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Experimental Study of Steam Flow in a Convergent-Divergent Nozzle

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Abstract: **In the present work an experimental investigation was carried out to study steam flow through a convergent – divergent nozzle. For the tests the geometry of rectangular cross section nozzle were used. The behavior of shock wave was investigated. Different inlet conditions were used at constant back pressure, in the divergent part of the nozzle the shock wave was induced caused instability in the flow.**

Keywords: **Experimental Investigation, Convergent-Divergent Nozzle.**

1. INTRODUCTION

Nozzles are widely used in many industrial applications to provide high speed flow. Flow in a convergent–divergent nozzle is a fundamental fluid phenomenon which affects a lot of applications. When a supersonic nozzle is operated at pressure ratios below its design point, a shock wave forms inside the nozzle and flow separation occur after the shockwave.

An accurate analysis of steam flow through the nozzles is no easy matter. Often it becomes necessary to use steam tables, an h-s diagram, or a computer program for the properties of steam .A further complication in the expansion of steam through nozzles occurs as the steam expands into the saturation region. As the steam expands in the nozzle, its pressure and temperature drop, and ordinarily one would expect the steam to start condensing when it strikes the saturation line.

Experimental results of steam condensing flow in C-D were presented by **Dykas, S., et. al. 2014 [1].** The effects of condensation and shockwave behavior effect in the wet steam region were analyzed. The study concluded the shock wave behavior in the wet steam region showed a coarse water formation in separation zone, in the place of shock wave interaction with solid wall. **Slawomir, D. [2013][2]** presented an experimental and numerical results of a steam condensing flow in the Laval nozzle. He also investigated the effect of homogeneous condensation and shock wave behavior in the wet steam region. Separation of water film on the nozzle walls and side walls may have occurred because of presence of coarse water droplets behind the shock wave. A shock wave study in a convergent-divergent nozzle by using numerical method employed in CFD code, FLUENT with experimental verification were introduced by **Padmanathan, p., et.al. [2012][3]**.The study concluded that there was an increase in static pressure, density and static temperature across the shock. **Hegazy, A. s., et. al. [4]** analyzed the condensation process steam flow through nozzle by using numerical method. The values of pressure ratio affected the location of the shock wave where increasing pressure ratio would move the shock wave further toward nozzle exit.

The main objective of the study is to predict the flow characteristic for superheated steam flowing through a convergent-divergent nozzle in off-design conditions and the propagation of the shock wave in the diverging section with the increase inlet pressure with constant back pressure.

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2. EXPERIMENTAL FACILITY

The experimental work was conducted at the steam labtroy in University of Technology. The test bench (Fig 1) was designed in order to perform the experiments for steam flows in a convergent-divergent nozzle. The superheated steam is provided from the super heater. The highest mass flow rate of the steam is about 0.27 kg/s. The steam first pass through a settling chamber In order to control the steam properties and remove any turbulence from the flow, which are supplied to the test section (Fig 2) and eliminate any excess water in the steam .properties ahead of the settling chamber and test section are controlled by means of the control valve. The total inlet pressure can vary in the range of 1.5 to 3 bar and the total temperature between (438 K- 478 K). The pressure behind the test section is kept constant at the ambient pressure.

The experiments were done for the geometry of a C-D (Fig 3). The applied nozzle length is 168 mm with width amounted to 60 mm. The static pressure measurement in the nozzles was carried out on a distance of 32 mm downstream the nozzle inlet along middle line of the nozzle width. The distance between the 17 pressure taps was 8 mm. These taps were connected through tubing to a U tube mercury manometer.

Fig.1: Test Bench

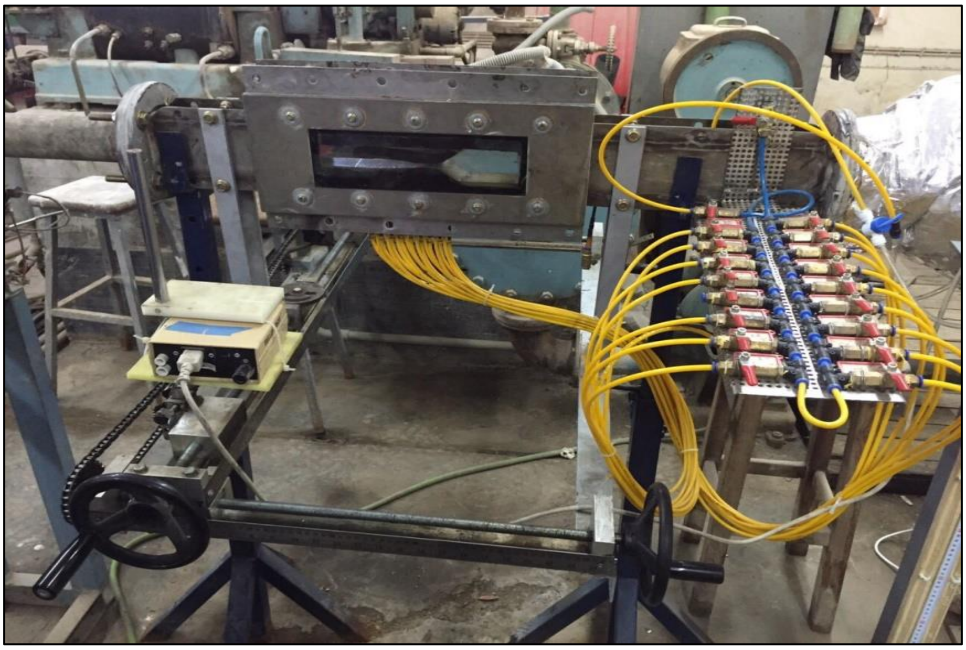

Fig.2: Test section

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Fig 3: Convergent-Divergent Nozzle Profile

3. EXPERIMENTAL PROCEDURE

The U-tube manometer was used to measure the pressure head difference (Δh), where

$$(\Delta P = \rho\ g\ \Delta h) \quad (1)$$

$$(P_s = \Delta P - P_O) \quad (2)$$

And Mach No. calculated from [4]:

$$M = \sqrt{\frac{2}{\gamma - 1}\left[\left(\frac{P_0}{P_s}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]} \quad (3)$$

Where $\gamma = 1.3$.

In case a shockwave is detected in the flow, which is denoted by a sudden and extreme pressure drop in the divergent section of the nozzle (after the throat), equation 3 can't be used to calculate the Mach No. downstream of the shock because the flow through the shockwave is irreversible.

To calculate the parameters in such case, the normal shockwave equations are used to calculate the change of flow characteristics across the shockwave, from which a new total pressure (reservoir pressure) is calculated and used as the new reference downstream from the shockwave location, as shown below:

$$\frac{P_{oy}}{P_{ox}} = \left[\frac{2\gamma M_x^2 - (\gamma - 1)}{\gamma + 1}\right]^{\frac{-1}{\gamma-1}} \left[\frac{(\gamma + 1)M_x^2}{2 + (\gamma - 1)M_x^2}\right]^{\frac{\gamma}{\gamma-1}} \quad (4)$$

$$M_y = \sqrt{\frac{2 + (\gamma - 1)M_x^2}{2\gamma M_x^2 - (\gamma - 1)}} \quad (5)$$

The stagnation temperature remains constant across the shock:

$$T_{oy} = T_{OX} \quad (6)$$

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4. RESULTS AND DISCUSSION

For nozzle at the inlet three different values of total pressure were used with different degree of super heat.

Figure 4 shows that the pressure behavior was similar to the "classic" shape of expansion in the convergent - divergent nozzle, as the reduction in cross-sectional area results increase in the flow velocity thus increase in the Mach number along the nozzle. As a result of this the curve of static pressure ratio falls down. It is obvious that Mach number reaches (1) at the throat area and continues to rise to reach supersonic speeds before it falls down sharply between X/L (0.05) and X/L (0.1). This sudden drop in Mach number with increase in pressure is an indication of a shockwave. From this point the flow continues to decelerate due to the increase of cross sectional area as after the shockwave the divergent part acts as a diffuser.

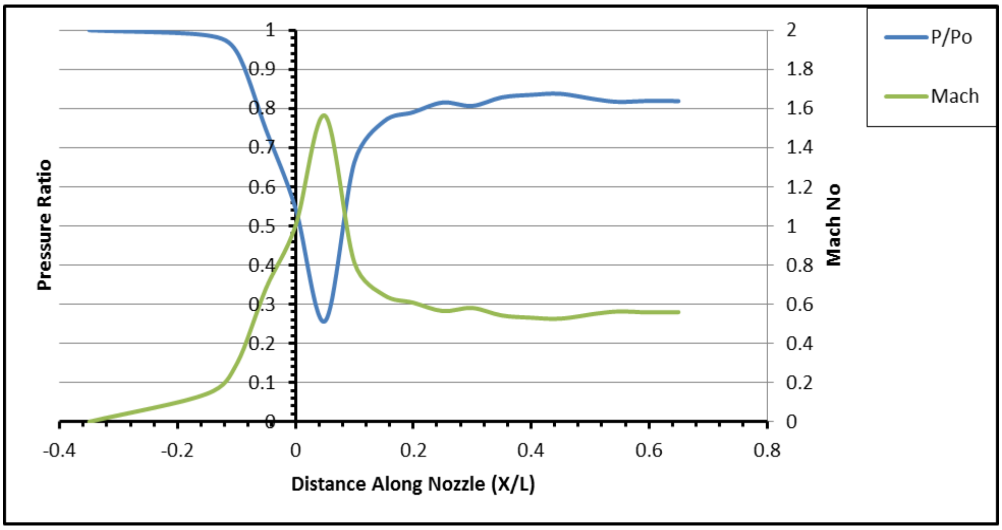

Fig 4: Pressure Ratio and Mach No. Distribution for PR=0.66

Figure 5 presents the values of pressure ratio and Mach No. along the nozzle. It shows the pressure behaves as "classic" shape of expansion in the convergent - divergent nozzle which states the reduction in cross-sectional area causes increase in the flow velocity thus increase in the Mach number along the nozzle. As a result of this the curve of static pressure ratio falls down. It is obvious that Mach number reaches (1) at the throat area and continues to rise to reach supersonic speeds before it falls down sharply between X/L (0.1) and X/L (0.15). This sudden drop in Mach number with increase in pressure is an indication of a shockwave. From this point the flow continues to decelerate due to the increase of cross sectional area as after the shockwave the divergent part acts as a diffuser.

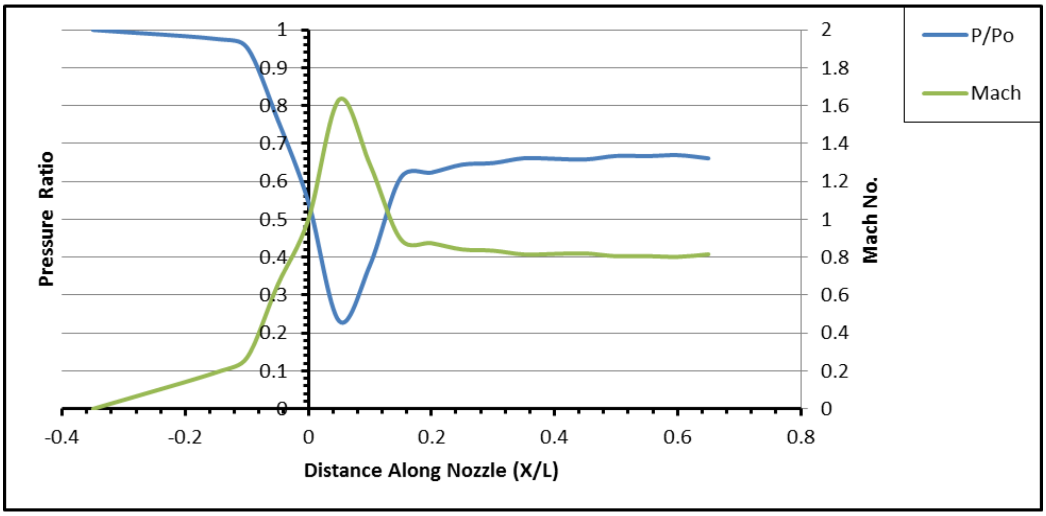

Fig 5: Pressure Ratio and Mach No. Distribution for PR=0.52

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In Figure 6 the static pressure ratio gradient is the same as in Fig 4, and Mach number has a general shape that increases due to the increase in the inlet pressure, thus the increase in the ratio of inlet pressure to back pressure. After the shockwave, Mach number is seen to decrease downstream of shockwave which is located between X/L (0.25) and X/L (0.3).

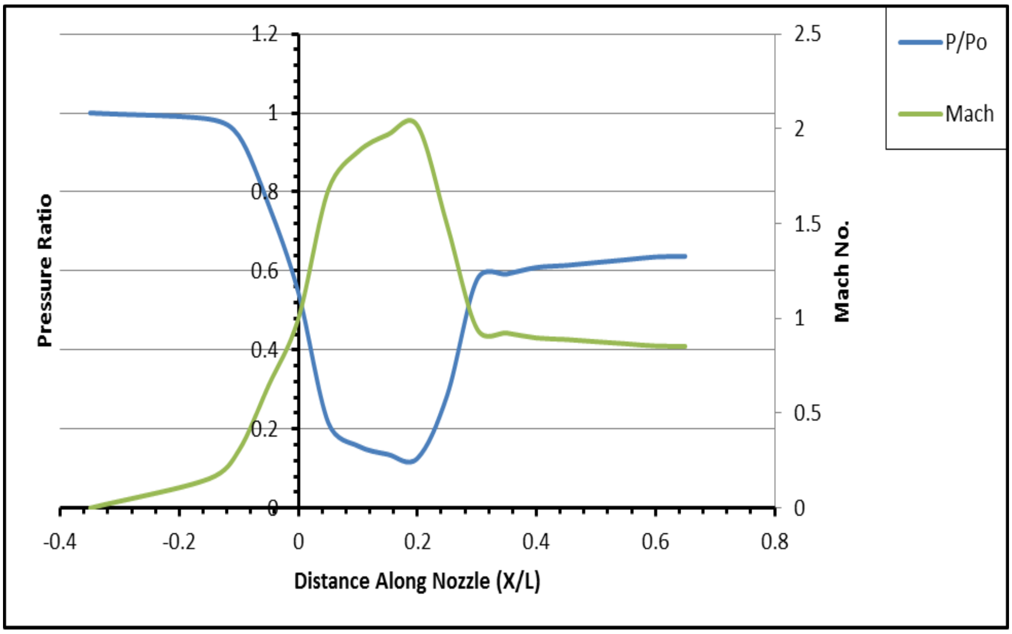

Fig 6: Pressure Ratio and Mach No. Distributions for PR=033

In figures 7and 8 the pressure ratio and Mach number distributions along the nozzle for the three cases are presented together, from which it can be concluded that the lowest ratio is decreasing with the increase of the inlet pressure and the location of the shockwave is moving forward from the throat area toward the exit plane. The same conclusion can be deduced from the Mach number distribution in figure 8 and the flow is converted from supersonic to subsonic through a shockwave in the divergent section of the nozzle.

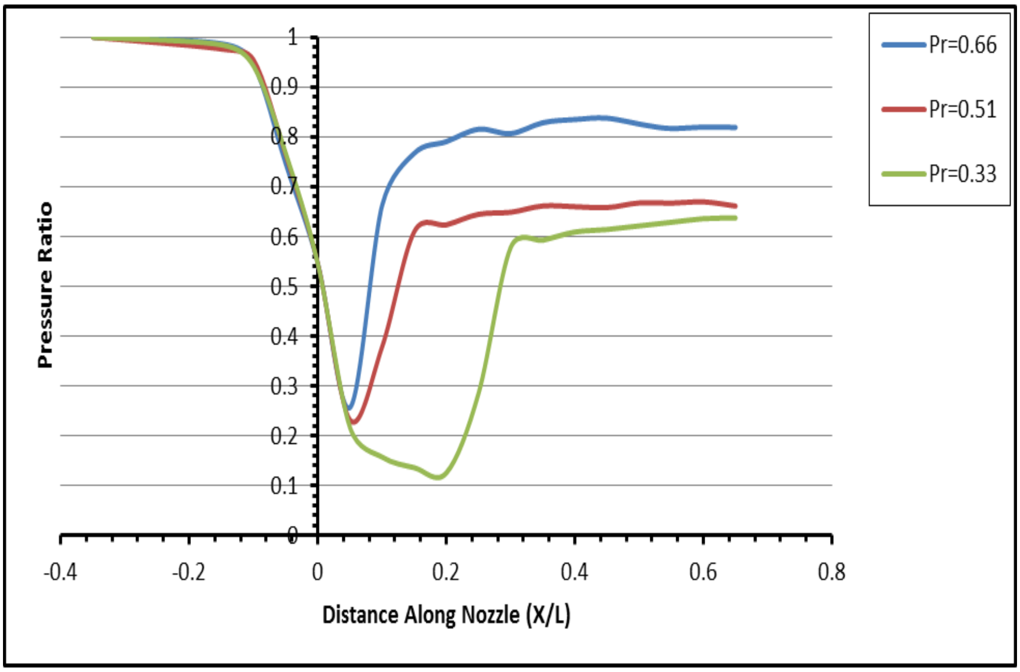

Fig 7: Pressure Ratio along the nozzle axis

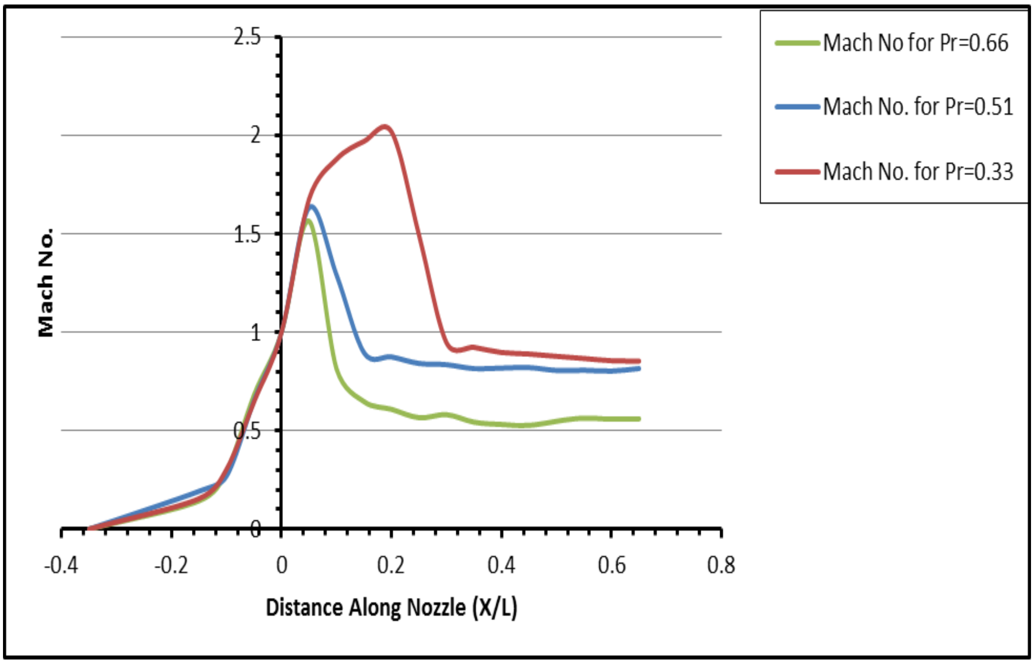

Fig 8: Mach No. Distribution along the nozzle axis

5. CONCLUSION

In the present work, steam flow in a C-D nozzle was studied with different inlet conditions. Experimental investigation was carried out for superheated steam over a range of inlet pressures.

The following can be deduced from the experimental investigation:

1. Shockwave was formed in the divergent section of the nozzle.
2. The possibility of shock wave occurrence increased and moved towards the throat, when the inlet pressure decreased.
3. The values of the inlet pressure affected the location of the shock wave where increasing inlet pressure would move the shock wave location to the nozzle exit.
4. An increase in static pressure take place across the shock, while Mach no. decreases

Nomenclature:

Latin Symbols

P_o	Total Pressure
P_s	Static pressure
P_{ox}	Total pressure before shock wave
P_{oy}	Total pressure after shock wave
M	Mach No.
M_x	Mach No. before shock wave
M_y	Mach No. after shock wave
Greek Symbol	
γ	Specific heat ratio

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