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ROCKET ENGINE ANALYSIS AND ITS FEATURES ON THE BASIS OF CRYOGENIC TECHNOLOGY

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Abstract:

Cryogenics originated from two Greek words 'kayos' which means 'cold or freezing' and 'genes' which means 'born or produced'. Cryogenic is the study of very low temperatures or the production of the same. This paper is all about the rocket engine involving the use of cryogenic technology at a cryogenic temperature (123K). This basically uses the liquid oxygen and liquid hydrogen as an oxidizer and fuel, which are very clean and non-pollutant fuels compared to other hydrocarbon fuels like: petrol, diesel, gasoline, LPG, NCG etc., sometimes, liquid nitrogen is also used as an fuel. The efficiency of the rocket engine is more than the jet engine. As per the Newton's third law of mechanics, the thrust produced in the rocket engine is outwards whereas that produced in jet engine is inwards.

Keywords: Cryogenic technology, Rocket engine, Cryogenic temperature, Liquid Hydrogen and Oxygen, Newton's third law of mechanics.

Introduction

Mechanical engineering is totally based upon the laws of physics, engineering mechanics, and mathematics. Cryogenics is the study of production of very low temperature nearly about '123K' in which the material behaviour and properties are studied at that temperature. Cryogenic rocket engine is a type of rocket engine designed to use the fuel or oxidizer which must be refrigerated to remain in liquid state. Cryogenics typically involves a deep freezing process and changes molecular alignment of the material structure. This change creates the new property. Cryogenic process has been researched and developed by universities and NASA since the mid sixties after NASA discovered that deep space exploration vehicles had improved their structural integrity due to extended exposure to Cryogenic temperature.

History of Cryogenic Rocket Engine

In 1963, United States of America was the first country to develop the CRE with the use of RL-10 engines with the successful flight and it is still used on Atlas-V rocket. Other countries are like: Japan used LE-5 in 1997, France used HM7 in 1979 used the respective rocket engines. Here the mixture of liquid Nitrogen, Hydrogen and Oxygen are used as fuels. In 1987, first CRE was launched with human in space.

Cryogenic Technology

A cryogenic tehnology is the process of involment or including of usage of rocket propellants at a cryogenic temperature. It can be combination of liquid fuels such as: liquid Oxygen (LOX), and liquid Hydrogen (LH2) as an oxidizer and fuel in the different mixtures or proportions. The mixture of fuels offer the highest energy efficiency for the rocket engines that produces very high amount of thrust. Here, the Oxygen remains liquid only at the temperature below (-183C) and Hydrogen below (-253C). This is a type of rocket engine that is functionally designed to use the oxidizer which must be refrigerated in the liquid state. Sometimes, the liquid nitrogen (LN2) ia used as a fuel because the exhaust is also nitrogen. Liquid oxygen is injected below critical temprature but above critical pressure. In our atmosphere nitrogen is nearly about 78%. Nitrogen is a non-pollutant gas and during exhaust no other harmful gases are produced. Hence its efficiency is very high than any other Jet engines.

Fig 1: ATLAS V ROCKET

Cause of High Efficiency

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According to Newton's third law of mechanics: 'Action and Reaction are equal and opposite direction'. Rocket engine operates through force of its exhaust pushing it backwards.

Thrust is in opposite direction and more efficient in lower atmosphere or vacuum. It makes the use of liquid oxygen as an oxidizer and liquid hydrogen as fuel. Pure liquid oxygen as oxidizer operates significantly at hotter combustion chambers due to which extremely high heat fluxes are produced which is not available in any jet engine. In jet engines petrol, diesel, kerosene, gasoline, LPG, CNG and PNG etc. are used having the property of hydrocarbons.

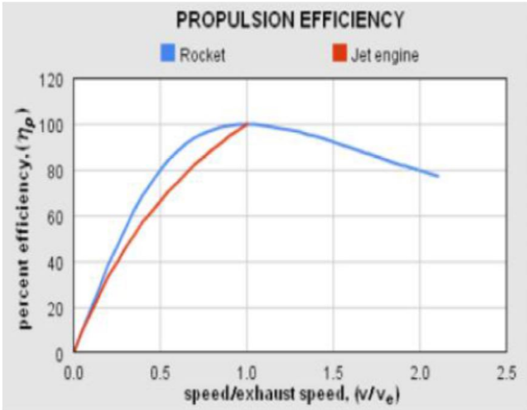


Fig 2: Propulsion Efficiency Curve

Construction of CRE

RL-10 CRE (shown in Fig3) which involve the complicated staged combustion cycle for increasing engine efficiency, the important parts are listed such as: turbines, pump, gas generator, propellant injection system, thrust chambers (combustion chamber + short part of divergent section of nozzle). The description of each part with function is explained below:

[a]Gas Generator--- the main function of gas generator is to deliver sufficient amount of driver gas at designed temperature and pressure which generates continuous propellant supply of thrust chamber.

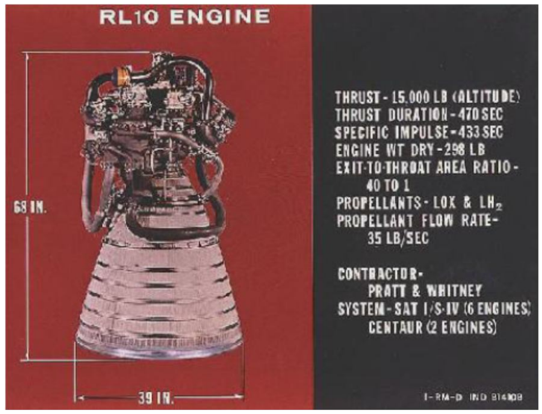


Fig 3: Details of RL-10 Cryogenic Rocket Engine

[b]Turbo Pumps--- They receive liquid propellants at low pressure from vehicle tanks which are then supplied to the combustion chamber. Generally, radial and axial turbines are used.
[c]Pump--- In simple word, pumps add energy to propellants through rotation. The material used for all the turbo machinery chambers are: Al alloys, H.S.S., S.S, and Ni-Ti-Co based alloys.
[d]Thrust Chamber--- Thrust is generated in thrust chamber by the efficiency conversion of chemical energy into gases kinetic energy. This can be obtained by combustion of liquid propellants. In the combustion chamber followed by the acceleration of hot gases throw conversion/diversion section of nozzle to acquire high gas velocity and hands thrust.

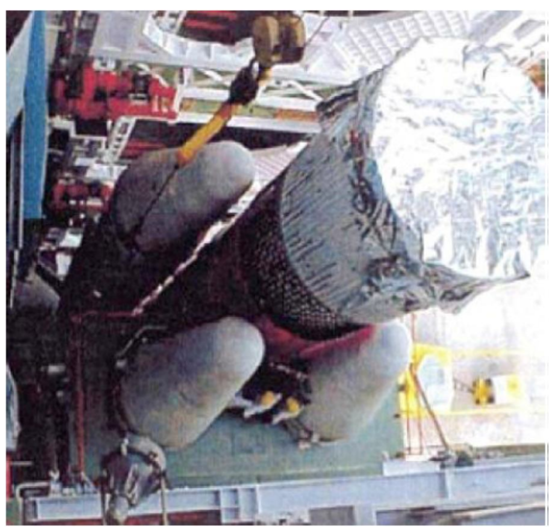


Fig 4: Manufacturing of Rocket Engine

[e]Nozzle--- The pressure generated in combustion chamber can be used increased thrust by acceleration of combustion gas to high supersonic velocity. Nozzle generally passes parabolic enters. Because when high velocity gases entrance and at exit of the nozzle, pressure of exhaust gas increases with high value and hence velocity and hence velocity reduces.

The thrust equation of 1-D flow of ideal gas at constant pressure is:

$$F = mu_e + (P_e - P_\infty) A_e$$

Where u_e is exhaust gas value at exit area.

A_e & P_e is respective area and pressure.

P_∞ is ambient pressure.

Working Principle of Cryogenic Rocket Engine

Cryogenics engines are rocket motors designed for liquid fuels that have to be held at very low ‘cryogenics’ temperatures to be liquids - they would otherwise be gas at normal temperatures. Typically, Hydrogen and Oxygen are used which need to be held below 20K and 90K to remain liquid.

The engine components are also cooled so the fuel doesn’t boil to a gas in the lines that feed the engine. The thrust comes from the rapid expansion from liquid to gas with the gas emerging from the motor at very high speed. The energy needed to heat the fuels comes from burning them, once they are gases. Cryogenic engines are the highest performing rocket motors. One disadvantage is that the fuel tanks tend to be bulky and require heavy insulation to store the propellants. Their high fuel efficiency, however, outweighs this disadvantage.

The space shuttle’s main engines used for liftoff are cryogenic engine. The shuttle’s smaller thrusters for orbital maneuvering use non-cryogenic hypergolic fuels, which are compact and are stored at warm temperatures. Currently, only the USA, Russia, China, France, Japan and India have mastered cryogenic rocket technology.

The cryogenic engine gets its name from the extremely cold temperature at which liquid nitrogen is stored. Air moving around the vehicle is used to heat the liquid nitrogen to a boil. Once it boil, it turns to gas in the same way that heated water forms steam in the steam engine. A rocket like the Ariane-5 uses oxygen and hydrogen, both stored as a cryogenic liquid, to produce its power. The liquid nitrogen stored at (-320) degrees Fahrenheit, is vaporized by the heat exchanger. Nitrogen gas is formed in the heat exchanger expands to about 700 times the volume of its liquid form. This highly pressurized gas is then fed to the expander, where the force of the nitrogen gas is converted into mechanical power.

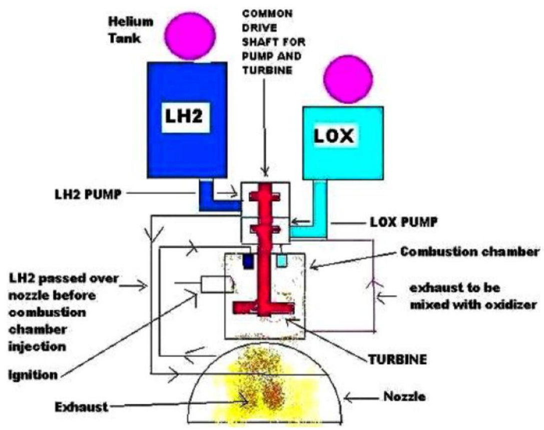


Fig 5: Complicated Staged Combustion Engine for Increasing Efficiency

Characteristic Temperature of Cryogenic Fluids

It is however with the advent of Boltzmann's statistical thermodynamics in the late 19th century that temperature until then a phenomenological quantity could be explained in the terms of micro structure dynamics.

Consider a thermodynamic system in a macro state which can be obtained by a multiplicity W of microstates. The entropy of system was postulated by Boltzmann.

$$S = k_b \ln W$$

$$k_b = 1.38 \times 10^{-23} \; s / k$$

Adding reversibility, heat to the system produces a change of its entropy (ds), with a proportionality factor 'T' which is pre critical temperature:

$$T = dq / ds$$

Boltzmann also found that the average thermal energy of a particle in a system in equilibrium at temperature T is $E \sim k_b T$

Consequently, a temperature of 1K is equivalent to thermal energy of $10^{-4} \; eV \; or \; 10^{-23} \; J / particle$

Cryogen	Triple Point	Normal B.P.	Critical Point
Methane (CH4)	90.7	111.6	190.5
Oxygen (O2)	54.4	90.2	154.6
Argon	83.3	87.3	150.9
Nitrogen	63.1	77.3	126.2
Neon	24.6	27.1	44.4
Hydrogen (H2)	13.8	20.4	33.2
Helium	2.2	4.2	5.2

Table-1

Cryogenic Fuels/ Propellants

In a cryogenic propellant, the fuel and the oxidizer are in the form of very cold, liquefied gases. These liquefied gases are referred to as super cooled as they are stay in liquid form even though they are at a temperature lower than the freezing point. So we can say that super cooled gases used as liquid fuels are called cryogenics fuels.
These propellants are gases at normal atmospheric conditions. But to store these propellants abroad a rocket is a very difficult task as they have very low density. Hence extremely huge tanks will be required to store the propellants. Thus by cooling and compressing them into liquids, we can vastly increase their density and make it possible to store them in large quantities in smaller tanks. Normally the propellant combination used is that of liquid oxygen and liquid hydrogen, liquid oxygen being the oxidizer and liquid hydrogen being the fuel. Liquid oxygen boils at 297 degree F and liquid hydrogen boils at 423 degree F.

Propellent	Liquid Hydrogen (Fuel)	Liquid Oxygen (Oxidizer)
Density (kg/m³)	70.8	1141
Boiling point at atmospheric pressure (K)	20.2	90.2

Table - 2

Application of Cryogenics Engine

- Cryo pumps and turbo molecular pumps are required in space as the level of vacuum required in space simulation chambers are very high.
- Life of tools, Die casting & their dies, forging, jigs & fixtures increase when subjected to cryogenic heat treatment.
- Cryogenic recycling-turns the scrap in raw material by subjecting it to cryogenic i.e. extremely low temperatures. This is mostly used for PVC, Rubber.
- Cryo-surgery is a novel technique in which the harmful tissues are destroyed by freezing them to cryogenic temperature. It has shorter recovery time.
- Preserving food at low temperature is a well-known technique.

Advantages

Storable liquid stages of PSLV and GSLV engines used presently release harmful products to the environment. The trend worldwide is to change over to eco-friendly propellants. Liquid engines working with cryogenic propellants (liquid oxygen & liquid hydrogen) and semi cryogenic engines using liquid oxygen and kerosene are considered relatively environment friendly, non-toxic and non-corrosive. In addition, the propellants for semi-cryogenic engines are safer to handle and store. It will also reduce the cost of launch operations.
This advanced propulsion technology is now available only with Russia and USA. India capability to meet existing mission requirements. The semi cryogenic engine will facilitate applications for future space missions such as the Reusable Launch Vehicle, Unified Launch Vehicle and vehicle for interplanetary missions.

✦ High Specific Impulse
✦ Non-toxic and non-corrosive propellants
✦ Non-hypergolic, improved ground safety

Disadvantages

→Low density of liquid Hydrogen- more structural mass
→Low temperature of propellants – complex storage
→Transfer system and operations
→Hazards related to cryogens
→Overall cost of propellants relatively high
→Need for ignition system

Drawback of cryogenic propellants

◆ Highly reactive gases:-

Cryogens are highly concentrated gases and have a very high reactivity. Liquid oxygen, which is used as an oxidizer, combines with most of the organic materials to form explosive compounds. So lots of care must be taken to ensure safety.

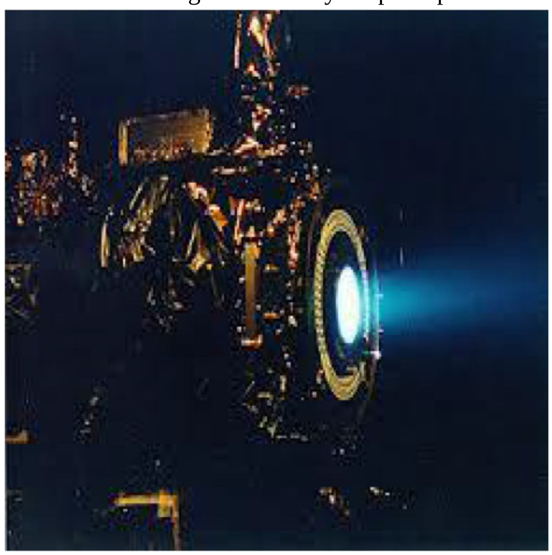
◆Leakage:-

One of the most major concerns is leakage. At cryogenic temperatures, which are roughly below 150K, the seals of the container used for storing the propellants lose the ability to maintain a seal property. Hydrogen, being the smallest element, has a tendency to leak past seals or materials.

Hydrogen can burst into flames whenever its concentration is approximately 4% to 96%. It is hence necessary to ensure that hydrogen leak rate is minimal and does not present a hazard. Also there must be some way of determining the rates of leakage and checking whether a fire hazard exits or not. The compartments where hydrogen gas may exist in case of a leak must be made safe, so that the hydrogen buildup does not cause a hazardous condition.

Next Generation of Rocket Engine

Generally any rocket engine burns their respective fuels to generate thrust. If any other engine has capacity to generate thrust efficiently then it can be called rocket engine. Currently NASA scientists are working on 'Xenon Ion Engine' which accelerates the ions or atomic particles to extremely high to create thrust more effectively and efficiently by usage of electrostatic or electromagnetic force by the principle of Lorentz force or Columbian force.



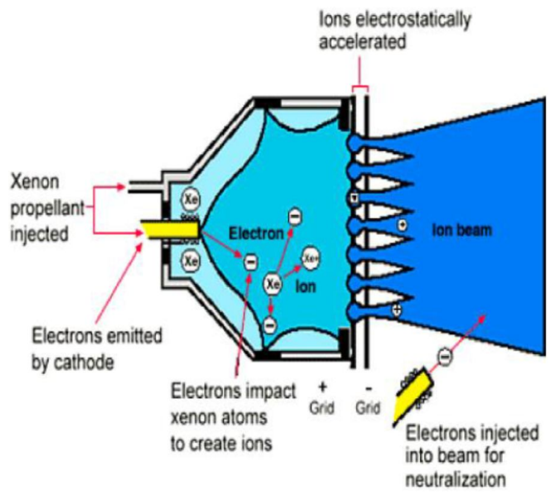


Fig 6: Xenon Ion Engine

Conclusion

This brief paper has presented the basic ideas and principles of the most important aspects of cryogenics i.e. cryogenics fluids and its application in developing cryogenic rocket engines.
The thrust produced in rocket engine is outwards and that in the jet engines is inwards. Hence, the efficiency of the cryogenic rocket engine is greater than the jet engine and it is very much economical by the use of liquid oxygen and liquid hydrogen.

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