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A Review of the Semi-Cryogenic Engines

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Abstract

Cryogenic Engines were a dream long-envisioned by many space organisations due to their exceptional efficiency and performance, until the 1960s. The mission to develop the first cryogenic engine-powered rocket started along with NASA's establishment, in the year 1958. NASA built it with the aim of putting heavy payloads into orbit. The first cryogenic engine-powered engine was successfully launched in 1963. From then on advancements in this field have been ongoing. **This paper presents a comprehensive review of the advancements in Cryogenic Engines, specifically the Semi-Cryogenic Engines. It will also explain the workings of Cryogenic and Semi-Cryogenic Engines and how they edge over normal rocket engines.** A Cryogenic Engine is the only engine that gives 100% efficiency without any greenhouse emissions or pollution. Cryogenic Engines utilize liquid hydrogen (LH2) as fuel and liquid oxygen (LOX) as an oxidizer, enabling a high specific impulse and superior fuel efficiency. Talking about Semi-cryogenic engines, a promising alternative that combines the benefits of cryogenic and conventional engines, employs a cryogenic oxidizer, typically liquid oxygen (LOX), along with a hydrocarbon-based fuel, such as kerosene (RP-1). By blending cryogenic and non-cryogenic propellants, semi-cryogenic engines achieve a balance between performance and operational simplicity.

Introduction

What drives the aerospace and aeronautical industry is the question of how fuel-efficient can the aircraft be made. As mentioned earlier, A **cryogenic engine** is a type of space launch vehicle which uses oxygen and hydrogen as a liquid instead of gas, unlike other spacecraft. The basic definition of propellant still remains the same, the fuel and the oxidizer come together from the propellant. Hydrogen is used because it does not corrode the engine parts. The use of liquid hydrogen here is what makes cryogenic engines one of a kind. Due to its high specific impulse characteristic and lightweightness (compared to gaseous hydrogen), comparatively more thrust can be generated with the same amount of fuel. Thrust is the force that moves the spacecraft through medium or space using Newton's third law of motion. For reference, usually, when we are travelling by aeroplane we see the functioning of air turbines to accelerate the aeroplane. The turbines suck in air from the surrounding and pass them through the high-speed turbine and out of the engine. Similarly, a working fluid (in the spacecraft case, the propellant) is accelerated by the system and the reaction to this is that acceleration produces a force on the system. A general derivation of the thrust equation shows that the force generated depends on the mass flow through the engine and the exit velocity of the gas. Getting further into this, we can talk about semi-cryogenic engines. A semi-cryogenic engine uses refined kerosene which is lighter and can be stored at normal temperatures thus making the spacecraft more efficient.

Historical development

Ever since rocket propulsion took off we've seen steady progress through innovations like the semi-cryogenic engine which attained its earliest forms during this era. Utilizing cryogenic oxidizers such as liquid oxygen (LOX) combined with non-cryogenic fuels like kerosene or other hydrocarbons birthed a marriage that balances extreme performance with hassle-free operation.

Dating us back to history. In the 1950s Valentin Glushko helped pioneer one such example with the Soviet RD 107 and RD 108 engines. Effective for propelling Sputnik and Vostok rockets, their semi-cryogenic systems were crucial for enabling modern human spaceflight as we know it today. American contributions would follow with the late 1950s development of the Rocketdyne E 1 model that relied on LOX and RP 1 as a propellant but was later replaced by an even more impressive F 1 engine. With its immense power from a single-chamber liquid to power Saturn Vs' first stage throughout NASA's Apollo program directed under George Muellers' lead at Rocketdyne.

Europe made significant strides in semi-cryogenic engines as Société Européenne de Propulsion (SEP), now a component of ArianeGroup, led on development. For instance, the Vulcain engine fuels Ariane 5's primary stage with LOX and liquid hydrogen (LH2) propellants representing the cream of the crop in European semi-cryogenic engineering. With potential reuse capabilities generating enthusiasm surrounding such propulsion methods today.

SpaceX's Merlin engine is another worthwhile modern-day example that powers Falcon 9 & Falcon Heavy rockets using LOX and RP-1 fuels while CEO Elon Musk designed them for reuse purposes. In line with enhancing space launch capacities further through propulsion innovation efforts is LPSC in India developing a semi-cryogenic engine that uses LOX and Isrosene fueling agents.

Semi-cryogenic engines were developed out of necessity for technology capable of efficient performance coupled with versatility within space launch vehicles. Renowned personalities such as Valentin Glushko alongside companies like George Mueller's Rocketdyne worked towards ensuring the success experienced today through SpaceX, ArianeGroup & LPSC operating out of India.

Basic principles and components:

A simple rocket propels itself high into the sky using Newton’s third law. When the rocket ejects high amounts of mass at high speed, then the rockets gain momentum for movement in the opposite direction. For this purpose, rockets have to burn highly combustible fuels. Liquid fuel-based rocket engines are the most efficient engines for travel to space. As there is no oxygen present in space, the rocket has to also carry the oxygen along. The fuel and oxygen are together called propellants. The choice of the type of fuel to use is a very important part. The higher the speed at which the exhaust gas is emitted, the measure of momentum lost. The fuels with the least molecular weight tend to have high specific impulses and a high calorific value. But it won’t be feasible to carry heavy hydrogen gas into space so instead of gaseous hydrogen, liquefied hydrogen is carried into the space. This is what makes cryogenic engines different from general rocket engines. In order to liquefy hydrogen, it is compressed and carried to the storage site and just before the rocket is launched, the liquefied hydrogen is put into the fuel tank of the vehicle. The same goes for oxygen. The fuel tank is covered with a highly durable aluminium-lithium alloy. This is further

covered with polyurethane which is a thermally insulating material, that protects the rocket from extreme heat while passing through the Earth's atmosphere.

To overcome the gravitational force on a rocket, it requires a significant amount of thrust. Liquefied propellants cannot generate this level of thrust, so the liquefied hydrogen must be converted back into gaseous hydrogen. This is done with a group of turbines in what is known as the expander cycle. In this cycle, liquid oxygen (LOX) is the oxidizer and liquid hydrogen (LH2) is the fuel. The propellants are compressed before being injected into the engine's combustion chamber during the expander cycle.

The engine's turbopump, which pressurizes and propels the propellants into the combustion chamber, is cooled using cryogenics during the expander cycle. The LOX and LH2 propellants move through "expander channels" in the turbopump, which cools the turbopump and removes heat from the propellants.

Only a small percentage of the propellants are diverted from the main flow and directed into the expander channels to create the cooling effect. As the propellants move through these channels, they undergo a phase shift from liquid to gas, absorbing a significant amount of heat. This phase shift is possible due to the cryogenic propellants' low temperature.

The high-pressure gas generated in the expander channels drives the turbine of the turbopump, which powers the propellant pumps. The expander cycle eliminates the need for a separate burner or gas generator, which are standard components in other engine cycles, by using cryogenic propellants to cool the turbopump.

Types of semi-cryogenic engines:

One type of semi-cryogenic engine is the staged combustion engine. There are two sections in this engine: one section has the oxidiser and another has the fuel. The exhaust from the chamber of the oxidiser is used to increase the temperature of the fuel and heat it in the second chamber to get more thrust. It is the most efficient semi-cryogenic engine in today's world because of its ability to produce the most thrust with the same amount of fuel in comparison to others. This is due to a higher specific impulse for a given amount of propellant. This also helps in making it extremely lightweight because less amount of fuel is required to achieve the same thrust to propel the system. This engine type has a low number of moving parts and objects, making it highly reliable with less chance of failure. However, due to its complex machinery, manufacturing this engine is costly and difficult. Additionally, it has been observed that the engine's impulse decreases at higher altitudes compared to other cryogenic engines.

Another type of semi-cryogenic engine are gas-generator engine. The mechanism of this engine is much simpler, a hot gas from a gas generator is used to move the turbine that pumps the propellants into the combustion chamber. The simplicity of this keeps the machine cheaper than the staged combustion engine and makes it easier to build. However, they are less reliable than the staged combustion engine due to more moving parts but are often used for smaller launch vehicles and aircraft. Due to this mechanism, and the engine not using the exhaust like the staged engine, the efficiency is relatively less and more propellent has to be used to see the same result. There is also a lower thrust-to-weight ratio, due to which the engine cannot carry a lot of weight.

Expander cycle engines are also a type of gas generator engines but in the expander cycle engine, the hot gas produced is used to expand the propellant which helps produce additional thrust. This results in a few advantages such as this engine becomes more efficient than the standard gas generation engine as it is able to produce the same amount of thrust with the same amount of gas. It also results in a higher thrust-to-weight ratio, due to which the engine is able to lift relatively more weight. These engines are less reliable than staged combustion engines because of more moving parts. However, looking at the opposite side, this engine is more complex than the simpler gas generator engines which makes it relatively difficult to build and increases the cost. It is more expensive than gas generator engines but cheaper than staged combustion engines.

Semi-cryogenic propellants:

Rocket systems often use semi-cryogenic propellants, which involve a cryogenic oxidizer (usually liquid oxygen) and a non-cryogenic fuel like kerosene or other hydrocarbons. This fuel combination provides a balance between the high performance of cryogenic propellants and the easier handling and storage requirements of non-cryogenic propellants like liquid hydrogen. The oxidizer, liquid oxygen, remains in a liquid state at extremely low temperatures and has a boiling point of -183 degrees Celsius. It is typically stored at this temperature as well (-183 degrees Celsius or -297 degrees Fahrenheit).

LOX is highly reactive and supports combustion vigorously, making it a powerful oxidizer. Although non-toxic, proper safety measures are essential during handling due to its combustible nature. Storage requirements for semi-cryogenic propellants involve specific considerations for each component. Liquid oxygen (LOX) necessitates cryogenic storage tanks that can maintain extremely low temperatures and prevent heat ingress from the surroundings. These tanks must be well-insulated and designed to handle the thermal stresses associated with extreme temperature differentials. Furthermore, proper safety measures are crucial to prevent the accumulation of flammable substances and potential ignition sources in LOX storage areas due to their strong oxidizing properties.

RP-1, also known as kerosene, is a non-cryogenic fuel used in semi-cryogenic propellants. It is a purified form of kerosene that stays in a liquid state even when the temperature is above its freezing point. Although it has a lower energy density than cryogenic fuels such as liquid hydrogen, RP-1 provides a higher energy density than storable propellants like hydrazine. Its handling is relatively easier as it is less volatile and does not require extreme cryogenic temperatures. However, RP-1 is a hydrocarbon fuel that can produce soot when burned, which presents challenges in terms of combustion efficiency and engine maintenance. For kerosene (RP-1) storage, tanks need to be designed to prevent leakage as it is a valuable and potentially hazardous material. Unlike LOX, RP-1 can be stored at room temperature, reducing the complexity of storage requirements. However, safety precautions are still necessary during handling due to its flammability.

Ensuring compatibility between LOX and RP-1 is vital to prevent adverse reactions or hazardous situations. All materials used in the propellant system, including seals, valves, and tanks, must be compatible with both LOX and RP-1 to prevent leaks, ignition, or other potential failures. Thermal management is another important aspect when dealing with semi-cryogenic propellants. The temperature differential between the cryogenic oxidizer (LOX) and the non-cryogenic fuel (RP-1) can pose challenges in maintaining propellant stability and optimizing engine performance. Designing effective cooling systems and managing heat transfer within the rocket engine is necessary to prevent thermal stresses and ensure efficient operation.

Various space launch vehicles have successfully implemented semi-cryogenic propellants despite the challenges. Two prominent examples are SpaceX's Falcon 9 and Falcon Heavy rockets, which use LOX as the oxidizer and RP-1 as the fuel. By striking a balance between performance and handling ease, semi-cryogenic propellants offer a reliable and efficient solution for space exploration.

Applications:

Space exploration greatly depends on functional semi-cryogenic engines that enable the successful accomplishment of various missions such as deep space expeditions, upper stages deployment, and launching spacecraft into orbit; they are highly efficient with superior performance capabilities to deliver effective results.

Semi-cryogenic rocket engines' most significant application is propelling a rocket's first stage intended for lifting a spacecraft beyond Earth's atmosphere. During takeoff or launch phase powerful thrust generated by the rocket engine results from its fuel mixture components - liquid oxygen along with liquid hydrogen igniting within controlled conditions to counter gravity while providing an energy boost needed to lift off successfully. Take the Space Launch System (SLS) for instance: this next-generation launch vehicle would rely on advanced technologies such as the RS 25 semi-cryogenic engine boasting immense power capabilities ideal for generating high performance required during liftoff precisely when entering orbiting speeds towards deep space destinations like Mars or the Moon. Other applications of semi-cryogenic engines lie in powering the upper stages of rockets tasked with deploying satellites into orbit. United States' Delta IV rocket. For example. Utilizes a RS 68 liquid-fueled engine as its second stage for launching a range of satellites, both military and commercial.

It is remarkable how Semi Cryogenic Engines are packed with diverse functionalities; they hold promise when used along with launch vehicles in deep space missions. In the planned future space missions to Moon and Mars by NASA RS 25 semi-cryogenic engine will power the SLS rocket's first stage while its upper stage will carry an advanced version of the J 2X engine fueled by liquid hydrogen as well as liquid oxygen propellants. These powerful Semi Cryogenic Engines offer scope for carrying heavy payloads efficiently even as they support crewed Missions at deep space locations. Their versatility makes them extremely attractive as viable options for use in various space exploration activities while remaining economical. The United States Space Launch System (SLS)rocket, Delta IV Rocket boasts of notable semi-cryogenic engines using RS 25 and RS 68 engines as key components for their stellar performance. Unlocking the full potential of these remarkable machines requires sustained research and development. It can unlock exciting opportunities for exploring even beyond our solar system.

Current research and advancements:

Multiple countries worldwide have advanced our knowledge of semi-cryogenic engines with major developments across several areas; most notably these significant findings can be seen within American SpaceX's leading-edge Merlin engines which power both Falcon heavy rockets and Falcon 9s for consistent improvements in the future. These Merlin Engines are designed specifically to promote reusability while maintaining focus on delivering reliable efficient mechanisms vital for lowering costs required for spacecraft launching overall.

The European Union also maintains an active role; evident through their longtime interest in working towards exceptional resourcefulness paired with performance-driven features showcased within their Vulcain engine. Fuelled by liquid hydrogen as technology to offer high functionality, these engines continue with a strong track record of reliability relating to Ariane 5 rocket launches in Europe. Looking forward, the ArianeGroup is passionately pursuing progress with their next-generation rocket developments in the form of semi-cryogenic engine-powered Vulcain 2.1.

Moreover, India's Liquid Propulsion Systems Centre (LPSC) has ventured further into technological expansion by creating semi-cryogenic engines using Isrosene and liquid oxygen; enabling booster stages that enhance flexibility overall while directly contributing towards advancements related to space launch capabilities that will continue to improve efficiency and diverse abilities along with other international ventures.

ISRO'S Liquid Propulsion Systems Centre (LPSC) has been making remarkable strides in semi-cryogenic engine technology with its SCE-200 project aimed at improving India's space launch capabilities. This project entails utilizing Isrosene fuel complemented by a liquid oxygen oxidizer to run a semi-cryogenic engine system.

The recent successful test results can be seen from conducting various vital testing components such as the turbo pump which delivered an exceptional power output exceeding 36 megawatts. This progress and advances bring ISRO closer to achieving its objective of developing an efficient propulsion system capable of versatile and diverse functionalities for their launches.

The research continues focussed on improving efficiency, reliability, and reusability with several organizations actively involved in collaborations with notable mention including SpaceX's Raptor engines that use full-flow staged combustion mechanisms utilizing liquid oxygen and methane - specifically ideal for interplanetary missions-enabled Starship spacecraft.

Challenges and Future Prospects:

Developing semi-cryogenic engines poses significant challenges that need careful exploration of effective solutions before any meaningful utilitarian function is achieved. These challenges include thermal management intricacies, material selection strategies & safety concerns involved in the operational stages.

Thermal management is critical due to extreme temperature differences between cryogenic oxidizers & non-cryogenic fuels necessitating ensuring appropriate heat balances to prevent structural damage or reduced performance capabilities. The United States Space Shuttle program serves as a useful point of reference as that program had its fair share of thermal issues resulting from adopting liquid hydrogen as fuel which called for advanced insulation protocols coupled with sophisticated cooling systems.

Materials proving capable of tolerating extreme pressure conditions arising from various shifting temperatures established in semi-cryogenic engines coupled with resistance against corrosion triggered due to the propellant corrosive nature remain crucial when selecting materials used for building these machines. Russia's RD-180 engine made from kerosene fuel faces serious materials degradation challenges over time due to the oil's destructive properties.

Safety concerns pose one of the greatest challenges facing semi-cryogenic engine development & usage; cryogenic propellants like liquid oxygen & hydrogen possess high flammability risks requiring stringent safety measures involving safe storage procedures while infusing practical safe operating guidelines towards activities where these chemicals are utilized effectively reducing exposure hazards associated with handling or accidental combustions leading to potential catastrophic failures such as those experienced earlier by Saturn V during the Apollo 6 mission.

Meeting challenges head-on calls for exploring innovative ideas to navigate uncharted territories like those presented by semi-cryogenic engines today - hence why researchers and engineers all over are focused intensely on pioneering new materials along with exceptional thermal management approaches that facilitate enhanced efficiency levels paired with heightened faith in dependability matters too! Thanks largely in part due to NASA's United States Space Launch System (SLS) program; where sophisticated insulation materials combined with cutting-edge thermal protection methods are already in use toward this mission-critical end goal - driven by a desire to improve thermal management abilities safely while mitigating any structural damage risk whatsoever. In addition, there's a strong focus on creating exceptional safety protocols and procedures that ensure everyone's well-being and the proper handling of cryogenic propellants before, during, and after launches of any kind.

The semi-cryogenic engine, having many applications in reusable launch vehicles and interplanetary missions, has a bright future ahead of it. By making propulsion systems that are both environmentally friendly and versatile with impressive efficiency levels it can change how we explore our solar system bringing these opportunities closer through more cost-effective methods.

A significant part of innovation involving these engines lies in developing rocket systems that can be used multiple times successfully. SpaceX's Falcon 9 as well as Blue Origin's New Shephard are some examples showing promise when launching crafts into space by reducing costs drastically thus enabling more people, eg. commercial interests or individual citizens- an opportunity for space exploration at reduced budgets.

As previously mentioned these engines are ideal for interplanetary missions since they offer high performance levels with efficient outputs suitable for these long-distance trips through space. Various agencies have considered this attribute significant plus even use semi-cryogenic engines specifically for elements like NASA’s Space Launch System (SLS) aimed primarily at journeys towards Mars or even exploring further on the moon.

Furthermore, apart from reusable spacecraft or long-distance expeditions beyond Earth's orbit, these types of propulsions could involve themselves in diverse other sectors like satellite launches or even tourism involving outer space. Henceforth ISRO aims to have reusable rockets for satellite launches around the early 2020s.

Conclusion

Multiple countries worldwide have advanced our knowledge of semi-cryogenic engines with major developments across several areas. The European Union has also maintained an active role in working towards exceptional resourcefulness paired with performance-driven features showcased within their Vulcain engine.

India's Liquid Propulsion Systems Centre has created semi-cryogenic engines using Isrosene and liquid oxygen to enhance space launch capabilities.

ISRO's Liquid Propulsion Systems Centre (LPSC) has been making remarkable strides in semi-cryogenic engine technology with its SCE-200 project aimed at improving India's space launch capabilities. The recent successful test results can be seen from conducting various vital testing components. But, developing semi-cryogenic engines poses significant challenges that need careful exploration of effective solutions, including thermal management intricacies, material selection strategies & safety concerns involved in the operational stages. The United States Space Shuttle program serves as a useful point of reference.

Safety concerns pose one of the greatest challenges facing semi-cryogenic engine development & usage. NASA's United States Space Launch System (SLS) program is already in use toward improving thermal management abilities safely while mitigating any structural damage risk whatsoever.

The semi-cryogenic engine has many applications in reusable launch vehicles and interplanetary missions and can reduce costs drastically when launching crafts into space, enabling more people to explore our solar system. And so by this review paper, we conclude that, Semi-cryogenic engines are ideal for interplanetary missions, and can be used in diverse other sectors like satellite launches or even tourism involving outer space.

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