



Parametric effect on the mixing of the combination of a hydrogen porthole with an air porthole in transverse gaseous injection flow fields



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ABSTRACT

The dual transverse injection system with a front hydrogen porthole and a rear air porthole arranged in tandem is proposed, and this is a realistic approach for mixing enhancement and penetration improvement of transverse injection in a scramjet combustor. The influence of this dual transverse injection system on mixing characteristics has been evaluated numerically based on grid independency analysis and code validation. The numerical approach employed in the current study has been validated against the available experimental data in the open literature, and the predicted wall static pressure distributions show reasonable agreement with the experimental data for the cases with different jet-to-crossflow pressure ratios. The obtained results predicted by the three-dimensional Reynolds-average Navier – Stokes (RANS) equations coupled with the two equation $k-\omega$ shear stress transport (SST) turbulence model show that the air porthole has a great impact on penetration depth and mixing efficiency, and the effect of air jet on flow field varies with different values of the aspect ratio. The air porthole with larger aspect ratio can increase the fuel penetration depth. However, when the aspect ratio is relatively small, the fuel penetration depth decreases, and even smaller than that of the single injection system. At the same time, the air porthole has a highly remarkable improvement on mixing efficiency, especially in the near field. The smaller the aspect ratio of the air porthole is, the higher the mixing efficiency in the near field is. This is due to its larger circulation in the near field. The dual injection system owns more losses of stagnation pressure than the single injection system.

1. Introduction

The scramjet (supersonic combustion ramjet) engine may be one of the most promising engine cycles for the hypersonic flight in the future [1]. An oxidizer tank is not required in these engine cycles, and they are simple in structure and low in cost. Moreover, the scramjet (supersonic combustion ramjet) engine is the most effective engine cycle when vehicles fly in or beyond the supersonic speed. Therefore, they are preferred to rocket and turbofan engines. The presence of these advantages has motivated researchers in recent years [2–5].

In the scramjet combustor, the mixing process is the initial phase for all the physical ones, and it is the primary factor to restrict the combustion process [6,7]. Hence, the realization of sufficient mixing is the key to the engineering implementation of the hypersonic propulsion system. Due to the short residence time of airflow within the scramjet combustor being on the order of milliseconds for typical flight conditions [8], an efficient injection strategy with high penetration and rapid mixing is required.

Many injection schemes have been proposed to enhance the mixing process, and they have been studied theoretically [9], numerically [10] and experimentally [11]. One simplest and reliable approach of fuel injection for a scramjet engine is transverse injection from a wall orifice [12,13], because the transverse injection provides rapid fuel-air mixing and high jet penetration into the supersonic airflow [14]. At first, the majority of studies have concentrated on a single transverse jet at a variety of conditions such as jet-to-crossflow pressure ratio [15,16], jet-to-crossflow momentum flux ratio [17], molecular weight [18], injector geometry [19], injection angle [20], incoming air steam angle [21]. Huang and Yan [13] provide a detailed review on the transverse injection flow field from four aspects, namely the jet-to-crossflow pressure ratio, the geometric configuration of the injection port, the number of injection port and the injection angle. On the other hand, in order to increase the penetration and mixing, many devices such as strut [22–25], ramp [26], pylon [27], cavity [28–30], aerodynamic ramp [31], and any other combination have been offered and enhanced mixing and penetration substantially, but at the expense of a larger stagnation pressure

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loss, increasing drag forces, and inciting considerable local heating loads [32]. In 2016, Huang [15] reviewed more than 130 documents and summarized systematically the research progress on the transverse jet in supersonic crossflow, especially on the interaction between jet and vortex generator and the interaction between jet and shock wave.

A variation on the traditional single jet in crossflow is the multiple transverse injection system [33–38], and several variable conditions such as distributions of mass flow rate and momentum flux, combination of injection angles, arrangement of injector geometry and spacing variation in both the freestream and spanwise directions can be applied in this approach. Since the multiple transverse injection system does not have physical obstruction to the combustor flow in comparison with the mixing enhancement devices, the stagnation pressure loss, the drag forces, and the local heating loads are small. The transverse injection flow field with a multiple transverse injection system owns better mixing characteristics than that with a single transverse injection system due to the interactions among the injection flows. In 2006, Lee [33] studied the mixing characteristics of a dual transverse injection system and showed the schematic view of the dual transverse injection flow field. The horseshoe vortices, the separation bubble, and the recirculation wake flows are formed along the jet direction. The streamwise vortices roll up the injection flows, so the mixing process between the fuel and the freestream is accelerated, but the dual transverse injection scheme would induce a slightly larger total pressure loss. In 2015, the influence of the jet-to-crossflow pressure ratio arrangement of the multiple injection system with four square-shaped portholes arranged in tandem has been investigated by Huang [39], and the mixing performance is determined by the jet-to-crossflow pressure ratio of the primary injector. In 2016, Huang studied the mixing process induced by an array of three spanwise-aligned small-scale rectangular portholes, and the influences of the jet-to-jet spacing, the jet-to-crossflow pressure ratio and the aspect ratio of the injector on the flow field properties were evaluated [40].

Recently, a creative injection strategy has been proposed by Barzegar et al. [41–44]. The characteristics of the transverse hydrogen jet in presence of multi air jets have been comprehensively investigated by Barzegar and his coworkers from four aspects, namely the number of air jets and fuel jets, the pressure of the air jets, the fuel jet space and the number of the air jets downstream of each fuel jet. According to the obtained results, the influence of the air jets is significant, and the effect of air jets on mixing performances of transverse gaseous injection flow fields varies on various conditions.

However, to the best of the authors' knowledge, the influence of the aspect ratio of the air porthole on the transverse injection flow field has rarely been investigated simultaneously in the open literature, and this issue is crucial for the design of the mixing device in supersonic crossflows. On the other hand, Computational Fluid Dynamics is an efficient approach to perform parametric studies and check whether design changes are worth testing experimentally. At the same time, it also provides important insight into complex flow phenomena like separations, shock wave, thus significantly improving the flowpath design process for relatively lower costs compared to costly experimental tests alone [45,46].

In the current study, the transverse injection flow field in a Mach 3.75 crossflow of air has been investigated numerically, and the numerical approaches are validated against the available experimental data in the open literature. The combustion process is out of the scope in this article, and it would be taken into consideration in the near future. However, the mixing process will go in a different way in the presence of combustion, especially taking into account diffusive character of combustion processes next to injection zones [47]. The dual injector system made up of a hydrogen porthole and an air porthole has been employed. The configuration is investigated in terms of variations in the aspect ratio of the air porthole in a parametric study. The influence of the aspect ratio of the air porthole on the supersonic mixing between the hydrogen and air has been evaluated. The main performance parameters concerned in the present study are mixing efficiency, penetration depth, and stagnation

pressure loss.

1.1. Physical model

The test section is a straight channel. The width of the flat plate is 30 mm, the height of the computational domain is 15 mm, and its total length is 200 mm. Fig. 1 shows the top view of the array of two rectangular portholes. The main configuration consists of a flat plate with a front hydrogen porthole and a rear air porthole arranged in tandem. The distance from the entrance of the channel to the trailing edge of the hydrogen porthole is 20 mm, and the origin of the coordinate system is set at the trailing edge of the fuel porthole. The width and length of hydrogen porthole are 0.5 mm and 2 mm respectively. The space between the hydrogen porthole and the air porthole is the same, and it remains constant, namely $S = 2$ mm in Fig. 1. The aspect ratio of the air porthole is set to be 8:1, 2:1, 1:2 and 1:8 respectively corresponding to model B, model C model D and model E. In order to retain a constant air mass flow, the area of air porthole keeps constant, and its value is 2.0 mm^2 . The length and width of air porthole for each model can refer to Table 1. Model A is a traditional single jet flow field, and it is simulated for comparison.

The air flows from left to right, and its air properties are set to be a Mach number M_∞ of 3.75, a static pressure P_∞ of 11090 Pa and a static temperature T_∞ of 78.43 K. The jet flow Mach number M_j is set to be 1.0 with a static temperature $T_j = 249$ K, and these conditions are representative of a typical generic scramjet combustor. The hydrogen is set as the fuel for it is generally a more energetic fuel than hydrocarbon fuels for a Mach number in the range 4–10 [48]. The jet-to-crossflow pressure ratio is defined as the static pressure ratio of injectant and supersonic airflow. The jet-to-crossflow ratio of the hydrogen porthole is set to be 25.15, and the jet-to-crossflow ratio of air porthole is set to be 4.86 according to the previous studies carried out by the same authors [19].

2. Numerical approaches

In the current study, the three-dimensional Reynolds-average Navier – Stokes (RANS) equations coupled with the two equation $k-\omega$ shear stress transport (SST) turbulence model have been utilized to numerically simulate the transverse injection flow field. The steady state computational data have been obtained using a density based (coupled), implicit, second-order upwind, double precision solver of FLUENT version 6.3.26 [49]. A Dell workstation at the Science and Technology on Scramjet Laboratory, China, using up to 32 processors, provided a parallel computing environment for flow solutions.

2.1. The governing equations

The RANS equations are considered for their ability to solve on coarse mesh and permit the simplification of steady flow with lower computational cost when compared with the other numerical methods, i.e. detached eddy simulation, large eddy simulation and direct numerical simulation. The governing equations are as follows [50]:

$$\frac{\partial(\rho Y_s)}{\partial t} + \frac{\partial}{\partial x_j} (\rho Y_s u_j) = \frac{\partial}{\partial x_j} \left(\rho D_s \frac{\partial Y_s}{\partial x_j} \right), \quad s = 1, 2, \dots, ns \quad (1)$$

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_j} (\rho u_j) = 0 \quad (2)$$

$$\frac{\partial(\rho u_i)}{\partial t} + \frac{\partial}{\partial x_j} (\rho u_i u_j + \delta_{ij} p) = \frac{\partial \tau_{ij}}{\partial x_j} \quad (3)$$

$$\frac{\partial(\rho E)}{\partial t} + \frac{\partial}{\partial x_j} (\rho H u_j) = \frac{\partial}{\partial x_j} \left(\tau_{ij} u_i + k \frac{\partial T}{\partial x_j} + \sum_{s=1}^{ns} \rho D_s h_s \frac{\partial Y_s}{\partial x_j} \right) \quad (4)$$

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