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Thrust measurement method verification and analytical studies on a liquid-fueled pulse detonation engine

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Abstract In order to test the feasibility of a new thrust stand system based on impulse thrust measurement method, a liquid-fueled pulse detonation engine (PDE) is designed and built. Thrust performance of the engine is obtained by direct thrust measurement with a force transducer and indirect thrust measurement with an eddy current displacement sensor (ECDS). These two sets of thrust data are compared with each other to verify the accuracy of the thrust performance. Then thrust data measured by the new thrust stand system are compared with the verified thrust data to test its feasibility. The results indicate that thrust data from the force transducer and ECDS system are consistent with each other within the range of measurement error. Though the thrust data from the impulse thrust measurement system is a litter lower than that from the force transducer due to the axial momentum losses of the detonation jet, the impulse thrust measurement method is valid when applied to measure the averaged thrust of PDE. Analytical models of PDE are also discussed in this paper. The analytical thrust performance is higher than the experimental data due to ignoring the losses during the deflagration to detonation transition process. Effect of equivalence ratio on the engine thrust performance is investigated by utilizing the modified analytical model. Thrust reaches maximum at the equivalence ratio of about 1.1.

1. Introduction

Pulse detonation engines (PDEs) are exciting propulsion devices which obtain thrust by generating detonations intermittently.[1] Thrust performance is the most important parameter of PDEs. Measuring the time-resolved thrust of PDEs has been proved complicated due to their periodic operating characteristics. However, the averaged thrust measurements of PDEs had been performed by using different methods.[2–8]

Typically, there are three kinds of methods to carry out the averaged thrust measurements of PDEs. The first one is direct thrust measurement method which is performed by attaching the PDE on a translating frame mounted on bearings and taking the measurement with a force transducer. This method requires special attention, because the firing frequency can

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excite resonances in the thrust stand structures and a typical improvement is to place a spring damper system between the force transducer and the translating frame. The second one is indirect measurement method: the thrust measurement system includes an integrated spring damper system and a linear variable differential transducer (LVDT). When the engine is fired, the spring will be compressed by the thrust generated by the engine. The thrust is proportional to the displacement of the engine which can be recorded by the LVDT. The third one is ballistic pendulum method. The PDE is horizontally hanged up by wires. A video camera is used to record the ballistic pendulum deflection during operation. Although the ballistic pendulum method offers better accuracy, it is typically limited to a single impulse measurement.[8]

Impulse method is an indirect thrust measurement method which uses a flat plate of large area to receive the total impulse of the jet, if there are no axial momentum losses, the thrust exerted to the plate is equal to the thrust produced by the thruster.[9] Paxson et al.[10] utilized a thrust plate to investigate an unsteady ejector performance driven by a gasoline-fueled pulsejet. Mizukaki[11] also developed a baffle plate for force measurements of high-temperature, supersonic impulse jet. But studies about utilizing the impulse method to obtain the averaged thrust of PDE have rarely been reported, only Wilson et al.[12] carried out a thrust augmentation measurement of a PDE driven ejector by utilizing the thrust plate. He found that when the thrust plate was directly placed in front of a load cell, the load cell signal was strongly oscillatory, and extracting the DC component from it proved unreliable. Finally, He used a video camera to measure the pendulum deflection of the thrust plate which was suspended by four wires and positioned downstream of the PDE exit.

This paper is aimed at developing and calibrating an averaged thrust measurement system that can be used to measure the thrust of a pulse detonation turbine engine.[13,14] The commonly used methods such as measurements with a force transducer or LVDT are not practical for such a complex experimental installation, so the impulse method is chosen for its convenience and relative simplicity. To achieve the goal of this research, a new thrust stand system based on impulse method is built up. To verify the feasibility of the thrust stand system, a liquid-fueled PDE is manufactured and the thrust data of the PDE at different operating frequencies are obtained with two different methods: direct thrust measurements with a force transducer and indirect thrust measurements with an eddy current displacement sensor (ECDS). After the accuracy of the thrust data is confirmed, the engine thrust data at different operation frequencies are measured by the force transducer and the impulse method synchronously to test the reliability of the new thrust stand system. Analytical thrust performance is also discussed in this paper. The analytical model is based on an updated numerical analysis carried out by Endo-Fujiwara.[15–17] A modification is conducted on this analytical model to consider the effect of droplets resistance and heat transfer on the tube on the detonation wave velocity. What's more, the thrust data obtained from the modified analytical model are compared with experimental results.

2. Experimental setup

2.1. Liquid-fueled PDE system

A schematic of liquid-fueled PDE system is shown in Fig. 1. The PDE consists of three different sections: mixing chamber, ignition chamber, and detonation chamber. All three sections have the same diameter of 0.06 m, with the length of 0.175 m, 0.160 m, and 1.270 m, respectively. The shchelkin type spiral is welded in the detonation chamber to accelerate the deflagration-to-detonation transition process. A twin-fluid air-assist atomizer is installed in the center of the thrust wall. Air is introduced into the engine in radial direction through flexible pipes at the engine head. A spark plug is mounted in the middle of the ignition chamber. Two high-frequency piezoelectric static pressure sensors are installed near the exit of the detonation chamber to verify the successful initiation of detonation wave. Another high-frequency piezoelectric static pressure sensor is placed at the tube head to obtain pressure history at the thrust wall. The PDE system is mounted on the moving frame which is supported by four ball bearings. The engine can slide on stainless steel rails only in axial direction. The force transducer or spring is connected to a rigid thrust block and the moving system.

2.2. Thrust measurement systems

Three kinds of thrust measurement systems are integrated together to carry out thrust measurements of a liquid-fueled PDE: direct thrust measurement with a force transducer, indirect thrust measurement with ECDS and impulse method with a flat plate. The force transducer is mounted on the thrust block and the moving frame is connected to the force transducer through a spring which has a stiffness of 240 N/mm.

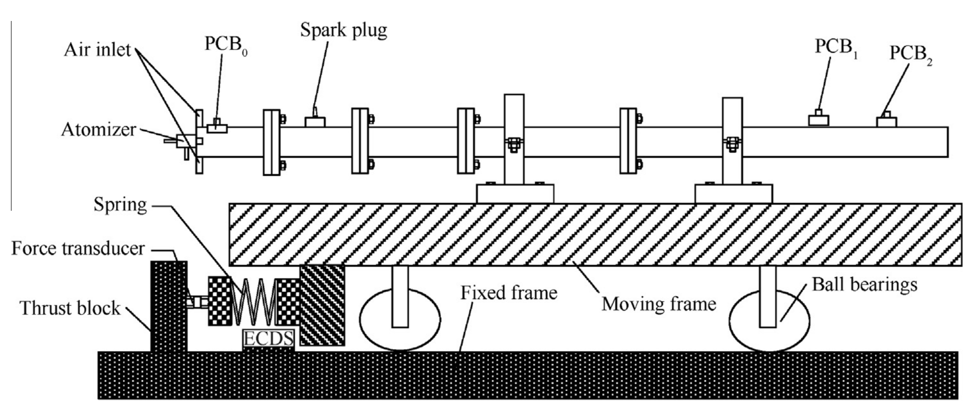

Fig. 1 Schematic diagram of the liquid-fueled PDE system.