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Review on Cryogenic and Jet Engine

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Abstract - *This paper gives an insight to the technology behind jet and cryogenic engines. A cryogenic engine uses liquid fuel and oxidizer stored at extremely low temperatures for combustion, whereas a jet engine burns its fuel with the help of air sucked in from the atmosphere. This paper gives an overview on how a cryogenic engine is different from a jet engine. Also, the components and working of both cryogenic engine and jet engine have been discussed. The liquid fuel and oxidizer, when stored at extreme conditions, gives high enthalpy of combustion on reaction, which makes it more efficient when compared to jet engine. CE-20 is the first indigenous cryogenic engine, which has proved to be highly effective when used in GSLV MK-III.*

Key Words: Liquid fuel, oxidizer, cryogenic engine, jet engine.

1.INTRODUCTION

Cryogenics is a branch of engineering that deals with the study of extremely low temperatures, behavior of different materials at these temperatures and their production.

Temperature range of 123 Kelvin (-150° Celsius) to absolute zero (-273° Celsius) has been defined as cryogenic temperature range.

Materials at cryogenic temperatures are nearly static and in an ordered fashion.

A rocket engine that uses cryogenic fuel and oxidizer for its operation is called a cryogenic engine. The fuel and oxidizer used in a cryogenic engine are liquefied gases, stored at extremely low temperatures. Generally liquid hydrogen liquefied at -253° Celsius is used as fuel and liquid oxygen liquefied at -183° Celsius is used as oxidizer. Several fuel-oxidizer combinations have been used, but hydrogen-oxygen combination was found to the best as they are easily available, economical and have very high enthalpy of combustion.

Jet engines are reaction engines. They are mainly used to propel aircrafts. They draw air from the atmosphere, increase its pressure by squeezing it and hence, use it for the most required combustion reaction. The resulting hot gases are released from the nozzle of the engine, providing enough thrust to the aircraft to move forward.

Jet aircrafts use turbojet engines which usually utilize an afterburn, which is a second combustion chamber, placed between the turbine and the nozzle of the engine. An afterburn elevates the temperature of the hot gases, thereby increasing the thrust of the aircraft by almost 40% during take-off and much higher during flight.

2. CRYOGENIC ENGINE VS JET ENGINE*:*

2.1 Definitions

2.1.1 Cryogenic Engine:

Cryogenic engines are used in space launch vehicles, in the last stage of a rocket. A Cryogenic engine uses both cryogenic fuel and oxidizer, liquefied at a very low temperature.

Fig - 1 : RS-25 Engine

2.1.2 Jet engine:

Jet engine, also known as a reaction engine, produces a fast-moving jet, which generates a thrust, for the aircraft to move forward. Few typical examples of jet engines are: turbojet, ramjet, pulse jet, turboprop, turboshaft and turbofan.

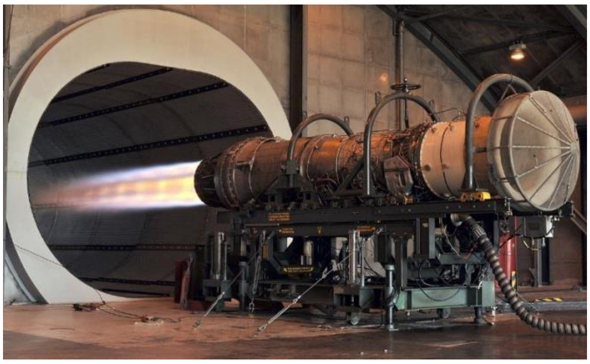

Fig- 2 : Jet Engine

- The working principle of cryogenic and jet engines is same, the thrust is produced by an internal combustion/pressure difference; this follows Newton's Third law of motion- "Every action has an equal and an opposite reaction".

- The jet engine gets the required oxygen from air to burn the fuel, whereas rockets carry their oxidizer, to operate in space.

- Intake and exhaust are two passages present in a jet engine, whereas a cryogenic engine has only one passage for exhaust.

2.2 Parts

Parts of cryogenic engine are:

1. Combustion/Thrust chamber.
2. Fuel injector.
3. Turbo pumps
4. Gas Generator
5. Cryogenic valves
6. Regulators
7. Tanks
8. Rocket engine nozzle

Parts of jet engine are:

1. Fan
2. Compressor
3. Combustor
4. Turbine.
5. Exhaust nozzle

2.3 Working

2.3.1 Cryogenic engine:

A cryogenic rocket engine works on the basis of thrust produced by high velocity exhaust jet. The fuel and oxidizer which are stored as liquids, evaporate as they get injected into the thrust chamber and they undergo combustion. The products of combustion, which is a mixture of hot gases, are allowed to expand through the exhaust nozzle and the resulting high velocity jet produces the propulsive thrust.

2.3.2 Jet engine:

Jet engines are similar to gas turbines, the working principle is one and the same for both. A jet engine sucks air into the engine by means of its fan. The air is made to pass through a compressor, which increases its pressure by compressing it. This pressurized air, enters the combustion chamber, where fuel is diffused. The mixture of fuel and air is ignited by means of an electric spark. As a result of the combustion reaction between the air and fuel, the gases burn and blast out through the nozzle present at the rear of the engine, providing the required thrust for the aircraft.

2.4 Efficiency:

2.4.1 Cryogenic engine:

The efficiency of a cryogenic engine is much higher than that of a jet engine. It is very cost-effective.

Cryogenic engine uses liquid hydrogen as fuel and liquid oxygen as the oxidizer.

It produces more thrust and generates enough power. This means the engine runs for a greater distance using less amount of fuel.

2.4.2 Jet engine:

The efficiency of a Jet engine or air-breathing engine is quite low as compared to cryogenic engines.

The formula for the efficiency of an air breathing engine is-

$$\eta_p = 2\,(v_e / v) / 1 + (v_e / v)^2$$

where,

v - Velocity of engine

v_e - Exhaust velocity

η_p – Propulsive Efficiency

Jet engines are said to be more efficient at higher altitude due to the fact that the air at that level is much colder and less dense, which minimizes the amount of fuel burnt. Jet engines provide high velocity to the aircraft as they increase the density of air inside the engine followed by a combustion reaction. This increases the pressure, which in turn results in higher forward thrust.

Table 1: Differences between cryogenic and jet engines

Cryogenic engines	Jet engines
No air intake is required in this engine.	Air intake is required to operate this engine.
The temperature of fuel must be very low.	Fuel storage does not require low temperature.
It runs efficiently when low temperature fuel transforms and mixes correctly and ignites.	It runs efficiently at supersonic speed that forcefully compress air before combustion.

2.5 PARTS AND WORKING OF CRYOGENIC ENGINE:

2.5.1 COMBUSTION CHAMBER/THRUST CHAMBER:

A combustion chamber is the heart of a rocket engine. Fuel and oxidizers which are stored at their respective tanks are pumped through the turbo pumps into the combustion chamber. On combustion, they get ignited. As a result of combustion between these condensed-phased propellants at high pressure, massive amounts of hot gases are released from the nozzle, where the flow accelerated.

A cryogenic engine uses liquid hydrogen liquefied at 20 Kelvin as fuel, and liquid oxygen, liquefied at 90 Kelvin as oxidizer. Several fuel-oxidizer combinations have been used, but hydrogen-oxygen combination was found to be the best as they are easily available, economical and have very high enthalpy of combustion.

2.5.2 FUEL INJECTOR:

Fuel injector in a cryogenic engine is responsible for the flow rate and the intermixing of fuel and oxidizer, as they are injected into the combustion chamber. It atomizes the liquid fuel and mixes it with the oxidizer in order to achieve rapid and complete combustion as a result of which, a huge amount of thrust is provided. In a cryogenic engine fuel injector is usually in the shape of a disc, which is perforated, and is present right above the combustion chamber.

2.5.3 TURBO PUMPS:

Turbo pumps are used to deliver liquid oxygen and liquid fuel to the combustion chamber form the oxygen tank and fuel tank respectively, at very low temperatures.

2.5.4 GAS GENERATOR:

For the fuel and the oxidizer to flow through the turbo pumps to reach the combustion chamber, some force is required. This force is provided by gravity when the rocket is on the launch pad, and during the time of flight, the upward acceleration of the rocket, provides the necessary downward force. However, these forces do not provide enough pressure. Therefore, a gas generator is used. Gas generator, provides the sufficient amount of gas which acts as a driving force to push the fuel through the pumps into the combustion chamber, during its operation.

2.5.5 CRYO VALVES:

Cryogenic valves or cryo-valves are used to store or transport liquefied gases at very low temperatures. They control the flow of fuel and oxidizer.

2.5.6 REGULATORS:

With the help of pressure regulators, liquefied gases can be stored at constant pressure inexpensively, during the time of operation.

2.5.7 TANKS:

The cryogenic fuel and the oxidizer are stored at extremely low temperatures, in two different tanks called fuel tank and oxidizer tank respectively.

2.5.8 ENGINE NOZZLE:

The engine nozzle expands and accelerates the hot gases produced as a result of combustion in the thrust chamber, so that the gases exit the nozzle at hypersonic speeds, providing the rocket enough thrust.

The key objective of a rocket's propulsion system, which includes all the parts that make up the rockets engine, is to provide enough thrust to the rocket, by ejecting high speed mass of gases through the nozzle, giving it enough reaction force to move upward.

Rocket engines follow the Newton's Third Law of Motion i.e. "For every action there is an equal and an opposite reaction." Rocket engine operates by the thrust which is given by the engines due to burning of fuel. Such an immense amount of energy for a short time creates enough impulse to provides thrust for lift-off.

The liquid fuel and oxidizer stored in their respective tanks is pushed into the combustion chamber, by means of the gas generator, to initiate the process of combustion. On reaching the combustion chamber, the fuel and oxidizer mix with each other, releasing a huge amount of hot gases through the nozzle. As a result, the rocket moves upward.

$F_{Thrust} = v(dm/dt)$
Where, dm/dt is rate of change of mass of combustion product.

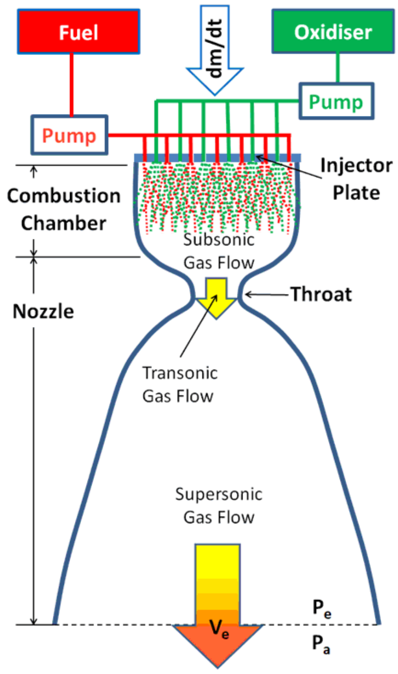

Fig- 3 : Rocket Engine

2.4 PARTS AND WORKING OF JET ENGINE

2.4.1 INTAKE:

Intake of a jet engine is the passage that guides in the atmospheric air and provides it to the fan/compressor at the required velocity and pressure.

2.4.2 [1]FAN:

The first part of the turbofan or the turbojet engine, is the fan. This huge spinning fan sucks in large quantities of air, increases its velocity and splits it into two parts. The first part of the air passes through the core of the engine, where the other components of the engine act upon it. Whereas the second part flows through the duct that surrounds the core to the rear of the engine. The advantage of having a bypass system of this kind is that it provides additional thrust to the aircraft.

[1]Fan is used only in turbojet and turbofan engines.

2.4.3 COMPRESSOR:

The compressor is the first component of the engine's core. The main role of a compressor is to increase the pressure of the air, which is done by squeezing the air and forcing it into the combustion chamber.

2.4.4 COMBUSTOR:

The third part of a jet engine is the combustor. Here, fuel is sprayed into the airstream which causes ignition resulting in a high temperature and high energy airflow.

2.4.5 TURBINE:

The turbine of the engine is connected to a shaft, which is connected to the fan in the front part of the engine. It receives the high energy airflow produced by the combustor which causes the blades of the turbine to rotate. As the turbine rotates the fan also starts to rotate.

2.4.6 EXHAUST NOZZLE:

The exhaust nozzle produces the require forward thrust for the aircraft. The energy drained airflow that passes through the turbine passes through a mixer, where this high-temperature air is mixed with the low-temperature air that bypasses the fan. The exhausted air produces a force, propelling the aircraft forward.

Air is sucked into the jet engine by the turbo fan at the front, and passes through the inlet.

The compressor of the engine squeezes the air by eight times, and increases the pressure. This dramatically increases its temperature.

The mixture of fuel and air gets ignited in the combustion chamber. As a result, hot gases are produced which increases the temperature to around 900°C.

The exhaust gases pass through the blades of the turbine. As the turbine gains energy, it spins.

A shaft connects the turbine and the fan. As the blades of the turbine spin, the fan starts to run.

These hot exhaust gases along with the cold air exit the engine through exhaust nozzle.

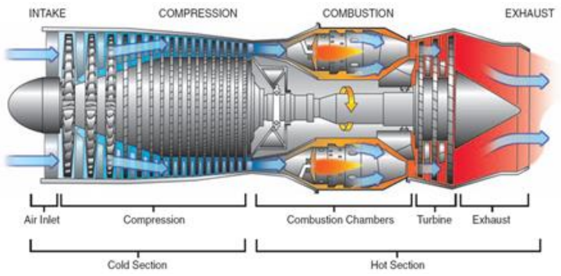

Fig- 4 : Jet Engine

3. WHAT MAKES CRYOGENIC ENGINE EFFICIENT?

In space shuttles, cryogenic engines have been one of the most efficient rocket engines. In cryogenic engines, Liquid Oxygen (LOX) is used as oxidizer and Liquid Hydrogen (LH_2) is used as fuel. Super cooling is done in order to have a high mass flow rate, which in turn increases rocket efficiency. On ignition, at a temperature of about 873 Kelvin, hydrogen fuel reacts with oxygen in a highly exothermic fashion to give more than 200 kilojoules per mole of energy along with an enormous amount of steam.

$$2\ H_2(g) + O_2(g) \rightarrow 2\ H_2O(g) + \text{High Energy}$$

Such an immense amount of energy from a 2 m wide exhaust results in upward thrust of the rocket by the superheated steam with enough velocity out of the atmosphere.

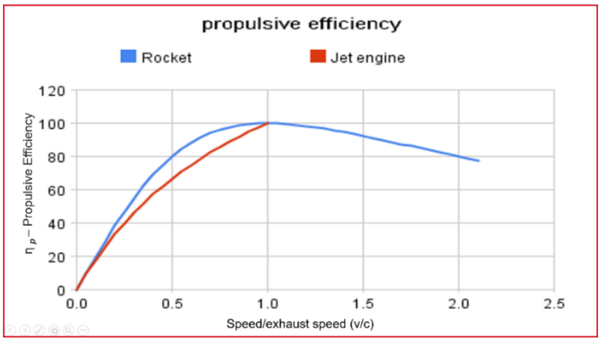

Chart - 1 : Propulsive Efficiency Curve

Liquid Hydrogen is used as a fuel and Liquid Oxygen, which is an oxidizer, is used to oxidize with the Liquid Hydrogen to give out a high amount of energy. Pure liquid oxygen used as an oxidizer at high temperature, i.e., in the range of 500 to 600°C, on reaction with

Liquid Hydrogen, releases huge amount of energy fluxes, unmatchable to any present-day jet engines.

4. INDIA'S FIRST CRYOGENIC ENGINE

Indian researchers are mainly responsible for the innovation of cryogenic engines, which in turn, has provided our researchers a greater hold in rocket motors. GSLV MK III, facilitated with the cryogenic engine has proved effective, which implies ISRO can manufacture and dispatch their satellites independently.

The Indians were able to make an indigenous cryogenic engine, thanks to the Russians under Mikhail Gorbachev, Glavkosmos, the space agency of USSR.

Unlike USSR, the US, Europe, Japan and China were against to share their expertise in cryogenic technology. USSR and India said cryogenic technology would be used only for weather and communication satellites and will not be used for military purposes.

The US did not have trust them. To impose sanctions on Indian and Soviet space agencies, they invoked the Missile Technology Control Regime (MTCR) in 1991. In 1993, when Yeltsin's government came to power, Yeltsin met Bill Clinton in the US and came to a compromise with the MTCR that they would not transfer the technology to ISRO, instead will sell all the seven cryogenic engines.

India decided to fight back with making a cryogenic technology of its own. After a lot of attempts, in December 2003, ISRO had ground tested three engines for about 90 minutes. One of those engines was fired for more than 16 minutes continuously, which is four minutes longer than the time for which it would be fired during flight.

In April 2010, GSLV D-3 with a GSAT-4 was the first flight, installed with an indigenous cryogenic engine. But it failed to run 3 seconds after its launch.

After the challenging task of engine operation and ignition testing under vacuum conditions, GSLV's fifth developmental flight carrying the GSAT-14 satellite was launched from Sriharikota with the indigenously developed CUS-05 engine.

CE-20 is the first cryogenic engine developed by ISRO's liquid propulsion system center, to facilitate the upper stage of the geostationary satellite launch vehicle (GSLV). It has an immense potential to produce an upward thrust of 186.36 kilonewton along with a specific impulse of 444 seconds.

Fig - 5: CE 20

5. CONCLUSION

A cryogenic engine imparts very high specific impulse, making it suitable for using it in a rocket's upper stage. The jet engine involves a bypass system. The air which enters the engine splits to two parts. One part passes through the core of the engine, while the other moves towards the rear of the engine. Such bypass system increases the thrust provided to the aircraft. Whereas in cryogenic engines, the release of huge amount of gases, which are combustion products, are enough to provide the upward thrust to the rocket. However, the efficiency of a cryogenic engine is very high when compared to that of a jet engine.

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BIOGRAPHIES

"Abhishiktha Pagadala is an 18-year-old from Hyderabad. She completed her entire schooling from Sanskriti School, Kondapur, Hyderabad. She is a very enthusiastic and confident individual who has taken part in various leadership and social activities during her schooling. She was an active participant in various national level competitions and conferences. She is currently pursuing bachelor's degree in Aerospace Engineering in Amrita Vishwa Vidyapeetham, Coimbatore. She plans to pursue her Masters in the same field."

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