Cryogenics Propellant for Upper Stage Launch Vehicles: Parametric Study

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ABSTRACT

It is important to identify the optimal design of a new launch vehicle because design decisions that made in the early development phase limit the later performance of the vehicles and determine the associated cost. An optimization framework for reusable launch vehicles is developed, it allows multidisciplinary design studies. Cryogenic propellants such as hydrogen and oxygen are crucial for exploration of the solar system because of their superior specific impulse capability. Reusable launch experiences a large range of thermal extremes, which reaching from cryogenic temperatures within propellant tanks to the high external heat flux encountered during re-entry of rockets. During these phases each component of rocket launcher has to be kept within the allowed temperature domains to assure reusability of the system. To perform research outside the Earth's atmosphere, extremely powerful rockets are needed. The placement of numerous communications, security, meteorological, information, and intelligence satellites in their designated orbits is another crucial function of these rockets. Scientists are attempting to reach Mars and other planets through the use of these potent rockets. These rockets function especially well with liquid propellants. After cryogenic technology was developed, these rockets developed quite quickly. From a strategic perspective, this technology is crucial, thus every country strives to develop it. However, only a very small number of countries are able to navigate this technology's technical challenges.

Keywords: Cryogenics, Propellants, Rockets, Space.

1. INTRODUCTION

Various semi-cryogenic propellants are analysed by species in this study. The ideal and estimated values of various parameters were calculated following the analysis. The ideal and estimated values, as well as the drawing of graphs with respect to different species, were computed using NASA's Rocket Propulsion Analysis programme. In this study, a semi-cryogenic propellant, 1,1,1,2-tetrafluoroethane, was employed to compare to other species like hydrogen, methane, and RPA-1. The important variables such as pressure, temperature, density, specific heat, and others were graphically represented with relation to the various nozzle positions [1].

Ankit et.aldescribes about a sounding rocket which is developed to perform certain scientific experiments in low earthorbit. The propulsion characteristics and calculations related to nozzles for both the booster stage and the sustainer stage of two-stage sounding rocket have been discussed and calculated using isentropic relations [2]. In this paper, Dinitrogen tetroxide as the oxidizer and Monomethyl Hydrazine as the fuel was studied in depth. Cryogenic propellant mixture of LH2/LOX outperformed the base composition. All hydride compounds improve the performance of upper-stage propellants. To test the performance amplification, selected energetic materials were used as energetic fuels and oxidizers [3]. This study discusses the key issues that have arisen while using liquid propellants, as well as the research that has been done to diagnose them. It also covers the main challenges that occur while using liquid propellant engines, such as tank pressurization related issues and boil-off problems. Identifying new cryogenic liquid pursuits may play a key role in designing better rockets for future space missions. Helium gas is used prominently for tank pressurization purposes. Use of an appropriate heat exchanger is recommended to solve some tank pressure related problems [4]. In general, when compared to ambient temperature, the strength, modulus, and fracture toughness of polymers rose at cryogenic temperatures. The tensile fracture strain of the polymer fell considerably as the impact resistance increased. Researchers used a variety of techniques to improve polymer ductility and reduce heat stress in polymeric composites for cryogenic applications [5].

Daub D. et. al. (2021) investigated with the help of DLR's project Akira and Transient in the history of spaceflight, there have only been a few numbers of operational reusable launch vehicles (RLV). On their reusable stages, none of them have used a cryogenic tank insulation. Akira which includes tests under launch pad conditions, under re-entry thermal loads and in arc-heated wind tunnel. The Transient project includes system aspects in order to ensure a better grasp of the full-sized vehicle and offer representative boundary conditions for the sizing of the pertinent subsystems, system aspects are also being studied. Also, Integration of reusable cryogenic insulation with external thermal protection system (TPS) which is the primary objective of the TRANSIENT project is to improve the reusable cryogenic insulation that is connected with an external TPS onto a propellant tank structure, then outlook on thermo mechanical experiments ITOs (Integrated Test Object) modelled as slices of an RLV (Reusable Launch Vehicle) propellant tank will incorporate the modified designs for the two potential base structures [6,7]. The DLR project looked into AKIRA technologies that were regarded essential for reusable booster stages but weren't covered by current flying demonstrator projects [8]. However, using cryogenic fuels has significant advantages for future RLVs in terms of mass, size, and environmental effect [9].Ankit et.al paper discussed a theoretical and conceptual design for compact size 2 stage sounding rocket by focusing on structural optimizations at various levels. The aim of the paper is to develop a two-stage sounding rocket with overall length constrained to 1 meter [13].The aim of paper is to design a two stage sounding rocket and its nozzles using fusion 360 and analysis of different properties using simulation on ANSYS software. The rocket is designed to reach maximum apogee to perform scientific experiments and can be recovered safely after use [18].

2. CRYOGENICS PROPELLANT

In the domains of aerospace, superconductivity, energy, and medicine, cryogenic liquids such as liquid helium (LHe), liquid hydrogen (LH), liquid oxygen (LOX), and liquid methane (LMG), among others, are crucial [10]. The study and use of polymeric matrix composites in cryogenic fields has been a hot topic, notably in aerospace, due to their light weight, high specific strength, great corrosion resistance, superior anti fatigue performance, and design ability.

An intense focus is placed on the top stage propulsion of spacecraft. Standard propellants have been studied and used for a few decades now. Liquid oxygen and hydrogen are two common cryogenic propellants utilised for upper stages. Active research efforts are being made for effective substitutes as a result of the overuse of cryogenic propellants. Nitrogen tetroxide and Monomethyl hydrazine (MMH), which have large specific impulses, extremely high storage stabilities, and a hypergolic nature, are used in many space applications as an appealing substitute [11]. The combination is frequently employed in response controls, launch vehicle propulsion, and orbital manoeuvres.

Rocket fuels are often used in either liquid or solid form. Although launch vehicles use both kinds of fuel, solid rocket motors (SRM) are typically used as the main fuel by smaller rockets and as strap-on boosters by larger launch vehicles. SRM's inability to be throttled is their main drawback. Contrarily, liquid-fueled systems offer a solution to the issue by providing better control and perhaps even more power. Mono-propellant and bi-propellant systems are two categories of liquid rocket engines. Only low thrust satellite propulsion systems use mono-propellant engines, whereas booster, main-stage, and upper stages use bi-propellant engines [12].

Most bipropellant low-thrust, auxiliary, or reaction control rocket engines, as well as large rocket engines for the first and second stages of ballistic missiles, utilise various ambient temperature storable propellant combinations. These propellant mixtures allow for long-term storage and almost immediate readiness.

Research has made substantial progress in improving the performance of rocket propellants with energetic materials (experimental, numerical, and theoretical). With a focus on important issues including:

1) Safe handling and operation,

2) Performance reliability and reproducibility, and

3) Cost minimizations, the investigations have grown over the years and have continued to surface.

Before discussing the impacts of adding energetic elements to the bi-propellant combination, it is crucial to comprehend the viability of doing so and the practical application of such materials through a case study using solid and hybrid propellants. Both explosive and propellant formulas contain energetic elements as additives. A number of families of high energy density matter propellants were discovered, including formulations based on high-nitrogen compounds, noble gases, metallic hydrogen, atomic radicals, and more. Due to significant challenges in large-scale manufacture, extensive storage, acceptable safety, and economic considerations, the most of them are still far from being employed effectively [14]. The same problem arises when thinking about energetic materials for the study of liquid propellants. Similar issues such as the implementation of metallic additives necessitate the study of many aspects of these substances' functioning in the combustion process, such as metal ignition, the process of metal combustion, the formation of condensed products and agglomeration, effects of metal combustion on propellant combustion, 2-phase flow loss, and slag formation loss, toxicity, and additional safety precautions.

As a cryogenic liquid propellant, liquid methane and liquid oxygen have also been employed in numerous space missions. This mixture has a rather clean burning profile and is non-toxic. Additionally, liquid fluorine-fuelled cryogenic engines have been developed. Fluorine can work as a super-oxidizer, giving the rocket engine a high specific impulse, as was discovered through experimental observation. Liquid oxygen is frequently added to it to increase its effectiveness as an oxidant [15].

The greater numbers of cycles to failure in the latter combination makes LOX/LH_2appear inferior when fatigue life is taken into account. The selection of the propellant has an impact on the engine's performance requirement of a minimum number of cycles before failure. The loads acting on the essential subcomponents are also significantly impacted by the operating regime [16].

The amount of propellant mixing, as well as other elements like tank design, a particular failure mode, and ignition timing, greatly influence the explosive properties. In comparison to LOX/Methane and LOX/RP-1, LOX/hydrogen has higher explosive energy (heat of combustion including the moles of oxygen) and higher TNT equivalence (ratio of weight of trinitrotoluene to weight of material with the same explosion impact). In comparison to LOX/hydrogen, LOX/LCH_4 mixtures have a wider detonable range (reaction wave propagating through reactants faster than the local speed of sound) [17].

Liquefied methane is effective for use in long-range missions for reusable launch vehicles, according to the comparative analysis of the propellants. Liquefied methane has not yet been used to launch any missions. The advantages of liquefied methane have been discovered by experts after tests were done on various fuels.

3. CONCLUSION

In space science, cryogenic rocket technology is particularly important. This technology made it feasible to develop better rockets, which facilitated space exploration. For upcoming reusable first stages, the DLR is still looking on the integration of reusable cryogenic insulation and external insulation onto a cryogenic propellant tank. The liquefied gases used in cryogenic liquid propellants are kept at extremely low temperatures. Since there are no toxic by-products of combustion while using this pure rocket fuel, the environment is also not harmed. Liquid hydrogen, liquefied methane, and kerosene are utilised as fuels while liquid oxygen is used as an oxidizer in numerous space missions that have been launched by organisations all over the world. These materials are combined to make propellant. The availability, specific impulse, corrosiveness, coking characteristics, storability, combustion stability, explosive characteristics, fatigue life, mass, density, chemical properties, production of thrust, toxicity, handling and maintenance, and transportation of the fuels are among the properties taken into account for the study. Each of the propellants has advantages and disadvantages, but when searching for a potential green propellant, liquid methane and liquid oxygen can be taken into consideration. They have a relatively high specific impulse, and their density makes it easier to store them in small tanks than liquid hydrogen would.

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