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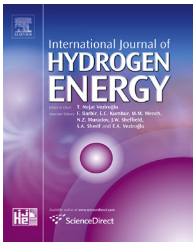

Numerical simulation on ignition transients of hydrogen flame in a supersonic combustor with dual-cavity

Yixin Yang, Zhenguo Wang*, Mingbo Sun, Hongbo Wang

Science and Technology on Scramjet Laboratory, National University of Defense Technology, Hunan Changsha 410073, China

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ABSTRACT

Consequent flame stabilization in a practical combustor is achieved via ignition transients. Given the background of supersonic combustion in a scramjet engine, the ignition transient phenomena is of millisecond time scale and will present complex characteristics. In the present paper, a hybrid Reynolds-Averaged Navier–Stokes (RANS)/Large Eddy Simulation (LES) approach is adopted to investigate the ignition transient process in the supersonic combustors with hydrogen jet upstream of parallel and tandem dual-cavity. Flame luminosity images are also obtained by using high speed camera to experimentally observe the dynamic behavior of the combustion. For both parallel and tandem case, simulations reasonably reproduce the spatiotemporal evolution of the hydrogen flame structures during the period from the moment after the ignition deactivation to a quasi-steady combusting state. In the transients of parallel dual-cavity, significant flame transformation in the combustor is performed, with the flame front moving upstream toward the jet exit region. Positive feedbacks are believed to function among the sub-processes: the strong heat release and hot products generate around the jet mixing region and cavity shear layer, the major vortex within the cavity recirculation zone transfers the active radicals, and high-pressurized combustion zone extends upstream and further compresses the incoming core flow. Regarding the tandem case, the overall flame development is dominated by the rapid growth of combustion from the downstream cavity to the upstream region, along with the concentrated heat release spreading against the main stream. Collaboration of the downstream combustion and the upstream flame packets provides appropriate temperature, pressure and velocity field in the middle section between the two cavities, which should be responsible for the flame transients.

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* *Corresponding author.*
E-mail address: wzg_nudt@163.com (Z. Wang).

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Introduction

For scramjet application, the widely-used cavity flameholder provides the flame stabilization capability but, however, yields quite a lot of knotty issues to research efforts. In a practical cavity-based combustor, the induced flow or mixing problems implied by shock waves, transonic recirculation zone, cavity shear layer and integrated fuel injections, will make combustion in it even more complicated. In spite of the limited experimental measurement approaches, numerical simulation offers an attractive alternative and nonetheless complementary tool for the study of high-speed turbulent reactive flows [1], where some complex physical phenomena, like ignition transients, are essentially involved.

In recent decades, a lot of work has been done to investigate ignition and flame stabilization of hydrogen or hydrocarbon fuel in supersonic combustor with wall cavities. Ben-yakar et al. [2] and Wang et al. [3] gave overviews of cavity flameholders for the progress in experimental and numerical studies. These works are mainly concerning about the model scramjet combustor with a single wall cavity. In practice, 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 [4], and some [5,6] indicate that dual flame holding cavities may provide additional benefits and increase combustor performance. Situ et al. [7,8] adopted dual-cavity in tandem to stabilize the kerosene-air flame 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. Another mixing study for tandem dual-cavity was carried out by Adam et al. [9], which investigated the impact of the configurations and injection locations of the upstream mixing cavity on the non-reacting flow. Pan et al. [10] implemented experiments to compare the ignition and flameholding ability between different types of dual-cavity, and found that intersected cavities installation lead to improved 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 [11]. In addition, a study by Wang [12] 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. [13] using liquid n-decane in a scramjet engine. Parallel dual-cavity combustor are also put forward for numerical research in Ref. [14] and Ref. [15].

In combustion systems, the ignition transient is a critical fundamental phase that has strong practical implications [16]. Ignition transience has been numerically and experimental studied in low-speed flow context, such as MICCA annular burner [16] and hydrogen/air counterflow [17]. For cavity-based supersonic combustor, on the other hand, ignition and flame stability are inevitably serious concerns in such a high-speed flow environment [18]. Sun et al. [19] used high speed photography and schlieren system to investigate the spark ignition process in a multi-cavities combustor. The spark kernel, the flame spreading process and shock structures were well captured in experiment. Pulse detonator was adopted to ignite the ethylene fueled cavity by Ombrello et al. [20], and they found that under certain cavity fueling conditions, a multiple regime ignition process occurred with the pulse detonator that led to decreased cavity burning and at times cavity extinction. Li et al. [21–23] and Yang et al. [24] had implemented a number of simulations or theoretical analysis to study the ignition transients and flame development in cavity-based scramjet engine with air throttling. They found that the shock train in the isolator functions vitally during the transient. Intensify chemical reactions produce sufficient heat release to maintain a flow environment conducive to flame stabilization and thus a self-sustaining mechanism is established between the flow and flame development [23]. Nevertheless, since there remains a lot of unknown flow and combustion physics of the cavity stabilized flame, the mechanism of ignition transients in supersonic flows is yet to be fully understood. Meanwhile, few researches are devoted to the analogous phenomena in dual-cavity.

The focus of the present study is to numerically investigate the ignition transients of hydrogen flame in a model scramjet combustor with parallel and tandem dual-cavity, along with the experimental observation on flame structure evolution. The paper is organized as follows: numerical approach, problem description and computation setup will be firstly presented in Section 2. After that, Section 3 provides the calculated transient process in parallel dual-cavity, where the simulation results and the plausible mechanism are discussed. Then it is followed by an analysis for tandem case in Section 4, focusing on the flame structure and heat release distribution evolution. Finally, key findings of this ignition to flame stabilization dynamic behavior in dual-cavity combustors is concluded in Section 5.

Numerical approach and problem configuration

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. A similar study and more details about the numerical method can be found in Ref. [25].

Numerical schemes and turbulence model

In the present study, the standard fifth-order Weighted Essentially Non-Oscillatory (WENO) scheme [26] is adopted for inviscid fluxes and viscous fluxes are calculated by the 2nd-order central scheme. Temporal integration is performed by a second-order dual time-step approach, with the inner

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