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Comparison of the single/multi transverse jets under the influence of shock wave in supersonic crossflow

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ABSTRACT

In this study, the effects of the shock wave on sonic transverse hydrogen through single and multi-jets for supersonic combustion were investigated numerically. This study presents the fundamental flow physics of the interaction between fuel jets (single or multi array) and incident shock waves into a Mach 4.0 crossflow. Parametric studies were conducted on the performance of the shock wave by using the RANS equations with Menter's Shear Stress Transport turbulence model. In a parametric study, both the streamwise spacing and jet-to-freestream total pressure ratio are varied. For all downstream mixing, the associated flow behavior was found to be a direct result of both the type of injection (single/Multi jet) and interactions between shock waves and injectors. According to the results, shock wave reduces the maximum concentration of the hydrogen jet more than 20% in both single and multi jet. Furthermore, a significant increase (approximately 40%) occurs in the mixing of the hydrogen jet at downstream when shock generator is presented in the multi jet with PR=0.27. Moreover, hydrogen-air mixing rate extends in streamwise direction as the jet space increases. Thus, an enhanced mixing zone occurs in the in far downstream of the jet and the shock wave.

1. Introduction

Scramjets as next-generation engines are extensively focused by researchers for high-speed flight. Several studies show that airbreathing propulsion systems are efficient systems for high speed flight. Since these engines operate in or beyond the supersonic flight regime, the development of these engines for far distance seems necessary. The performance of these devices is highly related to the good injection and mixing of the fuel in the free stream chamber flow. Furthermore, mixing enhancement is a matter of concern for several other aeronautical applications such as combustion chamber optimization, ejector-thrust augmentation, jet noise and infrared reduction [1–7].

An extensive research effort was developed worldwide on diverse mixing devices [8]. Nonetheless, few solutions have been proposed for conventional transverse jets at supersonic regimes. Shock waves, which are studied here, are a classical means that introduce streamwise vortices to speed up the mixing rate [9–11]. Our goal is to characterize the efficiency of such a device in various conditions. Streamwise vortices have the advantage of being hardly influenced by the compressibility and the highly three-dimensional character [12–14] of the compressible mixing layers. Moreover, multi-jet injection seems more attractive, because it can be easily adapted to the flow conditions; additionally, they are expected to distribute and mixed efficient in downstream. Recent studies investigate single and multi jet under the influence of the shock wave and compare their efficiency on the mixing [3–7].

The significant amount of studies has been available in the field of transverse jet interactions since 50 years ago. The most of this research is focused on the behavior of isolated jets in crossflow: that is jets that are not in close enough proximity to each other as to cause substantial jet-to-jet interaction or coupling behavior. Furthermore, studies in this area typically investigate the complex flow physics induced by the jet, which is most often termed the “jet interaction.” Several applications, including fuel injection, surface film cooling, and control systems have been used jets in crossflow.

During the recent years, many types of injectors have been proposed including in-stream, hypermixers and wall porthole micro injectors, each with their respective profits [15,16]. The work reported here investigates both porthole injectors and single

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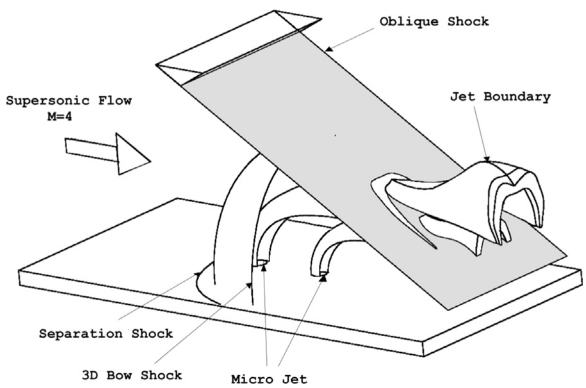

Fig. 1. Schematic representation of the flow field features around the transverse micro jet under influence of the oblique shock.

jet. The porthole injector has no physical obstruction to the combustor flow, with a typical reduction in drag and cooling requirements compared with other methods.

Although multi transverse injection has been established to be an efficient scheme for supplying fuel in scramjet's combustor and has been greatly studied by researchers [8–13], little work has been done to understand the fundamental mechanism of the interaction between the incident shock wave and the transverse micro injections [17,18]. Although several investigations revealed detailed understanding of the near field mean flow structure in a single jet-supersonic cross flow [2,4,7], there is little study on mixing of the micro jet under shock wave. The flow structure of the micro jet under effects of shock wave is illustrated in Fig. 1.

The schematic diagram of supersonic freestream with an array of transverse micro jets injected in the presence of shock generator is shown in Fig. 1a. In the flow field, the hydrogen jet released through the array of the micro slots, and the shock wave is produced by the wedge. As hydrogen move to downstream for a long distance and the shock wave affect the structure of the outer flow field.

In our previous studies [17,18] extensive works was performed on the optimum position of the shock generator and the angle of shock on the mixing distribution of fuel jet. The main scope of present study is to compare the effects of interaction between the shock wave and jet injected through a single and transversal array of micro jet on fuel-air mixing rate and flame holding. It has been done by investigation of three dimensional flow structure and recirculation zones. Also, various jet conditions (Pressure Ratio) are investigated and revealed the effects of each on mixing and dispersion of hydrogen micro jet in downstream of the flow. In facts, the difference of this technique with single transverse jet over the flat plate is investigated. Moreover, this work studies the influence of the space of micro transverse jets on the mixing and distribution of hydrogen gas in a downstream of the high speed free stream.

The flow structure is numerically simulated by solving the three-dimensional Reynolds-Averaged Navier–Stokes equations. The numerical code incorporates real gas effects and turbulence model for numerical simulation. The numerical solution is first validated with experimental data for a micro jet injected into the supersonic cross flow, and is injected into a turbulent supersonic flow over a flat plate.

2. Numerical approach

2.1. Geometry and grid

This investigation focuses on the injection of a hydrogen jet through single and/or an array of micro injector cross to the free stream flow on a flat surface. The main size of model is the 52 mm-wide, 25 mm-high semi direct-connect nominally two dimensional scramjet combustion chamber used by O'Byrne et al. [19] with a typical reference one-jet case consisting of a single spanwise row of four 2 mm-diameter injector ports. The computational domain selected for the present simulation is a small region along the center of the engine in the vicinity of the injector ports, and employs local symmetries in order to reduce computational expense.

A wedge shock generator was used to produce the shock wave. The supersonic flow impinges upon the shock generator to produce an oblique shock wave. Fig. 2a shows the geometry with the shock wave generator. The flows were analyzed with wedge angles θ of 30 exactly upon first jet. The wedge shock wave generator base was 2 mm long. The whole channel was 0.1 m long with 0.01 m height and 0.00153 m width as it is shown in Fig. 2a. The same geometry without the shock wave generator was also used to study the flow without the shock wave.

As previous studies [15,16] investigated effects of multi jets, the computations for each case will not retain a constant fuel mass flow, but rather the overall scramjet fuel mass flow will remain constant. It was therefore necessary to use an additional parameter that would allow geometric comparison of the Multijet to single jet case, taking this into consideration. The parameter of choice is the equivalent jet diameter which is the representative single jet diameter based on the sum of the area of the multi-jet injectors for a given streamwise row. The required equation is given as

$$d_j^* = \sqrt{\frac{4\sum A_j}{\pi}} \tag{1}$$

where A_j is the sum of the areas of each individual jet in the multijet streamwise row. In the present study, the influence of the shock wave on mixing of the hydrogen jet through array of four micro jets is extended compared to the single jet. Thus, the equivalence 4 micro jet diameter of single jet (with 1 mm diameter) is 0.5 mm with Eq. (9) [15]. Moreover, three streamwise injector spacing ($4d_j$, $7d_j$ and 10 d_j) has been investigated for multi-jet condition.

In the present configuration, the complex multi-jets interactions occur close to the wall and completely within the boundary layer. Very fine meshes were required to adequately resolve the flow features and, therefore, the problem was broken down into three separate computational domains to work within the constraints of available computational resources, as shown in Fig. 2a.

Grids were constructed using a fully structured approach in all three dimensions. Cell refinement was achieved manually in the region immediately adjacent to each outlet of micro jet and, in the wall normal direction, the cells were arranged such that the distance from the wall to the first cell centroid provided a Y^+ of approximately 1.0. The grid spacing was stretched to the opposite boundary using a hyperbolic tangent function to ensure all regions of the boundary layer and injection flow structures close to the wall were adequately resolved. An example of the grid in the vicinity of an injector is shown in Fig. 2b. Furthermore, close up view of grid in the vicinity of the micro injector and shock generator are displayed in Fig. 2b.

One of the controlling factors of the numerical simulation is the proper grid arrangement. The structure grid points are generated to improve accuracy. Also, an extensive grid refinement study (mesh sizes from 1,084,000, 2,292,000 and 4,722,000) was conducted to determine grid independence in mass distribution to resolve the boundary layers (Fig. 3). The results show that fine grid (2,292,000) has enough precision for the present investigation.