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Effect of cavity fueling schemes on the laser-induced plasma ignition process in a scramjet combustor

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A B S T R A C T

Laser-induced plasma (LIP) ignition processes in a cavity-based scramjet combustor were investigated experimentally in this study. CH* spontaneous emission recorded at a flame rate of 50 kHz was used to characterize the ignition and flame stabilization processes. Numerical calculation was also performed to characterize the non-reacting flow-field structures. Effect of cavity fueling schemes on the LIP ignition process in the rear-wall-expansion cavity was then examined. It is found that the cavity fueling scheme acts as a dominant factor in a LIP ignition process. After a LIP ignition in the cavity rearward, the initial flame kernel is likely to anchor and grow directly in the rearward of the cavity under cavity upstream fueling schemes. However, the flame kernel will propagate towards the cavity leading edge and grow there under cavity direct fueling schemes. It is concluded that both chemical and turbulent issues of the flow-field affect the LIP ignition process. Local fuel-rich environment inside the cavity is favorable for a LIP ignition process, and the fueling scheme with parallel fuel injectors upstream the cavity is most favorable for a LIP ignition which presents a stable combustion process.

1. Introduction

In a scramjet combustor, ignition and flame stabilization processes are of particular importance for the supersonic air-breathing propulsion system. Specially, the cavity-based flame-holders are more attractive in a scramjet combustor when the fuel injectors integrating into the flame-holders. In the past decades, cavity-stabilized ignition and flame stabilization have been widely investigated [1–8].

Ignition processes in a cavity-based scramjet combustor are highly transient events which could be influenced by supersonic inflow, cavity geometry, ignition source and cavity fueling scheme [9]. Due to the severe environment in a supersonic flow, many techniques have been utilized to achieve a successful ignition in the scramjet combustor, such as spark plug [10], pulse detonation [11], pulse discharge [12], plasma torch [13] and laser-induced plasma [14]. To date, laser-induced plasma (LIP) has been widely investigated in a supersonic flow. Comparing with other traditional ignition methods, laser-induced plasma ignition has several advantages, such as, accurately controlled laser excitation time, spatially adjustable ignition locations and precisely controlled energy deposition. Besides, LIP can also minimize the interference to the flow-field due to lack of the electrodes.

Phuoc [15] studied the laser-induced plasma process, showing that four mechanisms exist during the ignition process: thermal initiation, non-resonant breakdown, resonant breakdown and photochemical ignition. Jacobsen et al. [16] studied the plasma igniter performance in a Mach 2 cavity-based scramjet combustor, and they found that a successful hydrogen ignition could be achieved by a produced excited gas with a peak temperature up to 5000 K. Brieschenk et al. [17] used planar laser-induced fluorescence of hydroxyl radicals to record the ignition process in a constant-area scramjet combustor, and they found that LIP can enhance hydrogen ignition in a hypersonic flow due to the formation of reactive hydroxyl radicals. Yang et al. [18,19] also achieved successful LIP ignitions in a cavity-based model scramjet combustor using successive laser pulses and detailed flame propagation processes were recorded.

In a real flight condition, cavity-based flame-holders are always susceptible to detrimental combustion processes. Thermal choking is a typical detrimental operation mode which is able to decrease the scramjet engine thrust and cause unsteady aerodynamics. Recently, it has been demonstrated that thermal choking prevention can be achieved in the combustor with a rear-wall-expansion geometry under a low-Mach flight condition [20]. Previous studies indicate that most researchers focused on recording detailed and time-resolved LIP ignition processes in a traditional

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Table 1
Boundary conditions for computational domain.

Parameter	Air	Cases 1–2	Cases 3–4
T_0 (K)	1530	300	300
P_0 (MPa)	2.6	1.5	1.5
Ma	2.92	1.0	1.0
Y_{O_2} (%)	23.3	0.0	0.0
Y_{H_2O} (%)	5.9	0.0	0.0
Y_{CO_2} (%)	9.6	0.0	0.0
Y_{N_2} (%)	61.2	0.0	0.0
$Y_{C_2H_4}$ (%)	0.0	1.0	1.0
Φ		0.30	0.05
Injectors		$2 \times \phi 2.0$ mm	$1 \times \phi 1.0$ mm

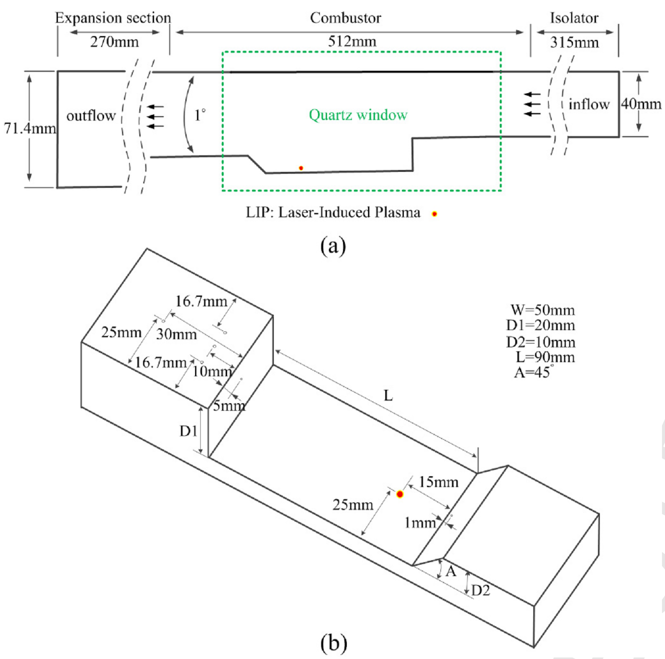

Fig. 1. Schematic of the scramjet combustor geometry in (a) and fuel injector setups in (b).

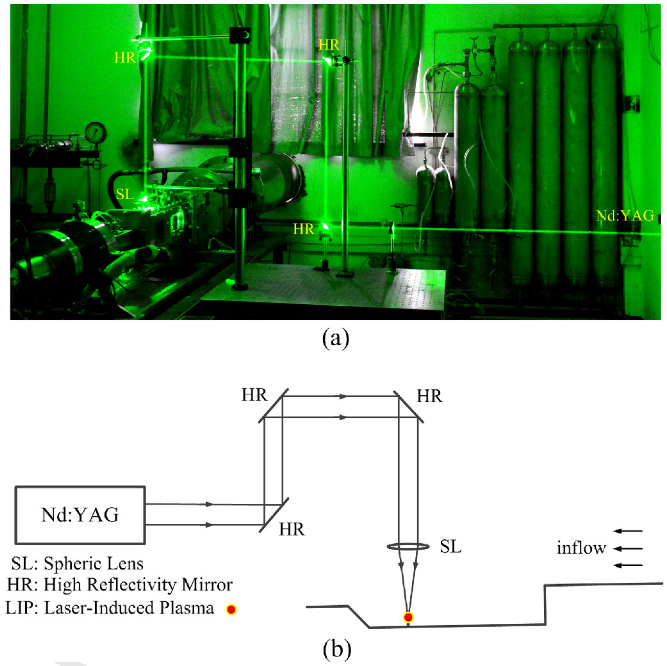

Fig. 2. Photo of the LIP ignition experiments test facility in NUDT in (a). A schematic of the optical arrangement of the LIP ignition experiments in (b).

combustor geometry. However, in the current work, the LIP ignition processes were investigated in a scramjet combustor with a rear-wall-expansion geometry operating on ethylene fuel, which is an industry promising dual-mode scramjet combustor configuration. The present work aims to investigate the effect of cavity fueling schemes on the LIP ignition process, and the non-reacting flow-field structures which affect the LIP ignition process will also be analyzed.

2. Experimental and numerical setups

2.1. Supersonic combustor and flow conditions

The ignition experiments were conducted in the NUDT (National University of Defense Technology). The test facility has four components: an air heater, an isolator, a scramjet combustor and a nozzle. The air heater provides a vitiated air inflow with a stagnation pressure of 2.6 MPa and a stagnation temperature of 1530 K from burnt gas which is produced by pure ethanol, oxygen and air. The vitiated air expands through a Ma = 2.92 nozzle, flows through the scramjet engine and finally exhausts into the atmosphere. The total mass flow rate of the vitiated air is approximately 1 kg/s. The detailed inflow conditions of the scramjet combustor could be seen in Table 1.

As depicted in Fig. 1(a), the bottom wall of the scramjet combustor has an expansion angle of 1° and the cavity in the combustor is a typical rear-wall-expansion cavity. The height difference between cavity front wall depth and rear wall depth leads to different bottom walls of the combustor expanding directly from the cavity rear wall. Thus, this geometry is referred to as the rear-wall-expansion cavity. As shown in Fig. 1(b), the front wall depth, rear wall depth, length and closeout angle of the cavity are 20 mm, 10 mm, 90 mm and 45°, respectively. There are also four 2.0 mm-diameter porthole injectors located upstream the cavity and two 1.0 mm-diameter porthole injectors located on the cavity front wall and rear wall. The detailed setups of the fuel injectors can be seen in Fig. 1(b) clearly. In addition, the laser focus point is located 1 mm vertical away from the cavity floor and the detailed ignition location is also marked clearly in Fig. 1. It should be noted that, in this study, the laser focus point is located according to previous ignition optimizations [21].

2.2. Laser setups and optical measurements

Fig. 2(a) depicts a photo of the LIP ignition experiments and the laser routine can be seen clearly. Fig. 2(b) presents a schematic of the optical arrangement of the LIP ignition experiments. In the experiments, a frequency-doubled Nd:YAG laser (Spectra Physics, Pro-250) with a 10 ns pulse duration at 532 nm is used. The laser beam is focused in the central plane of the combustor and above the cavity by a spherical lens (SL, $f = 130$ mm), after reflected by several high-reflectivity mirrors (HR). There will be another bright dot on the cavity floor, and it is caused by the metal reflection by the residual laser after the focus. It has been proved that the majority energy of the laser is focused above the cavity floor and the metal reflection effect could be neglected. In this study, the laser energy is kept about 300 mJ/pulse and it is estimated that the energy absorbed by the LIP is approximately 250 mJ/pulse.

A combination of a high-speed photography (FASTCAM SA-X2) and a $f/1.4$ Nikkor lens is used to visualize the flame in the experiments. The frame rate of the high-speed camera is set at 50 kHz with a resolution of 768 × 328 pixels and with a exposure time 18 µs in order to record the ignition and flame spreading processes particularly. A 10 nm bandpass filter centered on 435 nm in conjunction with the high-speed photography camera is used to

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