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REDEFINING COMBUSTION: THE SCRAMJET SURGE

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Abstract

India witnessed a historic milestone on the 25th of April 2025. The Defence Research and Development Organisation (DRDO), through its arm Defence Research and Development Laboratory (DRDL), demonstrated a successful test of an active cooled 'Scramjet combustor'. The engine was fired for over 1000 seconds, making it the longest recorded to date.[1] *This article is an attempt at a comprehensive analysis of what this could mean to India in terms of its defence capability, as well as the other applications that the technology has to offer. The science behind the technology, along with a comparison with conventional Turbojet, Turbofan, Turboprop as well as Ramjet engine is also briefed upon. India has joined the elite group of nations to have demonstrated this technology. The influence that this could have on next generation missiles to future space adventures is truly immense and the same has been tried to convey through this article.*

Introduction

The term "Scramjet" is short for 'Supersonic Ramjet'. A *ramjet* is a form of air breathing jet in which the incoming air is compressed using the forward motion of the vehicle for combustion without the need of a rotating compressor[i]. A scramjet engine is an improvement over this as it efficiently operates at speeds hypersonic speeds i.e., Mach[ii] > 5 and allows 'supersonic combustion'.[2] The Indian scramjet development complements its goals of technological sovereignty under *Atmanirbhar Bharat* initiative. This technology's offers dual use potential in both military (for hypersonic missiles) and space (for reusable launch vehicles) to address India's strategic vulnerabilities in *Indo - Pacific region* that is growing more volatile by the days. Rapid advancements in hypersonic capabilities of adversaries are of prime concern. India's developmental trajectory, challenges, and future prospects are briefly discussed in the upcoming sections. Its role in enhancing national security and economic growth is underscored as well. As of now, India's progress, including tests of missiles like 'Extended Trajectory - Long Distance Hypersonic Cruise Missile (ET-LDHCM)'[3], and the one scheduled for the end of 2025, 'Dhvani hypersonic glide vehicle (HGV)'[4] will potentially strengthen India's defence arsenal which would position us as a global leader.

Science behind Propulsion

A Propulsion system develops the 'thrust' that is necessary for the forward movement of vehicles in air. This production varies depending on the type of propulsion system in play. The basic science behind these systems is the Newton's third law of motion which states that "*for every action there is equal and opposite reaction*".[5] A working fluid is accelerated by these systems and the reaction to this is a 'force' on the moving body. The incoming air is first compressed that increases its temperature and pressure. Next it is passed through a 'combustor' or a 'combustion chamber' where it is mixed with fuel and ignited. This then is allowed to expand there by increasing the velocity and finally is expelled. Based on the type of propulsion system some variation in this process occurs although the core mechanism remains the same. The table given below compares this process happening across various types of combustion engines.

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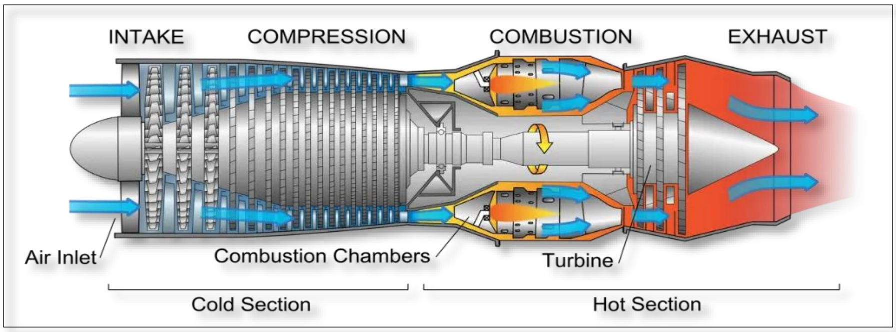
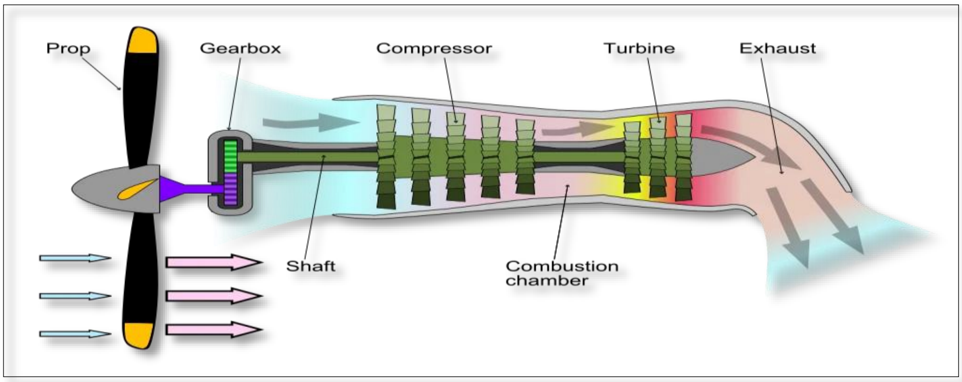
[i] Compressor - A machine that increases the pressure and slows down the fluid moving through it
[ii] Mach - Ratio of speed of vehicle to that of speed of sound in a given medium

<table>
<tr><th>Engine</th><th>Thrust Generation Mechanism</th></tr>
<tr><td>Turbojet[6]</td><td>Incoming air is compressed by a ‘compressor’. This increases the pressure and temperature and lowers the velocity. This air is then mixed with fuel in a ‘combustor’ where ignition takes place. Further it is expanded in the ‘turbine’ there by reducing the pressure and finally expelled at high velocity through a ‘nozzle’.


(Image Source: DefenceXP)</td></tr>
<tr><td>Turbofan[7]</td><td>Thrust produced is through two systems, a ‘core jet’ and a ‘fan’. The fan accelerates a bypass stream of air around the core. The thrust contributed by this bypass air is significant, especially at subsonic speeds. The process in the core is same as that of a turbojet engine i.e., compressor to combustor to turbine and expelled through nozzle.


(Image Source: DefenceXP)</td></tr>
<tr><td>Turboshaft[8]</td><td>A ‘shaft’ is connected to a ‘rotor’ or ‘propeller’ and is driven by the turbine. There is a conversion of combustion energy into mechanical work. Exhaust contributes minimal thrust compared to the prior. Passage of air in core remains same to that of turbojet and turbofan.</td></tr>
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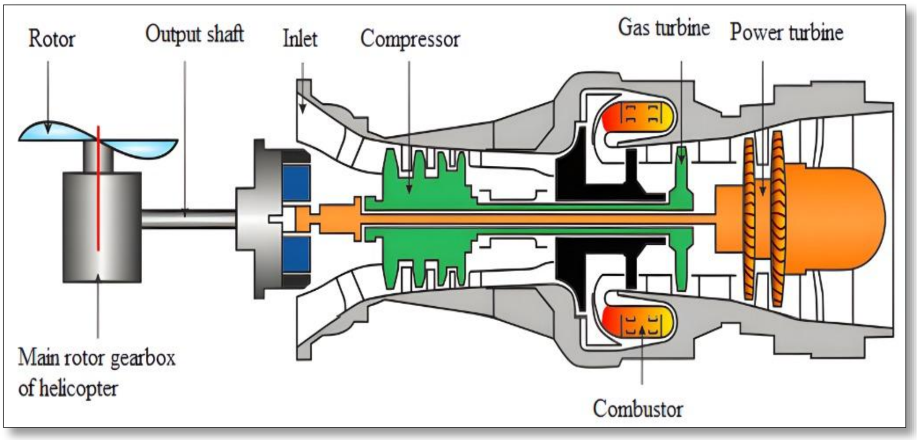
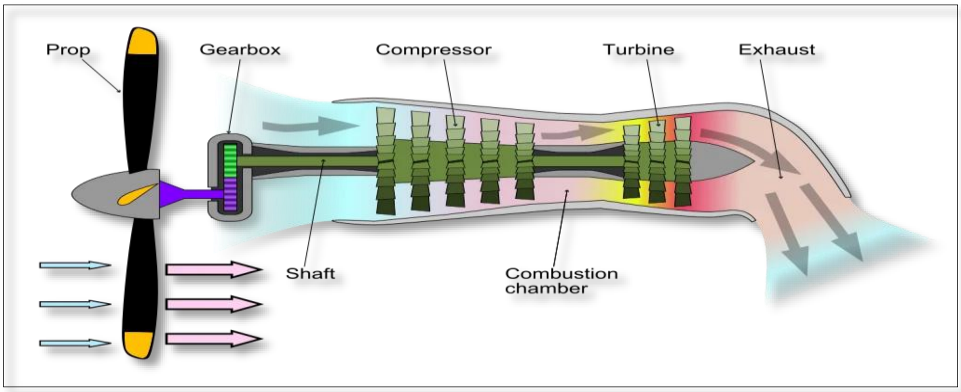
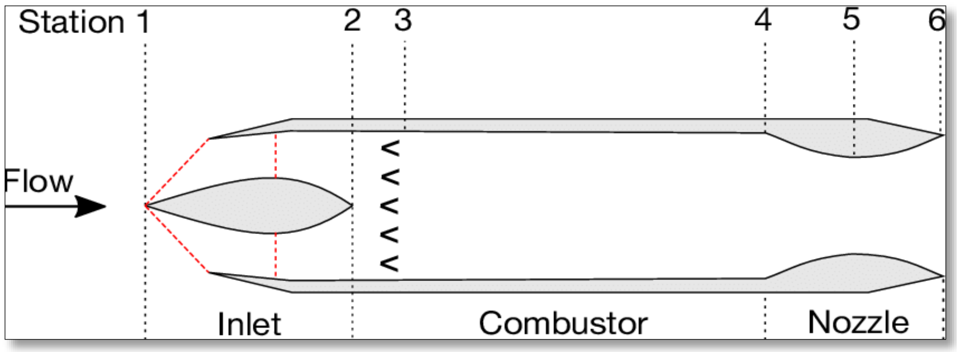
<tr><td></td><td>

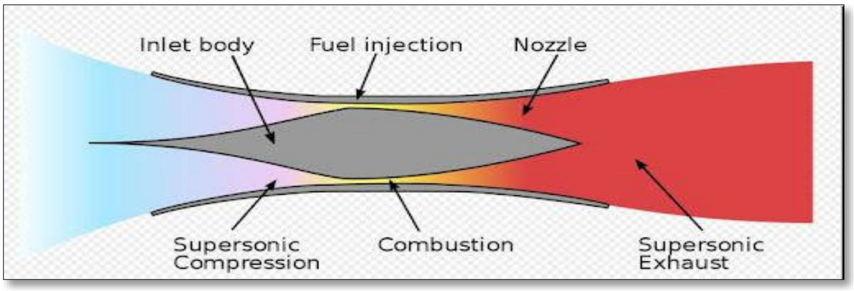
(**Image Source:** ResearchGate)</td></tr>
<tr><td>Turboprop[9]</td><td>Thrust is primarily generated by a ‘propeller’. It driven by a gas turbine. Contribution from exhaust jet is minimal. Air as seen in other engines mentioned prior, passes through compressor, then through combustor, then expanding and accelerating in a turbine. This is connected to the propeller via a ‘gearbox’.


(**Image Source:** DefenceXP)</td></tr>
<tr><td>Ramjet[10]</td><td>There are no moving parts like compressor or turbines. Thrust is Incoming air is compressed through very high speed forward motion (ram effect). It is mixed with fuel in a combustor. Finally is expelled through a nozzle.</td></tr>
</table>

	 (**Image Source:** ResearchGate)

(**Table:** Comparison of Thrust Generation in different Propulsion Systems)

(**Source:** Compiled by the Author)



(**Image Source:** Skill-lync)

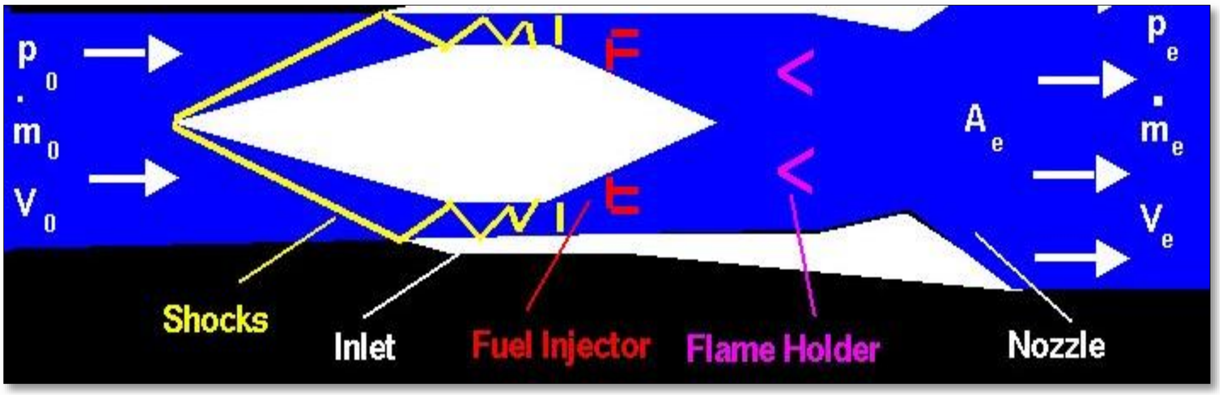
(**Table:** Comparison of various Performance Parameters of Propulsion Systems)

(**Source:** A compilation by the Author)

Engine Type	Compression Method	Fuel Types	Starting Method	Noise Level	Altitude Range (ft)
Turbojet	Mechanical (Compressor)	Jet fuel (kerosene based)	Electric or air starter	High (Exhaust)	Up to 50000
Turbofan	Mechanical (fan & compressor)	Jet fuel	Electric or air starter	Moderate	Up to 45000
Turboprop	Mechanical (compressor)	Jet fuel or Avgas	Starter motor	High (Propeller)	18000 - 30000.
Turboshaft	Mechanical (compressor)	Jet fuel	Starter	High	Ground to 20,000
Ramjet	Aerodynamic (Shockwave)	Hydrocarbon or Hydrogen	Booster rocket or carrier aircraft	Moderate	Up to 100000
Scramjet	Aerodynamic (Shockwave)	Hydrogen (for cooling)	Booster to Mach 5	Low (at high altitudes)	Up to 150000

Working of a Scramjet

As mentioned earlier, unlike a turbojet, turbofan, turboprop, turboshaft engines, scramjets have ‘no moving parts. It has only an ‘inlet’, a ‘combustor’ that consists of a ‘fuel injector’ and a ‘flame holder’, and an ‘exhaust nozzle’.[11] A Scramjet is as mentioned earlier a modified version of ramjet accounting for the ‘Supersonic Combustion’. [12] It doesn’t have any moving parts. It relies totally on the *very high forward moving velocities* of the vehicle to perform compression.



(**Image Source**: Glenn Research Centre, NASA)

Large amounts of surrounding air are brought into the engine inlet on a continuous basis as the vehicle moves forward with high velocities. While the air goes through the inlet its velocity is reduced. The dynamic pressure[iii] due to velocity is converted into high static pressure[iv]. There is an increase in the pressure of this air it being more at the exit of the inlet than at the entry. The free stream velocity may be subsonic[v] or supersonic[vi] but at the exit of the inlet it is supersonic. Fuel is combined with the air and it is ignited in the combustion chamber/burner. This Burning occurs supersonically. The burner stage is followed by a nozzle passing through which the velocity of this air is increased. This exit velocity being greater than the free stream velocity, results in the generation of Thrust.

This is governed by the general thrust equation given as:[13]

$$\mathbf{F = (m_e * V_e - m_0 * V_0) + (p_e - p_0) * A_e}$$

In the above equation,

F	Thrust generated	Newton (N)
m_e	Mass flow rate at the exit of the nozzle	kg m^2
m_0	Mass flow rate at the entry of the inlet	kg m^2
V_e	Velocity at the Exit of the nozzle	ms^{-1}
V_0	Velocity at the entry of the inlet	ms^{-1}

[iii] The pressure exerted by a fluid due to its motion.
[iv] The pressure that fluid exerts in all directions when it is not moving
[v] Travelling at speeds lower than that of sound in the given medium (generally Mach < 0.8)
[vi] Travelling at speeds more than that of sound in the given medium (generally Mach > 1.2)

p_e	Pressure at the exit of the nozzle	Nm^{-2}
p_0	Pressure at the entry of the inlet	Nm^{-2}
A_e	Area at the exit of the nozzle	m^2

(**Table:** Terms in the Thrust equation with their SI units)

(**Source:** A compilation by the Author)

Addressing Limitations of Conventional Propulsion

Aircraft propulsion systems are diverse, and are designed to fulfil specific demands that arise during an operation. However, they have certain limitations and disadvantages. The turbojet, turbofan, turboprop, turboshaft, and ramjet engines, for sure are revolutionary in their respective domains. But the fact that they do exhibit limitations cannot be ignored.

- The “turbojet engine” consumes high amount of fuel.[14] This makes them less economical for flights that are intended to cover longer distances. It is less efficient at low speeds.[15] This affects its versatility as it cannot provide sufficient thrust during the takeoff or landing phases. These are extremely noisy[16] hence contribute to environmental concerns and do require stricter noise regulations at airports. The risk of compressor stall[17] is a prime concern. During this there is an airflow disruption within the engine. This could cause sudden loss of power and poses safety hazards.
- “Turbofan engines” are widely used in modern commercial aviation as they address the shortcomings of turbojet engines to certain extent. However they suffer from challenges of their own. Their design is complex as it has to incorporate a large fan and a bypass system. This increases weight which could lead to reduction in fuel efficiency and payload capacity. This gets coupled with increased maintenance costs and requires expertise to handle the same. They operate quieter in comparison to the turbojets but the added weight and cost make them less ideal for smaller aircraft causing budget related constraints.
- “Turboprop engines” are generally opted for regional and short haul flights. They are excellent when it comes to fuel efficiency at lower speeds however, are constrained by their design. They have limited speed capability and can operate

efficiently only below 400 knots[vii].[18] This makes them unsuitable for high speed applications like fighter jets. Significant weight is added by the gear box that is necessary in order to transfer power from the turbine to the propeller. This reduces their overall aircraft performance and increases maintenance demands. Also, turboprops are noisy[19] which can affect passenger comfort and limit their use.

- “Turboshaft engines” are most commonly found in helicopters and some fixed wing aircraft are designed to deliver power to a rotor or shaft rather than producing direct thrust. The mechanical complexity is increased as they require complex gear mechanisms. This comes with increased risk of mechanical failure and elevated maintenance costs. Turboshaft engines are loud.[20] This creates challenges for operations in noise restricted areas.
- “Ramjet engines” are designed for high speed applications. They face significant constraints. At low speeds they produce no thrust.[21] To overcome this, a booster system is required such as a rocket or another engine in order to accelerate the aircraft to required operational velocities. This adds complexity and weight to the system. They have a limited operational range as they function efficiently only at very high speeds (typically M>3).[22] Thus for most conventional aviation applications their use turns impractical. They stay limited to specialized vehicles like missiles or high speed aircrafts.

Do scramjets address these issues?

The scramjets are able to overcome many of the above mentioned disadvantages of turbojet, turbofan, turboprop, turboshaft, and ramjet engines. They leverage their unique design that is optimized for hypersonic speeds (typically M>5).

While turbojet, suffers from high fuel consumption and less efficiency at low speeds, scramjets operate very efficiently at higher velocities as they use the aircraft’s forward motion to compress incoming air. This eliminates the need for heavy, complex rotating components like compressor. There is reduction in weight and maintenance compared to turbofans or turboshafts. They also mitigate the risk of compressor stall as seen in turbojets.

[vii] 1 Knot = 1.852 kmph

Scramjets enable combustion in supersonic airflow. This allows for a sustained operation at higher speeds without the strict Mach range limitations like that of the ramjets. While turboprops and turboshafts suffer from speed limitations and rely on heavy gearboxes, scramjets avoid these issues entirely, as they require no mechanical power transmission system. They are designed solely for direct thrust at higher velocities.

By focusing on high speed efficiency and simple designs, they address many of the inefficiencies, complexities, and operational constraints of other engine types. This makes them ideal for specialized applications like hypersonic travel or space access. However they suffer from limitations of their own which are discussed in the sections to come.

The Application of Scramjets

1. Military Domain

- Due to its ability to operate in hypersonic speeds (M > 5) the scramjet engine has become a transformative propulsion system offering immense military potential. They allow "combustion in a supersonic airflow" environment. Their design with reduces moving parts that enhances reliability and offers minimal weight. This is critical for military platforms that require agility and endurance in extreme conditions. The hypersonic weapons enabled by this technology can evade detection and interception systems by virtue of their immense speed.[23] There is a drastic reduction in enemy's response times.
- The development of scramjet technology was driven by the demands for an efficient alternative to the rocket propulsion. Scramjet uses "atmospheric oxygen and this eliminates the need to carry oxidizers.[24] This eventually results in extended range and payload capacity in comparison to the rockets. They become ideal for rapid global strike capabilities by allowing forces to engage targets effectively. Scramjets offer a revolutionary shift in modern warfare by enabling platforms that combine speed, maneuverability, and detection avoidance through velocity. Aircrafts powered through scramjets conduct swift over flights in sensitive contested areas offering an effective reconnaissance role. They gather critical intelligence before adversaries could be prepared to respond.

- The military applications are most evident in "hypersonic air breathing weapons", such as cruise missiles and those aircraft that are designed for high-speed operations. Leveraging scramjet propulsion to achieve long range strike capabilities these systems enable missiles to be launched from multiple platforms such as aircraft, ground systems, or naval vessels while sustaining hypersonic velocities for extended durations.[25] This helps in effective penetration of advanced air defence networks. Scramjets also hold an immense potential in unmanned aerial vehicle (UAVs) domain. These could be dedicated to intelligence, surveillance, and reconnaissance (ISR) missions. Emergence of solid fuel scramjets could simplify logistics by eliminating complexities that the liquid fuels are associated with.[26] This allows for quicker deployments in field conditions.
- Scramjet powered vehicles are also able to execute "mid - flight manoeuvres" by altering their trajectories. This helps them to escape the interceptors as the tracking efforts become more complicated. The air-breathing efficiency of scramjets reduces the fuel requirements. This enables the user for smaller, more payload carrying capable systems without compromising the range or attack intensity.
- In anti - ship roles the scramjets empower missiles to effectively enhance naval defences with unmatched velocity. Thus, enhances maritime security strategies. Dual mode scramjet designs that are capable of operating as ramjets at lower supersonic speeds before transitioning to scramjet mode can broaden applicability across various mission profiles. These systems demonstrate their versatility in meeting the multifaceted warfare needs.

2. Space Launch Vehicle

Scramjet leverages air breathing propulsion to enhance efficiency and reduce costs. This offers immense potential for space launch vehicle operations. They perform at speeds of about Mach 5 - 12 i.e., Hypersonic regime. Atmospheric oxygen is used for combustion. This eliminates the need to carry oxidizer mass. This reduces vehicle weight in comparison to conventional rockets. Higher payload fractions are enabled and so does the possibility of reusable stages. Here the hypersonic vehicle boosts payloads to higher velocities within the atmosphere before orbital insertion is completed.

The specific impulse of scramjet is around 1000 - 4000 seconds that exceeds that of rockets i.e., 450 seconds by a multi fold magnitude.[27] They optimise fuel efficiency while in atmospheric flight. Scramjets could lower launch costs by replacing lower rocket stages. Reusable systems that return to Earth mitigate the expense of expendable components. Enabling travel at hypersonic speeds scramjets could drastically reduce intercontinental travel times.

Limitations of Scramjet

Scramjet technology surely promises hypersonic propulsion but, faces significant limitations. These hinder its widespread deployment and make its implementation not so practical in certain situations.

- "Launch Requirement" remains one of the most prominent challenges. The scramjet is not able to generate thrust from low speeds. There is a necessity for an initial velocity of at least Mach 3 - 6 for ignition and efficient operation.[28] This creates a dependency on auxiliary propulsion systems such as rockets, turbojets, or ramjets in order to accelerate the vehicle. It complicates vehicle design while also increasing overall system complexity and adds more weight. This makes the integration into missiles more expensive and less versatile. Requirement of such multiple propulsion modes leads to less efficient fuel usage.
- "Combustion Control" is another formidable obstacle. Precise fuel injection, mixing, and ignition within milliseconds are required to achieve a stable combustion in supersonic speeds. The high velocity of airstream results in 'incomplete combustion' as no enough time would be provided for proper mixing and ignition.[29] It causes flame blowout, or choking phenomenon that creates disruption in the flow. Advanced techniques that might help mitigate this require cryogenic storage and poses safety risks.
- Scramjets present "Short Operational Windows". They function efficiently only within narrow hypersonic flight profiles typically Mach 5 to 12 where atmospheric oxygen is sufficient for combustion. But, outside of this regime, the performance faces degradation. This puts restriction on their utility in certain suborbital or atmospheric applications.

- "High fuel consumption" adds another challenge. These systems prioritise speed over efficiency. They yield poor specific impulse[viii] compared to conventional engines. This makes long duration flights impractical for commercial as well as for military transport.
- "Thermal management" is also one the most critical limitation in its development. Extreme heat loads are generated due to hypersonic speeds from air friction. This can exceed 2500°C on surfaces![30] Development of lightweight materials to withstand such extreme temperatures requires active cooling systems like regenerative hydrogen cooling or advanced ceramics. This adds weight and complexity. These materials elevate costs while also limiting engine lifespan and reliability to maintain sustained hypersonic conditions.
- "Testing and Validation" are additional problems because the ground-based facilities cannot replicate hypersonic environments required for the same. This necessitates costly flight tests via launch vehicles or hypersonic chambers. This increases the expenses. Scramjet research has witnessed limited successes even after spanning for decades. "Economic Factors" complements this.
- Scramjets offer poor "Thrust to Weight Ratios".[31] This makes them less preferred against rockets. Their hot exhaust and structural signatures compromise stealth capabilities. Variable Mach number operation creates unpredictability as engine behaviour shifts dramatically across speeds. This creates complexities in control systems and acceleration profiles.

Collectively, these limitations should tell one as to why the scramjets remain largely experimental. Few of these problems if not all, can be addressed by advancing research in artificial intelligence and advanced simulations using efficient design and analysis tools.

Evolution over the decades

The use of 'ram pressure' for propulsion was proposed by a French engineer Rene Lorin in 1913.[32] This laid the groundwork for ramjets. This idea witnessed an evolution during the World War II. The ramjets were powering experimental aircraft and missiles. There existed limitations that arose at supersonic speeds. This paved the way for exploration into supersonic combustion.

[viii] Amount of thrust produced per unit fuel consumed per second

Theories regarding scramjets started coming up in the 50's and the 60's by the researchers in the US and the Europe. The aim was to make sure the flow remained supersonic throughout the engine that would enable efficient operation at hypersonic speeds above Mach 5. Credit goes to an Italian – American engineer *Antonio Ferri* at the Polytechnic Institute of Brooklyn for designing advanced combustors for supersonic burning.[33] These addressed challenges like flame stability and thermal management.

The US in the 70's, invested in hypersonic programs with an aim to develop subsonic combustion ramjets for missiles that would reach Mach 2 to 4. Parallel to this, the scramjet research was focused on hydrocarbon fuels and mixed cycle engines combining ramjet, scramjet, and rocket modes. This made developing ground testing facilities crucial.

In the 1980s, Australia's University of Queensland commissioned the *T4 shock tunnel*.[34] It was the first of such kind that was capable of simulating scramjet conditions across a wide Mach range. This allowed the measurement of thrust and combustion efficiency.

By the 1990s with intensified international collaborations, the US aimed for single stage to orbit vehicles powered by scramjets. Efforts in Russia explored scramjets for anti-ship missiles, while the computational modelling of hypersonic flows was offered by France. In wind tunnel validations at facilities like NASA's Langley Research Centre the arc heated tests simulated Mach 8 conditions.[35]

The breakthrough came on July 30, 2002, with Australia's *HyShot project*. It achieved the first in flight scramjet combustion at Mach 7.7.[36] This validated the supersonic burning for several seconds using a sounding rocket launch. In 2004, NASA's *X-43A* set a record at Mach 9.6 during a free flight test and this demonstrated the autonomous hypersonic controls and sustained combustion for 77 seconds.[37] In 2007, efforts under the DARPA[ix] and DSTO[x] reached Mach 10 using rocket-boosted scramjets.[38] The *X-51A WaveRider*, in a 2010 testing, marked aviation history with the longest scramjet-powered flight at nearly 200 seconds. This was powered by a dual mode engine transitioning from ramjet to scramjet modes

[ix] Defense Advanced Research Projects Agency
[x] Defense Science and Technology Organisation of Australia

using hydrocarbon fuels.[39] By the 2010s, scramjet integration expanded globally. Russia's advanced scramjet assisted missiles like the *Zircon* achieved Mach 8 in operational tests.[40]

The Indian Journey in the realm of Scramjet Propulsion

May 2008	DRDO publicly announced the HSTDV program at *Aero India exhibition* in Bengaluru. A mock-up was displayed which outlined the goals for scramjet performance at 15-20 km altitude for hypersonic vehicles, satellite launches, and long-range missiles.[41]
Aug 2016	ISRO conducted a maiden in-flight test of dual scramjet engines. Engines ignited at Mach 6 for ~5 seconds.[42]
June 2019	The HSTDV separated at about 30 km altitude. Scramjet was auto ignited, and cruised at Mach 6.[43]
Sep 2020	HSTDV achieved sustained scramjet combustion for 20 seconds at ~Mach 5.9 (2 km/s). This validated the aerodynamics, ignition, separation, and material aspects of the program.[44]
Nov 2024	DRDO successfully tests an HGV prototype.[45] Scramjet derived tech for maneuverable hypersonic strikes was included.
Jan 2025	Defence Research & Development Laboratory (DRDL) conducts extended ground test of active-cooled scramjet subscale combustor at Hyderabad's Scramjet Connect Test Facility. Stable ignition and combustion at >1.5 km/s air speed was achieved.[46]
Apr 2025	DRDL achieved the world's longest sustained scramjet operation for 1,000 seconds. This validated the thermal management for prolonged hypersonic flight.[47]

Challenges faced by India

India’s scramjet program although has achieved remarkable milestones such as the 1,000+ second ground test in April 2025 does face unique challenges. These reflect the resource constraints it faces to achieve the desired technological ambitions.

There is a limited availability of advanced hypersonic test facilities in India. This is one of the most prominent hurdles. When compared with global front runners like the United States and China, India lags behind in possessing advanced test facilities. Thus, a need arises for expensive and complex flight tests. Most are done using launch vehicles. This increases the expenses that were originally intended. The development further can suffer from delays due to the same.

Another big issue is the dependency on imported high temperature materials. These include advanced ceramics for thermal protection. The program also suffers from budgetary constraints. This further complicates the progress that was aimed originally. India’s hypersonic research and development funding is far less in comparison to that of its contemporaries. This has an impact on the scale of testing and material innovation. It hence requires India to prioritise cost effective solutions. This could in a way compromise the quality of the outcome and its further deployment.

Conclusion

India's achievements in the field of Scramjet technology marks a pivotal moment in the nation's aim to achieve of hypersonic dominance. These highlight and showcase its innovative and cost-effective approach in order to overcome the limitations of traditional propulsion systems. It has sustained a supersonic combustion for over 1000 seconds. By this it surpassed the global benchmarks. This has led to the validation of critical technologies that could address critical challenges which have long delayed scramjet development. This positions the *Hypersonic Technology Demonstrator Vehicle* (HSTDV) and upcoming ones like the *Dhvani* hypersonic glide vehicle (HGV) and *BrahMos-II* missiles for operational deployment in times to come. They have the potential to enhance India's strategic deterrence in the dynamic and volatile Indo Pacific region (IOR) against rapid advancements of its adversaries.

The scramjets offer a dual use potential. It extends well beyond the military applications. It can have a revolutionary impact on upcoming space exploration programs and also in civilian sectors. They possess the ability to shrink intercontinental distances. This enhances ease of logistics and in a way, can boost the economic growth. By fostering indigenous R&D, job creation in aerospace manufacturing and international collaborations India is redefining the global hypersonic landscape. As scramjets evolve from experimental models to strategic assets, they symbolize India's resolve to innovate amid global competition. This would secure national security, economic prosperity, and a play a prominent role in hypersonic future.

Disclaimer

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