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Influence of jet-to-crossflow pressure ratio on nonreacting and reacting processes in a scramjet combustor with backward-facing steps

*Wei Huang**, *Liang Jin, Li Yan, Jian-guo Tan*

Science and Technology on Scramjet Laboratory, National University of Defense Technology, Changsha, Hunan 410073, People's Republic of China

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ABSTRACT

The jet-to-crossflow pressure ratio has a large impact on the combustion mode transition in the scramjet engine, and this information needs to be explored comprehensively. The effect of the jet-to-crossflow pressure ratio on the mixing and combustion processes in a backward-facing step combustor has been investigated numerically, and two similar cases have been utilized to validate the numerical approaches employed. The obtained results show that the wall pressure distribution for the nonreacting flow field has been predicted well, and the peak pressures are all a bit underestimated. However, the predicted wall pressure distribution for the reacting flow field does not match well with the experimental data, and it is overestimated. When the hydrogen is injected only from the bottom wall of the combustor, the mixing efficiency decreases with the increase of the jet-to-crossflow pressure ratio irrespective of the nonreacting or reacting flow field. When the hydrogen is injected simultaneously from the top and bottom walls, the separation shock wave is pushed forward to the entrance of the combustor, and it varies from an oblique one to a normal one. This means that the jet-to-crossflow pressure ratio has a great impact on the combustion mode transition for the scramjet engine, and the stable ramjet/scramjet mode transition can be obtained by controlling the fuel injection scheme.

Introduction

From combustion point of view, hydrogen owns superior characteristics to any other hydrocarbon fuel in terms of ignitability, low ignition delay, and higher flame stability [1]. There inherent advantages turn it as the only potential fuel for scramjet engines. However, its low molecular weight can not promote the mixing and combustion process in supersonic flows efficiently, and thus, some flameholding mechanisms have been proposed by the researchers, i.e. the wall-stalled cavity, the backward-facing step, the strut, the ramp. Due to its simple configuration, the backward-facing step has been widely employed in the flowpath of the scramjet engine [2–5], and the laminar flow field properties in the backward-facing step has been visualized by using the nanotracer planar laser scattering (NPLS) technique [6].

* *Corresponding author*. Tel.: +86 731 84576447; fax: +86 731 84576449.
E-mail address: gladrain2001@163.com (W. Huang).
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The shadowgraphs, broadband flame emission photographs, and planar laser-induced OH fluorescence images have been combined by Abbitt III et al. [7] to investigate the influence of the chemical reaction on the supersonic reacting flow field with the hydrogen injected behind a rearward-facing step, and this is the first complete flow visualization study for the hydrogen-air supersonic combustor. Karagozian et al. [8] have investigated the jet penetration and jet structure in a rearward-facing step combustor experimentally and theoretically, and the transverse gas jet has been injected behind the rearward-facing step as well. However, in their study, the jet-to-crossflow pressure ratio has not been varied, and its effect on the combustion process has not been studied as well.

Altay et al. [9] have analyzed the influence of the equivalence ratio oscillation on combustion dynamics of propane-air flames in a backward-facing step combustor by varying the fuel injector location. They have found that the combustion dynamics are primarily induced by the flame–vortex interactions, and the equivalence ratio oscillations own secondary effects on the dynamics. However, the effect of the equivalence ratio on the flow field properties has not been explored completely.

From the above literature reviewed, the effect of the jet-to-crossflow pressure ratio on the flow field properties of the backward-facing step combustor has rarely been analyzed, and it has a large impact on the combustion mode transition in the scramjet engine. Therefore, this information needs to be explored further.

In the current study, the effect of jet-to-crossflow pressure ratio on mixing and combustion processes in a two-dimensional scramjet combustor has been investigated numerically, and the ram-to-scram mode transition process induced by the jet-to-crossflow pressure ratio has been analyzed as well. The jet-to-crossflow pressure ratio has been set to be 16.43, 25.15, 42.79 and 63.5.

Physical model and numerical method

Physical model

The combustor model with backward-facing steps studied in the present article is shown in Fig. 1, and it consists of an isolator, a constant area combustor and a diverging area combustor. The fuel is injected to the supersonic crossflow vertically 594.36 mm away from the entrance of the combustor. This means that the fuel injectors are located in the isolator [10], and the length of the isolator is 677.418 mm. The width of the injection port is 3.9624 mm, and the hydrogen is injected only from the bottom wall or from both top and bottom walls of the combustor. There is a backward-facing step exist on the top and bottom walls respectively, and its height is 3.302 mm. The length of the combustor with the constant area is 551.18 mm, see Fig. 1, and that of the diverging area combustor is 1063.752 mm.

The origin of the coordinate system is set at the entrance of the combustor, see Fig. 1. The air flows from left to right with the Mach number being 3.3, the static pressure being 48,166 Pa and the total temperature being 2333.333 K. The hydrogen is injected into the core flow with the sonic velocity and the total temperature being 277.7778 K. The jet-to-crossflow pressure ratio is set to be 16.43, 25.15, 42.79 and 63.5.

Numerical approach

The two-dimensional Reynolds-averaged Navier–Stokes (RANS) equations and the two equations SST k-ω turbulence model has been utilized to simulate the combustor with backward-facing steps numerically, and the equations are solved along with density based (coupled) double precision solver of FLUENT [11]. The two-dimensional assumption may result in the inadequate result for the intensity of the shock wave, as well as the shock wave/boundary layer interaction [12]. However, it would quicken the decision process for the overall design of the scramjet combustor, and thus, it has been employed as the basis approach for the flowpath design of the scramjet engine. The Finite-Rate/Eddy-Dissipation model and the one step hydrogen-air mechanism have been used to model the combustion process in the scramjet engine, and they have been proved to be suitable for the combustion simulation [13,14].

The RANS method is the efficient and rapid approach to receive the mean flow properties for the further mixing and combustion optimization in the supersonic flow [15]. The SST k-ω turbulence model is a combination of the Wilcox 1988 k-ω model in the near wall region and the standard k-ε model in the detached regions [16], and it has been proved to be more suitable to capture the turbulent generating mechanisms induced by the shock wave and the boundary layer in the scramjet engine [17,18], as well as the flow field properties in jet flows [18,19]. Thus, it has been employed to couple with the two-dimensional Reynolds-averaged Navier–Stokes (RANS) equations to simulate the flow field in the scramjet combustor with backward-facing steps, and the Reynolds-averaged Navier–Stokes equations have been utilized due to its lower

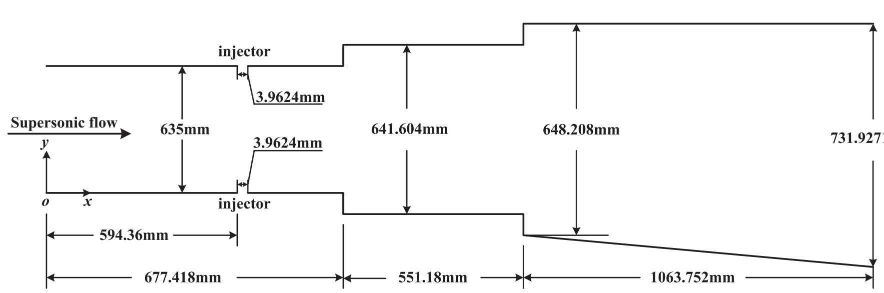

Fig. 1 – Schematic diagram of the scramjet combustor with backward-facing steps employed in the current study.