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Propulsive performance of a pulse detonation rocket engine without the purge process

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A B S T R A C T

To measure the propulsive performance of a high-frequency PDRE (pulse detonation rocket engine), an experimental facility was established. Utilizing the valveless mode, the PDRE was operated without the purge process at a maximum operating frequency of 110 Hz successfully. In this study, oxygen-enriched air instead of oxygen was utilized as oxidizer and liquid gasoline was used as fuel because its vaporization would cool the hot combustion products, which would create a buffer zone and ensure stable operation without the purge process. The thrust under a wide range of operating frequencies was obtained including over and partially filled cases. Based on the results of partially filled conditions, one empirical formula for the partial fill effect was developed. In addition, analysis was carried out which resulted in a quite similar equation. Therefore, a partial fill model for the valveless PDRE without the purge process was obtained. Finally, comparisons between the proposed model and other models developed in traditional operations were performed.

1. Introduction

As an extremely rapid chemical energy release process, detonation has been explored for propulsion applications in the past few decades and received considerable interest worldwide. However, only the past 60 years or so has seen such a change because the practical combustion-based devices are still dominated by the easier-tamed deflagration. The dramatic energy release rates that can be achieved in the same mixtures in detonation conditions have for decades enticed engineers to seek ways to harness such waves [1]. One of the propulsion applications for detonation is the PDE (pulse detonation engine). The PDE has great potentials for increased performance and hardware simplicity compared to traditional propulsion systems, e.g., turbojet engines and conventional rocket engines. With oxidizer on board, the PDE operates in the rocket mode, which is called the PDRE (pulse detonation rocket engine).

There have been many studies on PDEs and several reviews have been published [2–4]. Cooper et al. [5] have directly measured the impulse by using a ballistic pendulum arrangement for detonations and deflagrations in a tube closed at one end and observed that an extension at the open end of the tube is helpful to increase the impulse. It is concluded that the increase in impulse is due to the increase of momentum transfer to the tube due to the additional mass contained in the extension. This is the so-called partial fill effect. Kasahara et al. [6] have investigated the thrust of a multicycle partially filled PDRE and verify that the multicycle PDRE also has the partial fill effect which is consistent with the single-cycle partially filled cases. Another work has been carried out by Li et al. [7] to study the propulsive performance of a PDRE utilizing liquid kerosene. In their work, the relationships among the operating frequency, fill fraction, and performance parameters were investigated with a maximum operating frequency of 49 Hz. Moreover, the partial fill effect has been studied by Li and Kailasanath [8] and Cooper et al. [9], and two different forms of empirical formulas for estimating the specific impulse have been proposed. Sato et al. [10] have numerically studied the performance of PDREs focusing on the partial fill effect. Their simulations indicate that the initial mass fraction of the detonable mixture to the total mass of gases is the predominant factor for the specific impulse of partially filled PDREs. Eventually, a simple empirical formula based on their numerical results was proposed. Previous studies on the propulsive performance of PDREs are limited at a relatively low operating frequency due to the great challenges in increasing the operating

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Nomenclature

f	operating frequency, Hz
F	average thrust, N
$\tilde{F}$	nondimensional thrust
g	gravity acceleration, m/s^2
I	impulse, kg m/s
m	mass, kg
q	heat release from the reactant of unit mass, J/kg
r	ratio of the fresh detonable mixture mass to the overall mixture mass in partial fill conditions
v	exhaust velocity, m/s
δ	fill fraction
ρ	density, kg/m^3
κ	thermal efficiency

Subscripts

burnt	burnt gases or combustion products
full	full fill cases
fresh	unburnt
partial	partial fill cases
sp	specific

frequency of a practical PDE. For example, many factors, such as efficient supply systems for fast injection of propellants, low-energy source to provide reliable and fast ignition, and geometry of the detonation tube to facilitate DDT (deflagration to detonation transition) at the lowest total pressure loss, restrict the operating frequency of a practical PDE [11]. Considerable attempts have been spent to solve these problems. Matsuoka et al. [12] have developed a rotary valve for a PDE and confirmed its basic characteristics and performance to obtain high-frequency operations. Another two types of rotary valves have been developed and tested for a single-tube PDRE by Wang et al. [13] to realize effective supply control. For solenoid valved PDREs, a novel control methodology has also been proposed to increase the operating frequency without reducing the system hardware simplicity [11]. Compared to mechanical valves, e.g., solenoid valves and rotary valves, the valveless operating scheme is more attractive in increasing the operating frequency and reducing the hardware complexity. However, such an operating scheme is usually employed in airbreathing PDEs, where air is used as oxidizer [14–16] because it is not stable in PDREs where a more reactive oxidizer (e.g., oxygen) is adopted [17,18]. Recently, this scheme has been successfully implemented in a PDRE utilizing a less reactive oxidizer (i.e., oxygen-enriched air) to eliminate the purge gas [19]. Based on this effort, a maximum operating frequency of 110 Hz was achieved.

Although several works have been carried out on the propulsive performance of a PDE, they were based on a relatively low frequency range and the purge process was used or gaseous fuels were employed in most of the previous studies. The present work focused on the propulsive performance of a valveless PDRE without the purge process. According to previous efforts, a wide range of operating frequency of 10 Hz–110 Hz was available under such an operation scheme. For a given supply capacity, the fill fraction decreases with the operating frequency leading to partial fill conditions at high-frequency cases. Therefore, the relationship between the propulsive performance and the operating frequency, including both fully filled and partially filled cases, was investigated. In addition, the partial fill effect for a PDRE without the purge process was studied.

2. Experimental setup

To achieve high-frequency operation, the valveless scheme in Ref. [19] was employed. Details of such an operation scheme and its implementation are available in Ref. [19]. Similar to the previous study, oxygen-enriched air (45% oxygen by volume) was used as the oxidizer and liquid gasoline was utilized as the fuel. Eventually, a wide operating frequency range from 10 Hz to 110 Hz was achieved.

A schematic of test bench and detonation tube is shown in Fig. 1. As illustrated in Fig. 1, the test bench comprised a stationary frame and a movable frame. The detonation tube was fixed with the movable frame which could roll freely parallel to the longitudinal direction of the detonation tube on the stationary frame by its wheels. Thrust generated by the detonation tube was measured by a load cell installed between the movable and stationary frames. Due to the unsteady thrust characteristics of PDREs, a dynamic piezoelectric thrust transducer (Kistler 9331B) was employed because it has a good performance in recording the instantaneous thrust. In the present study, signals were acquired at a rate of 200 kS/s. With the instantaneous thrust known, an average value would be available easily. To eliminate impact of the friction on the wheels and the resistance from the supplying pipes, the difference between the load on the movable frame and the load cell output was measured and corrected utilizing the facility introduced in Ref. [20].

As shown in Fig. 1, the detonation tube consisted of three sections, i.e., an injection and ignition section, a DDT section, and a measurement section. The lengths for these three sections were 110 mm, 230 mm, and 320 mm, respectively. The length and inner diameter of the tube were 660 mm and 24 mm. To reduce fuel deposit on the tube wall, liquid gasoline was sprayed into the detonation tube through a pressure swirl atomizer axially while oxidizer was injected through an annular gap surrounding the atomizer. An ordinary automobile spark plug with an ignition energy of about 50 mJ was used to initiate the combustion. A typical Shchelkin spiral, which could accelerate the DDT process, was installed in the DDT section. The pitch and wire diameter of the spiral were 24 mm and 3 mm creating a projected blockage ratio of 0.43. Dynamic piezoelectric pressure transducers (SINOCERA CY-YD-205, natural frequency larger than 200 kHz with a measurement precision of ±3%) were utilized to record the pressure history along the tube. Three pressure transducers (p_1, p_2, and p_3) were located 330 mm, 400 mm, and 470 mm axially away from the spark plug, respectively. They were recessed in mounting ports and water-cooled to prevent them from being damaged by extremely high temperature and avoid thermal effects on the transducer [21]. Raw pressure signals were also sampled at 200 kS/s.

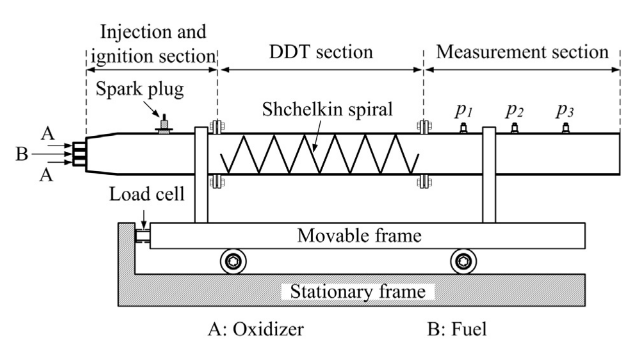

Fig. 1. Schematic of test bench and detonation tube.