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Investigation of the effects of fuel injector locations on ignition and flame stabilization in a kerosene fueled scramjet combustor

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ABSTRACT

The effects of fuel injector locations on ignition and flame stabilization in a kerosene fueled scramjet combustor have been investigated in the present paper. Various measurements are made during the experiments in an attempt to better understand the combustion characteristics, including wall pressure measurements and high speed color flame emission images. The results are obtained under the inflow condition of *Ma* number 2.0, total pressure 1.0 MPa and total temperature 1100 K which corresponds to *Ma* 4.5 flight condition. When the pilot hydrogen and kerosene were injected into the combustor from the injector K2 (in the cavity) and K1 (upstream the cavity), respectively, the kerosene could be ignited successfully by a lower equivalence ratio (*ER*) of pilot hydrogen, but the kerosene flame was blowout after the pilot flame was removed. When the injector locations of pilot hydrogen and kerosene were exchanged, the ER of pilot hydrogen must be increased to achieve successful ignition, the kerosene flame stabilization could be achieved after successful ignition. When the equivalence ratio of kerosene was decreased to 0.13, the lean blowout occurred and flame stabilization could not be achieved after the pilot hydrogen was removed.

1. Introduction

Air entering the scramjet combustor must be supersonic to avoid excessive dissociation of both nitrogen and oxygen gases when the flight Mach number is bigger than 6. Consequently, time available for fuel injection, vaporized, fuel/air mixing, and combustion is very short, of the order of milliseconds [1]. So achieving successful ignition and flame stabilization in the scramjet combustor is an important factor which has to be addressed in the scramjet design.

Yu et al. conducted an experimental study [2] to evaluate the effects of cavities on the flame-holding and mixing enhancement characteristics of supersonic reacting flow. Several configurations of acoustically open cavities were placed inside a supersonic combustor just downstream of the fuel injectors. The results changed in flame behavior and combustion characteristics which were assessed by schlieren images and wall pressure measurements along the duct. Yang et al. [3] investigated the effects of air throttling on ignition transients and flame developments in an ethylene fueled scramjet combustor. Cases both with and without air throttling downstream of the cavity were examined in detail. Successful ignition could only be achieved with the aid of air throttling, and stable flames are achieved even after the deactivation of air throttling. Li et al. [4] analyzed the effects of dual-cavity configuration on ignition and flameholding, their results showed the dual-cavity flameholding scheme could promote the ignition ability and the downstream cavity could stabilize the flame convected from the upstream cavity. Le et al. [5] studied on the effects of the local equivalence ratio in the shear layer on ignition and flame stabilization in hydrocarbon fueled scramjet combustor. Two flame stabilization regimes were observed in their experiments: shear layer stabilized flame and recirculation zone stabilized flame. A data-fitted correlation curve of flame ignition and stability limits was also determined in their paper. Bao et al. [6] investigated the ignition of room temperature kerosene via a spark plug by direct-connect facility experiments, their results indicated that the pressure of the direct injection and the length of the baffle were key factors for the emergence of the weak combustion inside the partly covered cavity, and fuel distribution near the shear layer of the partly covered cavity was indicated to be the key factor in flame propagation process. Bao et al. [7–17] studied the effects of the strut, fuel injection allocation, pilot oxygen, and air throttling on ignition and flame stabilization in the scramjet combustor. Yu et al. [18] investigated kerosene combustion in a Mach 2.5 flow with different integrated fuel injector/flameholder cavity modules, experiments with pure liquid atomization and with effervescent at-

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Nomenclature

Ma	Mach number	*L*	Length of cavity
ER	Equivalence Ratio	*P*	Wall pressure of combustor
H	Depth of cavity step	*t*	Time
W	Width of cavity	*x*	Distance from combustor entrance

omization were characterized and compared. A high-temperature radical pool was located in the cavity flameholder, which played a crucial role in promoting kerosene combustion in a supersonic combustor. effervescent atomization generally leads to better combustion performance than the use of pure liquid atomization, they also found the cavity characteristics could be different in non-reacting and reacting supersonic flows.

Based on the above discussions, many factors influenced the ignition and flame stabilization in the scramjet combustor. But few published papers focused on the effects of fuel injector location on ignition and flame stabilization, which was our main purpose of the present paper. The effects of pilot hydrogen and kerosene injected locations on flame stabilization were investigated in this paper, wall pressure measurements and high speed color flame emission images were used for understanding the combustion flowfield, also the lean blowout limits was analyzed.

2. Experimental and numerical methods

2.1. Experimental methods and combustor configuration

All the experiments in the present study were conducted on a supersonic combustion facility (Fig. 1) with a two dimensional nozzle for Mach 2.0 flow, which had already been introduced in our previous works [19–21]. The air was heated by the hydrogen combustion and additional oxygen was added to maintain a 21% O_2 mole fraction in the vitiated air, and the mole fraction of H_2O and N_2 were 12%, and 67%, respectively. The total temperature and total pressure of the inflow air were 1100 K and 1.0 MPa. High speed color images were captured by a CCD camera, and the exposure time was 0.5 ms and the frame rate was 2000 fps [19]. The chemiluminescence of CH^* was used to mark the kerosene flame zones in the combustor. The luminosity from CH^* was imaged by a CCD camera with ±5 nm bandwidth interference filters centered at 430 nm and the exposure time was 1/2000 s [19]. The sampling frequency of pressure transducer was 1 kHz, which was used for measuring the wall pressure. There was a pressure monitor near the cavity ramp (500.0 mm from the isolator entrance), which was used to monitor the pressure changing during different tests.

Fig. 2a and Fig. 2b shows the supersonic model scramjet combustor [19], which has a total length of 1100 mm and consists of a 300-mm-long section of nearly constant cross-sectional area, a $L/H = 11.0$ cavity (L: length of the cavity; H: depth of the cavity, $H = 16.0$ mm) and four divergent sections of 58.0, 144.0, 150.0, and 272.0 mm in length and 1.4, 2.0, 8.0, and 15.0 deg in expansion angle, respectively. The cross section of the combustor at its entrance is 30.0 mm in height by 150.0 mm in width. "0" indicates the beginning of the constant cross section and also represents the starting point for the static pressure measurement. The 0.5 deg divergence angle in the isolator is used to compensate for boundary-layer growth. Fifteen orifices of 0.3 mm in diameter are used for kerosene injection and ten orifices of 1.0 mm in diameter are used for pilot hydrogen injection, each of them can be located at the cavity floor (Injector K2, 325.0 mm from the isolator entrance or 25.0 mm downstream the cavity step) or at the wall upstream of the cavity (Injector K1, 285.0 mm from the isolator entrance or 15.0 mm upstream the cavity step), as shown in Fig. 2. Pilot hydrogen is used to enhance the ignition of kerosene in the supersonic combustor.

Fig. 1. Photo of the supersonic combustion facility in CARDC.

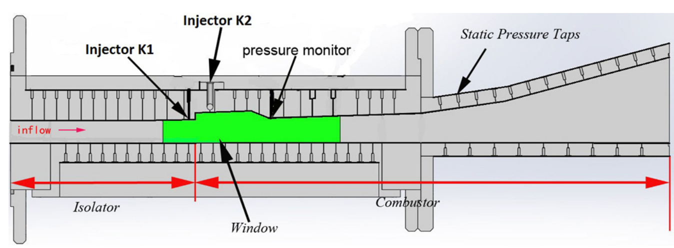

Fig. 2a. Schematic illustration of the combustor.

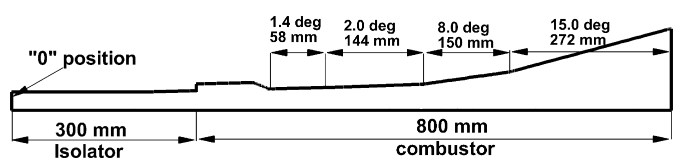

Fig. 2b. Length description of the combustor.

2.2. Numerical methods

In this study, the inhouse CFD code AHL3D software which had been introduced in reference was used for computation [19–25]. A fully coupled form of species conservation equations and Reynolds averaged Navier–Stokes equations were used as a governing equation set for a chemically reacting supersonic viscous flow.

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 [26] was used in turbulence simulations. The kerosene reaction mechanism modified version of CARDC's chemistry mechanism, involving 12 elementary reaction steps and 10 reaction species was