CFD Analysis of the Aerodynamic Interaction Effects Due to Lateral Jet Injection in to Hypersonic Flow

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Abstract
Reentry vehicle often uses reaction control system for providing necessary critical forces during reentry. The effect of lateral jet due to reaction control system on aerodynamic characteristics especially stability aspect of a reentry vehicle has been investigated .CFD analysis of the interaction of a lateral jet on Leeward side has been investigated on a reentry body with a circular sonic air jet injected normally in to hypersonic flow from the body surface. A systematic numerical analysis for a lateral jet interaction was performed at angles of attack 0, 2, 5, 8, and 10 degrees at free stream Mach number 8.1.The methodology has also be verified by comparing the pressure distribution at an angle of attack of 20 degrees with experimental data. The effect of lateral jet on aerodynamic characteristic has been studied by comparing the variation of aerodynamic characteristic along the length with and without lateral jet. The aerodynamic coefficients variation of aerodynamic characteristics along the axial length is studied with and without jet. Force coefficients, pitching moment coefficient and centre of pressure are studied with jet and without jet conditions by varying the angle of attack. The Mach contours, velocity vectors and path lines represent the effect of lateral jet. The computational results are validated here to compare the experimental results obtained from open literature.

Keywords: Hypersonic flow, Lateral jet interaction, Angle of attack, ICEAE-2009

NOMENCLATURE

α	=	angle of attack
C_N	=	Normal force coefficient
X_{cp}	=	Centre of Pressure
C_A	=	Axial force coefficient
C_m	=	Moment coefficient
p	=	Static Pressure
T	=	Temperature
p_∞	=	Free stream Pressure
d	=	Reference diameter
X_{cp}/d	=	C_m/C_N

1. INTRODUCTION

Re-entry vehicles often require the use of lateral divert jet at higher speeds/altitudes to provide the necessary control force needed to make corrections in the trajectory. Such vehicles often do not have aerodynamic control surfaces. Even with reentry vehicle employing aerodynamic surfaces for control during reentry, the reaction control system is still important. Even if they provided with control surfaces, they are highly ineffective because of very low dynamic pressure at higher altitude. Hence the application of reaction control system is very important for such vehicles. The model considered in the present analysis is a blunt cone has been taken from Ref.1. The effectiveness of lateral jet is strongly influenced by aerodynamic interactions between the jet and external flow field. These interactions are highly dependent on trajectory (speed/altitude/pitch-yaw), thruster design, jet location and on the details of the physics and thermo chemistry. The experimental data for this model is available. The commercial code ANSYS FLUENT is first used to compute pressure distribution on this model and compared with experimental data available in Ref.1.The comparison between the computational results and experimental data are good. Subsequently this code has been applied to investigate the effects of lateral jet on aerodynamic characteristics with special emphasis on stability of vehicle during reentry has been investigated and presented in this paper.

1.1. Aerodynamic Interaction

When the jet is injected into a hypersonic flow, complicated interaction between the jet and flow occurs. The typical jet interaction flow field is complicated due to the jet interaction of the oncoming external flow. The qualitative features of the jet interaction flow field include regions of shock wave, boundary layer interaction and flow separation that have an influence on the overall flow around the body. This phenomenon may change the body surface pressure. The jet plays a role of an obstacle to the main flow, so that a strong shock wave is produced .As a result the disturbances generated by this pressure rise, propagate upstream through a boundary layer so that a wedge shaped, separated flow region occurs ahead of the jet where an oblique shock wave called the jet separation shock is generated. These shocks basically increase the pressure on the body surface. However in the region with the jet separation shock, some vortices are produced inside it. Especially the magnitude of a horse shoe vortex is rather strong, which suppresses the pressure rise mentioned. Jet interaction effect is shown in Fig-1.

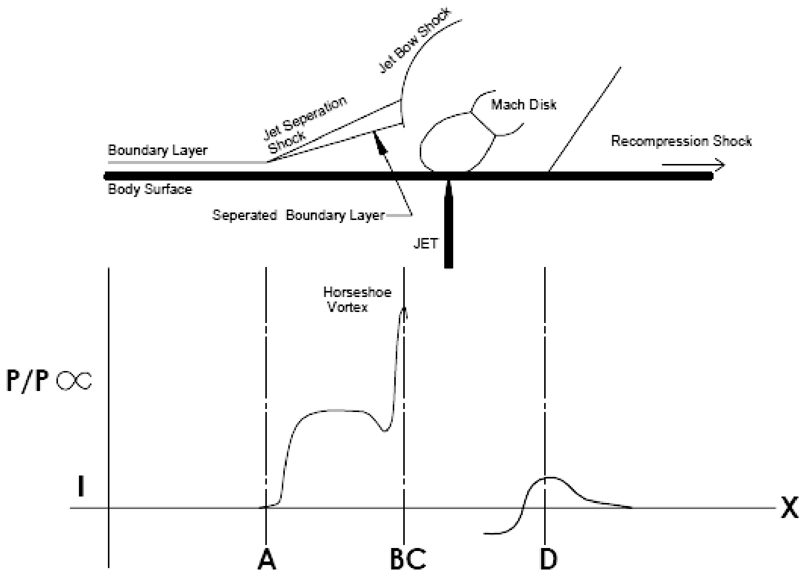

Figure 1. Interaction Flow field and pressure Distribution on a flat plate

In the downstream of the jet, the surface pressure becomes lower than that of the external flow. Regarding this two factors are considered. One is the effect of entrainment, and other is the effect of separation vortex. Further downstream, the jet attaches the body surface where a recompression shock wave is created so that surface pressure rises up to the same level as the external pressure. The lateral thrust produced is de amplified by the interaction of the jet with the reentry body aerodynamics via elevated pressure levels in the induced separation zone. The jet/flow interaction greatly increases the surface pressure in front of the jet, which results in an increase of the jet reaction force.

Another important effect noted in the interaction is the induced moment resulting from the upstream and downstream interaction. The upstream over pressure and downstream under pressure regions produce a nose down moment about the injection location. The resulting angle of attack gives rise to an aerodynamic force that acts in the opposite direction as the direct thrust force and can serve to decrement further the control force.

1.2. Objective:

The main objective of the paper is

1. To study the effectiveness of the lateral jet to provide the necessary control force in the presence of external flow.
2. To study the effect of lateral jet on aerodynamic stability.
3. To validate the present CFD methodology using commercially available code [ANSYS FLUENT] for such study.

1.3. Geometry details and flow parameters:

The standard model selected for analysis is taken from Ref.1.This model is considered because of experimental data is available. The model is a blunt cone having half cone angle of 10.3^{0} with bluntness ratio of 52.5% .The location of lateral jet with 2mm diameter is at a distance of 25.4mm from base on leeward side. The blunt body configuration used for analysis is shown in Fig-2.

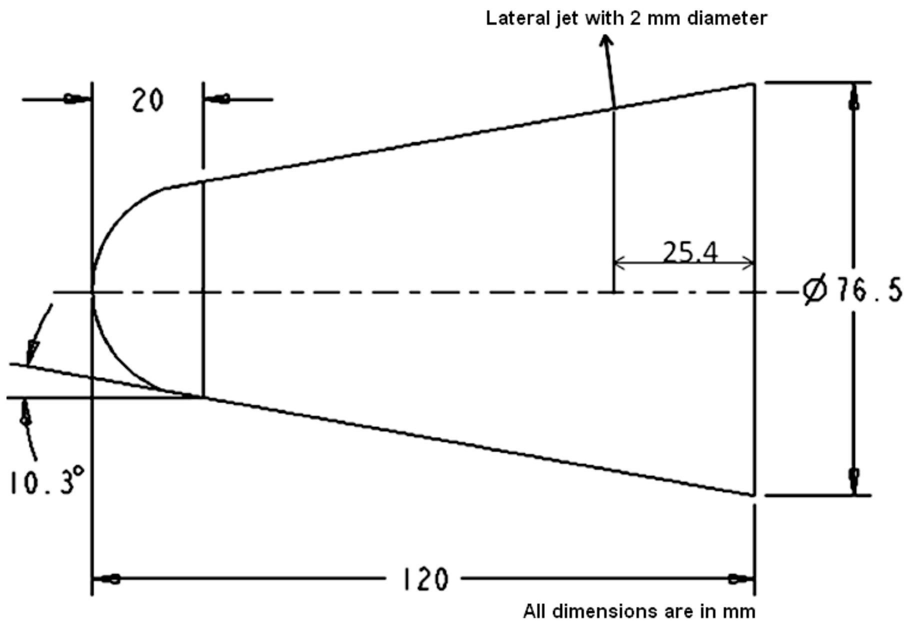

Figure 2. Schematic View of Model Employed.

Table 1

Free stream conditions	**Values**
Stagnation pressure	4MPa
Stagnation Temperature	900K
Mach number	8.1
Static Pressure	550Pa
Static Temperature	267.3K
Density	0.02026Kg/m3
Angle of attack	0,2,5,8,10

Table 2

Lateral jet conditions	Values
Jet pressure	640000 Pa
Mass flow rates used	0.068 Kg/s

2.2. Boundary/Initial Conditions

Free stream conditions are taken from Ref.1 which are at 30 Km altitude and have been used for their shock tunnel tests. Free stream and Lateral jet conditions are given in Table-1 and Table-2. Pressure far field and pressure outlet are used as boundary conditions at inlet and outlet of free stream. Mass flow inlet boundary condition is defined on jet area normal to the boundary. Density based solver with implicit formulation was used for computation. K-ω SST Viscous model has been used for CFD simulation. Grid adaption has been done to maintain Y-plus value less than one. CFL number used for the analysis to resolve the convergence issues is 0.5.

2.3. Experimental Data

Experimental results for the validation have been taken from Ref.1. Experiments were conducted at Nagoya university shock tunnel test facility, Japan. The results of the computational approach for the jet interaction problem were closer to the results of the shock tunnel investigation. The flow parameters considered in computation is taken from Ref.1 are given above.

2. COMPUTATIONAL STUDIES:

2.1. GRID GENERATION:

Grid is generated using the grid generation software Gambit. Grid is generated to capture shock and the effects of boundary layer and jet. Parabolic domain is considered around the blunt cone. The first cell height is computed based on the operating conditions for hypersonic flow given in Table-1.The Y Plus values are maintained less than 5 with a first cell height 3mm and a growth rate of 1.05 has been maintained to capture the Viscous effects. Fine mesh is used in the jet region to capture the effects of Jet and the Density of elements are maintained in fluid domain to capture the shock wave. The computational grid is used to generate the presented results consist of 0.64 million hexahedral elements. The grid used for analysis is shown in Fig-3.Grid requirements for hypersonic flow is listed out from previous literature and an appropriate use of density and packing of computational grid required for Mach 5-10 flows was implemented .Grid convergence study has been carried out. Grid points were concentrated more near jet exit and shock regions to resolve the large gradients in flow variables.

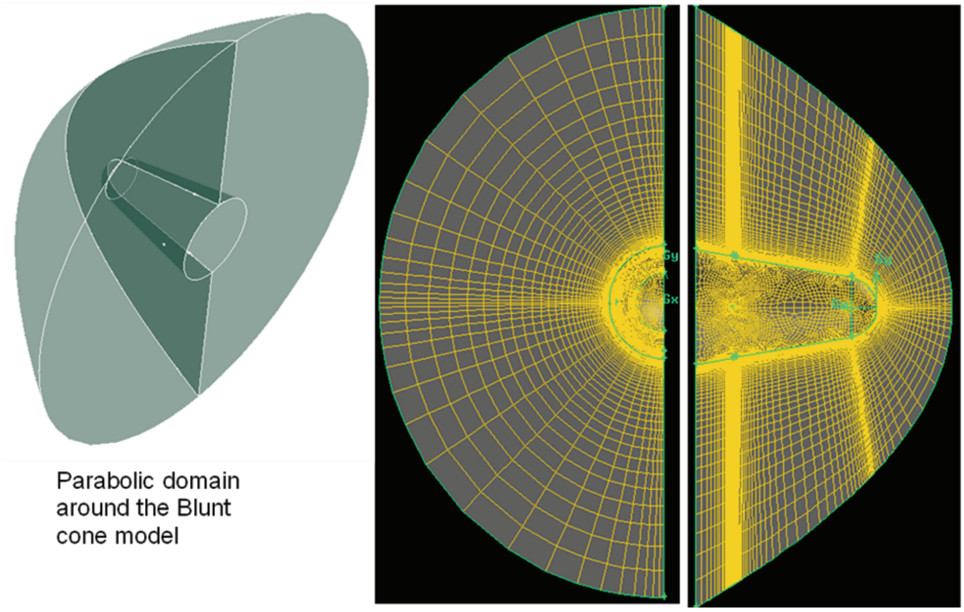

Figure 3. Three dimensional model and mesh with fluid domain

RESULTS AND DISCUSSION

The flow fields are analyzed and demonstrated by Mach number contours on the body surface in pitch plane. Mach contours with and without jet for α =5 and 10 are shown in figure 4and 5. The shock wave around the blunt body, jet bow shock, flow separation are clearly captured with jet. The flow pattern near the jet region is shown with velocity vectors and path lines at an angle of attack of five in Fig-6. A separated flow ahead of the jet and the jet bow shock and oblique shock are captured. The base area of the blunt cone was taken as reference area to calculate the aerodynamic force coefficients. The pitching moment coefficient is calculated with reference to the nose point. Aerodynamic forces can be obtained by integrating the surface pressure and viscous force. Aerodynamic characteristics for reentry body with and without jet are plotted in the present work.

Effect of angle of attack:

The normal ,axial force coefficients ,Moment coefficient and Centre of pressure variation with angle of attack corresponding to 0.068 kg/s mass flow rate with 8.1 Mach number are plotted in Fig-7. The aerodynamic coefficients with jet and without jet are compared for α =0, 2, 5,8 and 10. The normal force coefficient, pitching moment coefficient increases with angle of attack for jet off and on. But the normal force coefficient and pitching moment coefficients are diminished with jet compared with jet off condition for all angle of attacks from zero to ten. To verify the stability of vehicle the centre of pressure is plotted against the angle of attack for jet on and off conditions. The centre of pressure is not varying significantly as the attack angle increases. The centre of pressure moves towards base of body with jet slightly.

Effect of lateral jet:

The main advantage of providing lateral jet is to produce the control force on reentry vehicle. The normal force coefficient, pitching moment coefficient, axial force coefficient distribution along the axial length is plotted with jet on and off at five deg angle of attack with a jet mass flow rate of 0.068 kg/s corresponding to 8.1 free streams Mach number in Fig-8.The distribution is almost same till the jet region. Ahead of jet region the normal force coefficient, pitching moment coefficient starts decreasing due to jet bow shock and is increasing after the jet due to the jet entrainment effect. The overall coefficient values are diminishing with jet compared with jet off condition. The centre of pressure in terms of Xcp/d is plotted against the non dimensional parameter (x/d) .The distribution in jet region is changed compared with jet off condition.

To verify the CFD methodology adopted for the current work ,the computations has been done for 20 Deg angle of attack for which the experimental data is available in reference [1]. Computational results at α=20 with jet are compared with the experimental results in Fig-9. There is a good agreement between computational results and experimental data.

The static pressure distribution along the length of the body with jet is plotted for an angle of attack of Zero and Twenty in Fig-10.The maximum pressure exists with α=20 compared with α=0 and the maximum pressure is in jet location.

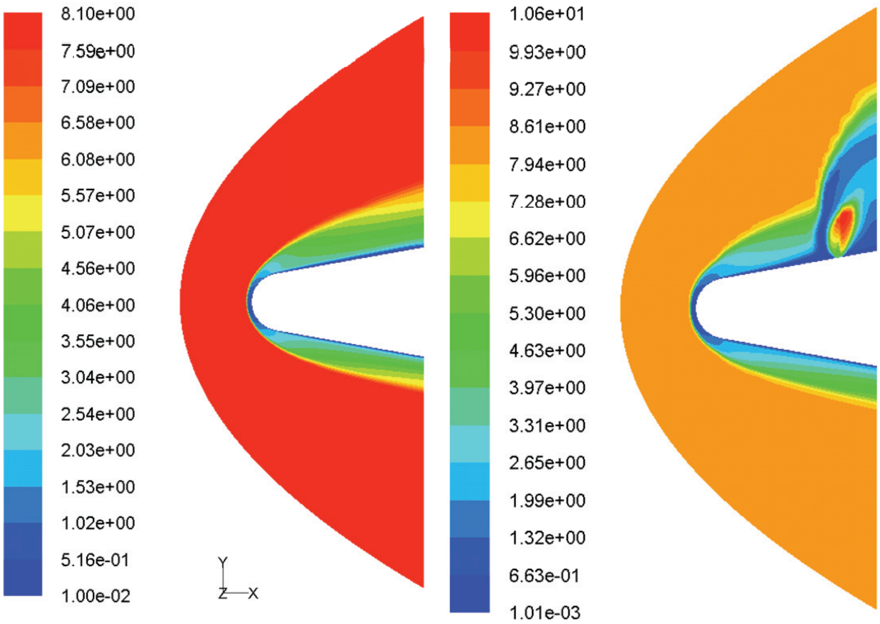

Figure 4. Contours of Mach number with and without jet α =5

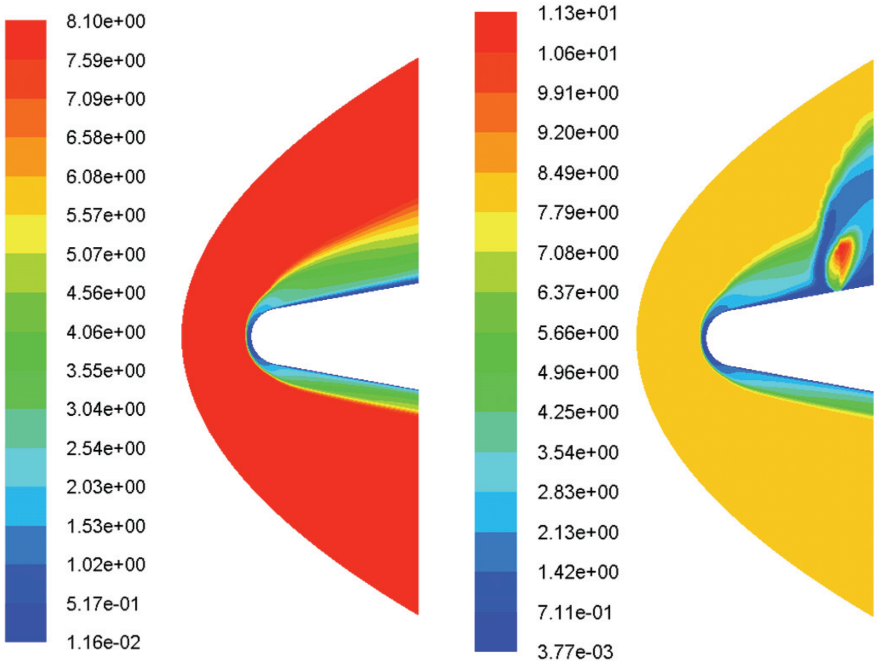

Figure 5. Contours of Mach number with jet and without jet α =10

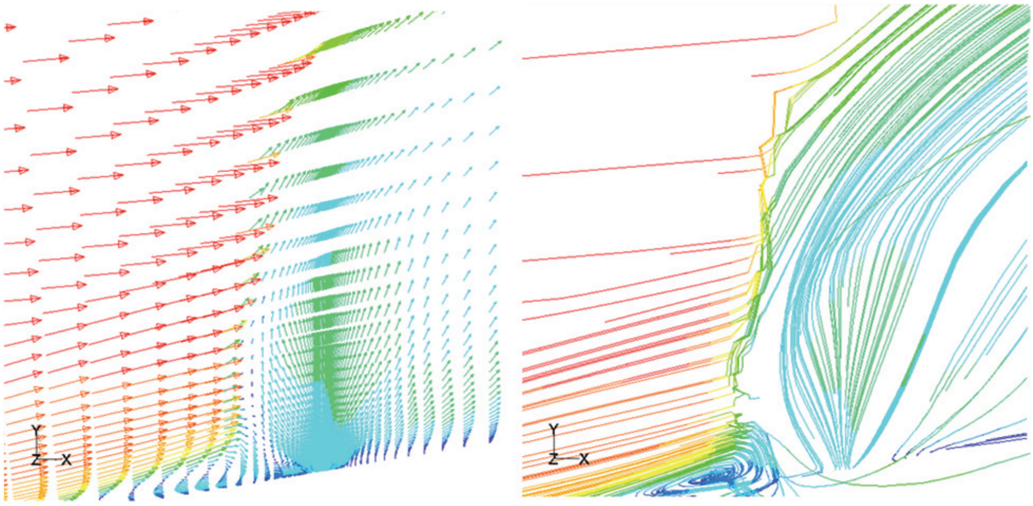

Figure 6. Velocity vectors and path lines in jet region

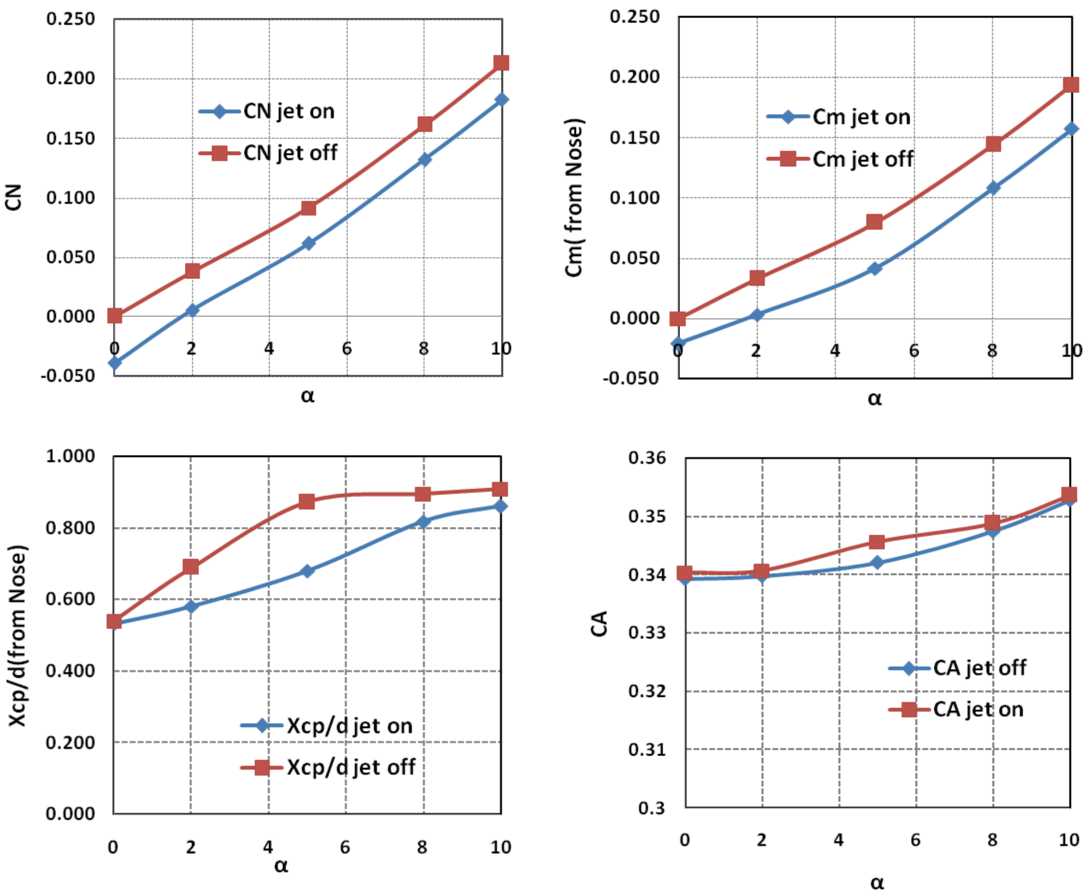

Figure 7. Variation of aerodynamic characteristics with and without jet at M∞ =8.1 and jet mass flow rate of 0.068 kg/s

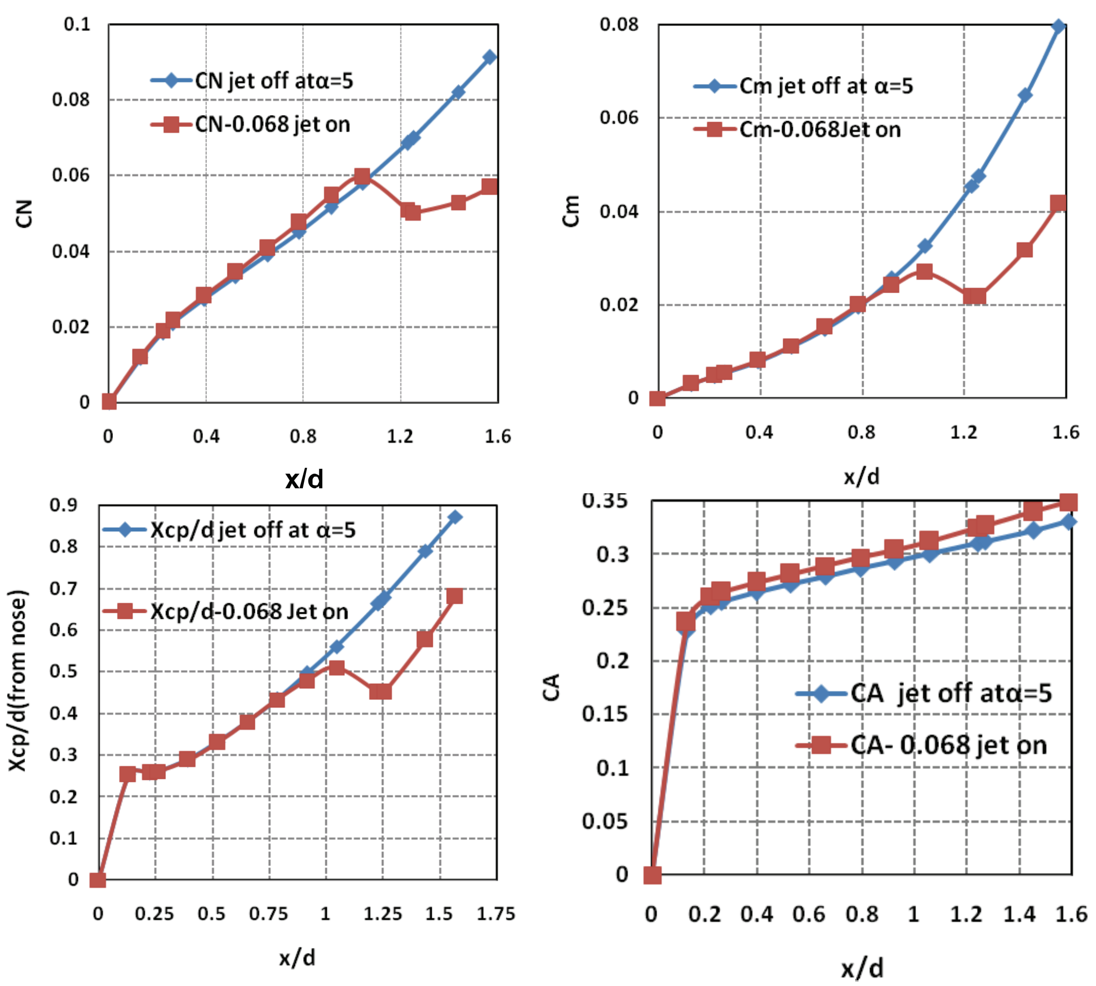

Figure 8. Distribution of aerodynamic forces and moments along the length of the body with and without jet

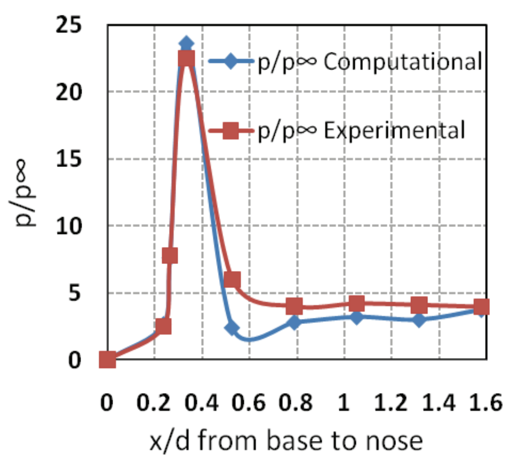

Figure 9. Comparision of CFD results with Experimental data

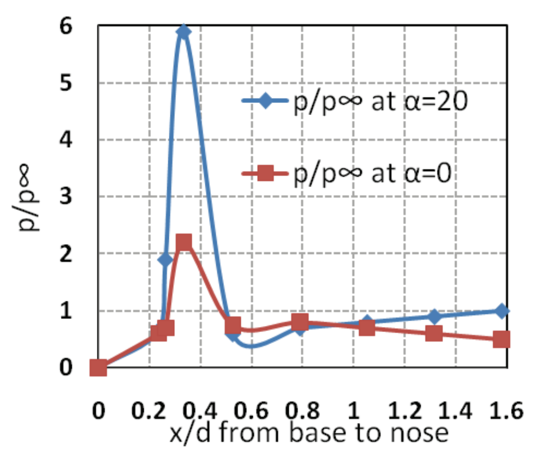

Figure 10. Contours of Mach number with jet and without jet at α=5

CONCLUDING REMARKS

1. Introduction of lateral jet reduces the normal force characteristics by 30% at 5 degree angle of attack with mass flow rate of 0.068 kg/s.
2. Pitching moment coefficient decreases by 45% at 5 degree angle of attack with mass flow rate of 0.068 kg/s.
3. With the introduction of lateral jet the centre of pressure moves forward about 0.2d.Hence making the vehicle more unstable.
4. Axial force coefficient is almost all constant with and without jet. There is no appreciable change with angle of attack.
5. The change in CN, Cm, Xcp/d and CA are evident by looking at the distribution of aerodynamic forces along the length. Fig-8 shows the CN and Cm decreases drastically after the jet.The effect of jet are influencing the region ahead of jet.
6. As the angle of attack increases the jets works efficiently to produce aerodynamic control force and stability of vehicle is good.
7. Analysis of reaction jet control has contributed to a fundamental understanding of the re-entry aerodynamics and performance at different angle of attack
8. This result gives us good evidence that we are able to successfully predict the actual jet interaction control performance using ANSYS FLUENT.
9. Even a small jet of 2 mm produces significant aerodynamic forces on hypersonic reentry body which can be applied to control the vehicle orientation.
10. Jet expands greatly due to decrease in pressure on the leeward side when the attack angle increases.
11. Interaction region extends more upstream of the nozzle as attack angle increases. This is because the boundary layer becomes thick due to decrease in density on the leeward side as a result of high attack angle so that the boundary layer is easy to separate.
12. In the downstream of jet there is a jet entrainment effect and boundary layer separation with vortices inside it.Hence the pressure decreases

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