CFD AERO THERMAL ANALYSIS OF SPACE CAPSULE RE-ENTRY INTO EARTH'S ATMOSPHERE AT DIFFERENT ALTITUDES

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ABSTRACT

Atmospheric re-entry refers to the movement of human made objects as they enter the atmosphere of a planet from outer space. Re-entry modules are blunt-bodies designed to withstand high heating loads experienced during entry into the atmosphere. Here conduct an external flow analysis on atmospheric re-entering vehicle called Apollo AS-202 developed by NASA. Computational fluid dynamics is used to obtain the flow field that develops around re-entry capsules. To evaluate the heat flux variation, velocity profile, temperature variation and pressure distribution at various locations of the capsules are presented. By specifying the appropriate boundary conditions, one can modify the speed and of the re-entry vehicle. It accounts for changes in temperature, density, and pressure of the surrounding atmosphere, and even includes viscous effects and shock waves. The analysis is carried out for turbulent flow and standard flow properties available for re-entry capsules in the literature using Navier-Stokes solver for different Mach numbers.

1.Introduction

The general objective of the European Space Agency FLPP program (Future Launchers Preparatory Programmed, [1]) is placing Europe inside the worldwide strategic area of atmospheric reentry for future international transportation, exploration and scientific projects. Several studies on experimental vehicle concepts and improvements of critical reentry technologies have been undertaken in recent years by ESA (ARD), France (Pre-X), Germany (Phoenix) and Italy (USV), in order to consolidate their worldwide position in this strategic field. The aero thermodynamic studies can support and address both aero shape consolidation and mission analysis, whose goal is to minimize the heat fluxes to the windward part of the vehicle (nose cap) and control surfaces (flaps). Body-flap efficiency prediction and environment characterization have been carried out in recent past with both thermo-chemical equilibrium and non-equilibrium flow assumption. A preliminary benchmarking phase has been performed in order to assess the numerical strategy to be adopted for the scheduled activity concerning both laminar and transitional simulations to be performed with different flow field hypotheses (chemical equilibrium and non-equilibrium), and also accounting for the effects of the angle of attack, the angle of sideslip, the Mach number (i.e. total enthalpy) and the symmetric and asymmetric flap deflection.

The numerical code used to carry out the aerothermodynamics analysis of the IXV vehicle is the CIRA code H3NS that solves the Reynolds Averaged Naiver Stokes equations in a density-based finite volume approach with a cell centered, Flux Difference Splitting second order ENO-like upwind scheme for the convective terms. The need for a safer access to space dictates the review of operational capabilities and hence of design approach for manned reentry vehicles of next generation. Research has shown that reentry vehicle designs with high L/D could be designed to take advantage of aerodynamic lift during reentry. Higher L/D is desirable because it increases the area from which a re-entering vehicle can be recovered (e.g. reentry window). Keeping constant the temperature of the nose stagnation in the radiation equilibrium conditions, restricting the g peak experienced to less than a tenth above normal ground-level values and, finally, with a wider than usual “reentry window” that would permit landing at any one of the many choices of airfields. The results, provided in this paper, consider a Mars entry scenario compliant with an approach to the red planet both by elliptic and hyperbolic orbit. These results may be used to provide numerical data for understanding requirements for the human exploration of Mars.

From the point of view of approach strategies, the different values of velocity at entry interface (given the entry angle) will characterize the MBS design by means of mechanical loads (i.e. pressure and acceleration), thermal loads (i.e. heat flux peak and integrated heat load), and landing dispersion. The flow around the capsules was computed by the DSMC method. The number of collisions was calculated by the majorant frequency technique. The collisions of molecules were computed using the variable hard sphere (VHS) model. The internal degrees of freedom were taken into account by the Larsen – Borgnakke model. The SMILE software system was used for computations.

A number of papers have been already written about EXPERT with different aims, from the evaluation of the aerodynamic behavior to the description of tests and experiments to be made during the re-entry. Preliminary computations of aero thermo-dynamic data base at high altitudes were provided by approximate engineering methods or bridging formulae. The aim of the present work is making an additional analysis and, hopefully, a better characterization of the aerothermo-dynamic data base in rare field regime.

2.Need of SPACE CAPSULE:

A **space capsule** is an often manned spacecraft which has a simple shape for the main section, without any wings or other features to create lift during atmospheric reentry. Capsules have been used in most of the manned space programs to date, including the world's first manned spacecraft Vostok and Mercury, as well as in later Soviet Voskhod, Soyuz, Zond/L1, L3, TKS, US Gemini, Apollo Command Module, Chinese Shenzhou and US, Russian and Indian manned spacecraft currently being developed. A capsule is the specified form for the Orion Multi-Purpose Crew Vehicle.

Figure 1 Apollo Reentry Capsule

3.NEED FOR CFD ANALYSIS

- When a capsule reenters an atmospheric environment, a strong shock wave is formed in front of it. Behind the shock wave, a shock layer with very high temperature appears where a high enthalpy fluid flows around a capsule, resulting in a severe heating environment.
- Moreover, in an environment where the capsule velocity exceeds 8 km/s such as a super-orbit re-entry, there appear complicated phenomena accompanied by the radiation and/or the influence of turbulence.
- The computed results are utilized to determine whether the aero-thermodynamic loads exceed the allowable values. If the loads are exceeding, then an optimized design is required to account for these loads. Moreover, if it is not exceeding, further analysis is done

on the other components to ensure their reliability.

4.AERODYNAMIC HEATING

Atmospheric re-entry vehicles are subjected to aerodynamic heating during re-entry phase of their operation. Aerodynamic heating is the heating of a solid body produced by the passage of fluid over the body. It is a form of forced convection in that the flow field is created by forces beyond those associated with the thermal processes. This process generates heat and consequently all external surfaces of the vehicle are heated. Due to aerodynamic heating external surfaces of the re-entry vehicle gets heated. Thermal Protection Systems are necessary in order to protect the internal structure of the vehicle from the elevated heat fluxes occurring on the external surfaces. The design of a Thermal Protection System is based on the principle that the energy released by the aerodynamic heating must be absorbed or rejected by the Thermal Protection System.

PROTECTION FOR CAPSULE FROM AERODYNAMIC HEATING

- Thermal Protection Systems are necessary in order to protect the internal structure of the vehicle from the elevated heat fluxes occurring on the external surfaces.
- The design of a Thermal Protection System is based on the principle that the energy released by the aerodynamic heating must be absorbed or rejected by the Thermal Protection System.

METHODOLOGY

- Model of the capsule and fluid flow domain are created in design modeler of ansys workbench as per the dimensions.
- Meshing is done using ANSYS ICEM mesh module
- CFD analysis is done by using ansys cfd code CFX taking high velocity aerodynamic heating model by setting the environmental process and design parameters.
- Post processing the solution to get the results.

AS-202 Flight Data

The flight data used for assessment/comparison of heat flux data on the capsule were taken from the AS-202 flight test which was performed as part of the Apollo program. Once the Apollo entry vehicle design was determined, two flight tests of the actual Command Module (AS-201 and AS-202) were conducted at super orbital entry velocities resulting from suborbital boosted trajectories with an intentional skip maneuver. Although AS-201 did not carry an on board inertial measurement unit (IMU), one was carried during the AS-202 flight, which enabled a reconstruction of the flight trajectory and vehicle orientation as a function of time.

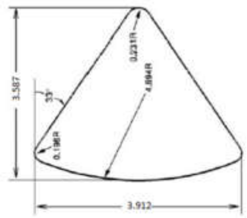


Figure 1.2 Capsule Dimensions

ANSYS FLUENT SETUP is opened to define the problem for the flow analysis with inlet velocities 6.49, 7.92, 5.09 km/s at the altitude is 77.2, 70.0 and 54.6 respectively. Inlet temperature(245.5k) was considered constant at all altitudes since it is negligible when compared to generated temperatures at capsule-air interface, the static pressure is P = 130.5Pa.

Case	Altitude (km)	Velocity (km/s)
1	77.2	6.49
2	70	7.92
3	54.6	5.09

Table 1 Considering the values of Altitude and Velocity

5.RESULTS AND DISCUSSION

The flow field around the Blunt-shaped body, Blunt body with wedge and triangular shapped spikes is initialized to free-stream values all over the domain. As the simulation progresses the bow shock and the boundary layer on the vehicle are formed, followed by flow separation on the after body. As the separation bubble forms on the windward side. A large recirculation bubble is formed on the leeward side and the shear layer enclosing the separation bubble coalesces at the neck, where the recompression shock is formed. While the re-entry vehicle enters into the atmosphere, a bow shock is created at the base of the Vehicle.

The pressure measurements on the conical section generally agreed with the wind-tunnel predictions. The conical pressure measurements were low during maximum heating. Maximum pressure at fore body and its value is 7.789E7 Pa. Minimum pressure is just above zero pascal. It shows the severe pressure drag at the two edges of the module base. High static pressure is created in the base of the reentry vehicle as illustrated in Fig Since, the pressure is high while re-entering in to the atmosphere due to the strong bow shock created. This bow shock will increase drag force acting on the re-entry vehicle and has the capability to decelerate the vehicle to low Mach numbers. The maximum static pressure is created at the far field of the re-entry vehicle because of the progressing bow shocks marching downstream of the vehicle. The increase in pressure is visualized exactly using the static pressure contour for 0^o angle of attack

5.1 Pressure variation:

Blunt Capsule

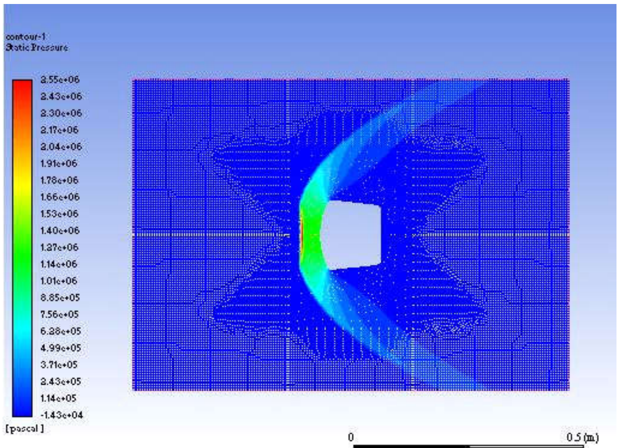


Figure 2 pressure variations Blunt Capsule

5.2 with wedge spike

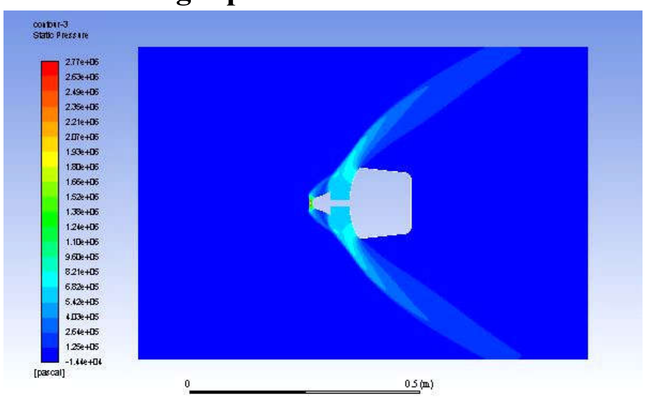


Figure 3 pressure variations at 70.0km altitude

5.3 sharp wedge spike

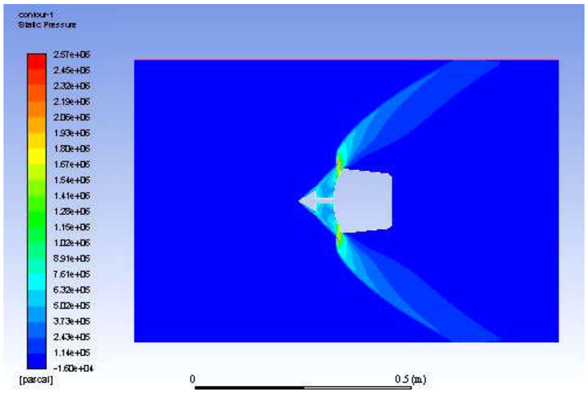


Figure 4 pressure variations at 77.2km altitude

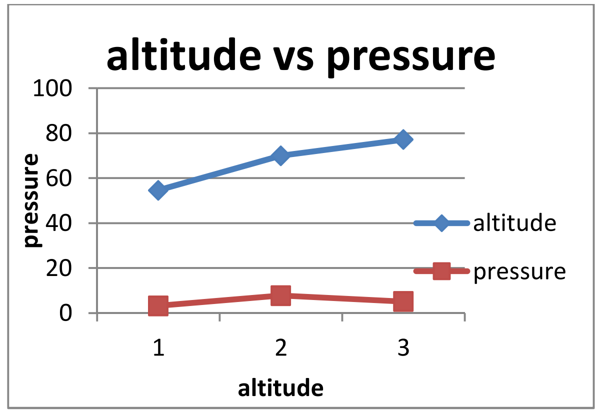


Figure 5 pressure between different altitudes

Pressure variation in fluid flow at Different Shape of spikesis shown in the above graph Pressure is value is high at 70km (7.92km/s velocity) when compared to other two altitudes since the velocity is high and impact of fluid flow on capsule is very high.

5.4 Velocity variation:

Fig. shows velocity distribution of two dimensional model Blunt Capsule. The maximum temperature is produced at the base of the re-entry vehicle and it is lowest amount at the edges.

5.5 Blunt Capsule

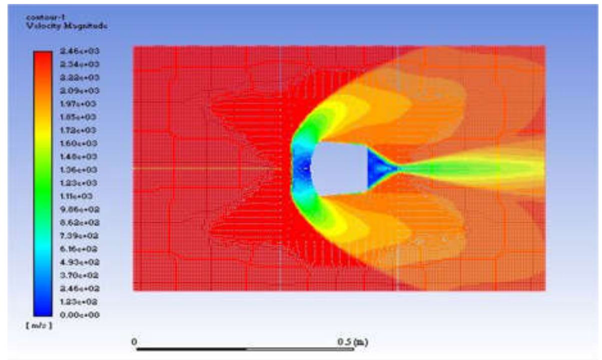


Figure 6 velocity variations Blunt Capsule

5.6 blunt wedge shapped spike:

Fig. shows velocity distribution of two dimensional model With extended wedge spike. The maximum temperature is produced at the base of the re-entry vehicle and it is lowest amount at the edges.

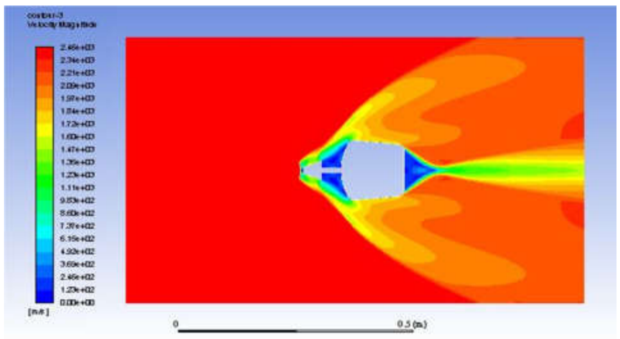


Figure 7 velocity variations With extended wedge spike

5.7 with sharp wedge:

Fig. shows velocity distribution of two dimensional model at 77.2 km altitude. The maximum temperature is produced at the base of the re-entry vehicle and it is lowest amount at the edges.

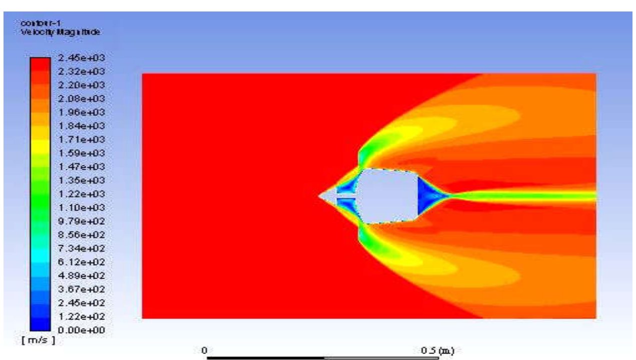


Figure 8 velocity variations at 77.2 km altitude

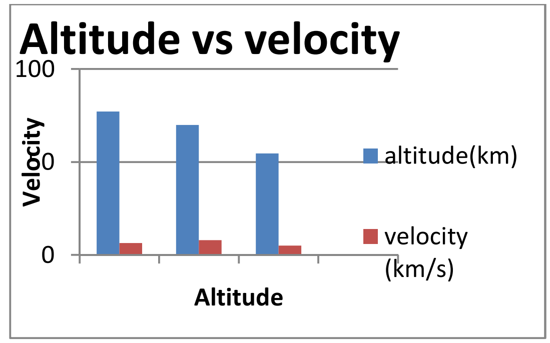


Figure 9 velocity between different altitudes

5.8 Mach number variation:

Fig. shows Mach number distribution of two dimensional model Blunt Capsule. The maximum Mach number is produced at the base of the re-entry vehicle and it is lowest amount at the edges.

5.8.1 Blunt Capsule:

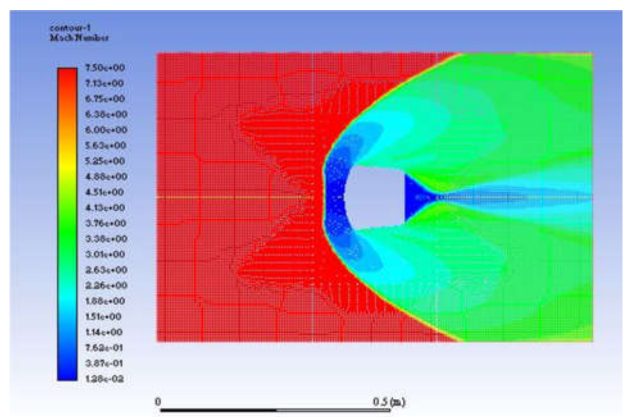


Figure 10 mach numbers variations at 54.6 km altitude

5.8.1 At 70.0 km altitude

Fig. shows Mach number distribution of two dimensional model With extended wedge spike. The maximum Mach number is produced at the base of the re-entry vehicle and it is lowest amount at the edges.

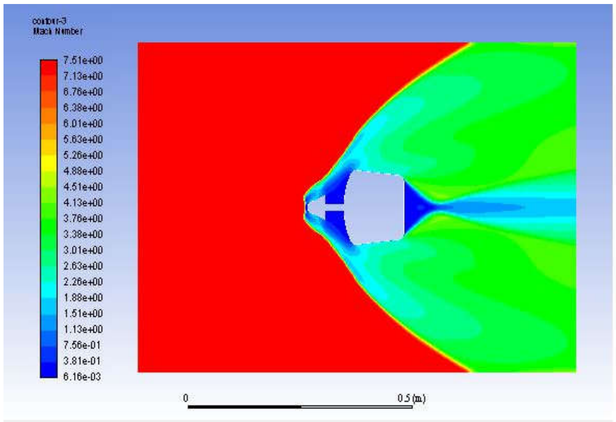


Figure 11 mach numbers variations With extended wedge spike

5.8.2 At 77.2 km altitude

Fig. shows Mach number distribution of two dimensional model at 77.2 km altitude. The maximum Mach number is produced at the base of the re-entry vehicle and it is lowest amount at the edges.

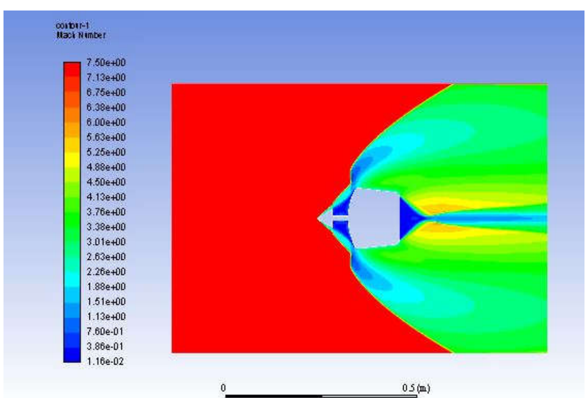


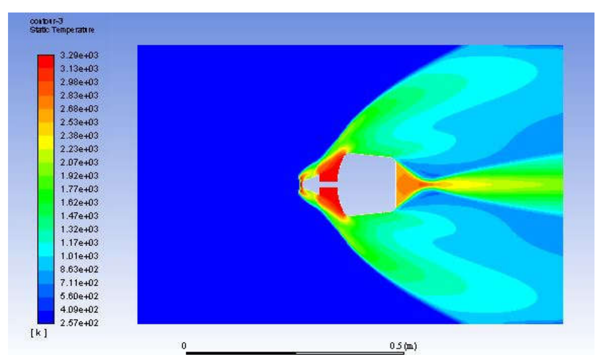
Figure 12 mach numbers variations at 77.2km altitude

5.9 Temperature variation:

The fig. shows the simulation of the temperature contours over the capsule. Here we can see, the temperature is maximum at the heat shield and it is also observed that the potential as well as kinetic energy decreases. So according to the law of conservation, if some energy function decreases so in order to be conserved some other energy should be increasing. Here the kinetic and potential energy is decreasing and it is dissipating in the form of heat energy. Maximum temperature was at fore body section and its value is 3600k for blunt capsule without any spike attached while the Minimum temperature raise value occurred for triangular aero spike and the value is 3210K

Blunt Capsule

Fig. shows temperature distribution of two dimensional model Blunt Capsule. The maximum temperature is produced at the base of the re-entry vehicle and it is lowest amount at the edge



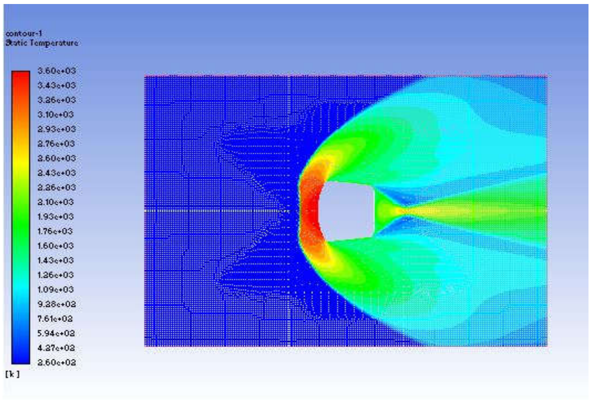


Figure 13 temperatures variations Blunt Capsule

With extended triangular spike

Fig. shows temperature distribution of two dimensional model With extended triangular spike. The maximum temperature is produced at the base of the re-entry vehicle and it is lowest amount at the edges.

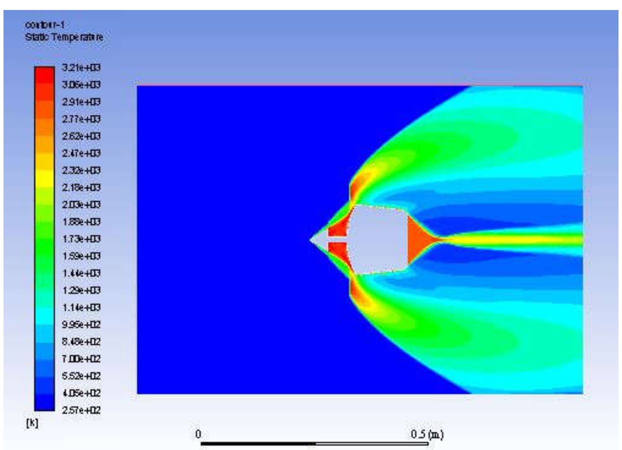


Figure 14 temperatures variations With extended wedge spike

At 77.2 km altitude

Fig. shows temperature distribution of two dimensional model at 77.2 km altitude. The maximum temperature is produced at the base of the re-entry vehicle and it is lowest amount at the edges.

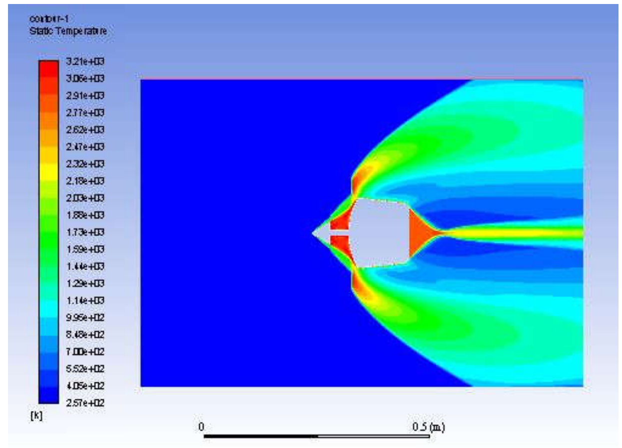


Figure 15 temperatures variations at 77.2 km altitude

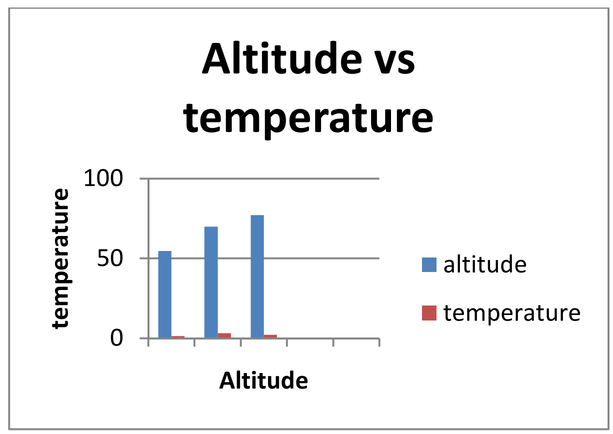


Figure 16 temperature between different altitudes

Above graph shows the variation of maximum temperature generated at the capsule wall. Maximum temperature is high when capsule is at 70.0km altitude because the wall shear is more at higher velocity. Temperature generated is proportional to wall shear.

Geometry	Pressure	Temperature	Viscosity (kg/m-s)	Density (kg/m3)
Blunt body without spike	3.55E 5	3600	16.11	3.74
With wedge spike	2.77E 5	3292	1.03	3.15
With triangular spike	2.57E 5	3210 k	1.70	3

Table 2 Variation of pressure, temperature and mach number at different altitudes

CONCLUSION

As observed in the figure above the velocity at the heat shield was minimum and increases as we move to the shoulder. This decrease in velocity results in increase in pressure gradient which results in the formation of shock wave. Major output parameters of the aero thermodynamic analysis are surface wall temperatures which are helpful in material selection for the survivability of the vehicle. Over the body for the decreasing Mach number conditions and wall outer surface temperature over the capsule is directly proportional to velocity of the capsule. The shock wave formed comes closer to the body with increase in velocity of the capsule. As the velocity increases the temperature also increasing due to friction. As temperature increases heat flux increases.. From this investigation, it is proved that this method can offer aerodynamic information on a timely basis while keeping the cost and schedule of commercial programs. Wind tunnel tests are important in the validation of prediction methods if they are not available, validated the results with actual flight data. Right choice of material can avoid the localized heating. This method will help future research on reentry much easier than it was before. The CFD code will help future researcher to calculate reentry parameters for their research work.

FUTURE WORK

An intense study on the transient aero-thermal analysis of all three flight conditions of X-IS and other available flight data with laminar and different turbulent models is in process.

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