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Experimental and Numerical Analysis of Combustion in Scramjet Engine: A Review

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Abstract—*The scramjet engines are an area that is still developing today. The fuel used in the scramjet engine is mainly either a liquid or a gas. It works at high Mach-number condition. In the scramjet combustor main problem is that it have very less time for the mixing of the fuel into the air. This paper tries to make a review on the various methods that have been adopted to improve the mixing effectiveness, combustion efficiency and reliability of the scramjet combustor. Study of scramjet engine is mainly focused at improving the mixing effectiveness of fuel and air. In this paper, authors have tried to consider most of the techniques currently use: Different, injection techniques, fuel mixing and flame holding mechanisms, design aspects, different cavity geometry of combustor. A brief discussion has been done on various numerical simulations methods andthe two-dimensional coupled implicit NS equations, the standard k-ε turbulence model and the finite-rate/eddy-dissipation reaction model used for investigation of scramjet combustor.This review paper also deals with the suggestions for the research work which can be carried out in the direction of improvement of scramjet engine.*
Keywords: Fuel injector, Mach number, scramjet combustor, thrust, hydrogen fuel, ram cavity.

1. INTRODUCTION

The high velocity of the air creates big challenges for mixing. Now a days improving the mixing and reducing ignition delay are an important factor in designing the scramjet engines. There are a number of techniques used today for fuel injection into scramjet engines for effective mixing of fuel in the air. These techniques preparestoichiometric mixture. This mixture improves the mixing and combustion efficiency. Therefor performance of the scramjet jet engine improves.Advantage of the scramjet engine is that,it is much lighter, faster,higher specific impulse, and cheaper than conventional rocket technology. The scramjet picks oxygen from the atmosphere and does not have rotating part. The scramjet is composed of three basic components, a converging inlet, combustor and a diverging nozzle. The incoming air is compressed and decelerated in the converging portion up to supersonic condition. This compress air is mixed into the fuel in the combustor. This mixture is burned in the combustor and produce heat. The heated air is expended and accelerated in the diverging nozzle to produce forward thrust.

2. LITERATURE REVIEW

Wen.Bao et al. [1] conducted study on multiple re-cooled cycle of hydrogen fueled scramjet. They investigated re-cooled cycle (RCC), indirectly increase the fuel heat sink and reduce the fuel flow rate for cooling. Due to this reason flight Mach condition could have increased. The fuel cooling heat was utilized in form of turbine work. This work was used to drive both the fuel feeding and power generation therefor efficiency of a scramjet engine improved. Cong Zhang et al. [2] conducted study of combined active and passive thermal protection system for hydrogen fueled scramjet. They developed active and passive thermal protection systems to avoid the overheating of combustor wall in case of insufficient fuel cooling and large Mach flight condition. It was made by joining the passive and active layers with help of graphite powder. This composite material could sustain more temperature than metal and reduce the heat flux, so coolant easy cooled the combustor wall. Due to this reason over heating problem will never occur. LingyunHou et al. [3] conducted a study of partially premixed flamelet modeling in a hydrogen-fueled supersonic combustor. They founded combustion process is commonly partially premixed in scramjet. They conducted experiments, in the experiments combustion chamber size was 45 mm × 50 mm and length of the chamber was 300mm. Entrance was divergent 3° along the upper wall. Air entered into the combustor at Mach 2.0 at time hydrogen was injected parallel to airstream with 15 identical holes with sonic velocity. After examining the experimental results, they compared computational results and experimental results and funded multi-regime flamelet (MRF) model with low Mach number flow results more deviated from experimental results as compared to a modified MRF model that applies to supersonic flow conditions. That amply a modified MRF model temperature profile prediction more accurate and precise. Shuhei Takahashi et al. [4] investigated experimentally and numerically of self-ignition and transition to flame-holding in scramjet combustor. They founded a Damkohler number (DA) greater than unity at boundary layer and recirculation zone behind the step and temperature was high due to fast reaction in this region. But the near field or the far-field Damkohler number was very low therefor self-ignition was allowed for the formation of the bulk flames.Kenichi Takita et al. [5] investigated optimization of double plasma jets (PJs) torches in a scramjet combustor by experimentally. They found the effectiveness of the double plasma jets and a single plasma jet had same. But working life and reliability of the double plasma jets got more than the single plasma jet, because double plasma jets minimized the erosion in the torch nozzle. Sudarshan Kumar et al. [6] investigated the performance of a generic scramjet combustor by application of CFD. They conducted 3D numerical simulations for the investigation of different strut configurations. They found the amount of thrust and combustion efficiency, enhance by the proper position of fuel injector struts. Cong Zhang et al. [7] investigated nonlinear characteristics and detection of combustion modes for a hydrocarbon fueled scramjet. They conducted an experiment and fond three different combustion modes with respect to equivalence ratio. These combustion modes were called scramjet mode, weak ramjet mode and strong ramjet mode. It was examined by wall-pressures and one-dimensionally estimated Mach number distributions. The static pressure and Mach number were continuous, rapidly changing when the mode transition occurred, especially near the fuel supply. So that mode transition becomes nonlinear in nature. After a lot of experiments they concluded pressure-magnitude-based detection technique is feasible. Tetsuo Hiraiwa et al. [8] conducted study a on the scramjet engine and the rocket–ramjet combined-cycle engine. They combined scramjet engine with the rocket engine. They investigated this study by experimentally and numerically. The objective of this study was enlarging operating range, limitation and effectiveness of scramjet engine. J.V.S. Moorthya et al. [9] investigated ramp-cavity on hydrogen fueled scramjet combustor by CFD solver Fluent. They created a combustor which had two sections. First, had constant height section with backward facing step and the second section had diverging section. The ramps were located on top and bottom walls of the first section and it produced vorticity therefor mixing efficiency enhanced. The diverging area section restricted thermal choking. This combustor had four hydrogen fuel injectors. The authors concluded that, ramp-cavity was improved the mixing efficiency and increase the residence time of the combustible mixture. Due to this reason performance of scramjet engine improved. Juice Hua et al. [10] investigated a flush wall scramjet combustor equipped with strut/wall fuel injection by experimentally. In this study liquid kerosene was used as the fuel and the flame was stabilized by oxygen. The fuel injected into the combustor in two parts, few amount of fuel injected by strut injection and rest amount of fuel injected by wall injection with a constant equivalence ratio of 0.8. The fuel was ignited by a plasma torch. The strut and wall injectors were located at the same axial position. They examined the combustion performance and wall temperature gradients with various fuel feeding. They concluded strut/wall injection combustor had best combustion performance and smaller wall temperature gradient. Ye Tian et al. [11] investigated the combustion performance of a kerosene fueled dual-mode scramjet engine by both experimentally and computationally. In this study results were analyzed under the inflow condition with Mach number of 2.0, total temperature of 1100 K, and total pressure of 1.0 MPa. They examined the combustion performance with various fuel distribution cases and 0.6 equivalence ratios. Then they found in case of kerosene distribution in front of the first cavity enhanced the combustion performance. They also concluded that a total equivalence ratio enhanced the thrust and subsonic combustion mode stabilized the flow structure. Zhen-guo Wang et al. [12] investigated combustion instabilities inside an ethylene-fueled scramjet combustor by experimentally. They took Mach 2.1 and stagnation temperature 846K for inflow condition of air into the scramjet combustor. In this study, they found combustion efficiency and combustion stability strongly depend on mixing process and low stagnation temperature. Shinji Nakaya et al. [13] investigated the combustion behavior of ethanol by experimentally. In this study liquid ethanol and gaseous ethanol were used in scramjet combustor. They found intensive and transient mode of combustion for liquid ethanol and stagnation temperature 2200 K. They concluded that the reactivity of the gaseous ethanol was varied between reactivity of ethylene and ethane. And gaseous ethanol ignited at minimum temperature. Daniel J. Micka t al. [14] investigated combustion characteristics of a dual-mode scramjet combustor by experimentally. In these study two fuel injectors and two fuels, hydrogen and a mixture of hydrogen and ethylene were used in the dual mode scramjet combustor. The wall cavity pilot flame was examined the ignition and flame stabilization. They founded hybrid stabilization mode was minimized the pressure fluctuations in the isolator and instability in combustion stabilization. HongboWanga et al. [15] investigated combustion oscillations in a supersonic combustor by computationally. They used hybrid RANS/LES (Reynolds- Averaged Naviere Stokes/Large-Eddy Simulation) simulation method. In this study, they found the unsteady flame spreading from the cavity shear layer to the main stream. The jet-with-cavity shear layer was caused of combustion oscillations. The intermittent auto-ignition of the combustible fluid packets were developed the local vorticity that was called jet vorticity. Therefore, they concluded combustion zones oscillations occurred due to the repeated generation of the local vorticity and the fluctuation of the cavity shear layer. And they told combustor work efficiently and reliability of combustor improved in case of less dynamic instabilities and the minimum combustor oscillation frequency. Wei Huang et al. [16] investigated mixing augmentation induced by the interaction between the oblique shock wave and a sonic hydrogen jet in supersonic flows. They did this study by computationally and numerically. In the scramjet combustor main problem is sufficient mixing of the fuel in the air. In this study the three-dimensional Reynolds-averaged Navier–Stokes equations coupled with the SST k–ω turbulence model for analysis. The strong oblique shock wave was induced. It was colliding with the bottom wall upstream and downstream of the jet orifice with the variance of the wedge angle. The authors found 20° wedge angle best for effective mixing. They concluded the mixing efficiency increases with the increase of the wedge angle irrespective of the value of the jet-to cross flow pressure ratio. They also found the mixing efficiency in the case of the induced oblique shock wave was colliding with the bottom wall upstream of the jet orifice was larger than the induced oblique shock wave was colliding with the bottom wall downstream of the jet orifice. Wei Huang et al. [17] investigated on the shock wave transition in a three-dimensional scramjet isolator by experimentally and numerically. The scramjet isolator is a component of hypersonic air-breathing engines, which is installed between the inlet and the combustor of a dual-mode ramjet/scramjet engine. It is used to hold the shock wave train and stop the interaction between the scramjet combustor. They examined the effects of the divergence angle and the back pressure on the shock wave transition. They concluded increase of the divergence angle, generated strong shock wave and the leading edge of the shock wave train varies from the oblique shock wave to the normal shock wave, and then to the oblique shock wave. Wei Huang et al. [18] investigated the cold flow field of a typical cavity-based scramjet combustor by experimentally and numerically. They used three-dimensional coupled implicit Reynolds Averaged Navier–Stokes (RANS) equations and the two equation standard k-ε turbulence model for analysis. They examined the effect of length-to-depth ratio of the cavity and the back pressure on the wave structure in the combustor. And they found a critical length-to-depth ratio of the cavity stopped the movement of the induce shock wave train in the flow field of the scramjet combustor. They concluded intensity of shock wave depend upon back pressure and the pressure distribution on the upper wall of the combustor. HouLingyun et al. [19] investigated the effect of staged injection on supersonic mixing and combustion by numerically. They installed the first-stage central strut injection and a swept ramp injector was selected as the second-stage wall injection. The second-stage wall injection was utilized the remaining oxygen near the wall and added more heat. It was increase wall pressure and provided the effective burning after the wall injection due to this reason more fuel to be injected into the combustor without causing thermal choking. They concluded the second-stage wall injection was become parallel, then low total pressure loss occurred and combustor efficiency improved more.Jianping Li et al. [20] investigated to vitiation effects on supersonic combustor performance. They conducted experiments in the laboratory of the Northwestern Poly technical University. The authors examined the variation of entropy in scramjet combustor with respect to pure air and vitiated air which contain H2O, CO2, CO, H, OH, O, and NO enter in combustor with Mach number 4.They found that level of vitiation airstream created fluctuation in combustion induced pressure and developed shock wave. It was decrease combustion efficiency and scramjet engine performance.Y. S. Chena et al. [21] did study on mixing effectiveness of scramjet combustion. They investigated scramjet combustion by numerically and computationally. The authors used parallel and vertical fuel injections for effective mixing. Due to proper mixing of air and the fuel, combustion efficiency and performance of scramjet engine enhance.JeongYeol Choi et al. [22] did study on combustion oscillations in a scramjet engine with transverse fuel injection. They used a comprehensive numerical analysis for investigation of non- reacting and reacting flow dynamics a scramjet combustor. They concluded transverse injected jet enhance fuel/ air mixing and flame-holding capacity.. A.M. Tahsini et al. [23] Investigated supersonic combustion efficiency for the jet-in-cross-flow by computational simulation. They developed impinging oblique shock by a wedge which was installed the upper boundary of the flow field. They examined the variation of combustion efficiency with respect to the different collision position of developed oblique shock where the fuel injector located at the bottom wall. They concluded the induced oblique shock was more enhanced combustion efficiency when it was collided on the upstream region of the injection hole. It was indicated that the combustion efficiency was increased when the induced oblique shock strength increase. And combustion efficiency also improved by increasing the wedge angle. Peter Gerlinger et al. [24] conducted a study on mixing and combustion enhancement in supersonic combustors by strut induced stream wise vorticity. The authors found that air/fuel mixing enhance by strong stream wise vorticity. The authors used the lobed strut injector which was located at the channel symmetry axis. Lobed strut injector creates counter rotating stream wise vortices into which the hydrogen is injected. It's created strong turbulence due to this reason mixing efficiency increase. Mixing efficiency enhances the scramjet performance.. R.F. Cao et al. [25] did study on combustion mode transition of hydrogen fueled dual-mode scramjet engine based on thermodynamic cycle analysis. They took two thermodynamic cycle ram mode cycle and scram mode cycle for analysis. These cycles were installed in the scramjet engine. They did a comparative analysis of both mode cycles on the basis of maximization of propulsive performance and economic performance. They found when Mack number less than 6 then rams mode cycle specific impulse more than a scram mode cycle. When Mach number was greater than 7 than result was opposite. They concluded that dual mode scramjet engine superior on the basis of performance optimization than ram mode cycle when the Mach number was less than 6 and Mach number 6 to 7 in case of high impulse.

3. FUTURE SCOPE OF RESEARCH

All the above studies refer to analysis and development of scramjet combustor design and injection technics to improve the combustion efficiency.Various numerical models have been built to accurately evaluate the performance of scramjet engine.Studies have shown the effect of various parameters like, injector type, injection angle, flame holding capacity, mixing length, combustor size, operating conditions.Based on these studies, a numerical model can be built considering each parameter as an independent variable and the effects of the required or the desire ones in a final equation to evaluate efficiency of the scramjet engine, which would be a function of all the above parameters or parameters which are more dominant. Optimization study can be undertook to find the optimum values of the design parameters and operating parameters which are under our control to improve the performance of the scramjet engine. Further investigated the scramjet combustor at different operating condition to enhancement of the combustion efficiency, mixing length and better thrust. It can be investigated the design parameters of chamber which induce strong shock wave and increased pressure loss for enhancement of mixing.

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