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Short communication

Intermittent back-flash phenomenon of supersonic combustion in the staged-strut scramjet engine

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A B S T R A C T

The scramjet-powered hypersonic vehicle depends on the sustained and stable supersonic combustion processes, which requires a balance between the flame propagation velocity and the fluid speed. Flame propagation inside a kerosene-fueled staged-strut scramjet engine was experimentally studied in Mach 3.0 incoming flow with the stagnation temperature of 1899 K. The fuel mass flow rate was linearly controlled by an adjustable venturi during the dynamic injection experiment. Two inspection windows were installed on the side and top walls of the combustor respectively. A mirror was utilized to change the light path from the top window to be horizontal to capture the flame structure in the two windows simultaneously. A high-speed imaging camera was employed to capture the flame propagation process described in this short communication. Video imaging showed that the flame was mainly stabilized in the boundary-layer separation region when the upstream equivalence ratio was less than 0.2. In particularly, this short communication reported an intermittent back-flash phenomenon while the fuel equivalence ratio was turned up near to 0.2. The back-flash flame was suggested to be detonation wave by a primary C-J analysis.

1. Introduction

The dual-mode scramjet engine is regarded as one of the most promising propulsion devices for the future space access and high-speed weapons [1,2]. As the airflow residing time is as short as millisecond order of magnitude [3], it is particularly difficult to observe and measure the supersonic combustion and flow field in the laboratory. The researchers worldwide have put a lot of effort to investigate the flame propagation and stabilization in the scramjet combustor [4,5]. Chun et al. investigated the conversion of the flame and flow structures between the weak combustion and strong combustion in a scramjet combustor [6]. Hu J.C. et al. studied the flame propagation process from the forced ignition to a stable combustion state. The propagation process of the pilot-O_2 strut flame was recorded by a high-speed imaging camera [7]. Fotia M.L. et al. gained a flame propagation upstream when the combustor was translated from scramjet combustion mode to the ramjet combustion mode [8]. Wang Z.G. et al. reported that flame propagation was observed against the supersonic inflow with a fixed fuel injection [9]. Micka et al. found the flame flashback from the "cavity stabilized flame" location to the "jet-wake stabilized flame" location under varying stagnation temperature [10]. However, most of the previous work was conducted in the dual-mode scramjet with single-staged injection. The multi-staged scramjet, which involves more complex combustion and flow process, is lack of investigations.

In this short communication, a scramjet combustor installed with two-staged-strut injector and a cavity flameholder was employed for the ground experiments. The flame propagation process at the heart of the staged-strut scramjet model combustor will be presented in Mach 3.0 with the stagnation temperature of 1899 K. Wall pressures were measured and the flame was captured by a high-speed imaging camera.

2. Experimental setup

A hydrogen combustion heater was employed to simulate the high enthalpy incoming airflow at the flight Mach number of 6.5. The incoming airflow stagnation temperature was set at 1899 K accordingly. Additional oxygen was injected into the air flow to keep a 0.21 O_2 mole fraction in the combustion products. The vitiated air entered the isolator at a Mach number of 3.0. The operating condition of the heater is shown in Table 1.

An isolator with a section size of 60 mm (height) × 100 mm (width) is connected to the outlet of the heater, as shown in Fig. 1. The top wall of the combustor is diverged at an angle of 2 de-

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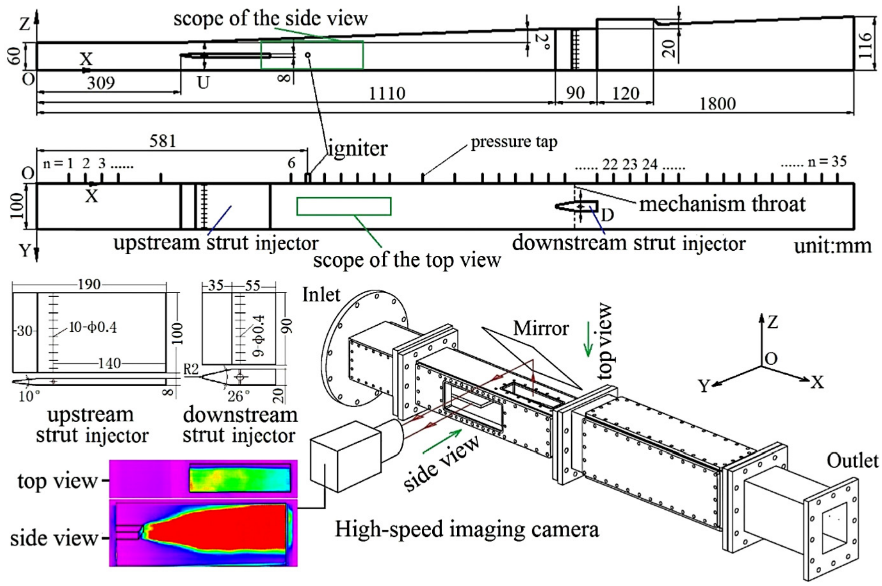

Fig. 1. Schematic of the dual-mode scramjet combustor of BEIHANG University.

Table 1
Operating condition of the heater.

M_{flight}	M_0	P_0^* MPa	T_0^* K	$\dot{m}_{air}$ kg/s	X_{H_2O}
6.5	3.0	2.13 ± 0.05	1899 ± 57	2.044 ± 0.053	0.24

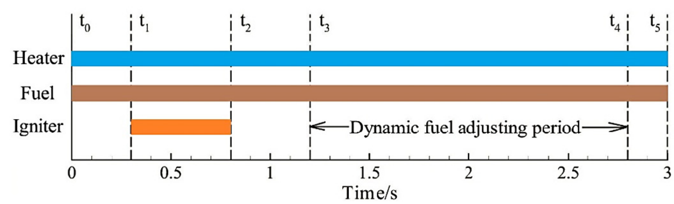

Fig. 2. Typical time sequence of the experiment.

gree. The two strut-injectors are installed perpendicularly. There are twenty and eighteen inject-holes, whose diameter is 0.4 mm, distributed on the upstream and downstream struts respectively. A cavity with a length-to-depth ratio of 6 is installed close to the downstream strut to enhance the flame-holding ability. A H_2/O_2 igniter is installed in the wake of the upstream strut on the left-side wall. Once the H_2/O_2 igniter is launched, the upstream strut is ignited immediately by the pilot flame. Subsequently, the downstream strut is ignited by the upstream burnt gas. No external cooling system is adopted for the combustor and the running time is limited to be 5 s to ensure the safety of the combustor. At most 2 s are left for the data acquisition after the establishment of the steady-flow.

There are 35 pressure taps located along the centerline of the left side wall. Pressure transducers, whose uncertainty are 0.5% of full-scale (1 MPa), are connected with the taps through plastic pipes. The length and diameter of the plastic pipe which connects the pressure tap and the pressure transducer are 1 m and 1 mm respectively. The time-delay caused by the plastic pipe is less than 3 ms. The acquisition frequency of the pressure signal is set at 1 kHz. The FP10 serials Programmable Logic Controller (PLC) is supplied by Panasonic and monitored by a computer. Two quartz windows are installed close to each other on the two adjacent side walls. A mirror is employed to change the light propagation direction from the upside window to be horizontal. Subsequently, these two views from different directions can be captured simultaneously. The images of the two upstream windows are recorded at 2000 frames/s using the Mega Speed Corp MS55K high-speed imaging camera. In order to demonstrate the flame structure more obviously, all high-speed images are processed to be pseudo-color images by a software named Adobe Photoshop CS4.

The mass flow rate of the kerosene fuel was controlled by an adjustable venturi, which was installed in the fuel supply pipe of the strut injector. As a controlling parameter of the supply system, the cross-sectional area of the pintle was designed to change linearly with the feed of the pintle. Under a fixed supply pressure (6 MPa), the fuel mass flow rate changed linearly when the pintle was fed at a constant speed. As the upstream equivalence ratio is changed from 0.1 to 0.4, the speed of the injected fuel is ranged from 7 m/s to 28 m/s. The injection temperature of the fuel is 300 K.

A typical time sequence of the fuel dynamic adjustment combustion test is shown in Fig. 2. The fuel valve opened simultaneously with the heater at t_0. The heater and fuel injector operated steadily after about 0.3 s. Subsequently, the H_2/O_2 igniter installed near the tailing edge of the upstream strut was launched at t_1. It costs about 0.5 s to ignite the dual-mode scramjet model combustor. The igniter was shut down at t_2, and the scramjet operated steadily with a fixed fuel supply. The fuel dynamic adjustment program was triggered at t_3, and finished at t_4. The fuel valve and heater were shut down at t_5. When the combustor operated in the dynamic fuel adjusting period, the upstream equivalence ratio was linearly increased from 0.1 to 0.4 during the whole 1.6 s.

3. Results and discussion

When the two-staged-struts flame holder was experimentally studied under the incoming airflow condition simulated the flight Mach number of 6.5, the stagnation temperature at the inlet of the combustor were set to 1899 K accordingly. The fuel preheating by the airflow with a high stagnation temperature might have a significant impact on the performance of the flame propagation. High-speed images and wall static pressures were collected to investigate the flame propagation in detail under that condition.