Impulse Measurement of Small Scale Detonation Tubes under Direct and Indirect Detonation Initiations

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1 Introduction

As a kind of near-isovolumetric combustion, detonation has attracted much attention and has been studied for a long time. It is believed that a pulse detonation engine (PDE) has many potential advantages over conventional aero-propulsion systems in simple configurations, high thermodynamic efficiency and wide operating conditions. Though recent studies reported that the operating frequency of a PDE could reach as high as 200 Hz [1], there might be great energy losses that affect the thrust and impulse generation. The impulse measurement and prediction of a real PDE is quite difficult at high frequencies.

To simplify the problem, single-shot experiments were usually conducted using a ballistic pendulum to study the PDE's performance [2-6]. The experimental results were compared to those of the analytical models to reveal the energy loss. Kawane et al. [5] argued that the DDT process and wall loss mechanisms such as heat transfer and friction are two major reasons that lead to the reduction of impulse. For the former one, many researchers pointed out that the expansion waves exiting from the tube prior to the detonation wave during the DDT process caused the spillage of the propellant, resulting in the impulse deficit. If there is no spillage, the impulses created by direct detonation initiation and DDT process are nearly the same.

To date, despite there have been researches on the impulse comparison of DDT and direct detonation initiation, they were all conducted in relatively large tubes. There are few investigations on the impulse measurement of a millimeter-scale detonation tube. Although it has been validated that the impulse decreases with the increasing of the tube's length to diameter ratio ξ, it cannot fully represent the impulse deficit because the tube diameter d itself is a characteristic parameter that affects the flame propagation in a detonation tube. Typically, in a thin and smooth tube [7], d will not only change the DDT distance, but also cause the boundary layer growth and velocity deficit, both of which produce losses.

The present study aims to provide a preliminary test on measuring the impulse of a millimeter-scale tube using a ballistic pendulum. There seemed quite few experimental measurements on such a small detonation system. The main difficulties are that we cannot install many pressure transducers and ion probes to monitor the pressure evolutions and detonation velocities as in large tubes. What's more, the wires connected between the pendulum system and the experimental devices for data transmission and many other accessories may create drag forces. To solve these problems, we utilized transparent detonation tubes for high-speed photographic observation and analysis. The impulses generated by DDT and direct initiations of detonation were compared with each other. Some experimental improvements were made based on our previous design [8].

2 Experimental Setups

Fig. 1 is a diagram of the impulse measuring system. A transparent polymethyl methacrylate (PMMA) detonation tube with the length *L* and inner diameter *d* is bound to the strings as a major part of the pendulum. Two groups of experiments are conducted. Group 1 and Group 2 use three and two kinds of tube sizes, respectively, and the corresponding length to diameter ratios ξ are listed in Table 1. It is worth noting that the Type C tube is composed of three identical parts which are connected by joints. (see Fig. 2)

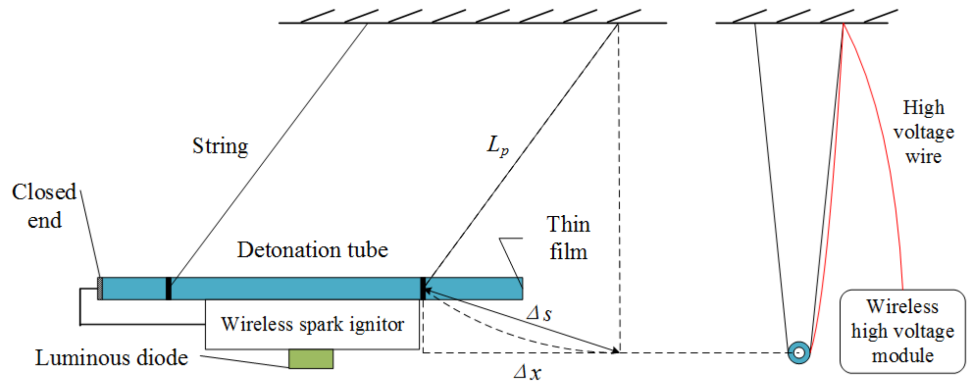

Figure 1. Schematic diagram of the ballistic pendulum

Table 1: Different types of the detonation tube

Group	Type	L (mm)	d (mm)	ξ
1	A	1000	4	250
	B	1000	8	125
	C	480	20	24
2	a	1000	4	250
	b	1000	8	125

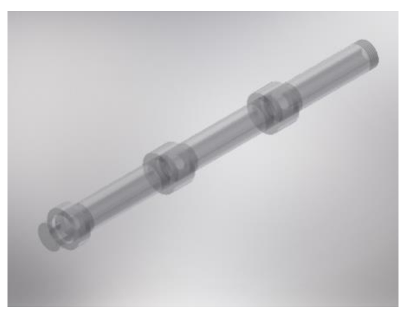

Figure 2. Schematic diagram of the detonation tube Type C

In Group 1, to minimize the system's displacement deviations created by the string's elastic stretching during the thrusting process, the material of the string is chosen as carbon fiber, whose tensile modulus of elasticity is about 4900 MPa. Considering the tube weight is relatively small and oscillations might occur due to great instantaneous impulse, the spark ignitor and other accessories are all attached to the detonation tube as additional weight. Furthermore, the ignitor is under wireless control to avoid negative drags of the wires. The spark energy for DDT initiations is about 70 mJ. For the direct initiations, a wireless high voltage module is also connected to the spark electrodes, but not attached to the whole system. To minimum the negative drag, the wires are suspended to the top of the pendulum and stretch along with the string. The maximum capacitance of the module is 1.1 μF, and the voltage range is 0~20 kV. Group 2 uses wired connection between the spark ignitor and the pendulum system but contains no high voltage module, which is our previous configuration [8].

The closed end of the tube is a threaded plug with two spark electrodes, and the open end is covered with a thin diaphram. Before ignition, both ends are open for the combustible mixture to fill into the tube; when finished, they are closed at the same time. The gaseous mixture used in this study is stoichiometric ethylene and oxygen with nitrogen diluted as Eq. (1) shows, where β is chosen as 0, 0.3, 0.6 and 0.8.

$$C_2H_4 + 3\left(O_2 + \beta N_2\right) \rightarrow 2CO_2 + 2H_2O + 3\beta N_2 \tag{1}$$

The displacement of the pendulum system is captured by a high-speed camera (Phantom 7.2), which is equal to that of the luminous diode because it is attached to the whole pendulum system (see Fig. 1). When the sampling rate of the camera reaches 60000-70000 frame per second, only the luminous diode and the flame propagation can be seen. Thus, the displacement and the DDT distance can be calculated by the data processing software. The measured impulse is shown in Eq. (2), where Δx is the maximum horizonal movement of the system; L_p is the length of the string; m is the system's weight, and g is the gravitational acceleration [3]. The volumetric impulse and the specific impulse are defined as in Eq. (3) and Eq. (4), where ρ_1 is the density of the initial unreacted mixture.

$$I_p = m\sqrt{2gL_p\left(1-\sqrt{1-\left(\frac{\Delta x}{L_p}\right)^2}\right)} \tag{2}$$

$$I_V = \frac{I}{V} \tag{3}$$

$$I_{sp} = \frac{I_V}{\rho_1 g} \tag{4}$$

3 Impulse Evaluation of Different Ballistic Pendulums

Fig. 3 shows the relationship of I_v with β and non-dimensional DDT distance ($\eta = L_{ddt}/L$) using the tube type of A and a in Group 1 and 2, respectively (see Table 1). Both groups of experiments use low energy spark ignition and the detonations are initiated by DDT. The system's weight m of Group 1 is about five times greater than that of Group 2, while the string lengths are the same. Considering there are drag forces in Group 2, the measured volumetric impulse when β=0 is still 30% larger than the average value of Group 1. In the right figure, it can be seen that I_v measured in Group 1 varies with η. There are two possible reasons for this. One is that the system is too heavy to be effectively pushed, which has greater impact than the drag forces. The other is that the different DDT distances lead to varying impulses. According to previous studies [3, 6], the impulses produced by direct initiation is nearly the same as produced by DDT, despite not mentioning whether different DDT distances also produce the same impulses. This topic will be discussed in the next section. But in Fig. 2, it can be seen that when β>0 (the chemical energy content of the combustible mixture decreases), I_v does not change with β or η. This is unreasonable because different values of β will definitely produce different I_v according to theoretical analysis. Thus, it can be deduced that the above first reason may be right.

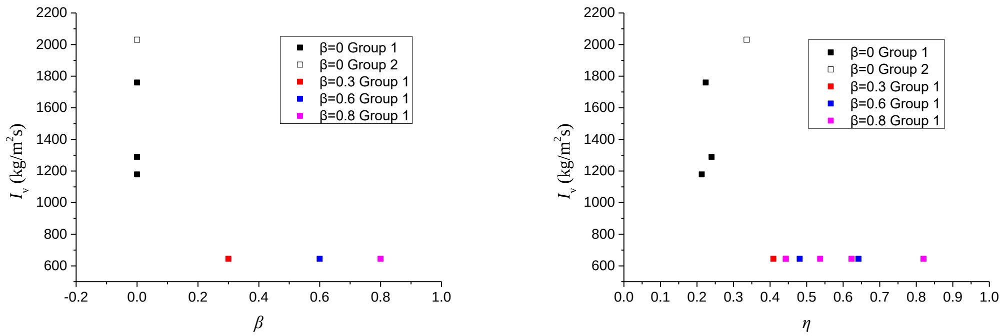

Figure 3. The relationship of I_v with β and η for tube type of A and a

4 The Effect of Direct and DDT Initiation

Fig. 4 illustrates the relationship of I_v with β and η using the tube type of B and b in Group 1 and 2, respectively. The solid symbols in the picture are all high-voltage ignited conditions, where β=0 is successful direct initiated detonation and β=0.6 is DDT initiated detonation. In this section, the pendulum weight is reduced to be easily pushed forward by the impulse.

For β=0 in the left picture, three shots are conducted, and two symbols of them overlap. It can be seen that the impulse of the direct initiated detonation is quite steady. The open symbols represent low-energy ignited shots (DDT initiated) in Group 2, which is inhibited by drag forces. The impulse seems unsteady, but the average value is very close to that of direct initiated detonation. This result conforms to other researchers' conclusions that the two initiation mechanisms produce the same impulse. For β=0.6, five shots are conducted and the impulses are all the same.

The detailed evolution of I_v against η is shown in the right picture. For β=0 under direct initiation condition, the DDT distance is zero, while the DDT initiation condition is not. The latter is probably affected by the drag forces. For β=0.6, η varies between 0.2 and 0.6, meaning that the DDT distance is quite unsteady. However, I_v does not change with η. Such result validates the former section's deduction that it is the over-weighted system that hinders the impulse measurement.

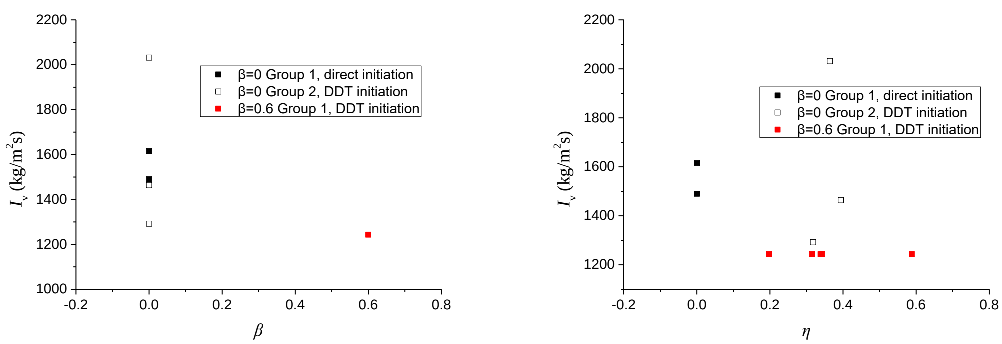

Figure 4. The relationship of I_v with β and η for tube type of B and b

Fig. 5 shows the evolution of I_v against η at high voltages in tube type of C. η=0 means that detonation is directly initiated. It can be seen that I_v at different η does not seem to vary a lot, but it's worth noting that the impulse generated by direct initiation is sometimes smaller than that of DDT initiation.

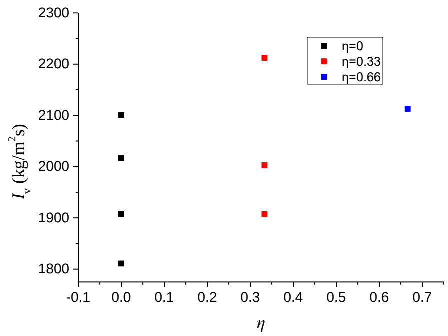

Figure 5. The relationship of I_v with η for tube type of C at high voltages

The flame propagation process under the two detonation initiation mechanisms is compared in Fig 6. and Fig. 7. The main difference lies in the wake flames and the shock propagation modes. In Fig.6, when the detonation wave exits the tube end, a reflected expansion wave goes back to the opposite direction. As it touches the closed end, it seems to gradually diminish with the purging process of the reactants. In Fig.7, when detonation occurs at the first joint (about one third of the whole tube), a retonation wave propagates oppositely to the closed end. At the time when the retonation wave touches the wall, it immediately reflects back to the tube exit, and generating a series of mach disks with the purging of the reactants. This means that the purged gas resulted from the secondary shock is supersonic and lasts for a very long time. This process probably contributes a lot to generate impulse, probably explains why the impulse is the same as or larger than that of the direct initiation. Although some researchers have pointed out the possible effect of retonation wave [3], our experiment provides a more clear visual illustration. However, the detailed mechanism still needs to be explored.

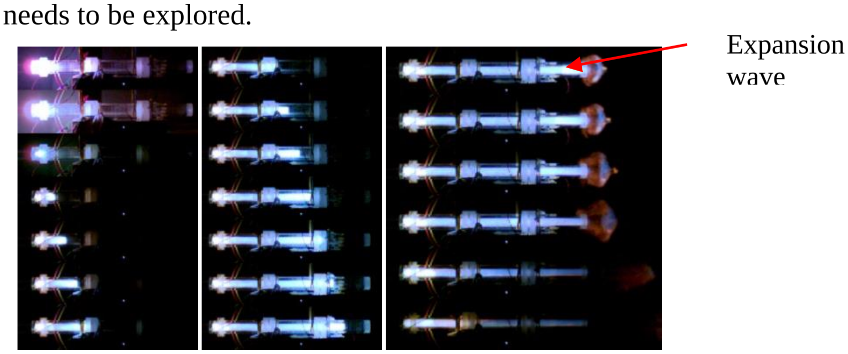

Figure 6. Flame propagation of direct initiation

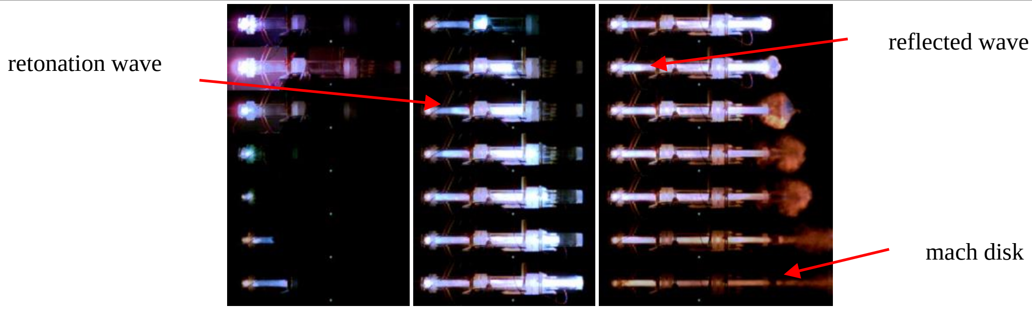

Figure 7. Flame propagation of DDT initiation

5 Conclusions

The present study conducted impulse measurements on millimeter-scale detonation tubes. The influence of the system weight was examined. It is concluded that over-loaded pendulum system may affect the results greater than the drag forces. The impulses generated by direct and DDT initiation of detonation are the same. Furthermore, it is also hardly affected by different DDT distances. When the tube's length to diameter decreases, DDT generated impulse may be possibly larger than that of direct initiation. A visualization of the flame propagation process revealed that the secondary purging of the supersonic gas may contribute a lot to the impulse production.

6 Acknowledgement

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