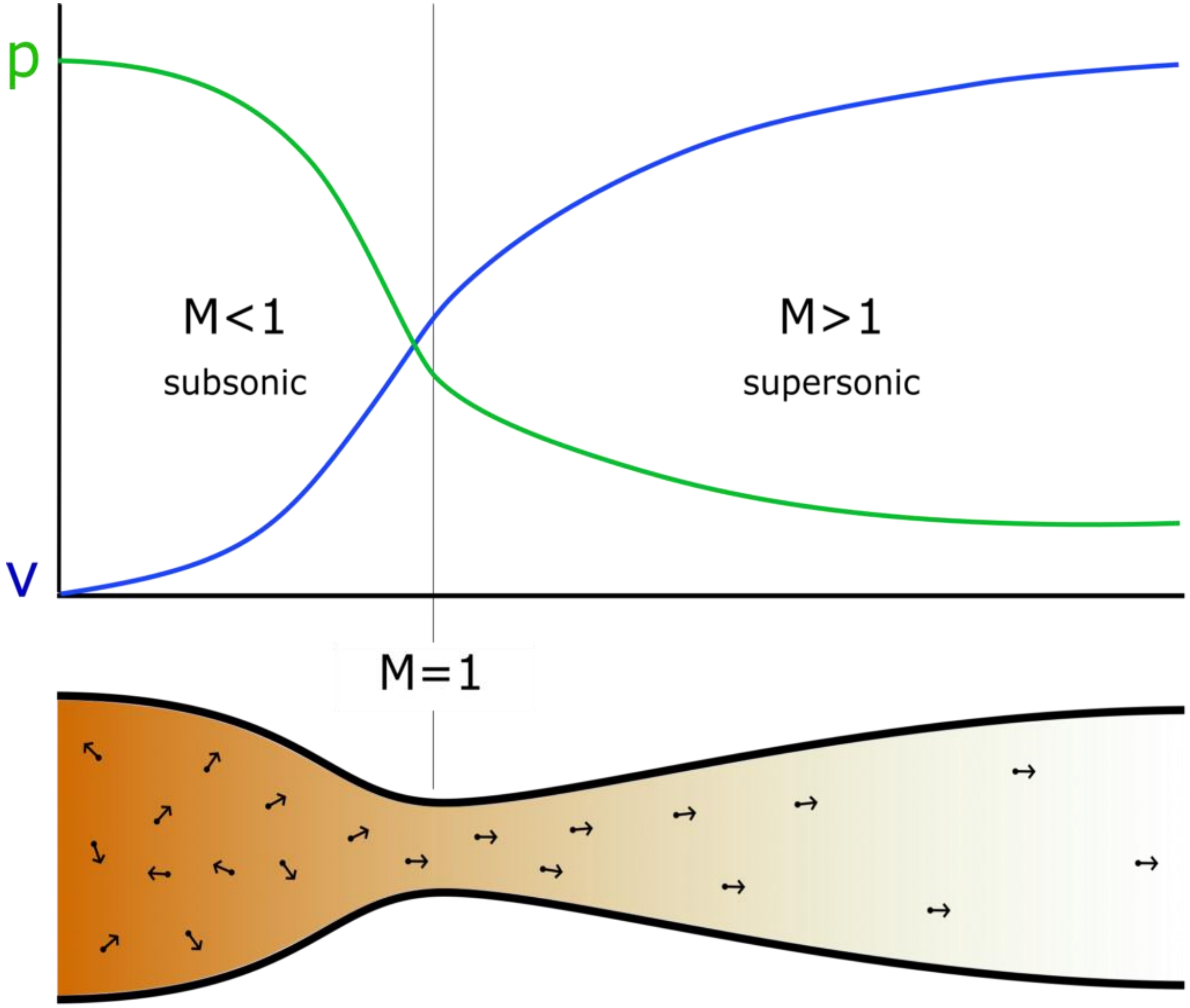


STEAM NOZZLE-CFD results

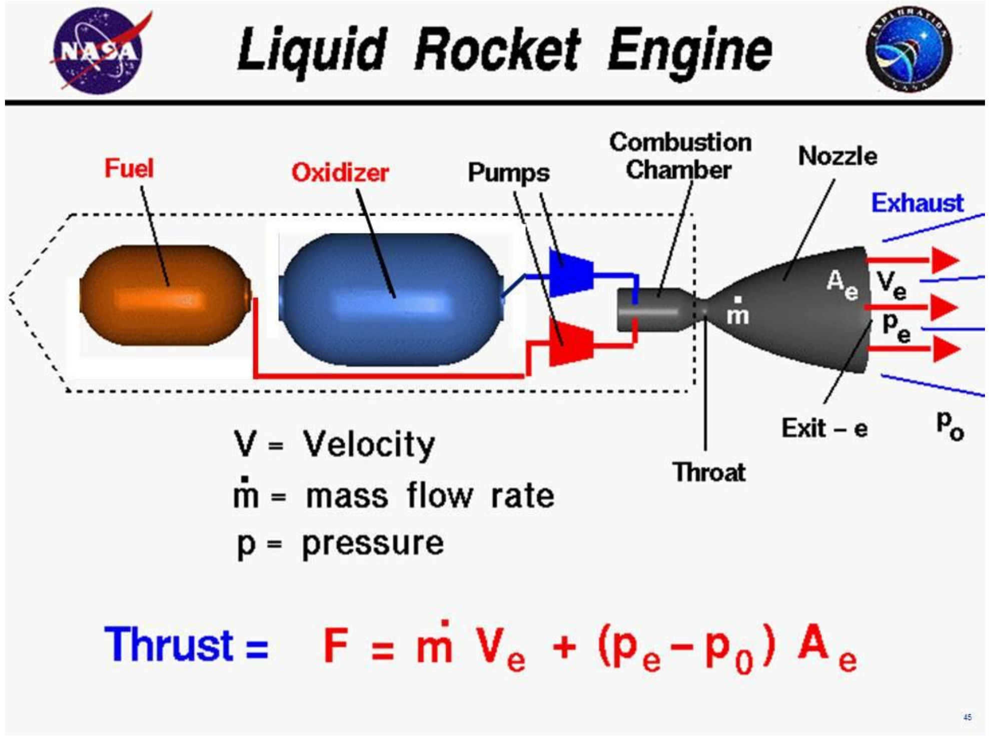


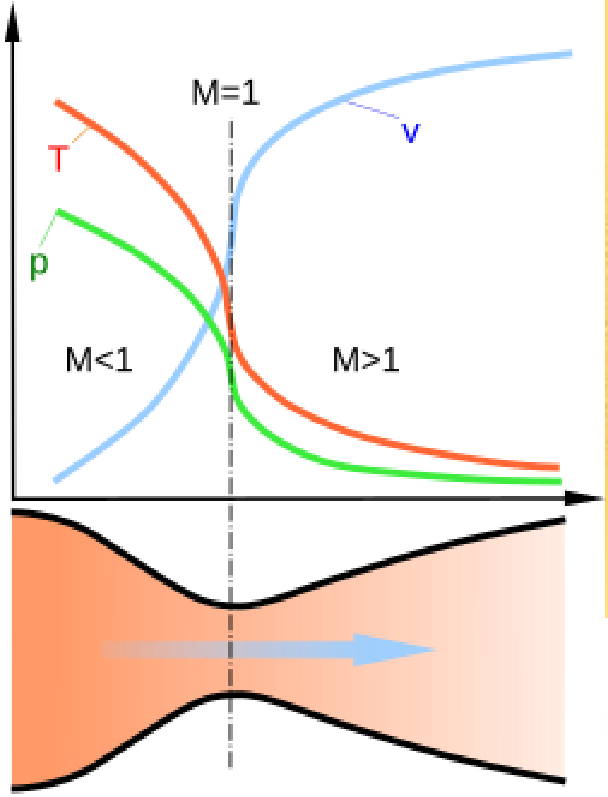
ROCKET NOZZLE-Pressure velocity variation

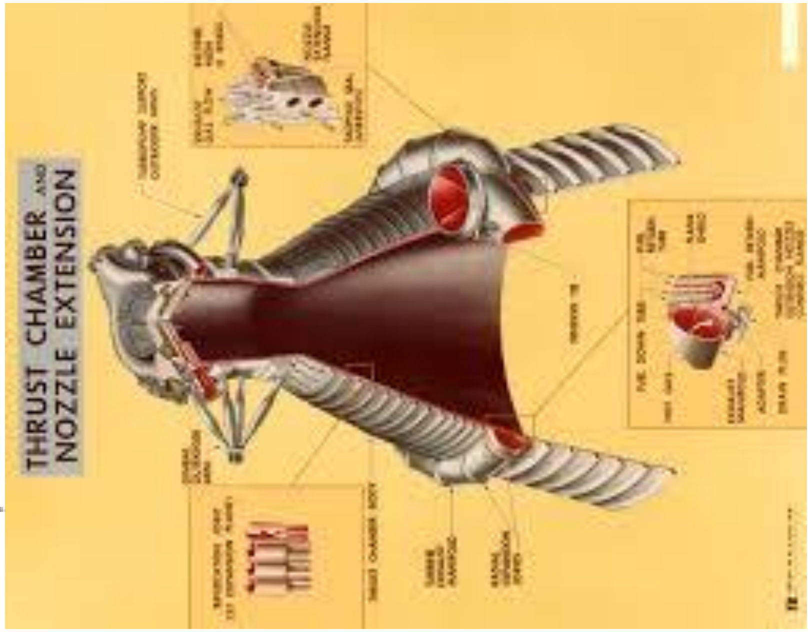


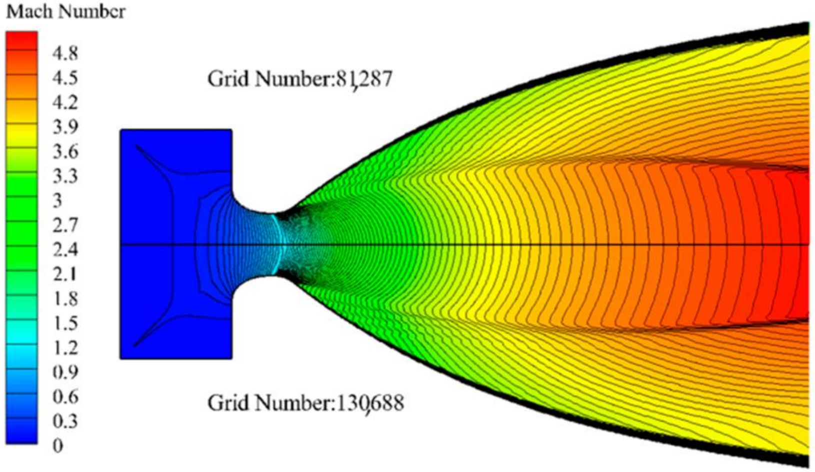


ROCKET NOZZLE









Steam Flow Through Nozzle

$$Applying\ steady-\ flow\ energy\ equation$$

$$h_1 + \frac{c_1^2}{2} + z_1 + q = h_2 + \frac{c_2^2}{2} + +z_2 + w$$

$$q = 0\,(No\ heat\ transfer)$$

$$w = 0\,(No\ work\ int\ eraction)$$

$$\Delta p = 0$$

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

$$h_1 = h_2 + \frac{c_2^2}{2} \quad (\because c_1 << c_2)$$

$$c_2 = \sqrt{2 \times (h_1 - h_2) \times 1000}$$

$$c_2 = 44.72\sqrt{(h_1 - h_2)} \qquad h \rightarrow kJ\,/\,kg$$

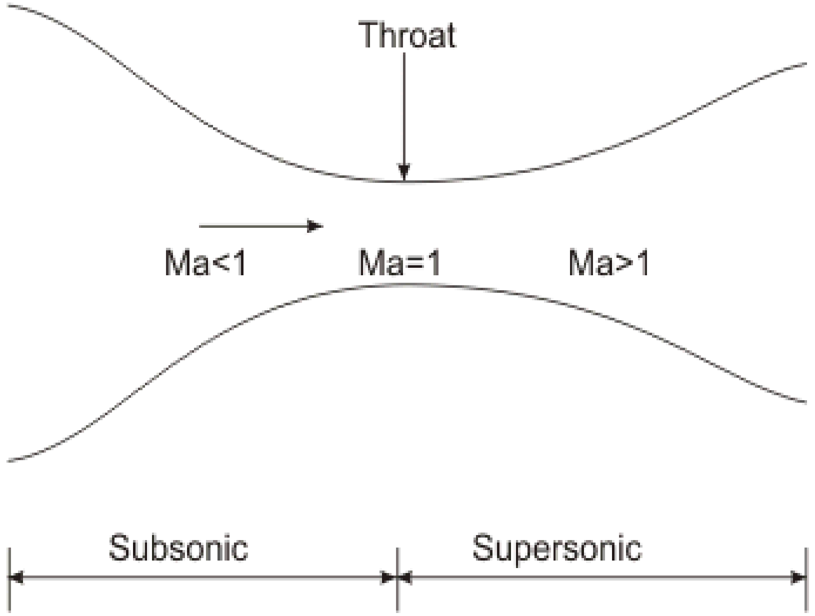


Fig 19.2 A convergent-divergent nozzle

$$Note:$$

$$(i)\ if\ 'c_1'\ is\ given$$

$$c_2 = \sqrt{c_1^2 + 2000\,(h_1 - h_2)}$$

Mass Flow Rate of Steam Through Nozzle

$$m = \rho_2 A_2 c_2 = \frac{A_2 c_2}{v_2}$$

$$where, c_2 = \sqrt{2 \times (h_1 - h_2)} \quad and\ h_1 - h_2 = \frac{n}{n-1}(p_1 v_1 - p_2 v_2)$$

$$m = \frac{A_2 \sqrt{2 \times \frac{n}{n-1}(p_1 v_1 - p_2 v_2)}}{v_1 \times \left(\frac{p_2}{p_1}\right)^{\frac{-1}{n}}} \qquad \because \frac{v_2}{v_1} = \left(\frac{p_1}{p_2}\right)^{\frac{1}{n}}$$

Taking $p_1 v_1$ *outside and simplyfy,*

$$m = A_2 \sqrt{2 \times \frac{n}{n-1} \frac{p_1}{v_1} \left[\left(\frac{p_2}{p_1}\right)^{\frac{2}{n}} - \left(\frac{p_2}{p_1}\right)^{\frac{n+1}{n}} \right]}$$

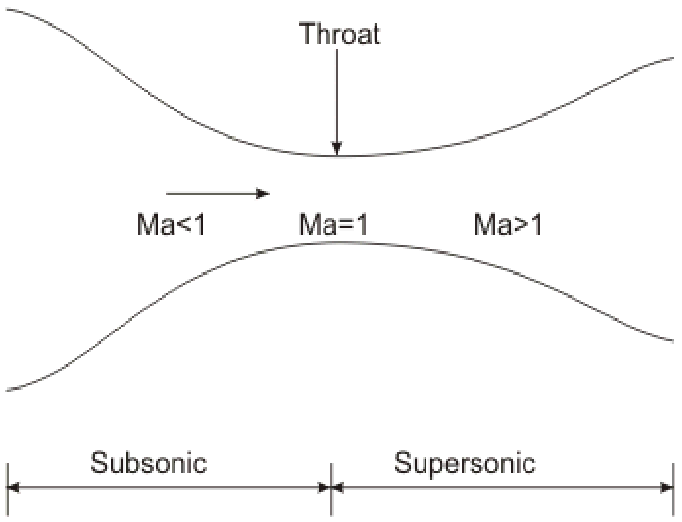


Fig 19.2 A convergent-divergent nozzle

Maximum Mass Flow Rate of Steam

$$m = A_2\sqrt{2\frac{n}{n-1}\frac{p_1}{v_1}\left[\left(\frac{p_2}{p_1}\right)^{\frac{2}{n}} - \left(\frac{p_2}{p_1}\right)^{\frac{n+1}{n}}\right]}$$

Condition for maximum discharge, $\dfrac{d(m)}{d\left(\dfrac{p_2}{p_1}\right)} = 0$

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

$$m_{\max} = A_2\sqrt{n\frac{p_1}{v_1}\left(\frac{2}{n+1}\right)^{\frac{n+1}{n-1}}}$$

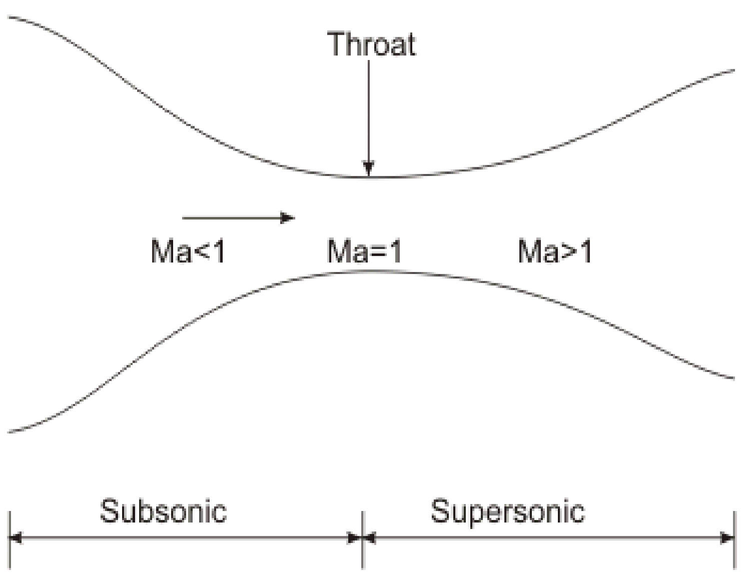


Fig 19.2 A convergent-divergent nozzle

Note:

- The maximum mass flow rate is depends only on the initial condition of steam ($p_1 v_1$) and the throat area. It is independent of final pressure of steam (i.e.) at the exit of the nozzle.
- The addition of divergent part of nozzle after the throat does not affect the discharge of steam passing through the nozzle but it only accelerates the steam leaving the nozzle.

Maximum Mass Flow Rate of Steam

$$c_{max} = \sqrt{2\left(\frac{n}{n+1}\right)p_1 v_1}$$

Index (n) value and pressure ratio for different condition of steam

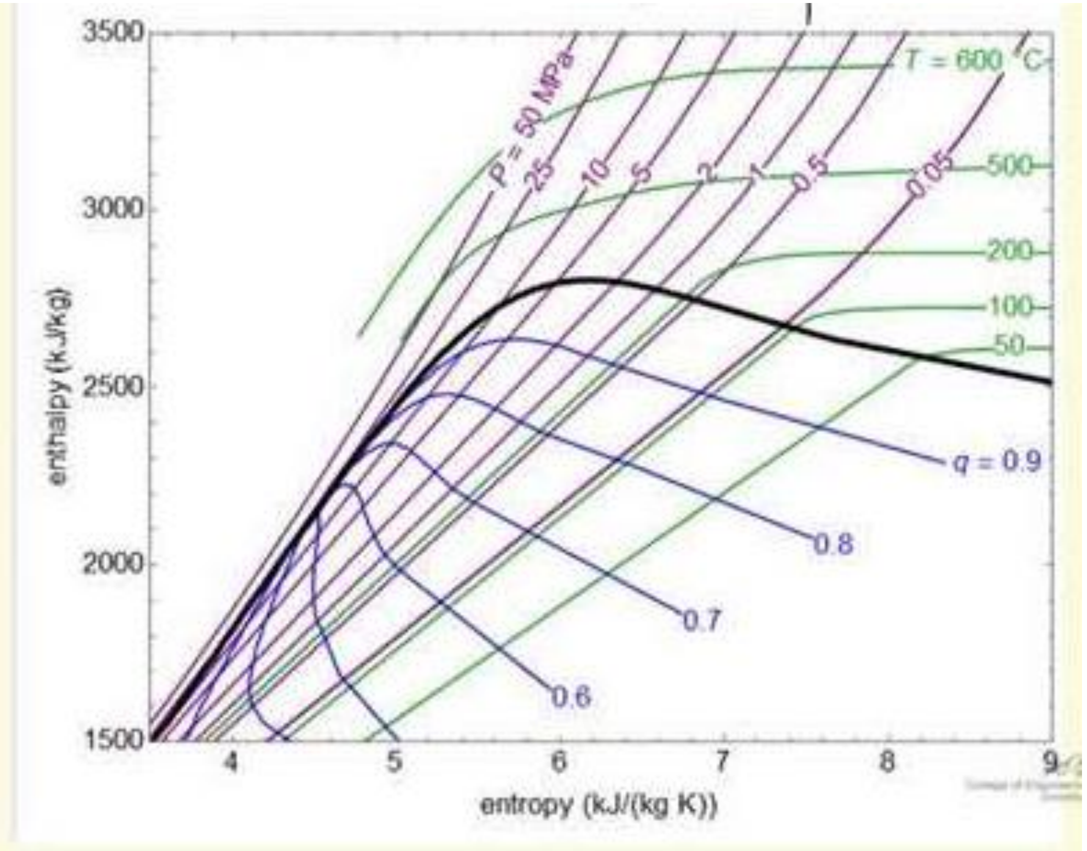
(i) Wet steam: $n = 1.035 + 0.1x; \frac{p_2}{p_1} = 0.582$

where, x = Initial dryness fraction

(ii) Dry saturated steam: $n = 1.135; \frac{p_2}{p_1} = 0.573$

(iii) Superheated steam: $n = 1.3; \frac{p_2}{p_1} = 0.546$

(iv) Air: $n = 1.4; \frac{p_2}{p_1} = 0.528$



Effect of Friction In Nozzle

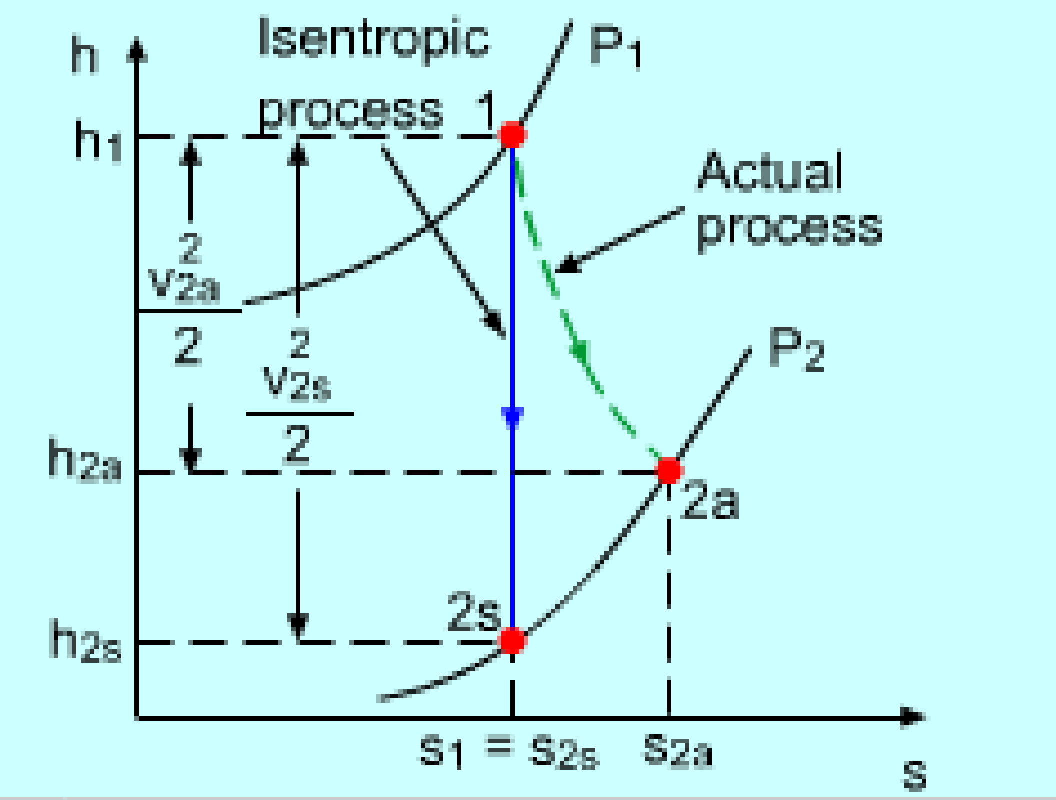
$$\eta_N = \frac{Actual\ heat\ drop}{Isentropic\ heat\ drop} = \frac{h_1 - h_{2a}}{h_1 - h_{2s}}$$

(i) Reduces the exit velocity

(ii) Reduces the efficiency of nozzle by reducing the available enthalpy drop

(iii) It improves the quality of the steam

(iv) Specific volume of steam increases



Note:

(i) Convergent part no friction loss

(ii) Frictional loss at divergent part of nozzle

$$c_2 = 44.72\sqrt{(h_1 - h_{2a})}$$

$$c_2 = 44.72\sqrt{\eta_N (h_1 - h_{2s})} \qquad h \rightarrow kJ/kg$$

Numerical on Steam Nozzle

1. Steam expands isentropically from the state of 8 bar and 250°C to 1.5 bar in a convergent nozzle. The steam flow rate is 0.75 kg/s. Find (a) Velocity of the steam at exit (b) Exit area of nozzle.

Given data :

Expansion of steam through nozzle

$P_1 = 8\,bar$

$T_1 = 250^\circ C = 523K$

$P_2 = 1.5 bar$

$m = 0.75\,kg/s$

To Find :

$(a)\, c_2 = 44.72\sqrt{(h_1 - h_2)}\,(m/s)$

$(b)\, A_2 = \dfrac{m \times v_2}{c_2}\,(m^2)$

Numerical on Steam Nozzle

Solution:

From Mollier chart, the properties of Steam

$State\,1: Steam\ at\ p_1 = 8\,bar\ and\ 250°C$

$$h_1 = 2940\,kJ/kg$$

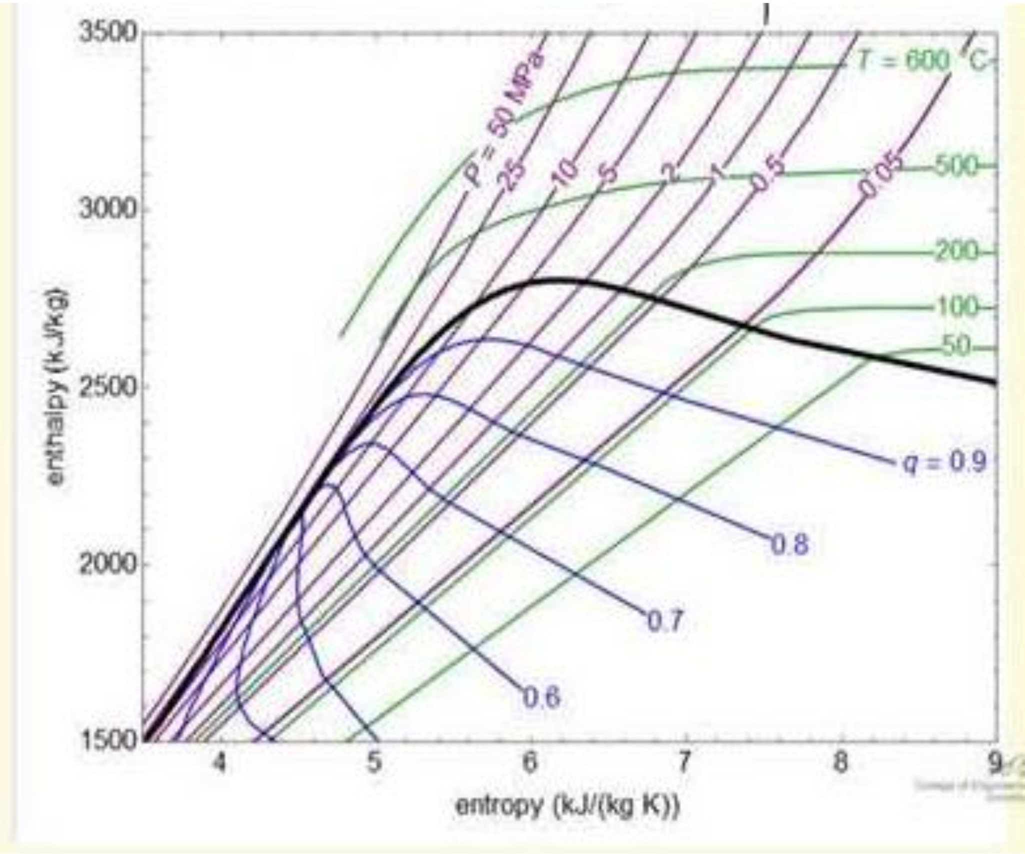
$State\,2: Steam\ at\ p_2 = 1.5\,bar$

$$h_2 = 2620\,kJ/kg$$

$$(a)\ c_2 = 44.72\sqrt{(h_1 - h_2)} = 800\ m/s$$

$$(b)\ A_2 = \frac{m \times v_2}{c_2} = \frac{0.75 \times 1.2}{812} = 1.108 \times 10^{-3} (m^2)$$

$from\ Mollier\ chart, v_g = v_2 = 1.2\,m^3/kg$



Numerical on Steam Nozzle

2. A nozzle is to be designed to expand the steam at the rate of 0.10 kg/s from 500 kPa, 210°C to 100 kPa. Neglect inlet velocity of steam. For a nozzle efficiency of 0.9. Determine the exit area of the nozzle.

Given data:

Expansion of steam through nozzle

$$m = 0.1 kg/s$$

$$P_1 = 500 kPa$$

$$T_1 = 210^{\circ}C = 483K$$

$$P_2 = 100 kPa$$

$$c_1 = 0$$

$$\eta_N = 0.9$$

To Find:

Exit area of the nozzle (A_2)

$$Exit\ Area\ (A_2) = \frac{m \times v_2}{c_2}$$

$$\eta_N = \frac{\Delta h_{act}}{\Delta h_{isen}} = \frac{h_1 - h_{2'}}{h_1 - h_{2s}}$$

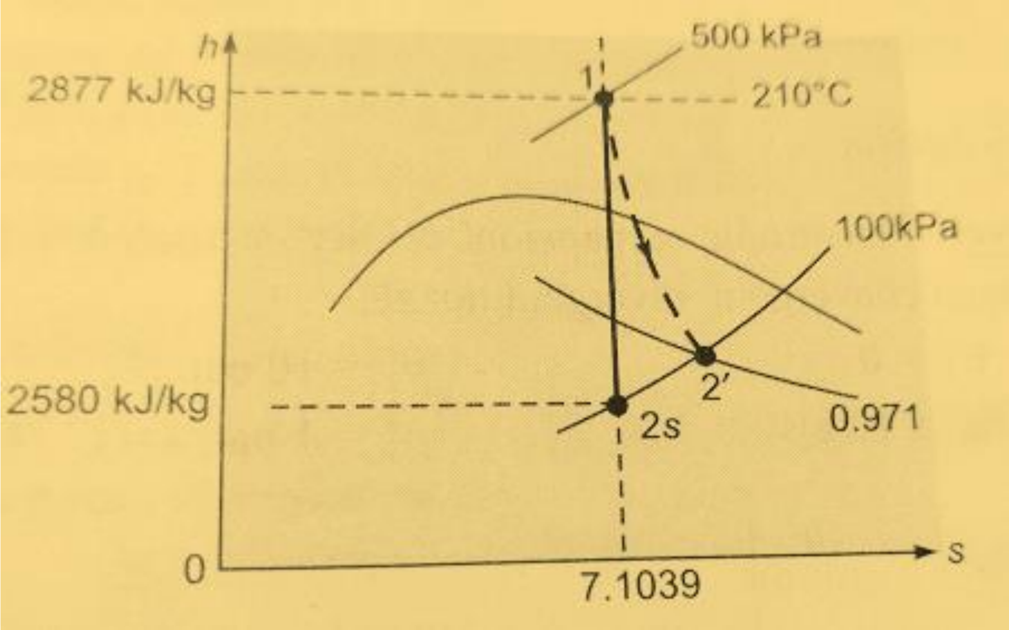
Numerical on Steam Nozzle

Solution :

From Mollier chart, the properties of Steam

$State\,1: Superheated\ steam\ at\ p_1 = 500\,kPa\ and\ 210°C$

$h_1 = 2877\,kJ/kg\ and\ s_1 = 7.1039\,kJ/kg-K$



$State\,2: Wet\ steam\ at\ p_2 = 100\,kPa$

$h_{2s} = 2580\,kJ/kg\ and\ s_1 = 7.1039\,kJ/kg-K$

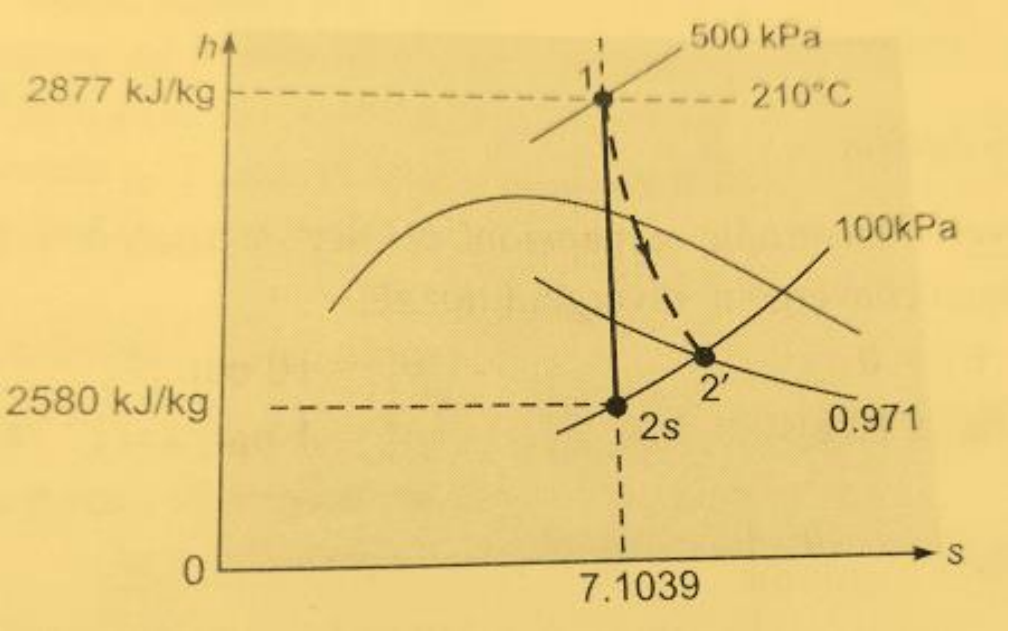
Numerical on Steam Nozzle

$$\Delta h_{isen} = h_1 - h_{2s} = 297\, kJ/kg$$

$$\Delta h_{act} = \eta_N \Delta h_{isen} = 267.3\, kJ/kg$$

Actual enthalpy at state 2

$$h_{2'} = h_1 - \Delta h_{act} = 2609.7\, kJ/kg$$



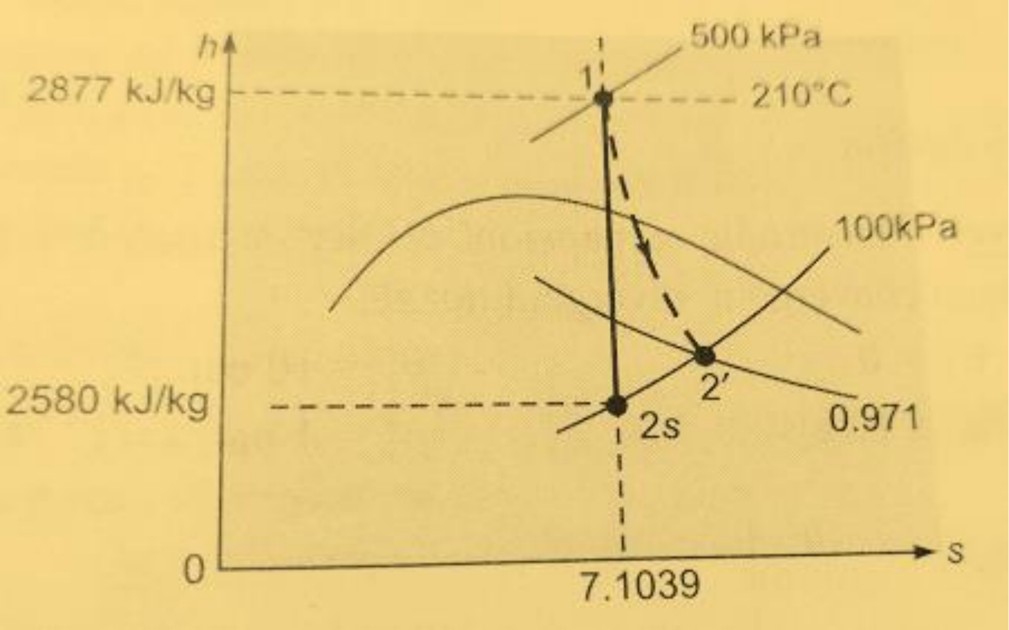
Numerical on Steam Nozzle

$$(i)\,Exit\ Area\,(A_2) = \frac{m \times v_2}{c_2}$$

On Mollier chart locate the intersection of p_2 & h_2

At this point, we get

$$v_2 = 1.5\,m^3/kg \quad and \quad x_2 = 0.97$$



$$c_2 = 44.72\sqrt{\Delta h_{act}} = 44.72\sqrt{\eta_N \Delta h_{isen}} = 731.14\,m/s$$

$$\therefore A_2 = \frac{m \times v_2}{c_2} = \frac{0.10 \times 1.645}{731.14} = 0.225 \times 10^{-3}\,m^2$$

Numerical on Steam Nozzle

3. Dry saturated steam enters into nozzle at 12 bar and exits at 1.5 bar. If the dryness fraction of exit steam is 0.95. Find (i) Exit velocity of steam (ii) Exit velocity of steam if 12% frictional loss (iii) percentage reduction in exit velocity (iv) Exit velocity if initial velocity is 135 m/s.

Given data:

Expansion of steam through nozzle

$P_1 = 12\, bar$

$P_2 = 1.5\, bar$

$c_1 = 135\, m/s$

$\eta_N = 88\%$

$x_2 = 0.95$

To Find:

$(i)\ c_{2-Isentropic}$

$(ii)\ c_{2-Actual}, if\ \eta_N = 88\%$

$$(iii)\ \%\, reduction = \frac{c_{2-Isen} - c_{2-Act}}{c_{2-Isen}} \times 100$$

$(iv)\ c_2, if\ c_1 = 135\, m/s$

Numerical on Steam Nozzle

Solution:

$$(i)\, c_{2-Isentropic} = 44.72\sqrt{(h_1 - h_2)}$$

From Steam Table

$$At\ p_1 = 12\, bar;$$

$$h_1 = h_g = 2782.7\, kJ/kg$$

$$At\ p_2 = 1.5\, bar;$$

$$h_2 = h_f + x\, h_{fg} = 467.1 + 0.95 \times 2226.3 = 2582\, kJ/kg$$

$$c_{2-Isentropic} = 44.72\sqrt{(h_1 - h_2)} = 633.41\, m/s$$

Numerical on Steam Nozzle

$$(ii)\, c_{2-Actual}, if\ \eta_N = 88\%$$

$$c_{2-Act} = 44.72\sqrt{\eta_N (h_1 - h_2)} = 594.187\, m/s$$

$$(iii)\, \%\, reduction = \frac{c_{2-Isen} - c_{2-Act}}{c_{2-Isen}} = \frac{633.41 - 594.19}{633.41} \times 100 = 6.19\%$$

$$(iv)\, c_2,\ if\ c_1 = 135\, m/s$$

$$c_{2-isen} = \sqrt{c_1^2 + 2000(h_1 - h_2)} = 647.65\, m/s$$

Numerical on Steam Nozzle

4. Dry saturated steam at a pressure of 11 bar is expanded in a C-D nozzle to 2 bar. Mass flow rate of steam through the nozzle is 15 kg/s. If the flow is isentropic, calculate

(i) Velocity at throat
(ii) Exit velocity of steam
(iii) Area of throat
(iv) Area of nozzle exit

$$To\ Find:$$

$$(i)\ c_2 = 44.72\sqrt{h_1 - h_2}\ (m/s)$$

$$(ii)\ c_3 = 44.72\sqrt{h_1 - h_3}\ (m/s)$$

$$(iii)\ A_2 = \frac{m \times v_2}{c_2}\ (m^2)$$

$$(iv)\ A_3 = \frac{m \times v_3}{c_3}\ (m^2)$$

$$Given\ data:$$

$$Expansion\ of\ steam\ through\ nozzle$$

$$P_1 = 11\,bar$$

$$P_3 = 2\,bar$$

$$m = 15\,kg/s$$

Numerical on Steam Nozzle

Solution:

From Mollier chart

$$At\,p_1 = 11\,bar \Rightarrow h_1 = 2785\,(kJ/kg)$$

$$\frac{p_2}{p_1} = \left(\frac{2}{n+1}\right)^{\frac{n}{n-1}} \Rightarrow p_2 = p_1 \times \left(\frac{2}{n+1}\right)^{\frac{n}{n-1}} = 6.35\,bar \quad (\because n = 1.135)$$

$$At\,p_2 = 6.35\,bar \Rightarrow h_2 = 2680\,(kJ/kg), and\; v_2 = 0.35\,m^3/kg$$

$$At\,p_3 = 2\,bar \Rightarrow h_2 = 2490\,(kJ/kg), and\; v_3 = 0.8\,m^3/kg$$

$$(i)\,c_2 = 44.72\sqrt{h_1 - h_2} = 458.2\,(m/s)$$

$$(ii)\,c_3 = 44.72\sqrt{h_1 - h_3} = 768.09\,(m/s)$$

Numerical on Steam Nozzle

$(iii)\, Throat\ Area\, (A_2):$

$$A_2 = \frac{m \times v_2}{c_2} = \frac{15 \times 0.35}{458.24} = 0.011457\,(m^2) = 114.57\,(cm^2)$$

$(iv)\, Exit\,Area\, (A_3):$

$$A_3 = \frac{m \times v_3}{c_3} = \frac{15 \times 0.8}{768.09} = 0.0156\,(m^2) = 156\,(cm^2)$$

Metastable flow

- Generally, when the superheated steam expands in the nozzle, the condensation will occur in the nozzle. Since the steam has more velocity, the condensation will be very slow.

- So, the equilibrium between the liquid and vapor phase is delayed and the steam continues to expand in a dry state. The Steam in such set of condition is said to be **supersaturated or metastable flow.**