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ANALYSIS OF SUPERSONIC FLOWS IN THE DE -LAVAL NOZZLE AT 2.1 INTO A SUDDENLY EXPANDED DUCT AT L/D=2WITH CAVITY ASPECT RATIO 1 USING CFD

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ABSTRACT

This paper presents solutions of supersonic flows in the de -laval nozzle at 2.1 into a suddenly expanded duct at l/d=2with cavity aspect ratio 1. Coupled implicit scheme with K-ε model have been used for modeling of supersonic flow. It is observed that due to increase in length of the duct the intensity of compression waves decreases, weak shock waves are generated and hence flow oscillation reduces. The nozzle is designed for streamline flow and hence the intensity of turbulence is less inside the nozzle as compared to the duct in all the cases. Moreover, this effect pacifies the flow oscillation and hence it proves the fact that increases in L/D not only reduces the intensity of compression wave but also flow oscillations.

Keywords: *- Supersonic flow, two-dimension, De Laval Nozzle, Mach No., Pressure ratio, flow reversal, stream line, cavity.*

I. INTRODUCTION

Swedish engineer of French descent who, in trying to develop a more efficient steam engine, designed a turbine that was turned by jets of steam. The critical component – the one in which heat energy of the hot high-pressure steam from the boiler was converted into kinetic energy – was the nozzle from which the jet blew onto the wheel. de Laval found that the most efficient conversion occurred when the nozzle first narrowed, increasing the speed of the jet to the speed of sound, and then expanded again. Above the speed of sound (but not below it) this expansion caused a further increase in the speed of the jet and led to a very efficient conversion of heat energy to motion.

The theory of air resistance was first proposed by Sir Isaac Newton in 1726. According to him, an aerodynamic force depends on the density and velocity of the fluid, and the shape and the size of the displacing object. Newton's theory was soon followed by other theoretical solution of fluid motion problems. All these were restricted to flow under idealized conditions, i.e. air was assumed to posses constant density and to move in response to pressure and inertia.

Nowadays steam turbines are the preferred power source of electric power stations and large ships, although they usually have a different design-to make best use of the fast steam jet, de Laval's turbine had to run at an impractically high speed. But for rockets the de Laval nozzle was just what was needed.

Armed with this expertise, the designer of an engineering device is able to choose the optimum design from among a number of alternative possibilities and can ensure the desired performance. Prediction offer economic benefits and contribute to human well-being.

The investigation of flow processes can be done by two main methods namely, experimental, theoretical. Experimental investigation offers the most reliable information about a physical process. However, there are serious difficulties of measurements in many situations and the measuring instruments are not free from errors. Often such measurement itself interferes significantly with the process being measured, thus making total experimental knowledge of the process impossible to obtain. Theoretical investigation works out the consequence of a mathematical model of the process, which often consists of a set of partial differential equations for the physical quantities of interest. These equations are often of such complexity that if the methods of classical mathematics were to be used for solving them there would be a little hope of predicting many cases of practical interest.

Fortunately, the development of numerical methods and the availability of large digital computers allow mathematical model to be solved for many practical problems. The advantage of theoretical investigation over a corresponding experimental investigation is its low cost, remarkable speed, detailed and complete information of the process under different conditions. Even with the remarkable success of numerical solutions, few accept

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them uncritically without some experimental validation. As in the saying by Albert Einstein, “A theory is something nobody believes except the person proposing the theory and an experiment is something everybody believes except the person doing the experiment”.

II. MATHEMATICAL FORMULATION

A. PHYSICAL MODEL

The problem being considered is the supersonic flow through de Laval nozzle to numerically simulate the flow

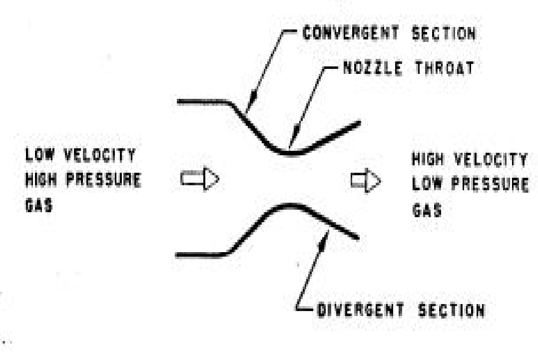

Figure 1: Physical model of supersonic flow through De Laval nozzle

The flow field for Mach no. 1.74And 2.1 is analyzed for fully understand the flow field.

B. APPROXIMATIONS AND IDEALIZATIONS

The physical model described in the preceding section is a simplified model, with respect to the surface geometry, when compared with typical components actually encountered in applications. The further approximations and idealizations made for the present investigations are as follows:

- The fluid is Ideal gas.
- The flow is Supersonic
- The flow is assumed to be two-dimensional.
- The flow is belongs to k-epsilon model.

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C. GOVERNING EQUATIONS

The unsteady, conservative and dimensionless form of the nevier-Stokes equations in two dimensions for the incompressible flow of a constant viscosity fluid is as follows:

Continuity

$$\frac{\partial U}{\partial X}+\frac{\partial V}{\partial Y}=0$$

X- Momentum

$$\frac{\partial U}{\partial{}^2}+\frac{\partial(UU)}{\partial X}+\frac{\partial(VU)}{\partial Y}=-\frac{\partial P_n}{\partial X}+\frac{1}{\mathrm{Re}}\left(\frac{\partial^2 U}{\partial X^2}+\frac{\partial^2 U}{\partial Y^2}\right)$$

Y-momentum

$$\frac{\partial V}{\partial{}^2}+\frac{\partial(UV)}{\partial X}+\frac{\partial(VV)}{\partial Y}=-\frac{\partial P_n}{\partial Y}+\frac{1}{\mathrm{Re}}\left(\frac{\partial^2 V}{\partial X^2}+\frac{\partial^2 V}{\partial Y^2}\right)$$

with

$$U=\frac{u}{u_\infty},V=\frac{v}{u_\infty},{}^2=\frac{tu_\infty}{D},X=\frac{x}{D},Y=\frac{y}{D},P_n=\frac{p}{\circ u_\infty^{\,2}}$$

Where u_∞ is the constant inlet velocity. Note that all velocities are non-dimensionalised by u_∞ And v_∞, respectively.

III. RESULTS AND DISCUSSIONS

The flow analysis is performed in the De Laval nozzle with common properties like aspect ratio one and pressure ratio 2.65. The Length to diameter ratio of the duct in which the analyses are performed is 1, 2, 4 and 6. Initially the study for L/D 6 is discussed below. Five common properties like Mach number, Total Pressure, Static Pressure, Static temperature and Turbulent Intensity are analyzed for each L/D and discussed over here. At the base, that is near the nozzle exit and in the duct flow reversal is clearly visualized in all the L/D cases. The figure 5.1 shows the reversal of flow at the base. The reattachment point can also be determined by comparing the various results obtained for various L/D.

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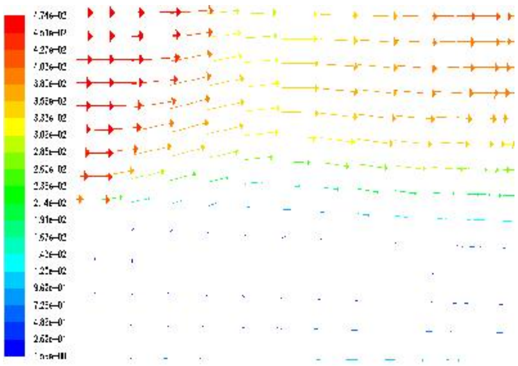

Figure -2 Flow Reversals.

Length to Diameter ratio 2 (ASR1)

Mach number

Actually Most of the flow properties are similar as in case of L/D 1.The Mach number at nozzle exit is 2.07 for nozzle which is design for Mach number 2.1; The Mach number decreases at the nozzle exit due to the formation of weak and oblique shock wave.

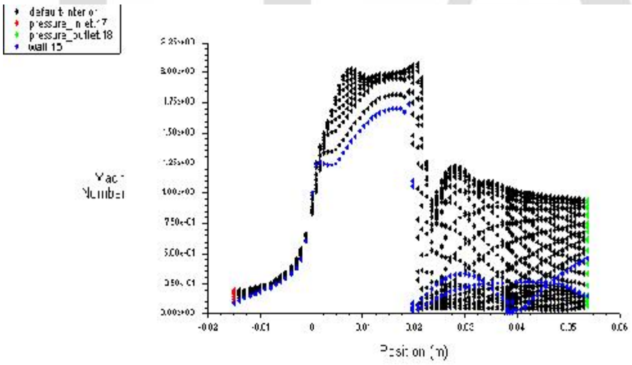

Figure – 3 Mach number

Total Pressure

The total pressure at the nozzle exit at the centre is 2.56e+5, while the total pressure in the duct at the centre is 1.97e+5. There is decrease in stagnation pressure near the nozzle walls due to viscous effects, whereas the stagnation pressure remains almost constant in the centre. After over expansion at the nozzle exit, there is a formation of weak shock wave. As large amount of losses accompany this shock, decrease in stagnation pressure can be observed.

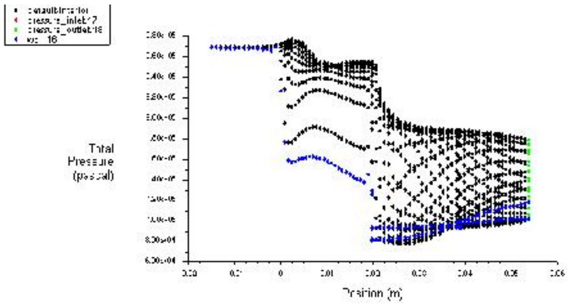

Figure – 4 Total Pressure

Static Pressure

The figure reveals the fact that the gas gets over expanded at the nozzle exit plane. Due to increase in L/D, the pressure of the compression wave is not so intense and hence a weak shock wave is generated causing reduction in rise in static pressure in comparison to previous result. Moreover, this effect pacifies the flow oscillation and hence it proves the fact that increases in L/D not only reduces the intensity of compression wave but also flow oscillations. Further downstream the expansion fan effect is observed and the value of static pressure reduces to 6.37 e +04 Pascal. The static pressure of flow then smoothly increases to back pressure.

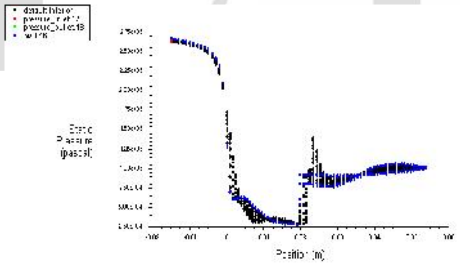

Figure – 5 Static Pressure

Static Temperature

As we have assumed the ideal gas properties, the static temperature is directly proportional to static pressure. Here the min. Static temperature in duct at the centre is 2.31e+02 while at the nozzle exit 1.97e+02. The static temperature decreases in the divergent part of the nozzle corresponding to decrease in static pressure. There is formation of shock, the static temperature increases due to decrease in Mach number across the shock. The static

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temperature is higher at the walls as compared to the interior because the effect of shock is more pronounced at the circumference of the jet.

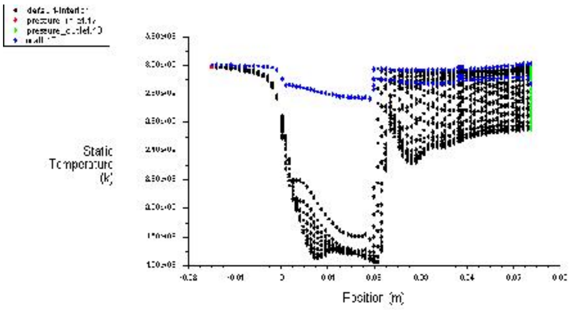

Figure – 6 Static Temperatures

Turbulence Intensity

The nozzle is designed for streamline flow and hence the intensity of turbulence is less inside nozzle as compared to compared to duct. The turbulence intensity has high value of 4.94 e +03 (%) at nozzle exit. This is because of the eddy creation and reversal of flow at the base region of circular duct. Further downstream, as flow gets agitated and the turbulence intensity increases.

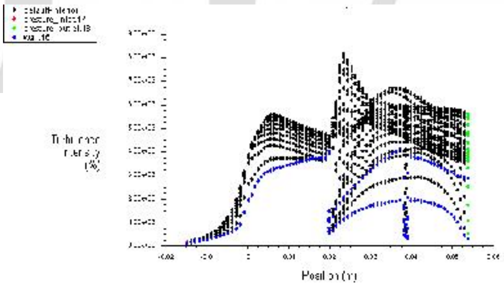

Figure – 7 Turbulence Intensity

IV. CONCLUSION

The fluid leaves the nozzle as free jet stream. As the fluid flows in the duct, Static temperature in duct at the centre is 2.31e+02 while at the nozzle exit 1.97e+02. The static temperature decreases in the divergent part of the nozzle corresponding to decrease in static pressure and in the cavity flow reversal is visualized. The Mach number was found to be very low at base region and in the cavities for all the cases. The total pressure was found to be very high at the nozzle exit compare to the total pressure at the duct exit. Near the wall the total pressure rapidly decreases. It is observed that due to increase in length of the duct the intensity of compression waves decreases, weak shock waves are generated and hence flow oscillation reduces. The nozzle is designed for streamline flow and hence the intensity of turbulence is less inside the nozzle as compared to the duct in all the cases. Moreover, this effect pacifies the flow oscillation and hence it proves the fact that increases in L/D not only reduces the intensity of compression wave but also flow oscillations. Further downstream the expansion fan effect is observed.

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