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Molecular weight and injector configuration effects on the transverse injection flow field properties in supersonic flows

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A B S T R A C T

The transverse injection flow field in the high speed conditions is more complex than that in the low speed, and more information should be explored to improve the overall performance of the airbreathing hypersonic propulsion system. The three-dimensional Reynolds-averaged Navier–Stokes (RANS) equations and the two equation SST k–ω has been employed to explore the influences of the molecular weight (hydrogen and nitrogen) and injector configuration (circular, square, diamond and equilateral triangular) on the mean flow field properties in the transverse injection strategy, and the wide range of the jet-to-crossflow pressure ratio (4.86, 10.29, 17.72 and 25.15) has been considered as well. The obtained results show that the low jet-to-crossflow pressure ratio can promote the mixing process between the injectant and the supersonic crossflow irrespective of the injectant species and the injector configuration, and the large molecular weight of the injectant can promote the mixing process as well when the jet-to-crossflow pressure ratio is fixed. The case with the equilateral triangular injector owns the highest mixing efficiency in the range considered in the current study, and it may be induced by the remarkable influence of the counter-rotating vortex pair. The injectant mole fraction decreases more rapidly with the increase of the streamwise distance for the case with the low jet-to-crossflow pressure ratio, and the jet plume spreads in the spanwise direction more rapidly for the case with the diamond injector irrespective of the injectant species.

1. Introduction

The mixing process between the injectant and the supersonic airstream is one of the crucial issues for the design of scramjet engine, and it has attacked an increasing attention worldwide [21, 4]. This is mainly induced by the very short residence time for the injectant in the supersonic flow [9]. Thus, lots of fuel injection strategies have been proposed in the past few years, i.e. transverse injection [8], strut [10], cavity [2], cantilevered ramp injector [13], et al. However, the transverse injection from a wall orifice has been proved to be one of the simplest and most promising configurations for the scramjet engine, and many experimental and numerical studies have been performed for this strategy. Mahesh [17] reviewed the fundamental understanding of transverse jets in both incompressible and compressible regimes, and he has deduced that more quantitative information should be available at high speeds.

Recently, the parametric analysis on the supersonic flow has become a hotspot for the hypersonic airbreathing propulsion system [12], and this is the fundamental step for the optimization process in the supersonic mixing and combustion flow field. As stated by Huang and Yan [8], the injector configuration is one of the most important aspects for the mixing improvement in the supersonic crossflow. Gruber et al. [7] compared the transverse injection flow field properties with a freestream Mach number being 2.0, and they stated that the injector configuration has only a slight impact on the transverse penetration in the near field. However, the lateral spreading of the elliptical injector is greater than that of the circular one.

The flow field characteristic comparison for the circular- and elliptic-shaped injector was carried out numerically by Wang et al. [28], and they found that the jet maximum penetration in the elliptic injection is lower than that in the circular injection. This conclusion is somewhat different from that obtained by Gruber et al. [7]. Additionally, the penetration band in the elliptic injection is narrower than that in the circular injection, and the elliptic injector spreads rapidly in the spanwise direction.

Srinivasan and Bowersox [24,16] gave a detailed characteristic comparison of the shock and vortex structures for diamond- and circular-shaped injectors, and they observed that a lateral counter-rotating vortex pair is only generated in the flow field with the diamond injector, and it acts as a gas-dynamic flame holder. At the same time, the large scale structures in the plume/wake region

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of the flow field are more organized in the case with the diamond injector. Further, Bowersox et al. [3] examined the near-field flows for the diamond- and circular-shaped injectors experimentally, and they found that the circular injector can induce larger total pressure loss. Tomioka et al. [27] investigated the supersonic combustion flow field with the diamond injector, and the obtained results show that the ability to attain ignition and mode-transition is weaker for the diamond injector.

At the same time, the molecular weight of the injectant has a great impact on the mean flow field characteristics as well, and Schetz et al. [20] found that larger molecular weight can increase penetration. However, its effect is weak. Watanabe et al. [29] examined a wider range of injectant, namely hydrogen, helium, nitrogen and ethylene, and they observed that the hydrogen jet can obtain higher mixing efficiency than the ethylene jet for the studied injection conditions.

However, to the best of the authors' knowledge, the effects of the molecular weight and injector configuration have not been investigated synchronously, and they both have a great impact on the mean flow field properties for the transverse injection. At the same time, the influence of the injector configuration has rarely been studied in detail, especially the wider range of the injector geometric configuration, and the flow field properties for the different injector configurations are not clear. This deficiency is not of benefit to the improvement of the overall performance in scramjet engines.

For more in-depth understanding the mean flow field properties in the transverse injection strategy, especially the molecular weight and injector configuration effect, the influences of the molecular weight and the injector configuration on the transverse injection flow field properties have been explored numerically in this article, and the effect of the jet-to-crossflow pressure ratio has been carried out as well. The jet-to-crossflow pressure ratio is set to be 4.86, 10.29, 17.72 and 25.15, and this is the same as that employed by Aso et al. [1].

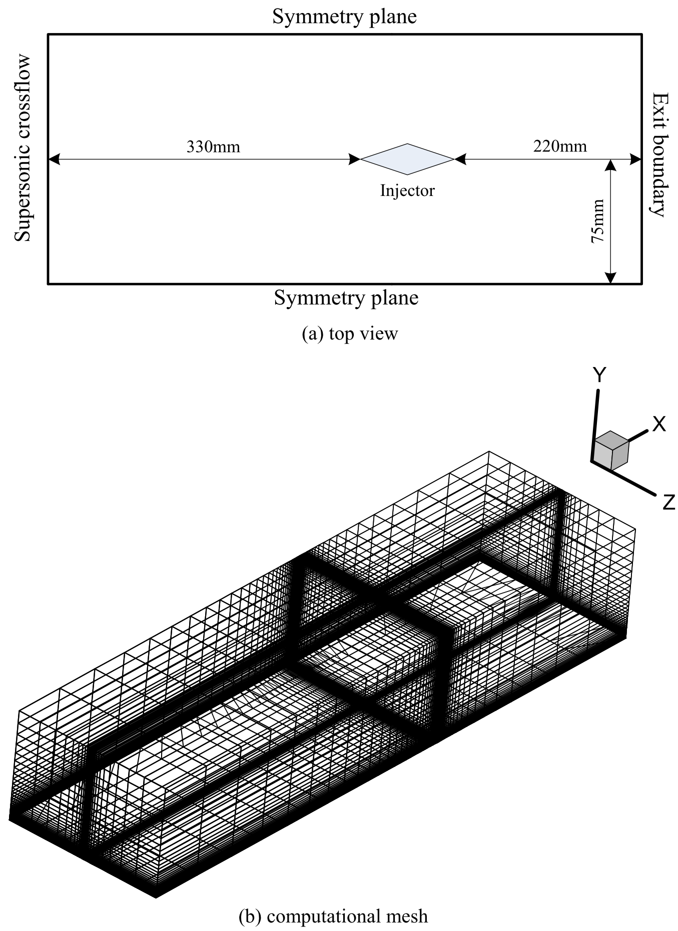

Fig. 1. The sketch for the transverse injection computational domain.

2. Physical model and numerical method

In the current study, four injector configurations are chosen to inject the injectant into the supersonic crossflow, namely the circular port, the equilateral triangular port, the square port and the diamond port, and the area of the injector maintains the same, namely $S = 0.3927\ \text{mm}^2$, and the other dimensions can be observed in Fig. 1(a). Fig. 1(a) depicts the top side of the transverse injection computational domain, and the origin is located at the intersectional point between the symmetrical plane and the entrance boundary for the computational domain. The wedge-shaped injector has been selected as one of the basic injector configurations because it can avoid the occurrence of the boundary layer separation ahead of the injection port [26,19]. Srinivasan and Bowersox [23] found that two new vortex features exist in the vicinity of the diamond injector, namely one located near the leading edge of the injector and the other located just downstream of the barrel shock wave. At the same time, the hydrogen and nitrogen are chosen as the injectant to explore the influence of the molecular weight on the transverse flow field properties.

The supersonic airstream flows from left to right with a freestream Mach number of 3.75, a static pressure of 11 090 Pa and a static temperature of 78.43 K. The jet flow Mach number is set to be 1.0 with a static temperature being 249 K and a jet-to-crossflow pressure ratio being 4.86, 10.29, 17.72 and 25.15. The jet-to-crossflow pressure ratio is proved to be a crucial parameter for the transverse injection flow field properties [30,15,11].

The three-dimensional Reynolds-averaged Navier–Stokes (RANS) equations and the two equation SST k–ω turbulence model has been used to simulate the transverse injection flow field numerically, and the equations are solved along with density based (coupled) double precision solver of FLUENT [5]. The RANS approach is the efficient and rapid method to obtain the mean flow behaviors for the further mixing and combustion optimization in the supersonic flow [22,14], and the SST k–ω turbulence model is suitable to solve the flow fields with adverse pressure gradients [18], especially for the transverse injection flow field [6,25]. The local mass fraction of each species Y_i is predicted through the solution of a convection–diffusion equation for the ith species, and the turbulent Schmidt number is set to be 0.7 [5]. The species are assumed to be ideal gases.

The second order spatially accurate upwind scheme (SOU) with the advection upstream splitting method (AUSM) flux vector splitting is utilized to quicken the convergence speed, and the Courant–Friedrichs–Levy (CFL) number is kept at 0.5 with proper under-relaxation factors to ensure stability [13]. The no-slip conditions are assumed for the walls of the channel. At the outflow, all the physical variables are extrapolated from the internal cells because of the flow being supersonic.

The air is assumed to be a thermally and calorically perfect gas, and the mass-weighted-mixing-law of viscosity is utilized. The solutions can be considered as converged when the residuals reach their minimum values after falling for more than three orders of magnitude, and the discrepancy between the computed inflow and the outflow mass flux is required to drop below 0.001 kg/s.

At the same time, the computational domain is structured by the commercial software Gambit, and the grid is multi-blocked and highly concentrated close to the wall surfaces and the injectant