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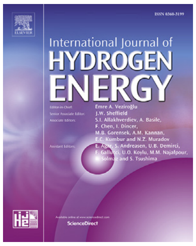

# Characteristics and mixing enhancement of a self-throttling system in a supersonic flow with transverse injections

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ABSTRACT

A three-dimensional self-throttling system is proposed in a scramjet combustor with transverse fuel jet, and investigated by Reynolds-averaged Navier-Stokes (RANS) simulations with the k-ω SST turbulence model. Numerical validation has been carried out against experiment and LES results. The effects of the jet-to-cross-flow momentum flux ratio and the throttling angle on mixing performance, fuel jet penetration depth and total pressure losses are all addressed. Through the proposed throttling system, the higher pressure upstream of the transverse fuel injection can drive part of the low momentum mainstream air into the downstream lower pressure region. The flow structures and the interactions between the shock waves and boundary layer are significantly changed to improve the mixing performance. The enhancement of mixing efficiency in the self-throttling system is closely related to the magnitude of the jet to crossflow momentum flux ratio, and a smaller throttling angle is found to further improve the mixing. On the other hand, the self-throttling system has a good performance in reducing the total pressure losses.

## Introduction

With increasing interest in supersonic and hypersonic flights, a good understanding of the mixing performance inside a scramjet combustor is essential. One of the critical issues is the mixing efficiency between fuel and air due to short residence time which is only about a millisecond under a typical flight condition [1]. Therefore, an effective fuel-air mixing strategy for the design of a scramjet combustor is required.

There are several methods for injecting fuel into a scramjet combustor, which are generally classified as two main categories [2], the wall injectors [3] and the strut injectors [4]. The wall injectors, i.e. transverse fuel injection through the wall of the combustor, has been widely used in the transverse jet in a supersonic crossflow (JISC) scramjet combustor [5].

Due to the complexity of JISC flow, the balance between better mixing performance and a lower total pressure losses is found to be a challenge in high Mach number flows [6,7]. Many injection schemes have been proposed to improve the mixing

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and reduce the total pressure losses [8]. Multiple transverse injections, i.e. fuel-stage [9] or air-stage [10,11], has been proposed and studied by many researches. Pudsey & Boyce [12] suggested that the number of fuel injectors has a great influence on the mixing efficiency and penetration depth. And there is an optimal number of fuel jets required to maximize the mixing performance. For the best mixing efficiency, an optimal distance between the multiple injectors was suggested by Lee [9].

On the other hand, the boundary-layer separation upstream of injection causes a large flow separation, which leads to a distorted velocity profile and increases the total pressure losses. In order to control the interactions between the shock wave and the boundary layer, one effective way is to place throttling holes, i.e. the bleeding holes in Ref. [13], upstream the fuel jet where the shock wave strikes the boundary layer [14,15]. It is found by Chyu et al. [13] that flow separation induced by shock/boundary interactions can be eliminated by introducing throttling hole. These throttling holes can remove the low momentum portion of the boundary layer to decrease the boundary-layer thickness, which could increase the velocity at the near wall region and reduces the severity of boundary layer separation. This approach is used by Kodera et al. [16,17] to effectively intensify the combustion process in a scramjet combustor. Although, the boundary layer thickness and separation are in some way controlled, the mass flow through the throttling holes is not usually re-injected into the mainstream which leads to the loss of mainstream mass flow [18]. Obviously, there are several parameters related to the throttling efficiency, such as, the diameter, the geometry [19] and the angle of the throttling hole [13].

Between the upstream and downstream regions of the fuel injection, there exists a large pressure difference at wall which is roughly three times of the freestream pressure [20]. Hence, Han et al. [21] designed a new self-throttling system to avoid the total pressure losses and to increase the mixing efficiency. Two-dimensional numerical investigation of the self-throttling system shows that the fluid flow upstream from the higher-pressure region merges into the downstream lower pressure region, which can increase the fuel jet penetration and improve the mixing. However, the two-dimensional results of self-throttling system does not reflect the characteristics of a typical three-dimensional shock wave/boundary interactions and turbulent flow structure. Moreover, the geometrical parameters of the design of the self-throttling system are also deficient.

The main objectives of the current work are: (1) to propose a three-dimensional self-throttling system in a typical JISC combustor model; (2) to numerically investigate the mixing performance and total pressure losses with and without the self-throttling system. The paper is organized as follows. The physical model and numerical methods are introduced in Section Numerical aspects and validations, and the numerical and grid validation are also given in this section. Then results and detailed analysis of three-dimensional self-throttling system in a typical JISC combustor model are exhibited in Section Results and discussion on the self-throttling system. Section Conclusions summarizes the conclusions of the paper.

## Numerical aspects and validations

### *Governing equations and numerical schemes*

The governing equations of Reynolds-averaged Navier-Stokes (RANS) simulation for turbulent mixing flow are expressed as follows:

$$\frac{\partial\overline{\rho}}{\partial t}+\frac{\partial(\overline{\rho}\tilde{u}_i)}{\partial x_i}=0 \tag{2.1}$$

$$\frac{\partial(\overline{\rho}\tilde{u}_i)}{\partial t}+\frac{\partial\left(\overline{\rho}\tilde{u}_i\tilde{u}_j\right)}{\partial x_j}=-\frac{\partial\overline{P}}{\partial x_i}+\frac{\partial}{\partial x_j}\left(\overline{\tau}_{ij}+\overline{\tau}_{ij}{}^R\right) \tag{2.2}$$

$$\frac{\partial\left(\overline{\rho}\tilde{H}\right)}{\partial t}+\frac{\partial\left(\overline{\rho}\tilde{H}\tilde{u}_j\right)}{\partial x_j}=\frac{\partial\overline{\rho}}{\partial t}+\frac{\partial}{\partial x_j}\left(\frac{\mu_{eff}}{Pr_t}\frac{\partial\tilde{h}_s}{\partial x_j}\right)+\frac{\partial}{\partial x_j}\left[\tilde{u}_j\left(\overline{\tau}_{ij}+\overline{\tau}_{ij}{}^R\right)\right] \tag{2.3}$$

$$\frac{\partial\left(\overline{\rho}\tilde{Y}_k\right)}{\partial t}+\frac{\partial\left(\overline{\rho}\tilde{Y}_k\tilde{u}_j\right)}{\partial x_j}=\frac{\partial}{\partial x_j}\left(\frac{\mu_{eff}}{Sc_t}\frac{\partial\tilde{Y}_k}{\partial x_j}\right) \tag{2.4}$$

where $\overline{\rho}$, $\tilde{u}$ and $\overline{P}$ are the density, velocity and pressure, respectively. $(\tilde{h}_s)$. is the sensible enthalpy, $\tilde{H}$ is the total enthalpy, where $\tilde{H}=\tilde{h}_s+\frac{1}{2}\tilde{u}_i{}^2$.The terms of $\overline{\tau}_{ij}$, $\overline{\tau}_{ij}{}^R$ are the molecule viscosity stress and Reynold stress. $\mu_{eff}$ is the effective viscosity, $\mu_{eff}=\mu+\mu_t$, where $\mu$ is the molecular viscosity computed by Sutherland's law $\mu=\frac{A_s\sqrt{T}}{1+\frac{T_s}{T}}$ and $\mu_t$ is the eddy viscosity closed by using the k-ω turbulence model in this study. $\tilde{Y}_k$ is the mass fraction. Turbulent Prandtl number $Pr_t$ and Schmidt number $Sc_t$ are assumed as 0.72. In this study, the Reynold stress $\overline{\tau}_{ij}{}^R$ is computed by k-ω SST turbulent model [22,23], which is a combination of the k-ω model in the near wall region and standard k-ε model away from the wall region. A switch function $F_1$ combines two turbulent models, which can be expressed as:

$$\frac{D\overline{\rho}k}{Dt}=\frac{\partial}{\partial x_j}\left[(\mu+\sigma_k\mu_t)\frac{\partial k}{\partial x_j}\right]+\overline{\tau}_{ij}{}^R\frac{\partial u_i}{\partial x_j}-\beta^*\overline{\rho}\omega k \tag{2.5}$$

$$\frac{D\overline{\rho}\omega}{Dt}=\frac{\partial}{\partial x_j}\left[(\mu+\sigma_\omega\mu_t)\frac{\partial\omega}{\partial x_j}\right]+\frac{\overline{\gamma}}{\nu_t}\overline{\tau}_{ij}{}^R\frac{\partial u_i}{\partial x_j}-\beta\overline{\rho}\omega^2$$
$$+2\overline{\rho}(1-F_1)\sigma_{\omega 2}\frac{1}{\omega}\frac{\partial k}{\partial x_j}\frac{\partial\omega}{\partial x_j} \tag{2.6}$$

where $\nu_t=\frac{a_1k}{\max(a_1\omega;|\Omega|F_2)}$ and $|\Omega|$ is the magnitude of vorticity. $F_2$ is a function to determine $\nu_t$, and the values of parameters can be referred to Wilcox [24]. The k-ω SST model has been widely used to study supersonic transverse injection [25–28].

The thermodynamic state equation for ideal gas is expressed as:

$$\overline{P}=\overline{\rho}R\tilde{T} \tag{2.7}$$

where R is the mixture gas constant.

The above governing equations are solved by using a finite volume method based on the CFD software OpenFOAM [29]. The code is a density-based solver rhoCentralFoam [30] which has been developed and validated in our previous simulations [31–33]. The convective fluxes are reconstructed using a second order TVD scheme and the second order central difference Gauss linear scheme is used for the viscous diffusion. Besides, the discretization of species transport equation

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