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Study of Characteristics of Different Liquid Propellants for Reusable Launch Vehicles

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Abstract- In this study, quantitative and qualitative analysis of different liquid fuels like LH2, Liquid Methane and RP-1 was carried out by taking various parameters like Equivalence ratio, molecular mass, mass, density, soot, Ignition delay time, Specific Impulse, Thrust, the pressure inside the combustion chamber and storability. A tabular representation of all three fuels with an oxidizer (LOX) is used to determine how different propellant combinations perform at different given conditions. An average payload mass that lies in a standard payload range for small satellite launchers was considered. The mass values were calculated to determine the size of the rocket and the performance of different propellant combinations. Mass flow rates of different propellant combinations were calculated to determine the engine requirements for achieving the total mass flow rate. Bio-fuel such as Ethanol was studied, but it did not stand out as an efficient fuel for the booster stage.

Keywords- Liquid Hydrogen, Liquid Methane, RP-1, Liquid Oxygen, Reusable launch vehicles, Mass ratio, Mass Flow rate, Liquid rocket engines, Specific heat values, Ignition delay time.

I. INTRODUCTION

The aerospace industry is constantly in a quest to improve rocket efficiency and to make it more cost-efficient. To improve the performance, different aerospace companies, are trying different fuel/ oxidizer mixtures for their launch vehicles to achieve a tremendous specific impulse, reducing the need of Propellant.

In this ever-growing age of space technology, the reusability of a space launch vehicle has become a requisite for a more economical launch. The booster stage of different Launch vehicles is recovered using different recovery techniques. From the first reusable launch vehicle, Space shuttle, which used a solid rocket booster, to the recovery of the booster stage of a Falcon 9 rocket which used vertical landing as recovery and RP-1/LOX as a liquid propellant, the space tech giants have come a long way.

Table 1. Data of different rockets.

Rocket	Propellant	I_{sp}(S)	Cc Pressure (Bar)	Payload(Leo) (Kg)	Thrust (Sea Level) (Kn)	Thrust (Vacuum)(Kn)	Engine
Electron	Lox/ Kerosene	311-343	100-200	300	225	26	Rutherford
Neutron	Lox/ Kerosene	-	110-130	8000	2200	-	Ar-1
New Shepard	Lh_2/Lox	260	134	-	490	710	1 Be-3

Space Shuttle	Lh_2/Lox	455	226.5	27,500	12500	1755	Srb / Rs25
Themis	Lox/ Methane	360	10	1200	980	-	Prometheus
Amur	Methane + Lox	-	33	10,500	980.67 Approx.	880	5rd-0169a
Hyperbola 2	Methane + Lox	-	-	1900	18.63	-	Jd-1
Xaero	Isopropyl Alcohol+ Lox	322	-	10	1.65	-	Cyclops-Al-3
New Line 1	Kerosene + Lox	-	-	200 (Ss0)	400	-	-
Vulcan Centaur	Methane + Lox / Lh_2+ Lox	453.8	134	27,200	4900	212	Be 4 / Rl 10
Falcon 9	Lox / Kerosene	282/311	300	22,800	7607	981	Merlin
Falcon Heavy	Lox/Rp-1	282/311	97	63800	22,819	16377.11	Merlin-1d
Starship	Lox/ Methane	330/380	300-330	100000+	72000	40000	Raptor
Falcon 5	Rp-1/Lox	-	-	4200	1590	-	Merlin
New Glenn	Liquified Natural Gas/Lox	440	134	45000	17100	1100	Be 3u/Be 4

This study focuses on the analysis of different liquid fuels to be used in reusable launchers. These fuels are frequently used in different launchers except for CH4 fuel, which was recently used in test flight Space X's Star ship and Blue Origin's New Shepard. Further, an analysis was carried out to decide which combination of fuels can be used for the first and second stage of the chosen payload.
This study focused only on the merits of Liquid fuels and not on Solid or Hybrid fuels.

II. LIQUID PROPELLANTS

1. RP-1 (Refined Petroleum) / LOX:

The propellant combination of RP-1/LOX has been widely used since ancient times for the booster stages of a launch vehicle. Considering the density of RP-1, it gives a considerable advantage in terms of structural size. This propellant combination is used in the new age reusable launch vehicles such as the Falcon 9 of Space X.

The recovery of the booster stage of Falcon 9 by retro propulsion landing is an engineering marvel itself. This propellant combination has an excellent thrust output in atmospheric conditions.

2. Liquid Hydrogen / LOX:

The propellant combination of LH2/LOX has been used mainly in the upper stage of a reusable launch vehicle. The upper stage of an RLV operates in the space of vacuum (outer space). The main advantage of using the LH2/LOX combination in the upper stage is the high value of ISP (specific impulse), which is the efficiency of a rocket. The energy per unit mass is the highest for hydrogen, but the energy per unit volume is the lowest.

3. Liquid Methane / LOX:

The propellant combination of CH4/LOX has been used in the new age RLVs such as the Star ship (the biggest rocket ever built).

This combination compensates for the advantages of both the propellants aforementioned. A good thrust value for the booster and a good ISP value for both booster and vacuum stage are observed for this combination.

It will be used in the Star ship for its booster and upper stage, which will take the first human to Mars. Table-2 below shows the propellant mass ratio for different fuels.

Table 2. Propellant Mass Ratio.

Propellant	The propellant mass percent of the rocket for LEO
RP-1 / LOX	94 %
CH_4/LOX	90 %
LH_2/LOX	83 %

III. PARAMETERS

Different parameters were considered to determine what propellant combination would be best suited for different mission requirements. The parameters are listed below, and a comparative analysis was carried out for each propellant combination.

Table 3. Fuels and their energy output at equivalence ratio 1.

Fuel	Density Kg/m3	Molar Mass gm/ mole	Moles	Energy/ mole KJ/mole	Total energy
CH_4	424	16.04	2650	890.8	2360620
LH_2	71	2.016	35218.25	286	10072419.5
RP-1	750	198.22	3783.67	3756.5	14213356.36

1. Equivalence Ratio:

The Equivalence ratio is the ratio of the actual fuel/oxidizer ratio used in a mission to the stoichiometric fuel/oxidizer ratio. The Equivalence ratios of RP-1, CH4, and LH2 with LOX as oxidizer were calculated to determine which propellant combination gives the highest equivalence ratio.

A value of Equivalence ratio 1 implies a high specific impulse and hence a better efficiency. After carrying out some hands-on calculations, it was seen that the mixture ratio of LH2/LOX was highest in comparison with the other two combinations. Hence, it was observed that LH2/LOX combination is very suitable for the upper stage of a rocket. In general, we use fuel-rich propellants to prevent structural damage.

2. Molecular Weight and Density:

The molecular weight is cumulative of the atomic weight in a molecule. The denser the propellant, the less space it will occupy, which will result in an increment of the mass. LH2 has the lowest molecular weight and the lowest density, following CH4 and RP-1.

For a given volume of a tank as a constraint, moles of the propellant can be calculated by taking in the relation of mass, volume, and density. An arbitrary volume of 1 m3 was taken for mole calculations to determine each combination's moles for the given volume. Table 3 is to be referred to for the results.

3. Mass:

The mass of a rocket has been a problem since the inception of RLVs. Taking the reference of the Falcon 9 rocket and a constant payload of 3000 Kgs to the LEO for all the propellant combinations, different masses were calculated for the rocket to determine which combination gives the best mass ratio. The ratio of Propellant mass to total rocket mass can be determined by referring to table 2.

Table 4. Mass values.

Fuel	CH4	LH2	RP-1
M(pr) Kg	190741.5	142217.81	225338
M(str) Kg	18193.5	26128.95	13596
M (pr landing) Kg	8698.81	6485.89	10487.7
M (pr booster) Kg	149979.64	111825.86	177791.682
M (str booster) Kg	15609.59	22418.6391	11665.968
M(LL) Kg	2653.63	3900.84	2039.4
M (pr upper) Kg	40761.86	30391.95	47546.318
M (str upper) Kg	2583.91	3710.31	1930.732

Assuming a payload of 3000 Kgs, and propellant combination of RP-1, LH2, and CH4 with LOX, total mass, propellant mass for the booster stage, upper stage, and retro-propulsion landing, the structural mass of booster and upper stage, and mass of the landing legs were calculated. The mass values of the other two combinations can be calculated. The mass ratio equation below can be referred to for calculating the masses:

Total mass: $M_f = M_{pl} + M_s + M_{pr}$ -3.3.1

Empty mass: $M_e = M_{pl} + M_s$ -3.3.2

Propellant mass ratio: $PMR = \frac{M_f}{M_e}$ -3.3.3

$PMR = 1 + \frac{M_{pr}}{M_e}$ -3.3.4

Payload ratio: $\zeta = \frac{M_{pl}}{M_f - M_{pl}}$ -3.3.5

$$\zeta = \frac{M_{pl}}{M_{pr} + M_s}$$

Structural Coefficient: $\xi = \frac{M_s}{M_{pr} + M_s}$ -3.3.6

$$PMR = \frac{1+\zeta}{\zeta+\xi} \quad \text{-3.3.7}$$

Rocket Equation: $\Delta v = V_e \times \ln \frac{M_{initial}}{M_{final}}$ -3.3.8

$$V_e = I_{sp} \times g_0$$

$$M(dot) = \frac{M_{(pr\ booster\ )}}{burn\ \ time} \quad \text{-3.3.9}$$

4. Mass Flow Rate:

The mass flow rate of propellant is the product of volume consumed per unit time and density. The mass flow rate of different propellant combinations was calculated to determine the number of engines needed to achieve the mission requirement.

An area ratio and nozzle exit area for different propellant combinations from a particular rocket engine was assumed to calculate the mass flow rate. A combustion chamber pressure of 100.33 bars was taken to calculate the total pressure.

Table 5. ISP and average thrust values.

Fuel	I_{SP} (sec)	M(dot) (Kg/s)	Avg Thrust for the booster stage	The volume occupied by prop.
CH_4	350	1009.14	3533.39	449.86
LH_2	450	752.42	3385.89	2003.06
RP-1	330	1195.02	3630.47	300.45

$$M\ (dot) = \left(\frac{\gamma+1}{2}\right)^{\frac{\gamma+1}{2(\gamma-1)}} \times \frac{\gamma P_t A}{\sqrt{\gamma R T_t}} f(M) \text{-3.4.1}$$

$$T_t = T_c \times \gamma \quad \text{-3.4.2}$$

$$P_t = P_c \times \left(\frac{T_c}{T_t}\right)^{\frac{\gamma}{\gamma-1}} \quad \text{-3.4.3}$$

Table 6. Mass flow rate and specific heat values.

Fuel	T(c) Kelvin	γ	T(t) Kelvin	m(dot) in Kg/s
CH_4	3550	1.207	4284.85	25.42
LH_2	2985	1.202	3587.97	27.72
RP-1	3670	1.218	4470.06	24.98

$$f(M) = \frac{A}{A_t} \quad \text{-3.4.4}$$

For f(M) and A, a value was assumed by referring to different rocket engines that use the same propellant combination. m(dot) is the mass flow rate of a single-engine. Mass flow rate determines that how many engines will be needed to meet the mission requirements.

5. Specific Impulse:

Specific impulse defines the performance of an engine. It plays a dominant role in the upper stage of a rocket. An excellent specific impulse helps in decreasing the economic factor of a rocket. ISP is the amount of time taken for burning the propellant.

The greater the specific impulse, the lesser the propellant is needed for the mission. It concludes that LH2 gives a great specific impulse value than the other two combinations, which makes it suitable for the upper stage of a rocket. The ISP of LH2 lies in the range of 400-450 seconds, whereas RP-1 and CH4 are 270-330 seconds and 310-360 seconds, respectively.

6. Thrust:

Thrust is the amount of force needed for a rocket to propel forward. Thrust is dominant in the atmospheric phase of spaceflight. In the Thrust equation below, the total thrust is a combination of momentum thrust and pressure thrust.

The pressure thrust highly depends on three different expansion types of flow inside the nozzle.

- Under expanded
- Over expanded
- Fully expanded (ideal condition)

Due to the atmospheric pressure at sea level, the pressure thrust has almost no impact on rocket propulsion as the nozzle is nearly fully expanded. The momentum thrust has a more significant effect on rocket propulsion in the atmospheric phase.

As there is no atmospheric pressure in the vacuum of space, the pressure thrust plays a vital role in rocket propulsion.

$$T = \dot{m} \cdot V_e + (P_e - P_a) \cdot A_e \text{ -3.6.1}$$

Thrust requirement is dominant in the atmospheric phase because the rocket has to overcome the atmospheric drag and carry the highest weight in the mission.

The greater the thrust, the better the propellant for the atmospheric phase. It was observed that RP-1/LOX gives the best thrust value, so this combination is best suited for the booster stage. LH2/LOX is not suited for the booster stage due to its low thrust value.

CH4/LOX has a higher energy/mole value than LH2/LOX but is lower than RP-1/LOX, but this can be taken care of by burning excessive propellant.

7. Ignition Delay Time (IDT):

The ignition delay time is the time gap between the injection of fuel and the rise of pressure in the combustion chamber due to the ignition of the fuel and oxidizer. The process of combustion contains a series of events such as vaporization, atomization, reaction, and product formation.

The ignition delay time is directly proportional to the density of the fuel. Reduced ignition delay time causes an increase in combustion efficiency as fuel has to burn fast on a constant length of combustor; otherwise, some fuel expelled remains unburnt, which leads to a reduction in performance. The lesser the density, the lesser is the IDT.

For the comparison of LH2, CH4, and RP-1, LH2 has the least density, and also, it is not a hydrocarbon fuel; hence it has the least IDT followed by CH4 and RP-1. CH4 has a similar composition to LH2 as four hydrogen atoms surround it.

IDT can be manually reduced by adding nitrogen compounds to the propellant combination. IDT is a significant characteristic of fuel to determine combustion efficiency.

8. The pressure inside Combustion Chamber:

The pressure inside the combustion chamber directly impacts the velocity of the propellant ejected. As the pressure increases inside the combustion chamber, the pressure difference increases between the combustion chamber and the atmosphere.

Due to the increase in pressure in the combustion chamber, the propellants tend to move outside the nozzle more quickly, increasing the exhaust velocity. An increase in exhaust velocity increases the thrust value of a rocket engine.

Combustion chamber pressure values lie in a range of 10-200 bars. When we compare the three propellants, it was observed that the combustion chamber pressure is highest for RP-1, followed by CH4 and LH2 at a fixed mass flow rate and a particular altitude.

9. Storability and Handling:

The storability of different propellants is always a concern for any Aerospace company. The temperature at which different propellants are stored in a rocket is given in table 7.

After analyzing the table, it can be observed that the storability of LH2 is a very burdensome process due to its low storage temperature. Storage of LOX is also tricky at such a low temperature. However, as it is the best oxidizer and can burn any fuel, Aerospace companies can sustain it at a low temperature. If the company successfully sustains LH2 at such a low temperature, the advantages of LH2 are enormous.

RP-1 is a propellant that can be easily stored at room temperature, but its ISP value is a disadvantage. CH4 is the best compromise for the other two propellant combinations, which have a storage temperature lower than LOX and a decent ISP value.

Table 7. Fuel/Oxidizer and their storage temperature.

Fuel/Oxidizer	Storage Temperature
Liquid Oxygen	-218.79°C
Liquid Hydrogen	-252.87°C
RP-1	25°C (Room Temperature)
Liquid Methane	-162°C

If a company wants to use LH2 as fuel, the propellant must be filled just 15-20 minutes before the rocket is launched. LH2 starts decaying if it is kept for more than 15-20 minutes. It is a significant disadvantage, and that is why the military never uses liquid propellants.

10. Soot:

Soot is produced as a by-product of the propellant, which eventually degrades the reusability of a rocket.

Soot is produced by the carbon content and impurities present in the propellant. RP-1 produces much soot, which eventually degrades the structure of a rocket. Black color on the structure of the rocket can be observed if the propellant produces soot.

LH2 is not a hydrocarbon; hence it does not produce any soot. CH4 is an excellent alternative as a propellant if soot production is an issue as the carbon is surrounded by four hydrogen’s and hence depicts similar properties of LH2.

RP-1 was used as a fuel in Falcon 9, and due to soot production, it can only be reused 9-10 times. CH4 is acquired by most companies now as a fuel due to its excellent performance and almost no soot production so that the rocket can be reused more often.

IV. OTHER FUELS

The talks of using “green propellants “as rocket fuel are around the corner. Bio fuels such as Ethanol for rocket propulsion are doing rounds. These green propellants impact the environment in a significant manner.

Ethanol as a fuel is not used in rocket engines due to its performance. It has a low ISP range of 220-245 seconds. Also, its density is 789 Kg/m^3, which is way higher than the density of other liquid propellants in use, and hence it increases the propellant weight of the rocket and the cost of the mission.

V. CONCLUSION

After studying all the parameters, it can be concluded that LH2/LOX propellant combination is mainly used in the upper stage of a rocket due to its high ISP value and low density. LH2/LOX combination is not used in the booster stage of a rocket because of its low thrust value. Another drawback of LH2 is its storage temperature which is lower than LOX.

RP-1 is an excellent fuel for the booster stage due to its high thrust value. RP-1 is used in missions that require more power. The Storability of RP-1 is a perk as it can be stored at room temperature. One of the drawbacks of this fuel is its low specific impulse, so it is not used in the upper stage of a rocket. Another drawback is that it produces soot as it’s by product, which decreases the frequency of Engine reusability and is a threat to sustainable development.

After all the analysis, CH4 is recommended as the best fuel for both stages of a reusable rocket. It produces minimal soot, which helps in reusing the same engine. It is stored at a temperature lower than LOX. Rocket's weight substantially reduces than its counterpart, RP-1. Also, it is readily available as it is a naturally occurring gas. Therefore, it affects the economic factor of the mission.

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REFERENCES

[1] Vernin, Hilda & Pempie, Pascal. (2009).”LOX/CH4 and LOX/LH2 Heavy Launch Vehicle Comparison,” 45th AIAA/ASME/SAE/ASEE 10.2514/6.2009-5133, pp 1-4.

[2] Burkhardt, Holger & Sippel, Martin & Herbertz, Armin & Klevanski, Josef. (2002). “Comparative Study of Kerosene and Methane Propellant Engines for Reusable Liquid Booster Stages,” 4th International Conference on Launcher Technology "Space Launcher Liquid Propulsion, pp 1-6.

[3] Houhou, Hatem & Layachi, Hemza & Boudjemai, Abdelmadjid. (2019). “Design of the thrust chamber: dimensional analysis of the combustion chamber and the nozzle of rocket engine using LOX/LCH4 propellants,” IOP Conf. Series: Materials Science and Engineering 715 (2020) 012085, pp 1-5.

[4] Petrukhin, N. V., Grishin, N. N., & Sergeev, S. M. (2016). “Ignition Delay Time – an Important Fuel Property. Chemistry and Technology of Fuels and Oils,” Chemistry and Technology of Fuels and Oils, Vol. 51, No.6, January, 2016, pp 1-4.

[5] Mark C. Grubelich, Stewart H. Youngblood, Michael J. Hargather, and Venner Saul “Nitrous Oxide Ethanol Bi-propellant Rocket Engine & Gas Generator Development and Testing,” pp 1-2.

[6] Kai Dresia, Simon Jentzsch, Günther Waxenegger-Wilfing, Robson Dos Santos Hahn, and Jan Deeken, Michael Oschwald, Fabio Mota “Multidisciplinary Design Optimization of Reusable Launch Vehicles for Different Propellants and Objectives,” JOURNAL OF

SPACECRAFT AND ROCKETS, pp 1-9.

[7] Mr. Brenday Rooney "Reusable launch vehicle ground operational challenges", AIAA/ICAS International Air and Space Symposium and Exposition, pp 1-4

[8] Kevin Bowcutt, Mark Gonda, Steve Hollowell,and Ted Ralston "Performance, Operational and EconomicDrivers of Reusable Launch Vehicles", AIAA-2002-3901, pp 1-8

[9] George P. Sutton, Oscar Bib larz "Rocket Propulsion Elements" John Wiley and Sons, INC. , pp 198-263

[10] George P. Sutton, Oscar Bib larz "Rocket Propulsion Elements" John Wiley and Sons, INC. , pp 48-96

Nomenclature:

LOX – Liquid Oxygen
LH2 – Liquid Hydrogen
RP-1 – Refined Kerosene
CH4 – Liquid Methane
Isp – Specific Impulse
RLV – Reusable Launch Vehicle
Me – Empty Mass
Mpl – Payload Mass
Ms – Structural Mass
Mpr – Propellant Mass
PMR – Propellant Mass Ratio
ζ – Payload Ratio
ξ – Structural Coefficient
γ – Specific heat value
Tc – Combustion Chamber Temperature
Tt – Total Temperature
Pc – Combustion Chamber pressure
Pt – Total Pressure
A – Nozzle exit area
At – Nozzle throat area
Δv – Change in velocity
Ve – Exhaust Velocity
M – Mach Number
M(pr booster) – The propellant mass of the booster stage
M(pr landing) – Propellant mass for the landing of the booster stage
M(str booster) – Structural mass of booster stage