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Design Consideration & Cost Optimization on Proper Choice of Material of Re-entry Vehicle

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Abstract

Re-entry involves the movement of an object from outer space; more specifically 'Re-entry vehicle' involves controlled entry of manmade space vehicle. Problems associated with re-entry includes atmospheric drag, high heat generation etc. Optimization of design, proper choice of material and appropriate heat resistance process together can resolve the crucial process. The scope of this paper deals with the design consideration due to high temperature developed by hypersonic speed and cost optimization based on CFD Simulation and proper choice of material. Using the simulation, amount of heat faced by different parts of the re-entry vehicle can be measured and using that result, material selection for different portions can be done accordingly.

Keywords: Reentry, Hypersonic speed, Ablative materials.

1. Introduction

The development of re-entry vehicles began in late 1950's due to need of development in the department of Defense and Central Intelligence Agency photo reconnaissance of soviet ICBM sites. NASA has also been involved in the use of re-entry vehicles since early 1960 including manned space program Mercury, Gemini and Apollo [1]. In the field of Aerospace Re-entry and its optimization is a very crucial term. Because safe return of astronauts and valuable equipment is an indispensable part of space mission. So the usages and necessity of Reentry vehicles grows higher with the increased number of space missions.

2. Atmospheric entry

Atmospheric entry is the movement of an object into and through the gases of a planet's atmosphere from the outer space. There are two main types of atmospheric entry, such as entry of astronomical objects or space debris (natural bodies) and controlled entry (or re-entry bodies) [2]. Controlled re-entry bodies have the technology for being navigated or followed a predetermined course.

3. Reentry vehicle

The type of vehicles which follows a controlled entry in earth's atmosphere at hypersonic speed at most of its flight and capable of being navigated and controlled are defined as Re-entry vehicle.
For Earth, Atmospheric entry occurs above Karman Line at an altitude of more than 100 km above earth surface.

4. Problems involving reentry vehicle

Re-entry vehicles face extreme adversities while proceeding into earth's atmosphere. The main problem involves hypersonic speed and effect of gravity which causes Atmospheric drag and Aerodynamic heating. Our atmosphere stats from 100 Km above surface of earth. It consists of different layers of gases, such as ozone, nitrogen and water vapor. While entering, reentry vehicles face hypersonic speed which causes extreme heat due to friction with atmosphere. High heat generation is also caused by creation of high aerodynamic drag. So, proper reentry procedure demands appropriate optimized shape and proper heat resistant method.

5. Design considerations

Earlier it was considered that in high speed flight vehicles sharp nose is desired while blunt nose is avoided. Because sharp nose avoid normal shock wave formation, eventually converts it into oblique shock wave. In traditional supersonic vehicles heat generation was not a major consideration. But as reentry vehicle is a hypersonic vehicle and experience extreme heat generation so design consideration involves heat resistance in its major parts. At present, most of the re-entry vehicles are blunt shaped. Due to this shape there forms a detached shockwave that provides a cushioning effect which helps to reduce the amount of heat, faced by the re-entry vehicle during re-entry.

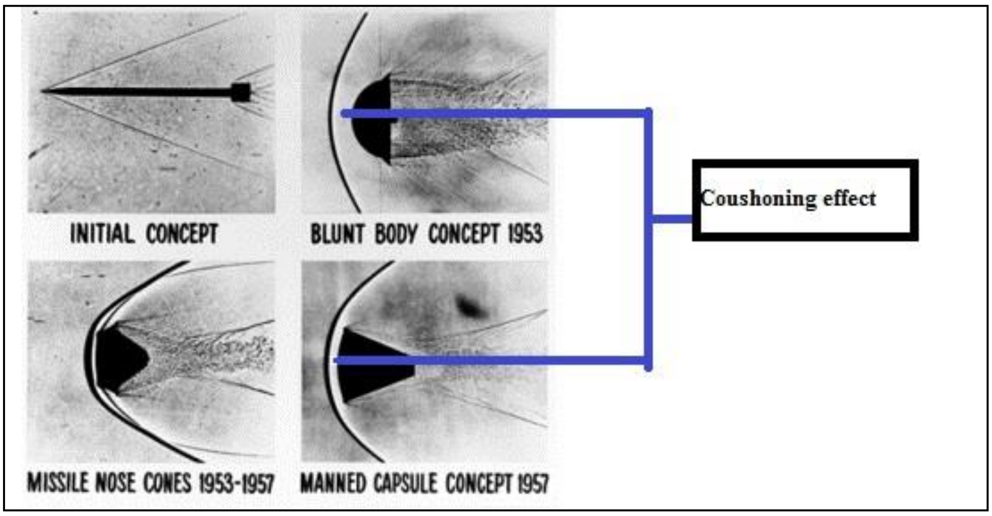

Fig. 1. Different shapes of re-entry vehicle & effect of shockwave

The following are the characteristics of hypersonic vehicle design.

- Very small frontal area and highly streamlined shape to minimize the total surface area.
- Very little wing area But fuselage is shaped to generate additional lift.
- Propulsion assembly highly integrated to the vehicle.

Another problem is low L/D ratio. This is due to the blunt shape of the vehicle as well as the high mach number. Kuchemann gave the general empirical relationship between L/D ratio and mach number from his analysis:

$(L/D)max = 4(M\infty+3)/M\infty$ ………… (1)

So, lift to drag ratio decreases with the increase in mach number. A waverider can be a solution to this problem.A waverider is hypersonic aircraft design that improves the lift to drag ratio by using the shockwave generated by its own flight as a lifting surface. This phenomenon is known as compression lift. Another important task is the choice of heat protection system. Heat shield, use of ablative material and UHTC is possible solution. Heat shield process involves providing cushioning effect by its variation of structure [3]. Another method is use of Ablative material and UHTC. Ablative material burns itself but protect the main vehicle. While UHTC has high heat resistance property which protects the vehicle from extreme heating, the usage of those materials throughout the entire vehicle cost huge money. It's a major point of consideration.

6. Thermal protection for re-entry vehicle

There are three thermal protection concepts: passive, semi passive, and active. The type of protection on any space-venturing vehicle or, more precisely, on any given area of a vehicle depends largely on the magnitude and duration of the heat load as well as various operational considerations. As the name implies, passive thermal protection systems have no moving parts. They are the simplest but, until the advent of the Space Shuttle, had the least capability. These concepts have fallen into three general categories: heat sink, hot structure, and insulated structure. There are two basic semi passive concepts. Heat pipes are attractive where there is a localized area of high heating with an adjacent area of low heating. The other semi passive concept is ablation. Ablation is a process in which a material (ablator) sacrifices itself to protect the underlying structure [4].

Hypersonic flight vehicles operating at higher speeds and altitudes are being developed day by day. The advances in propulsion systems, aerodynamics and flight control design have allowed flight vehicles to technically operate at speeds beyond mach 5. However, many problems still exist with various materials due to aerodynamic heating and shock wave interactions. This results in high temperatures which can burn the vehicle. This increased heat complicates material selection and aerospace manufacturing since an efficient thermal control system must be inherent within the design structure of reentry vehicle. In reentry vehicle ablative material will first act as a heat sink. As a critical temperature is reached, a thin layer of material at the surface will begin successively to melt, vaporize, depolymerize or decompose chemically. Exotic materials are being developed and employed to withstand the harsh environments associated with reentry vehicles. Ablative heat shield and UHTC can be used too. The ablative heat shield lifts the shock layer gas, away from the outer wall of the surface of the vehicle. In this way, ablative heat shield protects the vehicle. When the outer temperature drops below the minimum, necessary for the effectiveness of ablative heat shield; in that case, thermal soak is used. In this case, we have to consider the cost efficiency of the materials. So, proper choice of material is important for the protection of the re-entry vehicle as well as overall cost efficiency.

7. CFD simulation

The front portion of a blunt shaped reentry vehicle was taken for flow simulation.

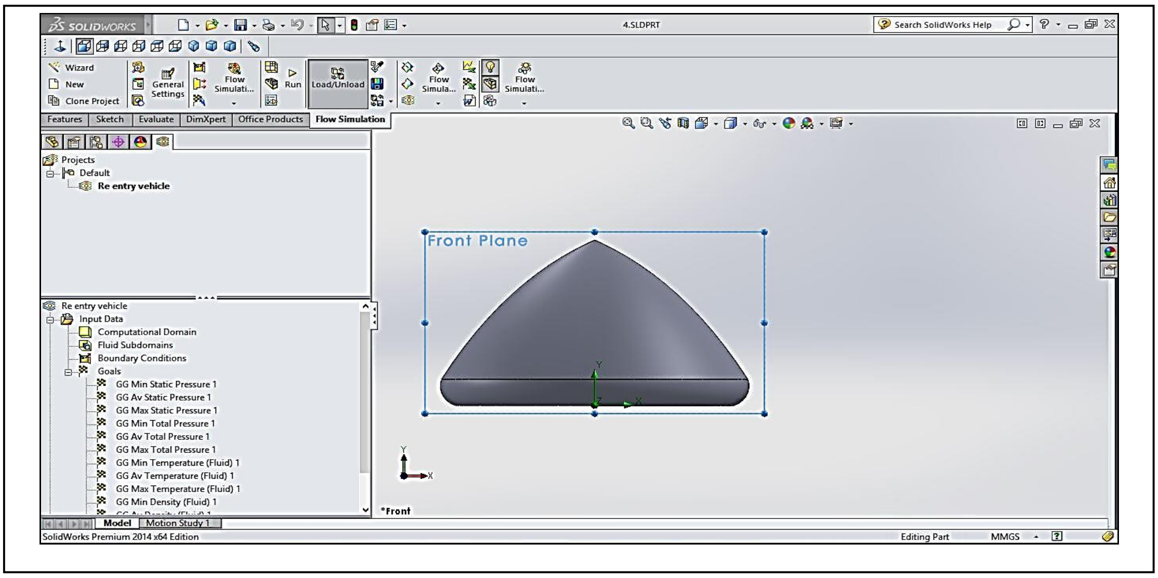

Fig. 2. Drawing of the front portion of the re-entry vehicle in Solidworks

'Solidworks Flow simulation' was used to observe the condition of re-entry vehicle during atmospheric re-entry. At first the following model was drawn.

Then we took this model to the Solidworks flow simulation wizard. We chose the Standard Unit (SI-Unit) and the analysis type was external flow.

Physical feature: Gravity

Fluid: The fluid was selected "Air" and "Humidity" was enabled.

Flow Type: Flow type was selected both laminar and turbulent.

Initial and Ambient condition:

Parameter definition: User defined

Thermodynamic Parameter:

Parameter: Pressure, Temperature

Pressure: 101325 Pa

Temperature: 293.3K

Velocity Parameter

Parameter: Mach number

Mach number: 10 Mach

Turbulence Parameter:

Parameter: Turbulence intensity and length

Turbulence intensity: 1 %(default)

Humidity:
Relative Humidity: 50%
Reference Pressure: 101325Pa
Reference Temperature: 293.2K
Result & Geometry Selection:
Result resolution: Level-5
Output Goals:

- Temperature
- Pressure

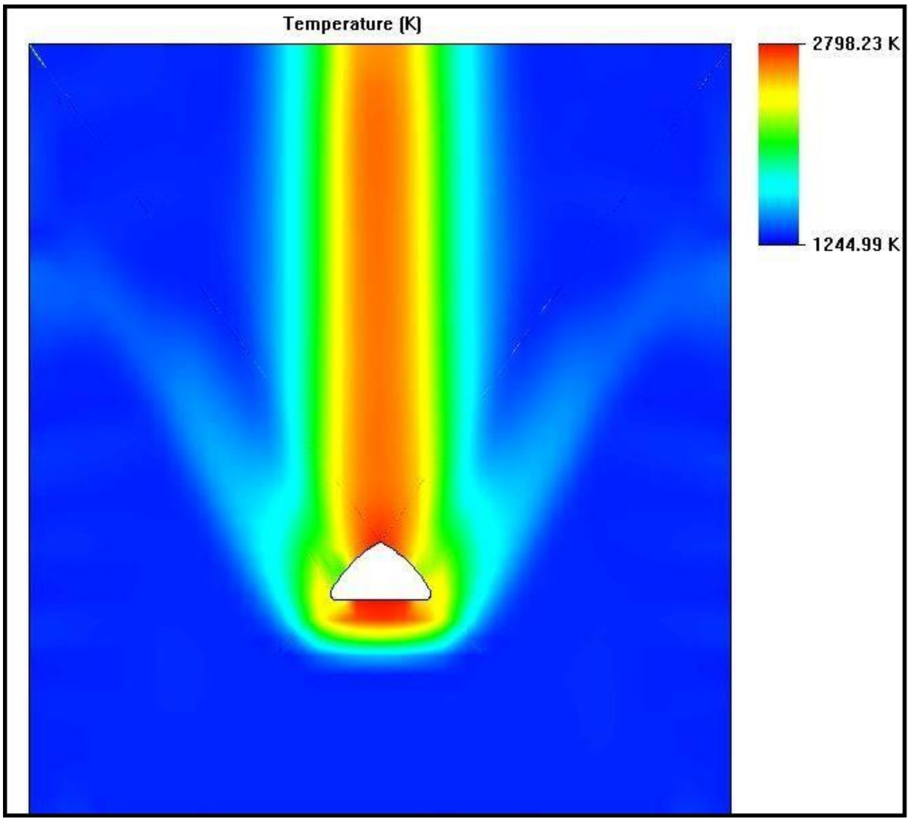

Fig. 3. CFD simulation for reentry vehicle for given conditions

8. Result

From the simulation, we can see that, the amount of heat faced by the reentry vehicle varies in different parts. Different parts face different amount of heat. It is an important issue. We can use this idea in case of material selection as well as reducing cost.

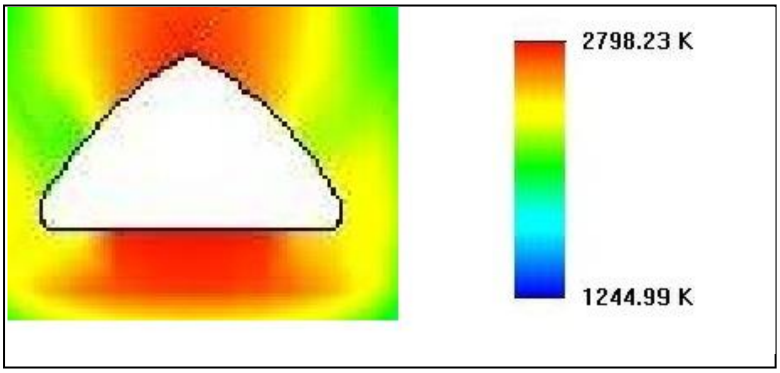

Fig. 4. Zoomed view of the front portion of re-entry vehicle during re-entry from previous figure

From the figure, we can identify some range of heat that is faced by the re-entry vehicle. We can use different materials, composites, alloys and combination of these for the reentry vehicle. For this we need to consider the amount of heat range faced by different parts of the reentry vehicle. From simulation we can divide the reentry vehicle surface into different parts according to temperature ranges.

Table 1. Temperature range for different portions of the re-entry vehicle

Temperature Range	Temperature (K)
Range 1	3800-2900
Range 2	2900-2500
Range 3	2500-1700

9. Discussion:

Materials are generally classified for use depending on the temperature range in which they can operate continuously on the reentry vehicle. We can use different types of materials for different parts according to the temperature faced by that specific part(s) during atmospheric reentry. For this we have to consider the availability of the material at the same time production cost associated with it. We can use different types of materials which is an alternative way to reduce cost and at the same time increase efficiency.

Materials for range 1 can sustain almost 3800k temperature. Materials having melting point from almost 3800k-2900 k can sustain this amount of heat. Metals like Graphite (melting point 3922k) [5], Tungsten (melting point 3695) can be used for range 1 portions. For range 1 we can also use Diboride based compounds: Hafnium Diboride and Zirconium Diboride. $HfBr_2$ and $ZrBr_2$ are both relatively new ceramic compounds that hold great potential for replacing traditional thermal protection systems in atmospheric reentry vehicles. They possess a remarkably high melting point of approximately 3473k. They are classified as Ultra High Temperature Ceramic Composites (UHTCs) [6].

For range 2 we can use Molybdenum (melting point 2896k) or any other combination of range 1 & range 2 materials. For range 3 we can use metals like Titanium (melting point 1941k), Zirconium (melting point 2128k), or Nickel (melting point 1728k). We can use different alloys to sustain the temperature of Range 3 .Titanium-Zirconium-Molybdenum alloy possess high recrystallization temperature up to 1873k and higher strength compared to many current super alloys. Although the cost of TZM alloy is 25% greater than that of Molybdenum, the manufacturing cost far outweigh this disadvantage as other exotic high temperature materials requiring elaborate machining tools and treatment processes, which consume a large amount of time and cost. Metal matrix composites can be used for range 3. Titanium metal matrix composite is capable of withstanding thousands of hours of cyclic loading in an oxidative e environment. This makes TMC an excellent candidate for its use in reentry vehicles since temperature can reach as high as 1922k as well as fluctuates by several hundred kelvins. [6]

Besides, researchers are investigating about the use of high temperature multi layer insulation technique. This is a low volume, light weight, multi layer foil insulation that has maximum heat capabilities up to 1900k which can be used too. [7]

10. Conclusion:

Material selection & cost optimization are two of the most important facts in case of a re-entry vehicle. From the simulation we can identify the range of amount of heat, faced by different parts of the front portion of the re-entry vehicle. Using that range we can choose different materials for different parts which will be easier and cost effective.

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