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Review

Transverse jet in supersonic crossflows

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ABSTRACT

The mixing and combustion process plays an important role in the realization of the scramjet engine, and the transverse injection from a wall orifice is widely employed for the simplest and most promising of its configurations. In the current survey, the research progress on the transverse jet in supersonic crossflows has been summarized systematically from four aspects, namely single injection, multiport injection, interaction between jet and vortex generator, and interaction between jet and shock wave, and the basic principle of the transverse injection has been provided as well. At last, some promising recommendations have been proposed, namely the refined vortex structure capture, the mixing and combustion process in the novel injector and multiport flow fields, especially with the incident shock wave interaction, and the combinatorial operating and optimization process between the fuel injection and the vortex generator.

1. Introduction

The scramjet (supersonic combustion ramjet) engine would become one of the most effective engine cycles for the hypersonic flight in the near future [1], however, it is very difficult to obtain a stable and efficient combustion flow field in a scramjet engine due to the very short residence time of the injectant inside the combustor, namely of the order of milliseconds [2], and the mixing process at the molecular level has to be completed in a limited combustor length [3]. The rapid mixing and combustion process is crucial for the realization of the scramjet engine, and it takes place nearly simultaneously in the combustor [4]. The mixing process is the initial phase for all the physical ones, as well as the primary factor to restrict the combustion process, i.e. ignition and flame propagation. Increased efficiency in fuel–air mixing may lead to reductions in size and weight of the engine, as well as reducing the amount of structure that needs to be cooled [5]. In order to promote the mixing process between the injectant and air, many fuel-injection systems have been proposed in recent years, i.e. ramp [6], aerodynamic ramp [7,8], strut [9], pylon [10–12], and any other combination, as well as the cantilevered ramp injector which has been used as the inlet injection scheme to shorten the length of the combustor [13,14]. Seiner et al. [15] have given a detailed review on the mixing enhancement devices in scramjet engines.

Transverse injection from a wall orifice is one of the simplest and most promising configurations to enhance the mixing process between the fuel and air in supersonic flows [3], and it attracts an increasing attention since the early sixties [16], especially on some scramjet powered vehicles [17–20], see Fig. 1. Fig. 1 represents the computational results obtained by the large eddy simulation approach for the HyShot II combustor, and the mixing process is dominated by the counter-rotating vortex pair (CVP) and Ω-shaped vortices in the near and far fields respectively [21,22], as well as the Kelvin–Helmholtz instabilities induced by the high levels of upper jet shear layer [23], see Fig. 2. That is to say its near-field mixing is predominantly controlled by an entrainment-stretching-mixing process [24], and the large protrusions of injectant are induced by the large-scale vortices on the windward side of the jet plume [25]. The far-field mixing is controlled by mass diffusion [26]. Horseshoe vortex is obtained by the interaction between the incoming boundary layer and the jet, and it remains close to the wall of injection, wraps around the jet periphery and propagates downstream. Therefore, the horseshoe vortex does not interact with the jet, and it does not take part in the mixing process [27]. A cavity has been utilized by Lee and Mitani [28] to modify the injector geometry in order to promote streamwise vorticity, and a surface ramp has been installed downstream a sonic transverse jet to reduce the low-pressure region behind the jet [29]. Nowadays, the transverse injection scheme has been utilized in the thermal protection system of the hypersonic vehicle [30], see Fig. 3, as well as its typical application in the attitude control of hypersonic missiles [31–34], and it is able to recast the bow shock wave into a conical shock wave without

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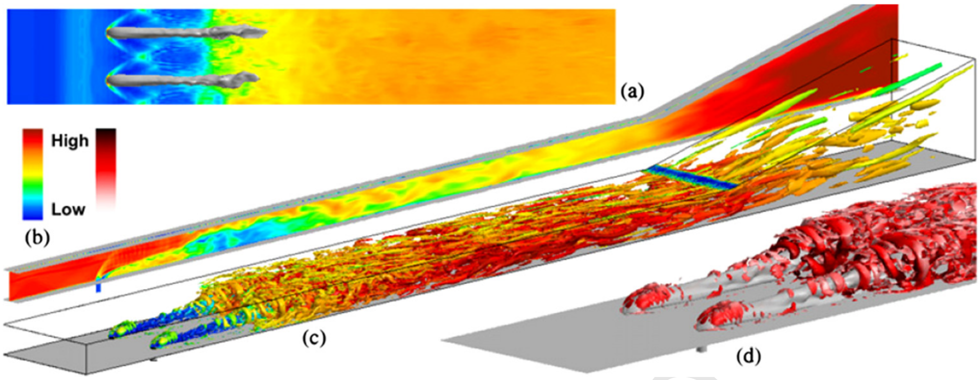

Fig. 1. Composite figure of the combustion flow field in the HyShot II combustor, (a) wall pressure and an iso-surface of the H_2 mass fraction, (b) axial velocity cut through a fuel injector, (c) iso-surface of the second invariant of the velocity gradient, λ_2, colored by the temperature and (d) iso-surfaces of the H_2 mass fraction (gray) and the heat release conditioned on λ_2 [17].

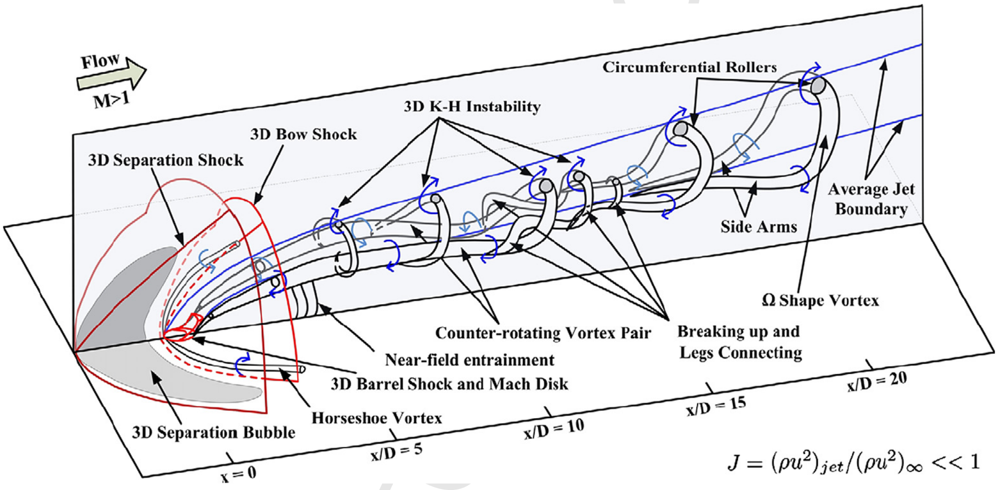

Fig. 2. Schematic of the three-dimensional unsteady vertical structures formed in the HyShot II combustor [21].

any shock wave/shock wave interaction occurring at the should of blunt bodies. In 2015, Huang [35] has provided a detailed review on this topic, and the drag and heat release reduction induced by a counterflowing jet and its combinations has been summarized. The combinatorial configurations include the combination of the counterflowing jet and a forward-facing cavity, the combination of the counterflowing jet and an aerospike, and the combination of the counterflowing jet and energy deposition. Further, he and his coworkers have investigated the drag reduction mechanism induced by a combinational opposing jet and spike concept [36], as well as the drag and heat reduction mechanism induced by the combinational opposing jet and acoustic cavity concept [37].

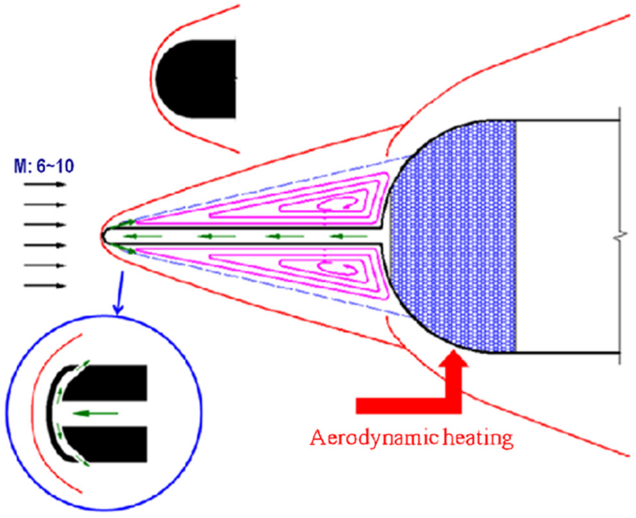

Fig. 3. Operational principals of Non-ablative Thermal Protection System (NaTPS) for aerodynamic force and heat reduction [30].

The transverse injection can provide rapider near-field mixing and better fuel penetration capability, and the recirculation region induced by the injection can hold the flame. Additionally, it does not need more cooling and cannot generate more drag force. However, it would generate complex flow field structure and strong shock wave, as well as large total pressure loss. The total pressure loss is not preferable because it leads to the thrust loss, and it grows with the increase of the injection angle [38]. At the same time, the compression effect is not beneficial to the vortex generation and shedding on the mixing layer between the fuel and air, and this restricts the entrainment mixing and slows down the far-field mixing and combustion process. Therefore, the supersonic mixing with very rapid mixing and lower total pressure loss ratio is highly requested [38]. Huang and Yan [39] have provided a survey on the transverse injection from four aspects, namely the jet-to-crossflow pressure ratio, the injector configuration, the injector number and the injection angle, and the multiobjective design optimization approach has been proposed to be applied in the design process of the transverse injection strategy for the first time. Further, they have obtained the Pareto fronts for the optimization of the two- and three-dimensional transverse injection flow fields, see Fig. 4, as well as that for a cantilevered ramp injector flow field

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