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Experimental investigation of effect of partial filling on the impulse of pulse detonation engine

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Using poor-detonable liquid C_8H_{16}/air mixture with low-energy system (total spark energy of 50 mJ) and a new one-step detonation initiation method developed in this study, partial-tube fill experiments have been conducted in a fixed length PDE tube with a fuel/air mixture section of different length, covering a wide range of the detonation tube fill fraction (ratio of fuel/air mixture length to tube length). Impulse was calculated by integrating the pressure differential at the closed end of the tube. Based on the results obtained experimentally, it is found that the fuel-based specific impulse declines when fill fraction increases. On the other hand, the total-mixture-based specific impulse rises as fill fraction increases. A multi-cycle partial-fill model is developed to predict the impulse obtained from a partially-filled detonation tube, which is valuable for the optimization of PDE performance.

pulse detonation engine, partial filling, impulse, fill fraction

Pulse detonation engines (PDE) are new-concept propulsion systems[1−3], which utilize repetitive detonations to produce thrust or power. PDE offers the potential to provide higher performance while simultaneously reducing engine weight, cost and complexity, relative to conventional propulsion systems currently in service. Due to its obvious advantages, worldwide attention has been paid to the scientific and technical issues concerning PDE.

Effective optimization is especially important because the PDE is a new engine competing against the well established turbojet and ramjet[4]. Only high installed performance and low cost will justify the investment needed to bring the PDE to production. While the PDE presents a mechanically simple device, its unsteady thermo-fluid dynamics are quite complex. As may be expected with such a relatively new technology, the study on the approaches for achieving optimum design and performance is only at the initial stage and needs further exploration.

In the past few years, numerous studies on the effects of partial mixture filling on PDE performance have been reported analytically, numerically and experimentally[5−12]. Zitoun et al.[5] measured the single-cycle impulse of ethylene-oxygen mixtures under standard conditions in a detonation tube and an extension with the same cylindrical cross section. They directly initiated a detonation with approximately 35 J of energy and the impulse was calculated by integrating the thrust surface pressure differential. Schauer et al.[6] studied the effects of the pressure relaxation rate upon thrust experimentally by adjusting the amount of detonable mixture in the tube while maintaining the same detonation tube length. Significant performance gains were observed. Falempin et al.[8] and Cooper et al.[9] used a ballistic pendulum to measure single-cycle impulse values of ethylene-oxygen mixtures in detonation tubes with attached extensions having a constant cylindrical cross section and also in extensions of varying dimensions. Li and Kailasanath[10] studied the effect of varying the length filled with the

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ENGINEERING THERMOPHYSICS

detonable mixture in constant cross section tubes. They applied an exponential curve fit to their data relating the fuel-based specific impulse to the amount of the tube length filled with the detonable mixture. Youngster[11] investigated the change in the performance of PDE resulting from the addition of a straight nozzle attached at the end of the detonation tube in his single-cycle numerical simulations. Impulse augmentation ratio of 1.26 was achieved. Dyer et al.[12] examined the effect of fill fraction by using time accurate CFD and Boeing's PDE cycle deck, DECADE. It is shown that as fill fraction is decreased, the efficiency of the cycle is increased.

The previous complicated observations reported in these studies indicate that the analysis of the flow field in a partially-filled detonation tube requires considering unsteady wave interactions. Analytical and accurate numerical predictions prove difficult, suggesting further experimental research on the effects of partial filling on PDE performance, particularly for multi-cycle operation where CFD studies have been limited mostly to quasi-one-dimensional analysis, and where no experimental data is available. In this paper the effects of various fill fractions on single-tube PDE performance for both single-pulse and multi-cycle operations are investigated.

1 Experimental setup

An experimental setup was developed to study the multi-cycle operation of a pulse detonation engine in this study. The test model of PDE consists of devices of air and fuel supply, mixing chamber, detonation chamber, pulse spark generator and data acquisition and processing system, which is shown in Figure 1. It was an idealized PDE model without inlets or nozzle. The liquid C_8H_{16}/air mixture was used. The air and fuel entered the mixing chamber through respective pipelines in which a tangential mode of air injection and a simple fuel nozzle were adopted. The one-way valves were used to control intermittent supplies of air and fuel flows. The experiment apparatus allowed the operating parameters such as air and fuel flow rates and the frequency of spark generator to be independently varied. The ignition frequency can vary with a signal generator. The spark igniter used in these experiments had initiation energy of around 50 mJ. The detonation tube was constructed from a steel tube of 50 mm in diameter and 1500 mm in length, including mixing chamber of 200 mm and detonation chamber of 1300 mm. The igniter was positioned about 300 mm from the front end. Two piezoelectric pressure transducers were used for measuring gas pressure in the tube. The first one (location 1) was at the thrust wall and the second one (location 2) was at 800 mm from the closed end. The data acquisition and processing system included a microcomputer and two data acquisition boards of CS22125. The calibration of pressure transducers from the manufacturer was applied to converting the raw values to pressure values. This value had an error of ±7.25 mV/bar. The second pressure transducer was employed to monitor the pressure profiles of detonation waves. A Shchelkin spiral was employed in the detonation chamber.

2 Experimental steps description

Here the definition of fill fraction (β) is presented first. Fill fraction is defined as the tube volume initially filled

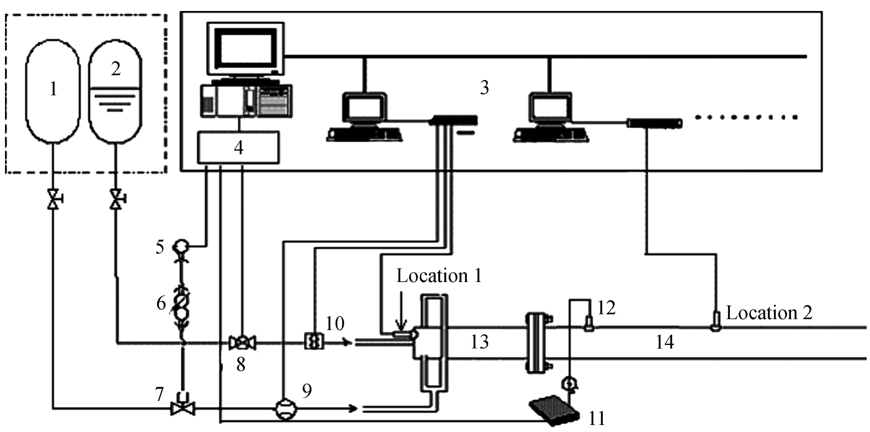

Figure 1 Experimental setup. 1, Air holder; 2, fuel tank; 3, data acquisition and processing system; 4, control enclosure; 5, servo motor; 6, driving gear; 7, air flow valve; 8, fuel flow valve; 9, air flow meter; 10, fuel flow meter; 11, ignition frequency control enclosure; 12, spark plug; 13, mixing chamber; 14, detonation chamber.

with a fuel/air mixture (V_f) to the overall tube volume (V_t), that is, for tubes with constant cross section, the ratio of fuel/air mixture length to tube length:

$$\beta = \frac{V_f}{V_t} = \frac{L_f}{L_t}. \quad (1)$$

For tubes with constant cross section, there is a critical fill fraction (β_{cr}) which is equal to β_{DDT} defined as the ratio of deflagration to detonation transition distance (L_{DDT}) to the total detonation tube length (L_t):

$$\beta_{cr} = \beta_{DDT} = \frac{L_{DDT}}{L_t}. \quad (2)$$

At fill fractions greater than 1.0, i.e. detonable mixture over-fills the tube, no increase in performance was observed because the external detonation process has no thrust surface to act on. Therefore in the experiments either fully or partially filled cases were studied, i.e. in the range of $\beta \leqslant 1$. And fill fraction of the tube was adjusted by changing ignition frequency. In the experiments, ignition frequency was set by 10 Hz firstly, and at the same time the tube was exactly fully filled by detonable mixture required by means of adjusting air supply and fuel feed, which means that fill fraction of the tube is equal to 1.0 at this detonation frequency. Then with air supply and fuel feed fixed, whereas ignition frequencies were adjusted to 12, 15 and 18 Hz step by step, corresponding fill fractions were 0.83, 0.67 and 0.56 separately, end-wall pressure histories were measured in various cases.

3 Results and discussion

It is shown that partial detonable mixture filling in PDEs has significant advantages, numerically and experimentally. Figure 2 shows schematics of partially filled thrust tubes, in which detonable mixture and unfueled air share an interface. When the tube is partially filled, the additional tube volume behaves like a straight nozzle delaying the formation of the expansion wave at the exit that propagates back to the head wall. The leading shock wave produced by a traveling detonation can be used to compress a noncombustible mixture. The resulting compressed flow will alter the blowdown process of the tube. It is by this mechanism that detonation products expands and does work on the unfueled air.

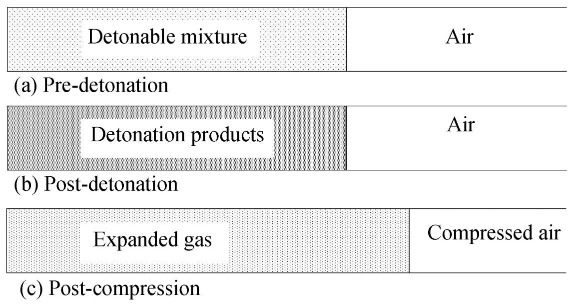

Figure 2 Schematic of partially filled PDE thrust tubes.

Figures 3—6 show pressure histories at the end-wall and the corresponding integral impulse developments with excess coefficient 1.3 and fill fraction 1.0, 0.83, 0.67 and 0.56 separately.

Figure 7 shows that single-cycle impulse varies with fill fraction experimentally. Single-cycle impulse decreased gradually as fill fraction decreased. This is due to the fact that the total chemical energy content per cycle in the tube is lower for a smaller fill fraction because of a shorter detonable mixture section, which leads to

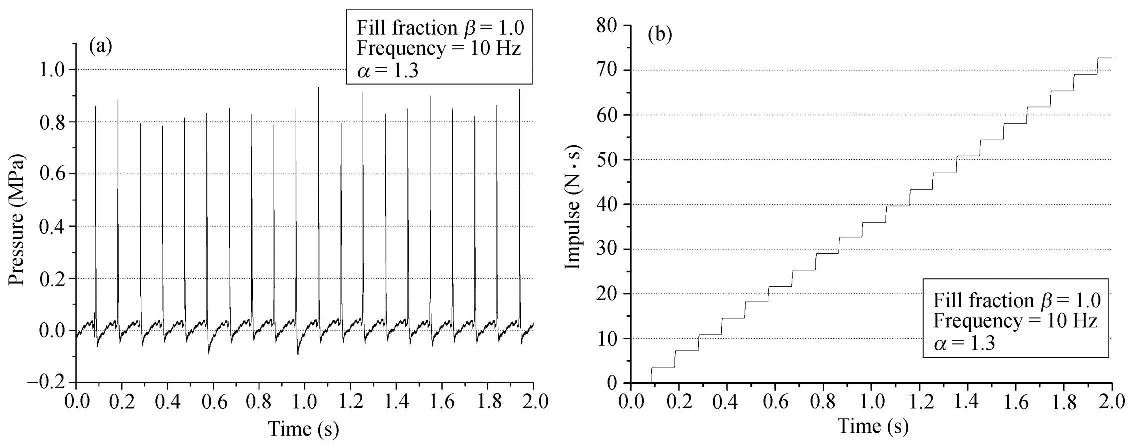

Figure 3 End-wall pressure history and impulse development from the case of multi-cycle detonations with fill fraction $\beta = 1.0$ and excess coefficient $\alpha = 1.3$. (a) End-wall pressure history; (b) impulse development.

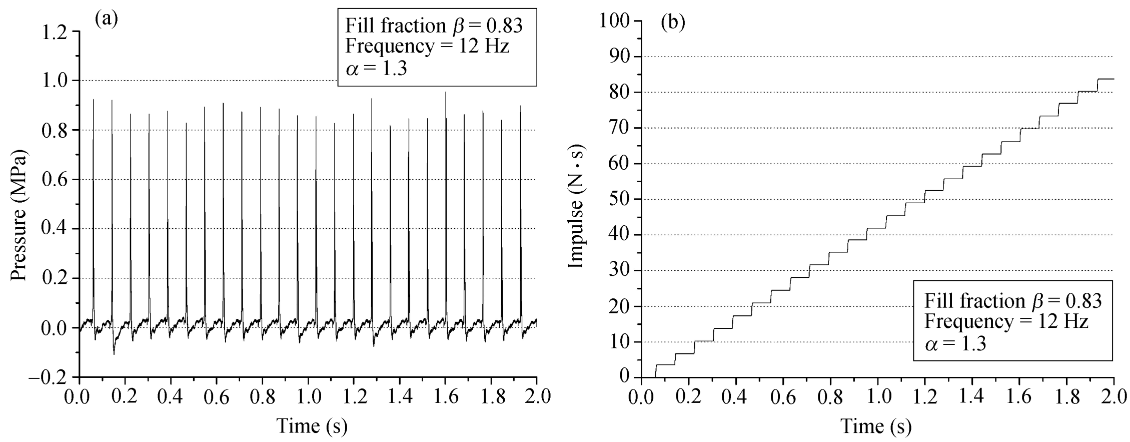

Figure 4 End-wall pressure history and impulse development from the case of multi-cycle detonations with fill fraction $\beta = 0.83$ and excess coefficient $\alpha = 1.3$. (a) End-wall pressure history; (b) impulse development.

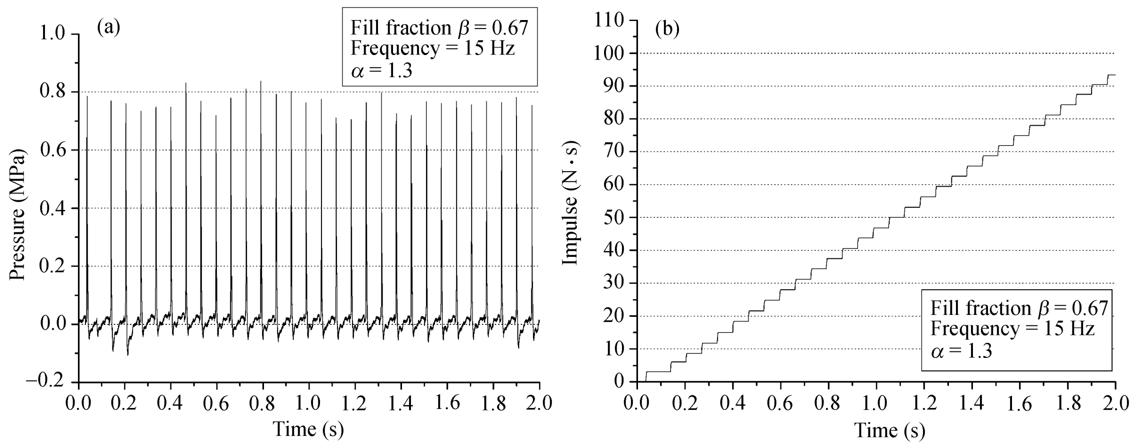

Figure 5 End-wall pressure history and impulse development from the case of multi-cycle detonations with fill fraction $\beta = 0.67$ and excess coefficient $\alpha = 1.3$. (a) End-wall pressure history; (b) impulse development.

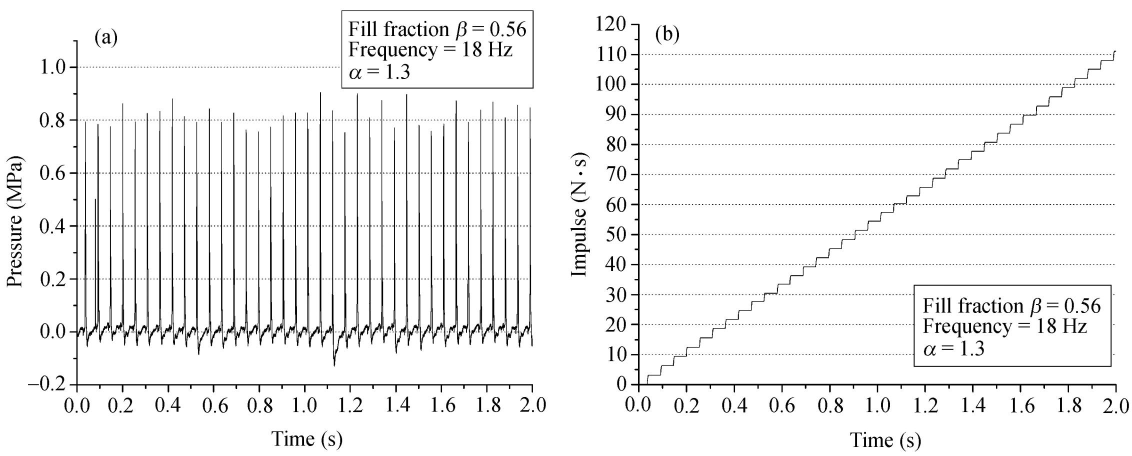

Figure 6 End-wall pressure history and impulse development from the case of multi-cycle detonations with fill fraction $\beta = 0.56$ and excess coefficient $\alpha = 1.3$. (a) End-wall pressure history; (b) impulse development.

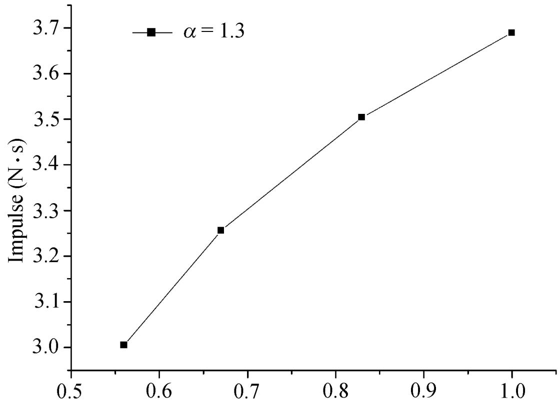

Figure 7 Single-cycle impulse varies with fill fraction.

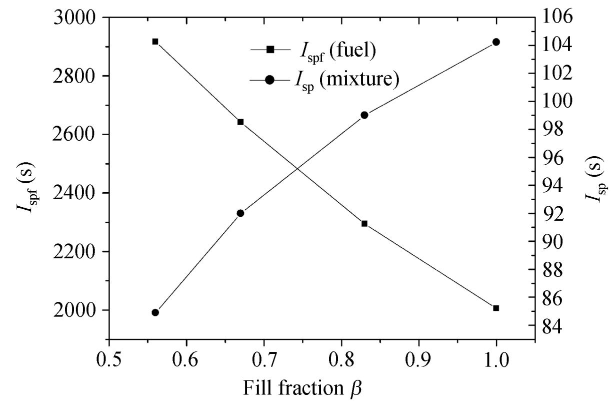

Figure 9 Specific impulse varies with fill fraction from a single-cycle detonation.

the decreased impulse.

Figure 8 shows that multi-cycle average thrust varies with fill fraction in the case. Multi-cycle average thrust increases gradually as fill fraction decreases. This is be cause in the case of constant mixture mass flow, fill fraction reduces as detonation frequency increases, which leads to the decreased single-cycle impulse. However, single-cycle impulse decreased comparatively slowly, and therefore, the increased detonation frequency dominates the average thrust trend. Figure 8 further shows that 46.6% thrust increase have been achieved as fill fraction is adjusted to 0.56.

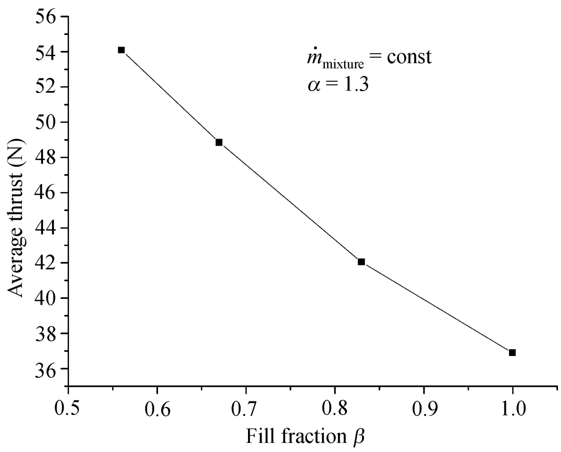

Figure 8 Multi-cycle average thrust varies with fill fraction.

Figure 9 shows that single-cycle specific impulse varies with fill fraction. The fuel-based specific impulse (I_{spf}) declines with fill fraction. On the other hand, the total-mixture-based specific impulse (I_{sp}) rises as fill fraction increases. More importantly, I_{spf} and I_{sp} scale together with fill fraction. Therefore, the impulse produced by a unit of fuel or total mixture is the same as long as fill fraction remains identical. Also, since the density difference between the fuel mixture and air is quite small, the total mass of the gaseous content in the fuel and air section in the fixed length tube considered does not change much. Therefore, I_{sp} follows a similar trend as that of the impulse.

The scaling relationship between specific impulse and fill fraction provides an important trend in the fuel efficiency for PDE applications in air-breathing propulsion. Since the amount of chemical energy is fixed for a given amount fuel, it is conceivable that specific impulse asymptotically approaches a limiting value as fill fraction decreases. Furthermore, the ratio of I_{spf} of a partially filled PDE to that of a fully filled one is confined:

$$\psi_f = \frac{I_{spf}}{I_{spf}^0}. \quad (3)$$

The ratio of I_{sp} of a partially filled PDE to that of a fully filled one is confined:

$$\psi = \frac{I_{sp}}{I_{sp}^0}, \quad (4)$$

where I_{spf}^0 and I_{sp}^0 are the fuel-based specific impulse and the total-mixture-based specific impulse with full mixture filling. Based on the results obtained from the multi-cycle detonation experiment, the two ratios can be expressed by the following fitting equations:

$$\psi_f = 0.40656 + 2.16588e^{-1.29539\beta}, \quad (5)$$

$$\psi = 1.09115 - 1.12632e^{-2.50973\beta}, \quad (6)$$

where β is fill fraction of the detonation tube. Eqs. (5) and (6) are suitable for the range of $\beta_{cr} \leqslant \beta \leqslant 1$. In other words, detonable mixture section length must be longer than that of deflagration to detonation transition, otherwise detonation cannot be achieved. However, when detonable mixture over-fills the tube, no benefit in performance was observed. In the experiment, critical fill fraction obtained is 0.53. According to eqs. (5) and (6), ψ_f and ψ has the range of $1.0 \leqslant \psi_f \leqslant 1.5$ and $0.79 \leqslant \psi \leqslant 1.0$ separately.

Figure 10 shows the end-wall pressure histories under various fill fractions. Figure 11 shows the impulse calculated by integrating the end-wall pressure differential over time based on the curves in Figure 10. It is noted especially that in the studied cases here ignition plug is not mounted on the end-wall but on a plot of the side wall 30 cm apart from it. Furthermore, detonations are achieved by means of DDT. In Figure 10, it is shown that as fill fraction is below 1.0, in the initial stage of time of operation, that is, in the process of DDT, the end-wall pressure goes up sharply, which is quite consistent with that in the fully filled case. This is due to the fact that in the partially filled case, detonable mixture section is longer than the distance of DDT, which implies that there is less effect on the process of DDT in the partially filled case. On detonation wave being generated, there are two strong shock waves, one travels upstream to the end wall, which is termed retonation wave, and the other downstream to the open end, which is the shock wave sustained by chemical reaction known as detonation wave. When the retonation wave reaches the thrust-wall, the pressure at that is increased to its maximum value. After then, retonation wave is reflected by the thrust- wall and then travels to the open end, followed by a series of rarefaction waves, when the thrust-wall pressure begins to drop. At the same time, detonation wave travels downstream to the open end at a nearly constant velocity.

In the fully filled case, detonation wave travels through the entire tube and exits the tube through its

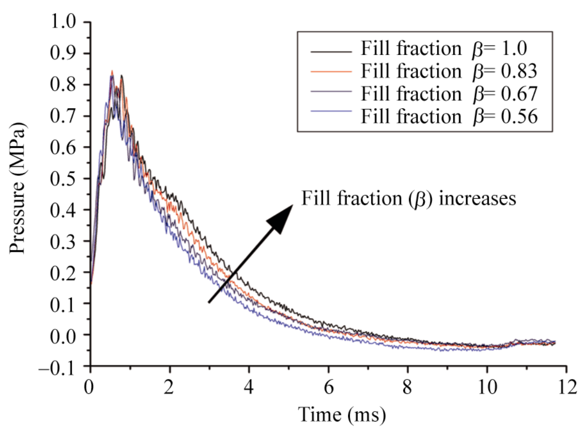

Figure 10 End-wall pressure histories from various fill fraction cases.

open end. After the detonation exits the tube, it is quenched in the surrounding air and degenerates into a non-reactive shock. In the partially filled case, the detonation is quenched and degenerates into a non-reactive shock inside the tube at the end of the detonable mixture section. This non-reactive shock later reaches the tube exit and exits the tube. In both cases, the pressure inside the tube is significantly higher than that outside the tube. Near the exit, the pressure inside reduces through expansion waves, approaching the ambient pressure level outside the tube. These expansion waves also travel upstream into the tube toward the end-wall, reducing the pressure inside the tube as well. After the expansion waves reach the end-wall, the end-wall pressure decreases gradually accordingly. Eventually, the pressure on the end-wall decreases to the level at which meaningful thrust cannot be obtained. Before the pressure drops to this level, the remaining burned combustion products in the tube should be removed, and the tube refilled with a fresh detonable mixture for the next detonation cycle.

In the partially filled case, however, the expansion waves are also generated at the material interface at the end of the detonable mixture section, interacting with the exit shock and making the pressure wave structures in the system considerably more complex. The detonation wave ceases when it reaches the detonable mixture. A reflected rarefaction wave propagates back to the thrust surface and a transmitted non-reactive shock wave travels through the air-filled extension. It is when the rarefaction wave reaches the thrust-wall that the pressure on which relaxes more rapidly. As the non-reactive shock later reaches the tube end and exits the tube, a series of reflected rarefaction waves are generated, which propagate back into the tube. After the first reflected rarefaction wave reaches the thrust surface, the pressure inside the detonation tube relaxes most sharply and eventually matching the ambient pressure. From the analysis, it is shown that when fill fraction is comparatively small, the expansion wave generated from the detonable mixture-air interface reaches the thrust-wall firstly, and this leads to a rapid pressure decrease inside the detonation tube.

In Figure 10 the time histories clearly show different trends in pressure for various partially filled cases. When fill fraction is 0.56, the thrust-wall pressure relaxes drastically firstly, subsequently the cases of 0.67 and 0.83 in turn. And in the fully filled case (with fill fraction 1.0) the pressure relaxes most slowly. Correspondingly, in Figure 11 with fill fraction 0.56, the integral impulse increasing rate becomes slow firstly, then the case of 0.67, 0.83 and 1.0 in turn. In Figure 10, at t = 10.7 ms the thrust-wall pressure histories in the cases of different fill fractions rise suddenly and then agree well again. This phenomenon can be explained by the fact that overexpansion of the detonation products leads to subatmospheric pressure at the tube exit, which subsequently generates reflected shock waves that propagate back to the thrust-wall and recover the thrust-wall pressure to ambient pressure. From the analysis, it is shown that when fill fraction is relatively small, a reflected rarefaction wave was generated at the detonable mixture-air interface firstly, which propagates back to the thrust-wall, and the discharge process begins. This means that comparative less detonation products employ relative more time, and this explains to some extent the reason of high fuel efficiency of the system in the partially filled case.

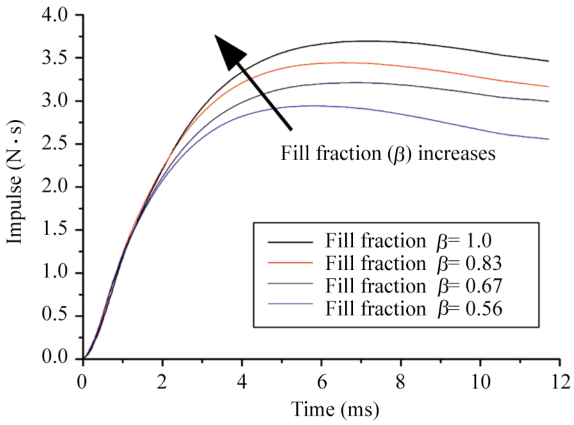

Figure 11 End-wall pressure histories from various fill fraction cases.

4 Conclusions

(1) There is a critical fill fraction for a detonation tube. And when fill fraction is below the critical value, some exceptional phenomena such as continuous combustion, oscillating combustion or extinction will appear.

(2) With the tube inner configuration fixed and detonable mixture mass flow constant, impulse per cycle decreases gradually as fill fraction increases, and on the other hand the average thrust goes up. When the tube is filled at the critical state, the impulse reaches its maximum value. In the experiments, as fill fraction decreases from 1.0 to 0.56, the average thrust increases from 36 N to 52.8 N, which implies that 46.6% thrust gain has been obtained.

(3) The fuel-based specific impulse declines with fill fraction. On the other hand, the total-mixture-based specific impulse rises as fill fraction increases. In the experiments the critical fill fraction (β_{cr}) obtained is 0.53. During fill fraction varying from 1.0 to the critical value, the fuel-based specific impulse ratio has the range of $1.0 \leqslant \psi_f \leqslant 1.5$ and the fuel-based specific impulse ratio has the range of $0.79 \leqslant \psi \leqslant 1.0$.

(4) A multi-cycle partial-fill model is developed to predict the impulse obtained from a partially-filled detonation tube, which is valuable for the optimization of PDE performance.

(5) Partial filling is one of the methods to adjust the thrust of PDE. Moreover, increased fuel efficiency of the system can be obtained in the partially filled case, which is suitable for cruise condition. While maximum thrust is required, the detonation tube should be fully filled.

1 Helman D, Shreeve R P, Eidelman S. Detonation pulse engine. AIAA-86-1683

2 Eidelman S, Grossmann W, Lottati I. A review of propulsion application of the pulsed detonation engine concept. J Propul Power, 1991, 7(6): 857－865

3 Fan W, Yan C J, Huang X Q, et al. Experimental investigation on two-phase detonation engine. Combust Flame, 2003, 133(4): 441－450[DOI]

4 Kaemming T A. Integrated vehicle comparison of turbo-ramjet engine and pulsed detonation engine (PDE). ASME, 2001-GT-451

5 Zitoun R, Desbordes D. Propulsive performances of pulsed detonations. Combust Sci Tech, 1999, 144(1): 93－114[DOI]

6 Schauer F, Stutrud J, Bradley R. Detonation initiation studies and performance results for pulsed detonation engines. AIAA-2001-1129

7 Kailasanath K. A review of research on pulse detonation engine nozzles. AIAA-2001-3932

8 Falempin F, Bouchaud D, Forrat B. Pulsed detonation engine—possible application to low cost tactical missile and to space launcher. AIAA-2001-3815

9 Cooper M, Shepherd J E. The effect of nozzle and extensions on detonation tube performance. AIAA-2002-3628

10 Li C, Kailasanath K. Performance analysis of pulse detonation engines with partial fuel filling. AIAA-2002-0610

11 Yungster S. Analysis of nozzle effects on pulse detonation engine performance. AIAA-2003-1316

12 Dyer R S, Kaemming T A, Baker R T. Reaction ratio and nozzle expansion effects on the PDE. AIAA-2003-4514