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Effect of jet-to-crossflow pressure ratio arrangement on turbulent mixing in a flowpath with square staged injectors

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HIGHLIGHTS

- The effect of jet-to-crossflow pressure ratio arrangement on turbulent mixing is analyzed.
- Higher jet-to-crossflow pressure ratio for the primary injector is better for mixing improvement.
- Cases with jet-to-crossflow pressure ratio of injector 3 being larger than that of injector 4 induce mixing improvement.
- The highest mixing efficiency is 73.6% in the location just downstream of the last injector.

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ABSTRACT

The rapid fuel–air mixing enhancement is one of the important issues for the efficient operation of scramjet engines, and it attracts an increasing attention all over the world. The influence of jet-to-crossflow pressure ratio arrangement on the turbulent mixing in the staged transverse injection flow field has been investigated numerically, and the multiport injection system with four square-shaped portholes arranged in tandem has been employed as the simplest configuration in the current study. The numerical approach 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 show that the larger jet-to-crossflow pressure ratio of the primary injector is beneficial to the mixing improvement irrespective of the arrangement of the other jet-to-crossflow pressure ratios, and the evolution of the vortex structure keeps nearly the same irrespective of the jet-to-crossflow pressure ratio of the primary injector. When the jet-to-crossflow pressure ratio of the injector 3 is larger than that of the injector 4, it is beneficial to the evolution of the vortex structure, and this would induce the mixing improvement, as well as the flame holding ability. The largest mixing efficiency is 73.6% at the cross-sectional plane $x = 340$ mm just downstream of the last injector in the range considered in this article.

1. Introduction

The maximization of rapid fuel–air mixing is one of the essential issues for the efficient operation of scramjet engines, and this is due to the very short residence time of the order of 1 ms for the combustion process at supersonic speeds [1]. In the past few decades, many mixing augmentation devices have been proposed [2], and the transverse injection scheme has been commonly utilized to enhance the mixing process between the fuel and air in supersonic flows for its simplest application. Recently, some novel injector configurations have been proposed to improve its mixing efficiency, namely the diamond- [3–8], sting- [9] and chevron-shaped [10] injectors, and the information in the transverse injection flow field has been optimized and explored as well [11,12]. This implies that the efficiency of the transverse injection device is influenced by many factors, i.e. molecular weight of the injectants [13], injection angle [14,15], slot width [16], etc., and it is a multi-variable problem in the engineering.

Recently, Huang and Yan [17] provided a detailed review on the influencing factors for transverse injection flow fields, namely jet-to-crossflow pressure ratio, injector configuration, number of injectors, and injection angle. In this review, they have stated clearly that the staged injection system with diamond-shaped injectors is more beneficial to the mixing enhancement for the low jet-to-crossflow momentum flux ratio, but the flow field properties with high jet-to-crossflow momentum flux ratio need to be explored.

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Lee [18] performed the investigation on the mixing characteristics of a dual transverse injection system numerically, and the dual injection system is proved to own a higher mixing rate and a higher penetration but have more loss of stagnation pressure than the single injection one. Takahashi et al. [19] investigated the advantages of two-staged injection system in terms of penetration and mixing by using the extended fluorescence ratio technique, but the diameters of the primary and secondary jets are different, as well as molecular weight of the injectant. They found that the staged-injection is useful to increase the penetration height, but it cannot provide significant advantage in mixing. An array of smaller secondary injectors were utilized to reduce the nose-down pitching moment and increase the normal force for present-day jet thruster configurations, and this advantage is induced by the reduction in both size and intensity of the low-pressure region downstream of the primary injector [20]. Pudsey et al. [21] studied the film-cooling drag reduction performance and potential for improved boundary-layer combustion conditions by using a multiport injector array system, and significant reductions in skin friction of between 37% and 60% over a 500 mm plate length are obtained. Huang [22] analyzed the influences of the injection angle, the injection angle arrangement, and the distance between the injectors on the two-dimensional flow field properties of the staged injection scheme numerically, and he found that the multiport injection scheme can provide better fuel penetration performance than the single one when the flow flux remains constant.

To the best of the author's knowledge, the interaction mechanism between the injection fluids makes a great difference to the flow field variation in the transverse injection scheme, as well as the mixing and penetration performance improvement. However, the influence of the jet-to-crossflow pressure ratio arrangement on its turbulent mixing has not been investigated in the open literature, and it is important for the operation of the scramjet engine.

In the current study, the influence of the jet-to-crossflow pressure ratio arrangement on the turbulent mixing has been investigated numerically, and the jet-to-crossflow pressure ratio is set to 4.86, 10.29, 17.72, and 25.15. The combustion process is not within the scope of this article, and it would be carried out in the near future. Accordingly, the multiport injector system with four square-shaped portholes has been employed. The physical model for the transverse injection system and numerical approach have been briefly introduced in Section 2, and Section 3 has presented the validation process for the numerical method employed. The effect of the jet-to-crossflow pressure ratio arrangement on the turbulent mixing has been analyzed in detail in Section 4, and some conclusions have been provided in the last section.

2. Physical model and numerical method

2.1. Physical model

In the present work, the multiport injection system with four square-shaped portholes arranged in tandem has been investigated as the simplest configuration, see Fig. 1, and the jet-to-crossflow pressure ratios of the portholes are set to be different from each other, see Table. 1. Fig. 1 represents the top view of the staged transverse injection computational domain, and the supersonic airstream flows from left to right in all cases studied. Table. 1 shows the jet-to-crossflow pressure ratio arrangements for the cases employed in the current study, and there are totally 24 cases studied in this article.

Table 1

Jet-to-crossflow pressure ratio arrangements for the cases employed in the current study.

	Injector 1	Injector 2	Injector 3	Injector 4
Case 1	4.86	10.29	17.72	25.15
Case 2	4.86	10.29	25.15	17.72
Case 3	4.86	17.72	10.29	25.15
Case 4	4.86	17.72	25.15	10.29
Case 5	4.86	25.15	10.29	17.72
Case 6	4.86	25.15	17.72	10.29
Case 7	10.29	4.86	17.72	25.15
Case 8	10.29	4.86	25.15	17.72
Case 9	10.29	17.72	4.86	25.15
Case 10	10.29	17.72	25.15	4.86
Case 11	10.29	25.15	4.86	17.72
Case 12	10.29	25.15	17.72	4.86
Case 13	17.72	4.86	10.29	25.15
Case 14	17.72	4.86	25.15	10.29
Case 15	17.72	10.29	4.86	25.15
Case 16	17.72	10.29	25.15	4.86
Case 17	17.72	25.15	4.86	10.29
Case 18	17.72	25.15	10.29	4.86
Case 19	25.15	4.86	10.29	17.72
Case 20	25.15	4.86	17.72	10.29
Case 21	25.15	10.29	4.86	17.72
Case 22	25.15	10.29	17.72	4.86
Case 23	25.15	17.72	4.86	10.29
Case 24	25.15	17.72	10.29	4.86

In Fig. 1, the space between the injectors is the same, and it remains constant, namely $s = 2.5569$ mm. The length of the square-shaped porthole is 0.4431 mm. The distance from the entrance of the channel to the leading edge of the primary injector (L_1) is 330 mm, and that from the trailing edge of the last injector to the exit boundary of the channel (L_2) is 211 mm. The width of the computational domain is 150 mm, namely $w = 75$ mm in Fig. 1, and its height is 100 mm.

The 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. These conditions are the same as those employed by Aso et al. [23], and the jet-to-crossflow pressure ratio for each injector can refer to Table. 1.

2.2. Numerical method

The three-dimensional Reynolds-averaged Navier–Stokes (RANS) equations and the Menter's shear stress transport (SST)

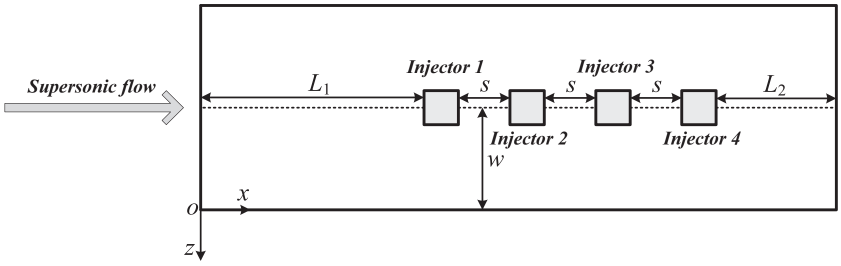

Fig. 1. Top view of the staged transverse injection computational domain.