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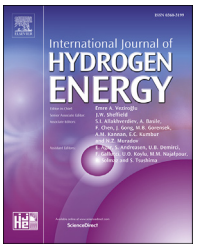

Effects of plate vibration on the mixing and combustion of transverse hydrogen injection for scramjet

Kun Ye[*], *Zhengyin Ye*, *Jie Wu*, *Zhan Qu*

National Key Laboratory of Aerodynamic Design and Research, Northwestern Polytechnical University, Xi'an, Shaanxi Province, 710072, PR China

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ABSTRACT

Transverse injection is an effective mixing enhancement technique for the combustor of scramjets. Vibration of the plate structure in combustor will easily be induced due to aerodynamic load and harsh aerothermodynamic load simultaneously. Effects of the plate vibration on the mixing and the combustion of the transverse hydrogen injection have been investigated numerically in this study. Finite rate chemistry model is used as combustion model. The supersonic jet experimental model of the Stanford University is modified slightly and used as the analysis model. Effects of the frequency and the amplitude of the plate vibration on combustion performance and flow field structure have been investigated in detail. The results show that the plate vibration increases the mixing efficiency, the combustion efficiency and the total pressure loss coefficient. Besides, it can change the flame structure and the shock wave structure, as well as increase the shock wave intensity at downstream of the injection. The vibration frequency has relatively little effect on the combustion efficiency and the total pressure loss coefficient. When the vibration frequency is large, it presents some high frequency pulsations for the total pressure loss coefficient. However, the vibration amplitude has large effect on combustion efficiency and the total pressure loss coefficient. When the vibration amplitude is small, the combustion efficiency presents regular periodic change with time. When the vibration amplitude is large, it diverges with time, and the flow tends to be unstable. The large vibration amplitude changes the stability of the original flow. Consequently, the combustion with large amplitude fluctuation can critically damage the combustion stability.

Introduction

Scramjet is regarded as one of the most promising air breathing propulsion systems for hypersonic vehicles. The residence time of flow in the combustor is very short, just within millisecond. Therefore, finishing the mixture and the ignition of the reactants, flame holding and stable combustion are critical issues in such a short time [1]. Transverse injection has been widely applied to scramjet as a mixing enhancement

* *Corresponding author.*
E-mail addresses: yekun@mail.nwpu.edu.cn (K. Ye), yezy@nwpu.edu.cn (Z. Ye), wujie@nwpu.edu.cn (J. Wu), 546877309@qq.com (Z. Qu).

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technique [2–5], for example, it has been used in the Hyshot and HyShotIIhypersonic combustors in the University of Queensland [6,7] and the supersonic combustor in Stanford University [8–11].

Transverse injection combustion includes amount of complex flows such as separation shock wave, bow shock, Mach disk, turbulence mixture and combustion and so on. Many scholars have carried out a large amount of researches concerning these problems. McClinton et al. [12] have investigated the effects of the angle of the transverse injection. Gruber et al. [13,14] have experimentally studied the effects of the circular and elliptic orifice on the transverse injection. Ben-Yakar [8,9] has experimentally carried out the flame-holding capability and the auto-ignition of a transverse hydrogen jet in high total enthalpy flow. The flow visualization techniques included planar laser induced fluorescence (PLIF) of OH and Schlieren imaging are used to study the flow and combustion characteristics. Gamba et al. [10,11] have experimentally studied the combustion characteristics of an inlet/supersonic combustor model in the Stanford Expansion Tube Facility. Mai et al. [15] have experimentally and numerically investigated the interaction between an incident shock wave and a transverse injection for the mixing and the combustion in a supersonic airstream. Their results show that flame-holding can be attained only when the incident shock wave was introduced downstream of the injection slot.

With the development of computational fluid dynamics (CFD) and computer technology, CFD is also widely applied to study the supersonic combustion. Huang et al. [16] have numerically studied the interaction between the incident shock wave and the transverse slot injection. Their results show that the size of the ramp has a great effect on the transverse injection flow field, and the shock wave forms upstream of the injection slot moves towards the entrance of the channel with the increase of the swept angle of the ramp and the jet-to-crossflow pressure ratio. They [17] also have studied the influence of jet-to-crossflow pressure ratio on nonreacting and reacting processes in a scramjet combustor with backward-facing steps. Shekarian et al. [18] have studied the effects of incident shock wave on mixing and flame holding of hydrogen in supersonic air flow based on OpenFOAM. They found that when the intersection of incident shock wave and lower surface is at the upstream of the injection slot, no significant change occurs in the flow field structure at downstream. In addition, when the intersection moves toward downstream of injection slot, dimensions of the recirculation zone and mixing efficiency increase simultaneously. Cecere et al. [19] have studied the complex flow structure of supersonic hydrogen combustion in the Hyshot II scramjet using three-dimensional Large Eddy Simulations (LES). Tahsini et al. [20] have studied the effects of impinging oblique shock on combustion efficiency of hydrogen injection. Gerdroodbary et al. [21–23] have numerically studied the influence of the shock waves on single/multi sonic transverse hydrogen micro-jets in supersonic crossflow. They [24–26] also have investigated the effects of using micro air jets on the mixing of the hydrogen micro jet in supersonic crossflow. Their results indicate that using micro air jets obviously increases the mixing efficiency of hydrogen. Han et al. [27] have proposed a self-throttling approach to enhance combustion efficiency in supersonic flow with transverse injection. Zhao et al. [28] have investigated the flow coherent structures and mixing characteristics in supersonic flow with transverse injection using LES method. Hariharan et al. [29] have numerically investigated the effect of variation in the inlet Mach number and stagnation temperature on the mixing of fuel with the oxidizer, as well as the subsequent stabilization of a flame in a combustor.

For practically designing and manufacturing scramjets, the thin plate structures would be adopted due to weight limitation [30,31]. In addition, when the scramjet engine works, the high temperature and high pressure gas will be generated in the combustor. Thus, the thin plate structure will bear the aerodynamic load and harsh aerothermodynamic load simultaneously. The high temperature would decrease the performance of the material properties. Meanwhile, the thermal stress caused by temperature gradient and boundary conditions would influence the structural rigidity as well. Therefore, the aerothermoelastic problem of plate in the combustor would be more easily induced. From the perspective of structure, the sustained vibration could lead to the structure fatigue breakdown and reduce the lifetime. From the perspective of flow, the flow field is sensitive to the configuration in the supersonic flow. Consequently, the plate vibration would influence the flow field structure in the combustor and further influence the mixing efficiency, the combustion efficiency and the stability of combustion. However, most of the current studies on the supersonic transverse injection combustion have assumed that the configurations of the combustors are rigid and the plate vibration caused by aeroelasticity has been neglected. Little work has been done to study the effects of vibration on transverse injection combustion. Therefore, it is necessary to study the effects of the plate vibration on the performance and flow filed structure of the combustor.

The aerothermoelastic problem of the plate in combustor is extremely complex for the practical scramjet. From the perspective of flow, accurate simulation of the three-dimensional combustion flow field of scramjet is still a huge challenge. The spatial scale and temporal scale of turbulent combustion are quite small, which will lead to large amount of computational costs when LES method [19,28] or Direct Numerical Simulation (DNS) method [32] is used. Even if the Reynolds-averaged Navier-Stokes equations are employed to simulate the turbulent combustion flow field, some factors like the turbulence model, chemical reaction model, spatial scheme and grid will have impact on the results [3]. From the perspective of structural design, the material properties and the boundary conditions of the plate structure are very complicated for practical scramjet structure. Dowell [33,34] has investigated amount of researches on the plate flutter, and his results show that under conditions of different flows and structural parameters, the plate vibration presents the different amplitudes and frequencies. Therefore, in order to reduce the computational cost, a two-dimensional combustor model which is designed based on the Gamber's experimental model in the Stanford University is taken as the research object. In addition, a vibration is imposed on the plate. The effects of the vibration amplitude and frequency on combustion performance and flow field structure are investigated in detail in this study.

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