Analysis of materials used for re-entry vehicle

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Abstract*— The surface heating of re-entry vehicle is due to convection. Laminar boundary layer over the body is required. Turbulent layer increase overall heating. So the material surface should not contain any gap or discontinuities. The surface should have high emissivity, high thermal resistance. The very high temperature in front of the vehicle is reduced by the presence of bow shock wave. The region between the body and shock layer undergo endothermic reaction and a result temperature is utilized to do the chemical reaction. The material should have high thermal insulation property-tiles, reinforced carbon-carbon etc. A low density material may lack tensile strength to resist spallation if dynamic pressure is too high. A layer of fluid is allowed to circulate over the body of the vehicle which acts as a coolant. Aerodynamic heating is the major problem faced during atmospheric re-entry. In order to overcome the aerodynamic heating problem we use thermal protection system. Thermal protection system has high strength, low density, high thermal resistance. So after the analysis we found that super alloys and Nano materials are best for re-entry vehicle.

Keywords —*convection, emissivity, thermal resistance, aerodynamic heating, thermal protection system*

1.INTRODUCTION

Atmospheric re-entry is the entry of an object from the outer space to the earth atmosphere or atmosphere of outer planet. The portion of a spacecraft which returns back to earth is the re-entry vehicle. During atmospheric re-entry the major problem faced is aerodynamic heating and atmospheric drag. Space craft , missiles, satellite and space probe travel at high velocities several times than speed of sound (Mach No greater than 5).[10,11] Increase in velocity decrease the thickness of the velocity boundary layer. This results in the velocity gradient near the wall and hence the viscous stresses decrease. The kinetic energy of the fluid stream results in an increase in internal energy of the fluid near the wall. This results in increase in the temperature of fluid near the wall and increase heat transfer to the wall. This is called aerodynamic heating. Due to skin friction, on the surface of the body, the kinetic energy is converted into heat.[9]

The velocity of a hypersonic vehicle is assumed to be hypersonic. The gravity of earth is an important factor which causes major physical changes and physical phenomenon to the vehicle. The natural thermal resistance depends upon the shape of the re-entry vehicle.[10] While comparing streamlined and blunt body concepts it is clear that blunt body offers natural thermal protection to a large extent. Since re-entry is at hypersonic speeds the vehicle should not be streamlined. During re-entry high heat energy is produced by the vehicle because of high speed and the lethal to the vehicle.[11] The shape of the re-entry vehicle should not be streamlined because the ballistic coefficient of streamlined body is very high. So the shape should be blunt , because ballistic coefficient is low for blunt body.[9,10,11]

Aerodynamic heating mainly depends upon

- Entry speed
- Shape of vehicle
- TPS material composition
- Properties of surface
- Atmospheric condition
- Trajectory path

One of the main reason for aerodynamic heating is convection. Another parameter which should be considered is g- loading. In order to protect the vehicle from the heat we use thermal protection system. The re-entry vehicle is purely a blunt body. Blunt body when travels with hypersonic speed will produce a bow shock wave. A bow shock wave is a combination of both normal shock and oblique shock. If we use streamlined body, then only oblique shock is produced. This will not be suitable for re-entry. The bow shock wave produced is the major reason for drag and aerodynamic heating. The re-entry vehicle is usually non-ballistic in nature, which means it doesn't use any engine.[8]

2. HEAT TRANSFER AT HIGH SPEED

In high speed flow, it is to be expected that the magnitude and direction of the heat transfer at the surface will depends on the difference between the wall temperature and the adiabatic wall temperature.[11] That is T_w is less than T_{wad} there will be heat transfer from fluid to the surface while if T_w is greater than T_{wad} the heat transfer from surface to fluid. It is usual in high speed gas flow to write[9,10,11]

$$Q = h A(T_w - T_{wad})$$

3. RE-ENTRY PROBLEMS

Re-entry problem does not occur in every space mission. Most satellite launches are one way mission and they go away from the earth and out of its atmosphere.[10] For LEO satellite re-entry may occur after useful life time.[11] For very high orbits re-entry may never occur. Satellites in general are not designed to survive the extreme forces and heat loading that occurs during re-entry.[9]

3.1 LARGE TEMPERATURE GRADIENT- THERMO STRUCTURAL CHALLENGES

A thermo structural challenge is related to the occurance of large thermal gradients. For instance in a cryogenic tank containing liquid hydrogen as a fuel , the liquid hydrogen will be at a temperature about -250^0 C and the outer surface of the thermal structure might be at a temperature between 1100^0 C and 1700^0 C. As different materials have to operate at a wide range of temperature, attaching various components (tank, insulation, structure, TPS etc) which expand and shrink, becomes a real challenge. In addition, production costs, life cycle and inspection need considerations.[12]

4. HIGH TEMPERATURE COATING

High temperature coatings based on SiC can be used up to about 1700^0 C. For higher temperature, different materials such as carbides, oxides and diboxides of Hf and Zr can be used. The later one can be used as part of composite matrix, Iridium, Ir is regarded appropriate for coating. The thermal conductivity of the material may also affect the surface temperature as carbon fiber is used and woven in various architectures.[12,13]

5. SURFACE EMISSIVITY OF HIGH TEMPERATURE MATERIALS

Surface emissivity is another important parameter affecting the surface temperature. In free space, absence of conduction and convection represents a unique heat transfer problem. In high vacum conditions, the molecules are few and far apart and can only transport a negligible of energy. Therefore thermal radiation is the only significant mode of heat exchange. A space vehicle can exchange radiant energy with sun, with a nearby planet such as earth and vast expanse of outer space.

6. HOW TO SELECT A APPROPRIATE MATERIAL?

- High capability material
- Material should be reusable
- Material must be test in relevant environment
- Ablative material

7.HIGH TEMPERATURE MATERIAL

The mentioned requirements have led to new approaches for the thermal protection and development of new material system is necessary to improvise the vehicle. For hypersonic air breathing vehicles the material must have high temperature capability, high strength at elevated temperature, high toughness, light weight and environment durability. A requirement for the materials is that they should maintain a high specific strength (strength divided by density) at elevated temperaure. Metallic based options include metallic matrix composites (MMCs), super alloys and titanium. At higher temperature, ceramic matrix composites (CMCs), carbon-SiC material, advanced carbon-carbon (ACC) and SiC-SiC provide high strength.[6]

8. THERMAL PROTECTION SYSTEM (TPS)

To protect the people and re-entry vehicles we introduced thermal protection system (TPS). Thermal protection system acts as a protective covering for the re-entry vehicle with a temperature of 1650^0C (3000^0F) heat at the time of atmospheric re-entry .The following are the TPS used in re-entry vehicles:[6]

8.1REINFORCED CARBON-CARBON

It can withstand temperature up to 2300 F during atmospheric re-entry. So mostly used in leading edge, wing, nose cap etc. It is a composite material consists of carbon fiber and matrix of graphite with reinforcement. It has extremely low coefficient of thermal expansion, high fatigue resistance,low density. Reinforced Carbon-Carbon composite is an amorphous carbon matrix. Both reinforcing fibers and matrix are pure carbon

- Excellent thermal shock resistance
- Low density (1830 kg/m^3)
- High modulus of rigidity(200GPa)
- High thermal conductivity(100W/m^*k)
- In Non oxidizing atmosphere it should have thermal resistance

8.2SLA-561V

SLA stands for super light-weight ablator. In this SLA-561V has been used as primary thermal protection system vehicle on all of the 70^0 of sphere cone entry vehicle. SLA-561V is applied to the ablative material inner the honeycomb cave, is rebounded to aero shell's structure.

8.3PLCA

It stands for phenolic impregnated carbon ablator, PLCA , a carbon fiber is applied in phenolic resin. It is a modern thermal protection system. It has a main advantage of low density that is much more lighter than the carbon phenolic. In this PLCA, when compared to other high heat flux ablative material, it has low thermal conductivity like convectional carbon phenolic.

8.4 HRSI

High temperature reusable surface insulation is one of the tiles used in the underside of the orbiter, where the tiles are coated with Li-900 silica ceramics. When the re-entry temperature was below 1200^0 C , then HRSI is used.

8.5 LRSI

Low temperature reusable surface insulation is another type tile mainly used on the upper part of the fuselage but sometimes it is used instead flexible insulation blankets. It is used where the temperature was below 649^0 C (1200^0 F)

8.6NANOMATERIALS

A material in which the size of the single unit lies between 1 to 1000 nanometres is the nanomaterial. As the size of the material is very small they have large exposed surface area which has variable applications better platform for occurring the chemical reactions . [20]While using nanomaterial for designing various parts in spacecraft, the overall efficiency of the vehicle can be increased by reducing the weight of the vehicle, safety and performance. The nanomaterial can have high damage tolerance.[19]

The re-entry vehicle is travelling at hypersonic speed and hence it produces a bow shock wave, as its shape is not streamlined. The presence of the bow shock wave introduced high drag and aerodynamic heating.[22] At higher temperature between the shock wave and vehicle, certain chemical reaction occurs, which is endothermic in nature. During this time radiation heat transfer reaches its peak and which damages the re-entry vehicle. So the material used for manufacturing the vehicle is important. The coatings

provided using nanomaterial can prevent the radiation heat transfer to a large extent. It also helps the protection system used in the vehicle and reduces fouling. [20]

Nanomaterial coating provides a barrier to oxidation, improved wear resistance and increase the detector properties. NASA developed the concept of thermal, radiation and impact protective shields (TRIPS). Nano texturing of surface includes superfine topographical characteristics to the vehicle. The adhesiveness can be reversible if we use nanomaterial. This helps for low cost servicing and inspection of spacecraft. [19]

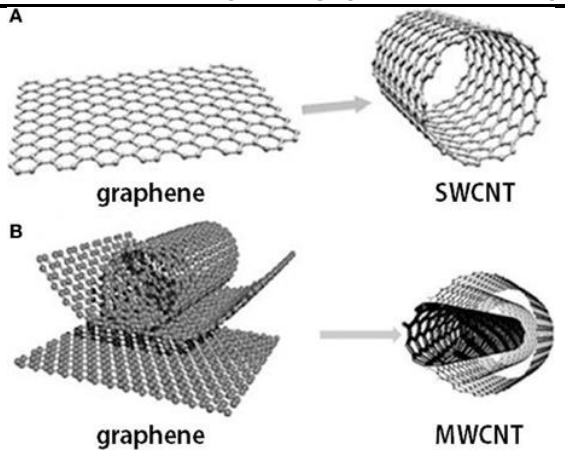
Char formation and stabilization are the important concepts of ablative materials. Char usually acts as a thermal protection layer for the layers under it. If char integration is not done perfectly it will lead to spallation and erosion. If char spallation and erosion will not occur, then the use of the ablative material also decreases. If we use nanomaterial instead of the conventional ablative materials like carbon-phenol, half of the weight can be reduced.[22]

The performance of the electrode of the battery can be increased with nanomaterial due to its large surface area, short diffusion length, higher ionic conductivity, safety and long life. Nanomaterial like carbon allotropes, alloys, metal-oxides have higher quality to use as the electrode. They assure higher power density than conventional batteries. Large surface area helps to faster redox mediated electron transfer.[19]

Use of nanomaterial in electronic components like sensors Provides in-situ and real-time monitoring with greatly improved sensitivity. Use of nanomaterial for the construction of electric components provides higher efficiencies at extreme operating temperatures and in radiation environments. It helps to reduces the power consumption as well as it reduces the weight of the components. Nanotechnology could introduce low volume, less invasive sensors and actuators with high performance. The sensitivity of sensors which uses the nanomaterial is high. It helps for the rapid detection of the ultraviolet, gamma and neutron radiation, fuel leaks and monitor the cabin air.[21]

- **Single wall carbon nanotubes**

One of the unique properties of this material is high strength. They are made up of light weight fibres and composites. They have high thermal conductivity. Radiation is the most important mode of heat transfer at higher temperature and hence the same is predominant in re-entry vehicles also. During radiation, electromagnetic waves are used to transfer the heat from one system to another system. They have high aspect ratio.[19]
They can be used in fuel cells, capacitors. They can be used as thermal protection materials and can be used to make sensors and emission display.[20]



Disadvantages of nanomaterial

High cost is one of the major disadvantages of the nanomaterial. The manufacturing of nanomaterial is costly and it is difficult. The ground test facilities are also limited. The implementation of the actual flight condition is challenging. Growth mechanisms are not thoroughly understands. Characterisation tools and techniques are not well developed for the single wall carbon nanotube.[22]

8.9 AEROGELS

They are low density, low thermal conductivity materials which can be used for various space applications. Since they have poor durability and poor mechanical properties uses is less in space application. It acts as a good thermal insulator and hence can be used in spacecraft for insulation purpose. The aerogel packed in composite box is called warm electronics boxes and can be used to protect the batteries, computer and other electronic components. Space shuttle uses cryogenic oxygen and hydrogen which means both the oxygen and hydrogen should be kept in the liquid state. Aerogels helps to keep the fuel in liquid state. They help to make fire resistant space suit.[21, 17]

8.10 TANTALUM CARBIDE AND BAFNIUM CARBIDE

The re-entry temperature during re-entry is of approximate 1649^{0} C. so we need to withstand this high amount of temperature. Tantalum carbide and bafnium carbide can able to withstand approximate 4000 ^{0}C.so we can safety ensure these material for hypersonic space vehicle or re-entry vehicles. These materials are refractory ceramics where they can able to withstand high temperature. We know that during re-entry (M=35) generate high temperature due to friction. Tantalum carbide Tacs and hafinum carbide Hfc can able to resist extreme heat generated, so it is anefficient material for us to make re-entry vehicle. Mainly we can use these materials for nose cap in re-entry vehicle (since temperature effect is high for nose part in re-entry vehicles). Their melting point is high enough than any other material (approximate 3800 ^{0}C for Hfc and Tac), make it as a good quality material for us to used for re-entry vehicle manufacture. So in future these

material plays an important role in spacecraft and re-entry vehicle.[8]

8.11 NOVEL NON-METALLIC- CORK

CORK is a major material for spacecraft. Its property like low density, low thermal conductivity, fire resistant and high heat absorbtion help us to use the material in re-entry vehicles. These material can use as a ablative material on re-entry vehicle due to its physical structure. So the use of ablative material help us to protect aerodynamic heating during re-entry into atmosphere. Cork material is made up of 90 % of gas and is a structure made up of dead cell, and each cells has a polyhedron of diameter (30 to 40m). as we know that the chemical reaction during re-entry reduces temperature effect on re-entry body. Also the charred layer act as good insulator, it has also good emissivity, thus the surface is eroded in the flow of passing air, thus we can able to dissipate heat away from the structure. Coke can help us to reduce friction effect on re-entry vehicle during re-entry. Coke can able to withstand re-entry temperature.[2]

8.12 NOVEL HYBRID ABLATIVE / CERAMIC LAYERED COMPOSITES

We require new thermal protection system to attain safety for astronauts as well as re-entry vehicles. Thus for future exploration at very high speed we want a system which resist high temperature than present. Hybrid TPS provides an extra layered ablator ceramic composite material for the protection of the metallic substructure in oxidative and high temperature for our new thermal protection system method. They prospective advantages is that, they have thinner ablative layer which can able to withstand very high surface heat loads and the tough ceramic composite underneath provides structural support, and this property help us to establish a special type shield shape which is an asset for aerodynamic performance(like shock formation, boundary layer formation) during re-entry. The main point is to be noted that heat loads are characterised by heat flux peak profile, which ensures or dissipate high heat loads during the peaking time materials(for hybrid or ablative layered composites). Ceramic matrix composite was delivered as plates and is consist of carbon fibers embedded in a silicon carbide matrix, which help us to make it strong for high temperature effects on re-enrty vehicles. The production of this process (material) is based on polymer infiltration pyrolysis process (PIP). The abrative material consist of carbon fibers (55-80%) and phenolic resin(20-45%), which makes it tougher to resist high temperature.[3]

8.12 POLYMERS

The properties in thermal condition make polymers to use in re-entry vehicles or spacecraft due to their long chain structure and molecular architecture make it different from metals and ceramics.[4] Polymers are mainly used for production of thermal blankets and thermal control paints which helps to reduce temperature effect on re-entry vehicles. Thermal blankets are used to regulate the temperature of most re-entry vehicles. The polymer film in thermal blanket reduce the effect of temperature((1)by absorbing sunlight using carbon black)((2) it also coated with a layer of vapour deposited aluminium which reflect sunlight reduce effect of temperature.). thermal blanket is a necessary product to regulate the temperature conditions in re-entry vehicle.[16]

Thermal control paint's also used to regulate temperature in the re-entry vehicles.[16] The paint consist of either black or white pigments dispersed in an organic or inorganic binder (material that hold or draws other material together to form a cohesive force), which have high emissivity and used to reject excess heat back into space or atmosphere. [16,4]The main point is to be noted that black paints are used to absorb sunlight and maintain the spacecraft at warmer temperature, while white paint have low solar absorbant and temperature is kept low enough to prevent over heating.[4]

Thermal blankets and thermal control paints helps re-entry vehicle to reduce thermal (temperature) effect and also act as protective layer for structure of re-entry vehicle.[4]

8.13 NANO PHOTONIC MATERIAL

Nano photonic materials helping to push re-entry vehicle closer to speed of light. Nano photonic material helps to achieve to go to other planets and return to earth. It is made out of Silica and its oxides, silica. The principle of Nano photonic materials is that the two by products convert into super thin structure could make conversion of infra red light into a momentum, that would accelerate a probe to speed of round 60000km/h (which is approximately 20% speed of light) in terms of temperature effect (heat), photon absorbs energy and emits quickly it as in form of radiation, many materials do not have this property (like aluminium and graphite). Light absorption(energy) and emission is very quick here, thus we can neglect the chance of over heating during light speed(approximate) so with the help of Nano photonic materials, we can easily able to achieve many space related project fastly in future days.[5]

8.14 INCONEL ALLOY 625

INCONEL ALLOY is a special type of alloy which is made from MOLYBDENUM And NIOBIUM on it's nickel-chromium matrix. The properties like high tensile, creep, rupture strength, excellent weldability and brazeability makes it perfect for aerospace industry. It is a high corrosion resistant alloy. The important feature of INCONEL ALLOY 625 has a good resistant to oxidation and a scaling at high temperature.[7] It has a special ability that, it can provide a protective oxide coating under drastic cyclic conditions. It can be used for micro structural evolution and thermal stability. This alloy can able to produce LASER DEPOSITION, which helps to find cracks, bonding error and porosity. The grain structure formation in microstructure also can be identified by this alloy. THE INCONEL ALLOY 625 plays an important role in manufacturing and finding defects in aerospace industry. The density is about 0.305 kg/m^3 and melting point is 2350 – 2460 ^{0} F (1290 – 1350) ^{0} C.[7]

9. CONCLUSION

In the analysis of materials used in re-entry vehicle we found that the material should have low thermal conductivity, low density, high strength, high tensile, creep and rupture strength, outstanding fatigue and thermal fatigue strength, oxidation and resistance thermal resistance etc. After the analysis we conclude that the material which is more suitable for re-entry vehicle is super alloys and Nano materials, due its properties. Both the materials super alloys and Nano materials can able to withstand maximum temperature. And the only disadvantage of both materials are high cost.

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