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Experimental investigation on ignition schemes of partially covered cavities in a supersonic flow

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ABSTRACT

In this study, ignition schemes of the partially covered cavity in a scramjet combustor were investigated under inflow conditions of $Ma=2.1$ with stagnation pressure $P_0=0.7$ Mpa and stagnation temperature $T_0=947$ K. It reveals that the ignition scheme of the partially covered cavity has a great impact on the ignition and flame stabilization process. There always exists an optimized global equivalence ratio of a fixed ignition scheme, and the optimized global equivalence ratio of ignition in the partially covered cavity is lower than that of the uncovered cavity. For tandem dual-cavities, ignition in the partially covered cavity could be enhanced with the optimization of global equivalence ratio. However, ignition in the partially covered cavity would be exacerbated with further increasing the global equivalence ratio. The global equivalence ratio and the jet penetration height have a strong coupling with the combustion flow-field. For multi-cavities, it is assured that fuel injection on the opposite side could hardly be ignited after ignition in the partially covered cavity even with the optimized global equivalence ratio. It is possible to realize ignition enhancement in the partially covered cavity with the optimization of global equivalence ratio, but it is not beneficial for thrust increment during the steady combustion process.

1. Introduction

Scramjet engines are promising candidates for future air-breathing propulsion systems [1–3]. A vital part of the effort to develop scramjet engines capable of sustaining hypersonic flight in the atmosphere is the ability to understand the complex mixing [4], ignition [5] and combustion [6] process inside a scramjet combustor. Among many flame-holding facilities, cavities had been widely validated to be efficient flame-holders for scramjet combustors [7]. Besides, a stable flame in the cavity can act as an ignition source for the core flow, which is fueled separately and provides the bulk of the heat release for producing thrust in a scramjet engine. For the past decades, investigation of the conception of cavity-based flame holder has been an active area of research all around the world [8–12].

As a result of cavity configuration optimization, the partially covered cavity is on the basis of the development of trapped vortex combustor [13], which is first widely used in aviation turbine engines [14]. As a new cavity conception, partially covered cavity has been studied in the acoustic oscillation field in the past investigations [15,16]. Jong et al. [17] conducted numerical simulation on a two-dimensional partially covered cavity under a low Mach number inflow condition. Syed et al. [18,19] used detached eddy simulation turbulence model and found that application of baffle changes the frequency, amplitude, and direction of the sound generated from uncovered cavity. Wittich et al. [20] put forward a modified

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Nomenclature

D	cavity depth
L	cavity length
A	cavity aft ramp angle
T_0	stagnation temperature
P_0	stagnation pressure
t	time after ignition
ϕ	global equivalence ratio
Ma	mach number
Pi	injection stagnation pressure
$\dot{m}_f$	ethylene mass flow rate

version of Rossiter's formula, called the "long-path" formula, and described the peak frequencies observed in the partially covered cavity pressure spectra. Unalmis et al. [21] investigated how the interaction between the cavity acoustics and the shear layer dynamics of the partially covered cavity is affected by increasing Mach number.

In addition to the study in the acoustic oscillation field, Bao et al. [22] conducted experiments to achieve kerosene ignition with room temperature by a spark ignitor in a supersonic flow, and they proved fuel distribution near the shear layer of the partially covered cavity is the key factor for the initial flame expanding. Cai et al. [23] conducted numerical simulations on the ignition and flame propagation process of the partially covered cavity, and found that the baffle is detrimental to flame propagation but beneficial for ignition enhancement.

Although the concept of partially covered cavity has existed for many years, the ignition schemes of partially covered cavities were rarely focused. As a new cavity configuration, it has been proved both experimentally and numerically that ignition in the partially covered cavity in a supersonic flow could be intensified due to the cavity configuration [22,23], and it may be a practical way to achieve the kerosene ignition with room temperature in the scramjet engine.

This paper is an effort aiming at investigating the influence of ignition scheme on the ignition process of the partially covered cavity. The comparison of ignition schemes with different cavity configurations will be discussed in detail.

2. Experimental description

A direct-connected test facility [24] was used in the experiments. The facility was composed of a pedestal, an air heater, a scramjet engine, a fuel supply system and a measure control system. The entire test rig, including the air heater and the model combustor, was mounted upright on a platform. A weight sensor mounted on the forehead of the air heater was used to measure the rig thrust changes during the experiments. This system yielded a maximum force reading of 10000 N with an uncertainty of 0.5%. The air heater burned pure ethanol and oxygen continuously to heat air from room temperature to 947 K and increase the stagnation pressure of vitiated air up to 0.7 Mpa. The total mass flow rate of vitiated air was 2.00 kg/s. The two-dimensional converging-diverging $Ma=2.1$ nozzle section, configured with a rectangular nozzle, was adopted to develop the designed inflow conditions. The detailed inflow conditions are shown in Table 1.

There were four integrated fuel-injection/flame-holder cavity installations in the test section, two of them were installed on the top wall, and the other two were on the bottom wall. Here, for brevity, we denoted the cavity installed on the top wall close to the isolator as T1 and the downstream cavity as T2. The cavities on the bottom wall were denoted as B1 and B2. Only cavity T1 was a partially covered cavity and the other three were uncovered cavities. The detailed installation scheme was shown in Fig. 1.

T1 cavity was a typical partially covered cavity. As shown in Fig. 2, the depth D, length L, width W and aft ramp angle A of T1 cavity were 25 mm, 170 mm, 75 mm and 45° respectively. We denoted T1 as D25L170W75A45. Besides, T2 cavity was $D25L125W75A45$, B1 and B2 cavities were $D15L110W75A45$. For all the cavities, each injector had four orifices with 2.0 mm in diameter, and the distance from the injector centerline to the cavity front wall was 20 mm.

Ethylene with room temperature was used in all the experiments. A spark ignition plug was mounted 50mm away from the cavity front wall of T1 cavity. The capacitive-discharge spark system was the most frequently used electrostatic ignition source in practice. The igniter with excitation energy of 5.0 J and excitation frequency of 50 Hz was used in this study [12]. Besides, the overall ignition time in the sequence was 400 ms. It has been shown numerically that the cavity flame stabilization will be decreased with a long baffle, while the ignition enhancement will be decreased with a short baffle [23]. In general, the length of baffle should be between 1/2 and 1/7 of the cavity open mouth. The baffle with a length of 50 mm covered 2/5 of the cavity open mouth, and it was 2 mm thick. This was chosen according to the experiments. In order to stabilize the flame in the combustor, a second cavity was placed downstream of the partially covered cavity.

The ignition and propagation process in the test section were visualized by the high-speed photography through two quartz window with a size of 190 mm × 100 mm. In order to observe and analyze the flame development process particularly, the camera was set at 10000*fps* to measure an area of 1024 × 512 pixels with a shutter time of 1/10,000 s and an aperture of 1.4. Besides, in order to obtain the wall-pressure distribution, static pressure taps were installed along the upper wall of the combustor, and the sampling frequency was 100 Hz.