International Journal of Heat and Mass Transfer 124 (2018) 109–123

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Mixing improvement induced by the combination of a micro-ramp with an air porthole in the transverse gaseous injection flow field

Lang-quan Li [a,b], Wei Huang [a,*], Li Yan [a], Shi-bin Li [a], Lei Liao [a]

[a] Science and Technology on Scramjet Laboratory, National University of Defense Technology, Changsha, Hunan 410073, People's Republic of China
[b] Hypervelocity Aerodynamics Institute, Chinese Aerodynamics Research and Development Center, Mianyang 621000, People's Republic of China

ARTICLE INFO

Article history:
Received 22 January 2018
Received in revised form 1 March 2018
Accepted 17 March 2018

Keywords:
Transverse injection
Micro-ramp
Air porthole
Mixing length
Penetration depth
Stagnation pressure loss

ABSTRACT

A new injection strategy combined with a micro-ramp and an air porthole is proposed in this paper, and the properties of the transverse gaseous injection flow field with such injection strategy have been investigated simultaneously. The numerical approach employed in the current study has been validated against the two-dimensional and three-dimensional experimental data in the open literature, and it can be used with confidence to investigate the influence of the air porthole aspect ratio and the distance between the air porthole and the fuel orifice on the transverse injection flow field with the combination of a micro-ramp and an air porthole. The obtained results predicted by the three-dimensional Reynolds-average Navier–Stokes (RANS) equations coupled with the two equation k-ω shear stress transport (SST) turbulence model show that the mixing performances of the transverse gaseous injection flow fields vary under different conditions, and a transverse injection flow field with short mixing length, low stagnation pressure loss and ideal fuel penetration depth has been achieved by adding the combination of an optimized micro-ramp with a proper air porthole, i.e. Case 6–8, and its mixing length decreases considerably by 14.26 mm on the basis of Case c, even shorter than the mixing length of Case a by 2.86 mm. However, its total pressure loss increases when compared with Case c, and its stagnation pressure loss is 2.7 percent smaller than Case a. Further, the hydrogen distribution on the flat plate of Case 6–8 is much less than that of Case a and Case b. Additionally, it is found that the mixing enhancement mechanism of the air jet is different from that of the micro-ramp. The micro-ramp enhances the mixing process between the fuel and air by inducing large-scale vortices, while the air porthole enhances the mixing process by seeding lots of air into the fuel boundary layer, as well as fuel plume.

1. Introduction

The scramjet (supersonic combustion ramjet) engine is one of the most promising propulsion systems, and it produces power for hypersonic vehicles [1]. These engine cycles take air from the atmosphere, and an oxidizer tank is not required. In addition, the scramjet engine owns the advantages of simple structure, high efficiency, and reusable use. Therefore, utmost importance has been attached to it in recent decades [2–5]. Due to the supersonic airflow from combustor inlet and a limited combustor length, the residence time of the injectant within a scramjet combustor is on the order of milliseconds for typical flight conditions [6], and mixing and combustion process takes place nearly simultaneously [7]. It is therefore difficult to obtain a stable and efficient combustion flow field in a scramjet engine. The mixing process is the initial phase for all the physical ones, and it is the primary factor to restrict the combustion process [8,9]. Hence, the sufficient mixing relates to the overall performance of the airbreathing hypersonic propulsion system, and an efficient injection strategy with rapid mixing, high penetration and low stagnation pressure loss is required.

The transverse fuel injection though a wall orifice has been proved to be a simple and reliable fuel supply approach for the scramjet engine [10,11], and it provides rapid fuel-air mixing and high jet penetration into the supersonic airflow [12]. In the early stage of the transverse injection flow field investigations, A great many of studies concentrated on a single transverse jet flow field at a variety of conditions, and its performance is determined by many design variables, including jet-to-crossflow pressure ratio [13,14], jet-to-crossflow momentum flux ratio [15], molecular weight [16], injector geometry [17], injection angle [18] and incoming air streaming angle [19]. Subsequently, a variation on the traditional single jet is the multiple transverse injection system

* Corresponding author.
E-mail address: gladrain2001@163.com (W. Huang).

https://doi.org/10.1016/j.ijheatmasstransfer.2018.03.061
0017-9310/

[20–27], and the complication of an efficient injection system setup arises due to more parameters, such as distribution 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 [25]. The transverse injection flow field with a multiple transverse injection system owns better mixing characteristics than those of a single transverse injection system due to the interaction among the injection flows. However, both the multiple and single fuel injection systems have some serious disadvantages, especially the highly inadequate penetration depth. Because of highly inadequate penetration, the transverse injection seeds lots of injectant into the boundary layer, leading to a phenomena known as flashback in the combustor [28].

Recently, a creative injection strategy has been proposed by Barzegar [29–33]. 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 effects of air jets on the mixing performances of the transverse gaseous injection flow fields vary under different conditions. In addition, when the air jet is presented downstream of the fuel jet, a significant increase occurs in the mixing performance of the hydrogen jet. Based on these research results, the dual transverse injection system with a front fuel porthole and a rear air porthole arranged in tandem was employed and investigated numerically by Li and his co-workers [34] in terms of variations in the aspect ratio of the air porthole in a parametric study, and the air pothole has a highly remarkable improvement on the mixing efficiency, especially in the near field. Further, the hydrogen distribution on the bottom of the flow field with the air jet is less than that of the flow field with a single fuel jet, whether the penetration depth increases or decreases by the air jet relative to the single jet. These indicate that the air jet leads to the increased efficiency in fuel-air mixing, as well as a minimization of the scramjet combustor wall heating. Such advantages of the air jet should be taken into favorable consideration.

On the other hand, in a bid to improve the performance of supersonic transverse jet flow field, various devices, such as strut [35–38], ramp [39], pylon [40], cavity [41–43], aerodynamic ramp [44] and any other combination, have been proposed. Seiner et al. [45] reviewed the approaches to improving the mixing efficiency of the fuel and the supersonic freestream in the scramjet engine, and they pointed out that the ramp injector is one of the most promising candidates. The supersonic flow over a ramp induces a pair of counter-rotating streamwise vortices, and these can increase fuel/air contact area and enhance mixing. Moreover, the low-momentum wake flow due to the blocking of the ramp provides an ideal condition to increase the penetration depth of the wall orifice behind the ramp. Wilson et al. [46] placed the jet orifice in the front of the ramp to enhance the penetration by the inclined ramp surface. The influence of the position of the micro-ramp relative to the jet orifice on the flow field was investigated by Zhang and his research partners [47], and it is found that the micro-ramp can improve the penetration depth obviously, while placing the jet orifice downstream the micro-ramp, due to the low freestream momentum in the ramp wake. At the same time, the effect of the distance between the micro-ramp and the jet orifice behind the micro-ramp was studied, and the results show that there exists an optimum distance between the micro-ramp and the jet orifice to enhance the mixing and improve the fuel penetration [48]. The effects of the delta wing height and the jet-to-crossflow pressure ratio were investigated numerically by Li and his co-workers [49]. In the case of higher values of delta wing height and jet-to-crossflow pressure ratio, higher penetration and more stagnation pressure loss are shown, and there is an optimum height of the delta wing for each jet-to-crossflow pressure ratio to achieve the maximization of rapid fuel/air mixing. The ramp enhances mixing and penetration substantially, but at the expense of a larger pressure loss, increasing drag forces, and inciting considerable local heating loads [50].

A novel slotted ramp-type micro vortex generator for flow separation control was proposed by Dong et al. [51] in 2017. The slot of the micro-ramp induces the additional vortices which can mix with the primary counter-rotating vortex pair, extend the life time, and strengthen the vertex intensity of primary vortex pair. Moreover, the slot can effectively alleviate, or even eliminate the backflow and decrease the profile drag induced by the standard micro-ramp. In 2018, four design parameters of the micro-ramp were taken into account by Li and his co-workers [52], and the extreme difference analysis was utilized to analyze the transverse injection flow field with a micro-ramp. At last, three optimization cases were obtained, namely Case a, Case b and Case c, corresponding to three different objectives respectively, i.e. the minimization of the mixing length, the maximization of the penetration depth and the minimization of the stagnation pressure loss. Table 1 statistics the geometric parameters of the three optimization cases, as well as their objective values. The mixing length, penetration and stagnation pressure of different configurations are illustrated in Fig. 1. It is obvious that the objective performance parameter value of each optimization case is superior to that of other cases. Since a larger scale of the counter-rotating vortex leads to more intense convection, but more stagnation pressure loss in the transverse injection flow field with a upstream micro-ramp and the fact that the mixing process is largely depended on flow convection in the near field, the stagnation pressure loss shows opposite trends from mixing length with a variance in geometric parameters and position of micro-ramp to a certain extent. This means that it is impractical to realize further improvement of both the stagnation pressure loss and the mixing length performance of the transverse injection flow field with a micro-ramp by only optimizing the geometric parameters of the micro-ramp.

As mentioned above, the air jet has a highly remarkable improvement on the mixing efficiency, especially in the near field. Moreover, the air porthole does not have physical obstruction to the combustor flow in compassion with other mixing enhancement devices, so the stagnation pressure loss induced by the air jet is small. By taking the micro-ramp in Case c whose geometric parameters were optimized for the minimization of the stagnation pressure loss as the objective and the advantages of the air jet into consideration, a new injection strategy combined with a micro-ramp and an air porthole is proposed in this paper. The micro-ramp of Case c is placed in the front of the fuel porthole to provide an ideal condition for increasing the fuel penetration depth, and the weakening of the mixing enhancement capability of the micro-ramp resulting from the optimization of its geometric parameters for the minimization of the stagnation pressure loss will be repaired by the air porthole placed downstream of the fuel porthole. Therefore, a better transverse injection flow field with short mixing length, low stagnation pressure loss and ideal fuel penetration depth may be achieved. To the best of the authors' knowledge, the combination of a micro-ramp with an air porthole in the transverse gaseous injection flow fields and the influences of the aspect ratio of the air porthole and the distance between the fuel orifice and the air porthole on the transverse injection flow field have rarely been investigated simultaneously in the open literature, and this issue is crucial for the design of the injection strategy in the scramjet combustor.

In the current study, the transverse injection flow fields in a Mach 3.75 crossflow of air have been investigated numerically, and the numerical approaches are validated by the available exper-