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The influence of micro air jets on mixing augmentation of fuel in cavity flameholder at supersonic flow

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ABSTRACT

In this study, numerical simulations are performed to study the effect of micro air jets on the mixing of fuel in the cavity flameholder of the scramjet. This research mainly focused the optimum position of fuel (C_2H_4) injection on the mixing rate inside the cavity. In order to simulate the cavity flameholder with micro air/fuel jets, a three-dimensional model is chosen and computational fluid dynamic approach is used for the simulations. The effect of significant parameters is studied by using the Reynolds-averaged Navier–Stokes equations with Menter's Shear Stress Transport (SST) turbulence model. In this work, the transient study is also performed to reveal the flow feature and mass distribution inside the cavity in the supersonic free stream ($M = 2.2$). Results show that the injection of the fuel in the middle of the vertical wall significantly enhances the mixing of fuel in the cavity. The obtained results reveal that the injection of micro air jets distributes the fuel uniformly inside the cavity. Therefore, an enhanced mixing zone occurs in the downstream of the injection slots which lead to flame-holding.

1. Introduction

Development of the scramjets (supersonic combustion ramjet) as the most efficient engine for the supersonic flight has been the main goal of the scientists [1,2]. This engine is superior to other engines due to low weight and simplicity. In fact, this type of engine does not have to carry oxygen and no rotating parts make it easier to manufacture than a turbojet. In addition, it has a higher specific impulse (change in momentum per unit of propellant) than a rocket engine; could provide between 1000 and 4000 seconds, while a rocket typically provides around 450 seconds or less. Moreover, higher speed of this engine could mean cheaper access to outer space in the future. However, difficult/expensive testing and development and very high initial propulsion requirements are the main disadvantageous of this engine [3]. These advantages have motivated researchers to increase the efficiency of this engine. Among various issues for improving the scramjets, good mixing of fuel to air is the primary goal for enhancement of this engine. Since the process of ignition occurs very fast in the scramjets, the proper injection of the fuel for the better mixing is highly significant [4–6]. In fact, the mixing of the fuel with air should be enhanced to reduce the fuel consumption and fuel tanks.

Since the mixing of fuel in the air plays a significant role in the performance of the scramjets, several types of research are devoted to recognize the main terms and improve the efficiencies. Several techniques have been developed for increasing the mixing inside the hypersonic engines i.e. ramp [11], aerodynamic ramp [12,13], strut [14], pylon [15,16], and any other combination, as well as the cantilevered ramp injector which has been used as the inlet injection scheme to shorten the length of the combustor [17,18]. Huang reviewed more than 140 research papers on various aspects of transverse jet [19]. We also studied new techniques such as adding shock generator in upstream [20–22] and injecting micro air jets [23–26] to increase the mixing in the downstream of the supersonic jets. We found that injection of micro air jets is an efficient method for the enhancement of the mixing in the downstream. One of the primary configurations inside the scramjets is cavity flameholder and several studies presented significant results on this problem. Gruber et al. [27] studied cavity-based flameholder concepts for supersonic combustors by experimental examinations. They investigated the effect of significant parameters such as aft ramp angles and the length-to-depth ratio of the flow feature of fuel inside the cavity. They found that higher drag coefficients and shorter residence times are established in cavities with shallower ramp angles.

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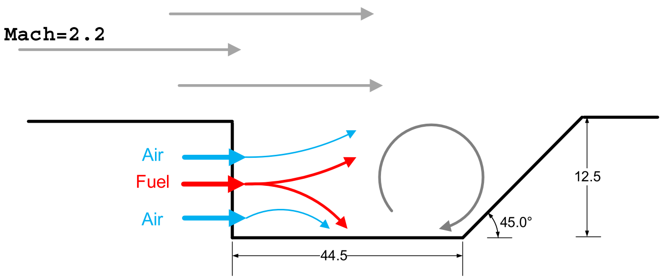

Fig. 1. Schematic representation of the flow field features inside the cavity flameholder.

Hsu et al. [28] primarily explained the role of cavity formation, injection pressure, and imposed back-pressure on the fuel mixing in a scramjet. Ukai et al. [29,30] investigated effects of dual jets distance on mixing characteristics and flow path within a cavity in supersonic crossflow. They also studied the effectiveness of jet location on mixing characteristics inside a cavity in supersonic flow. Huang et al. [31] investigated the effect of geometric parameters on the drag of the cavity flameholder based on the variance analysis method. Although cavity flameholder has been used as an efficient model for supplying fuel in a combustor of the scramjet and it has been prominently examined by researchers [32–35], a little study has been done to improve the mixing inside the cavity. Also, numerous works have focused on the injection of single micro fuel jet in the cavity and there are little studies on mixing of the fuel jet with micro air jets. The flow structure of fuel jet in the presence of the two micro jets is illustrated in Fig. 1.

Previous studies performed various numerical and experimental works to develop the mixing rate and flame holding inside the cavity. Although their works are significant, they have tried to find new techniques for increasing the mixing in this configuration. Our previous studies [24–27] showed that the injection of the micro air jets could significantly increase the mixing in the supersonic flow. Thus, we want to examine the presence of the air jet on the main characteristics of fuel distribution and mixing in this region.

The purpose of this work is to investigate the effects of air jets on fuel–air mixing rate and flame holding inside the cavity flameholder. In order to simulate the flow feature and mass distribution, a computational fluid dynamic method is used to solve the Navier–Stokes equations. Furthermore, extensive parametric studies are performed to reveal the effects of various feed rates of air and ethane (C_2H_4) on the mixing of the fuel. In order to extend the physics of fuel jet inside the cavity, the transient studies are also done and the fuel concentration inside the cavity is compared.

2. Numerical approach

2.1. Geometry and grid

The main geometry of the present study is obtained from the experimental work of Barnes [36]. The main size of the geometry is presented in Fig. 1. The length, height and width of domain are 15 cm, 2 cm and 0.17 cm, respectively. Since the main interactions occur inside the cavity, proper grid should be generated in this section. Fig. 2 illustrates the grid of the domain and presented the close-up view to show the detail of the grid.

2.2. Freestream and boundary condition

The inflow supersonic airstream was chosen to have the stagnation pressure of 2.7 atm, stagnation temperature 300 K and Mach number $M_\infty = 2.2$. Boundary conditions were applied to the freestream inflow (pressure far field); flat-plate wall (no-slip adiabatic zero heat flux); both lateral sides and top plane (symmetry planes); and outflow (pressure outlet equal to ambient pressure); injector inflow (total pressure and temperature respect to sonic inflow).

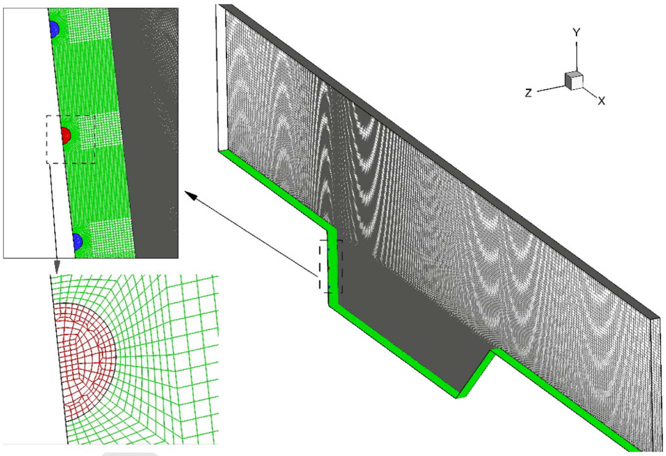

Fig. 2. Grid generation.

As shown in Fig. 2, the ethylene gas was injected from the cavity front wall at three different pressures. These pressures were selected to correspond to ethylene–air equivalence ratios. In this study, three ethylene–air equivalence ratios (φ) of 0.04, 0.065 and 0.1 are chosen according to the experimental study.

2.3. Treatment of numerical

The simulations were performed using an implicit CFD code [37–42]. In this code, the Navier–Stokes equations are solved by using cell centered finite volume approach.

Conservation of mass:

$$\vec{\nabla}.(\rho\vec{V}) = 0 \tag{1}$$

Conservation of momentum:

$$\vec{\nabla}.(\rho\vec{V}\,\vec{V}) = -\vec{\nabla}p + \vec{\nabla}.\bar{\bar{\tau}} + \rho\bar{g} \tag{2}$$

Conservation of energy:

$$\vec{\nabla}.\left((\rho E + P)\vec{V}\right) = \vec{\nabla}.\left(k_{eff}\vec{\nabla}T - \sum_j h_j\vec{J_j} + \bar{\bar{\tau}}_{eff}.\vec{V}\right) \tag{3}$$

species transport equation:

$$\vec{\nabla}.(\rho\vec{V}Y_i) = -\vec{\nabla}.\vec{J_i} \tag{4}$$

And equation of state:

$$PM = \rho RT \tag{5}$$

where $\bar{\bar{\tau}}$ is the stress tensor, E is a modified total energy, Y_i is the mass fraction, and $\vec{J_i}$ is the diffusion flux of species i, respectively. These terms are given by:

$$\bar{\bar{\tau}} = \mu\left[-\frac{2}{3}(\vec{\nabla}.\vec{V})\bar{\bar{1}} + (\nabla\vec{V} + {}^t\nabla\vec{V})\right] \tag{6}$$

$$E = h - \frac{p}{\rho} + \frac{v^2}{2} \tag{7}$$

$$\vec{J_i} = -\left(\rho D_{i,m} + \frac{\mu_t}{Sc_t}\right)\vec{\nabla}Y_i \tag{8}$$

where μ is the molecular viscosity, ρ is the density, $\bar{\bar{1}}$ is the unit tensor, Sc_t is the turbulent Schmidt number, $\vec{V}$ is the velocity vector and μ_t is the turbulent viscosity. Also J_i can be expressed in

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