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Study on the effects of thermal throat on flame stabilization in a kerosene fueled supersonic combustor

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A B S T R A C T

The effects of thermal throat on flame stabilization in a kerosene fueled supersonic combustor were numerically and experimentally studied in the present paper. The results were obtained under the inflow condition of stagnation temperature 1100 K, stagnation pressure 1.0 MPa and Mach number 2.0. Wall pressure measurements and flame emission images were made during the experiments in an attempt to better understand the flame development, results showed the combustion organization scheme had a great effect on flame stabilization in the combustor. The flame development process in each case was different according to the flame luminosity pictures. When the pilot hydrogen was removed, the flame of case 1 and case 2 was still stable, and that of case 3 was blown off by the high-speed air flow, but it was surprised to find that the flame of case 4 was blowout even the pilot hydrogen existed. A shock train had generated in the isolator due to the thermal throat existing, which decreased the high-speed main stream, and increased the temperature and pressure, also enhanced the fuel mixing efficiency in the combustor, this was why the flame stabilization was achieved. But if the thermal throat disappeared, the shock train would be pushed out of the combustor by the high-speed air flow. The residence time for mixing, ignition and combustion was getting shorter, the flame was blown off finally.

1. Introduction

No matter under the subsonic combustion or supersonic combustion condition, more researchers often focus on the ignition [1–3] and flame stabilization [4–6] in the engine. This problem applies especially to the kerosene in the supersonic combustor, which has longer reaction time than smaller molecules (such as hydrogen and ethylene). Also, the time available for fuel injected, vaporized, mixed with air, and combustion is very short, of the order of milliseconds. So, the investigation on flame stabilization in kerosene fueled supersonic combustor will be of great challenge and significance.

Zhang [7] experimentally studied the blowout limits of cavity-stabilized flame of supercritical kerosene by using Mach 2.5 and 3.0 direct-connect supersonic model combustors. Results showed that there existed two blowout limits corresponding to the lean-fuel and rich-fuel conditions for a given stagnation temperature, the location of fuel injection had substantial influence on the blowout limits, but the influence of the stagnation pressure and the divergence angle of the combustor could be neglected. Zhu [8] investigated the flame stabilization in a dual-mode scramjet under the inlet Mach numbers of 2.0 and 3.0. The results showed that the flame could only be stabilized in the recirculation region or two thin regions of the upstream strut under the lower inflow enthalpy condition, but an additional stabilized flame could be found in the boundary-layer separation region of the side walls under the higher inflow enthalpy condition.

The flame stabilization in a liquid-kerosene-fueled supersonic combustor was numerically and experimentally investigated by Hu [9], Results showed that the strut strategy could organize stable supersonic combustion at the center of the combustor, even with an 8 mm thick strut, the combustion could be stable in a wide range of equivalence ratio from 0.25 to 1.0 by using liquid room-temperature kerosene. Sun studied the spark ignition process in a hydrogen fueled scramjet combustor under Mach 4 flight condition [10]. The experiments revealed that flame kernel occurred near the igniter and grew to form flame in the cavity. The expand angle of the upper wall and the disturbance caused by the upstream cavity had an obvious effect on the fuel diffusion and the ignition, hydrogen fuel could improve the ignition performance.

Yu studied the combustion enhancement and stabilization in a liquid kerosene fueled scramjet combustor [11]. It was found that cavity configuration was demonstrated to have better combustion performance than the single-cavity module, also, kerosene injection location and injection scheme had strong effects on the minimally required pilot hydrogen equivalence ratio for flame stabilization. The flame

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Nomenclature

Ma	Mach number
ER	equivalence ratio
H	depth of cavity step
W	width of cavity
L	length of cavity
P	wall pressure of combustor
T	time
x	distance from combustor entrance

establishment and propagation processes in a supersonic combustor fueled by liquid kerosene at Mach 6 condition were studied by Zhang and Chang [12–16], the thin strut was used as the flame holder in the center of the combustor. The results showed the attribute of the flame was partially premixed flame and the flame could be divided into three main parts, and different flame propagation patterns in the flame establishment processes were found in different equivalence ratios. Mohamed Ali [17] investigated the aft-ramp cavities on flame stabilization in supersonic flows. The results indicated that cavities with a lower ramp angle could be effectively used for suppression of oscillations and entrainment control, the improvement in the flame-holding characteristics with aft-wall modification for the high-aspect-ratio cavity was less significant than that of the low-aspect-ratio case.

Based on the above discussions, it was found that many factors influenced on flame stabilization in a supersonic combustor. The thermal throat was common in the scramjet combustor, but few published papers focused on its effect on flame stabilization, which was our main purpose of this paper. So, this research helped to understand and realize the combustion characteristics in the scramjet combustor. In the present paper, experimental and numerical methods were used to investigate the effects of thermal throat on flame stabilization in a kerosene fueled supersonic combustor.

2. Experimental and numerical simulation methods

2.1. Facility and combustor configuration

The present experimental investigation was conducted in the dual-mode scramjet test rig of China Aerodynamics Research and Development Center [18,19], as shown in Fig. 1. High-enthalpy vitiated air was provided by burning hydrogen, oxygen, and air in a heater, which had a molar composition of 21% O_2, 12% H_2O, and 67% N_2. The combustor inflow Mach number was 2.0, stagnation temperature and stagnation pressure were 1100 K and 1.0 MPa, respectively. The mass flow rate of the isolator entrance was 2.92 kg/s.

Figs. 2 and 3 showed the schematic of the model scramjet combustor that had an entrance cross section of 30 × 150 mm^2, which could be divided into two sections, including a 300 mm length isolator and an 800 mm length combustor. The depth and length of the cavity were 11 mm and 121 mm, respectively. Detailed length descriptions about the scramjet combustor could be seen in Fig. 3, the “x = 0” position was defined as the isolator entrance of the top wall in the symmetry plane. There were five fuel injected positions shown in Fig. 2, the K injectors (K1, K2, K3 and K4) were designed for injecting room temperature liquid kerosene, the pilot hydrogen injector (x = 325 mm) was designed for introducing pilot hydrogen which was used to ignite the kerosene. The locations of the four K injectors were 285 mm, 525 mm, 450 mm and 470 mm from the isolator entrance, respectively. The kerosene was injected into the airflow by fifteen 0.3 mm in diameter fuel injection holes, and the hydrogen was injected by ten 1.0 mm in diameter fuel injection holes. There were two spark plugs in the cavity, which were used to ignite the pilot hydrogen. The energy and frequency of the spark plug were 10 J and 50 Hz, respectively.

There was a pressure monitor located in the cavity floor near the cavity ramp (x = 425 mm) which was used to monitor the pressure changing at this position. The monitor pressure could be used to describe the flame development process, because the monitor was located in a lower speed, higher temperature and pressure recirculation zone where was benefit to the flame existence.

In this paper, the pilot hydrogen was only used to ignite the cold room temperature kerosene, which must be injected into the combustor firstly. Then, the kerosene injected from K1 injector was ignited by the pilot flame and more heat would be released, so, the kerosene injected from K2 injector could be ignited successfully. Finally, the kerosene was injected into the combustor from K3 and K4 injector. After the kerosene combustion and heat release sufficient, the pilot hydrogen was removed.

The test sequence of the studying case was shown in Table 1, the cold flow generated at t = 0.0 s. The pilot hydrogen was injected into the combustor from t = 0.12 s to t = 0.39 s, the kerosene was started to be injected into the combustor from K1, K2, K3 and K4 at t = 0.23 s, t = 0.26 s and t = 0.29 s, respectively. The running time of the facility was about 0.4 s, the equivalence ratio (ER) distribution of each case had been shown in Table 2.

The sampling frequency of pressure transducer (0–700 kPa) was 1 kHz, which was used for measuring the sidewall pressure. Also, high-speed framing of flame luminosity was introduced to characterize the combustion flow, which was captured by a CCD camera, and the frame rate was 2000 fps.

2.2. Numerical methods

In this study, the inhouse CFD code AHL3D [20–22] software was used for computation. A fully coupled form of species conservation equations and Reynolds averaged Navier-Stokes equations (Eq. (1)) were used as a governing equation set for a chemically reacting supersonic viscous flow.

$$\frac{\partial Q}{\partial t}+\frac{\partial F}{\partial x}+\frac{\partial G}{\partial y}+\frac{\partial E}{\partial z}=\frac{\partial F_v}{\partial x}+\frac{\partial G_v}{\partial y}+\frac{\partial E_v}{\partial z}+S \quad (1)$$

Here, $Q=(\rho,\rho u,\rho v,\rho w,\rho E_t,\rho Y_i)^T$, and C_i was the mass concentration for species *i*. E_t was the total energy, including kinetic energy and internal energy. E, F and G were the inviscid fluxes. E_v, F_v and G_v were the viscid fluxes. S was the source term, u, v and w were the velocity components in Cartesian coordinates x, y and z, ρ was the density.

Cell-averaged finite volume techniques were used to solve the conservative form governing equations. *LU-SGS* method was used in time-marching. In space terms difference, third order *MUSCL* interpolation method and *AUSMPW+* scheme were used in inviscid fluxes construction, central difference method was used in viscous fluxes. Kok's modified *k-ω* TNT two-equation turbulence mode was used in

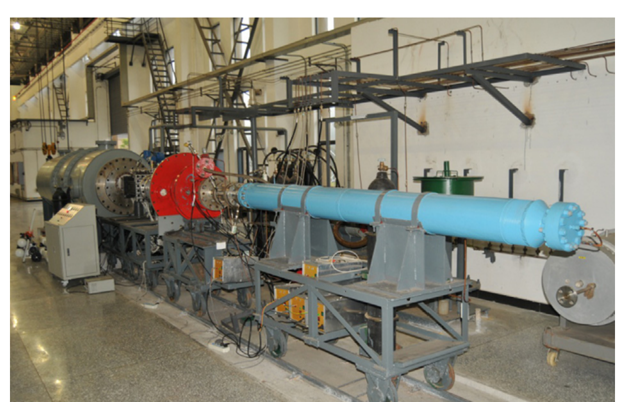

Fig. 1. CARDC's 3 kg/s pulse combustion wind tunnel.