Computational Fluid Dynamics analysis on the Reusable Launch Vehicle

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Abstract: *Computational fluid dynamics and Additive manufacturing are the two important and recently used technique in the reusable launch vehicle. In this article the design and flow simulation of the re-entry capsule has been performed using Computational Fluid Dynamics in order to optimize the suitable re-entry capsule design. Computational fluid dynamics can be used to simulate the real time supersonic flow during re-entry which helps in predicting the important characteristics during the formation of shock waves. The study considered Mach 5 conditions and an altitude of 5km. In addition, the formation of shock waves was delayed in the present studies compared to previous work. It should be noted that the current aerospace industry uses the advantage of additive production in prototyping to test re-entry launch vehicles.*

Key Words: *Additive manufacturing, reusable launch vehicle, computational fluid dynamics, shock waves*

1. INTRODUCTION

Computational fluid dynamics has been playing a vital role in aerospace Industry. Additive Manufacturing has also become an important technology in the aerospace applications. Many companies are using this technology to make components for launch vehicles and satellites, which are lighter and less expensive when compared to the conventional techniques of fabrication. Rocket manufacturers have adopted 3D printing as the process is faster and cost effective due to the reduced number of human labor. It also provides options for the revision of vehicle designs in a quick manner.

Additive manufacturing has an exponential growth opportunity in the field of aerospace engineering [1].

Topology optimization is the hardest part of this process which is figuring out exactly what features makes a part optimal. The use of topology optimization is to reduce the mass of spacecraft part.

The Federal Aviation Administration (FAA) is aiding in the development of additive manufacturing by introducing policies regarding certification, manufacturing and maintenance. A team from FAA has formulated a draft on Additive Manufacturing Strategic Roadmap which discusses the growth of additive manufacturing through education as well as research and development.

2. ADDITIVE MANUFACTURING IN AEROSPACE INDUSTRY

The Aerospace industry has benefited greatly from the use of additive manufacturing, especially in the manufacture of launch vehicles and satellites. Manufacturing of aerospace components has always been a challenging task due to the complexity of geometry and dimensions of certain components [1]. Manufacturing and machining of such complex components using conventional method like casting and forging has not only increased the cost and time of production but also the consumption of raw material. The use of additive manufacturing for intricate components like those of launch vehicles has been providential due to its numerous benefits.

The laser sintering process results in 40 to 60% of weight reduction. Every gram of weight that is reduced in the manufacture of aerospace components saves hundreds of dollars for aerospace companies. The weight reduction of vehicle components has also resulted in lower fuel consumption and hence less carbon dioxide emissions.

Prominent aerospace manufactures have employed the use additive manufacturing in the production of aircraft parts. Boeing 787 Dreamliner has been installed with Norsk Titanium 3D printed parts. Airbus Defence and Space Company produces 3D printed satellite components for the International Space Station. The production cost of the satellite has been claimed to be reduced by 20%. The US based private industry SpaceX has built its launch vehicles using additive manufacturing.

3. REUSABLE LAUNCH VEHICLE

One of the breakthroughs in the field of Aerospace Technology is the development of reusable launch vehicles, see figure 1. The two main challenges faced by a reusable launch vehicle at the time of re-entry is aerodynamic heating and large structural loads. An efficient heat shield is used to protect the vehicle during the re-entry phase. The shape and aerodynamics of the vehicle plays an essential role in reducing the aerodynamic heating. Another important characteristic that the re-entry vehicle has to possess is good mono-stability characteristics [2]. The improvement of the mono-stability characteristics of the re-entry capsule using flap and strake has been achieved. [3], [4], [5] and [6] worked on the aerodynamic characterization of re-entry vehicles in hypersonic flow conditions using both computational fluid dynamics and numerical methods.

Aerodynamic heating is caused during the re-entry phase because of the air friction over the surface of the vehicle. The re-entry vehicles are optimally blunt bodies which produces bow shock at supersonic speeds. These bow shocks help in dissipating the heat caused by friction into the surrounding atmosphere. It is essential that the re-entry aerodynamics and heat transfer rates of the Apollo control module be analyzed. [7] has worked on the prediction of hypersonic heating of re-entry capsules using computational method.

In the mathematical form, the heat balance equation is given by

$$G\frac{dT_s}{dt} + hT_S + \varepsilon\sigma T_S^4 = hT_B \tag{1}$$

When the vehicle is flying at constant velocity, the equilibrium temperature of the skin is given by

$$h = \frac{\varepsilon\sigma T_{S,Bq}^4}{(T_B - T_{S,Bq})} \tag{2}$$

Another important parameter that has been characterized during the re-entry of vehicles is the distribution of sound pressure.

The prediction of the aero-acoustics of the re-entry vehicle helps in overcoming the structural vibrations arising due to the propagation of sound waves [8].

Figure 1: Orion CEV Crew Module [9]

4. DESIGN AND ANALYSIS

In this work we have taken the geometry of the Crew Exploration Vehicle (CEV) [9] to predict the performance of the re-entry capsule. The CFD work has been performed because the experimental prediction using a wind tunnel is not only expensive but also the duration for which the supersonic flow can be simulated in the test section in only a few seconds. (Anderson, 2006) documented the issues related to hypersonic vehicles.

As shown in figure 2, the geometry was created using ANSYS and was finely meshed using triangular and quad elements. The boundary conditions for the re-entry capsule were assumed at 15 km altitude above the mean sea level where the gauge pressure is 12043 Pa and temperature is 205.65. The analysis is carried out at a supersonic speed of Mach 5. Further, the shock wave formation over the re-entry capsule is simulated for the given flow conditions. In the solution methods, under the gradient criteria the Least Squares cell-based method is used to obtain a linearly varying solution. The courant number which determines the time step during the flow has been set to a value of 5.

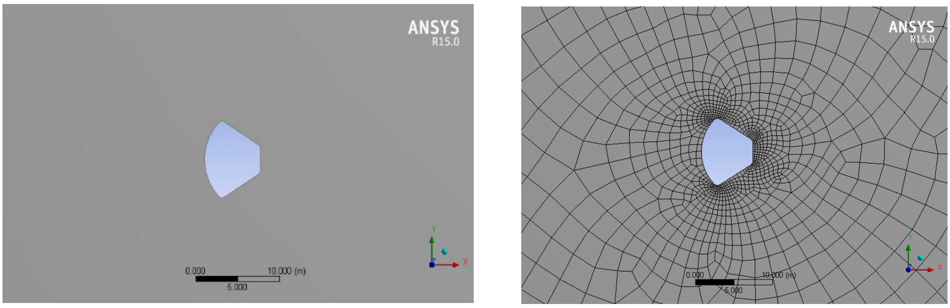

Figure 2: Geometry and meshing of the CEV

5. RESULTS AND DISCUSSIONS

The CFD simulation of the CEV at Mach 5 and 15 km altitude has yielded various results among which the contours of static temperature, coefficient of pressure and velocity have been depicted in figures 3 and 4.

Due to the blunt shape of the CEV, the formation of a bow shock can be observed at the front of the vehicle. The bow shock results in the variation of the flow parameters behind the shock wave.

In figure 3 it can be observed that there is a drastic increase in the static temperature and pressure coefficient behind the shock wave whereas the velocity has been significantly reduced.

Due to the formation of shock waves, the static temperature close to the walls of the capsule has increased from 205K (at 15 km altitude) to 1220K. The maximum static temperature of 1220K has been observed at the front and rear sides of the capsule. A small portion of the flow in front of the capsule experiences high pressure coefficient of $6.35e^{+06}$ where a major part on the frontal region experiences pressure coefficients ranging from $300e^{+06}$ to $500e^{+06}$.

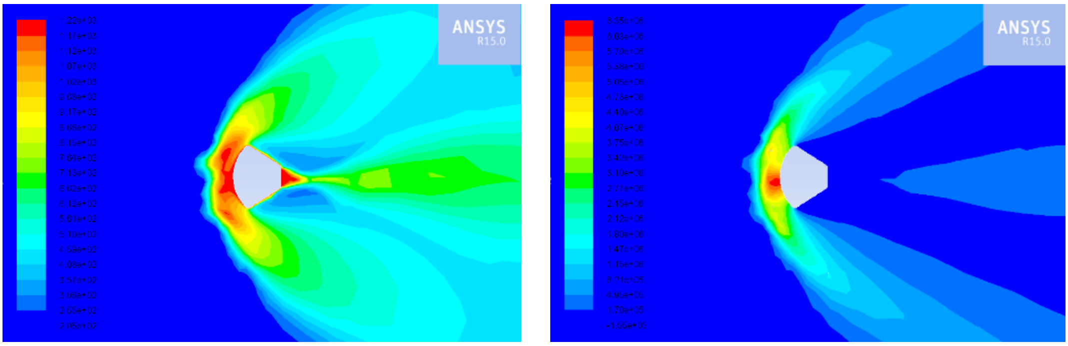

Figure 3: Contours of Static temperature and Pressure coefficient at Mach 5

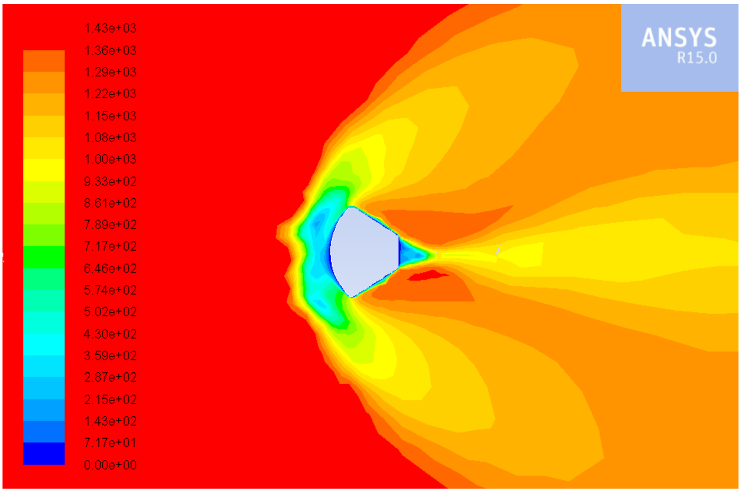

Figure 4: Contours of Velocity at Mach 5

The velocity contours in figure 4 depict stagnation velocity condition close to the wall of the CEV.

Also, the flow close to the front of the capsule has retarded to velocities ranging from 215m/s to 574m/s.

It can be observed that the flow begins to accelerate after a certain distance behind the capsule and this might be because of the tapering design of the CEV.

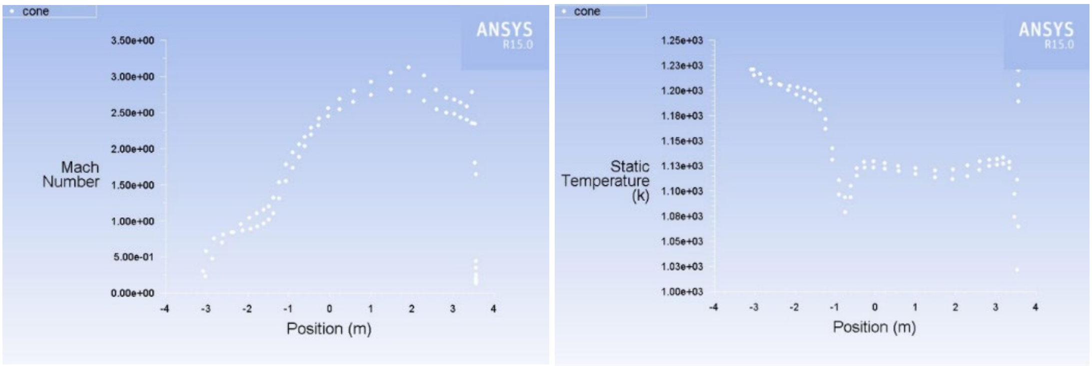

Figure 5: Plots of Position versus Mach number and Static temperature of the CEV

The plots shown in figure 5 depict the variation of Mach number and static temperature with the position of the CEV. As already discussed above, the Mach number at the frontal position is close to zero due to stagnation conditions and is observed to steadily rise over the surface of the capsule.

The maximum static temperature has been plotted at the foremost and aft most position of the capsule.

The sudden dip in the static temperature at the -1 position is because of the flow separation that occurs at that point of the capsule. The book by Anderson Jr, John D. Hypersonic and high-temperature gas dynamics has been useful in this article for data references for high-speed flow [10].

The influence of additive manufacturing in reusable launch vehicles has been similar to the literature survey [11].

The overall integrated design aspects of a space transportation system like flight mechanics, propulsion, structures and materials, thermal systems, stage auxiliary systems, navigation, guidance and control and the interdependencies and interactions with other subsystems has been provided [12].

6. CONCLUSIONS

Using computational fluid dynamics, the launch vehicle can be optimized and the additive manufacturing process can be performed in the aerospace engineering production sector due to its remarkable benefits. The use of additive manufacturing technique in the production of reusable launch vehicle can be implemented only after the thorough optimization of the geometry and design using Computational Fluid Dynamics. The physical simulation of supersonic and hypersonic flows using wind tunnels can be achieved only for very short periods of time and hence computational flow simulation is the best alternative. From the analysis we can optimize that the material used for the manufacture of the reusable launch vehicle should be able to withstand more than 1220K of temperature and possess good structural stability. Further, additive manufacturing can be initiated for manufacturing the parts of a reusable launch vehicle.

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