The Influence of Heat-Transfer and Friction on the Impulse of a Single-Cycle Pulse Detonation Tube

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1 Introduction

A pulse detonation engine (PDE) is an internal-combustion engine which produces thrust by using self-sustained detonation waves. A PDE has a simpler structure and a higher theoretical thermal efficiency compared with conventional gas turbines and rocket engines. The PDE can get thrust even in configurations such as very long tube which can be transformed easily into the functional shape due to the simplicity of the structure. On the other hand, several experimental studies show that the measured thermal efficiency is less than the theoretical value. This is because in the actual flow fields of PDE, the high-temperature burned gas accelerated by detonation wave blow down in very high velocity and momentum losses due to heat transfer and friction are generated. It is known that these losses increase with the PDE tube length.

Until now, experimental and numerical studies have been performed on the influence of the non-dimensional tube length *L/D*, where *D* is tube diameter, on the performance of PDE. Kasahara et al. [1] showed in their experiments with hydrogen-oxygen that the loss of specific impulse increases remarkably with the *L/D* ratio increasing. Radulescu et al. [2] modeled the gasdynamics in the tube by a one-dimensional formulation and solved it by the method of characteristics. The results are in good agreement in range of $L/D<60$. They found the specific impulse losses increase quasi-linearly with *L/D* in that range.

As just described, studies on heat losses and the *L/D* ratio have ever been done but quantitative estimations are few, especially about frictional losses, therefore in the present paper, we estimate the loss of specific impulse due to heat transfer and friction through the higher-accuracy experiments.

2 Experimental Setup and Variables

Single-pulse operation experiments with the detonation tube shown in Fig. 1 were carried out by using a ballistic pendulum arrangement. The stoichiometric C_2H_4-O_2 mixture in the standard condition is sealed in the tube with a 15-μm-thick PET diaphragm at the open end of the tube and ignited with a spark plug at the tube's thrust surface (closed end), where the deflagration wave is generated and transits to the detonation wave quickly by the effect of the Shchelkin spiral of BR=0.43 (BR, blockage ratio), whose pitch and length were 10 mm and 50 mm respectively. Three pressure transducers (CH1-

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CH3) are installed at the right, bottom and left side tube surfaces and 5 mm far from the thrust wall as shown in Fig. 1. Since 5 mm is much less than the tube length, we consider the measured value is the pressure histories at the thrust wall. The tube was hung as the ballistic pendulum from the ceiling by wires and the maximum horizontal displacement of the tube was measured with a laser displacement sensor and a video camera with ruler. The latter is used for cross-checking.

Two kinds of impulse are given by the following formulas, the first with the pressure history at the thrust wall integrated with time and the second with the maximum tube displacement Δx related to the initial velocity of the pendulum [3]:

$$I_{thrust} = \pi (D/2)^2 \int_0^{t_{cyc}} p\, dt$$

$$I_{net} = m\sqrt{2gL_w\left(1-\sqrt{1-(\Delta x/L_w)}\right)}$$

and dividing them with the weigh of the propellant, we decide the specific impulses for each. The former is named the specific impulse at the thrust wall, $I_{sp,thrust}$, and the latter the net specific impulse through one cycle, $I_{sp,net}$. For calibrating the $I_{sp,net}$ we had measured how much impulse we need to move the tube a certain displacement and decided the $I_{sp,net}$ corresponding to the maximum displacement accurately. This can eliminate the effect of the resistance generated by the lines of ignition and measurement systems

The non-dimensional tube length *L/D* and the surface roughness of the tube wall were used as the experimental variables. Changing the length of 25.5-mm-diameter tube, *L/D* varies between three lengths, 49, 103 and 151. The surface roughness is defined as *Ra/D*, where *Ra* is the arithmetical mean roughness and we used three kinds of tube shown in Table 1. Since *L/D* and *Ra/D* were varied between three conditions, there are nine conditions of *L/D* and *Ra/D*.

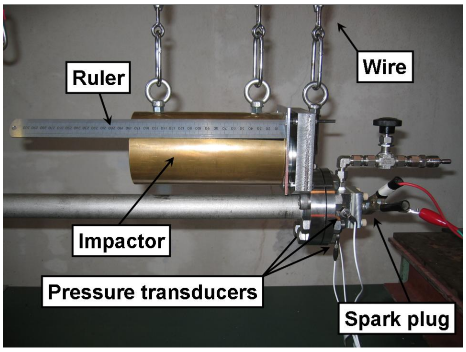

Figure 1. Experimental setup of the detonation tube.

Table 1. Surface roughness of three kinds of tube and the ratio of *Ra/D* to polished tube.

Surface finish	Roughness *Ra/D*	Ratio to polished tube
Polished	5.00×10^{-5}	1.00
Normal	1.96×10^{-4}	3.92
Screwed	5.88×10^{-2}	1.18×10^{3}

3 Results and Discussion

Fig. 2 shows the distribution of the specific impulses for all shots carried out in the present experiment. In the transverse direction, shot numbers are sorted by surface roughness and *L/D*. As to screwed tube the surface asperity seems to be nonuniform, so that we made measurements with tubes inverted. We named the tube directions forward and backward for convenience but note that this does not mean the surface roughness varies uniformly. In each longitudinal row, there line up five specific impulses obtained through experiments, from which we decide the representative value of the shot both for $I_{sp,thrust}$ and $I_{sp,net}$ as below. From among three $I_{sp,thrust}$ (CH1-CH3), we choose two which are the nearest each other and decide the representative value of the shot as the average of them. And as to $I_{sp,net}$, the value with the laser displacement gauge is adopted as the representative. Averaging up these representatives for each of twelve experimental conditions, we decide the most probable value of the condition for $I_{sp,thrust}$ and $I_{sp,net}$. And as the typical pressure history of the condition, we use the one whose time integration is the closest to the most probable value.

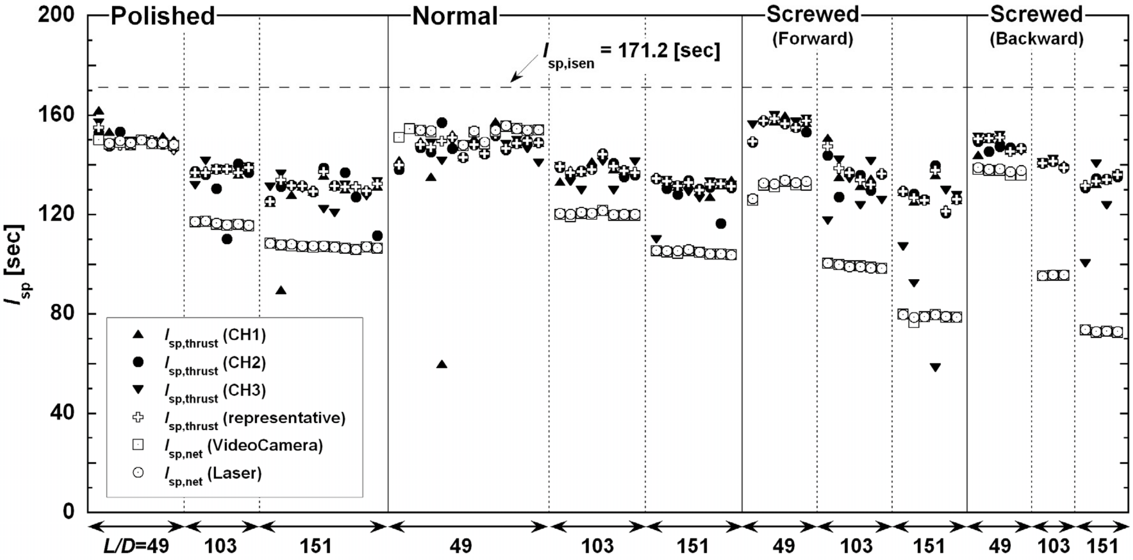

Figure 2. Distribution of the specific impulses for all shots sort by experimental conditions, *L/D* and *Ra/D*.

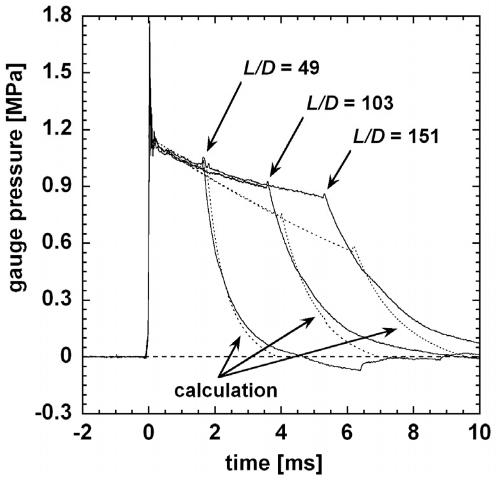

Figure 3. Variation of the difference in pressure between experiments and calculations with *L/D*.

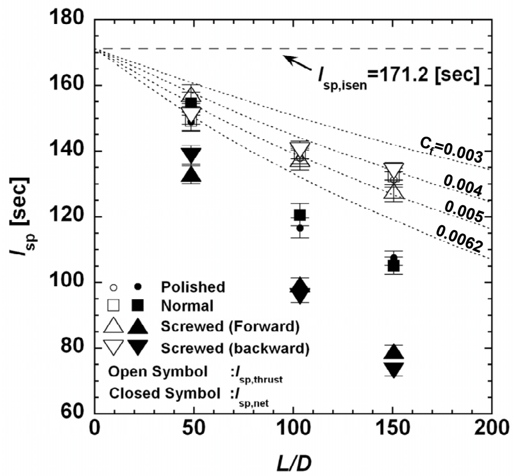

Figure 4. Specific impulse with varying *L/D* and surface roughness.

Fig. 3 compares the typical pressure histories in the case of polished tube with the numerical results solved by the method of characteristics, which shows that the slight difference in the pressure at the plateau region grows larger with *L/D*.

In Fig. 4, $I_{sp,thrust}$ for each experimental condition are plotted with *L/D*. Through this paper, final errors are estimated by substituting measurement errors to the standard formula of error propagation [4]. As a measurement error, a mean error is used, which is the square-root of the sum of the squares of a standard error and a systematic error. The rough dashed line indicate the ideal specific impulse when the flow is considered isentropic and the fine dashed lines are the numerical results where the C_f value is varies from 0.003 to 0.0062, where C_f is friction coefficient, which is adjustable parameter of the numerical model. Radulescu et al. decided the C_f value is 0.0062 by calibrating their model against experiment measurements of the heat flux immediately behind the detonation front. As the figure shows, for good agreement of experiment and calculation, we have to decrease the C_f value gradually as the L/D ratio increases, which can not be explained with the model C_f is assumed constant.

Heat and frictional losses are estimated here by considering the differences of specific impulses. The reduction from $I_{sp,isen}$ to $I_{sp,thrust}$ is attributed to the pressure decay caused by heat transfer, and from $I_{sp,thrust}$ to $I_{sp,net}$ to the frictional loss because if no friction acted on the wall, the tube would move only the displacement corresponding to the added impulse, that is, $I_{sp,net}$ would equal $I_{sp,thrust}$. The specific impulse losses due to heat transfer and friction are given by

$$\Delta I_{sp,heat} = I_{sp,isen} - I_{sp,thrust}$$
$$\Delta I_{sp,fric} = I_{sp,thrust} - I_{sp,net}$$

and shown in Fig. 5 and Fig. 6. $\Delta I_{sp,fric}$ increases rapidly over than L/D = 103 and for screwed tube it is comparable or more than $\Delta I_{sp,heat}$, therefore it is necessary to consider frictional losses as well as heat losses when we discuss the thrust of PDE.

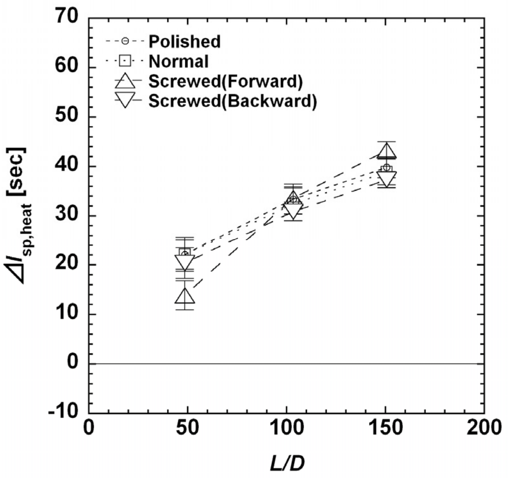

Figure 5. Specific impulse losses due to heat transfer.

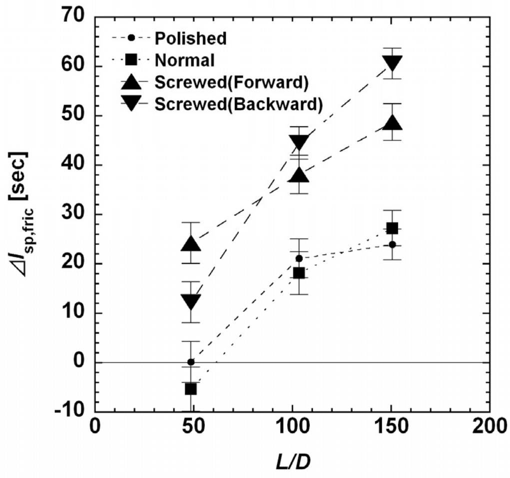

Figure 6. Specific impulse losses due to friction

4 Conclusions

The present study evaluated the loss of specific impulse caused by heat transfer and friction with a high degree of accuracy in the single-cycle detonation tube experiments and compared the results with the numerical model solved by the method of characteristics. At the high L/D region more than 103, while the losses due to heat transfer is less than the calculated results, the losses caused by friction increase too large to be ignored.

References

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