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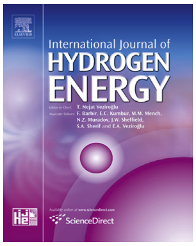

Mixing augmentation mechanism induced by the pseudo shock wave in transverse gaseous injection flow fields

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ABSTRACT

The mixing process between the injectant and air is very crucial for the engineering implementation of the scramjet engine, and this is due to the very short resident time of fuel in supersonic flows. In the current study, the three-dimensional Reynolds-average Navier–Stokes (RANS) equations coupled with the two equation k-ω shear stress transport (SST) turbulence model have been employed to investigate the transverse injection flow field with the pseudo shock wave induced by the high back pressure, and the freestream Mach number is 3.75. At the same time, the influence of the back pressure on the flow field properties has been evaluated as well. The obtained results show that the pseudo shock wave induced by the back pressure plays an important role in the mixing enhancement between the injectant and air. When the back pressure ratio is larger than 5.0, the mixing efficiency increases with the increase of the back pressure ratio. However, when the back pressure ratio is 3.0, the near-field mixing process has been improved, and accordingly its mixing efficiency in this region is larger than the benchmark. This implies that the intense combustion downstream of the injector can enhance the mixing process between the injectant and air, and the mixing and combustion process can be enhanced mutually. When the pseudo shock wave has been pushed upstream of the wall orifice, more injectant has been brought into the separation zone upstream of the injector, and this is beneficial for the mixing process between the injectant and air.

Introduction

Scramjet fuel injection has received considerable attention since the mid-1950s [1]. Glagolev and his coworkers [2,3] investigated supersonic flow with freestream Mach number being 3.0 past an air jet issuing at the speed of sound, and the obtained quantitative data are useful for further study of the same phenomenon. Recently, numerous fuel injector concepts have been proposed and investigated, especially for the cantilevered ramp injector located in the forebody/inlet of hypersonic vehicles [4,5] and pylon used as the vortex generator ahead of the orifice [6–8]. However, these devices are intrusive to the flow, generate drag, and require cooling [9].

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Therefore, the flush-wall injection continues to remain one of the simplest and most promising strategies to enhance the mixing process between the air and injectant in supersonic flows, and it attracts an increasing attention since the early sixties [10–17]. Huang and Yan [18] provided a detailed review on the transverse injection flow field in supersonic flows, and its four aspects were summarized, namely the jet-to-crossflow pressure ratio, the geometric configuration of the injection port, the number of injection ports and the injection angle. A stinger-shaped injector with a sharp leading edge in front of a streamwise slit was employed by Kouchi et al. [19] to enhance the mixing and combustion process between the fuel and air, and the measured data were compared with those of a conventional circular injector.

Further, the oblique shock wave is proved to be an important issue on the mixing enhancement, and this is due to the strong axial vortices generated by the interaction between the mixing layer and the oblique shock wave. The axial vortices stretch the fuel/air interface [20]. Schetz et al. [21], Huang et al. [22,23] and Gerdroodbary et al. [24] investigated the shock wave effect on the supersonic mixing in scramjet engines experimentally and numerically, and they found that the impinging shock wave reduces the penetration and increases the mixing for the injectants irrespective of the molecular weights. Zare-Behtash et al. [25] studied the effect of an impinging shock wave on the jet–cavity interaction experimentally, and a relatively uniform velocity distribution within the cavity was induced by the interaction between the shock wave and the transverse jet. Based on his recent research works, Huang [26] gave a comprehensive survey on transverse jet in supersonic crossflows, and the research progress on two main additional topics has been included, namely the interaction between jet and vortex generator, and the interaction between jet and shock wave.

At the same time, when the combustion process occurs downstream of the fuel injection location, the supersonic mixing process would be affected as well, and this may be due to the high back pressure generated by the intensive combustion between the fuel and air. Then, the pseudo shock wave which is common in the isolator [27] would be formed if the back pressure is high enough, and it has a large impact on the deflagration-to-detonation transition in metastable systems as well [28]. The pseudo shock wave could lower the flow velocity of the mainstream and increase the size of the counter-rotating vortex pair [29]. In order to clarify the mixing enhancement mechanism induced by the pseudo shock wave, more detailed information is required about the flowfield generated by the pseudo shock wave. Unfortunately, the experimental investigations of these complex flows are costly to perform, and the computational studies can often offer insight into the mechanics of these flows [30].

Ogawa et al. [31] conducted cold flow experiments to investigate the mixing process of fuel in the duct flow with a pseudo shock wave presents. Kouchi et al. [32] took high-speed schlieren movies of transverse injection flow fields with and without the pseudo shock wave, and they observed that the injectant plume penetrates much deeper into the mainstream when a pseudo shock wave is present.

In the current study, the transverse injection flow field with the pseudo shock wave has been investigated numerically, and the influence of the pseudo shock wave on the supersonic mixing between the fuel and air has been evaluated. The pseudo shock wave is formed by setting a high back pressure at the exit of the channel, and the back pressure ratio is set to be 3.0, 5.0, 8.0, 10.0 and 15.0.

Physical model and numerical approach

Physical model

The test section is a straight channel with a square cross section of 30 × 30 mm, and its length is 290 mm. Hydrogen is injected perpendicular to the test section from a sonic circular orifice 1.0 mm in diameter, positioned on the bottom wall of the section, see Fig. 1. Fig. 1 shows the schematic diagram of the physical model studied in this paper. The injection port is located on the centerline of the wall, 200 mm downstream of the entrance of the channel.

The air properties are set to be a Mach number M_∞ of 3.75, a static pressure P_∞ of 11,090 Pa and a static temperature T_∞ of 78.43 K. The air flows from left to right. The jet flow Mach number M_j is set to be 1.0, with a static temperature $T_j = 249$ K and a jet-to-crossflow pressure ratio $P_j/P_\infty = 10.29$. These parameters are the same as those set by Aso et al. [33]. A Cartesian coordinate system, with its origin at the center point of the jet orifice, see Fig. 1, is employed to represent the predicted results, where the streamwise direction is along the *x* axis, the direction of injection is along the *y* axis, and the spanwise direction is along the *z* axis. In order to evaluate the effect of back pressure on the supersonic mixing process between the air and fuel, a high back pressure is provided at the exit of the channel, and the back pressure ratio (P_b/P_∞) is set to be 3.0, 5.0, 8.0, 10.0 and 15.0.

Numerical approach

The steady state computational data have been generated using FLUENT version 6.3.26, and the mesh generation has used the commercial software Gambit [34]. A Dell workstation at Science and Technology on Scramjet Laboratory, using up to 32 processors, has provided a parallel computing environment for flow solutions.

For this study, the three-dimensional Reynolds-average Navier–Stokes (RANS) equations have been solved using a coupled, implicit, second-order upwind solver, and it is a steady-state model. Cell fluxes have been computed using

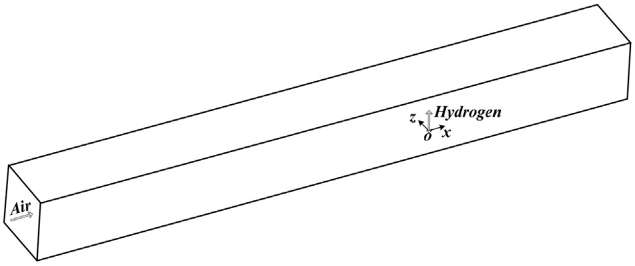

Fig. 1 – Schematic diagram of the transverse injection flow field with the pseudo shock wave.