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Experimental investigation on ignition schemes of a supersonic combustor with the rearwall-expansion cavity

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ABSTRACT

In this study, ignition schemes of the rearwall-expansion cavity in a model scramjet combustor were investigated under inflow conditions of $Ma=2.52$ with stagnation pressure $P_0=1.6$ Mpa and stagnation temperature $T_0=1486$ K. It is concluded that under the current experimental condition, it is necessary to apply combined injection setups to achieve a successful ignition process for the rearwall-expansion cavity, including the cavity upstream transverse injection and direct spanwise injection setups. Compared with the cavity direct injection on the rear wall, the cavity direct injection on the leading edge is more beneficial for the formation and propagation of the initial flame and it will performs a more robust combustion in the combustor. For the rearwall-expansion cavity, the combined injection (cavity upstream transverse injection and cavity direct spanwise injection on the leading edge) is an optimized injection setup during the ignition and flame stabilization processes. Due to the configuration characteristics of rearwall-expansion cavity, the wall-pressure distribution in the isolator will not be affected substantially by the heat release in the combustor during a robust combustion process, which is important for the prevention of thermal choking and the unstart of scramjet inlet.

1. Introduction

Scramjet engines are promising candidates for future air-breathing propulsion system [1–3]. The scramjet engine design involves ramjet-scramjet transition [4], start–unstart characteristics [5], mixing [6] and combustion performance [7]. These problems mostly are coupled by some complex physical processes, such as ignition [8], turbulent combustion [9] and shock-boundary layer interaction [10]. Due to the complicated physical process and harsh environment, it is a significant work to study the ignition and combustion performance of a dual-mode scramjet combustor. For the past decades, investigation of the dual-mode scramjet combustor with cavity-based flame-holder has been an active area of research world-widely [11,12].

Micka et al. [13] found that there were two distinct combustion stabilization modes for ramjet operation with fuel injection sufficiently upstream of the cavity: jet-wake stabilized (at high inflow stagnation temperature) and cavity stabilized (at low inflow stagnation temperature), however, only the cavity stabilized combustion mode was found for scramjet operation mode. Wang et al. [14] studied the effect of combustor configuration on the performance of dual-mode combustor and found that combustion apparently is well organized with smaller divergent angle. Combustor could avoid inlet unstart and get disperse heat release with double cavities, but there is still space to increase efficiency by changing the location of recirculation zone. Bao et al. [15] investigated the effect of cavity configuration on kerosene spark ignition process in a scramjet combustor. The local equivalence ratio in the shear layer is the dominating factor in determining the developing process of local flame. The final steady combustion mode of the combustor is dependent on the flame developing process. When employing the longer cavity, the establishment of intense combustion state can be much easier.

As a result of combustor configuration optimization, the rearwall-expansion cavity is on the basis of the development of back-step combustor [16], which has been proved to be an effective configuration for the dual-mode scramjet combustor. Milligan et al. [17] compared two scramjet combustor configurations and found that the tapered configuration produced marginally greater stream thrust, although the tapered configuration was very near an unstart condition. The back-step configuration shows a significant advantage in fueling capacity, due to the area relief provided by the back-step. It was found that back-step configuration can achieve a total equivalence ratio of 1.0, while the tapered could only achieve a maximum fueling of about 0.5 before turning unstart. Both the CFD(Computational Fluid Dynamics) and

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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_i	ignition time
ϕ	global equivalence ratio
Ma	mach number
P_i	injection stagnation pressure
$\dot{m}_f$	ethylene mass flow rate

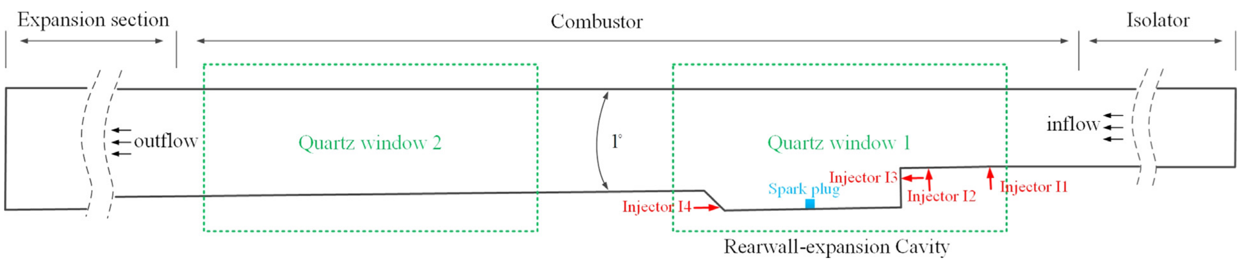

Fig. 1. Schematic of the scramjet engine and cavity installation scheme.

experiment [18] concluded that area relief provided by the back-step combustor allowed for increased fuel and thus greater overall thrust as compared with the tapered combustor that is fully divergent.

As a new cavity configuration, the supersonic combustor with the rearwall-expansion cavity has the similar shape with the back-step combustor, and it has been proved experimentally a practical way to achieve thrust increment and to prevent the thermal choking after ignition in the rearwall-expansion cavity. This paper is an effort aiming at investigating the ignition and combustion characteristics of the supersonic combustor with a rearwall-expansion cavity. The comparison of different ignition schemes of the rearwall-expansion cavity will be discussed in detail.

2. Experimental description

A direct-connected test facility [19] 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. The air heater burned pure ethanol and oxygen continuously to heat air from room temperature to 1486 K and increase the stagnation pressure of vitiated air up to 1.6 Mpa. The total mass flow rate of vitiated air was kept to be about 1.00 kg/s. The two-dimensional converging-diverging $Ma=2.52$ nozzle section, configured with a rectangular nozzle, was adopted to develop the designed inflow conditions. The run time is 6–7 s for the air heater and 1.8–2 s for the fuel injection, and the non-cooling supersonic combustor walls are directly exposed to the atmosphere. The detailed inflow conditions are shown in Table 1.

Table 1
Experimental inflow conditions.

Parameter	Air
T_0 (K)	1486
P_0 (Mpa)	1.6
Ma	2.52
Y_{O_2}(%)	23.3
Y_{H_2O}(%)	5.9
Y_{CO_2}(%)	9.6
Y_{N_2}(%)	61.2

The detailed installation scheme was shown in Fig. 1. An integrated fuel-injection/flame-holder rearwall-expansion cavity was installed on the lower wall of the combustor. The expansion angle of the combustor lower wall was 1°. A spark ignition plug was mounted 45 mm away from the cavity leading edge. 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 [9]. Besides, the overall ignition time in the sequence was 400 ms. Two quartz glass windows were mounted on one side wall of the combustor to allow optical access.

The cavity in the combustor was a typical rearwall-expansion cavity. As shown in Fig. 2, the depth *D1,D2*, length *L*, width *W* and aft ramp angle *A* of T1 cavity were 20 mm, 10 mm, 90 mm, 50 mm and 45° respectively. The difference between D1 and D2 caused the lower wall of the combustor expanding directly from the back of the cavity, therefore, this configuration was called the rearwall-expansion cavity. The upstream wall and the downstream wall of the rearwall-expansion cavity were parallel with the same expansion angle 1°. There were four fueling injectors in the combustor, injector I1 and I2 were cavity upstream transverse injections and located 30 mm and 10 mm upstream of the cavity respectively. Injector I3 and I4 were cavity direct spanwise injections, I3 was located in the cavity leading edge with 5 mm away from the upstream wall, and I4 was located in the cavity rear wall

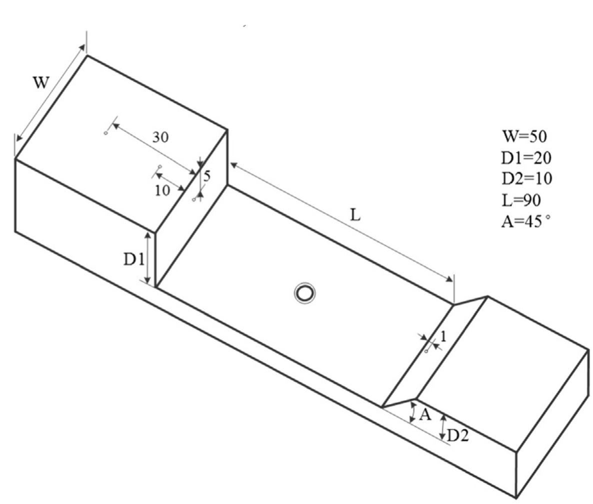

Fig. 2. Schematic of the rearwall-expansion cavity.