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VISCOUS FLOW ANALYSIS IN A CONVERGENT-DIVERGENT NOZZLE

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ABSTRACT: The classical one-dimensional inviscid theory does not reveal the complex flow features in a choked CD nozzle accurately. The code Fluent has been used to compute RANS flow in a 2-D CD nozzle for nozzle pressure ratios (NPR) corresponding to presence of shock inside the diverging part of the nozzle. The computed solutions differ from the simple theory so far as shock location, shock structure and after-shocks are concerned.

1. INTRODUCTION

The one-dimensional inviscid isentropic flow in a convergent-divergent (CD) nozzle is a classical textbook problem, which has different flow regimes depending upon the nozzle pressure ratio (NPR). The inviscid theory predicts a simple shock structure consisting of a normal shock followed by a smooth recovery to exit pressure in the divergence part of a choked nozzle for the nozzle pressure ratios corresponding to the over-expanded flow regime. But, in reality, multi-dimensionality and viscous effects like wall boundary layer and flow separation drastically alter the flow in a CD nozzle. The over-expanded flow regime in CD nozzles of different shapes and sizes has been a subject matter of numerous investigations because of their wide range of applications. More relevant to the present study are the investigations [1-4] concerned with flow regime in which shock appears inside the divergent portion of the nozzle. One of the more recent investigations [3] is an experimental study of flow in rectangular over-expanded supersonic nozzles exploring the complex nature of such flows. The prediction of such flows also presents a great challenge to any CFD code. The present computational work was aimed at simulating one of the flow cases of Reference [3] with the help of a commercial code Fluent, with the twin objectives of validation of the code and understanding the complex flow structure in a CD nozzle for a range of nozzle pressure ratios.

2. METHODOLOGY

The code Fluent has been used to solve 2-D steady state Reynolds-averaged Navier-Stokes equations in a CD nozzle having an exit to throat area ratio $A_e/A_t=1.5$ and half nozzle wall angle $\theta_e=2.12^\circ$. The standard $k-\epsilon$ turbulence model with wall function was employed. From accuracy and convergence consideration, the second order upwind scheme was used for all the conservation equations. Grid adaption based on pressure gradient criterion was invoked in order to capture the flow discontinuities accurately. Computations were started with the initial grid size (quadrilateral grid) of 50×100 in the whole nozzle, but with grid adaption, the final solutions in most of the cases were obtained on grids that had 3 to 4 times the original number of cells. The inlet boundary conditions consisted of total pressure $P_0=3.5 \times 10^5$ N/m² and total temperature $T_0=300$ K. The exit static pressure was varied to obtain nozzle pressure ratios NPR=1.20, 1.29, 1.34, 1.44, 1.72, 1.97, 2.09 and 2.26.

3. RESULTS AND DISCUSSION

The NPR values selected for computations are in the range where the nozzle is choked and a normal shock is expected in the divergent part of the nozzle. Figure 1 shows the pressure contours in the nozzle for different NPR values. The curvature of the pressure contours indicates that the flow is not totally uniform across the height of the nozzle due to presence of boundary layers on the walls. A more complex shock structure namely, a lambda shock (not just a normal shock) is visible in the nozzle. The location of this shock is very different from that predicted by the one-dimensional inviscid theory as discussed below.

Table 1 compares the location of shock obtained from the present CFD prediction, the inviscid theory and the experimental result [3]. The location of the shock is defined here in terms of centerline axial distance from the throat section. Both predicted and measured shocks sit at smaller axial distance (i.e. smaller area ratios) than that estimated from the theory. The predicted values generally compare well with the experimental results. Table 1 also indicates that the computed and measured NPR values for the shock to sit on exit plane is quite different from the theory. Figure 2 schematically shows the locations of the shock structure for different NPR values. For $NPR \geq 1.29$, the shock structure consists of a central normal shock (Mach stem) and two oblique shocks near the nozzle wall. The point where the three legs of the lambda meet is the triple point. The two oblique shocks are also called incident and reflected shocks. The incident shock turns the flow away from the wall and the reflected shock turns it back towards the axial direction. Interestingly, this shock structure does not remain symmetric with respect to the nozzle centerline at higher NPR values. This asymmetry has been observed in the experiment [3] and has been attributed to the flow unsteadiness and possible asymmetry in initial start-up. In computational work, it is more difficult to explain such asymmetry when the geometry and boundary conditions are all symmetric. The steady state turbulent flow solutions obtained here are basically representative of the ensemble-averaged flow situation and therefore, the asymmetry must have resulted due to the inherent numerics in computation, which appears to act like asymmetry in initial condition and obtains asymmetric solution for high NPR values. The computed and measured flow features are, indeed, symmetric for lower NPR.

In the centerline region also, very interesting phenomenon takes place for $NPR > 1.20$. The usual normal shock does not sit alone but is followed by aftershocks, which cannot be predicted by the one-dimensional inviscid theory. The appearance of aftershocks is illustrated in Figure 3, which shows the computed centerline static pressure distribution for different NPR values. The corresponding centerline Mach number distribution is shown in Figure 4. The pressure distribution exhibits sharp oscillations, which indicates that the flow decelerates through a normal shock, re-expands to higher speed, shocks down, re-expands, and so on, giving rise to aftershocks. The re-expansion may lead to local subsonic or supersonic velocities depending upon NPR values as seen in Figure 4. The after-shocks become stronger with increase in NPR. These aftershocks have been observed in the experiments too [3]. In contrast, the simple inviscid theory obtains a normal shock followed by a smooth recovery to exit pressure and thus, differs from reality.

It is interesting to note that the complex flow features discussed above were seen in the computed flow even though there was no separation of flow in any of the computed cases.

4. CONCLUSION

The flow in a CD nozzle in over-expanded flow regime is quite complex. The one-dimension inviscid theory cannot reveal all the flow features correctly. One can capture such complex flows by employing a CFD code. The code Fluent has been successfully used here to compute the real life flow features like lambda shock, location of shock and after-shocks in a CD nozzle.

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Table1: Shock location (axial distance from throat section, mm) for different NPR

NPR	1-D inviscid	Experiment	Prediction
1.2	28.77	11.27	10.9
1.29	46.87	30.14	34.34
1.34	56.23	41.94	39.02
1.44	70.37	48.73	48.39
1.72	Outside the nozzle	64.21	62.45
1.97	Outside the nozzle	74.54	67.13
2.09	Outside the nozzle	76.75	72.4
2.26	Outside the nozzle	80.59	78.3

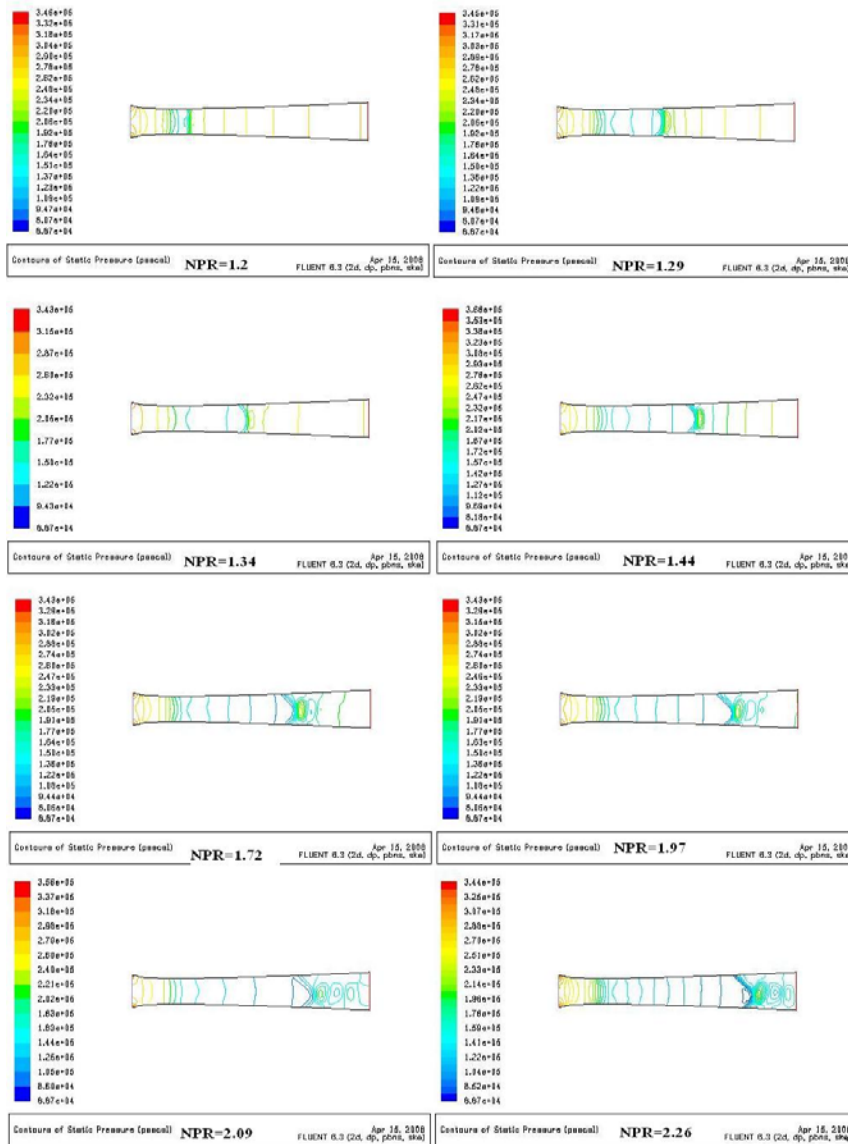


Figure 1: Static pressure contour plot for different NPR

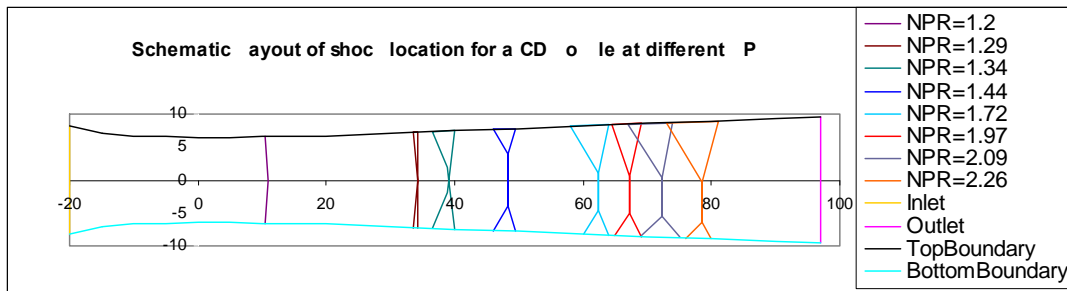


Figure 2: Schematic layout of shock location at different NPR

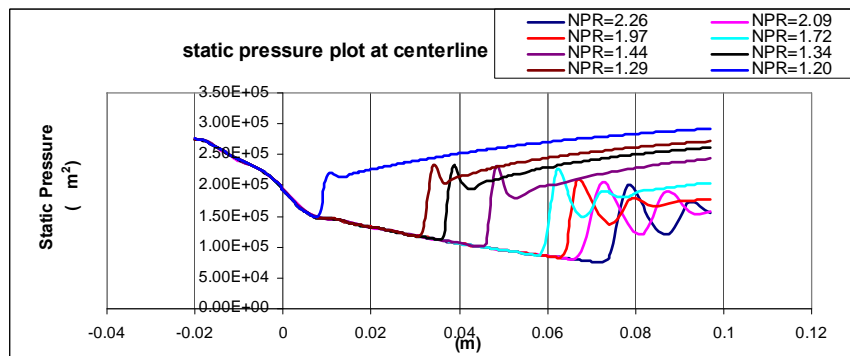


Figure 3: Centerline static pressure plot for different NPR

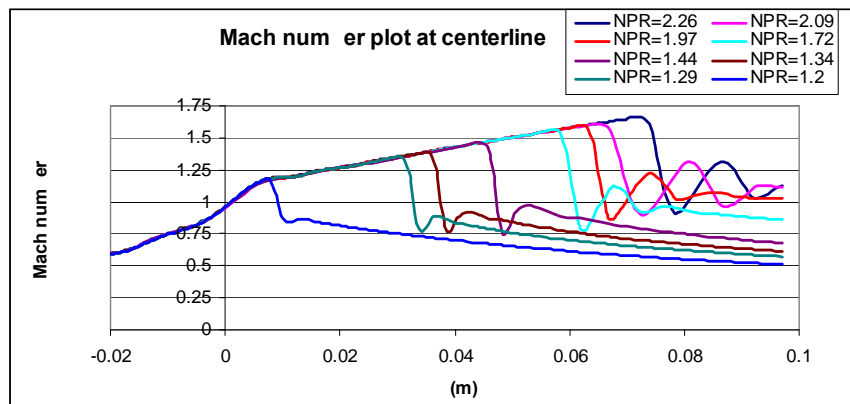


Figure 4: Centerline Mach number plot for different NPR