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Conceptual Study on Propulsive Characteristics and Performance of Cryogenic Propellants

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Abstract**—** In the era of cryogenic propellants with high specific impulse; under microgravity situations, long-term storage and higher energy thruster management are highly needed. As methane is a reasonable cooling membrane for radiation and ablation chambers so high LOX/LCH_4 combustion efficiency and reliable spark ignition to be achieved to develop a methane engine. To maintain the thermocouple system in the spacecraft and to prevent outer harmful radiation in space, the respected agencies may use thick-walled propellant containers with high pressure. To check the feasibility and effectiveness of a subcooled cryogenic propellant, a combination of pump depressurization as active cooling and liquid choke evaporation as passive cooling has been proposed and analyzed.
Keywords**—** **Cryogenic propellants, Specific impulse, Microgravity, Spark ignition, Stirling cycle, Reverse Turbo-Brayton cycle, Recirculation, Subcooled, Liquid choke**.

I. INTRODUCTION

Methane/oxygen rocket engines have the ability to provide tremendous undertaking lifestyle cycle benefits over traditional rocket propellants presently in use within side the United States. Liquid methane (LCH_4) and liquid oxygen (LOX) propulsion are notably aggressive because of their bulk density momentum as compared to the booster-propellant combos historically used these days in the area. There is a resurgence of hobby in methane-oxygen propulsion structures because of the probable improvement of the latest rocket motors to help area exploration and business markets. Cryogenic propellants utilized in massive rockets have grown to be one of the maximum usually used fuels because of their benefits of being non-toxic, non-toxic, inexpensive, excessive particular impulse and massive thrust. Currently, the temperature of cryogenic fuels is broadly speaking near the ordinary boiling point, ensuing in negative thermophysical performance, particular for liquid hydrogen. In cryogenic propulsion structures, a cooling system is done earlier than every ignition to modify the temperature of the delivered strains and rapid pumps. A recirculating cooling device is a candidate to lessen this intake on long-period area missions that require a couple of firings of the cryogenic engine. In a recirculating cooling device, a cryogenic pump attracts gasoline from the tank via a delivery line and into the engine. In essence, destiny cryogenic orbital propulsion structures would require a cryogenic propellant recirculation device to chill the recirculation, lively cooling, and tank stress and temperature management for green propellant utilization.

II. LITERATURE REVIEW

Methane/oxygen rocket engines have the potential to offer significant mission life cycle advantages over conventional rocket propellants currently in use in the United States. Liquid methane (LCH_4) and liquid oxygen (LOX) propulsion is highly competitive due to their bulk density momentum compared to the booster-propellant combinations traditionally used today in space. There is a resurgence of interest in methane-oxygen propulsion systems due to the likely development of new rocket vehicles to support space exploration and commercial markets. These propellants have

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several advantages over their counterparts. Methane propulsion is suitable for use in a variety of rocket applications [2] [7].

Cryogenic propellants used in large rockets have become one of the most commonly used fuels due to their advantages of being non-toxic, non-toxic, inexpensive, high specific impulse and large thrust. The specific impulse of cryogenic propellants is 30-40% higher than propellants at normal atmospheric temperatures. Currently, the temperature of cryogenic fuels is mostly close to the normal boiling point, resulting in poor thermophysical performance, especially for liquid hydrogen. A number of studies have shown that supercooled cryogenic propellants can significantly improve their own thermodynamic performance in engineering applications. For example, when the temperature of liquid hydrogen is lowered from the normal boiling temperature (20.39 K) to the triple point temperature (13.8 K), the density per unit volume and the sensible cooling capacity increase by 8.8% and 20%, respectively. An 8% and 10% increase in the densities of liquid hydrogen and liquid oxygen, respectively, reduces the rocket's total takeoff weight by up to 20% [4][9][10][11].

In order to shorten the supercooling time, a method for rapidly obtaining the degree of supercooling has been proposed. To describe the thermodynamic properties of the proposed method as a whole process system, a thermodynamic analysis is performed to describe the choke cooling process. To quantitatively compare and describe the rapid features, we develop a thermodynamic model of the cooling rate to calculate the subcooling time and fluid consumption and numerically solve the nonlinear equations. Then the influence of some important parameters is analyzed. The results show that the method presented in this article is practical and effective. Compared to the conventional pump depressurization method, the supercooling time of the high-speed method can be greatly reduced, and in some cases can be shortened to less than half. The cooling path has changed from the traditional method of passive cooling to a new method that combines active and passive cooling. Subcooling time and fluid consumption are inversely proportional to pumping speed, linearly positively correlated with throttle valve inlet pressure, and exponentially positively correlated with throttle valve inlet temperature [4] [10].

Kerosene fuel is widely used in aircraft jet engines and rocket engines. For rocket applications, the liquid hydrogen (LH_2) and liquid oxygen (LOx) blended fuel combination provides a 30% higher specific impulse compared to the kerosene and LOx combination. However, the lower density of LH_2 results in larger tank volume, higher vehicle mass, and higher drag. Alternatively, kerosene has about 10 times the density of LH_2, so the combination of kerosene and LOx propellants is competitive, even at the expense of performance, especially in first stage engines and high-thrust boosters. Additionally, non-cryogenic kerosene offers the additional benefits of lower operating costs, easier handling and no need for fuel tank insulation compared to the cryogenic properties of LH_2 [6].

Following recent trends in liquid-fuel rocket technology, the chamber pressure has been gradually increased to meet the practical demands for increased performance and compactness of the thrust chamber. The nozzle expansion rate is increased at the stall point by increasing the chamber pressure, thus greatly relaxing the stall-related design constraints. Typical engines operate at combustor pressures above 6 MPa. This is above the critical pressure of kerosene (typically 2.3 MPa) and oxygen (5.04 MPa). Therefore, a basic understanding of the essential physics underlying high-pressure mixing and combustion processes is critical to the reliability of these combustion devices in order to meet the conflicting requirements in terms of performance, combustion stability, and heat transfer characteristics. However, detailed measurements based on laser diagnostics are very challenging due to the soot produced mainly by the combustion of higher hydrocarbons and the harsh environment of the combustion chamber under high pressure (6 MPa to 25 MPa) and high insulation [6].

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A number of recent studies have provided a detailed understanding of the combustion of cryogenic propellants under subcritical and trans critical conditions. In this study, we investigated liquid oxygen and gaseous hydrogen injected from a single element at different chamber pressures (0.1–7 MPa). There is current interest in developing reusable liquid rocket engines that use methane and oxygen as propellants. Injection of liquid fluids at subcritical temperatures into environments whose temperature and pressure exceed thermodynamic critical conditions is a key phenomenon in many high-performance devices such as liquid propellant rocket engines. This can be seen, for example, in the space shuttle main engine and the Ariane 5 Vulcan engine. Both work with liquid oxygen (LOx) and gaseous hydrogen (GH_2) [3] [8].
Liquid rocket engines using cryogenic propellants provide high specific impulse. Therefore, liquid oxygen and liquid hydrogen are widely used mainly in the upper stages of rockets, and the practical application of liquid methane is currently under consideration. Investigations have been made to use cryogenic propellants not only in conventional chemical propulsion systems, but also in advanced electric propulsion systems for future orbital transport vehicles to the Moon and other planets. Cryogenic propellant transfer between orbital vehicles, so-called propellant reservoirs, has been investigated to expand the possibilities of space exploration beyond Earth orbit. In order to achieve more flexible operation and higher performance of cryogenic orbital vehicles, the multiple launch capability of cryogenic thrusters and efficient use of propellant (e.g., reduction of engine cooling consumption, effectiveness under low gravity conditions, etc.) are required. A recirculating cooling system is a candidate to reduce this consumption on long-duration space missions that require multiple firings of the cryogenic engine. In a recirculating cooling system, a cryogenic pump draws fuel from the tank through a supply line and into the engine. The enthalpy of the propellant increases to cool the turbopump, and the warm propellant circulates back to the tank without being discharged to the outside [5] [14].

III. BRIEF ON CRYOGENIC PROPELLANTS

Research is underway to improve the use of highly specific impulse propellant combinations such as liquid hydrogen, oxygen and methane (LH_2, LO_2 and LCH_4). These efforts are a prerequisite for achieving a human presence on the surfaces of various planets and facilitate an extended presence throughout the solar system. Achieving these goals demonstrates the need for long-term storage and management of high-energy thrusters under microgravity conditions. Volumetric considerations require hydrogen, oxygen, and methane propellants to be stored in liquid form at extremely low temperatures. This poses a technical challenge under the expected natural environmental conditions in space [6].

LOX & LCH_4 thrusters

The designs must be generated using validated analytical methods to develop a methane engine at a reasonable programmatic risk. Legacy and recent research programs have provided the test data and experience needed to carry out the development of methane rocket engines with a reasonable understanding of the risks involved. Recent research has shown that methane is a reasonable cooling membrane for radiation and ablation chambers. In addition, high LOX/LCH_4 combustion efficiency can be achieved without compromising strong combustion stability. Reliable LOX/LCH_4 spark ignition is achievable for high impulse response control applications as well as large engines [2].

Cry cooler

Heat radiating into the spacecraft from the sun or other celestial bodies in the spacecraft's vicinity (Earth, Moon, Mars, etc.), along with heat transferred to the container from other sources on the spacecraft, and pressurizes the cryogenic material. To compensate for these losses, the stage must contain excess propellant, greatly increasing the volume of the stage. Alternatively, space agencies

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may use thick-walled propellant containers in combination with higher working pressures, but the additional capacity of the containers may be prohibitive depending on the mission [1].

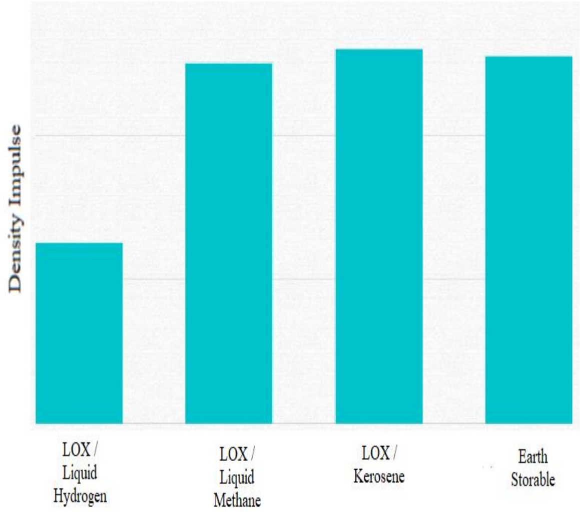

Figure 1 Density impulse comparisons show methane comparable with traditional propellants [2].

Figure 2 LOX/LCH$_4$ TCA hot fire test using columbium chamber [2].

Figure 3 LOX/LCH4 TCA hot fire testing with ablative chamber [2].

Cryogenic Propellant Recirculation

Next-generation orbital propulsion systems will apply cryogenic propellant recirculation to reduce engine cooling consumption through recirculation cooling and achieve efficient propellant utilization through active propellant cooling. A recirculation test campaign was conducted using liquid nitrogen as the working fluid to understand recirculation between tanks. The electric circulation pump developed for this experiment requires vent holes in the impeller to expel the vapor rather than the liquid to operate in the two-phase flow model [5].

Subcooled cryogenic propellants

Subcooled cryogenic fuels are receiving increasing attention, which can significantly improve thermodynamic performance. A combination of pump depressurization and liquid choke evaporation has been proposed and analyzed. It is a combination of active cooling and traditional passive cooling. This rapid cooling method to obtain subcooled cryogenic propellants is feasible and effective. Compared to the traditional pump depressurization method, the subcooling time used in this method can be shortened, by more than half, and is not limited by the pumping speed. Liquid consumption of cryogenic propellants is mainly used to reduce its temperature drop [4].

Transcritical LOx and Supercritical LCH_4 Combustion

Basically, it's the high-strain combustion of LOx and methane. The flame is shaped via way of means of a coaxial injector fed with a gradual go with the drift of oxygen within side the centre, surrounded via way of means of a quick go with the drift of methane. Stabilization happens within side the close area whilst each reactant is, to begin with trans critical. The flame has emissive areas in which mild emission comes from OH^- and CH^+ radicals. This suggests the lifestyles of response layers. These emission regions are kind of conical. The floor isolating those areas is barely disturbed because of the huge distinction in density between the internal and outer liquids. The go with drift and flame shape that arise within side the double trans critical injection scenario investigated right here are very exclusive from conditions in which the simplest one of the reactants is injected within side the subcritical or trans critical state. This has been shown via way of means of experiments performed via way of means of injecting gaseous methane at the same time as preserving the liquid oxygen parameters constant. Changes in behaviour among subcritical and trans critical situations are revealed. In the latter case, we discover that it's far specially managed via way of means of turbulent mass switch procedures from the vital core [3].

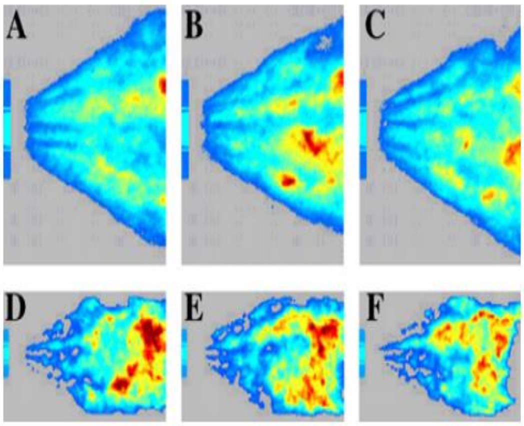

Figure 4. (A–C) Instantaneous CH^+ emission images, close-up on the nearfield, exposure time 30 ls. (D–F) Instantaneous OH^- emission images, field of view equal to the visualization window, exposure time 30 ls [3].

IV. CONCLUSION

Cryogenic systems are more efficient than existing ones and some new certain developments like recirculation, green propellant, cooling techniques (cryo cooler and subcooled) and combustion

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stability etc. enhanced the usability of this system. Liquid methane as an opportunity for liquid hydrogen may be an alternative because it opens up plenty of doorways for unexplored effective area space exploration possibilities.

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