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Liquid Oxygen Augmented Gas Core Nuclear Thermal Rocket

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Abstract

Conventional propulsion technology (chemical and electric) currently limits the possibilities for human space exploration to the neighborhood of the Earth. If farther destinations (such as Mars) are to be reached with humans on board, a more capable interplanetary transfer engine featuring high thrust and high specific impulse is required. The source of energy which could in principle best meet these engine requirements is nuclear thermal energy. So an innovative gas core nuclear thermal rocket concept which combines conventional liquid hydrogen cooled nuclear thermal rocket and supersonic combustion ramjet (scramjet) technologies is described. Known as the Liquid oxygen augmented Gas core Nuclear Thermal Rocket (LAG-NTR), this concept utilizes the large divergent section of the gas core nuclear thermal rocket's nozzle as an afterburner into which liquid oxygen is injected and supersonically combusted with nuclear preheated hydrogen emerging from the LAG-NTR's choked sonic throat- scramjet propulsion in reverse. By varying the oxygen-to-hydrogen mixture ratio, the LAG-NTR can operate over a wide range of thrust and specific impulse values while the gaseous core reactor's power level remains relatively constant. This thrust augmentation feature means that a larger engine performance can be obtained with a comparatively smaller LAG-NTR engine.

Keywords: Nuclear thermal rocket, gas core, afterburner, scramjet, thrust, specific impulse, supersonic combustion.

1. Introduction

To achieve any measure of space travel there is one tool that has always been indispensable, rockets. Rockets have been the primary tool for sending spacecraft into orbit and accelerating them beyond Earth orbit to other planets in the solar system, and for a few craft, on their way out to the rest of the galaxy. Despite the amazing advances in rocket technology, were still forced to rely on chemical combustion to propel vehicles off Earth and to space destinations in a relatively short time period. Chemical rocket engines, while producing a lot of thrust, are highly inefficient and very dangerous as several rocket accidents in the past have proven. Electrical propulsion is a useful alternative for long-term small probes due to its high efficiency, but it produces very low thrust and is not useful for shorter-term manned missions. Nuclear thermal rockets, or NTRs for short, are better alternative for operating over a wide range of thrust and specific impulse values.

The energy available from a unit mass of fissionable material is nearly 10^7 times larger than that available from the most energetic chemical reactions. That is because nuclear fission has an energy density of 8×10^{13} J/kg compared to chemical reactions with an energy density of 10^7 J/kg. Therefore, nuclear fission is very attractive for propulsion.

The general operating principles for gas core nuclear thermal rocket propulsion are similar to those of conventional chemical rocket propulsion. A propellant is heated in the rocket chamber, thereby raising its stagnation enthalpy, and exhausted through a converging-diverging nozzle to achieve supersonic exit flow. The gaseous reactor core is designed to efficiently transfer heat from the fission reactor core to the propellant while minimizing system mass. The reactor core uses U-235 in plasma form. The propellant is usually LH_2, which is also used to cool the reactor. LH_2 is a low molecular weight propellant, which therefore allows the LAG-NTR to achieve very high specific impulse (I_{sp}) values. For thrust augmentation, liquid oxygen is injected into the large divergent section of the nozzle where it burns spontaneously with the nuclear reactor-heated hydrogen exhaust. This has many advantages such as reduction in size of the nuclear reactor and propellant tank volume for a given payload.

2. Theory of Operation of LAG-NTR

In a LAG-NTR, hydrogen is pumped into one end of a cylindrical reaction chamber, with an exhaust at the other end. The hydrogen expands as it passes through the chamber, and not all of it goes out the exhaust, instead flowing back up the chamber. This creates a toroidal vortex of hydrogen gas that can be used for fission reaction containment. Dust-sized particles of uranium are injected into the toroid and accumulate at its center. A number of long cylinders are mounted on the interior of the reaction chamber outside the toroid. These cylinders normally absorb radiation emitted by the uranium, but they can be rotated to reflect it, initiating a fission reaction. The cylinders are the equivalent of control rods in an Earth-based reactor. Once fission begins in the center of the hydrogen gas toroid, the high temperatures heat the gas into a plasma, which flies out the exhaust at high velocity to provide thrust. A small magnetic nozzle could be used to ensure that the uranium remains in the reaction chamber, while allowing the hydrogen plasma to escape.

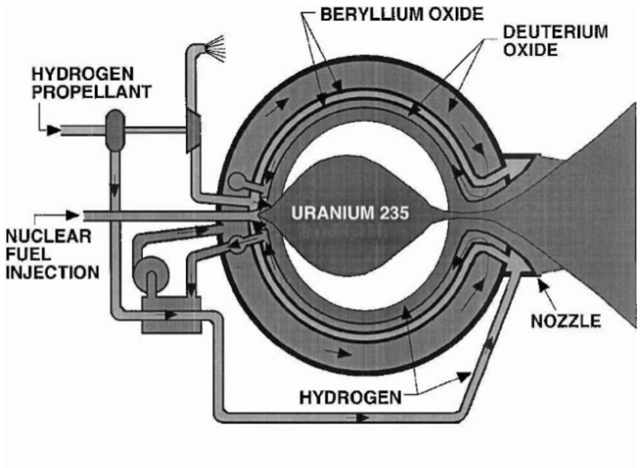

Figure 1: Gas Core Nuclear Thermal Rocket Engine.

3. Fissile Fuel Containment in Reactor Core

The shape of the fissile gas core can be either cylindrical, toroidal or counter flow. Since there are issues regarding the loss of fissile fuel with the cylindrical and toroidal designs, the counter-flow toroidal gas core geometry is preferred. The counter flow toroid is the most promising because it has the best stability and theoretically prevents mixing of the fissile fuel and propellant more effectively than the above-mentioned concepts. In this design, the fissile fuel is kept mostly in a base injection stabilized recirculation bubble by hydrodynamic confinement. Most designs utilize a cylindrical gas core wall for ease of modeling. However, previous cold flow tests have shown that hydrodynamic containment is more easily achieved with a spherical internal wall geometry design.

The formation of the fuel vortex is complex. It basically comes down to flow over a projectile shape with a blunt base. The vortex is formed by placing a semi-porous wall in front of the desired location of the fuel vortex but leaves room along its sides for hydrogen propellant. Propellant is then pumped inside the reactor cavity along an annular inlet region. Dead spaces then develops behind the semi-porous wall due to viscous and shear forces creating a counter toroidal rotation. Once the vortex develops, fissile fuel can be injected through the semi-porous plate to bring the reactor critical. The formation and location of the fuel vortex now depends on the amount of fissile fuel that bleeds into the system through the semi-porous wall. When more fuel bleeds into the system through the wall, the vortex moves farther downstream. When less fuel bleeds through, the vortex moves farther upstream.

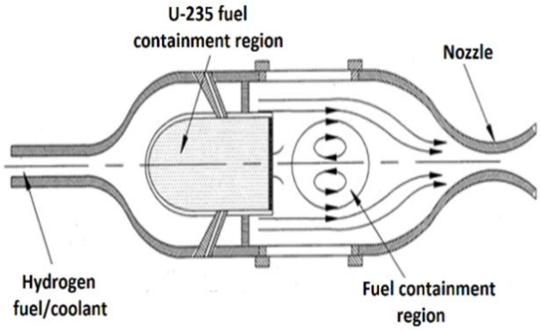

Figure 2: Open Cycle Gas Core Nuclear Thermal Rocket Engine with counter-flow toroidal vortex fuel containment.

4. Thrust Augmentation with LOX Injection

The LOX augmentation of gas core nuclear thermal rocket involves the use of a conventional hydrogen propellant nuclear thermal rocket with LOX injected into the exhaust nozzle. Cascade scramjet injectors introduce oxygen into the supersonic nozzle, whereby the injected oxygen acts like an afterburner and operates in a reverse scramjet mode. Supersonic combustion of oxygen in the nozzle substantially increases the thrust-to-weight ratio of the gas core nuclear thermal rocket. This makes it possible to augment and vary the thrust at the expense of reduced I_{sp}.

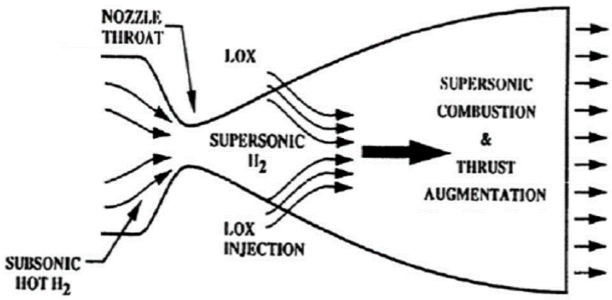

Figure 3: Thrust augmentation of LAG-NTR by LOX injection.

5. Potential Applications of LAG-NTR

Using a nuclear engine in low earth orbit may be regarded hazardous, as there is possibility of re-entry and contamination of the atmosphere. The firing of the engine should therefore be confined to high earth orbits and to interplanetary transfer maneuvers. In such orbits and maneuvers, there is little probability of re-entry because of the energy required to de-orbit. The liquid oxygen augmented nuclear thermal rocket is therefore ideal for interplanetary missions and deep space explorations and is unlikely to find applications in near earth maneuvers.

6. Conclusion

Liquid oxygen augmented gas core nuclear thermal rocket represents the next evolutionary step in high performance rocket propulsion. LAG-NTR is an outstanding propulsion candidate for deep space human missions to Mars and possibly also to near earth asteroids. Because of its inherent power density LAG-NTR is capable of reducing drastically travel time and thus crew radiation dose. While there are still engineering issues to be solved to apply LAG-NTR to future human missions, its capability and potential outclass any conventional chemical rocket's performance, enabling faster travel with drastically reduced mass consumption making it a potential candidate for financially affordable human space explorations.

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