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Investigation of flameholding mechanisms in a kerosene-fueled scramjet combustor

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ABSTRACT

Laser-induced fluorescence and high-speed photography were employed to investigate the kerosene flame stabilization mechanism in a cavity-based scramjet combustor with an inlet condition corresponds to flight Mach number of 4. Pilot hydrogen was used to ignite the kerosene fuel. The PLIF results of kerosene distribution in the reacting cases showed that the mixing process was dramatically enhanced compared to the non-reacting cases. Sharp OH gradients were observed in the shear layer and the aft region of cavity, which indicated that the flame was located at these positions. A portion of hot products participated in the recirculation of the cavity and preheated the kerosene-air mixture in the leading edge. The heated mixture was ignited in the mid-cavity and the reaction zone spread into the mainstream flow. Due to the competition between the local flame speed and the local flow speed, the high-speed images showed that the spreading location was in fluctuation. This movement was observed to cause a low-frequency wall pressure fluctuation.

1. Introduction

The scramjet engine is expected to be the most efficient propulsion system at hypersonic and the development of its combustor becomes an active area of research around the world [1]. In the choice of the fuel, liquid hydrocarbon fuel has a higher energy density and favorable handling characteristics compared with hydrogen fuel [2]. However, their additional atomization, evaporation processes and longer ignition delay time [3] poses a significant challenge in flameholding due to the extremely short flow residence times. Hence, more attention is being given to the flameholding characteristic of liquid hydrocarbon fuel in scramjet combustor [4–10].

Wall-mounted cavities have been considered as a preferred flameholding device since they can form large recirculation zones and avoid higher stagnation pressure loss caused by intrusive structure [11]. Their effectiveness in flame stabilization has been demonstrated in both gas and liquid fuel [12–16]. As a result, a comprehensive understanding of cavity-based flameholding has become a research issue of practical and scientific importance.

Two methods of fueling the cavity have been used. For the passive injection, where fuel is injected upstream of the cavity, many flame stabilization modes were proposed. Micka et al. [12] investigated the combustion characteristics of a dual-mode scramjet combustor with a sufficient distance between fuel injection port and leading edge of the cavity. They found two distinct combustion stabilization locations, the jet-wake stabilized combustion is initiated upstream of the cavity leading edge at higher air stagnation temperatures and the cavity stabilized combustion is anchored within the cavity shear layer at lower air stagnation temperatures. For an intermediate range of stagnation temperature, the reaction zone oscillated between the jet-wake and cavity stabilization locations. Wang et al. [13] studied the combustion characteristics in a supersonic combustor with several cavity geometries, fuel injection port and fueling conditions. Three combustion modes were observed: cavity assisted jet-wake stabilized combustion, cavity shear layer stabilized combustion and combined cavity shear-layer/recirculation stabilized combustion. The cavity assisted jet-wake stabilized combustion was observed to be the most unstable mode, while the combined cavity shear-layer/recirculation stabilized combustion mode seemed to be the most robust mode. These combustion modes can be shifted by changing the cavity geometry, fuel injection ports or equivalence ratio. The other fueling method is directly injecting fuel into the cavity. Gruber et al. [14] study the mixing and combustion processes of the two methods of fueling. Direct injection provides advantages of wider range of stability and more robust flameholding during transient conditions compared with passive injection. Their work highlighted the importance of fuel injection location on the transient stability of a typical cavity-based flameholder. Rasmussen et al. [15] investigated the flame stabilization mechanism of directly injection where fuel is injected from the aft wall and the cavity floor. Their results showed that primary combustion occurred under the shear layer and in the aft region

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of the cavity when fuel was injected from the aft wall and the combustion occurred on the underside of the shear layer when fuel was injected from the floor.

Much of the current insight regarding the flameholding mechanism and mixing characteristic is from advanced optical diagnostic techniques examining reaction zone or select species. Imaging of the natural flame emission was often used to identify reaction zone [12,13]. More sophisticated techniques like PLIF were employed to provide spatial distribution of select intermediates in the combustion process [13–15]. Among the many intermediates, OH is commonly selected to be excited by laser radiation and forced emission. Its peak concentrations are known to occur in the reaction zone. Although OH can be measured in post flame gases due to its long lifetime, sharp OH gradients appear only in the flame boundaries and more gradual OH gradients occur in the transport process.

Much of the previous studies are still mainly focused on gaseous fuels. For the liquid kerosene fuel, little work has been done to examine the flame stabilization scheme. The optical diagnostic technology for the combustion field of gaseous fuel needs further development to apply in the liquid fuel. For example, the use of OH-PLIF techniques in combustion cases is limited because of the possible interference. It is known that the spectrum of induced kerosene fluorescence covers the OH spectrum band and therefore kerosene fluorescence appears on the image of OH fluorescence as well. The interference from kerosene fluorescence is necessary to be evaluated and eliminated.

In the present study, PLIF and high speed photography are used to investigate the kerosene flame stabilization mechanism in a cavity-based scramjet combustor with a Mach 2.0 inflow which corresponds to flight Mach number of 4. In consideration of the possible interference in OH fluorescence, the distribution of kerosene was present by kerosene-PLIF to eliminate the interference. Processed OH gradients distributions were used to determine flame boundaries of kerosene. High speed images of flame luminosity was used to show oscillatory behavior of the flame and related to the pressure fluctuation. Based on the results, the mechanisms of kerosene flameholding were analyzed.

2. Experimental methods

All experiments were conducted in the Northwestern Polytechnical University methane fueled vitiator direct connected test system with an entrance Mach number of 2.0, a stagnation temperature of 885 K and a stagnation pressure of 1.05 MPa. Room-temperature kerosene was chosen as the fuel and the equivalence ratios (ER) were controlled at around 0.25. Hydrogen was injected in the combustor as the pilot fuel to ignite kerosene fuel. Wall pressure measurements and optical measurements were applied simultaneously, but only one type of optical measurements can be applied during each run. Hence, different types of optical measurements were accomplished in different experiments of same condition. Wall pressure measurements were used to confirm the repeatability of experiments.

2.1. *Experimental facility*

The methane heater direct connected test system includes: air source, methane fueled vitiator, combustor model, fueling system, experimental control system and data acquisition system. In the methane fueled vitiator, oxygen is mixed with air firstly and then reacting with methane. The air can be heated to stagnation temperatures between 850 and 2100 K through the methane-air-oxygen combustion. The ratios of methane/air/oxygen are obtained by theoretical arithmetic to contain oxygen mole fraction of 0.21 in the vitiator products.

The combustor model is directly connected to the vitiator through a Mach 2.0 nozzle. It consists of three section s: a constant cross section, a 1.4 deg divergent section and a 2 deg divergent section. The combustor width is constant over the whole length at 40 mm. A cavity flameholder with a depth of 10.8 mm and a length-to-depth ratio of 10.8 is located at Section 2. Kerosene fuel was injected upstream of the cavity through three injectors with namely diameter of 0.35 mm and the distance between the injection port and the cavity leading edge was 35 mm. The kerosene was at room-temperature and the injection pressure was about 1.5 MPa, so the injected kerosene existed in liquid state. Pilot hydrogen fuel was directly injected into the cavity in the floor. A schematic of the combustor model can be found in Fig. 1.

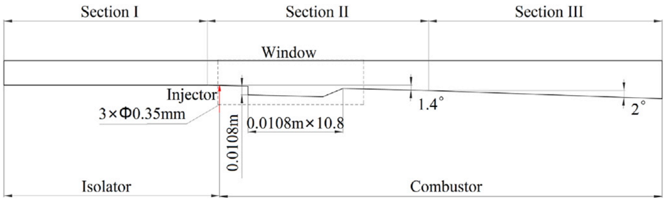

Fig. 1. Schematic of the scramjet combustor model.

In this experiment, 31 pressure-tap ports along the streamwise direction of the combustor model on the upper wall were instrumented with transducers which provided an uncertainty of 0.5%. The detected wall pressures were sampled at 30 kHz using an IDTS-4516U data acquisition instrument.

2.2. *Optical setup*

For both kerosene- and OH-PLIF, a Nd:YAG pumped dye laser at an wavelength of 282 nm was used to excite the Q1(3) transition of the A→X(1,0) band of OH. A micro-cylindrical lens array and a spherical lens were used to create a laser sheet with a height of 90 mm and a thickness of 200 μm. The laser sheet was positioned at spanwise centerline of the combustor and extended from the fore wall to the aft region of cavity, as shown in Fig. 2. An ICCD camera was fitted with an f320 filter and used to collect the OH fluorescence. It should be noticed that kerosene fluorescence was also induced by the laser and its spectrum covers the radiation band of OH fluorescence. As a result, OH fluorescence is interfered by the kerosene fluorescence. In order to evaluate and eliminate the interference, kerosene fluorescence was collected through an f340 filter in the experiments of same condition. The ICCD camera has an imaging array of 512 × 640 pixels, a framing rate of 10 Hz and an exposure time of 50 ns to obtain the instantaneous information. The spatial resolution was about 176 μm per pixel along the dimensions of the image.

A high-speed video camera with an array of 128 × 512 pixels, a framing rate of 2000 Hz and a shutter time of 0.5 ms was used to image the flame luminosity through the observing windows. The imaging area is about 55 mm × 220 mm and the spatial resolution was about 429 μm per pixel. It should be noticed that the exposure time of the high-speed camera was too long to obtain instantaneous information compared with the camera used in PLIF. However, its high frame rate provides information of dynamic characteristics.

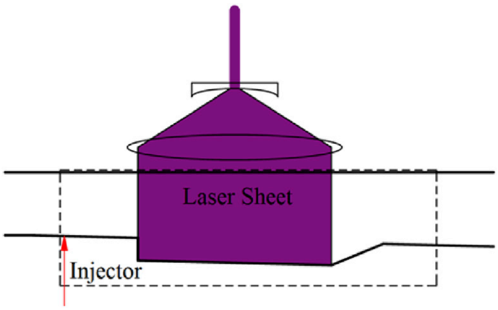

Fig. 2. Schematic of the laser sheet coverage.