COMPARATIVE STUDY ON PROPELLANT CHARACTERISTICS FOR REUSABLE LAUNCH VEHICLES

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ABSTRACT

Advanced rocket technologies are often based on cryogenic fuels which form a part of liquid propellants. The classification of liquid propellants and comparison between its two types of case studies are explained. Nowadays cryogenic and semi cryogenic technology has been used for propelling a rocket. It is the preferred technology because of its high performance. The growing demand for high energy density fuels, as well as concerns about their safety, has prompted researchers to concentrate on green propellants that are both efficient and long lasting. Collation of four propellants has been carried out for semi cryogenic and cryogenic fuels. The Oxidizer preferred to be used is the same for all fuels which have the best reactivity. Cryogenic propellants taken for comparison are Liquid Hydrogen, Liquefied Methane and for semi cryogenic fuels considered are RP-1 (Kerosene) and UDMH with Liquid Oxygen as the Oxidizer. The scope of this work addresses the comparison among the propellants, on their chemical properties, overall efficiency and fatigue life which is a major criterion for RLVs.

Key Words: *Propellant Characteristics; Semi Cryogenic; Cryogenic; Efficiency; Reusable Launch Vehicles.*

INTRODUCTION

A large amount of rocket fuel is needed to launch a rocket into space by overcoming earth's gravity while delivering a small payload. Hence space tech remains expensive. Reusability of rocket components could have a significant impact on the overall cost of rocket technology by reducing the materials used. This feat is being achieved by various space tech companies launch vehicles like SpaceX's Falcon 9 and Falcon Heavy, Rocket Lab's Electron, and Blue Origin's New Shepard. While the above said models are operational, there are various other companies which are in their developmental stage of RLVs such as Virgin Galactic, NASA, I-space's Hyperbola, Roscosmos's partly reusable Amur, Relativity Space's Terran R, ISRO's RLV-TD and much more, with the use of cryogenic propellants.

Cryogenic propellant is a classification of propellants that need to be stored at extremely low temperatures to maintain them in liquid state and are used in space missions where there is no atmosphere. Some of the advantages include being cleaner, therefore qualifying as a green fuel; reduction of transportation cost due to their abundance in comparison to the fast-depleting fossil fuels; higher mass flow rate, hence more thrust and power and no environmental hazard in case of any spillage. Despite the difficulty to use due to the complex engine architecture such as cryogenic cooling, pumping mechanisms, etc.; the current

operational models prefer cryogenic propellants due to their excellent characteristics. The combined benefits of low toxicity and easy handling may shorten ground processing time from weeks to days, simplifying the launching of satellites and spacecraft.
In this paper a detailed comparison is carried out between Cryogenic and semi cryogenic propellants and deducing the important characteristics making them a more sought-after propellant.

LITERATURE REVIEW

Abishek et.al (2018) compares the flow and combustion characteristics of LOX/methane and LOX/hydrogen propellant combination at single element level using swirl coaxial injector by computational fluid dynamics model at supercritical pressure of 6.8MPa. In combustion simulation, the effect of large swirl velocity and radial expansion results in large LOX core length with hydrogen and it is restricted in radial and axial directions in case of methane for oxygen mass fraction. The high temperature and low swirl velocity properties of methane restricts the inner oxygen core to expand radially when compared with hydrogen for fuel mass fraction. Density varies axially for both hydrogen and methane. Due to low operating density of hydrogen the swirl velocity is higher than in methane case, which in turn delays mixing with reduced shear layer diffusion and high temperature combustion zone extends up to exit. In case of Lox/methane there is higher diffusion and the high temperature combustion zone ends within the domain.[1]

Dhruv Mehendiratta and M.Ramachandran (2018) explained that liquid Methane is a hydrocarbon. Liquified Methane has more advantages when compared with Kerosene as it has specific impulse of higher values, has uncomparable properties of cooling, having higher limits of coking, soot production is very less and the pressure will be reduced in the cooling surfaces. For reusability, coking and soothing properties are very important. Methane cost is about three times lesser when compared to Kerosene, due to its impressive long-haul stability. Due to high expansion of engine mass and an expandable booster capacity with the blend of higher volume leads to high drag penalty and plethora of mass penalty. Methane is a smooth cryogen that can be stored at a lower temperature than kerosene and higher temperature than Hydrogen. There is a formation of carbon soot in the combustion chamber; it acts as a protective layer mainly for kerosene, and tends to oppose the nozzle exhaust flow. Oxygen with any other hydrocarbon produces less performance characteristics when compared to Oxygen/Hydrogen. Liquid Methane is helpful to decrease the flammability whereas liquid Hydrogen has less specific impulse than Methane.[2]
Youhong et.al (2016) experimented on the corrosion damage and SCC (Stress corrosion and cracking) behavior on LD 10 Aluminum alloy structure (pressure vessel for storing the propellants). Double Cantilever Beam (DCB) was taken and subjected to constant amplitude cycle loading with maximum tensile stress and then put into three solutions of 3.5% Nacl, N2O4 and UDMH. The specimen was taken out every 15 days and checked for the crack lengths and this continued until a condition where crack growth doesn’t propagate. Finally, the last crack length was recorded, and initial stress intensity factor was calculated. Corrosion pits were found on the one in the NaCl solution, a layer of white corrosion was produced on the one, in the UDMH solution and asymmetric yellow speckles were formed on the one in the N2O4 solution. The corrosion damage degree was severe on the one in Nacl solution. This paper gives us an idea of how the corrosion property of UDMH might impact the storage tank and sometimes the engine as well.[3]
Mohammad et.al (2011) studied the properties of UDMH. It has high vapor pressure at room temperature and forms a stable liquid at lower temperatures. There is good intermolecular interaction due to strong hydrogen bonds. Increasing the boiling properties of UDMH may arise due to colligative properties. Viscosity of UDMH does not change. It has a low freezing point. It has low density and a high refractive index. It has low heat of vaporization at the boiling point, high molecular weight and has low flash point.[4]

Sakaguchi Hiroyuki et.al (2018) studied the future use of Methane in reusable launch vehicles and performed some experiments and tested for long span, out of earth atmosphere operations. The Methane engine was developed under the IHI corporation and researched on it. Liquid oxygen as Oxidizer and liquified Methane as fuel are used as Propellant in methane machines for combustion. While compared to Liquid Hydrogen, the value of density multiplied by specific impulse should be higher for liquified methane. Large amount of soot will be deposited at the time of combustion when hydrocarbon fuels like kerosene is used and it may cause clogging trouble at the time of reusable operations of the vehicle. When liquid Methane is used for reusable operations there is no production of soot while combustion and no chance of clogging at the passage of propellant flow. Liquid Methane and liquid Hydrogen don't have the formation of soot but liquid Hydrogen vaporizes quickly and cannot be stored for a long span, while Liquid Methane can be stored for longer duration and the vaporization is comparatively less. Liquified methane is safer and less explosive, leakage is very low due to its higher molecular weight when compared with liquid Hydrogen. Propellant tanks or its valves can be designed and standardized for liquid methane as fuel and Liquid Oxygen as Oxidizer to reduce production cost. For the transportation systems, liquified methane is very efficient as it is cost efficient, reduces the size of propellant tanks, reusable, and can be stored for a long time. Liquified methane can also be used as a regenerative cooling system which is most likely to reduce combustion chamber temperature.[5]

K.A. Zona in their NASA article stated the advantages of using liquid Hydrogen as rocket fuel. Hydrogen is an extremely powerful and light propellant that is being used in rockets. Burns with high intensity due to its lower molecular weight. When liquid hydrogen reacts with liquid oxygen as Oxidizer, it produces a high amount of specific impulse and propellant consumption is very efficient compared to other propellants in rockets. Due to the cryogenic nature of both liquid oxygen and liquid hydrogen, the gases could be liquified only at very low temperatures hence tends to have more technical challenges. To avoid it from boiling and evaporating, from all the sources of heat where the liquid hydrogen is stored or fueled in the rocket engine, it should be insulated carefully and friction of air molecules in the atmosphere should be avoided. When the vehicle is in space, liquid hydrogen is protected from the radiation and heat of the sun. To avoid tank explosion, vent is a must in the system due to rapid expansion while the absorption of heat by liquid hydrogen. Liquid hydrogen becomes brittle when the metal is exposed to the extremely cold temperatures. Liquid hydrogen has the tendency to leak even from welded pores. Technical solutions are required to solve all the problems that will be faced by liquid Hydrogen. Large tanks are required because of their low density. It is energetic and gases produced during combustion are very light.[6]

Waxeneggaer et.al (2017) studied the failure mechanisms and the parameters affecting it in liquid rocket engines for reusable launch vehicles. Different combustion cycles, propellant combinations and design parameters like chamber pressure significantly affects fatigue life of the engine. Simulation tools like EcoSimPro and Ansys are used for cycle and thermal analysis. Finite element model for fatigue life prediction. Results showed that the combustion chamber of the gas generator cycle has the highest number of cycles to failure (66) and staged combustion cycle with approximately 50 cycles to failure, this is due to the different pressure present in cooling channels at the throat. When considering fatigue life, LOX/CH4 is found to be better than LOX/LH2 due to the increased number of cycles to failure in the latter combination. The propellant choice affects the requirement to have a minimum number of cycles to failure and reduces the performance of the engine. Also operating regime has a significant influence on the loads which act on the critical subcomponents.[7]

Alan et.al (2019) examined the regulations to be followed when choosing the propellant combination to check for explosion and hazards especially the blast pressure, fragments, and thermal effects. The explosive characteristics depend widely on the degree of mixing of the propellants and other factors such as tank configuration, specific failure mode and time of ignition. The study showed that LOX/hydrogen has high explosive energy (heat of combustion including the moles of oxygen) and high TNT equivalency (ratio of weight of trinitrotoluene and weight of material with same blast effect) compared to LOX/Methane and LOX/RP-1. LOX/LCH4 mixture in vapor phase have a broader detonable range (reaction wave propagating through reactants faster than the local speed of sound) than LOX/hydrogen.[8]

Stappert et.al (2018) evaluates the launch systems with reusable vertical takeoff and vertical landing booster stages by comparing different propellant combinations, staging's and engine cycles. The study shows that LOX/hydrogen launchers are the lightest followed by LOX/RP-1, LOX/LCH4 and LOX/LC3H8. The Gross lift-off mass of hydrocarbons is 2.8 times higher compared to hydrogen launchers. In hydrocarbons LOX/RP-1 has the lowest dry mass followed by LOX/C3H8 and LOX/CH4. LC3H8 offers significant cooling potential. It is evident that the propellant chosen for the launchers has an effective exhaust velocity and structural index (dry mass/propellant mass).[9]

Zejun et.al (2012) investigated the morphological changes of gelled UDMH droplets during combustion to explore the effects of ambient pressure and oxygen fraction on burning rate and micro explosions. The burning properties of gelled UDMH were studied. Combustion process involves a classical combustion stage with a steady flame envelope around the droplet, then a bubble appears with vigorous micro explosions until most of UDMH fuel is consumed followed by a gellant combustion stage. Increase in the chamber pressure suppresses the bubble formation and delays micro explosion of the droplet due to increase in boiling temperature of UDMH as the pressure increases. This results in the increase in burning rate. Increase in oxygen fraction rises the flame temperature and the droplet heat increases, decreasing the bubble formation time and the micro explosion time with an increase in the burning rate constant.[10]

RESULTS AND DISCUSSION

Various studies on the propellant characteristics of cryogenic and semi cryogenic propellants for reusable launch vehicles have been discussed. Comparison is done between cryogenic propellants(liquid methane and liquid hydrogen) and semi cryogenic propellants (RP-1 Kerosene and UDMH).

Fatigue Life:

When considering fatigue life of LOX/CH4 is found to be better than LOX/LH2 due to the increased number of cycles to failure in the latter combination. The propellant choice affects the requirement to have a minimum number of cycles to failure reducing the performance of the engine. Also, the operating regime has a significant influence on the loads which act on the critical subcomponents [7].

Explosive Characteristics:

The explosive characteristics depend widely on the degree of mixing of the propellants and other factors such as tank configuration, specific failure mode and time of ignition. LOX/hydrogen has high explosive energy (heat of combustion including the moles of oxygen) and high TNT equivalency (ratio of weight of trinitrotoluene and weight of material with same blast effect) compared to LOX/Methane and LOX/RP-1. 1.LOX/LCH4 mixture in vapor phase have a broader detonable range (reaction wave propagating through reactants faster than the local speed of sound) than LOX/hydrogen. RP-1 presents a lower explosion hazard and also has a fraction of the toxicity and carcinogenic hazards [8].

Maximum vacuum thrust:

It is observed that for cryogenic (LOX/hydrogen) propellants, for maximum vacuum thrust 22 chambers can be used with gas generation cycle, for semi cryogenic (LOX/RP-1), 16 chambers with gas generation cycle and for storable propellants (NTO/UDMH) 25 chambers can be used. LOX/hydrogen launchers are the lightest followed by LOX/RP-1, LOX/LCH4 and LOX/LC3H8 [9].

Mass and density:

Increased density of Hydrogen at liquid state requires large pipe diameters and a large pump for large volume but provides higher specific impulse. RP-1 is far denser than LH2, giving it a higher energy density (though its specific energy is lower). Semi-cryogenic and storable propellants have identical propellant mass density and specific impulse levels. Gross lift-off mass of hydrocarbons is 2.8 times higher compared to hydrogen launchers. In hydrocarbons, LOX/RP-1 has the lowest dry mass followed by LOX/C3H8 and LOX/CH4. Use of kerosene as propellant leads to a lower booster dry mass, making it the preferred choice if no operational benefits of methane can be identified. Kerosene's high density enables a compact design of turbomachinery and minimal stage sizes.[11]

Storability:

Methane is a soft cryogenic propellant with a storage temperature of about 111 K .This temperature is in proximity to LOX and can enable, under favorable circumstances, a simplified architecture. Its density is desirable for easy storage in small tanks, compared to what would be required for liquid hydrogen. While considering the leakage, liquid Hydrogen tends to leak and it's difficult to store for a longer period than the liquid Methane and it tends to react faster and explosively in some cases, than liquefied Methane. UDMH and RP-1 are both storable liquid propellants [11].

Combustion Characteristics:

Combustion stabilization of the methane-oxygen diffusion flame was examined and the study observed a detached flame regime (stable combustion) and a blow off regime where flames were not generated due to uneven mixing. The effect of the mixer ratio of methane and oxygen lowered and chemical reaction rate increased as the stoichiometric ratio approached creating a stable lifted flame (detached) even in high oxygen Reynolds number. This detached flame can prevent excessive heat transfer due to combustion gas thereby preventing thermal damage and destruction in the injector and propellant supply system.[12]

Boiling Point and Melting Point:

Kerosene has higher kinematic viscosity than methane, freezing point and critical temperature and pressure of kerosene are higher than methane [8]. The boiling point at one atmospheric pressure for hydrogen is -252.8° C, for Methane being 161° C and 150-300° C for RP-1. Liquid Hydrogen has the highest flash point among liquid methane, RP-1 and UDMH.

Specific Impulse:

Hydrogen provides the highest specific impulse and RP-1 provides a lower specific impulse than liquid hydrogen (LH2), but is cheaper and stable at room temperature. Methane has higher impulse than kerosene so it has higher characteristic velocity than kerosene. UDMH with Nitrogen tetroxide being the storable liquid propellant has a specific impulse close to that of RP-1.

Coking and Corrosion:

Coking is the thermal deposition of propellant on channel walls. Every hydrocarbon has a threshold wall temperature after which there is coking deposition stimulated. It is influenced by the wall temperature and the chemical composition of hydrocarbons. Some of the effects of coking are increased pressure drop due to reduced cross section, reduction in heat transfer between chamber wall and cooling channel due to the formation of a layer from coking and composition of fuel changes. Corrosion-degradation of metallic surfaces leading to decreased pressure drop due to loss of wall material, increased heat transfer between chamber wall and cooling channel wall due to reduced wall thickness and change in composition due to reaction for the fuel and metal.[13]

Table 1: Properties of CH4, LH2,UDMH & RP-1

Properties	**Methane**	**Liquid Hydrogen**	**UDMH**	**RP-1**
Melting point (°C)	-182.456	-259	-57	-43
Boiling point (°C)	161.5	-252	64	150-300
Molar mass (g/mol)	16.043	2.016	60.1	23.30
Density (kg/m^3)	422.8 (liquid at -162°C)	70.85	791 (at 22°C)	0.81
Flash point (°C)	-188	585	10	38
Autoignition temperature (°C)	537	585	248	295
Explosive limits	4-17%	4-74%	2-95%	0.6-4.9%
Combustion Temperature (K)	3550	3070	3415	3670
Oxidizer Fuel Ratio	3.7:1	6:1	2.61	2.7:1
Specific Impulse (seconds)	459	532	333	370

CONCLUSION

The research done on propellant characteristics of reusable launch vehicles leads to the preference of Liquid propellant, which is further classified as semi cryogenic and cryogenic propellants. Compared to other fuels, cryogenic has higher efficiency .A detailed comparison on the different properties among the liquid propellants such as liquified Methane, liquid Hydrogen, RP-1 and UDMH had been carried out for Reusable launch vehicles. In many space missions, which have been launched by organizations across the world, liquid Hydrogen, liquefied Methane, kerosene are used as fuels and liquid Oxygen as Oxidizer, combined to form a propellant. The properties considered for the study are its availability, specific impulse, corrosiveness, coking characteristics, storability, combustion stability, explosive characteristics, fatigue life, mass and density along with its chemical properties, production of thrust, toxicity, handling and maintenance and transportation of the fuels. Each of the propellants have their pros and cons but when looking for a potential green propellant, liquid Methane with liquid oxygen can be considered with a fairly high specific impulse and its density is desirable for easy storage in small tanks, compared to what would be required for liquid Hydrogen.

Liquid Hydrogen when compared with liquefied Methane, both are suitable as rocket propellants, but liquid Hydrogen tends to leak from gaps and it's hard to store for a while due to its evaporation property, transportation should be done with taking extreme measurements whereas, Methane is easy to handle and transport, safe to store for a longer period. Liquefied Methane is preferable for longer range missions and an optimized one due to its properties when compared to Liquid Hydrogen. Still some tests are going on with liquefied Methane, for single stage to orbit missions. It is very efficient in using liquefied Methane rather than liquid Hydrogen and for two stages to orbit, it is efficient in using combined propellants of liquid Hydrogen and liquefied Methane to achieve the most efficient mission. It is better to use Liquid methane in the upper stages and LH2 in the first stage. Liquid Methane has high heat transfer characteristics which can be used for regenerative cooling. It also has high characteristic velocity and good mixture ratio which can produce high thrust. Methane is also abundant in the outer solar system. It can be harvested from Mars, Titan, Jupiter and many other planets and moons. Major disadvantage of other propellant being explosive hazardous and coking property.

From the comparative study of these propellants, it is safe to say that liquefied Methane is efficient to use in long range missions for reusable launch vehicles. Till date, missions have not been launched using liquefied Methane. After conducting tests on various fuels, scientists have discovered the benefits of liquefied Methane.

LOX/LCH4 has been considered as green propellant for future space missions. Since liquid methane has high specific impulse out of all four chosen propellants liquid methane and liquid oxygen can be preferred as a propellant for reusable launch vehicles.

Why choose methane in future rocket engines?

One of the most important factors while considering any of the fuel for rocket engines are cost and maintenance, hence Methane is preferable because it's cheaper and can be maintained with less cost, for storing the Methane in the form of liquid a passive system of cooling is sufficient. When compared to Hydrogen, Methane is denser and it is possible to store over a long period, fuel tank insulation is not needed, doesn't require a complex design of rocket like hydrogen propellant does, doesn't have the property of leak and for lift off the quantity of methane requirement is very less due to its high specific impulse. Methane requires simple and light fuel feed systems. There is a special process known as autogenous pressurization for Methane (self-pressurization in the tanks), so it doesn't require bulky and complex pressurization systems. The first engine to test with Methane is Raptor by SpaceX.

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