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Propulsion System in Hypersonic Spacecraft Rocket: A Review of Recent Development and Future Prospects

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Abstract - *Hypersonic spacecraft propulsion is an area of active research due to its potential to revolutionize space travel. Hypersonic vehicles can travel at speeds greater than Mach 5, which could drastically reduce travel times to and from space. However, achieving hypersonic speeds presents numerous engineering challenges, particularly in the design and development of propulsion systems. This paper provides a comprehensive review of current research on hypersonic spacecraft propulsion, focusing on the various propulsion technologies being developed and the challenges associated with each. Additionally, future directions for research in this area are discussed, including the potential for new propulsion technologies to enable even faster and more efficient hypersonic travel.*

Key Words: Hypersonic propulsion, Fuels, Hypersonic vehicle, Propulsion system. Turbojet, Ramjet, Scramjet. Air-breathing engine. Specific impulse.

1.INTRODUCTION

In the aviation industry, larger aircraft manufacturers have shifted their focus towards developing more efficient, reliable, and environmentally friendly designs that are also cheaper to produce. However, achieving these goals requires addressing several aspects that are essential for efficient and affordable designs. The design and development of hypersonic vehicles pose many challenges, including the need to travel beyond a Mach 5 and the capability to transport passengers or cargo from one destination to another in a significantly shorter time than conventional aircraft.

The use of hypersonic vehicles has both commercial and space applications. In commercial aviation, hypersonic vehicles offer faster and more efficient travel between long distances, with a Tokyo to Los Angeles journey taking only 110 minutes. In the space industry, hypersonic vehicles have revolutionized space launches by offering cost-effective and more efficient access to orbit without the need for expendable launch vehicles.

The history of hypersonic vehicles dates back to the mid-20th century when Dr. Walter Dornberger, a key figure in World War II rocket programs, initiated research and development in high-speed and long-range missiles during the Cold War. The development of hypersonic vehicles continued in the 1960s with the launch of the first space launch vehicle that carried astronauts and cosmonauts into space. In recent times, the National Aeronautics and Space Administration (NASA) has made significant progress in developing supersonic propulsion technology such as ramjet and scramjet engines.

The design and development of hypersonic vehicles require consideration of several challenges, including lift to drag ratio, which affects the aerodynamic efficiency under given flight conditions. The US Air Force initiated the Dyna-Soar program in 1957 to address the low lift to drag ratio, which limited the flexibility of the mission profile. Recent research in hypersonic technology aims to develop more flexible and efficient designs that can accomplish space missions more readily.

This review paper discusses the historical background, recent progress, and challenges in the design and development of hypersonic vehicles. The paper will focus on various aspects such as the engine types, design challenges, and lack of research challenges, along with the progress made by the aviation.

2. Brief History

Hypersonic propulsion has been a topic of significant interest in the aerospace industry for several decades, as researchers and engineers continue to explore the possibilities of supersonic and hypersonic flight. Early experiments in the early 20th century paved the way for the development of rocket engines in the 1940s, which could propel aircraft to hypersonic speeds. This led to the creation of experimental planes like the X-15, which set several speed records in the 1960s.

In the 1950s, ramjet engines were developed that could sustain supersonic and hypersonic speeds without the need for onboard oxygen. This technology was later integrated into missiles and unmanned aerial vehicles. The 1990s saw the first successful test of a scramjet engine, which compresses and ignites air moving at hypersonic speeds and operates at even higher speeds than ramjet engines.

Hypersonic propulsion has significant potential to revolutionize air travel by substantially reducing travel times. Therefore, several countries, including the United

States, China, and Russia, are investing in the development of hypersonic technologies for military and civilian applications. Overall, the history of hypersonic propulsion in aerospace is one of continuous innovation and progress, with researchers and engineers pushing the limits of what is possible in high-speed flight.

The development of hypersonic vehicles has been an ongoing process for many decades. One of the earliest examples of such a vehicle was the Silbervogel, or "Silver bird," which was proposed by German rocket scientist Eugene Sanger in 1930. This rocket-powered boost-glide vehicle was never built, but it laid the groundwork for future hypersonic vehicles.

One such vehicle was the X-15, which was developed by American Aviation in 1954. The X-15 was a rocket-powered aircraft that was dropped from a modified B-52 aircraft at high altitude. It set numerous altitude and speed records, with a maximum altitude of 107.96 km and a top speed of 7273 km/h. The X-15 program paved the way for the development of the Space Shuttle, which began in 1969 as the Space Transportation System.

The Space Shuttle was a partially reusable shuttle system that was in use from 1981 to 2011. It was the first spacecraft capable of carrying large payloads into orbit and returning them to Earth intact. Although the program was successful in many respects, it was also plagued by technical problems and safety concerns. This led to the development of other hypersonic vehicles, such as the Soviet Union's Buran spaceplane, which was lighter than the Space Shuttle but was cancelled in 1988 due to lack of funding.

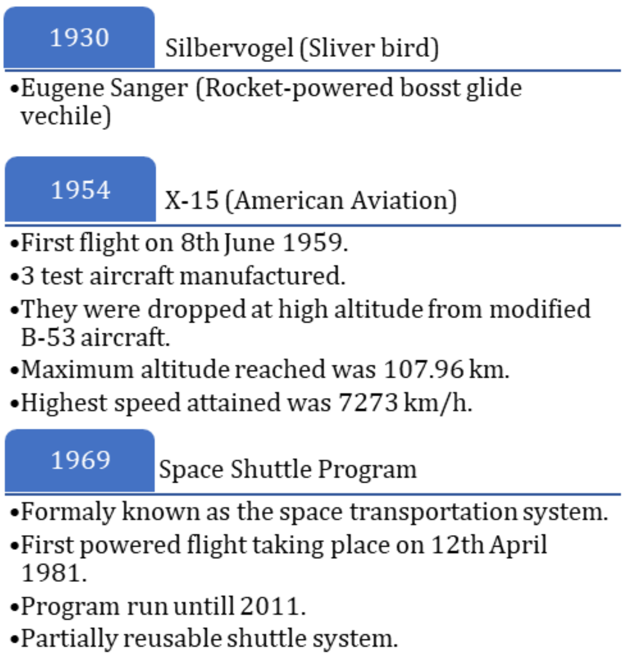
More recently, the SpaceShip was developed by Virgin Galactic and made its first flight on May 20, 2003. This aerospace vehicle was the first to launch three people to an altitude of at least 100 km. While it achieved a maximum speed of only Mach 3, it represented a significant milestone in the development of hypersonic vehicles.

Another hypersonic vehicle is the Boeing X-37 Orbital Test, an unmanned aerospace vehicle that was developed since 1999 and made its first flight on April 22, 2010. It was launched on top of an Atlas V rocket and has been used for various military and scientific missions.

In conclusion, the development of hypersonic vehicles has been a long and challenging process, marked by successes and setbacks. The vehicles mentioned above represent important milestones in this ongoing endeavor, and further research and development will undoubtedly lead to even more advanced hypersonic vehicles in the future.

Fig -1: Boeing X-37B Orbital Test Vehicle.

The flow diagram below presents the year-wise development of aerospace vehicles.



1988 Buran

- Soviet union spaceplane.
- The program was cancelled in 1988 due to lack of funding.
- Orbiter was lighter itself than space shuttle.

2003 SpaceShip

- First flight on 20th May 2003.
- Being the first aerospace vehicle to launch three peoples to at least 100 km altitude.
- The highest speed so reached was only Mach 3.

2010 Boeing X-37 Orbital Test

- Unmanned aerospace vehicle.
- Being developed since 1999.
- First flight on 22 April 2010.
- Was launched on top of an Atlas V rocket.

3. Propulsion System

The propulsion systems that are powered by rockets may use either solid or liquid propellants. In the context of space missions, there are two ways in which rockets can take off and land: horizontal take-off or vertical take-off and landing. Vertical landing offers greater flexibility similar to that of airplanes. The key parameters for rocket propulsion systems include specific impulse (I_{sp}), the thrust (T), and the inert mass fraction (f_{inert}), where

$$f_{inert} = m_{inert} / (m_{prop} + m_{inert})$$

3.1 Nuclear Rocket Propulsion System

It works similarly to liquid propulsion systems. The fuel, combined with oxygen, is transferred to a combustion chamber, where a spark is generated to ignite the mixture. The resulting exhaust gases pass through a convergent-divergent nozzle section at high velocity. In a nuclear rocket, the fuel is passed through a heat addition section, where heat is generated from a nuclear fission reaction. The exhaust gases then pass through the convergent-divergent nozzle section at high velocity. This technology was developed between the late 1940s and the 1960s, but its complexity and weight of the nuclear reactor remain significant drawbacks.

Nuclear rocket engines are a type of propulsion system that use nuclear energy to heat a working fluid, usually liquid hydrogen, which is then expanded in a nozzle to generate high ejection velocities. There are two types of nuclear energy sources that have been investigated for this purpose: the fission reactor and the fusion reactor.

In a nuclear fission reactor rocket, heat is generated by the fission of uranium in the solid reactor material, which is then transferred to the working fluid. This type of engine is primarily a high-thrust engine, with specific impulse values up to 900 sec. However, concerns about endurance of materials at high temperatures and intense radiations, power level control, cooling a reactor after operation, moderating high-energy neutrons, and designing lightweight radiation shields have prevented further ground tests of nuclear fission rocket engines.

On the other hand, fusion is an alternate way to create nuclear energy, which can also heat a working fluid. Several concepts have been studied, but none are currently feasible or practical.

Despite the potential benefits of nuclear rocket propulsion, concerns about the accidental spreading of radioactive materials in the environment and the high cost of development programs have prevented the experimental development of large nuclear rocket engines. Unless there are significant new findings and a change in the world attitude towards nuclear radiation, it is unlikely that a nuclear rocket engine will be developed or flown in the next few decades.

Overall, while nuclear rocket engines have potential for high performance and flexibility in interplanetary travel, the current limitations and concerns make it unlikely to be a viable option for hypersonic propulsion systems in the near future.

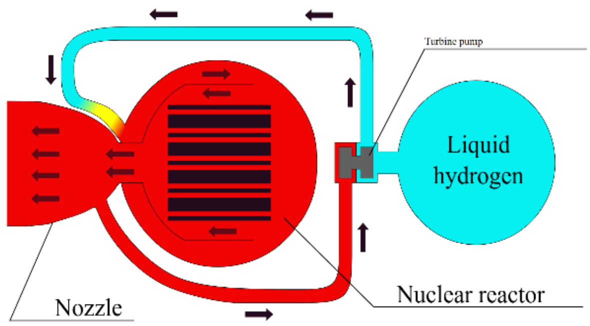


Fig -2: Sketch of a solid core fission nuclear thermal rocket.

Stanley and Piland noted that hydrogen propulsion systems are more efficient than Space Shuttle Main Engines. The use of dual fuel designs incorporating solid and liquid propellants has been incorporated into many hypersonic vehicle concepts proposed since 1988.

The Orbiter staging Mach number for a Two-Stage-Two-Orbit system depends on various criteria, including the theoretical potential of the orbiter, requirements for realistic air-breathing and rocket propulsion systems, and thrust-to-weight ratio of the orbiter components. The theoretical velocity potential function versus second-stage weight graph shows that an orbital velocity of 185 kilometers requires an orbiter with a thrust of 100 Newton and a staging Mach number of 0.8, 0.6, and 8.0.

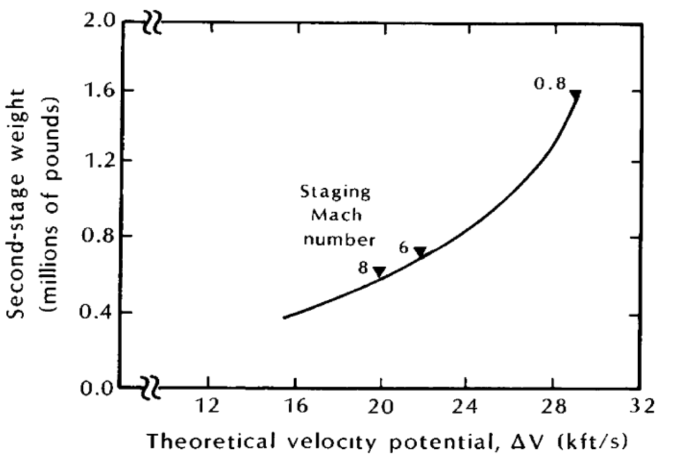


Fig -3: The Second Stage (Orbiter) Weight as a Function of DV for a 50; 000 lb.

When launching a vehicle with a booster powered by air-breathing propulsion systems, such as scramjets, at Mach 8, the orbiter must weigh approximately 2.45 million Newtons. Air-breathing propulsion systems include turbojet, ramjet, and scramjet propulsion, with scramjet being used in hypersonic speed vehicles.

The air-breathing propulsion system requires consideration of the thermodynamic conditions, propulsion system, structure, and flight control system. Turbojet propulsion has a Mach number limit when the combustion chamber heat exceeds the limit. Ramjet concept is used when the Mach number limit of turbojet is reached. For hypersonic propulsion, a multi-stage propulsion system is needed, which might operate as a turbo accelerator up to Mach 4.0, then transition to subsonic ramjet operation up to Mach 6.0, and finally operate as a supersonic combustion engine for speeds above Mach number 7.0.

Foster et al. on reference no. [4] note: "Combined Cycle Engines' functionally and physically integrate more than one propulsion engine cycle into a single engine assembly. They should not be confused with 'combined cycle vehicles', 'combination propulsion systems', 'multi-cycle' propulsion or 'Multi-Mode Vehicles' having more than one physically separate propulsion cycle in a single vehicle."

The development of efficient propulsion devices has been crucial to the advancement of space exploration and transportation. Specific impulse, which measures the efficiency of a propulsion system, is a key factor in determining the performance of these devices. Propulsion systems fueled by hydrogen or hydrocarbons are commonly used in a variety of applications, from rocket engines to air-breathing engines. The specific impulse ranges for these devices can vary widely, depending on factors such as the type of engine, the propellant used, and the operating conditions. In this context, understanding the specific impulse ranges for various propulsion devices fueled by hydrogen or hydrocarbons is essential for optimizing their performance and achieving more efficient and cost-effective space transportation.

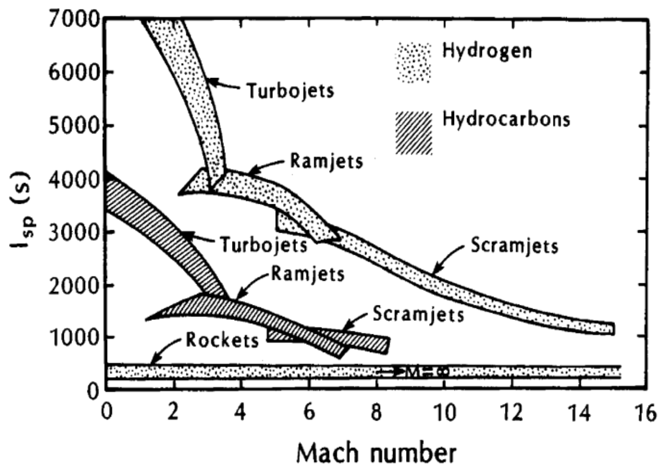


Fig -4: Specific Impulse for Various Propulsion Devices Fueled by Hydrogen or by Hydrocarbons.

3.2 Duct Jet Propulsion:

These air-breathing engines use oxygen from the atmosphere to burn fuel stored in the flight vehicle, and they offer superior range capabilities at relatively low altitudes compared to chemical rockets, which require carrying their own oxidizer

The most common ducted engine is the turbojet engine, while ramjets become attractive for flight within the atmosphere at supersonic speeds above Mach 2. Ramjets work by increasing the momentum of the air as it passes through the engine, similar to the turbojet and turbofan engines, but without the need for compressors or turbines.

Ramjets with subsonic combustion and hydrocarbon fuel have an upper speed limit of approximately Mach 5, while hydrogen-fueled ramjets with hydrogen cooling can reach at least Mach 16. Scramjets, which have supersonic combustion, have flown in experimental vehicles.

All ramjets require rocket boosters or other methods, such as being launched from an aircraft, to reach their design flight speed and become functional. Ramjets with subsonic combustion have been primarily used in shipboard and ground-launched antiaircraft missiles, but there is promising research on hydrogen-fueled ramjets for hypersonic aircraft.

Finally, a supersonic flight vehicle combines a ramjet-driven high-speed airplane with one or two-stage rocket boosters, enabling it to travel at speeds up to a Mach number of 25 at altitudes of up to 50,000 meters.

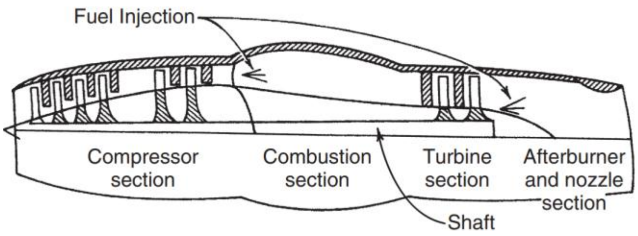


Fig -5: Schematic Diagram of Turbojet Engine.

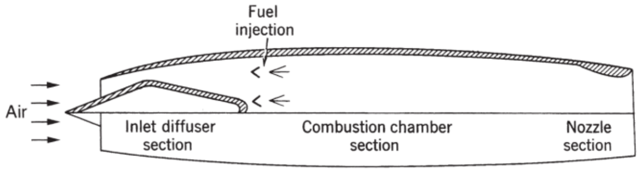


Fig -6: Simplified diagram of a ramjet with a supersonic inlet.

3.3 Combination of Ducted jet Engine and Rocket Engine

The use of combinations of ducted jet engines and rocket engines is a critical aspect of hypersonic propulsion rocket technology. One example of this is the Tomahawk surface-to-surface missile, which uses two stages of propulsion in sequence. The solid propellant rocket booster is discarded after its operation, while a small turbojet engine sustains the low-level flight at nearly constant speed toward the target.

In addition, the use of a ducted rocket, also known as an air-augmented rocket, combines the principles of rocket and ramjet engines. It gives higher performance in terms of specific impulse than a chemical rocket engine, while operating within the earth's atmosphere. The ducted rocket is boosted to operating speed and uses the rocket components more as a fuel-rich gas generator.

The principles of the rocket and ramjet engines can also be combined, as shown in the integral rocket-ramjet propulsion system. This low-volume configuration can be attractive in air-launched missiles using ramjet propulsion. The transition from the rocket to the ramjet requires enlarging the exhaust nozzle throat, opening the ramjet air inlet-combustion chamber interface, and following these two events with the normal ramjet starting sequence.

Furthermore, solid fuel ramjets use a grain of solid fuel that gasifies or ablates and reacts with air. Good combustion efficiencies have been achieved with a patented boron-containing solid fuel fabricated into a grain similar to a solid propellant and burning in a manner similar to a hybrid rocket propulsion system.

In summary, the use of combinations of ducted jet engines and rocket engines is critical to the development of hypersonic propulsion rocket technology. The principles of rocket and ramjet engines can be combined to achieve higher performance in terms of specific impulse, and solid fuel ramjets offer an alternative method of propulsion. These propulsion systems are key to achieving the high speeds and altitudes required for hypersonic flight.

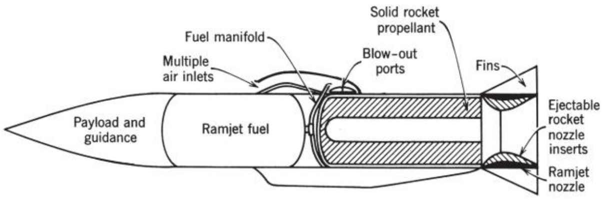


Fig -7: Elements of an air-launched missile with integral rocket–ramjet propulsion.

4. Fuels

The hypersonic air-breathing engine uses two types of fuels: hydrocarbon and liquid hydrogen. The detailed specifications of these fuels are discussed in Table No. 1.

Table -1: Comparison of fuel characteristics, as taken from Ref. [5]

Property	Hydrocarbon	Hydrogen
Heat of combustion (J/kg)	44×10^6	118×10^6
Specific heat (J/kg/K)	1926	11307–15495
Liquid density (kg/m^3)	817	72
Boiling temperature at 1 atm (K)	456–508	20

Hydrocarbon fuels are easily extracted and have a much lower cost of preparation compared to hydrogen fuel. However, liquid hydrogen has several advantages over hydrocarbon fuels, including a larger heat of combustion and specific impulse.

Additionally, liquid hydrogen is able to cool the engine significantly, which prevents permanent damage to the nozzle wall due to the high temperature of fuel combustion. These advantages make liquid hydrogen a promising fuel option for hypersonic propulsion systems.

5. Challenges and Future Directions

Hypersonic propulsion systems have seen significant progress in recent years, but there are still numerous challenges that need to be addressed. These challenges include the development of advanced materials and manufacturing techniques that can withstand the extreme temperatures and pressures of hypersonic flight, as well as the need for a better understanding of the fluid dynamics and combustion processes involved in hypersonic propulsion. Another challenge is the need for more advanced control systems to manage the complex interactions between the propulsion system and the airframe.

Despite these challenges, future research in hypersonic spacecraft propulsion is likely to focus on the development of new propulsion technologies that can enable even faster and more efficient hypersonic travel. One area of research that shows promise is the use of alternative fuels, such as hydrogen, which can provide higher energy density and combustion efficiency than traditional hydrocarbon fuels. Furthermore, advances in materials science and additive manufacturing techniques may enable the development of new materials that can withstand the extreme conditions of hypersonic flight.

Several agencies have been working on hypersonic technologies in recent years. For example, NASA's X-59 Quiet Supersonic Technology (QueSST) aircraft completed its preliminary design review in 2020, marking a significant milestone in the agency's efforts to develop quiet supersonic flight technology. DARPA's Hypersonic Air-breathing Weapon Concept (HAWC) program has also been working on developing high-speed, air-launched weapons capable of striking targets at long ranges. Additionally, Boeing's X-51A WaveRider set a new record for the longest hypersonic flight by a jet-powered aircraft in 2013, reaching speeds of up to Mach 5.1. In 2021, the National Hypersonic Science Center (NHSC) was established as a joint research center between the University of Virginia and the University of Texas at Austin to advance the understanding of hypersonic flight and develop new hypersonic technologies. Lastly, the European Space Agency's Space Rider is a planned reusable spaceplane that is being developed for use in a range of space missions, including scientific research and satellite servicing, and is expected to be capable of hypersonic flight during its re-entry phase.

6. Nomenclature:

f_{inert} - inert mass fraction,

m_{inert} - inert mass

m_{prop} - propellant mass

m_{inert} - inert mass

I_{sp} - Specific impulse

T - Thrust

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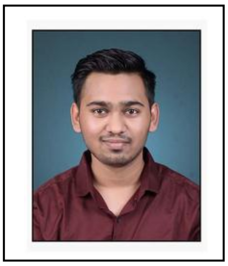
BIOGRAPHIES



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