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A Review on Experimental Work in Combustion Process of Scramjet Engine

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Abstract— A Scramjet (Ramjet with Supersonic Combustion) also known as air-breathing jet engine which facilitates combustion at supersonic airflow velocities. The scramjet engine has numerous applications in military operations and space launches, with ongoing modifications aimed at enhancing its effectiveness. In this scramjet engine, combustion transpires at supersonic airflow, making the phenomenon of combustion crucial to understand in depth. This study provides an overview of several experimental studies conducted on the combustion processes of scramjet engines. The issue with Ramjets is that at elevated speeds (about Mach 6), the temperature of the input air approaches the exhaust temperature due to compression at the intake. Consequently, there will be a significant decline in the engine's efficiency and thrust. The velocity of ramjets cannot exceed Mach 6. To address numerous challenges, a new type of ramjet has been introduced, known as the scramjet engine. In a scramjet, all components are identical to those of a ramjet; however, the airflow remains supersonic throughout the compression process, meaning that the airflow within the entire engine is at supersonic velocity. This paper analyzes the characteristics of combustion within a scramjet combustor utilizing a modified flamelet model, presents an experimental assessment of the combustion performance of a dual-mode scramjet engine with kerosene as fuel, studies the process of incomplete combustion in a scramjet engine, along with the analysis of the characteristics of combustion of hydrogen and cracked kerosene in a DLR scramjet combustor employing a hybrid Reynolds-Averaged Navier-Stokes (RANS) and Large Eddy Simulation (LES) methodology, where the grid spacing are smaller than turbulent scales are resolved, It functions by resolving the larger turbulent scales while simulating the smaller scales, so greatly improving the comprehension of intricate flows that involve turbulence, compressibility, and combustion reactions; in addition to examining fuel injection, combustion efficiency, and the performance of scramjets with various fuels.

Keywords—Scramjet, Injection Strategy, Mach Number, Combustion Efficiency

1. INTRODUCTION

The Supersonic Combustion Ramjet(SCR) engine is a jet engine that enables combustion at elevated airflow velocities, hence producing adequate thrust. Ramjets slow air to subsonic speeds before combustion, while scramjets compress incoming air using vehicle velocity. The scramjet engine's airflow is supersonic. This makes the scramjet very efficient at high speeds. Their propulsion comes from fuel and oxidiser burning. Similar to conventional jet engines, scramjet-powered aircraft carry fuel aboard and obtain the requisite oxidiser by extracting oxygen from the atmosphere, differentiating them from rockets that transport both fuel and oxidiser concurrently [1]. This provision restricts scramjets to suborbital atmospheric propulsion, when the oxygen concentration in the air is adequate for combustion. The scramjet comprises three essential components: a converging inlet, a combustor, and a diverging nozzle. A converging nozzle is one that compresses entering air. A combustor that ignites gaseous fuel with ambient oxygen to produce heat. A diverging nozzle, wherein heated air is propelled to produce thrust. All scramjet engines contain these three components; however, some engines may include an area that acts as a flame holder. Owing to the heightened stagnation temperature, a region of concentrated waves may be employed in lieu of a separate engine component, as noted in turbine engines. Other engines employ pyrophoric fuel additives, such as silane (SiH_4), to avert flameout. In this present study, some experiments which have been performed on scramjet engine are discussed[2]. Study mainly includes the combustion part where combustion characteristics, combustion performance with different fuels and other experiments too have been discussed.

2. ANALYSIS , METHODS AND TECHNIQUES

Guoyan Zhao et. al [3] executed an experiment in a directly linked testing facility at the National University of Defence Technology. The testing gear included a pedestal, an air heater, a scramjet combustor, a fuel delivery system, and a measurement control system. For testing, the air warmer and model combustor were placed vertically on a platform. The scramjet combustor behind the air heater nozzle burned pure ethanol and oxygen to heat the air. The illustrated model combustor consists of a single constant area segment and three diverging parts featuring expansion angles. Three fuel injectors were positioned upstream of the cavity's leading edge. Each injector contained three orifices orientated at a 90° angle relative to the downstream wall. Each orifice possesses a diameter of 1.0 mm, with a separation of 10 mm in the transverse direction. The flow field was seen through a quartz window using a high-speed imaging camera. An advanced high fps camera with superior shutter speed was utilised to examine the dynamics of the flame. The axial pressure distribution was obtained by pressure sensors placed along the centerline of the combustor's upper walls. The cavity generates a low-speed recirculation zone in supersonic flow, enhancing flame stabilisation through partial subsonic combustion. The stable flame in the cavity serves as an ignition source for the core flow. The experimental results solely demonstrate qualitative analysis; nonetheless, the specific combustion characteristics within this scramjet combustor remain ambiguous.

2.1 FUEL INJECTION

Frisov et al have discussed the possibilities of utilizing plasma assisted ignition for both Ignition and flame holding in SCRAMJETS. Savelkin at al. have given experimental results exhibiting Paramount performance enhancement predicated on incipient mechanisms present scheme with collocated plasma generation and fuel injection.

A. FACTORS AFFECTING FUEL-AIR MIXTURE

Wedges are incorporated into the channel's upper wall to improve air-fuel mixing in scramjets. The oblique shock wave produced by the wedge enhances the mixing of air and fuel. The wedge angle substantially impacts the interaction of the produced shock waves, hence affecting the mixing efficiency. Wei Huang and colleagues found the ideal wedge angle by computationally studying wedge-induced oblique shock waves. Oblique shock waves upstream and downstream of the injection port increase mixing by interacting with the bottom wall [4].

B. JET TO CROSSFLOW RATIO

The research conducted by Wei Huang has investigated the influence that the jet-to-cross-flow ratio has on mixing efficiency. The findings of this investigation indicate that a lower jet-to-cross-flow pressure ratio improves the mixing process between the injectant and the supersonic airstream. On the other hand, the mixing efficiency decreases significantly as the cross-flow pressure increases.

C. SLOT WIDTH

Slot width is another parameter that influences the mixing efficiency in case of transverse wall injection. Wei Huang et al, have examined the influence of slot width over mixing efficiency. The experiment was carried out for two values (high and low) of jet to cross flow ratio. The jet perforation depth is found to grow with the increase in slot width, which is accomplished due to the increase in length of the upstream disunion region with the increase in slot width [5]. This is the conclusion that can be drawn from the fact that the jet to cross flow ratio remains constant.

D. SHAPE OF THE INJECTORS

Using three-dimensional Reynolds-averaged Navier-Stokes (RANS) equations and the two-equation SST k-ω turbulence model, Wei Huang and colleagues conducted an investigation to determine the influence of injector configuration on the mean flow field characteristics across a wide range of jet-to-cross flow ratios. A number of different forms are incorporated into the injector, including a square, a diamond, an equilateral triangle, and a circular shape. In the context of transverse wall injection, the contours of the injector mole fraction are analysed and evaluated for a variety of injector designs and jet-to-crossflow ratios. The outcomes of the experiment denotes that the equilateral triangle shape brings out highest mixing efficiency.

The Reynolds-averaged Navier–Stokes equations, in conjunction with the SST k-ω turbulence model[6], have been utilized to examine the interaction mechanism within the staged sonic injection flow field, and a thorough analysis of the effects of the injection angle, the arrangement of injection angles, and the distance between injectors on the characteristics of the flow field has been conducted.

Hence, the fuel mixing efficiency is governed by two mechanisms namely molecular diffusion and Kinematic mixing. Former one is a natural process which can't be modified whereas kinematic mixing can be incremented by turbulent structures and vortices and thus sundry methods to increment air fuel mixing has been studied [7].

2.2 Performance With Other Fuels

The performance of scramjet varies with the use different fuels are as follows-

A. Hydrogen

Hydrogen fuel has strong diffusivity, reduced ignition energy, extensive flammability limits (4-75%), elevated calorific value (120 MJ/kg), and low density. There are numerous advantages to use hydrogen as a fuel. Hydrogen is very flammable; it requires minimal energy to ignite and combust. Hydrogen possesses an extensive flammability range, indicating that it can ignite when it constitutes between 4% and 74% of the air by volume. However, due to hydrogen's gaseous state, it readily amalgamates with air, facilitating highly efficient combustion. In a study examined various equivalency ratios of fuel and air, concluding that a higher equivalence ratio enhances combustion efficiency [7]. Another benefit of hydrogen compared to hydrocarbon-based fuels such as JP-8 or gasoline is its lack of hazardous emissions, including carbon monoxide (CO) and carbon dioxide (CO_2). [9]

B. Acetylene

It has a low calorific value (45MJ/Kg), a high density, and broad flammability limits (2.7-36%). In addition to being an atmospheric gas, acetylene (C2H2) is also a synthesis gas that is often created when calcium carbide and water react. It is a gaseous hydrocarbon that smells strongly of garlic, is colorless, unstable, and extremely flammable. When coupled with oxygen, it forms a very intense flame that can reach temperatures of about 5400°F (3000°C). Calcium carbide and water often react to form acetylene. The reaction can be carried out without the need for complex apparatus or equipment and happens continuously.

C. Kerosene

The substance is a liquid with high density, a calorific value of 45 MJ/Kg, and a flammability limit that ranges from 0.6 to 4.9. A numerical comparative study was performed on kerosene and hydrogen fuel within a model scramjet combustor [10]. The impact of the fuel-air equivalence ratio on the flow field characteristics in a cavity-based mixing mechanism at a free stream Mach number of 2.08 has been examined. The study used a two-dimensional numerical model with a 2-length-to-depth cavity on one flow channel wall. The flow field shock shape changes with fuel-air equivalency ratio. Total pressure loss depends on fuel-air equivalency ratio and fuel type. Fuel distribution in the test portion varies greatly in equivalency ratio [11] [12].

3. Combustion efficiency

The hydrogen-fuelled scramjet engines, measuring 2.1 m in length, generated net thrusts exceeding engine drag and exhibited fuel-specific impulses of around 10 km/s at Mach 4 to 8 flight circumstances. A three-dimensional, reactive computational fluid dynamics algorithm with unstructured hybrid grids was created to accelerate engine research. Simulations of combustion in the scramjet engine under Mach 6 conditions were performed using this code. The document first outlines the engine testing and the computational fluid dynamics (CFD) code. The time evolution of hydroxyl radicals was analysed to clarify the auto-ignition and preceding events of combustion in the engine. Auto-ignition occurred in the cowl section 0.1 ms after the fuel mixing was completed. The reaction zones progressed upstream at velocities of approximately 500 m/s, reaching the backward-facing steps of the combustor 1 ms after auto-ignition. Steady-state solutions revealed small flames encircling each fuel jet within the combustor and a significant diffusion flame downstream in the engine. Sonic combustion was independently realised in the combustor, producing a maximum thrust of 2250 N under stoichiometric conditions. Variations in combustion efficiency indicated that combustion performance was restricted to a narrow region of 0.15 m within the combustor, with downstream combustion controlled by a significant diffusion flame.

The impact of injectant species on the turbulent structure and mixing state of jets in supersonic crossflow was examined by large-eddy simulation. Hydrogen, helium, nitrogen, and ethylene were injected transversely into a Mach 1.9 airflow at a constant momentum flux ratio between the jet and the crossflow. [13]

4. RESULTS AND DISCUSSION:

Hydrogen-fueled scramjet engines, each 2.1 meters long, exhibited the capability to generate net thrusts surpassing engine drag during testing, attaining fuel-specific impulses of around 10 km/s at flying circumstances between Mach 4 and Mach 8. Experimental investigations were enhanced by a three-dimensional reactive computational fluid dynamics (CFD) code created with unstructured hybrid grids, which markedly expedited engine research. Simulations performed at Mach 6 demonstrated intricate combustion behaviors. The time-resolved study of hydroxyl radical (OH) concentrations elucidated the auto-ignition mechanism, indicating that ignition transpired in the cowl section a mere 0.1 milliseconds following the completion of fuel mixing. Subsequent to ignition, the reaction zones advanced upstream at roughly 500 meters per second, arriving at the backward-facing steps of the combustor 1 millisecond post the initial auto-ignition event. Steady-state solutions revealed the existence of miniature, stable flames surrounding each individual fuel jet within the combustor. A predominant diffusion flame was detected further downstream in the engine. Sonic combustion, autonomously realized within the combustor, facilitated a peak thrust production of 2250 N under stoichiometric combustion conditions.

Analysis of combustion efficiency indicated that efficient combustion was confined to a limited zone roughly 0.15 meters in length within the combustor. Outside this zone, combustion was mostly influenced by the extensive downstream diffusion flame. Subsequent examination of jet injection dynamics by large-eddy simulation (LES) yielded insights into the interaction of different injectant species (hydrogen, helium, nitrogen, and ethylene) and a supersonic crossflow at Mach 1.9. Each species was injected transversely at a uniform momentum flux ratio. The simulations demonstrated substantial impacts of injectant type on turbulent structures and mixing properties, underscoring the criticality of species selection for enhancing fuel-air mixing and overall combustion efficacy in scramjet applications.

5. FUTURE SCOPE

The velocity of a scramjet may reach 15 times the speed of sound. This article presents examinations of a three-dimensional FLOW FIELD and temporally resolved planar Rayleigh scattering measurements for Mach 1.7 helium injection into Mach 6 air, aimed at developing a single-stage-to-orbit hypersonic vehicle [14].An airplane equipped with this sort of jet engine might significantly decrease travel time, potentially enabling any location on Earth to be reached within a 90-minute flight; for instance, an 18-hour journey from New York City to Tokyo could be reduced to a two-hour flight. It may be utilized in delicate military operations. ISRO has successfully tested two 'air breathing' scramjet engines, marking the initial phase in refining an advanced technology for missile launches, deploying heavier satellites into orbit, and enabling hypersonic travel for personnel usage.

When installed on a space plane, the engine can significantly reduce intercontinental travel time, enabling passengers to reach New York in merely one hour [15]. Development of India's Scramjet will persist to attain sustainable engine operation in the hypersonic flight regime prior to its use on the RLV-TD space vehicle. The flight of the RLV-TD equipped with a Scramjet will represent the apex of the ongoing test program, however it remains some years away. The test will involve the RLV-TD launching atop a rocket to achieve a velocity adequate for the Scramjet to commence operation, followed by a controlled return to a runway being constructed at the Satish Dhawan Space Center. The RLV-TD will serve as an aerial test platform to assess technologies such as powered cruise flight, hypersonic flight [16], and autonomous landing utilizing air-breathing propulsion to save launch expenses.

6. CONCLUSION

The scramjet engine is the most efficient means of attaining hypersonic velocities in aircraft utilizing an air-breathing engine. The scramjet engine has surpassed expectations in both experimental flying tests and ground-based research. While additional testing is necessary prior to the manufacture of scramjet-powered aircraft, these engines represent the future of propulsion systems, with the capability to achieve speeds surpassing Mach 15. Scramjets are reusable and comparatively economical to operate, rendering them a more feasible alternative to existing propulsion technology. The integration of scramjet technology in military and aerospace domains will maintain the USAF and NASA at the front of aviation innovation. Although the future remains ambiguous, it is certain that evolving circumstances necessitate technological breakthroughs. Although, the implementation of LES markedly improves the analysis of combustion in high-speed air-breathing [17] engines by offering a more precise and comprehensive insight into turbulent flows and combustion dynamics, further enhancements in modelling and validation are essential to fully actualise its potential in practical applications.

Research on scramjet engines should persist inside aerospace programs. If no superior options arise, this technology should be utilized not only for military and space purposes but also for commercial transportation, since it has the potential to transform global travel and interaction.

The scramjet engine represents the most efficient means of attaining hypersonic velocities in air-breathing aircraft.

Scramjet engines have surpassed anticipations in both experimental flying evaluations and terrestrial research.

Despite the necessity for further testing prior to commercial manufacturing, scramjets are positioned to dominate the future of propulsion systems, with theoretical velocities exceeding Mach 15.

Scramjet engines are reusable and comparatively cost-effective, rendering them a more feasible alternative to current propulsion systems. The incorporation of scramjet technology in military and aerospace domains will sustain the USAF and NASA's exposures in the aviation innovation. The future is unknown, although continuous technical breakthroughs are crucial to address emerging difficulties. Large Eddy Simulation (LES) enhances the analysis of combustion in high-speed air-breathing engines by offering a more comprehensive understanding of turbulent flows and combustion dynamics.

Nonetheless, additional progress in modeling and experimental verification is essential to realize the complete promise of LES for practical scramjet applications. Ongoing research on scramjet engines is essential in aerospace programs. In the absence of superior alternatives, scramjet technology need to be embraced for military, space research, and commercial transportation, with the potential to transform global travel and connection.

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