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Design and Optimization of De Lavel Nozzle to Prevent Shock Induced Flow Separation

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***Abstract:** Nozzle is used to convert pressure energy to kinetic energy in order to produce thrust. Depending on the exit mach number a suitable nozzle is designed. For subsonic flows, convergent nozzle is used and for supersonic flows a convergent–divergent (CD) nozzle is employed. In a CD nozzle flow is accelerated from low subsonic to sonic velocity at the throat and further expanded to supersonic velocities at the exit. This paper focuses on designing a de Lavel nozzle to attain supersonic flow and optimizing it to achieve maximum thrust without flow separation due to Shock waves. For maximum thrust and efficiency the direction of the flow must be parallel to the axis of the nozzle. A CD nozzle is designed with the help of GV Rao method, which is based on the Method of Characteristics and is analyzed using CFD for various performance parameters. The flow conditions were selected based on the pressure and temperature and gases that are available at the exit of the combustion chamber. At the exit of the nozzle, the Shock induced flow separation due to over expansion and optimum expansion are studied.*

***Keywords:** CD Nozzle; Over/Optimum expansion; CFD; Shock Induced flow separation.*

1. INTRODUCTION

A nozzle is capable of transforming pressure energy into kinetic energy and vice versa, Depending on shape of the nozzle above transformations occur. De Lavel nozzle which is a C-D nozzle is used to attain supersonic flow speeds. An ideal de Lavel nozzle is depicted in the figure-1. The inlet mach number is less than one, Convergent section accelerates it to sonic velocity at the throat and further accelerated to supersonic velocities by the diverging section.

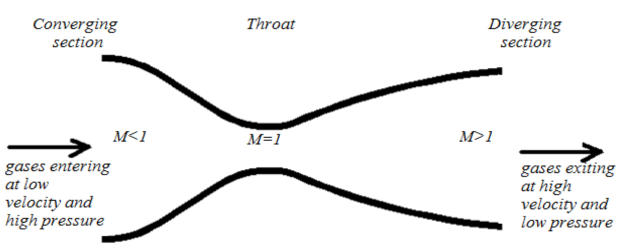

Fig. 1. De Lavel nozzle

The flow through the de Lavel nozzle is a compressible flow for higher mach numbers but the compression of flow is reversible. By second law of thermodynamics reversible process has constant entropy thus the flow through the de Lavel nozzle is an Isentropic flow. The following equations govern the isentropic process

$$M = \frac{V}{a}$$

$$a = \sqrt{\gamma\frac{p}{\rho}} = \sqrt{\gamma RT}$$

$$\frac{p}{\rho^{\gamma}} = Constant = \frac{p_t}{p_t^{\gamma}}$$

$$\frac{p}{p_t} = \left(\frac{\rho}{\rho_t}\right)^{\gamma} = \left(\frac{T}{T_t}\right)^{\frac{\gamma}{\gamma-1}}$$

$$q = \frac{1}{2}\rho v^2 = \frac{\gamma}{2}pM^2$$

$$\frac{p}{p_t} = \left(1 + \frac{\gamma-1}{2}M^2\right)^{\frac{-\gamma}{\gamma-1}}$$

$$\frac{T}{T_t} = \left(1 + \frac{\gamma-1}{2}M^2\right)^{-1}$$

$$\frac{\rho}{\rho_t} = \left(1 + \frac{\gamma-1}{2}M^2\right)^{\frac{-1}{\gamma-1}}$$

$$\frac{A}{A^*} = \left(\frac{\gamma+1}{2}\right)^{\frac{-\gamma+1}{2(\gamma-1)}} \frac{\left(1 + \frac{\gamma-1}{2}M^2\right)^{\frac{\gamma+1}{2(\gamma-1)}}}{2}$$

Fig. 2. Isentropic Relations

The gases that exit the combustion chamber is different in composition than that taken by the compressor, The exhaust gas is composed of several other constituents like water, carbon monoxide, hydrocarbons, nitrous oxides and sulfur dioxides therefore the 'γ' ratio of specific heats takes a different value and has to be considered during the analysis

2. DESIGN OF THE NOZZLE

The nozzle shape is fundamental in the design process of a CD nozzle the walls have number of parabolas governed by partial differential equations. These partial differential equations are reduced to ordinary differential equations by methods of characteristics.

Contour nozzle was chosen was expansion region due to its ability to expand efficiently and it took only 80 percent of length taken by conical nozzle to provide same area ratio. *G.V.R. Rao determined that parabola was a good approximation for contour curve and can be tangent to exit,* *This allows parabola to be determined by simple geometric analysis. The throat approach radius of 1.5 rt and throat expansion radius of .4 rt were used for plotting the de Lavel nozzle.*

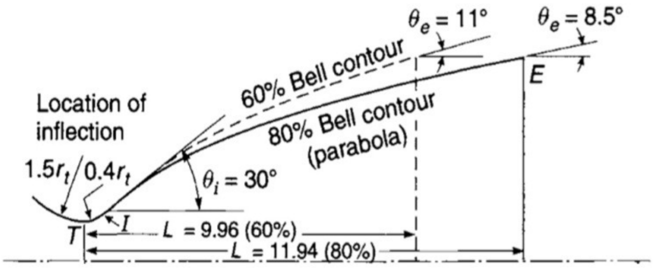

Fig. 3. Contour nozzle

The temperature, Operating Mach number for the system was determined and the total pressure of 80 Bar the total temperature of the inlet gas was 3500 K with exit mach number of 4.5, Corresponding Area ratios were calculated. Depending on these values and G.V.R Rao method nozzle was designed in GAMBIT.

3. NOZZLE FLOW ANALYSIS

The designed model is analyzed in Fluent with boundary conditions given below and various plots such as Pressure plot, Mach number plot were obtained.

Table 1. Boundary Conditions:

Pressure at Nozzle Inlet	80 Bar
Pressure Far Field	1 Bar
Temperature	3500 K

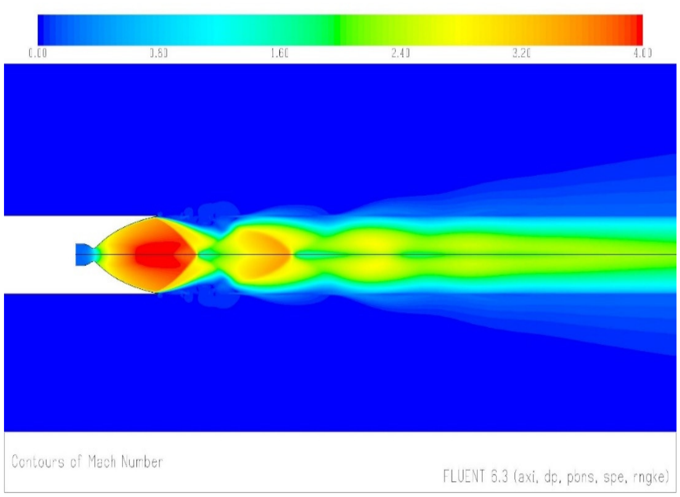

Fig. 4. Mach number plot

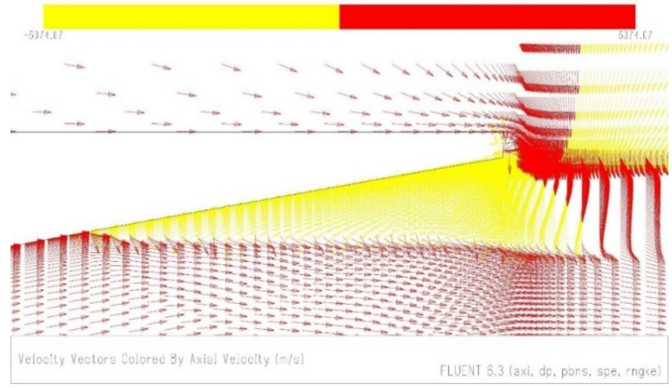

Fig. 5. Shock Induced flow separation Vector plot

The process of iteration is finding result of a function and replacing the output as input for next iteration. Fluent works on this principle to find converging result. The imported model is meshed before the flow analysis in fluent. The type of mesh used here is quadrilateral mesh. Shock induced flow separation occurs when there is an adverse increase in the pressure gradient near the boundary layer due to Shock. Here the static pressure increases drastically as a result of formation of Shock and the flow separates from the walls of the nozzle affecting flow direction there by affecting the efficiency of the nozzle.

4. DISCUSSION ON RESULTS

From the Mach number plot the regions of Shock formation are visible and the Shock is formed before the exit due to over expansion where the exit pressure is less than ambient pressure. The sudden change in the colour in the mach number plot from red to yellow indicate the region of Shock and magnified view in fig: 4 shows the flow separation which is Shock induced flow separation. This is an inefficient operating mode and has to be optimized to have exit pressure same as that of ambient pressure and prevent over expansion.

5. OPTIMIZATION OF NOZZLE

When exit pressure and ambient pressure are equal optimum expansion takes place to achieve this Pressure is changed to an optimum value and in these expansions, Shock waves are not formed. Hence, losses are minimum and there is no rapid proliferation of pressure gradient near the boundary layer at walls of the nozzle. This absence of adverse pressure gradient prevents Shock induced flow separation.

Table 2. Boundary conditions:

Pressure at Nozzle Inlet	100 Bar
Pressure Far Field	1 Bar
Temperature	3700 K

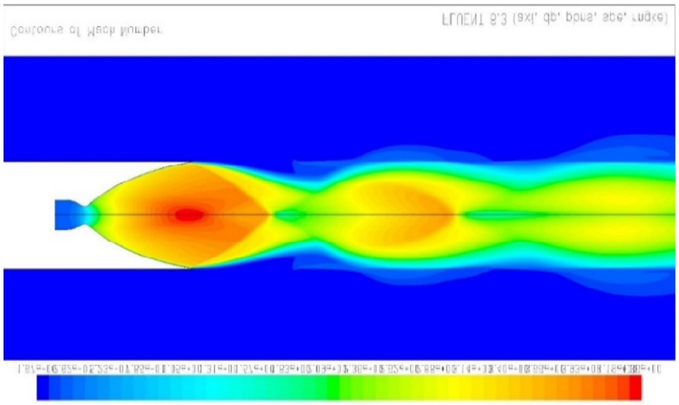

Fig. 6. ***Optimized Nozzle Mach plot***

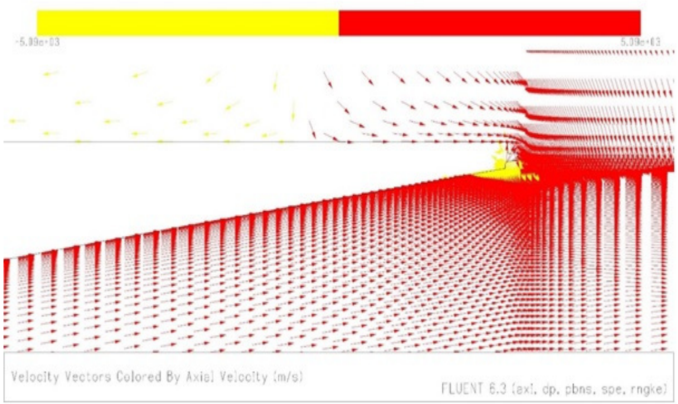

Fig. 7. ***Magnified Flow visualization Vector plot***

6. CONCLUSION

Optimum expansion of gas at exit is critical for efficient operation of nozzle.The designed de Lavel nozzle is optimized for optimum expansion with out adverse pressure gradient ie. Shock at the tip of the nozzle preventing Shock induced flow separation. This is achieved by changing the pressure in the flow field from 80 Bar to 100 Bar. This mode is efficient mode of operation of de Lavel nozzle as the flow is aligned in the direction of thrust. The magnified vector plot in figure 6 depicts this alignment of flow parallel to the axis of the nozzle thereby increasing the efficiency of nozzle.

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