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Semi-free-jet simulated experimental investigation on a valveless pulse detonation engine

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HIGHLIGHTS

- The semi-free-jet simulated ground experiments of a two-phase PDE were performed.
- The processes of pressure back-propagation were analyzed.
- The average thrusts of the PDE with different induction systems were compared.

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ABSTRACT

The total pressure recovery coefficient, flow coefficient and intake resistance of a valveless pulse detonation engine (PDE) with five different induction systems were measured based on the semi-free-jet simulated ground experiments. The proof-of-principle experiments of pulse detonation engine mockup with above five different induction systems were all successfully carried out, by using liquid gasoline-air mixture with low-energy ignition system (total stored energy less than 50 mJ). The process of back-propagation of pressure and average thrust of PDE mockup with these different induction systems were compared. The results indicated that induction system 1 had higher performance in total pressure recovery coefficient, flow coefficient or flight resistance. The time interval (Δt) between the time of detonation initiation and the time of backward pressure perturbation propagating to the PDE inlet decreased gradually at the increased operating frequency. The average thrust of the PDE with induction system 4 was the highest in case of lower operating frequencies, while that of PDE with induction system 1 was the highest when operating at higher frequencies.

1. Introduction

A pulse detonation engine (PDE) is a pulse or intermittent jet engine based on multi-cycle detonation, which utilizes burnt products of high temperature and high pressure produced by pulse detonation wave to achieve thrust. The process of detonation is quasi-constant volume combustion. Its main advantage is the very quick process of detonating combustion, which can produce large energy density. Over the past decades, most of the PDE or detonation researches were based on detonation tube (or detonation combustion chamber) and focused on the detonation theory, the feasibility, operational characteristic and the working characteristic of PDE for propulsion system [1–7]. But the overall study of air-breathing pulse detonation engine which contained an inlet was rarely considered [8,9]. The inlet was mainly used to capture and provide a steady flow which combustion chamber needed, to ensure a high total pressure recovery coefficient and a high stability margin in different states. The coupling and matching of the inlet with the core engine for designers was crucial. In addition to this fundamental role to provide suitable air flow, the inlet also had deterministic effects on aerodynamic performance of the entire system, and interaction with the downstream combustion chamber. Due to the pulse characteristics of air-breathing PDE, this unsteady interaction is more complex. Butuk et al. [10] considered that one of the key technologies was the integration of the unsteady pulse detonation chamber with the steady inlet. Yang et al. [11–13] conducted a series of numerical and analytical study of the air-breathing pulse detonation engine, and obtained many important and useful conclusions. A performance map was established over the flight Mach-number range of 1.2–3.5. The PDE outperformed its ramjet counterpart for all the flight conditions [12]. Then an integrated theoretical/numerical framework has been established to investigate the internal flow dynamics and to assess the propulsive performance of an airbreathing valveless pulse detonation

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combustor using ethylene as fuel. Results indicated that the mass flow rates in the main chamber and initiator need to be carefully tuned to provide effective gasdynamic isolation of the combustor from the inlet and to avoid the occurrence of flow recirculation in the combustor. The calculated pressure histories and gross specific impulse of 1215 s show good agreement with experimental results [13]. A single-test of PDE was carried out by Falempin [14] to investigate the effect of inlet area ratio on air-breathing PDE performance. As the inlet area ratio increased, the PDE specific impulse decreased.

Due to the restriction of the engine size and weight in practical applications, the preferable fuel is liquid fuel, such as aviation kerosene, JP-10, gasoline and so on. Using liquid fuel would bring a lot of two-phase problems which would not appear when using gaseous fuel, such as fuel atomization, partial evaporation and mixing with air and so on. These problems would make it difficult to initiate detonation [15,16].

A feasible two-phase airbreathing valveless PDE mockup with different induction systems was designed and a PDE testing platform was established in this paper. Air flow tests, multi-cycle detonation tests and thrust measurement tests in case of semi-free-jet condition were carried out based on the two-phase PDE mockup, and some useful conclusions were obtained, which provided some theoretical and experimental bases to the future design and application of PDE.

2. Experimental setup

2.1. PDE system

An air-breathing valveless two-phase PDE mockup with inner diameter of 50 mm consisted of of inlet, mixing chamber, ignition chamber and detonation chamber. A schematic of the experimental setup is shown in Fig. 1. The liquid fuel (gasoline) and air were introduced to the PDE mockup by adaptive control without valve.

The air in the air inlet was continuously supplied by a convergent coming air nozzle. There was no control valve between the inlet and the mixing chamber. The velocity of the air upstream of the air inlet could be regulated from 0 to 0.7 Ma, so a subsonic inlet was designed. The combination induction system was made up of coming air nozzle and inlet of PDE, as shown in Fig. 2, the sizes of the coming air nozzle and the import of air inlet could be adjusted. D_1, D_2, D_3, D_4 represented the diameter of the coming air nozzle, air inlet, cone and inlet shell respectively. L_1, L_2 represented the length of the cone and inlet shell. θ represented the cone angle. Five induction systems were included in this paper, the specific structure parameters of which are shown in Table 1.The blockage ratio of circumferential seam was 0.69. The blockage ratio was defined as the ratio of the blockage area to the total area in this paper.

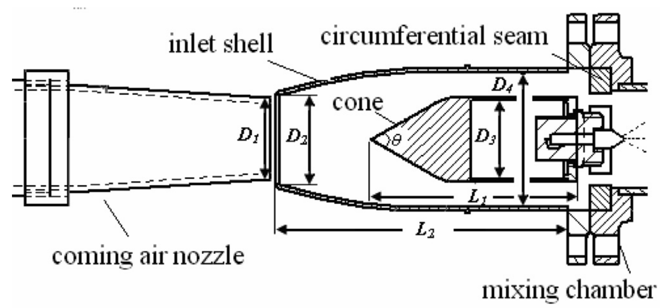

Fig. 2. Combination induction system of coming air nozzle and inlet.

The fuel was injected along the axial direction by a twin-fluid air-assist atomizer. When the pressure of assist air is about 0.3 MPa and the flow rate of gasoline is less than 2 L/min, the Sauter mean diameter of gasoline droplet at the position of 100 mm from atomizer is 25–100 μm [17]. The mixing chamber was designed to mix the liquid fuel/air as enough as possible in short distance and form fully developed turbulence before reaching the ignition chamber in order to ignite and initiate two-phase detonation easily. The automobile spark plug with ignition energy less than 50 mJ was used as the igniter and installed in the ignition chamber between position 0 and 1. The Shchelkin spiral was welded in detonation chamber to accelerate deflagration to detonation transition (DDT) and reduce DDT distance.

2.2. Test system

The pressures were measured along the length of the PDE mockup at several positions with piezoelectric pressure transducers to analyse the processes of PDE mockup initiation and back-propagation of pressure. The locations of the nine transducer positions −2, −1, 0, 1–6 with the distance of −500 mm (−850 mm in the case of induction system 5), −420 mm (−770 mm in the case of induction system 5), −210 mm, 225 mm, 525 mm, 625 mm, 725 mm, 825 mm and 925 mm from the spark plug in PDE mockup are shown in Fig. 1, and seven positions −2, −1, 0, 1, 2, 5, 6 of which

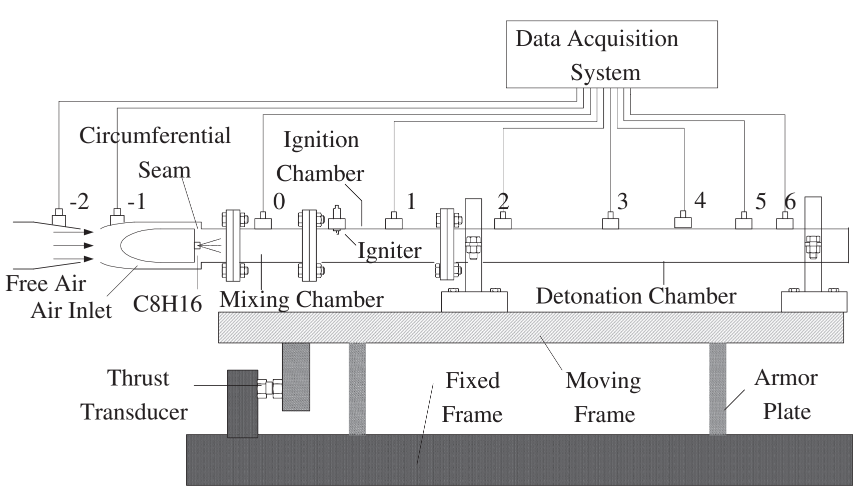

Fig. 1. Schematic of air-breathing PDE experimental setup.