Experimental Studies on L/D Ratio and Heat Transfer in Pulse Detonation Engines

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Introduction

The pulse detonation engine (PDE) has recently become recognized as a possible new aerospace propulsion system[1-4]. The PDE system has high thermal efficiency because of its constant-volume combustion[3], and it has a simple structure composed of tubes.

We have a plan to fabricate the simplest PDE system, the ethylene-oxygen pulse detonation rocket engine (PDRE) system, within a few years, in order to verify that PDEs have large fuel-oxidizer mass flow rates in spite of their intermittent thrust. To design the PDRE engineering model, we have to do preliminary experiments to ensure the net momentum and heat transfer obtained in this system. In the present study, we measured net momentum by the ballistic pendulum method with varying L/D ratio (a length divided by a diameter of PDE tubes), and also measured heat transfer from the burned gases to the tubes using a radiation thermometer. From these experimental results, we estimated the L/D and the heat transfer effects determining the PDRE configuration.

Experimental Equipments and Conditions

The type 1 tubes are 50 mm in inside diameter and 400, 900, or 1800 mm long. The type 2 tubes are 26 mm in inside diameter and are 4000 mm long. Type 1 and type 2 are made of 5- and 3-mm-thick stainless steel, respectively. Mylar diaphragms 12- or 24-µm thick were used to contain the gas mixture in separate areas of the tubes during single-shot experiments. A Shchelkin spiral for DDT (deflagration-to-detonation transition), a spark plug to initiate combustion, a piezo-pressure gauge (PCB HM113A26), and hydrogen-oxygen injectors were placed at the end wall of each tube. The Shchelkin double spirals were made of wires 1.5 mm in diameter. The inner spiral's length, diameter, and pitch were 165, 40, and 15 mm, respectively, and those of the outer were 150, 20, and 15 mm. Automotive spark plugs (NGK BPR5EY) were used. We performed the experiments in a premixed stoichiometric hydrogen-oxygen gas at an initial fill pressure of 101 kPa and at room temperature (291.1 ± 6.6 K). The tubes were hung by stainless wires 1280 mm long. We used laser displacement gauges (Keyence LC-2450) to measure the displacement of the tubes. We determined the velocity and the momentum values of the tubes at arbitrary times by differentiating the displacement data. We measured temperature at the outer wall of the PDE tubes by a radiation thermometer (CHINO CPA-1000).

Results and Discussion

Figure1 shows pressure histories at the closed end of the tubes at the two cases, L/D =18 and 167. The horizontal axis is the non-dimensional time (V_{CJ} is the Chapman-Jouguet velocity of the mixture, 2850 m/s). The history of the case L/D =18 is synchronized by matching the arrival times of detonation waves in these two cases. The pressure of L/D =167 does not have the plateau zone and successively decreases with an increase in time. The area $S_1(=\int_{t_1}^{t_2}(p_w - p_1)\mathrm{d}t)$ surrounded by the data of L/D=167 and p_1=101.3 kPa, which is equal to the impulse density obtained by the closed end of the tube at L/D =167, is 45.2 % of the area $S_2(=\int_{t_3}^{t_4}(p_w - p_1)\mathrm{d}t)$ surrounded by the data of L/D=18 and p_1=101.3 kP. This decrease can be explained by the heat transfer from the burned gases to the tube wall.

Assuming that the heat transfer process is isovolumetric change, the decrease of the effective specific impulse by heat transfer can be expressed by

$$I'_{\mathrm{sp,eff}} = I_{\mathrm{sp,eff}}\left(1 - \frac{T_{g0}-T_w}{T_{g0}}\frac{p_3}{p_3-p_1}\left[1-\exp\left(-a\frac{L}{D}\right)\right]\right),$$
$$a = \frac{8\left(\gamma_1^2-1\right)}{\gamma_1}\frac{M_{\mathrm{CJ}}^2}{\left(M_{\mathrm{CJ}}^2-1\right)^2}\frac{C_1 h T_{g0}}{p_1 V_{\mathrm{CJ}}}$$

$I_{\mathrm{sp,eff}}$: specific impulse with no heat transfer, $I'_{\mathrm{sp,eff}}$: specific impulse with heat transfer, T_{g0}: gas initial temperature (=2734 K), T_w: wall temperature (=285.5 K), p_1: gas initial pressure(=101.3kPa), p_3: plateau pressure obtained by End-Fujiwara theory[5], γ_1: specific-heat ratio, C_1: non-dimensional time (=8.734), and h: time-averaged heat transfer coefficient.

Figure 2 shows the effective specific impulse of the type 1 and 2 tubes plotted against the *L*/*D*. The solid curve is the heat transfer model fitted into the experimental data. The effective impulse decreases almost exponentially up to *L*/*D*=167. This fact indicates that the heat transfer is dominant to the impulse loss. From Fig.2, we determined that the time-averaged heat transfer coefficient and heat flux were 500J/(sK) and 1.2MW/m^2, respectively.

The multi-shot operation at 10 Hz for 4.4 sec (44 cycles) was carried out. The initial temperature was room temperature. Figure 3 shows the inner and outer wall temperatures in this operation, plotted against operational time. The opened square, circle and triangle in Fig.3 mean the locations from the closed end of the tube, 145mm, 435mm and 815mm, respectively. The solid curves in Fig.3 are obtained from the one-dimensional unsteady-state heat conduction analysis. From Fig.3 we found that the heat flux at the wall was about 0.4 MW/m^2. It means that the heat transfer on the wall has the same order of magnitude as the heat release of the C-J plane in a detonation wave.

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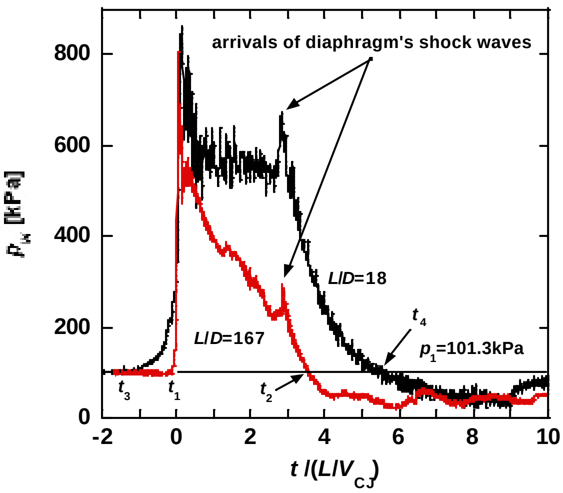

Fig. 1 Comparison of the pressure histories at the closed end of the tube between the two L/D cases

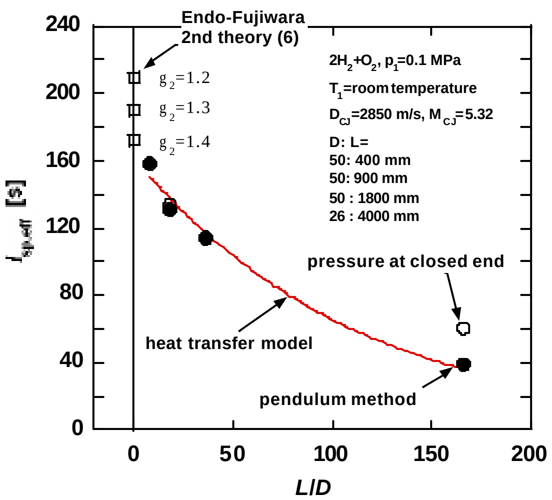

Fig.2 Specific impulses plotted against L/D

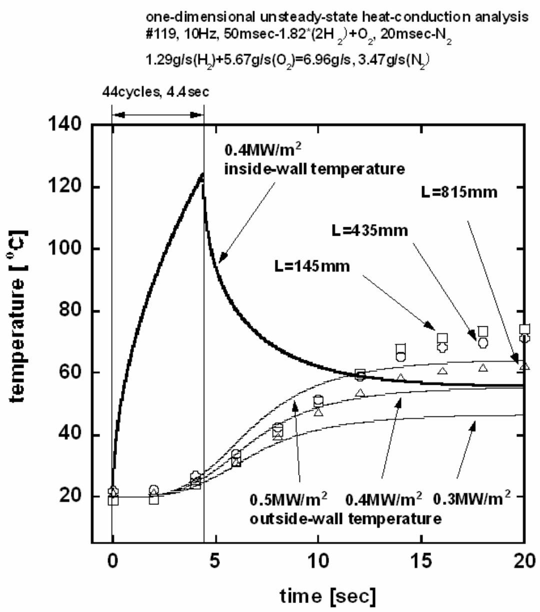

Fig.3 Tube-wall temperature profiles and heat flux calculations