Development of Thermal Protection System for Re-Usable Launch Vehicle

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ABSTRACT

The Thermal Protection System of a Reusable Launch Vehicle is the hardware that is used to guarantee the structural integrity of aircraft from various forms of heat sources such as Atmospheric Friction, Engine Exhaust and Hot Particles. Exploring our nature, one of the most basic substances that could be used to overcome this problem is sand. It has the capacity to sustain extremely high temperatures during the day and frigid temperatures during nights. Using this science as the basis new technologies have come up with the idea of Thermal Protection Systems. In this review paper we would be discussing about various methods used for development of Thermal Protection. With a deep dive into Material Sciences, the paper deals with Metallic TPS which consists of superalloy honeycomb. This technology deals with improvements for more efficient internal insulation and a simpler light weight configuration. The second part would deal with soft objects, which is developed and used to assign an almost arbitrary distribution of insulation materials over vehicle surface. Analysis was done by implementing one or multidimensional models when TPS was subjected to low speed impact, hypervelocity impact, rain corrosion testing and arcjet exposure.

Introduction

Introduction Space exploration has long been a pinnacle of human achievement, pushing the boundaries of our scientific knowledge and technological capabilities. One of the most significant challenges in this endeavor is the safe and cost-effective transportation of payloads and astronauts to and from outer space. In pursuit of this goal, reusable launch vehicles have emerged as a revolutionary concept, promising to revolutionize space access by reducing the exorbitant costs and environmental impact associated with expendable launch systems. At the heart of every reusable launch vehicle's success lies the Thermal Protection System (TPS), a critical component responsible for shielding the vehicle from the extreme heat generated during reentry into Earth's atmosphere. The TPS serves as the first line of defense, ensuring that the vehicle and its occupants remain unharmed as they reenter the Earth's atmosphere, traveling at velocities that can exceed Mach 25. The extreme heat generated during reentry results from the tremendous kinetic energy conversion into thermal energy, primarily due to air compression in front of the vehicle. The temperatures experienced by the vehicle's surface can reach several thousand degrees Celsius, and this intense heat can lead to catastrophic failure if not adequately managed. This paper aims to explore the evolution and advancements in TPS technology within the context of reusable launch vehicles. As space exploration has entered a new era marked by commercial ventures, international collaboration, and a growing interest in human colonization of other celestial bodies, the significance of TPS in ensuring the safety and sustainability of these endeavors cannot be overstated. The development of efficient, durable, and cost-effective TPS solutions is pivotal in achieving the goal of routine space travel, making it accessible to a broader range of applications. The historical background of TPS development for space vehicles can be traced back to the early days of human spaceflight, with the heat shield of NASA's Mercury and Apollo missions serving as precursors to the technology required for reusable launch vehicles. Since then, numerous advancements have been made in TPS materials, design, and manufacturing techniques, driven by the need to extend the operational life of reusable launch systems while minimizing maintenance and refurbishment costs. In this paper, we will delve into the fundamental principles of TPS design, explore the various materials used in TPS, and discuss the challenges and innovations that have emerged in this field. Furthermore, we will examine the role of computational simulations, testing methodologies, and lessons learned from past missions to enhance the TPS's reliability and performance. The future of space exploration, particularly with respect to ambitious plans for lunar landings, Mars missions, and beyond, hinges on the success of reusable launch vehicles and their TPS. This paper aims to shed light on the latest developments in TPS technology and the crucial role it plays in making these missions not just viable but also economically sustainable. With continued advancements in TPS, we are poised to witness a new era of space exploration that promises to benefit humanity and the planet in myriad ways. In the subsequent sections of this paper, we will dive deeper into the history, design principles, materials, challenges, and future prospects of TPS for reusable launch vehicles, ultimately providing a comprehensive understanding of this critical aspect of space travel.

LITERATURE REVIEW

Yao Caogen (et.at, 2008) said ,TPS are a key technology that may help achieve the goal of reducing the cost of space access for RLV.A pivotal facet of this exploration is the fabrication of a Ni-based superalloy honeycomb TPS panel, underscored by encouraging thermal insulation results.Ni-based superalloy honeycomb sandwich is maintaining lower surface temperatures even when subjected to elevated outer surface temperatures.

Delma C(et.al,1997) said reliable space transportation is a major focus of current government and commercial launch industry efforts. This paper reviews the current status of the RLV technology program including the DC-XA, X-33and X-34 flight systems and associated technology programs.

Delving into the collaborative endeavors within the Industry/NASA domain. This collaborative pursuit is acutely attuned to the imperatives of designing, testing, and developing technologies that culminate in commercially viable launch systems meeting national needs at sustainable recurring costs. A testament to the strides made in comprehending the technical intricacies of fully reusable launch systems.

Burkhard Behrens (et.al, 2003) state that EADS ST is developing and qualifying TPS components and technologies for a wide range of applications and temperatures. And the Major steps are the reduction of the launch mass of such a system and the optimization of the operational costs and EADS ST has been working on the development of TPS for more than 15 years. They using new advanced Titanium-Aluminium (γ-TiAl) alloys and Oxide dispersion strengthened (ODS) super-alloys. It's higher limit temperature may now significantly reduce the specific mass of this metallic system

Lü Hongjun (et.al, 2008) states that RLV will greatly reduce the cost of launching a payload into space [1-7]. Metallic thermal protection systems (TPS) are a key technology that may help achieve the goal of reducing the cost of space access for RLV.The honeycomb sandwich is made of the GH4141 nickel-based superalloy foils.And also low maintenance costly than competing system.

T. Pichona,∗ (et .al ,2009) it studies the objective of increasing the technology readiness level (TRL) of technologies applicable to future reusable launch vehicles .the mechanical testing and dynamic validation performed on the panel, that The panel has successfully withstood a severe pressure differential load (130mbar), as well as very demanding sine and random vibration loadshis test campaign strongly enhances the validation level of this TPS technology.

Melvin J.Bulman (et.al, 2000) said we can increase the rocket's thrust by adding mass and releasing chemical energy in the rocket's nozzle. In this paper, they discussed hot-fire testing and compared CFD performance. This LANTR is a hypothesis, in which, Thrust from an NTR can either be tripled or quadrupled. The main benefit of this concept is higher thrust will be provided with a small nuclear reactor. At last, This LANTR concept increases thrust by over 40% to arouse nuclear-heated hydrogen.[1]

Scott Forde(et.al, 2005) In this paper, they have discussed the TAN (Thrust Augmentation Nozzle) hypothesis. The authors patented this concept to authenticate elevation sea-level thrust. This TAN concept is a supplement to augmented Nuclear Thermal Rocket(LANTR). This concept allows for a high lift-off thrust.[2]

Lt. Col Timothy Lawrence(et.al, 2005) said many developed systems which were used in the olden days are currently in use. Added to a conventional chemical rocket, The higher resultant thrust, and specific impulse will not be feasible. If we consider a nuclear reactor, which can directly heat the propellant or create nuclear electricity.[3]

Samit K. Bhattacharya (et.al, 2011) This paper discussed the basic idea of developing a Nuclear Thermal Rocket. He has said some challenges of developing nuclear rockets. Apart from challenges, The main purpose is an overview sense to approach the basic layout of NTR.[4]

David R. McCurdy (et.al, 2012) As a nuclear thermal rocket generates high thrust and high specific impulse around 900 seconds than chemical rockets. It's been considered as next step in evolution. They have discussed how this NTR propulsion is going to be the next evolutionary step for Human Space Exploration.[5]

Stanley K. Borowski (et.al, 2013) discussed past achievements, current efforts, and future expectations of Nuclear Thermal Propulsion. Especially, This paper focused on the use of NTP for Human Space Exploration. He further discussed controlling NTR during its start-up, full thrust, and shutdown. He concluded with the future testing of small, scalable NTR.[6]

V. Krishnamurthy (et.al, 2013) said, currently, this chemical and electric propulsion technology is limiting the chances of inspecting the other planets. He also said the operating fundamental for gas core Nuclear Thermal Rocket propulsion. Thrust to Weight ratio will be increased by supersonic combustion of oxygen and this triggers to augment and thrust will be varied.[7]

Michael L.Blair(et.al, 2013) in his paper, the authors created 4 NTR Model in NPSS Which has been further divided into 2 categories. They analyzed the working factors like thrust augmentation, specific impulse and etc…, The main aim of this work is to analyze operation and system performance.[8]

John. R.Bucknell (et.al, 2015) propose a new Nuclear Thermal Turbo Rocket for eath orbit applications. He said the propellant thermal flow of a chemical rocket is comparably high to the thermal power of a reactor. Therefore, Thrust to the ratio is far low. The early Nuclear Thermal Rocket project demonstrated 5:1 Thrust- Weight. At low Mach numbers, sufficient thrust will be produced in this NTTR.[9]

Seung Hyung Nam(et.al, 2015) said nuclear propulsion is one of the best ways to conquer the hard environment of space. Due to its high thrust and efficiency, NTR is a choice for space missions to Mars. This paper introduced some principles of nuclear thermal propulsion and they also introduced a concept with the help of NTP'S design features.[10]

Francisco J. Arias (et.al, 2016) The aim of this paper is to see the advantage when pulsing NTR in respect of thrust and specific impulse. The proposed postulation is to evaluate the NTR. By increasing propellant mass flow rate, There will be excessive use of energy in thrust augmentation. The author said, In a static mode, the rising thrust will not be a good idea when the power is limited.[11]

Paolo Venneri (et.al, 2017) this paper describes the design of LEU-NTR. They have also compared the two thrust classes. In this paper, the authors have given the methodology to implant low-enriched uranium in NTR. In the end, they compared and showed how LEU-NTR is applied for different thrust levels.[12]

Steiling (et.al, 1975) Explored thrust augmentation of various afterburner ejectors. Using H/o2 sonic rocket as primary gas generator, static test were conducted.

Green C J(et.al, 1963), Experiment has been conducted by injecting liquids into supersonic region to get the thrust vector.The author presented the study of various injections of liquid combined with different physical parameters.

OVERVIEW OF ANSYS SIMULATION FOR TPS

Ansys Parametric Design Language, is used to perform a trajectory-based sizing of a TPS for a Rocket Launch Vehicle which is designed for a Lower Earth Orbit Re-entry Mission. Analysis such as Aerodynamics, heating analysis, trajectory estimation, and mass estimation are performed to determine the aerothermal loads on RLV.

1. Aerodynamics : In this section the Newtonian Flow Theory for hypersonic flows was taken into consideration. According to this theory flows are modelled as an ensemble of particles impacting the surface of a body to a flat plate at incidence. The force is expressed by the relation :
   $\delta F = -p_i \delta A_i n_i$
   The Newtonian approximation is thus acceptable for Mach Numbers ranging upto 2. Th purpose behind partitioning of nose and the body region is related to the different flow incidence occurring on wing-body panels. Aerodynamic coefficients of the vehicle at an incompressible Mach number are computed by :

$$S_{\mathrm{ref}} \begin{pmatrix} C_X \\ C_Y \\ C_Z \end{pmatrix} \approx -\sum_{i=0}^{N} C_{pi} \delta A_i \hat{\mathbf{n}}_i,$$

   A wake surface based on quadrilateral panels was added to apply Kutta Condition on each panel at trailing edge. The intensity is set equal to the double strength of the upper and lower panels at trailing edges.

2. Mass Estimation : The mass of the TPS was estimated with two materials namely: Reinforced Carbon-Carbon (RCC) composite and High Temperature Re-Usable Surface Insulation Tiles (HRSI). RCC is used thermal insulation of nose, leading edge, or trailing edge, where the temperature is at peak. The mass of vehicle is computed as :

$$m_{\text{tot}} = m_{\text{vehicle}} + m_{\text{tps}},$$

$$m_{\text{vehicle}} = m_{\text{dry}} + m_{\text{ecd}} + m_{\text{av}} + m_{\text{ecl}} + m_{\text{par}},$$

The mass of Thermal Protection System is given by

$$m_{\text{tps}} = \sum_{i=1}^{n_{\text{panel}}} \rho_i S_i \cdot \text{th}_i,$$

Where:

pi: density of insulating material
Si: area of i^{th} panel of panel of TPS

Th_i: thickness of i^{th} panel

3. Heating Analysis : The thermal state of TPS is determined by computing its exterior and interior wall temperatures which would determine the choice of material. The analysis is performed on the windward side because this is the maximum heated side of the TPS and the leeward side is supposed to be a fixed wall temperature region. However in such analysis Catalytic Recombination , low density effects, thermal radiation from non-convex surfaces are neglected. Radiative equilibrium is considered on wall as :

$$\dot{q}_{w_2} = \varepsilon\sigma T^4_{w2},$$

where ε is emissivity and σ is the Stefan's Boltzmann constant . Also the convective heating is represented as :

$$(\dot{q}_{w2})_{\text{stag}} = 1.83 \cdot 10^{-8} \left[\frac{\rho}{r_{\text{nose}}}\right]^{0.5} V^3 \left(1 - \frac{C_{pw_2} T_{w2}}{0.5V^2}\right),$$

where C_{pw2} is the specific heat all the wall, p the free-stream density, and V is the vehicle velocity. The windward convective heating is represented as :

$$(\dot{q}_{w2})_{\text{win}} = C\rho^N V^M,$$

where C is determined by turbulent boundary layer. TPS wall temperature are determined using kinetic trajectory in range 2<Mach No.<23. Newton-Raphson method is used to determine the wall temperature on each panel. The internal wall temperature was computed at each discrete panel of TPS integrating in time a 1D unsteady heat-diffusion model.

$$T\left(y_{w2,i},0\right)=T\left(y_{w1,i},0\right)=285\,\mathrm{K},\quad T\left(y_{w2,i},t\right)=T_{w,i},$$
$$\left(\frac{\partial T}{\partial y}\right)_{y_{w1i}}=0,$$

The thermal state of TPS is globally defined assuming, for each computational element I, the following relations.

$$T_{\mathrm{Int}}=\sum_{i_{w1}=1}^{\mathrm{npan}}\left(T_{\max,i_{w_1}}-T_{\max,w1}\right)\delta_i,$$
$$T_{\mathrm{Out}}=\sum_{i_{w2}=1}^{\mathrm{npan}}\left(T_{\max,i_{w_2}}-T_{\max,w2}\right)\delta_i,$$

Where the maximum interior wall temperature is : 430K , 1920K for exterior wall composed of RCC and 1644K for exterior wall composed of Li-900.

COMPARISON OF VARIOUS THERMAL PROTECTION SYSTEMS

Metallic thermal protection systems

Metallic thermal protection systems: are used in spacecraft to shield against the extreme heat generated during atmospheric re-entry. These systems often incorporate materials like titanium or other metallic alloys that can withstand high temperatures, dissipate heat, and protect the spacecraft's structure. The metal's properties help manage and redirect the intense heat experienced during re-entry, ensuring the safety of the spacecraft and its occupants or payload. The temperature range for metallic thermal protective systems can vary based on the specific materials used and the purpose. Generally, these systems can withstand temperatures ranging from a few hundred degrees Celsius up to around 1,300 degrees Celsius or higher, depending on the composition and design of the materials. They are commonly utilized in applications like spacecraft heat shields or industrial environments requiring high-temperature resistance. Metals with stronger metallic bonds have higher melting and boiling points, as well as higher thermal conductivities. This is because stronger bonds allow for more efficient transfer of heat energy between atoms. Thermal conductivity is the ability of a material to conduct heat.

Advantage and disadvantage of metalic thermal protection system,

Advantages of metallic thermal protection systems:

1.High Thermal Conductivity: Metals efficiently conduct and dissipate heat, offering effective thermal protection.

2.Durable and Robust: Metallic materials are generally strong and durable, capable of withstanding high temperatures and physical stress.

3.Relatively Lightweight: Some metal alloys used in thermal protection systems offer a good balance between strength and weight, enhancing spacecraft efficiency.

4.Ease of Manufacture: Metals are often easier to fabricate and work with compared to other materials, reducing manufacturing complexities.

5.Reusability Potential: Certain metallic thermal protection systems can be reusable, making them cost-effective for multiple space missions.

Disadvantages of metallic thermal protection systems:

1.Weight: While some metal alloys are relatively lightweight, they can still add significant mass, impacting the overall spacecraft weight.

2.Limited Insulation: Metals can transfer heat, which might not provide as much insulation as some other materials, potentially affecting the inner components during re-entry.

3.Oxidation and Corrosion: Certain metals are susceptible to oxidation or corrosion in extreme conditions, potentially compromising the system's integrity.

4.Complex Cooling Systems: Metal thermal protection might require additional cooling mechanisms, adding complexity to the overall spacecraft design.

5.Limited Heat Resistance: While capable of withstanding high temperatures, certain metals have upper thermal limits, restricting their use in extremely hightemperature environments. The selection of a thermal protection system depends on the specific mission requirements, considering a balance between weight, heat resistance, durability, and cost-effectiveness.

Ceramic thermal protection systems:

Ceramic thermal protection systems are used in spacecraft for re-entry into the Earth's atmosphere. These systems utilize ceramic materials, such as reinforced carbon-carbon or other composite materials, due to their exceptional ability to withstand high temperatures. Ceramic thermal protection systems offer excellent heat resistance, lightweight properties, and insulation against extreme temperatures, ensuring the safety and integrity of the spacecraft during atmospheric re-entry. They are known for their durability and ability to handle the intense heat generated during the re-entry phase. As a result of their high bond strengths, Ceramics typically have very high Melting temperature, often much higher than Metals And Polymers. Most Ceramics have a melting temperature above 2000ºC. As the result of their very low elasticity of advanced ceramics are particularly able to withstand vertically applied pressure forces, the value ranges from 1500MPa to over 3000MPa According to ceramics. advantages and disadvantage of ceramic thermal protection system.

Advantages of ceramic thermal protection systems:

1.Exceptional Heat Resistance: Ceramics offer high-temperature resistance, capable of withstanding extreme heat during reentry.

2.Lightweight: Ceramics are often lightweight compared to metals, contributing less to the overall weight of the spacecraft.

3.Excellent Insulation: They provide effective insulation, protecting the spacecraft's interior from extreme temperatures during re-entry.

4.High Strength and Durability: Ceramic materials are known for their strength and durability, maintaining structural integrity under harsh conditions.

5.Resistant to Oxidation: Many ceramics are resistant to oxidation and corrosion, ensuring the system's reliability in extreme environments.

Disadvantages of ceramic thermal protection systems:

1.Brittleness: Some ceramics can be brittle, making them susceptible to damage from impacts or mechanical stress.

2.Complex Manufacturing: Producing ceramic components can be complex and costly due to specific fabrication requirements.

3.Surface Porosity: Certain ceramic materials can have surface porosity, potentially affecting their performance under extreme conditions.

4.Fragile at Room Temperature: While they perform well under high temperatures, some ceramics can be fragile and prone to damage at lower temperatures.

5.Limited Repairability: Repairing or refurbishing damaged ceramic systems can be challenging, sometimes necessitating component replacement rather than repair.

CONCLUSION

Two TPS concepts of current interest, ceramic and metallic TPS share similar weight and durability . However, the concepts are considerably different in configuration and operation. Although the results varied somewhat over the range of parameters studied, the metallic TPS were found to be reusable in most situations. Metallic panels and ceramic tiles were found to have comparable weight over most of the parameter ranges studied. Projected improvements in metallic TPS offer the potential for significant weight savings over ceramic TPS. NASA LARC is building on its long history of metallic TPS development to help develop the technologies required for metallic TPS to meet the needs of future RLV's. Metallic thermal protection systems are an attractive technology to help meet the ambitious goals of future space transportation systems. Improved concepts are being developed to meet the lowmass, durability and operability criteria required to dramatically reduce the cost of delivering payload to orbit.

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