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A Computational Study on the Unsteady Lateral Loads in a Rocket Nozzle

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ABSTRACT

Highly over-expanded nozzle of the rocket engines will be excited by non-axial forces due to flow separation at sea level operations. Since rocket engines are designed to produce axial thrust to power the vehicle, non-axial static and/or dynamic forces are not desirable. Several engine failures were attributed to the side loads. Present work investigate the unsteady flow in an over-expanded rocket nozzle in order to estimate side load during a shutdown/starting. Numerical computations has been carried out with density based solver on multi-block structured grid. Present solver is explicit in time and unsteady time step is calculated using dual time step approach. AUSMDV is considered as a numerical scheme for the flux calculations. One equation Spalart-Allmaras turbulence model is selected. Results presented here is for two nozzle pressure ratio i.e. 100 and 20. At 100 NPR, restricted shock separation (RSS) pattern is observed while, 20 NPR shows free shock separation (FSS) pattern. Side load is observed during the transition of separation pattern at different NPR.

Key Words: Free Shock Separation, Restricted Shock Separation, Unsteady, AUSMDV

1. Introduction

The demand for efficient performance of rocket launchers necessitate the development of nozzles with higher performance by increasing the expansion ratio. However, thismay lead to flow separation, asymmetric forces and side-loads, which may cause life-limiting constraints on both the nozzle itself and other engine components [1]. These large side load, which generate in rocket nozzle during startup and shutdown transients cause not only serious trouble at launch but also destroy the engine hardware. In order to avoid the destructive side-load, much work have been done experimentally and numerically to clarify the origin of the side load generation.

Frey and Hagemann [2] conducted numerical computations of flows in a conical nozzle and a nozzle proposed by Rao. They have studied the separation position of the flow in nozzle and the parameters affecting the separation point. Onifri et al. [3] has numerically

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investigated the flow separation in the nozzle with over-expansion condition. Their results show two flow patterns called FSS (Free Shock Separation) and RSS (Restricted Shock Separation) as shown in Fig. 1 and Fig. 2. FSS is a normal type of the separation pattern and the separated free jet does not reattach to nozzle wall. In FSS, incoming flow separates due to adverse pressure gradient and after the separation an oblique shock wave and a recirculating flow region are observed. FSS can be observed in various types of nozzles such as conical contour nozzles used for solid rocket boosters and bell type nozzles including TP (Truncated Perfect), CTP (Compressed Truncated Perfect) and TO (Thrust Optimized) nozzles. RSS is a peculiar type of the separation pattern and has been observed only in TO nozzle and CTP nozzles [4]. In RSS condition, internal shock wave and Mach disc, which are generated in the nozzle, interact each other and induce shock wave/boundary layer interaction. An incoming boundary layer separates and reattaches. Also a recirculating flow region is formed between separation point and reattachment point. Shock waves cause local high temperature regions as a cause of the heat load around the reattachment point. This heat load reduces the life of the components. The pressure increase in the separated region of RSS is much higher than that of FSS and sometimes much higher than the ambient pressure [5].

Many researches had been conducted to reveal the mechanism of the generation of the significant lateral force. However, the detailed flow structure and flow mechanism have not been understood sufficiently to enhance the reliability of rocket engines. Present study numerically investigate the unsteady lateral side forces on the nozzle wall.

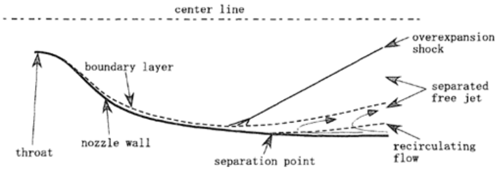

Fig. 1 Flow patternof FSS (Free Shock Separation)

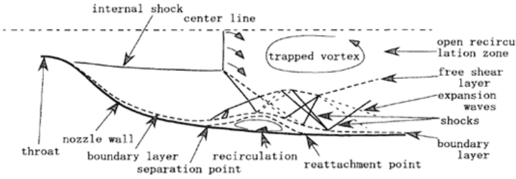

Fig. 2 Flow pattern of RSS (Restricted Shock Separation)

2. Numerical Simulations

Present solver is a three dimensional finite volume code written for structured multi-block meshes. This code can be configured as Euler, Laminar and Reynolds Averaged Navier Stokes (RANS) solver for solving 2D, axisymmetric or three dimensional problems. The code uses explicit time marching scheme and calculates numerical fluxes using AUSMDV scheme. Second order accuracy is achieved by calculating variables reconstructed by using MUSCL (Monotonic Upwind Scheme for Conservation Laws) approach and limiting fluxes by min-mod limiter. The code is capable of supporting a number of boundary conditions including adiabatic and isothermal walls. Second order central difference scheme is used for viscous term. Viscous coefficient and thermal conductivity is calculated by Sutherland's formula. The time step is calculated using the CFL (Courant-Friedrichs-Lewy) number. Dual time stepping is used for marching the time.

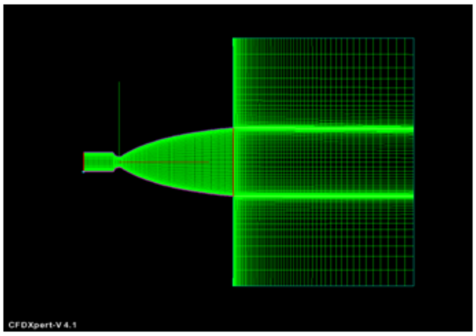

Fig. 3 Computational domain

The computational grid used in present study is shown in Figure 3. A configuration of a Compressed Truncated Perfect Nozzle [4] is selected as shown in Fig. 3. The computational grid consist of 298 points in the axial direction (230 points inside the nozzle) and 101 points in radial direction. Non-slip boundary condition is assumed on the nozzle wall. The total pressure and total temperature are assumed at the inlet of nozzle and static pressure at the external exit of nozzle.

3. Results and Discussion

Computational domain was set to a pressure of 1 atm, a temperature of 290K and a velocity of zero as a initial condition. At inlet, 100 times the atmospheric pressure was set. Static pressure of 1 atm was given as back pressure and varied to 5 times to atm pressure.

Figure 4 shows the Mach number plot for NPR of 100. At the NPR of 100, the separation pattern is FSS and the separated jet is symmetric. The incoming flow separates due to adverse pressure gradient and after the separation an oblique shock wave and recirculating flow region is observed. Pressure plot on the wall of nozzle is shown in Fig. 5. There is an increase in pressure observed near the nozzle exit. This region shows the recirculation of flow as explained in Fig. 1. The first peak in wall pressure is because of the flow attachment to the wall after passing through throat of a nozzle.

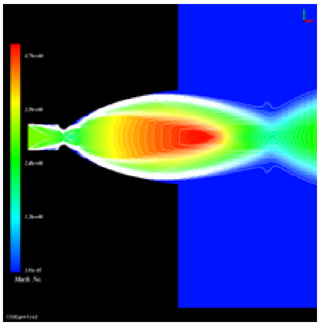

Fig. 4 Mach number distribution for 100 NPR

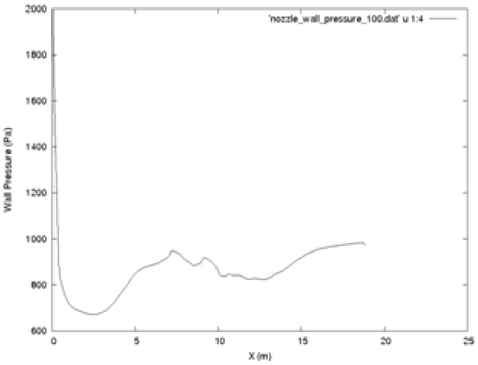

Fig. 5 Wall pressure distribution

Further, pressure at the outlet has been increased so that nozzle pressure ratio becomes 20. Figure 6 shows the Mach contour plot for 20 NPR. A shock is seen after flow passing through throat i.e. close to throat. The position of shock is different as seen for 100 NPR. A complex flow structure is observed at NPR of 20. We can see from the wall pressure plot shown in Fig. 7 that there is increase in wall pressure. Thus, we have observed the different load (wall pressure) on the nozzle wall as the NPR varies.

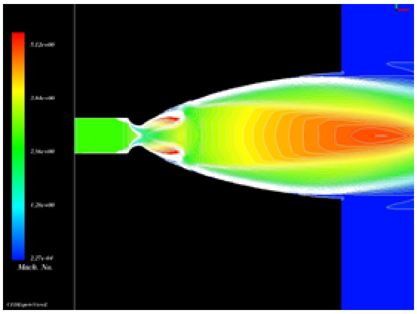

Fig. 6 Mach number distribution for 20 NPR

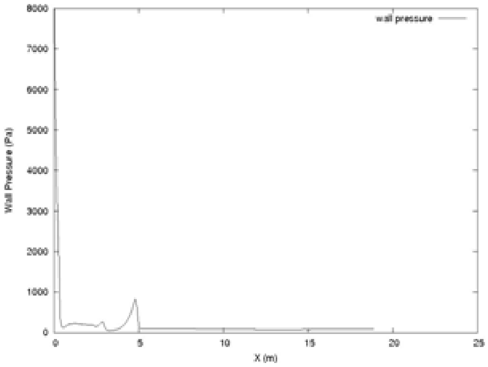

Fig. 7 Wall pressure distribution

4. Conclusion

Rocket engines are designed to produce axial thrust to power the vehicle. Several engine failures were attributed to non-axial static and/or dynamic forces (side load). Present work investigate the unsteady flow in an over-expanded rocket nozzle during a shutdown. The aim of present study is to investigate the lateral side load during the nozzle shutdown or starting condition using computation methodology. The present numerical computations has been carried out with density based solver on multi-block structured grid. Present study considers two nozzle pressure ratio i.e. 100 and 20. At 100 NPR, restricted shock separation (RSS) pattern is observed while, 20 NPR shows free shock separation (FSS) pattern. Side load is observed during the transition of separation pattern at different NPR.

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