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Numerical and experimental study on flame structure characteristics in a supersonic combustor with dual-cavity

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ABSTRACT

Combined numerical and experimental approaches have been implemented to investigate the quasi-steady flame characteristics of supersonic combustion in tandem and parallel dual-cavity. In simulation, a hybrid Large Eddy Simulation (LES)/assumed sub-grid Probability Density Function (PDF) closure model was carried out. Comparison of calculation and experiment as well as comparison of the two configurations are qualitatively and quantitatively performed regarding the flame structure and other flowfield features. Simulation shows a good level of agreement with experimental observation and measurement in terms of instantaneous and time-averaged results. Given the same fuel equivalence ratio, the parallel dual-cavity with the two opposite injections gathers the major combustion around the cavities, thus leading to the concentrated heat release, the greatly extended recirculation zones and the converging–diverging core flow path. Only intermittent stray flame packets can be found in the downstream region. Flame in the combustor with tandem dual-cavity appears to be stabilized by the upstream cavity shear layer and grows gradually to the second cavity, peaking its most intensity in the middle section between the two cavities. For both dual-cavity configurations, the strongest reaction takes place in near chemistry stoichiometric region around the flame edge, and is mainly confined in the supersonic region supported by the inner subsonic combustion. The coexistence of three parts plays a vital role in flame stabilization in the parallel and tandem dual-cavity: a reacting reservoir transferring hot products and activated radicals within the cavity recirculation zone, the hydrogen-rich premixed flame in the jet mixing region, and the downstream diffusion flames supported by the upstream premixed combustion region. In addition, for the parallel dual-cavity under the given condition, significant reaction are present near jet exit upstream the cavity leading edge.

1. Introduction

Seldom is the flow dynamics more complex than when supersonic turbulent combustion exists. For scramjet application, the inlet flow remain supersonic throughout the engine and the combustion occurs at supersonic conditions [1]. A scramjet combustor may be simple in configuration, yet the contained problems appear quite hard to tackle. Because of the involved difficulties in measuring reacting flow quantities and the complexity of the aerothermodynamics in experiment, Computational Fluid Dynamics (CFD) becomes a more attractive approach for complementary analysis and design for scramjet application [2]. Rapid development in computational ability helps us to implement more detailed simulation, and meanwhile more advanced numerical methods are now being put forward.

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However, the reaction chemistry, turbulent compressible flows and their interaction still yield many issues for an accurate CFD research for supersonic combustion.

Organization of robust combustion in the high-speed flows, which is believed to be one of the most crucial issues for scramjet combustor design [3], often requires flame stabilization devices like cavity flameholders [3,4]. In recent years, a lot of experimental studies and numerical investigations has been done to investigate the combustion characteristics of cavity flameholders. Rasmussen et al. [5] used planar laser-induced fluorescence imaging to observe the flame characteristics with direct cavity fuel injection. The results show that location of the stabilized flame base was shown to vary with changing the fuel mass flowrate and the location of the fuel injectors. Micka et al. [6] investigated the combustion characteristics of a dual-mode scramjet combustor with cavity flameholder, and they found two distinct combustion stabilization modes for upstream fuel injection, the cavity and jet-wake stabilized flame. Another mode, the combined cavity shear-layer/recirculation combustion, is added by Wang et al. [7] in their experimental study for single cavity. Sun et al. [8] carried out a combined experimental and numerical study on the flame characteristics in single-cavity-based jet combustion, which indicates the important role of jet counter-rotating vortex and the interaction with cavity shear layer in the flame propagation. Despite these research efforts, a full understanding towards the flameholding mechanisms is far from realization. Despite the difficulty to obtain an insight to the supersonic combustion physics, flame structure characteristics observed in experiment and calculation may contribute to uncover the plausible mechanisms.

Instead of one single cavity in flow path, a combustor with more wall cavities installed has also drawn researchers' interest. Multiple cavities flameholders are early reported to be used in model scramjet combustor test at CIAM [11], and some [9,10] indicate that dual flame holding cavities may provide additional benefits and increased combustor performance. Situ et al. [12,13] adopted dual-cavity in tandem to stabilize the kerosene combustion with the piloted energy of fuel-rich hot gas injected into the upstream cavity, and evaluated the flameholding and mixing enhancement of supersonic reacting flow of kerosene fuel over dual-cavity. The results show that dual-cavity promotes combustion due to decelerating the inflow hot gas and increasing the air entrainment into the reacting layer. Another mixing study for tandem dual-cavity was carried out by Adam et al. [14], which investigated the impact of the configurations and injection locations of the upstream mixing cavity on the non-reacting flow. This study indicates that injection at the upstream wall of the cavity provided greater penetration height into the freestream as well as faster mixing with the freestream compared with injection at the center or downstream wall of the cavity. Pan et al. [15] implemented experiments to compare the ignition and flameholding ability between different types of dual-cavity, and found that intersected cavities installation lead to better performance while tandem cavities installed too closer was not beneficial for ignition and flame stabilization. A similar experimental study was conducted in dislocated dual cavities with a longer distance [16]. In addition, a study by Wang et al. [17] indicated that tandem cavities enlarge the recirculation zone and achieve much better mixing but need an accurate cooperation with injection schemes to be efficient. Another tandem case is simulated by Zhang et al. [18] using liquid n-decane in a scramjet engine. Parallel dual-cavity combustor are also put forward for numerical research in Ref. [19] and Ref. [20]. In general, among the existing experimental research, the advanced techniques has barely been used for observation or measurement, leading to a lack of quantitative information and systematic knowledge toward supersonic combustion stabilized by combustor with the two basic multiple-cavity configurations, parallel and tandem dual-cavity.

Some numerical investigations are focused on the flame characteristics in dual-cavity combustor. Wang [19] used Large Eddy Simulation (LES) with a Reynolds-Averaged Navier–Stokes (RANS) model for near-wall treatment to investigate the hydrogen jet flame stabilized by parallel dual-cavity, and the results showed the combustion characteristics and flow structure influenced by parallel dual cavities. And tandem cases [18,20] were also conducted to analyze the combustor performance with the two cavities in tandem. However, few research gives a detailed description relating to the flame structure characteristics in parallel and tandem dual-cavity, which impedes a further exploration into the flame stabilization mechanism for practical supersonic combustion.

The purpose of the current study is to investigate the supersonic turbulent combustion in model scramjet combustor with two configurations, the parallel and tandem dual-cavity, also aiming to further understand the plausible stabilization mechanism provided by dual-cavity flameholders via combined numerical and experimental approaches.

This paper is organized as follows: In Section 2, a hybrid RANS/LES simulation along with the numerical methods or models will be present. The experimental rig and several observation approaches are introduced in Section 3, along with the simulation set-up details. Instantaneous results in Section 4.1 and time-averaged characteristics in Section 4.2 are to be analyzed in comparisons between parallel and tandem dual-cavity, also between calculation and experiment. Section 4.3 is expected to discuss the intrinsic flame structure constitution for combustion stabilization. Finally, conclusions are drawn in Section 5.

2. Numerical approach

The in-house code used in this investigation is developed by the group from Science and Technology on Scramjet Laboratory in National University of Defense Technology. The computational methods adopted in the code is designed to simulate the shock-containing reactive or non-reactive flowfields, which can be implemented for supersonic turbulent flow or combustion problem in a scramjet combustor. The code solves the Navier–Stokes equations governing a mixture of thermally-perfect gases where non-equilibrium chemistry is involved. More details are given in Refs. [21] and [22].