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Short communication

Relative Time scale analysis for pressure propagation during ignition process of a scramjet

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ABSTRACT

The supersonic combustion ramjet (scramjet) engine is expected to become the most efficient air breathing propulsion system in the hypersonic flight regime. The behavior of wall pressures propagation was examined using a direct-connect model scramjet experiment along with high-frequency pressure measurements. High-frequency pressure transducers are employed to record the history of pressure response during ignition process. A first order plus dead time (FOPDT) model is employed to model the S-shape step response curve. The time scale distributions of pressure propagation are reported in this paper. The characteristics of pressure propagation are closely related to the combustion mode of the scramjet.

1. Introduction

The scramjet is believed to be the most promising candidate for air-breathing hypersonic flight [2]. The ignition characteristics of the scramjet engine have been a subject of investigation for many years and fuel ignition presents fundamental challenge to the design of a hydrocarbon-fueled scramjet engine [12,3]. Rapid spontaneous ignition and complete reaction of fuel are required to achieve efficient combustion, however, if too rapid, they can promote dynamic instabilities, or even unstart of the scramjet engine [1].

In the open literature, Yeol Choi et al. [7] carried out a comprehensive numerical investigation on ignition transients in an ethylene-fueled scramjet engine. To achieve stable combustion in the chamber, a self-sustaining feedback mechanism is established between the flow evolution and flame development. Zhong et al. [15] numerically studied the unsteady process of ignition of partially cracked kerosene. Compared to uncracked kerosene, the finish time of ignition for cracked kerosene is significantly decreased. Mirko Gamba et al. [4,5] experimentally investigated the mixing and combustion of a transverse hydrogen jet in supersonic flow. The OH PLIF imaging was used to map the instantaneous combustion zone. The point of ignition delay is independent of the jet-to-crossflow momentum flux ratio for low values. Jinhyeon Noh et al. [10] carried out a high-resolution numerical study of the auto-ignition process of ethylene-fueled scramjet. It presented the flame evolution during the ignition transient. Moreover, many researchers focused on the investigation of the ignition delay time and the burning time of kerosene-based fuel [9,8,14,6]. The definition of the ignition delay time has received different formulations. Petersen et al. [11] define the ignition delay time from the reactant time history as the intersection of the steepest decay rate with the initial concentration. It is defined as the time interval between the creation of a combustible mixture and the onset of a flame in Ref. [1]. The time required for the mixture to attain 5% of the equilibrium rate is defined as the ignition delay time by Rogers et al. [13], who also defined the burning time as the time required to achieve 95% of the equilibrium temperature, which depends on pressure and initial stagnation temperature for hydrogen–air system.

However, there have been few studies on time scale analysis of the pressures propagation along the combustor length during ignition process of the scramjet. Investigation on the delay time of pressure change and relative time of pressure propagation during the ignition process would be particularly useful for operational dual-mode scramjet engine control. The ignition will cause a significant change in the wall static pressure profile. And this causes a corresponding abrupt change in the thrust force and the pitching moments on the vehicle that may result in instability of the vehicle. In particular, the ignition time characteristics are

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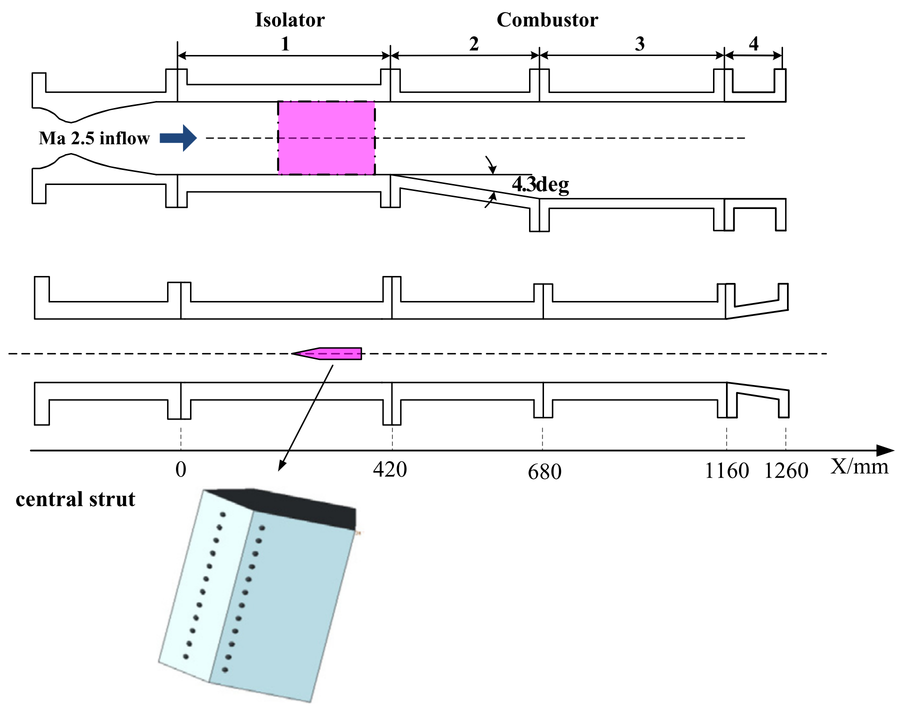

Fig. 1. Schematic diagram of the strut-based combustor.

also significantly affected by the combustion modes of the scramjet. Dependence of fuel ignition on temperature, pressure, and composition is critical in describing the combustion of liquid fuels in scramjet engine, which vary greatly for different combustion modes. When the engine operates in the scramjet mode, there is an adverse pressure gradient in the combustor. However, there is a favorable pressure gradient in the combustor for the ramjet mode. And this correspondingly causes change in the temperature, even for the fuel–air mixing between the scramjet mode and ramjet mode. Therefore, the study on the ignition process under different combustion modes is also necessary.

There are no closed-form solutions of unsteady aerothermodynamics ignition of the scramjet. Applicable numerical simulations are still largely in their infancy, especially for a hydrocarbon-fueled combustor. Therefore, the experimental work on time scales of pressure variations during ignition is of great significance.

This paper carried out a quantitative research on the ignition time features in terms of the wall pressures. Firstly, a brief description of test facility and instrumentation used in the experiments are specified. Time-resolved high frequency pressure measurements are then presented. Then, first order plus dead time (FOPDT) models are used to identify the pressure response dynamics. Characteristics of axial pressures propagation are analyzed during two typical ignition processes, corresponding to scramjet mode and ramjet mode respectively.

2. Experimental apparatus and data reduction

A schematic of the dual-mode scramjet combustor is provided in Fig. 1. The high enthalpy inlet air supplied to the scramjet combustor was produced by a hydrogen–oxygen burner. Additional oxygen was injected to maintain a 0.21 O_2 mole fraction in the heated products. The heater total temperature was 1520 K. The total pressure was 1970 kPa. A strut-based scramjet combustor model was directly connected to a two-dimensional nozzle of the heater. The air enters the isolator at a Mach number of 2.52.

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, Section 2, and a constant area, Section 3. The cross-sectional area was changed from 40 × 110 mm in the isolator to 60 × 110 mm in the exit of the combustor. The length of each section has been included in Fig. 1. To minimize aerodynamic disturbance on the flow field and the strut drag, a thin strut is employed locating at the centre of the isolator, only about 3% in the blockage ratio. Thermal loads at the leading age of the strut may be intense due to the high enthalpy inflow. Therefore, cooling of the structure of the central strut is necessary. As shown in Fig. 1, this is done internally by the liquid fuel, which later on is injected from the side wall surfaces of strut. The liquid fuel used in our experiments is China No. 3 aviation kerosene.

Axial pressure distributions are recorded during the ignition process. A total of 25 pressure-tap ports (labeled as T1–T25) are located along the length of scramjet combustor. Each port is instrumented with a high-frequency pressure transducer. The transducers have the ability to measure over a frequency range of 50–810 KHz. High-frequency pressure signals were acquired using a 12-bit National Instruments NI-6070 data acquisition board. The board was capable of a maximum sampling rate of 1.25 mega samples per second. In this paper, time-resolved measurements were sampled at 80 kHz.

This paper uses the standard deviation as the value of the experimental uncertainty. To calculate the standard deviation, six different tests under the same fuel equivalence ratio are carried out. Then, we will get the original wall pressure data for a fixed fuel equivalence ratio and location, $p_1, p_2, p_3, p_4, p_5, p_6$. The average value of pressure p_{av}

$$p_{av} = \frac{1}{6}(p_1 + p_2 + p_3 + p_4 + p_5 + p_6) \tag{1}$$

The values of the deviation from the average value are used to calculate the experimental uncertainty. The quantity that is used to estimate these deviations is known as the standard deviation s_p and is defined as:

$$s_p = \left(\frac{1}{5}\left[(p_1 - p_{av})^2 + (p_2 - p_{av})^2 + (p_3 - p_{av})^2 + (p_4 - p_{av})^2 + (p_5 - p_{av})^2 + (p_6 - p_{av})^2\right]\right)^{1/2} \tag{2}$$