A brief review on the recent advances in scramjet engine

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Abstract. The scramjet engine is the most favourable air breathing propulsive system and suitable option for high-speed flight (Ma<4). Several scientists across the globe are continuously working on the advancement of the high-speed scramjet engine due to its implementation in the military missiles, low-cost access to space etc. The mixing phenomena associated with air and fuel is the salient feature for the effective combustion process and the fuel and air should be mixed adequately before entering into the combustor. But the key challenges associated with scramjet engine are the high speed of air inside the combustor and low residence time which actually deteriorate the combustion phenomena. That's why numerous computational, as well as experimental researches are being carried out by several researchers. The flow-field inside the scramjet engine is very complex. Hence an elaborated approach of the complicated combustion and mixing process inside the combustor is essential for the upgradation of the effective scramjet engine. This paper clearly signifies a brief review of the current development in scramjet engine.

Keywords: Scramjet; Cavity based injection; Mixing efficiency

INTRODUCTION

Significant focus towards enhancing the performance of the scramjet combustor is given to the efficient mixing of air and fuel. The cross stream mixing between fuel and air is very complicated due to very high kinetic energy of the air stream. Hence in order to achieve better mixing, special fluid mechanism is needed. The presence of fuel injectors and flame holding play an important role in the design of scramjet engine. Air and fuel should be mixed in an appropriate amount for the efficient combustion to take place and also the flow losses associated with fuel injectors' should be minimum.

The use of Cavities is a special perspective as flame holder and fuel injector. The design of cavities were firstly completed and applied by CIAM (Central Institute of Aviation Motors) in Moscow in a joint Russian/French dual-mode scramjet flight-test [1]. The existence of recirculation area inside the cavities enhances the combustible mixture's residence time and thus cavities are preferable candidates for flame holding.

The use of cavities for stabilization of flame in a solid fuel supersonic combustor was mainly performed by Ben-Yaker et al. [2]. In his work, he revealed sustained combustion and self-ignition of polymethyl-methacrylate (PMMA) for supersonic inlet conditions. The experimental investigation on eight different types of integrated wall injector cavity configurations was actually carried out by Yu, et al [3]. He mainly used hydrogen fuel to study the combustor performance and flame holding characteristics inside scramjet combustor. The effect of backpressure and cavity length-to-depth ratio (L/h) on the scramjet combustor flow field for non-reacting flow was computationally studied by Huang, et al [4]. Again Kim, et al [5] performed computational analysis of combustion enhancement using cavity flame holder to resolve the effects of aft wall angle, cavity length, depth on pressure loss and combustion efficiency. To improve the mixing process between the fuel and air in supersonic flows [6], transverse injection from a wall orifice is one of the easiest and most favourable configurations. Huang and Yan [7] performed a computational simulation on the transverse injection from four aspects. In their work, they actually revealed the effect of the injection angle, the injector number, the injector configuration and the jet-to-cross flow pressure ratio on the combustion enhancement of scramjet engine. They also performed optimisation which was mainly non-dominated sorting genetic algorithm (NSGA II) coupled with the Kriging surrogate model [8]on the two-dimensional transverse jet flow field .

In order to promote the stream wise vorticity inside the scramjet, Lee and Mitani [9] proposed a modified injector geometry which also used cavity to enhance the fuel penetration property as well as the mixing rate. But the additional disadvantage of this system is that pressure loss is more. The mixing process between the fuel and air is also improved by injecting the fuel inside the cavity as well [10]. The use of pylon was mainly carried out by Lee [11] to improve the combustion performance in the transverse injection flow field. The effect of mixing characteristics of different injection schemes for supersonic transverse jet was computationally performed by Gao and Lee [12]. They mainly compared the influences of the injector diameter, number and injection angle for slot, and circular-hole and two-stage injections on the mixing efficiency and also concluded that higher mixing efficiency is observed for circular-hole injection case. The two- stage injection is found to be better than single-stage. Watanabe et al. [13] numerically investigated the influence of injectant species on the mixing properties in the transverse injection. They mainly used four different kinds of fuel such as nitrogen, ethylene, hydrogen and helium and also not considered the combustion properties. Again, there are some technological issues which are associated with scramjet engine [14]. These are mainly the dissociation properties of the reactants prior to combustion phenomena because of their high temperatures. As a result, there will be a reduction in combustion efficiency as well heat release process. There are numerous computational and experimental works regarding fuel injections techniques such as single strut injection [15-17], two-strut injection[18,19, 40], wall injection[20], cavity injection[21] etc. in order to enhance the performance of scramjet combustor. This is because an effective fuel injection inside the combustor is the key challenges of the scramjet. Again due to the short residence time of fuel inside the supersonic combustor, better fuel injection techniques with maximum penetration and mixing plays an important aspect for fast and most significantly successful combustion.

DISCUSSIONS ON THE RECENT PROGRESS ON SCRAMJET ENGINE

The presence of transverse fuel injection helps in the formation of a detached Bow shock and a large separation region and a small separation region downstream and upstream of the injection region, respectively which is in support of flame stabilization [22]. Generally the fuel injectors are placed inside the cavity in direct injection, and the injection of fuel take place directly in to the recirculation zone, which may enhance the combustion environment within the cavity region [23]. The simplified schematic sketch of the cavity flow field oscillation mechanism proposed by Rossiter [34] is shown in fig.1. For double cavity injection techniques [24-26] (fig.2), obtaining optimal fuel mixing and transport is the key issue in modeling the fuel injection process in a supersonic combustor. However, in recent year most of the researchers are working on double cavity scramjet combustor and obtained some fruitful results.

Scramjet combustor mainly includes a very short residence time (of the order of milliseconds), hence obtaining flame stabilization is another issue. This has increased the concentration of many researchers. The flame holding mechanism and stability limits in cavity-stabilized mode was investigated mainly by Rasmussen et al. [27, 28]. When injection of fuel took place from the aft wall, primary combustion obtained in the aft region of the cavity and also under the shear layer. On the other hand, when the injection of fuel took place from the down wall, then the presence of a jet driven recirculation region adjacent to the upstream wall of the cavity act as a flame holder, and also the reaction took place on the underneath the shear layer. Lin et al. [29] investigated both computationally as well experimentally the operating limits and the performance of an ethylene-fueled recessed cavity flame holder with various cavity lengths. In their work, they revealed that the cavity with L/D ratio 6 showed the weakest performance among the other three cavities which is shown in fig.1. Sun et al. studied the flame stabilization mechanism and flame characteristics with hydrogen injection upstream of cavity flame holders [30]. They concluded that the transportation of hydrogen fuels took place into the cavity shear layer and also there was an existence of steady partially premixed flame front in the cavity shear layer.

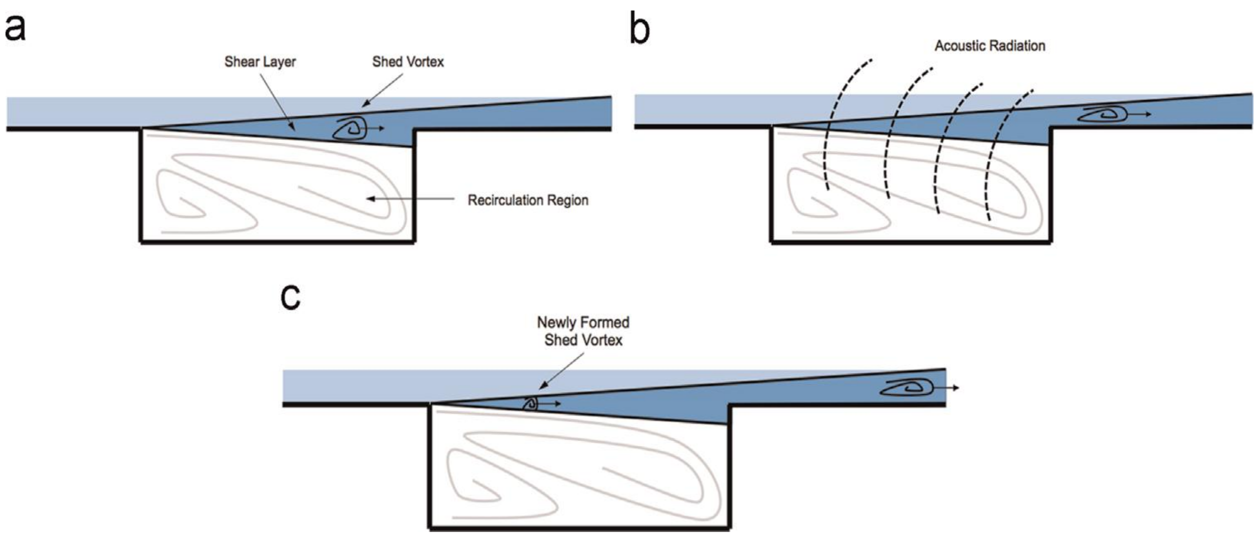

FIGURE 1. Simplified schematic of the cavity flow field oscillation mechanism proposed by Rossiter [34]. (a)Shed vortex is advected through the shear layer downstream towards the cavity trailing edge (b) Upstream propagating acoustic disturbances (c) Interaction of the acoustic disturbances with the developing shear layer stimulates further vortex shedding

Investigation on the combustion characteristics of a dual-mode scramjet combustor with cavity flame holder was mainly performed by Micka et al. [31]. The revealed that the combustion zone was attached at the leading edge of the cavity at low stagnation temperature and sustained a smaller distance at high stagnation temperature in the downstream direction of the fuel injection jet. The cavity sustained combustion was persistent with the theory associated with the controlled reaction premixed flame spreading and the flame progress into the main flow as uninterrupted reaction layers, while the jet-wake sustained combustion was persistent with a lifted jet flame and the reaction zone was mainly mostly pulverized and uninterrupted layers were not noticed.

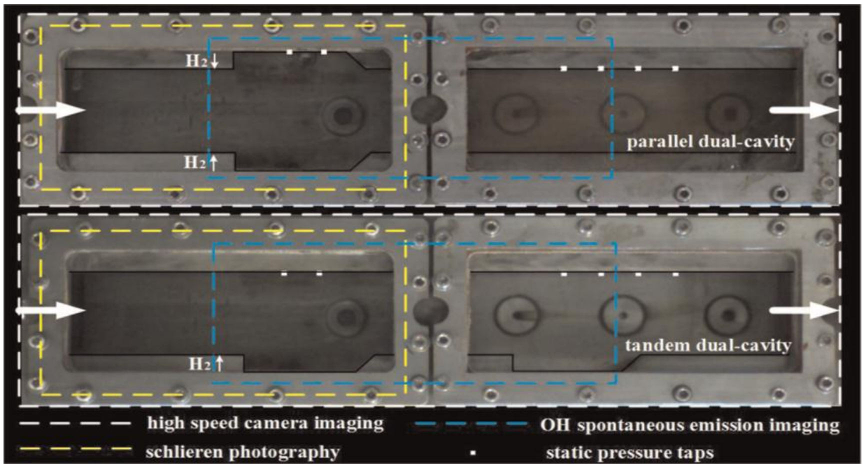

FIGURE 2 Model combustor and experimental investigation approaches for double cavity [25]

The combustion characteristics in a ramjet combustor with cavity flame holder were numerically studied by Tuncer [32]. It was noticed that flame attached at the leading edge cavity, and the flame was sustained in the cavity mode as compared to the jet-wake mode. The combustion modes in a supersonic combustor were experimentally performed by Masumoto et al. [21]. In their work they observed four combustion modes which were primarily non ignition, weak combustion (with little pressure rise), dual-mode combustion and supersonic combustion.

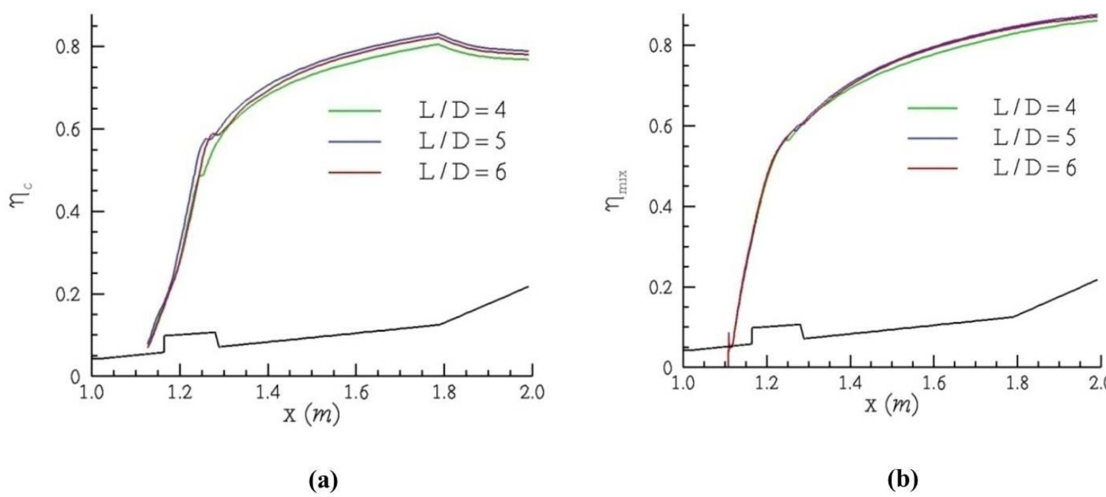

FIGURE 3 Numerical mass-averaged 1-d distribution profiles of (a) combustion efficiency (b) mixing efficiency [29]

Recently many researchers are also working in the field transverse injection in supersonic combustor. Among them Huang et al. [35-37] performed several computational investigations that focused on transverse injection. Gerdroodbary et al. [38] also performed several computational analyses on the effect of micro air jets on the mixing enhancement of transverse H_2 jet in high-speed flow. In his work he have noticed that the mixing of the H_2 jet appreciably increases (> 60%) in the downstream direction only when the fuel jets are situated just upstream of the air jets. As a result, enriched mixing zone is noticed in the downstream direction of the injection area which is followed by the flame-holding region. In another work [39], it is noticed that the presence of air jet significantly affect the penetration height associated with single fuel jet in the neighborhood of the fuel jet region.

CONCLUSIONS

A brief review of mixing phenomena of scramjet engine is discussed in this research paper covering the recent advances in scramjet engine. The primary consequence to view in scramjet combustion is the high-speed of the flow, which has a significant effect on the mixing performance of the air and fuel. Additionally, better mixing can be obtained at the cost of pressure loss. An increased rate of mixing enhances the performance of the scramjet, as it helps in reducing the length of the combustor and thus the skin frictions drag

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