Article

A study for development of hydrogen-fueled pulse detonation engines

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Abstract

Pulse detonation engine (PDE) holds promise to increase performance of air breathing propulsion systems by taking advantage of high cycle efficiency due to constant volume heat addition characteristics of detonative combustion. Currently, PDE is an active research topic with experimental developments reported by many researchers. Several of these investigations attempted multiple cycle experiments, however, it is uncertain as to whether detonations were produced on a regular basis in these tests. The experimental results for development of hydrogen-fueled pulse detonation engine are discussed in this paper. Although characteristics of premixed detonation of hydrogen-air mixture are well investigated, characteristic of detonation in non-premixed or partially premixed gases has not been studied yet. As the first step, a single cycle test was conducted to research of deflagration to detonation transition (DDT) of hydrogen / air directly injected to combustion chamber. As the second step, a multiple cycle test up to 10 Hz was conducted to demonstrate the feasibility of multiple cycle operation of PDE. Thrust wall pressure, tube wall pressure along the tube, and ionization current were measured. Sharp pressure spike was observed. It shows that the overdriven detonation wave was formed at thrust wall. The injection systems were also studied for single injection and double injection. It should be noted that, although the detonation waves could not be initiated instantaneously at the igniter, the resulted impulse on thrust wall could be improved by double injection system as compared with single injection system.

Nomenclature

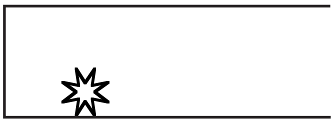
A	cross-sectional area of detonation tube
c_3	sound speed of burned gases behind Taylor wave
F	thrust
I	Single-cycle impulse
I_V	impulse per unit volume
$I_{sp,f}$	fuel-based specific impulse
L	length of detonation tube
p	pressure
t	time
t_1	time taken by the detonation wave to reach the open end of the tube
t_2	time taken by the first reflected characteristic to reach back the thrust surface
t_3	time associated with blowdown process
U_{CJ}	Chapman-Jouguet detonation velocity
V	inner volume of detonation tube
α	non-dimensional parameter corresponding to time (t_1+t_2)
β	non-dimensional parameter corresponding to blowdown process
Δp_3	pressure differential at the thrust surface

1. Introduction

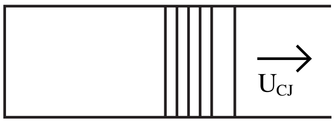
Pulse detonation engine (PDE) is one of the future candidates of aerospace propulsion devise. It is air-breathing engine, which can utilize air as oxidizer. In the earlier half of the last century, pulse combustion engine had been developed for V1 rocket. Liquid rocket engine for V2 was successfully developed, hence the pulse combustion engine had been abandoned. Pulse engine has an advantage to rocket because it can utilize air, which fills the space where projectile such as the aerospace plane will fly. It also has an advantage to turbo or ram jet engines because it performs a constant volume cycle (Humphrey cycle), which has higher thermal efficiency than that for the constant pressure cycle (Brayton cycle). Pulse detonation engine is an evolved engine from pulse combustion engine. It utilizes detonation wave rather than deflagration wave, which pulse combustion engine uses. Because of detonation has much greater pressure increase and much greater propagation velocity than deflagration wave, the efficiency of pulse detonation engine is expected much higher than that of pulse combustion engine.

Among early studies on PDE, Nicholls et al.[1)] had succeeded in developing an experimental pulse detonation engine. After a long period devoted for the development of rockets and SCRAM jet engines, several researchers[2)–6)] had begun to develop PDE by the need of highly efficient aerospace propulsions for the present century.

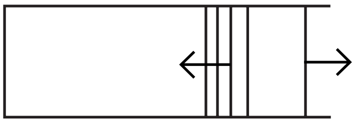
Concept of single combustor, multiple cycle PDE operation is shown in Fig. 1. A typical combustor consists of a tube, open at one end, with an injector at the other end. Fuel gas and air are injected, filling most of the tube. A detonation is initiated at the end of tube. The detonation travels through fuel / air mixture. Note that an expansion fan follows the detonation wave to enforce zero velocity condition at close end of tube. The detonation exits the tube and a blow down process begins with propagation of an expansion fan back into the tube. Once the blow down process is completed, fresh fuel gas and air are injected to start next cycle.



1. Detonation is initiated at the tube wall.



2. Detonation, followed by Taylor wave, propagetes to the open end of tube.



3. Expansion fan is reflected off of the interface and immediately interacts with Taylor wave while detonation products start to exhaust from tube.

4. First characterristic of reflected expansion wave reaches thrust wall and decreases pressure at the wall.

Fig. 1 Concept of pulse detonation engine cycle.

Gas dynamics inside idealized tube can be analyzed using distance-time (x–t) diagram shown in Fig. 2. x–t diagram displays detonation wave propagating at Chapman-Jouguet velocity U_{CJ} followed by Taylor expansion wave. First reflected characteristic from mixture-air interface at the open end of tube is also shown. This characteristic has an initial slope determined by the conditions at the interface, which is then modified by the interaction with Taylor wave. Once it has passed through Taylor wave, this first characteristic of reflected expansion wave propagates at sound speed of the medium c_3. The region lying behind this first characteristic is non-simple, as reflected expansion fan interacts with the incoming Taylor wave. Two characteristic times can be defined: t_1 corresponding to reflection of detonation wave at the interface, and t_2 corresponding to the time necessary for first reflected characteristic to reach thrust surface. Pressure variation at thrust surface generates the impulse. Therefore, it is interesting to focus on pressure history at thrust wall.

In this study, as a preliminary study for the development of this engine, the initiation stage of detonation is studied experimentally by using an experimental engine. The experimental engine has cylindrical combustion chamber with length of 1,450 mm and inner diameter of 30 mm and nozzle with length of 595 mm and inner diameter of 30 mm. Hydrogen is selected as fuel and oxidizer is air. A first step of this study is devoted for experiments on DDT (Deflagration to Detonation Transition) process in the mixture with insufficient mixing after injection of fuel and

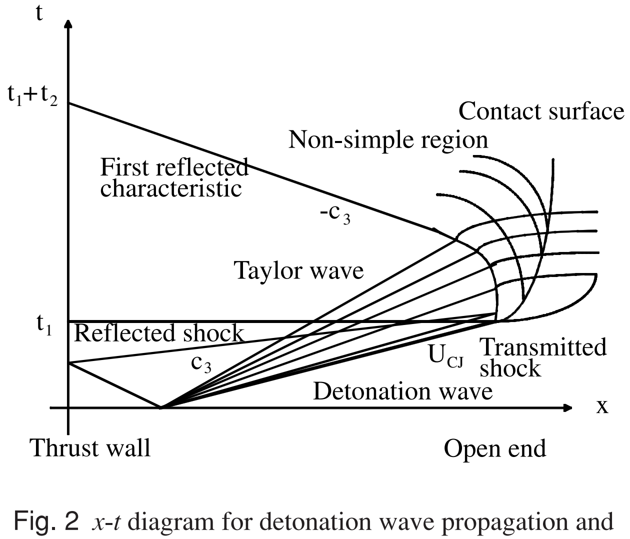


Fig. 2 x-t diagram for detonation wave propagation and interaction with tube open end.

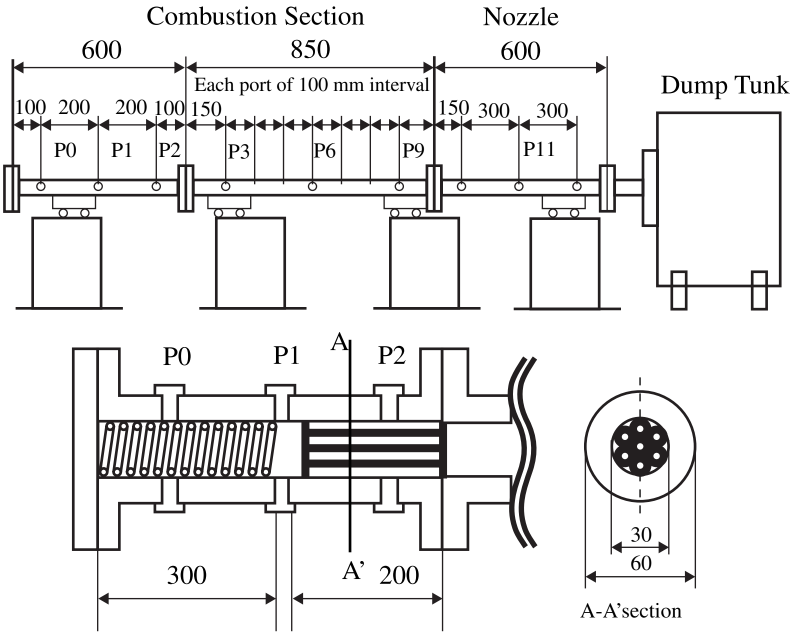


Fig. 3 Schematic of multiple cycle experimental apparatus.

air from injectors into combustion chamber. The second step is to develop a multiple cycle system. In this step, intermittent combustion up to 10 Hz is obtained and it is demonstrated that the intermittent detonation is achieved.

2. Single Injection PDE

2.1 Experimental

A schematic of the apparatus is shown in Fig. 3. It consists of a stainless steel tube with 30 mm inner diameter and 2,045 mm length. The tube is divided into combustion section of 1,450 mm and nozzle tube of 595 mm. In the combustion section, Shchelkin spiral and tube bundle are inserted to enhance detonation transition. Wire diameter and pitch of Shchelkin spirals were 5 mm and 20 mm and total length was 300 mm. The tube bundle was located downstream of Shchelkin spiral and it was consisted of eight tube with 5 mm diameter and 200 mm length. A dump tank with 0.40 m^3 is connected to nozzle. A spark plug is located at 300 mm from thrust wall (left end plate in Fig. 3). Two injectors for fuel gas and oxidizer gas are situated at 100 mm from thrust wall. They are connected with solenoid valves (AB41-02-1, -2, CKD Inc.) and adapters, which can modify jet direction. In the present experiment, two injectors for fuel (hydrogen) and air were situated in the opposite side for each other at the same location. We call this type of injectors as “counter flow type”. Diameters of the nozzles were 2.0 mm. Fuel and air were fed from gas cylinders through reducing valves. Reservoir pressures for each gas were 0.8 MPa for hydrogen and 2.0 MPa for air. Injection durations for each gas were determined by flow rate at critical condition. Pressure transducers (PCB 113A24, Piezotronics Inc.), which can detect high-speed pressure waves, can be mounted flush at ports named P0 through P11 along the tube wall. Two-needle type ionization probes, which can detect combustion wave are also mounted at the same position in opposite side of the pressure transducer. A pressure transducer is also equipped on the thrust wall. Data from the transducers were stored in two 4-ch storage oscilloscopes (DL1520, Yokokawa Electric Inc.) with 1.0 MS s^{-1}.

Table 1 shows experimental conditions. The tube is evacuated at first to remove residual gas of the previous experiment. Then it is filled with fresh air at atmospheric pressure. Fuel gas, which is hydrogen throughout this experiment, and oxidizer air are injected into the tube through the injectors mentioned above. Amount of these gases injected is determined to form a mixture denoted in Table 1 in the combustion section by controlling injection durations of two gases. Chapman-Jouguet pressure and propagation velocities are 1.62 MPa and 1,960 m s^{-1}, which are calculated by the chemical equilibrium code developed by

Table 1 Experimental conditions.

Fuel and Oxidizer	H_2+Air (O_2+3.76N_2)
Initial Pressure [kPa]	92.6
Equivalence Ratio	1.00
Injection Pressure [MPa]	H_2 : 0.8 Air : 2.0
Mixing time before ignition [ms]	40
DDT augmentation device	Shchelkin spiral 300 mm and multiple tube 200 mm

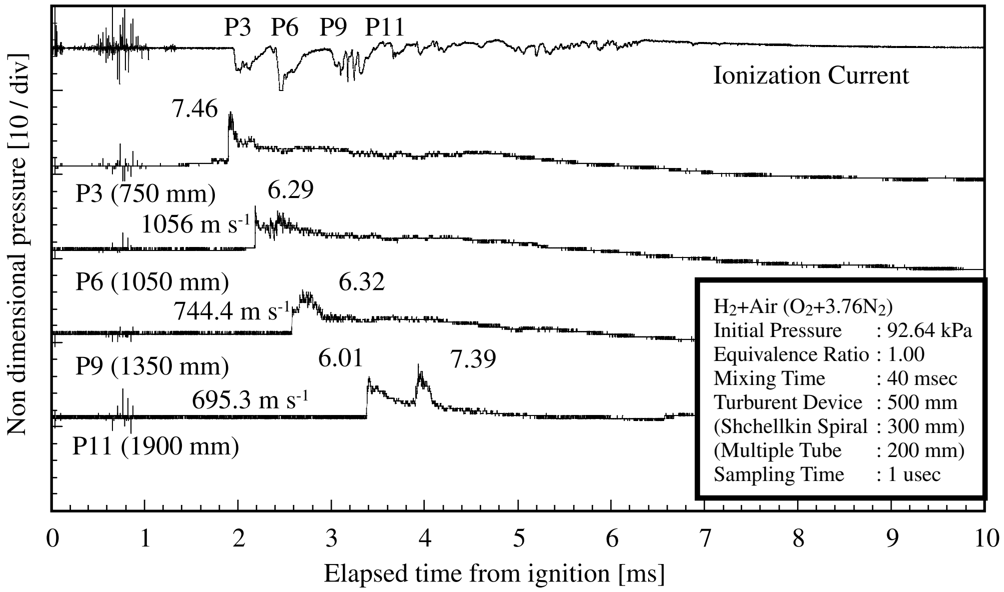


Fig. 4 Tube wall pressure histories in single cycle test.

our laboratory. Signals, which control the valve opening / closing and ignition, are produced by a personal computer. Mixing time, which is defined as time between valve closing and ignition is very important for DDT (Deflagration to Detonation Transition) in the mixture. In this experiment, 40 ms for mixing time is selected because it is revealed that this is optimum for DDT. In the multiple cycle test, ignition frequency can be variable, but in this experiment it was fixed at 10 Hz. Number of cycles was limited to 10 as the tests was performed in closed condition.

2.2 Results and Discussions

2.2.1 Single Cycle Test

Figure 4 shows typical pressure records at P3 (750 mm from thrust wall), P6 (1,050 mm), P9 (1,350 mm) and P11 (1,900 mm) with an ionization current record at the same positions for the conditions of Table 1. The abscissa denotes a time elapsed from ignition. Numerals near the pressure profiles denote peak pressures (divided by the initial pressure) and propagation velocities at each point. Peak pressures and propagation velocities are far less than Chapman-Jouguet values so that the detonation wave was not initiated in this condition. A shock front coincides with a flame front at P3 so that a detonation-like combustion wave might be formed but the pressure is not enough to be judged as a detonation wave. At the other positions, shock fronts and flame fronts separate from each other so that it is concluded not detonation.

Figure 5 shows pressure history on thrust wall. A sharp pressure spike was observed about 1.6 ms after the igni-

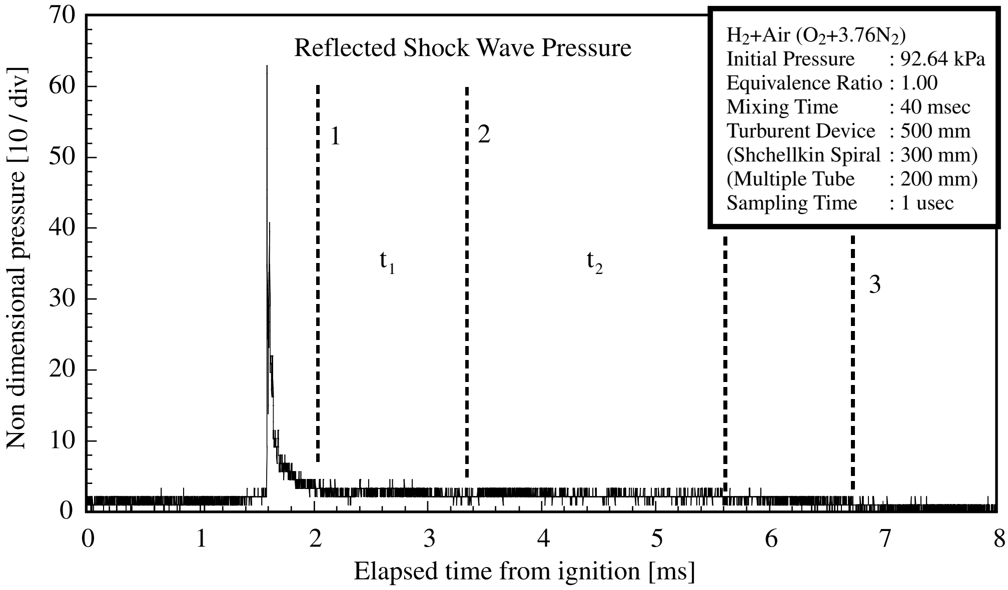


Fig. 5 Thrust wall pressure history in single cycle test.

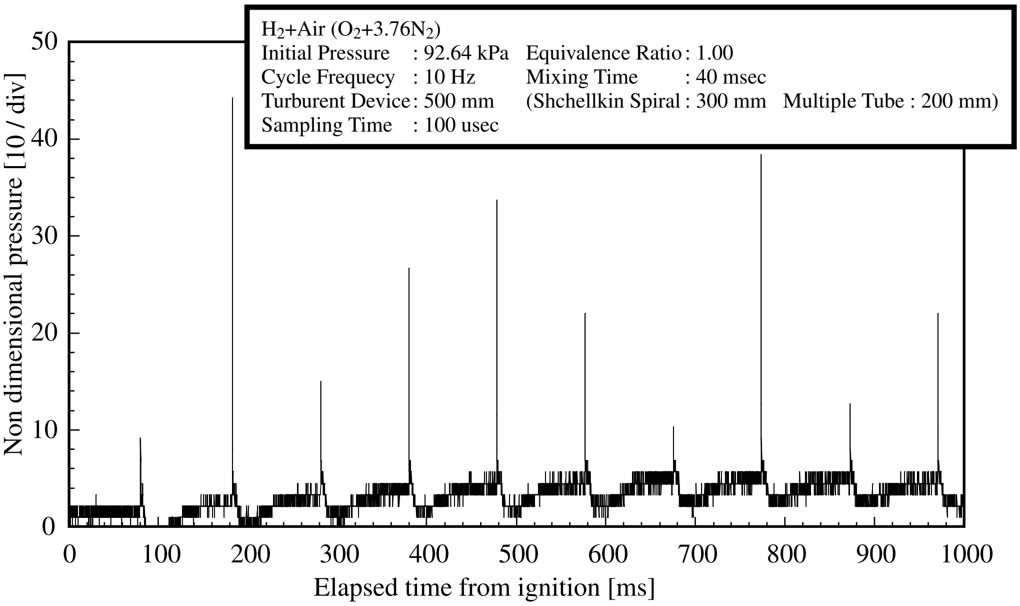


Fig. 6 Thrust wall pressure history in multiple cycle test for a 10 cycles, 10 Hz.

tion. Its peak was about 60 times the initial pressure so that it is sure that the overdriven detonation wave is formed at thrust wall. Detonation induction time is less than 1.6 ms. After the wave leaves from the wall, Taylor expansion wave continues for 0.4 ms followed by a pressure plateau whose pressure is about 0.3 MPa (Region 1-2 in Fig. 5). Region 2-3 is an exhaust process to dump tank. It is concluded that at least 6.8 ms is necessary for combustion and exhaust processes in the engine cycle. Detonation wave initiated at thrust wall decayed to shock- reaction complex as it propagated downstream as was shown in Fig. 4 because the mixture might not be uniform.

2.2.2 Multiple Cycle Test

Figure 6 shows a typical pressure record on thrust wall of a multiple cycle test. In each cycle, there exist three stages, that is, compression stage or injection stage, combustion stage and exhaust stage. In the first cycle, as the tube was filled with air initially, there was no compression stage. Pressure spikes were observed in combustion stages. Maximum non-dimensional pressure was largely varied from 10 to 45. This cycle-to-cycle variation may be occurred due to the incompleteness of the exhaust stage. Of course, it is undesirable for a practical engine, and it should be investigated. After combustion stage, there existed the exhaust stage for several milliseconds as was mentioned in the previous section. Minimum pressure of this stage should be dependent on the exit condition. In this experiment, dump tank was not evacuated but was filled with air at atmospheric pressure, and it should be atmospheric pressure. However, minimum pressure seems to be less than one atmosphere in the first cycle. It might

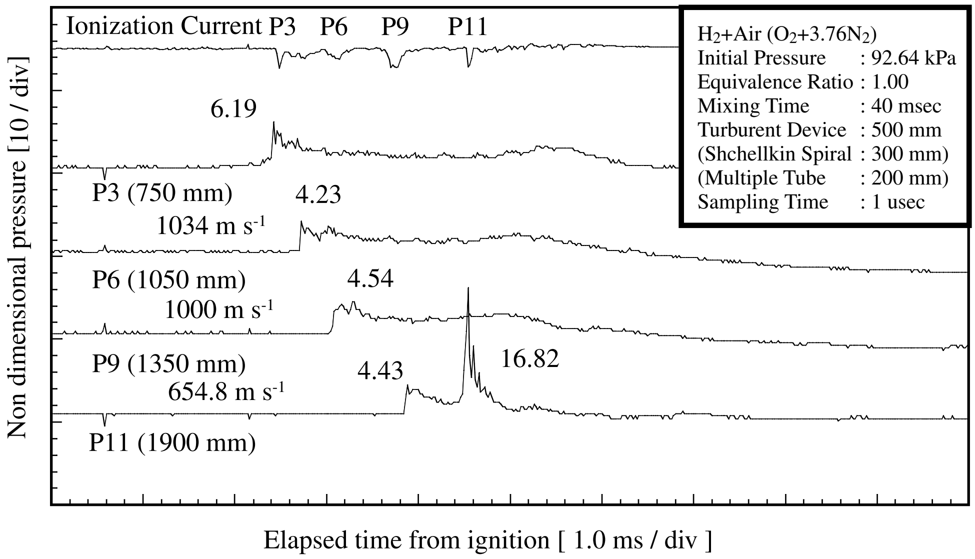


Fig. 7 Tube wall pressure histories of the 2nd cycle shown in Fig. 6.

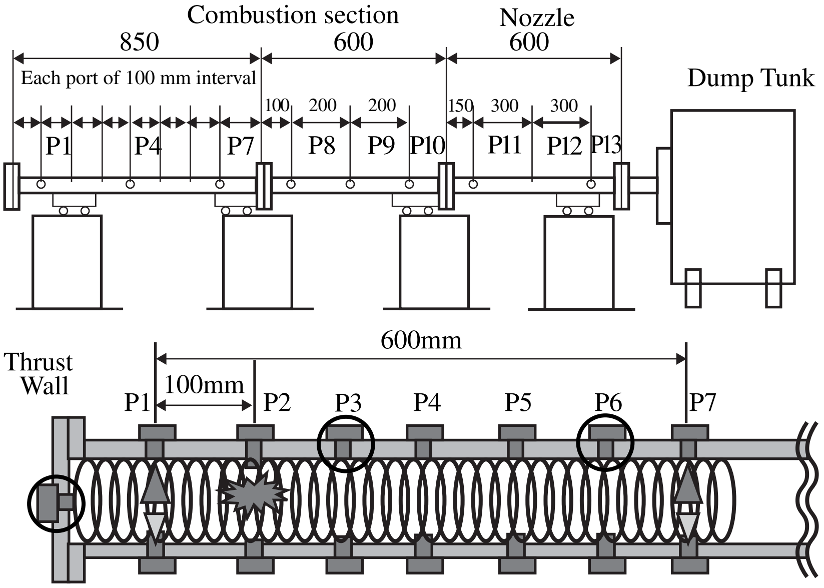


Fig. 8 Schematic of double injection experimental apparatus.

Table 2 Experimental conditions.

Fuel and Oxidizer	H_2+Air (O_2+3.76N_2)
Initial Pressure [kPa]	102
Equivalence Ratio	1.89
Injection Pressure [MPa]	H_2 : 0.8 Air : 2.0
Mixing time before ignition [ms]	40
DDT augmentation device	Shchelkin spiral 1,200 mm

be attributed to the characteristics of pressure transducer of piezo-type. After the exhaust stage, fuel gas and air were injected to fill the tube. This stage occupies longest period in the cycle, and depends on the diameter of injector as well as on the number of injectors. Pressure level was seemed to slightly increase through the whole ten cycles. Although piezo characteristic of the sensor is uncertain, it should be noted that the whole system including dump tank was closed, so that the pressure level should be increased.

Figure 7 shows the pressure and ionization current along the tube wall for multiple cycle condition. The data corresponds to second cycle of the experiment in Fig. 6. It seems to be nearly same as the data in Fig. 4. Detonation wave initiated at thrust wall decays as it propagates along

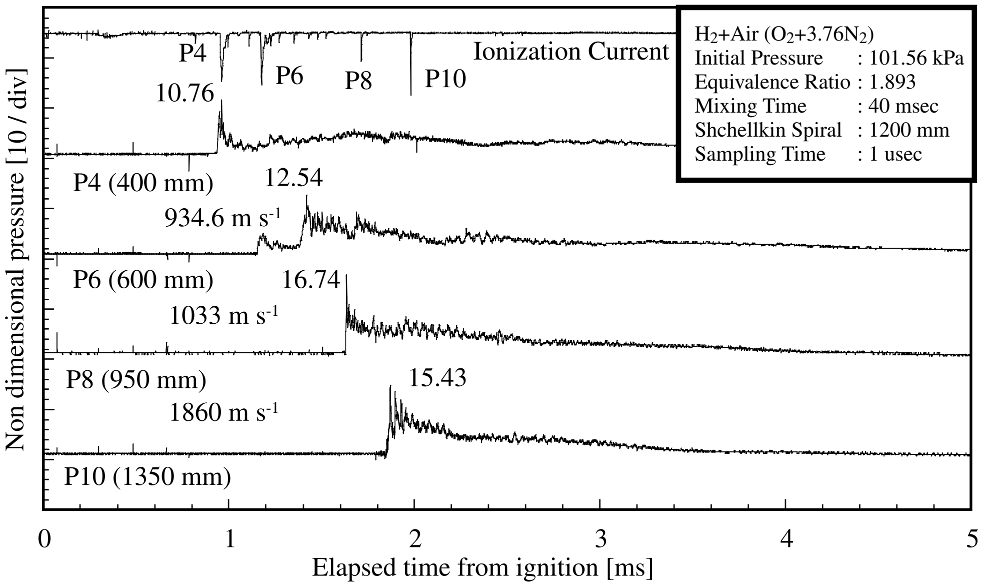


Fig. 9 Tube wall pressure histories in single cycle test.

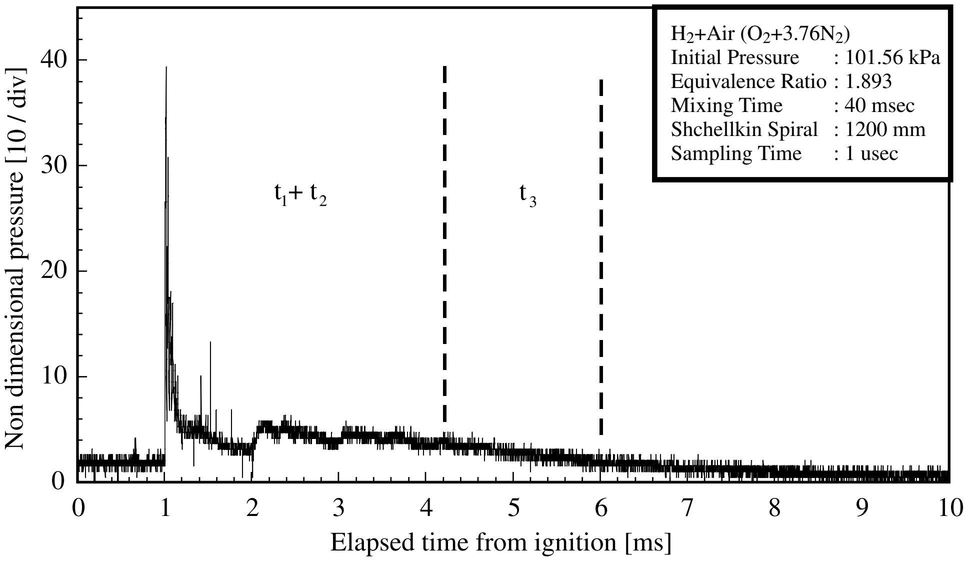


Fig. 10 Thrust wall pressure history in single cycle test.

the tube. Combustion wave in the tube was not detonation but shock-reaction wave complex.

In the single injector experiment of this section, we conclude that it is difficult to develop detonation in a whole tube because its non-uniformity of mixture. So we decided to continue our study by adding an injector.

3. Double Injection PDE

3.1 Experimental

A set of injectors was added to single injection PDE described in the previous section. The location of second set of injectors was 700 mm from thrust wall. Figure 8 shows present arrangement of the apparatus. The location of first set of injectors was 100 mm from thrust wall. The injectors were at P1 and P7. The igniter position was also changed to be 200 mm. Tube bundle was not used in this case. We selected only Shchelkin spiral of 1,200 mm long. The other experimental conditions are essentially same as the single injection experiment described in Table 2, but the initial pressure and equivalence ratio were changed to 102 kPa and 1.89 due to the addition of injectors because the injection time was not changed from the single injection case. Chapman-Jouguet values of pressure and propagation velocity at this condition are 1.46 MPa and 2,137 m s^{-1}.

3.2 Results and Discussions

3.2.1 Single Cycle Test

Figure 9 shows wall pressure along the tube and the ionization current record. Peak pressures were still smaller than CJ value but it is evident that the wave developed to detonation wave as it propagated across second injectors. The ionization record was not so clear in this case, while peak pressure and propagation velocity became high as 16.74 and 1,860 m s^{-1} around P8.

Figure 10 shows thrust wall pressure. Pressure peak reached 40 so that the overdriven deto-nation was initiated

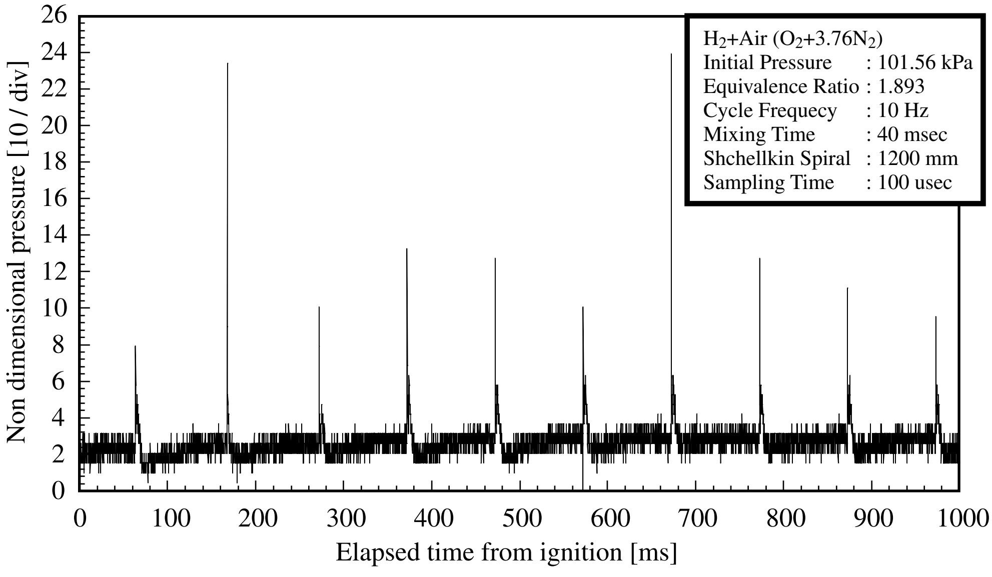


Fig. 11 Thrust wall pressure history in multiple cycle test for a 10 cycles, 10 Hz.

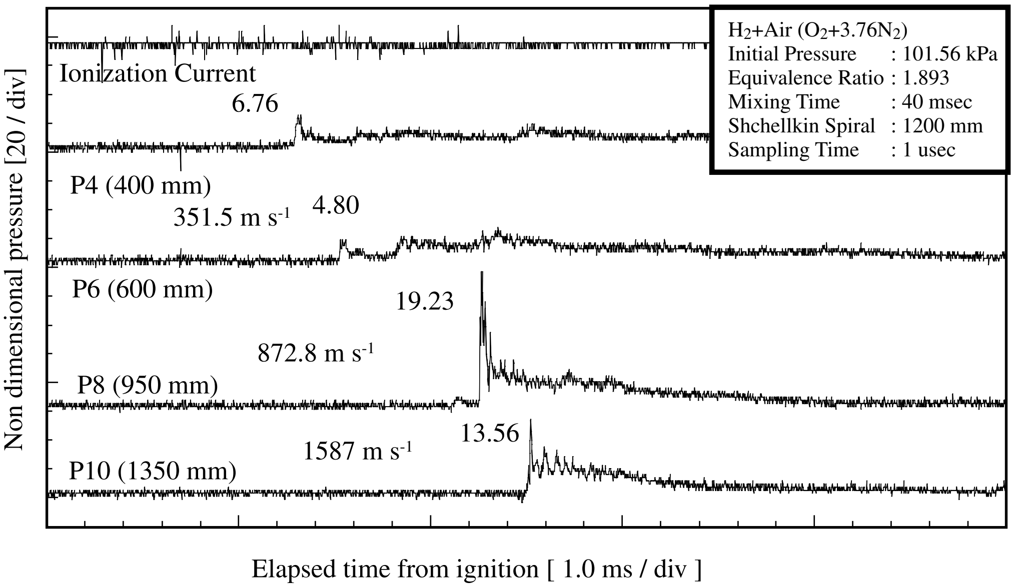


Fig. 12 Tube wall pressure histories of the 5th cycle shown in Fig. 11.

at the wall. After Taylor expansion wave, there exists some pressure recovery or fluctuations in pressure plateau period due to DDT process occurred in the tube.

3.2.2 Multiple Cycle Test

Figure 11 shows thrust wall pressure record for 10 cycles. Maximum pressure spike was lower than that of single injection case and cycle-to-cycle variations became small. Decrease in maximum peak might be caused by the fact that the distance from the igniter was increased.

Figure 12 shows wall pressure along the tube for fifth cycle of this experiment. The similar results were obtained in the single cycle case where DDT process was observed. Detonation induction length (DID) was shortened due to double injection.

By increasing a number of injectors, it is evident that the uniformity of mixture will be increased to result in shortening DID. Then it can be said that the engine was developed to the ideal detonation engine.

4. Impulse

The impulse on thrust wall for one cycle is defined as

$$I \equiv A\int_{0}^{\infty} \Delta p(t)dt \tag{1}$$

where A denotes a cross-section area of the tube and $\Delta P(t)$ denotes a pressure difference across thrust wall. According to the theory developed by CALTEC group[5], the impulse can be approximated as

$$I \equiv \frac{AL\,\Delta p_3}{U_{CJ}}\left\{1+\frac{U_{CJ}}{c_3}(\alpha+\beta)\right\}, \tag{2}$$

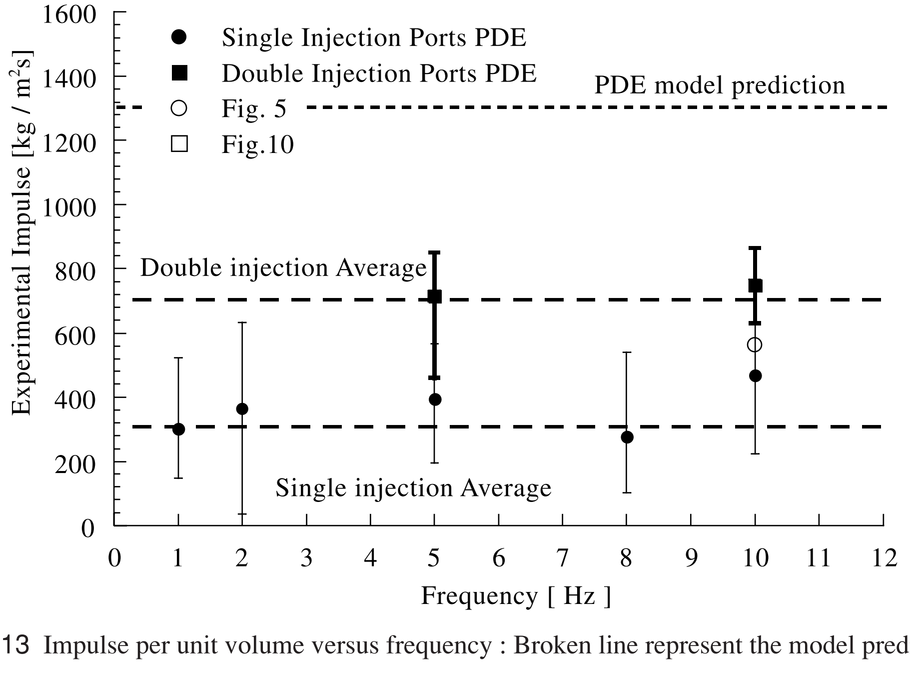


Fig. 13 Impulse per unit volume versus frequency : Broken line represent the model predictions.

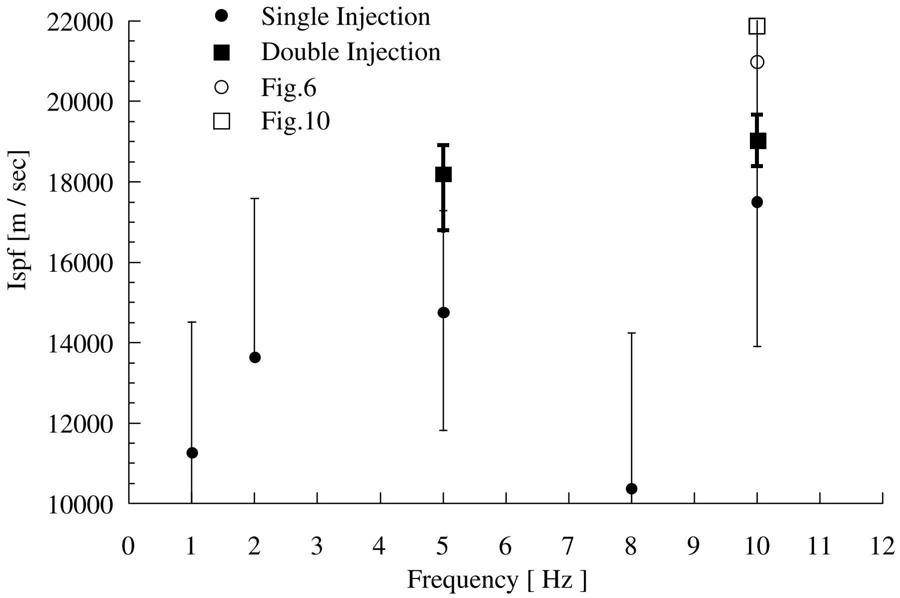


Fig. 14 Fuel specific impulse versus frequency.

where L, U_{CJ}, Δp_3 and c_3 denote tube length, tube volume, Chapman-Jouguet propagation velocity, plateau pressure and sonic velocity behind Taylor expansion and α and β denote numerical constants, which are assumed to be 1.1 and 1.0. This theory assumed that detonation wave was directly initiated at thrust wall. It means zero induction distance.

For the present condition, $U_{CJ} = 1{,}972\ \mathrm{m\ s^{-1}}$, $c_3 = 944.7\ \mathrm{m\ s^{-1}}$ and $\Delta p_3 = 477.0$ kPa .
Then,
$I_V \equiv IV^{-1} = 1{,}302\ \mathrm{Nsm^{-3}}(=\mathrm{kgm^{-2}\ s^{-1}})$, where $V = AL$ denotes a volume of combustion chamber.

Figure 13 shows this volumetric impulse with cycle frequency. It is clear that the impulse of double injection case was improved from that of single injection case. The differences between the theory and experiments might be caused by the existence of DDT processes in the experiments. It should be noted that the impulse does not depend on frequency up to 10 Hz at least. So, it shows a possibility of increasing frequency further.

Figure 14 shows frequency dependence of fuel specific impulse defined by

$$I_{sp,f} \equiv \frac{Ft_{cycle}}{m_f} = \frac{I}{m_f}[\mathrm{m\ s^{-1}}], \qquad (3)$$

where F, m_f and t_{cycle} denote thrust force, mass of fuel per cycle and period of cycle. It is a matter of course that specific impulse does not depend on frequency, but the results indicate that some variations with frequency exist. It should be attributed to the incompleteness of DDT process. Further improvement on the injection and ignition systems should be made for rapid transition to detonation.

5. Conclusions

A preliminary experimental study was performed on the development of pulse detonation engine by using hydrogen-air mixtures as propellants. As a first step, DDT process in the mixtures formed by injecting directly into the tube was investigated. Based on the experiences on these single cycle experiments, the multiple cycle system was developed and confirmed to operate for 10 Hz cycle frequency. The injection systems were also studied for single injection and double injection. It should be noted that, although detonation waves could not be initiated instantaneously at the igniter, the resulted impulse on thrust wall could be improved by double injection system as compared with single injection system. Further studies should be made on DDT process as well as on the improvement on the injection system for realizing higher frequency of the cycle.

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