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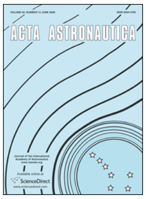

Nonlinear characteristics and detection of combustion modes for a hydrocarbon fueled scramjet

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ABSTRACT

An experimental investigation of combustion mode transition in a hydrocarbon fueled scramjet combustor model is reported under Mach number 2.1 and 2.5 inflow conditions. Three different combustion modes with respect to equivalence ratio are observed, namely, scramjet mode, weak ramjet mode and strong ramjet mode. The typical features of different combustion modes are analyzed by wall-pressures and one-dimensionally estimated Mach number distributions. The processes of combustion mode transitions show significant nonlinear characteristics. The static pressure and Mach number have discontinuous sudden changes as the mode transition occurs, especially near the fuel-supply region, emphasizing the importance of detection and control of combustion modes. The nonlinear characteristics of wall-pressures near the exit of the isolator can be used in the detection of different combustion modes. A series of experiments prove that this pressure-magnitude-based detection technique is feasible.

1. Introduction

Given the broad range of aero-thermodynamic conditions experiences during hypersonic flight [1,2], the supersonic combustion ramjet (scramjet) would operate under different combustion modes [4]. The transition between ramjet mode and scramjet mode is triggered through either changing flight Mach number, or control of the heat release due to combustion at a fixed Mach number ([3]). At flight Mach number of the vehicle below 5, the three leading features of the ramjet-mode include a strong precombustion shock train in the isolator, the thermal throat, and the subsonic combustion zones. With the vehicle accelerating, the shock train and thermal throat disappear. The engine operates in the scramjet mode, and the combustion occurs predominantly in supersonic flow [5].

Some researches on combustion mode transition have been carried out experimentally and numerically for the development of a scramjet engine. Billig [2] firstly demonstrated mode transition in ground experiments. Heiser and Pratt [9] used a one-dimensional analysis approach to comprehend the complex aero-thermodynamics of dual-mode combustion system. The flow-field can be classified as three modes: scramjet with shock-free isolator, scramjet with oblique shock train and ramjet with normal shock train. Takahashi et al. [15], Kouchi et al. [16] distinguished four different combustion modes with respect to the fuel equivalence ratio, namely blow out, weak combustion, strong combustion, and thermal choking. While the mode transition occurred, Takahashi et al. [14] also showed that thrust and heat-flux distribution varied considerably. Daniel et al [7] reported two distinct reaction zones corresponding to jet wake stabilization and cavity stabilization in the combustor with wall injection and a cavity, and scramjet mode combustion zone appeared only in the cavity. By increasing the total temperature of airflow to simulate a real acceleration process, Sullins [13] experimentally achieved the mode

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Nomenclature

A	cross-sectional area
D	the hydraulic diameter
P	pressure, Pa
M	Mach number
k	the ratio of specific heats
x	streamwise distance from the entrance of isolator, mm
φ	equivalence ratio of hydrocarbon fuel
η	combustion efficiency

Subscripts

0	Inflow stagnation value

transition from a scramjet with a pre-combustion shock system to the one without pre-combustion shock system. Chun et al. [6] developed that the combustion mode transitions were caused by a higher back pressure and resulted in changes in the shock train structures. Ryou et al.[12] investigated the effect of combustor length and total temperature on combustion modes, and the minimum combustor lengths to attain the supersonic and dual-mode combustion was recommended.

During combustion mode transition, lots of nonlinear phenomenon appears, such as shock-motion, shock-boundary layer interaction, combustion coupled flow dynamics, etc. To support the dual mode scramjet engine operating in the real flight, there is a deep need for greater understanding of the transition process. At the same time, the mode transition processes are unstable and may cause the combustion instability. Therefore, it is particularly important to effectively detect and control the combustion mode. However, few papers report the engine performance difference under different combustion modes in detail, particularly in a strut-based combustor. In addition, there have been no researches about the detection technique of the combustion mode. The successful development of a scramjet engine depends on further understanding and control of nonlinear mode transition process.

In the present paper, we systematically study the transition characteristics of combustion modes for a hydrocarbon fueled scramjet combustor model with a central strut. Through a series of experiments performed under inflow Mach number 2.1 and 2.5, three combustion modes are observed namely scramjet mode (mode 1), weak ramjet mode (mode 2), and strong ramjet mode (mode 3). A detailed analysis of the combustion mode transition is carried out. Each transition, from mode 1 to mode 2 (transition 1–2) or from mode 2 to mode 3 (transition 2–3), is characterized by nonlinear sudden changes in wall pressure and Mach number. And then a detection technique of different combustion modes, namely the pressure-magnitude-based detection method is developed. This detection approach is essentially using nonlinearities in the transition process of combustion mode, and it is validated for some ground experiments.

2. Experimental setup and data reduction

Fig. 1 shows a schematic illustration of the experimental setup. High enthalpy air flow was created with a hydrogen heater. A strut-based scramjet combustor model is directly connected to a two-dimensional nozzle. The inflow conditions at the combustor entrance are shown in Table 1.The combustor has four segments (labeled as I, II, III, and IV in Fig. 1). Segment I is a constant area isolator, followed by a divergent combustor section along the lower wall, a constant area part and a symmetric divergent section. The cross-sectional area in the isolator is 40 mm × 110 mm, then that at the entrance of Segment III is 60 mm × 110 mm, and it is 60 mm × 130 mm at the exit of the combustor. Segment III is a constant area section with 480 mm long; the length of this section has a great influence on the flame stabilization and heat release efficiency. The half-angle of the wedge-shaped strut is equal to 10°. The maximum thickness of the strut is 8 mm. And it is installed at the center of the combustor with the strut front is 280 mm to the isolator entrance. Hydrocarbon fuel at room temperature (about 300 K) is injected from the strut in the direction normal to the airflow direction, with equivalence ratios ranging 0.1–1. The hydrocarbon fuel used in our experiments is China No. 3 aviation kerosene. In order to solve the issues associated with thermal protection of the central strut, the liquid hydrocarbon fuel injectant serves as active cooling agent and effectively relieves the aerodynamic heating on the thin strut.

To measure the wall static pressures along the streamwise direction, 25 pressure transducers (labeled as T1–T25) are distributed on the centerline of one side combustor wall (as shown in Fig. 1). All of them have ranges of 0–1000 kPa. The transducers were first to be calibrated, the temperature shift below 0.05% F.S./°C,

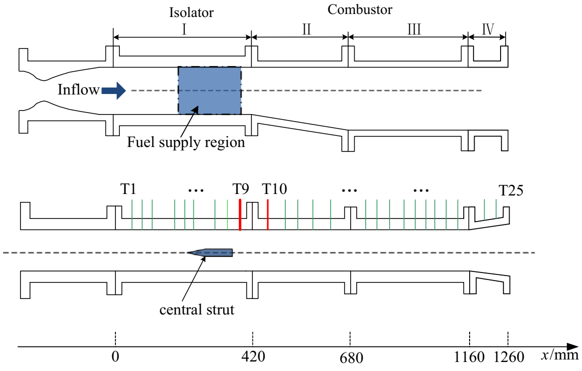

Fig. 1. Schematic diagram of the strut-based combustor.