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Effect of dual micro fuel jets on mixing performance of hydrogen in cavity flameholder at supersonic flow

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ABSTRACT

In this article, numerical simulations were done to study the influence of the various hydrogen injections on the mixing rate in the cavity flameholder of the scramjet. This study tried to present the main effective parameters on the flow feature and distribution of the hydrogen jet within a cavity in supersonic free stream domain. 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. The effect of horizontal and vertical fuel injection is comprehensively studied. Moreover, the characteristics of the mixing in various free stream velocities ($M = 1.2$, 2.2 and 3.2) are examined and the effects of micro air jet on the size of ignition domain for preserving flame holder are investigated. Results show that the increase of free stream Mach number significantly enhances the mixing of horizontal fuel injection in the cavity. The obtained results reveal that the injection of micro air jets enhances the mixing rate in low Mach number ($M = 1.2$). Our findings also show that vertical hydrogen injection considerably increases the mixing zone within the cavity and the mixing rate significantly improves by rising free stream velocity.

Introduction

In recent decades, scholars and scientists have focused on the supersonic vehicles to reach the outer space. To do this, development of the scramjets (supersonic combustion ramjet) as the most efficient engine for the supersonic flight has been the main goal of the scientists [1–3]. This engine is superior to other engines due to low weight and simplicity. These advantages have motivated researchers to increase the efficiency of this engine. Among various issues for improving the

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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.

Recently several studies have focused on the mixing of fuel in the air to increase the performance of the scramjets. According to this, various approaches and techniques have been examined for developing the mixing inside the hypersonic engines. Huang et al. [7] studied mixing augmentation induced by the interaction between the oblique shock wave and a sonic hydrogen jet in supersonic flows. They also investigated effects of molecular weight and injector configuration effects on the transverse injection flow field properties in supersonic flows [8]. Effect of swirling impinging jets ejected from nozzles with twisted tapes utilizing CFD technique is also studied by Amini et al. [9]. Kutschenreuter [10] comprehensively focused on supersonic flow combustors.

Investigations on different methods 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 numerous research papers on various aspects of transverse jet [19]. Our team 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.

Various parameters have been studied by scholars and scientists in this subject. The role of cavity formation, injection pressure, and imposed back-pressure on the fuel mixing in a scramjet is investigated by Hsu et al. [28]. Ukai et al. [29,30] studied effects of dual jets distance on mixing characteristics and flow path within a cavity in supersonic crossflow. The influence of geometric parameters on the drag of the cavity flameholder based on the variance analysis method was analyzed by Huang et al. [31]. 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. Fig. 1 illustrates the schematic of flow feature of vertical fuel jet within cavity in presence of free.

Preceding works performed numerous numerical and experimental works to advance the mixing rate and flame holding inside the cavity. Although their works are substantial, they have tried to offer new methods for increasing the mixing in this configuration. Our previous studies [24–27] showed that the replacing single jet by multi jets could significantly increase the mixing in the supersonic flow. In addition, the presence of the air jet could highly influence on the main characteristics of fuel distribution and mixing within cavity flameholder.

The primary goal of this study is to study the difference feature and mixing performance of vertical and horizontal hydrogen jet within a cavity. In addition, the effect of free stream velocity on the mixing performance of fuel is comprehensively studied. Then, we focused on the influence of the micro air jet on flow feature and mixing efficiency. In order to simulate the flow feature and mass distribution, a computational fluid dynamic method is used to solve the Navier-Stocks equations. In followings, the procedure of the simulation and obtained results are presented.

Numerical approach

Geometry and grid

The primary geometry of this study is attained 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.

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 $M_\infty = 1.2,\ 2.2$ *and* 3.2. 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).

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 Hydrogen–air equivalence ratios. In this study, the pressure was the value required to achieve global fuel/air equivalence ratio $\varphi = 0.5$ (total pressure ratio PR = 0.27) is chosen according to the experimental study.

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. Since the full details of the governing equations are comprehensively presented and explained in our previous works [40–42], we refer readers to these works.

To discretize both momentum and continuity equations, a second-order upwind scheme was used with a coupled solver. The convective fluxes were treated using the Roe Flux-Difference Splitting Scheme, which has been shown to