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Numerical investigation of the impact of asymmetric fuel injection on shock train characteristics

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ABSTRACT

Numerical simulations are carried out to investigate the impact of asymmetric fuel injection on shock train characteristics using the commercial-code FLUENT. The asymmetry of fuel injection is examined by changing the fuel flow rates of the upper and lower wall fuel injectors. The numerical approach solves the two-dimensional Reynolds-averaged Navier–Stokes (RANS) equations, supplemented with a k-ω model of turbulence. As a result, different ways of fuel injections will always lead to shock train transitions, with the variations of shock train structure, strength and leading edge position. For symmetric fuel injection, the flowfield of the isolator is quite asymmetric with the boundary layer of the upper wall side developing much stronger than that of the lower wall, which is due to the heterogeneity of the incoming flow. Regarding to asymmetric fuel injection with more of lower wall side, though the pressures in the combustor are nearly the same, the first shock of the shock train converts between 'Distinct symmetric X type shock' and 'Obscure and weaker asymmetric shock' and the shock train leading edge moves upstream with the increase of the asymmetry level. With regard to asymmetric fuel injection with more of upper wall side, 'incomplete asymmetric X type shock' occurs and the shock train structures keep nearly the same with low level of fuel injection asymmetry. Unexpected results like unstart will happen when increasing the level of fuel injection asymmetry. And the isolator will come back to normal state by decreasing the differential of upper and lower wall sides fuel injections.

1. Introduction

Scramjet isolator is a critical component designed to prevent inlet unstart. Combustion pressure rise leads to the formation of a shock train in the isolator, which can greatly influence the properties of the internal flow. Interest in the formation and behavior of shock train, and the pseudo-shock phenomenon has been persistent for a long time. First, some are focusing on the shock-wave/boundary–layer interactions (SWBLI) [1–3], which will lead to the separation of boundary layer and cause large total pressure loss. Secondly, the configuration of the shock train has also been concentrated on. Tamaki et al. [4,5] reported that with an increase of the main flow Mach number, the configuration of the pseudo-shock wave changed from λ-type shock wave to X-type shock wave. Besides, numerical and experimental researches have been conducted about the symmetric and asymmetric shock wave system in a planar nozzle [6–8]. The location, structure and characteristics of the Mach 2 and 4 pseudo-shock waves in the square duct were investigated by color Schlieren photographs [9], the symmetric λ-type pseudo-shock of Mach 2 and the asymmetric X -type pseudo-shock of Mach 4 were analyzed. Tu and Segal [10] referred to isolator/combustion chamber flow interactions

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in response to transient pressure rise and the corresponding structure of the isolator shock train. The types of flow structure during deflagration to detonation transition (DDT) process have been discussed by Smirnov et al. [11–13]. The shock wave interactions, the formation of contact surfaces due to shock interaction and formation of detonation structures were analyzed carefully. Thirdly, as the shock train is approaching the inlet entrance, unstart will occur. So the detection of the shock train leading edge has also been investigated. Many techniques [14–16] have been put forward to detect the location of the shock train leading edge. On the whole, the isolator shock-wave boundary-layer interaction, the shock train configuration and the shock train leading edge that greatly affect the isolator flow field have been discussed in detail previously [17–25].

A lot of research works on supersonic combustor have been conducted in the paper [26–33]. However, only a few studies have considered isolator–combustor interactions, with most of them using room-temperature air and mechanical valves to create the backpressure that produces shock train. Fotia and Driscoll [30,31] focused on the isolator–combustor interactions in a preheated airflow, which are more complex than isolator performance with a mechanical backpressure valve. Experiments were carried out by Fischer and Olivier [32] to investigate the influence of the wall temperature on the pressure distribution in the shock train. A high-resolution numerical study was conducted by Choi et al. [33] to investigate the transient process of the combustion and the shock-train developments in an ethylene-fueled direct connect dual-mode scramjet combustor. In a word, due to the intricate phenomena in the combustor, like the coupling between the fuel injector and the response of the isolator, the heterogeneous isolator exit caused by combustion or the high isolator and combustor wall temperature, the isolator–combustor interactions should be taken into account.

For the combustor of the Scramjet, it is widely recognized that its performance is substantially influenced by fuel injection modes. When the flowfield of the combustor is altered with different fuel injection modes, the isolator flowfield may be affect. So in this research, the effects of asymmetric fuel injection caused by fuel rate ratio differences with symmetrically located fuel injectors when combustion is considered will be studied carefully. This paper is constructed as below. First the physical model, numerical method and code validation are described in detail in Section 2. For Section 3, to begin with, the Mach number contours, the wall pressure distributions and the Schlieren images of the simulation are depicted and discussed. After that, the summary of shock train transitions with different fuel injection modes is presented. Some conclusions are given in the final section.

2. Physical model, numerical method and code validation

2.1. Physical model and numerical method

In the investigation, the simulation model is a two-dimensional scramjet. As presented in Fig. 1, the scramjet consists of an inlet, an isolator and a combustor. The constant cross-section isolator length is about 450 mm, of which the exit locates at where $X=0$, and its height is about 43 mm. The simplified dump combustor contains an expansion section of which the area expansion ratio is about 1.7 and the length is about 504 mm, a cavity, a constant area section and then the second expansion section. It should be noted that before the second expansion section of the combustor, the isolator–combustor is symmetric along the center line. There are five fuel injectors in the combustor, as presented in Fig. 2, which are labeled from one to five beside them. And their partial enlarged maps can be seen in Fig. 2, of which three that are labeled 1–3 are in the form of strut. The fuel is injected parallel to the main stream for injectors labeled 1–3 and normal to the main stream for injectors labeled 4–5. What should be emphasized is that the five fuel injectors are symmetrically distributed along the center line.

The two-dimensional coupled implicit Reynolds-averaged Navier–Stokes equations are adopted as the governing equations, and the SST (shear stress transport) k-ω two-equation model [34] is employed as the turbulent model. The SST k-ω model combines the near-wall robustness of the k-ω turbulence model with the capabilities of the k-ω model away from the walls. It also includes the effect of turbulent shear stress transport based on Bradshaw's assumption [35] that the shear stress in a boundary layer is proportional to the turbulent kinetic energy, the modification of which improves the ability of this model to predict flow separation better than the k-ω model. The conservation of Mass, momentum and energy are described as the following equation.

$$\frac{\partial U}{\partial t}+\frac{\partial (E-E_V)}{\partial x}+\frac{\partial (F-F_V)}{\partial y}+\frac{\partial (G-G_V)}{\partial z}=H$$

where

$$U=\begin{Bmatrix}\rho\\ \rho u\\ \rho v\\ \rho w\\ \rho e\end{Bmatrix}, E=\begin{Bmatrix}\rho u\\ \rho u^2+p\\ \rho uv\\ \rho uw\\ (\rho e+p)u\end{Bmatrix}, F=\begin{Bmatrix}\rho v\\ \rho uv\\ \rho v^2+p\\ \rho vw\\ (\rho e+p)v\end{Bmatrix},$$

$$G=\begin{Bmatrix}\rho w\\ \rho wu\\ \rho wv\\ \rho w^2+p\\ (\rho e+p)w\end{Bmatrix},$$

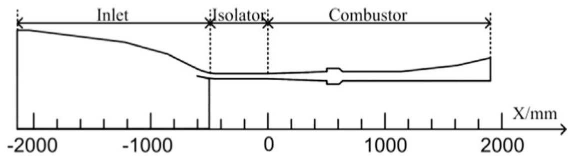

Fig. 1. The schematic of the physical model.

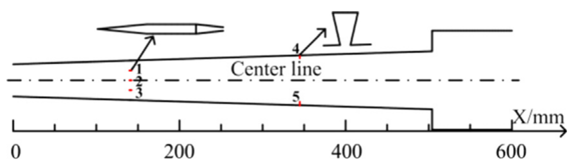

Fig. 2. A close-up view of fuel injectors.