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Mixing augmentation induced by the interaction between the oblique shock wave and a sonic hydrogen jet in supersonic flows

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ABSTRACT

The mixing process between the injectant and air is very important for the operation of scramjet engine, and the injectant and air should be mixed sufficiently before entering into the combustor. The three-dimensional Reynolds-average Navier–Stokes equations coupled with the SST k–ω turbulence model have been employed to investigate the interaction of the oblique shock wave and the hydrogen jet, and the influence of the wedge angle has been taken into consideration, namely the intensity of the produced oblique shock wave, as well as the jet-to-crossflow pressure ratio. In this paper, the produced oblique shock wave collides with the bottom wall upstream and downstream of the jet orifice with the variance of the wedge angle. The obtained results show that the incident shock wave makes a great difference to the mixing enhancement between the injectant and air, and there exists a critical value of the wedge angle for the scramjet engine with a certain boundary condition. This value is 20° in the range considered in the current study, and the hydrogen is brought into the separation zone upstream of the jet orifice when the wedge angle is 20°. At the same time, the produced oblique shock wave nearly collides with the Mach disk produced by the hydrogen jet.

1. Introduction

The organization of the mixing and combustion process is crucial for the flowpath design of the scramjet engine, and the injectant and air should be mixed sufficiently before entering into the combustor. In the past few years, many injection devices have been proposed to improve the mixing between the injectant and air, especially the cantilevered ramp injector located in the forebody/inlet of the scramjet engine [1], and Seiner et al. [2] gave a detailed summary on this topic.

Transverse injection from a wall orifice is one of the simplest and most promising configurations to enhance the mixing process between the injectant and air in supersonic flows [3], and it attracts an increasing attention since the early sixties [4], especially on some scramjet powered vehicles [5]. Huang and Yan [6] provided a survey on the transverse injection from four aspects, namely the jet-to-crossflow pressure ratio, the injector configuration, the injector number and the injection angle, and the two-dimensional transverse jet flow field was optimized by the non-dominated sorting genetic algorithm (NSGA II) coupled with the Kriging surrogate model [7]. The effect of the turbulence model on the flow field properties was tested as well [8]. Mahesh [9] reviewed the fundamental understanding of the physical behavior of single-phase, nonreacting transverse jets in incompressible and compressible regimes.

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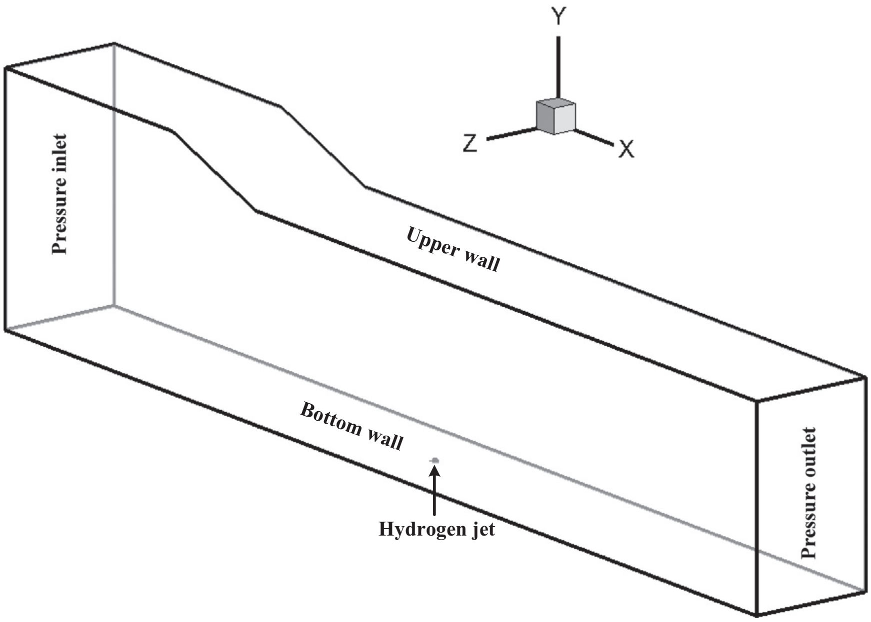

Fig. 1. A sketch of the interaction between the incident shock wave and the hydrogen jet.

In order to enhance the mixing process between the injectant and air, the influence of the injector configuration has been evaluated by many researchers [10–14], as well as the staged injection strategy [15,16]. Lee and Mitani [17] proposed a method to promote the streamwise vorticity by modifying the injector geometry using a cavity to increase the mixing rate, as well as the fuel penetration property, but additional loss of stagnation pressure was induced. The fuel was injected inside the cavity to improve the mixing process between the injectant and air as well [18]. The pylon was adopted by Lee [19] to enhance the mixing performance in the transverse injection flow field.

Recently, the interaction between the incident shock wave and the transverse jet has attracted an increasing attention [20–24], and an enhanced mixing level can be achieved with an increased residence time when an incident shock wave impinges close to the transverse jet injection location [25]. Thus, it is necessary to evaluate the influence of the incident shock wave on the mixing process in the transverse injection flow field. However, this information is rare and not comprehensive, and the three-dimensional interaction between the oblique shock wave and the boundary layer on the mixing enhancement between the injectant and air in supersonic flows has not been evaluated by the authors. Especially, the effects of the intensity of the produced oblique shock wave and the jet-to-crossflow pressure ratio have not been considered simultaneously, and they would have an impact on the mixing process between the injectant and air.

In this paper, the mixing enhancement induced by the oblique shock wave has been evaluated numerically, and the oblique shock wave has been obtained by a wedge with angle of 10°. Meanwhile, the wedge angle is varied to analyze the effect of the incident shock wave intensity on the mixing process, and its additional values are 20° and 30°. Further, the influence of the jet-to-crossflow pressure ratio has been evaluated as well, and its value is set to be 4.86, 10.29, 17.72 and 25.15. The variation of the combustion process induced by the oblique shock wave has not been considered in the current study, and it would be conducted in the near future.

2. Physical model and numerical approaches

2.1. Physical model

To produce the incident shock wave, a wedge with angle of 10° is utilized at the upper wall of the channel, see Fig. 1, and this is the same as that employed by Shekarian [23] and Tahsini [24]. Fig. 1 depicts a sketch of the interaction between the incident shock wave and the hydrogen jet, and the produced shock wave collides with the bottom wall downstream of the injection port in order to enhance the mixing process [24]. At the same time, the wedge angle is varied to evaluate the influence of incident shock wave intensity on the mixing process between the air and fuel, and the additional wedge angles are set to be 20° and 30°. The length, width and height of the channel are 90 mm, 10 mm and 20 mm, and a circular jet orifice is located at the center of the channel, namely its coordinate is (45, 0, 5). The diameter of the jet orifice is 0.5 mm.

At the same time, the effect of the jet-to-crossflow pressure ratio (P_j/P_∞) has been considered as well, and its value is set to be 4.86, 10.29, 17.72 and 25.15. The jet-to-crossflow pressure ratio is defined as the static pressure ratio of injectant and supersonic airflow. 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 hydrogen jet flow Mach number M_j is set to be 1.0 with a static temperature T_j being 249 K.