Influences of Angles of Attack and Sideslip on the Flow Field of a Cantilevered Ramp Injector in Supersonic Flows

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The cantilevered ramp injector has been employed as an effective fuel injection strategy in the shock-induced combustion ramjet engine, and its flow field characteristics have attracted increasing attention. Three-dimensional Reynolds-Averaged Navier-Stokes (RANS) equations coupled with the RNG $k$-$

$ turbulence model have been employed to investigate the flow field of a cantilevered ramp injector in a freestream with a Mach number of 6.0. The effects of the angles of attack and sideslip on the flow field of a cantilevered ramp injector have been studied, and the predicted axial distribution of the maximum injectant mole fraction shows good agreement with the available experimental data in public literature. The obtained results show that the case with an angle of attack $3^\circ$ can promote the mixing process between the fuel and air most efficiently in a typical cantilevered ramp injector. However, it cannot prevent the premature ignition of the premixed combustible flow. The mixing process cannot be promoted when the normalized axial distance is larger than 7.55 in cases with different angles of sideslip, and larger angles of sideslip can reduce the effect of premature ignition for the premixed combustible flow.

Key Words: Aerospace Propulsion System, Cantilevered Ramp Injector, Mixing Enhancement, Premature Ignition, Angle of Attack, Angle of Sideslip

1. Introduction

The cantilevered ramp injector has been employed as an effective fuel injection strategy in the shock-induced combustion ramjet (shramjet) engine, and the shramjet engine is one of the promising propulsion systems for air-breathing hypersonic vehicles. Therefore, the flow field characteristics around the cantilevered ramp injector in supersonic flows have attracted increasing attention worldwide.

Additionally, the scramjet-powered hypersonic vehicle would encounter a serious environment, i.e., the variance of the incoming boundary condition, and this has a great impact on operation of the engine. Thus, an investigation on the effect of the incoming boundary condition on the operation of an engine is important.

Alexander and Sislian conducted a parametric study of the relative locations of fuel injector arrays located on opposing walls in the inlet of a mixed-compression shramjet engine, and a range of mixing efficiencies between 0.459 and 0.681 was obtained. Sislian and Parent performed an investigation on nonreacting hydrogen/air mixing in an external-compression inlet using an array of cantilevered ramp injectors. Parent and Sislian studied the effects of the injector array spacing, injection angle and sweeping angle on the mixing performance of cantilevered ramp injectors. Further, they investigated the influences of the convective Mach number and global equivalence ratio on the mixing efficiency of a cantilevered ramp injector.

From the above review, it is clear that there has been little research on the effect of the variance in incoming boundary conditions on the flow field of the cantilevered ramp injector, and it is necessary and urgent to carry out this investigation.

In the present study, the flow field of a typical cantilevered ramp injector was investigated numerically, and the numerical code was validated by the available experimental data in other literature. Additionally, the effects of the angles of attack and sideslip on the mixing process between the fuel and the air stream in the supersonic flow were studied comprehensively: the angle of attack was set to $-6^\circ$–$8^\circ$, and the angle of sideslip was set to $-4^\circ$–$4^\circ$.

2. Physical Model and Numerical Method

2.1. Physical model

The configuration with a 10° swept angle ($\theta$), a 7° ramp angle ($\beta$) and a step length of 9.75 mm is employed in the current study, see Fig. 1. Figure 1 shows the sectional geometry of the cantilevered ramp injector. The fuel jet slot is 2.7 mm in diameter ($D$), and the height of the ramp ($H$) is 5 mm. These dimensions are the same as those of the experimental model employed by Donohue et al., and the physical model employed in the current study has been modified according to the experimental model of Donohue et al. It is a combination of the ramp and step.

The air flows from left to right at Mach 6.0, the static pressure is 2511.01 Pa and the static temperature is 221.65 K. The fuel is injected from the base of the ramp into the supersonic flow, parallel to the top surface of the ramp,
at Mach 1.7, and with a static pressure of 50.24 kPa and static temperature of 189 K.

2.2. Numerical method

In the current study, three-dimensional Reynolds-Averaged Navier-Stokes (RANS) equations are solved using a density-based (coupled), double-precision solver of Fluent, and the RNG k-ε turbulence model is employed to simulate the flow field around the cantilevered ramp injector. The RANS equations are selected since they can be solved on coarser meshes and permit the simplification of steady flow compared to other numerical methods, and the RNG k-ε turbulence model is preferred due to its low requirements for grid density near the walls.

The equations are solved using a finite-volume integration scheme, and the first-order spatially accurate upwind scheme with the advection upstream splitting method (AUSM) flux vector splitting is utilized to quicken the convergence speed although this may cause a large discrepancy between the numerical results and experimental data in specific regions. The Courant-Friedrichs-Levy (CFL) number is kept at 0.5 with proper under-relaxation factors to ensure stability. Non-equilibrium wall functions are introduced to model the near-wall region flow, and no-slip conditions are assumed for the walls of the channel. At the outflow, all the physical variables are extrapolated from the internal cells due to the flow being supersonic. The air is assumed to be thermally and calorically perfect gas, and the mass-weighted-mixing-law of viscosity is employed. 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 difference between the computed inflow and the outflow mass flux is required to drop below 0.001 kg·s⁻¹. The results obtained by the second-order spatially accurate upwind scheme (SOU) do not obey the convergence criterion proposed in the current study, thus they are not provided here.

At the same time, the computational domain is unstructured by the commercial software Gambit. Because of the symmetry of the region of the cantilevered ramp injector configuration, only half of the region of the flow field is required in order to perform the numerical simulations for the angle of attack performance of the cantilevered ramp injector, and the grid consists of 258,017 cells. However, due to the asymmetry of the flow field with the angle of sideslip, the whole configuration is employed, and the grid consists of 594,177 cells.

The grid is highly concentrated close to the wall surfaces, the fuel inject slot and near the step corners in order to ensure the accuracy of the numerical simulation. The height of the first row of cells is set at a distance of 0.01 mm from the wall, which results in a suitable value of y⁺ for the wall of the flow field. The maximum y⁺ value is 262.3, and this value occurs near the base surface of the ramp on the bottom wall of the combustor. The computational domain is a cuboid surrounded by adiabatic walls at the forward, top and bottom surface, supersonic inlet at the left boundary and the injection slot, an outlet at the right boundary and finally a symmetric condition on the backward boundary, see Fig. 1. Figure 1 depicts the computational boundaries for the whole configuration, and this is used to investigate the influence of the angle of sideslip.

3. Code Validation

In order to investigate the accuracy of the code program, a compression wall-mounted ramp is applied to discuss the code validation, and the experimental model is considered following the experimental work of Donohue et al. This model is similar to that employed in the current study, but the boundary conditions are different. The air flows from left to right at Mach 2.0, and with a static pressure of 33.5 kPa and static temperature of 163 K. The fuel is injected from...
the base of the ramp at Mach 1.7, and with a static pressure of 50.24 kPa and static temperature of 189 K. Three different grid scales are employed to analyze the grid independency in the numerical simulation of the compression wall-mounted ramp: namely, the coarse (148,700 cells), moderate (264,400 cells) and refined (385,200 cells) grids, and the predicted results are compared with the experimental data obtained by Donohue et al.\textsuperscript{11} It is observed that the axial distributions of the maximum injection mole fraction obtained by the RNG $k$-$\varepsilon$ turbulence model match well with the experimental data, with differences mostly confined to specific regions, see Fig. 2. In Fig. 2, the $X$ coordinate is normalized with respect to the height of the ramp. The numerical results obtained by the different grid scales are all slightly underpredicted compared to the experimental data, and the discrepancy increases as the grid cells increase. At the same time, it is obvious that the numerical results predicted by the moderate grid show better agreement with the experimental data than that obtained by the refined grid (see Fig. 2), and there is almost no difference between the moderate and coarse grid results. Therefore, the grid, which consists of 258,017 cells, is employed in the subsequent research, and the number of cells for the whole configuration is 594,177 cells.

4. Results and Discussion

In this section, the effects of angles of attack and sideslip on the flow field of a typical cantilevered ramp injector are discussed comprehensively: the angle of attack is set to $-6^\circ$ to $8^\circ$, and the angle of sideslip is set to $-4^\circ$ to $4^\circ$. The ranges of the angles of attack and sideslip are chosen due to the cantilevered ramp injector being widely employed as an effective fuel injector in the forebody/inlet of the scramjet engine,\textsuperscript{3} and the forebody/inlet would encounter a serious environment when the vehicle is cruising in near-space,\textsuperscript{5} i.e., the variance of the incoming boundary condition.

4.1. Effect of angle of attack

Figure 3 shows a comparison of the axial distributions of the maximum injectant mole fraction for different angles of attack, namely $\alpha = -6^\circ$, $-4^\circ$, $-2^\circ$, $2^\circ$, $4^\circ$, $6^\circ$ and $8^\circ$. In Fig. 1, the angle of attack is positive if the $M$ vector is above the horizontal line. It is observed that the maximum injectant mole fraction is much higher than that with the low incoming Mach number at the same location (i.e., results shown in Fig. 2), and the descending gradients are all smaller than those with the low incoming Mach number. The low incoming Mach number is of benefit to the mixing process in supersonic flows because of the fuel staying in the supersonic flow for only several milliseconds.\textsuperscript{18,20} Meanwhile, the descending gradient of the maximum injectant mole fraction is larger for cases with a negative angle of attack, and this implies that the negative angle of attack has a greater impact on the mixing process than a positive one in this typical cantilevered ramp injector.

However, the distributions of the maximum injectant mole fraction for $\alpha = 3^\circ$ and $\alpha = -3^\circ$ are different from those with other angles of attack (see Fig. 4). Figure 4 shows a comparison of the axial distributions of the maximum injectant mole fraction for these two angles of attack. It is found that the distribution of the maximum injectant mole fraction descends more sharply at $\alpha = 3^\circ$ than the
other positive angles of attack when comparing Fig. 4 with Fig. 3. Additionally, when $X/H > 5.65$, the maximum injectant mole fraction cannot decrease any more. This illustrates that the cantilevered ramp injector with the angle of attack $3^\circ/C14$ is the best choice for the fuel injection strategy in the scramjet engine for the range considered in the current study. Additionally, the distribution of the maximum injectant mole fraction decreases more slowly at $X/C11 = C03/C14$ than other negative angles of attack. This implies that there must be an optimal angle of attack for the cantilevered ramp injector to promote mixing between the supersonic flow and injectant.

In order to illustrate the generation of the phenomenon, the mole fraction profiles of the injectant and streamlines for cases with $\alpha = 3^\circ$ and $\alpha = -3^\circ$ at the planes of $X/H = 0, 3$ and 6, and $Z = 6.76$ mm.

Fig. 5. Mole fraction profiles of the injectant and streamlines for cases with $\alpha = 3^\circ$ and $\alpha = -3^\circ$ at the planes of $X/H = 0, 3$ and 6, and $Z = 6.76$ mm.

decreases more sharply in the core flow when the angle of attack is $3^\circ$. However, the vortices are not formed in the core flow of the channel when the angle of attack is $-3^\circ$ (see Fig. 5(b)). This is influenced by the variation of the boundary conditions imposed on the entrance of the channel. The variation of the boundary conditions may induce large pressure gradient distributions around the cantilevered ramp injector, and this is different from the flow field structure in the experimental model employed by Donohue et al.\textsuperscript{11)} They are generated in the corners of the channel, and they move from the top wall to the bottom wall when the mixing process is carried out further downstream. This may imply that the corner flows suppress the generation of vortices around the injector in the flow field of the cantilevered ramp injector. At the same time, the maximum injectant mole fraction in the centerline is larger than that in the case with an angle of attack of $3^\circ$, and the centerline is the intersectional line between the plane $Z = 6.76$ mm and the symmetrical plane.

Figure 6 shows the static temperature contours and streamlines for cases with $\alpha = 3^\circ$ and $\alpha = -3^\circ$ at the symmetrical plane.
4.2. Effect of angle of sideslip

Figure 7 shows a comparison of the axial distributions for the maximum injection mole fraction of different angles of sideslip. The maximum injectant mole fraction decreases as the angle of sideslip increases. The maximum injectant mole fraction does not decrease any more in the case with different angles of sideslip when $X/H$ is not less than 7.55. This implies that the mixing process cannot be promoted further downstream. This may be caused by the disappearance of the vortices along the axial direction. At the same time, the angle of sideslip makes a slight difference to the distribution of the maximum injectant mole fraction, and the maximum injectant mole fraction distributions are almost the same for the angles of sideslip with the same magnitude.

Figure 8 shows the static temperature contours for cases with $\gamma = 2^\circ$ and $\gamma = 4^\circ$ at the symmetrical plane. We observe that the larger angle of sideslip can reduce static temperature in the region between the cantilevered ramp injector and the bottom wall of the channel. This phenomenon may be induced by the different intensity of the shock wave system. In Fig. 8, $\gamma$ is the angle of sideslip.

5. Conclusions

In this article, the effects of the angles of attack and sideslip on the flow field of a cantilevered ramp injector with a 10° swept angle, a 7° ramp angle and a step length of 9.75 mm were investigated numerically. The angle of attack was set to $-6^\circ$–$8^\circ$, and the angle of sideslip was set to $-4^\circ$–$4^\circ$. We came to the following conclusions:

- The maximum injectant mole fraction distribution of the compression wall-mounted ramp predicted shows good agreement with the experimental data, and the grid with 258,017 cells is suitable for this investigation.
- There exists an optimal angle of attack for the mixing process between the fuel and air in this typical cantilevered ramp injector, and its value is 3°. However, the case having the angle of attack of 3° cannot prevent the premature ignition of the premixed combustible flow effectively because of the static temperature in the region between the cantilevered ramp injector and the bottom wall of the channel being larger than the auto-ignition temperature of the hydrogen.
- The mixing process cannot be promoted when $X/H$ is larger than 7.55 in the case of different angles of sideslip, and the angle of sideslip makes a slight difference in the distribution of the maximum injectant mole fraction. Meanwhile, the larger angle of sideslip can reduce the effect of premature ignition for premixed combustible flow.

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