Combustion Optimization of a Scramjet – A Numerical Flow Investigation Approach

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ABSTRACT

The Scramjet (Supersonic Combustion Ramjet) engine stands at the forefront of next-generation hypersonic propulsion systems, offering exceptional performance by sustaining combustion at supersonic speeds. However, achieving stable, efficient, and complete combustion within the extremely short residence time of high-speed airflow remains one of the most critical and challenging aspects in scramjet development. This study focuses on the optimization of combustion within scramjet engines to enhance overall efficiency, thrust output, and operational stability under hypersonic flight conditions. The primary objective of this project is to investigate and improve the combustion process by examining key influencing parameters such as pressure and velocity. Various computational and theoretical analyses are employed to simulate and study the effects of these parameters on combustion efficiency and stability. Computational Fluid Dynamics (CFD) simulations are conducted to visualize the supersonic flow behaviour, pressure variation, velocity variation and species concentration within the combustion chamber. The study concludes with optimized design recommendations that significantly improve combustion efficiency, reduce total pressure loss, and support high specific impulse generation. These findings not only contribute to better scramjet performance but also pave the way for further research in scramjet-integrated hypersonic platforms for military, space, and commercial applications. Overall, this project contributes to the growing body of knowledge aimed at overcoming combustion challenges in scramjet engines and accelerating the development of reliable and reusable hypersonic propulsion systems.

Index Terms - Scramjet engine, supersonic combustion, hypersonic propulsion, combustion optimization, combustion efficiency, CFD simulation, pressure variation, velocity variation, specific impulse, total pressure loss.

INTRODUCTION

The demand for faster and more efficient aerospace propulsion systems has led to significant research and development in hypersonic technologies. Among the most promising propulsion concepts for hypersonic flight is the scramjet engine, or Supersonic Combustion Ramjet. Unlike traditional jet engines or even ramjets, scramjets are air-breathing engines that maintain supersonic airflow throughout the combustion process. This unique capability allows scramjets to operate efficiently at speeds exceeding Mach 5, making them suitable for high-speed atmospheric vehicles, missile systems, and even potential space launch platforms.

Despite the theoretical simplicity of scramjets—no moving parts, relying purely on aerodynamic compression and combustion—the real-world challenges they present are immense. Chief among these is the issue of achieving stable and efficient combustion in a highly compressed and extremely fast-moving airstream. In scramjets, the residence time of air in the combustion chamber is often less than a few milliseconds, leaving very little time for fuel injection, mixing, ignition, and complete combustion. This makes combustion optimization not just desirable but absolutely essential for practical scramjet application. Combustion efficiency in a scramjet is influenced by several interrelated factors. These include the choice of fuel (gaseous, liquid, or solid), injection strategy (transverse, angled, or axial), combustion chamber geometry, flame holding design, and thermal management. At hypersonic speeds, the interaction of shock waves, boundary layers, and fuel jets further complicates the flow field inside the combustor. Failure to control these factors can lead to incomplete combustion, thermal choking, flame blowout, or even structural failure due to localized heating.

The goal of this project is to analyse and optimize the combustion process in a scramjet engine through advanced computational modelling and theoretical investigation. Emphasis is placed on understanding how modifications in fuel injection techniques, chamber shape, and flameholder configurations can lead to better mixing, faster ignition, and sustained combustion. By simulating these conditions using CFD tools, the study aims to identify configurations that improve combustion efficiency while minimizing pressure losses and thermal stresses.

This project not only contributes to academic understanding but also has real-world implications in the fields of defence and aerospace technology. As the race for hypersonic capability intensifies globally, achieving reliable scramjet propulsion becomes a key enabler for future high-speed systems.

OBJECTIVES

To Analyse the Supersonic Combustion Process in Scramjets -Study the fundamental principles of supersonic combustion and how it differs from subsonic combustion. Understand the effect of high-speed airflow on flame stability, ignition delay, and combustion efficiency.

To Identify Key Parameters Affecting Combustion Performance - Investigate how parameters like fuel type, injection angle, pressure, temperature, and Mach number affect combustion. Examine the influence of equivalence ratio, residence time, and fuel-air mixing on combustion efficiency.

To Develop a Reliable Combustion Model for Simulation - Construct or implement a chemical reaction mechanism suitable for scramjet conditions (e.g., hydrogen-air or hydrocarbon-air mixtures). Use turbulence-chemistry interaction models (e.g., finite rate/eddy dissipation models) for realistic combustion prediction.

To Optimize Fuel Injection and Mixing Techniques - Explore different fuel injection strategies (axial, transverse, angled) to improve fuel-air mixing. Analyse how injector geometry and placement influence the ignition and flame holding capabilities.

To Improve Flame holding Mechanisms - Investigate the role of flameholders, cavities, and shock-induced ignition zones in stabilizing combustion. Optimize combustor design to maintain a stable flame at varying speeds and altitudes.

To Perform CFD Simulations for Combustion Analysis - Conduct high-fidelity simulations using tools like ANSYS Fluent, Open FOAM, or STAR-CCM+ to visualize temperature, pressure, and species distribution. Validate simulation data with theoretical results or experimental benchmarks (if available).

To Maximize Combustion Efficiency While Minimizing Losses - Reduce total pressure losses and heat losses within the combustor. Maximize energy release per unit mass of fuel to enhance specific impulse and overall engine performance.

To Evaluate and Compare Different Fuel Options - Compare liquid (e.g., hydrogen, kerosene) and solid fuels in terms of combustion speed, energy density, and compatibility with supersonic combustion. Assess trade-offs between performance, complexity, and weight.

To Ensure Thermal and Structural Viability of Combustor - Analyse the thermal loads on combustor walls due to optimized combustion. Suggest cooling strategies and material choices to withstand extreme operating conditions.

To Provide Design Recommendations for Future Development - Identify the most effective design changes that enhance combustion stability and efficiency. Recommend potential areas for further research such as active combustion control, advanced materials, or pulsed combustion concepts.

Uses of Scramjets

Hypersonic Missiles - Scramjets enable missiles to travel at extremely high speeds (Mach 5–10+), making them much harder to detect, intercept, or defend against. Examples: Hypersonic cruise missiles developed by the U.S., China, and Russia.

Space Launch Systems - Scramjets could be used as first-stage propulsion in reusable spaceplanes, reducing the cost of launching payloads into orbit. They allow air-breathing propulsion up to the edge of space, reducing the need for heavy onboard oxidizers.

High-Speed Reconnaissance Aircraft - Scramjets can be used in unmanned reconnaissance aircraft for rapid intelligence gathering with minimal risk of interception.

Rapid Global Strike Platforms - Enable military platforms capable of reaching any location on Earth within an hour, allowing fast precision strikes.

Scientific Research - Scramjet test vehicles (e.g., NASA X-43A, Boeing X-51) help researchers study hypersonic aerodynamics, high-temperature materials, and combustion dynamics.

Commercial High-Speed Travel (Future Potential) - Though not yet practical, scramjets could one day be used for passenger flights between distant cities in a fraction of current flight times.

Types of Scramjets

Based on Flow Configuration

Isolator-Equipped Scramjet - Has an isolator section between the inlet and combustor to stabilize shock waves and pressure.

Helps prevent unstart, a condition where the shock wave is ejected from the inlet, disrupting combustion.

Integrated Scramjet - Inlet, combustor, and nozzle are designed as a single continuous flow path. Common in test vehicles (like NASA X-43A). More compact and lighter.

Based on Fuel Type

Hydrocarbon-Fuelled Scramjet - Uses fuels like JP-7, JP-10, or kerosene-based mixtures. Easier to handle and store; better suited for missiles or tactical applications. Example: Boeing X-51A Waverider.

Hydrogen-Fuelled Scramjet - Uses liquid or gaseous hydrogen. Offers higher energy efficiency and faster speeds. Requires cryogenic storage, which is complex. Example: NASA X-43A.

Based on Mission Objective

Experimental/Testbed Scramjets - Designed for scientific and engineering research. Often single-use or short-duration.

Examples: X-43A, X-51A, HIFiRE.

Operational/Weaponized Scramjets - Built for use in hypersonic cruise missiles or glide vehicles. Designed for high speed, range, and payload. Examples: BrahMos-II (India-Russia), Hypersonic Attack Cruise Missile (U.S. DARPA).

Based on Speed Range

Dual-Mode Ramjet/Scramjet - Operates first in ramjet mode (subsonic combustion) up to about Mach 5. Transitions to scramjet mode (supersonic combustion) above Mach 5. Useful for vehicles with wide operating speed ranges.

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Difference between solid fuel scramjet and liquid fuel scramjet

Solid-Fuel Scramjet

Uses solid fuel embedded in or lining the combustion chamber walls.

Fuel burns off as high-speed air flows over it.

No fuel injection system needed – simpler and lighter design.

Lower control over thrust and burn rate (fixed fuel geometry).

Typically used in short-duration, tactical applications.

Easier to build and maintain; no moving parts.

Less efficient compared to liquid-fueled scramjets.

Example: India's HSTDV.

Liquid-Propelled Scramjet

Uses liquid fuel (e.g., hydrogen, kerosene) stored in onboard tanks.

Fuel is injected into the combustor using pumps and valves.

Provides precise control over combustion and thrust.

More complex and heavier due to additional systems.

Suitable for longer-range missions and reusable vehicles.

Offers higher efficiency and flexibility in performance.

Commonly used in experimental or advanced hypersonic platforms.

Examples: NASA X-43A, Boeing X-51A Waverider.

Scramjet Working

Basic Working Principle of a Scramjet

Unlike traditional jet engines, a scramjet has no moving parts like compressors or turbines. Instead, it uses the forward motion of the aircraft to compress incoming air.

Step-by-Step Working:

Air Intake (Compression):

The high-speed aircraft forces supersonic air into the inlet.

The shape of the inlet slows the air slightly and compresses it — but not to subsonic speeds (unlike in ramjets).

In a scramjet, the airflow remains supersonic throughout the engine.

Combustion:

Fuel (usually hydrogen) is injected into the supersonic airflow.

Combustion occurs while the air is still moving at supersonic speed (hence "scram" – Supersonic Combustion Ramjet).

This is a major technical challenge because mixing and burning fuel in supersonic flow is extremely fast and complex.

Expansion & Thrust (Exhaust):

The hot gases expand through a nozzle.

The expansion accelerates the flow further, producing thrust to propel the aircraft.

Fuel Injection Strategies and Enhanced Mixing in Scramjets

Efficient fuel-air mixing in a scramjet engine is one of the most critical challenges in achieving sustained, high-performance supersonic combustion. Due to the extremely short residence time of air within the combustor (on the order of milliseconds), fuel injection must be carefully designed to promote rapid mixing and ignition while minimizing total pressure losses and maintaining flame stability.

Injection Strategies: -

Transverse Injection

Fuel is injected perpendicular to the freestream airflow.

Generates strong shock waves and vortices to enhance mixing.

Downside: causes significant flow separation and total pressure loss.

Angled/Ramped Injection

Fuel is injected at an angle (typically 15°–45°).

Balances mixing efficiency and aerodynamic losses.

Common in scramjet designs due to improved flow alignment.

Wall Jet Injection

Fuel is introduced through slots or orifices along the combustor wall.

Encourages boundary layer interaction and vortex formation.

Often combined with cavity flame holders.

Strut-Based Injection

Fuel is injected through struts placed in the flow.

Can also act as flame holders and shock generators.

Effective in 3D configurations and compact combustors.

Cad Design

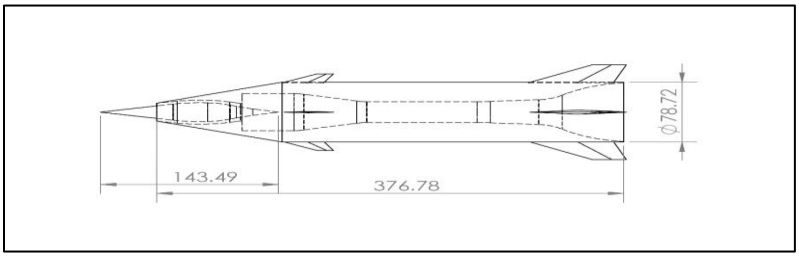

Fig 1: Scramjet Cross-section

CFD Analysis Details

Input Parameters:

In this above give model of scramjet we have two inlets

External Velocity Inlet - Mach: approximately 2.5 to 3

Internal Pressure Inlet – Total Pressure: approx. 8 million

Outlet Conditions: Pressure outlet.

Solver: Type: Pressure-based solver

k-ω(k-omega) Model

Why Used:

- The k-ω model helps simulate turbulence—the chaotic motion in fluids like air and gas.
- It is good at predicting flow near walls, like inside pipes, engines, or over wings.
- In high-speed flows, such as in scramjets, it works well with shock waves and boundary layers.
- It gives accurate results for heat transfer and pressure changes in complex areas.
- The SST version of k-ω is better because it combines two models for best performance in all regions.
- It is often used in ANSYS because it is stable, accurate, and works well in aerospace problems.
- Compared to other models, k-ω is more reliable for flows with separation, recirculation, or high speed.

RESULTS

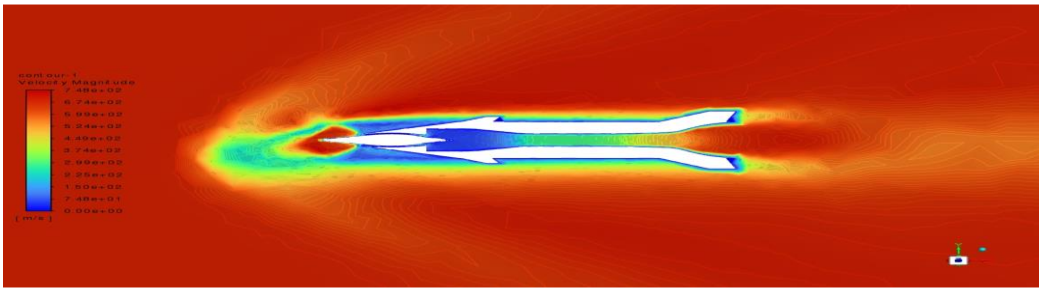

Fig 2: Scramjet – Velocity Magnitude Contour

The speed of the air is low at the inlet, where it slows down.

It increases after combustion, where fuel is burned.

The air leaves the nozzle at very high speed, which creates thrust.

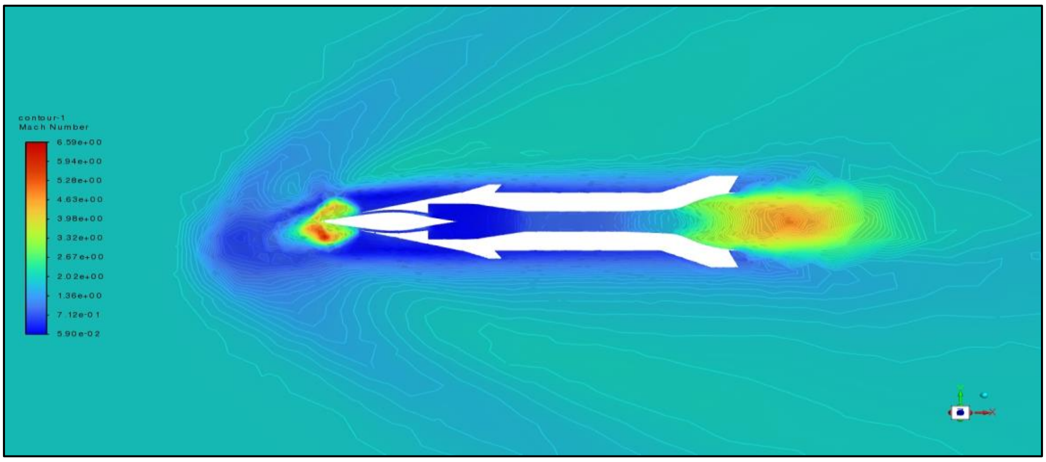

Fig 3: Scramjet – Mach Number Contour

The engine operates at a very high Mach number – above Mach 6.

At the front, the air slows down due to shock waves.

Inside the engine, the air gets faster again after combustion.

The airflow becomes very fast at the nozzle, which helps push the engine forward.

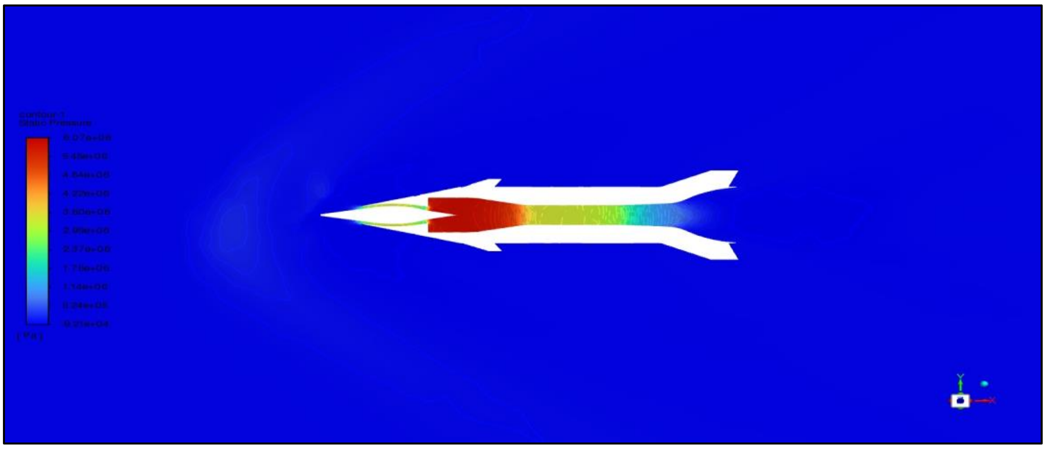

Fig 3: Scramjet – Pressure Contour

The pressure is very high at the front of the engine (inlet).

This pressure comes from the air being compressed as it enters.

The pressure drops gradually as the air moves through the engine and exits.

This shows that the engine is compressing and expanding air correctly, which is needed to produce thrust.

CONCLUSION

Scramjet (Supersonic Combustion Ramjet) propulsion is a breakthrough technology that offers the potential for sustained hypersonic flight using atmospheric oxygen, eliminating the need for onboard oxidizers.

Operating efficiently at speeds above Mach 5, scramjets are key to advancing next-generation aerospace vehicles, military systems, and even future space access platforms. Unlike conventional engines, scramjets have no moving parts and rely on the vehicle's forward motion to compress incoming air, making their design both elegant and highly complex.

This report examined the fundamental principles of scramjet operation, with a focus on combustion behaviour, fuel injection strategies, flame holding mechanisms, and the role of solid fuels in air-breathing systems. One of the main challenges in scramjet technology is ensuring stable and efficient combustion in a supersonic airflow, where the residence time is extremely short. Techniques like cavity flame holders, strut injectors, and boundary layer recirculation are vital for sustaining flame under these conditions.

The report also highlighted the use of Computational Fluid Dynamics (CFD) tools in the design and analysis of scramjet engines. In particular, the k-ω (k-omega) turbulence model, especially its SST (Shear Stress Transport) variant, plays a critical role in accurately predicting turbulence, shock-wave interaction, and near-wall effects. These simulations are essential for understanding complex flow phenomena and improving combustor performance.

In conclusion, while scramjets offer tremendous potential for hypersonic propulsion, significant research is still needed to address the challenges related to fuel mixing, flame stability, thermal loads, and material limitations. Continued advancements in experimental testing and numerical modelling will be crucial in making scramjet technology viable for real-world applications, paving the way for faster, more efficient flight systems in the near future.

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