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Experimental and numerical investigations of freejet and direct-connect dual-mode scramjet

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ABSTRACT

To understand scramjet operations, comparisons between direct-connect and freejet dual-mode scramjet tests were investigated in this paper via experiment and numerical simulation. Being in accord with the condition of flight Mach number 6.0, the inlet flow conditions of the isolator were achieved with Mach number 3.0, total temperature 1500 K and total pressure 2.1 MPa. Based on these parameters, two tests with equivalence ratio 0.6–600 and 1.0–604 were carried out. In the experiment, pressure at the centerline of the combustor down wall was measured. Simulation including the Mach number distribution at the combustion chamber, the shock wave structures in the isolator, and heat release of the combustor were proceeded and compared. Experimental results show that the measured pressures match the numerically calculated outcomes. Simulation results show that when the combustion case is 1.0–604, the combustor operates in the ram-mode for the freejet test while it is in the scram-mode for the direct-connect test. When the case is 0.6–600, the combustor in both freejet and direct-connect tests operates in the scram-mode. In addition, the specific thrust in the freeject test presents a prominent difference to that in the direct-connect test when the engine operates in the same combustion mode. For case 1.0–604, the thrust difference is 4.38% and for case 0.6–600, the discrepancy is 8.19%. Besides, influence of the heat release on the thrust performance was analyzed for the two tests.

1. Introduction

With in-depth research of hypersonic airbreathing propulsion technology, a large number of experiments and calculations of the dual-mode scramjet have been investigated [1–4]. Ground experimental techniques mainly include freejet and direct-connect tests. In comparison of a direct-connect test, significant advantage of a freejet test is that the forebody inlet flow condition can be accurately reproduced, and the engine performance and operating characteristics are much closer to a real flight condition. However, the test complexity and the expense are costly [5]. On the contrary, a direct-connect test costs low. In a direct-connect test, the flow is discharged directly by a ground facility nozzle into the isolator, and the required experimental condition is gained by changing the inflow upstream of the nozzle. Since the direct-connect test does not need a forebody, hence, the flow is uniform compared with that in the freejet test, which is the most distinctive difference between the two type of tests. In order to effectively use direct-connect test results to investigate the full flowpath scramjet, the difference and its influence to the engine performance and operating characteristics are essential to be considered. Some related research works have been carried out.

Currently, influence of ground test facilities on the scramjet performance is usually studied by the following combined programs: the Short Duration Propulsion Test and Evaluation (SDPTE) Program and the Hy-V Program [6]. Effects of the generated test medium vitiates in the combustor and test flow duration on the operation of two dual-mode scramjet flow-path geometry have been examined using a range of facilities, such as a continuous-flow direct connect facility, a freejet blowdown facility and an impulse facility. Cases of different incoming flows, which are distorted from an inlet or are clean from a facility nozzle, have been experimentally studied to investigate their effects on the combustor ignition and steady-state operation [7]. And the effects of flow distortion on ignition by adopting a same experimental geometry and flow condition were achieved. In addition, an alterable geometry in the dual-mode combustor was used to investigate the effect of different incomings on the combustion performance [8].

In the freejet configuration, distortion of the forebody and inlet flow is apparent. The thickness of the boundary-layer increases along the forebody inlet wall, which directly affect the resistance ability of the back pressure of the engine [9]. On the other hand, a series of compression waves may be produced near the forebody

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Nomenclature

L1	Length of the 1st cavity	P_{in}	Static pressure of the inlet flow
L2	Length of the 2nd cavity	Ma	Mach number
H1	Depth of the 1st cavity	Tt	Total temperature
H2	Depth of the 2nd cavity	Pt	Total pressure
H	Isolator height	ER	Equivalence ratio
P_{wall}	Wall pressure measured	X	Coordinates along direction of flow

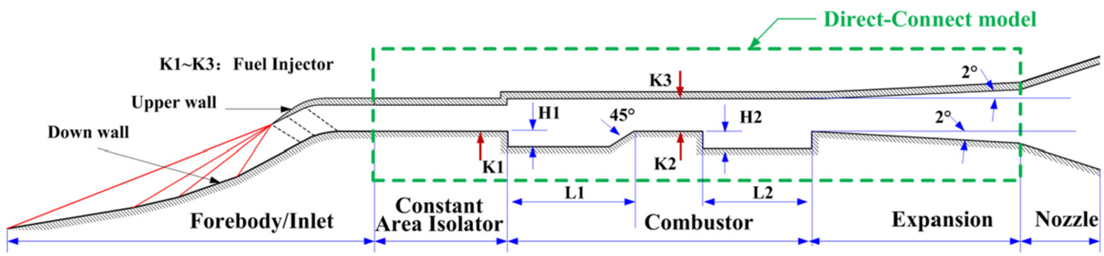

Fig. 1. Sketch of the freejet and direct-connect combustor model.

inlet and then interact with the growing forebody boundary layer. This will induce a local separation at the isolator [10]. As described in reference [9], the maximum sustainable back pressure decreases approximately 5% owing to the doubling of the boundary-layer thickness.

The comparison between direct-connect and freejet dual-mode scramjet has been briefly conducted by T.B. Steva [1], which uses an identical dual-mode scramjet flowpath geometry in the freejet and direct-connect configurations. A series of performance and operability mechanism were established to quantify the similarities and differences of the results, and the effects of the inlet current distortion and backpressure on the performance and operability of the dual-mode scramjet were analyzed. Results show that the inlet current distortion lengthens the shock train for a given pressure ratio, and the mode transition (in one dimensional perspective) is delayed from equivalence ratio with 0.5 in the direct-connect configuration to that with 0.7 in freejet test when given an increasing equivalence ratio.

Numerical investigation of effects of the inlet flow distortion on the performance of a dual-mode scramjet was as well carried out in reference [2,3]. In [2], a detailed computational fluid dynamic (CFD) study with Reynolds-Averaged Navier Stokes (RANS) method was performed, which analyzed the performances of the isolator under three conditions. Which is the isolator locates at downstream of a flight inlet, downstream of a direct-connect facility nozzle with distorted flow and downstream of that without distorted flow. CFD results showed that there is no change for the isolator shock position in all cases. However, differences between the shock trains were observed when the pressure rose, and change of the mass flux distribution at the exit plane of the isolator emerged. Generally, the forebody inlet and the isolator were considered as a whole element in numerical calculation [11,12].

If parameters of the isolator entrance in the freejet test can be matched exactly to that in the direct-connect test, then the experimental and numerical investigation can be regarded as a direct and reliable method to quantify the similarities and differences for identical dual-mode scramjet flowpath geometry in the freejet and direct-connect configurations. To obtain these results, experiment and simulation of freejet and direct-connect dual-mode scramjet tests were implemented in this paper. Wall pressure and Mach number distribution in the combustion chamber, shock wave structure in the isolator and combustor performance were compared under the condition of two different equivalence ratios. Combustion mode and transition process were as well presented.

2. Experimental methods and numerical simulation

The experimental setup and computational method have been introduced detailedly in our previous work [13], and this paper only introduces some of the changes.

2.1. Experimental setup

The freejet and direct-connect combustor model is sketched in Fig. 1, where the cross section of the constant area isolator is 30 mm height (H) and 150 mm weight, and there are 36 fuel injection holes at the K1 position and 16 injection holes at the K2 and K3 position, respectively. The injection holes at K1 point is 15 mm away from the end of the isolator, and the holes at K2 and K3 point is 10 mm away from the second cavity. Diameter of each injection hole is 0.3 mm and all the holes are lined up in a row.

To accurately measure the pressure of the down wall, the pressure taps are located at the centerline of the combustor model and transducers with uncertainty of 0.2% of the full scale (±1.0 kPa) are instrumented. The sampling frequency of the data acquisition card is 1000 Hz. In order to reduce the measurement error, same sensors were used to measure the wall pressure during the freejet and direct-connect tests and calibration of the sensors was carried out after the experiment. To simplify the comparison, the measured pressure (p_{wall}) is normalized by the static pressure (p_{in}) of the inlet flow of the isolator.

To be in accord with the condition of flight Mach number 6.0 for the inlet flow of the isolator, the inlet air was heated up to 1500 K stagnation temperature through H_2–O_2 combustion and O_2 mole fraction is maintained with value of 0.21 in the heated products. Then, the total pressure of the inlet air is about 2.1 MPa, the Mach number is around 3.0 and the mass flux is approximately 2.6 kg/s. Detailed inflow parameters in the isolator entrance are shown in Table 1. Differences of the static temperature and the static pressure between the two types of ground tests are 30 K and 300 Pa, respectively. In addition, combustion tests with two different fuel equivalence ratios are studied, parameters of which are shown in Table 2, where case 0.6–600 means the total fuel equivalence ratio is 0.6, and the fuel equivalence ratio at fuel injector K1, K2 and K3 is 0.6, 0.0 and 0.0, respectively. The parameters in case 1.0–604 are analogous.