

Experiments on Inter-Tube Interference in a Four-Tube Pulse Detonation Engine

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1. Introduction

Pulse detonation engine (PDE) has inherently higher thermal efficiency than the conventional gas turbine engine, because the heat release process is performed by detonation. However, the kinetic energy is not easily extracted from the exhausted gas and the turbine efficiency tends to be low, because the exhaust from PDE is intermittent. It is indispensable to make intermittent gas flat and smooth for improving in the turbine efficiency.

Although various methods can be considered for smoothing the exhaust gas, one of the effective methods is bundling the several detonation tubes and raising the total-system frequency. It is assumed that the exhaust interference between the detonation tubes prevents the inspiration and purge in the vicinal tubes, and makes the exhaust friction large. However, there are very few experimental open data of exhaust interference in multi-tube PDE.

We have developed the four-tube pulse detonation engine with hydrogen-air mixture. Confirmed maximum operational frequency of this PDE was 30Hz at one tube, which was 120Hz in the system total frequency. In the present report, the fact that the instability of detonation generation increases at the multi-tube operation caused by the inter-tube exhaust interference is reported.

2. Experimental arrangements

Developed pulse detonation engine shown in fig.1 and table 1 consists of four individual detonation tubes. Hydrogen-air mixture was chosen as detonable mixture, which can be detonated relatively easily by deflagration to detonation transition. Thus, we chose the method of installing the Schelkin spiral in the detonation tube for detonation initiation instead of the usage of the initiator, which tends to complicate the system. The hydrogen-air mixture also yields the benefit of miniaturization of the equipment, because the mixture of hydrogen has smaller detonation cell size and critical diameter than that of general hydrocarbons. The detonation tube diameter of developed multi-tube PDE is 29.8mm, which is large enough for hydrogen-air mixture to propagate in detonation phase.

Figure 2 shows the hydrogen-air supply system to the detonation tubes. Hydrogen and air to each tube are fed from independent bombs and supply system from other tube. Hydrogen and air are injected individually to the tubes, and they are mixed in the tubes. The injections are controlled by the pneumatically driven solenoid

valves (H₂: MAC 52series, Air: MAC 55series). The gaseous feeding speed is adjusted not by changing the gaseous supply pressure, but by installing the orifice to minimize the changing of feeding speed affected by raised backpressure. The calibrations of both hydrogen and air feeding speed were measured by the water substitution method. Two ignition plugs are installed at the downstream of gaseous feeding ports in each tube. The gaseous injection and ignition timing are controlled by the signals from PC via digital IO board (Interface: IBX 2724CL).

The inside of the collecting duct, which collects up the exhausts from four detonation tubes, is con shape with taper angle of 15 degree. The collecting duct converges from the inner diameter of 130 mm, which circumscribes the bores of four detonation tubes, to the diameter of 29.8mm that is equivalent to the inner diameter of detonation tube. There is a room to install the device for reducing the effects of exhaust interference in the collecting duct, such as partition plate. However, it should be noticed that no devices were installed there in the present series of experiments.

The behaviors of shock waves in the tubes were observed by PCB pressure gauges (HM102A06). The three pressure gauges were installed at the end of Schelkin spiral in the 1st tube (P1), exit of 1st tube (P2), and the exit of collecting duct (P3).

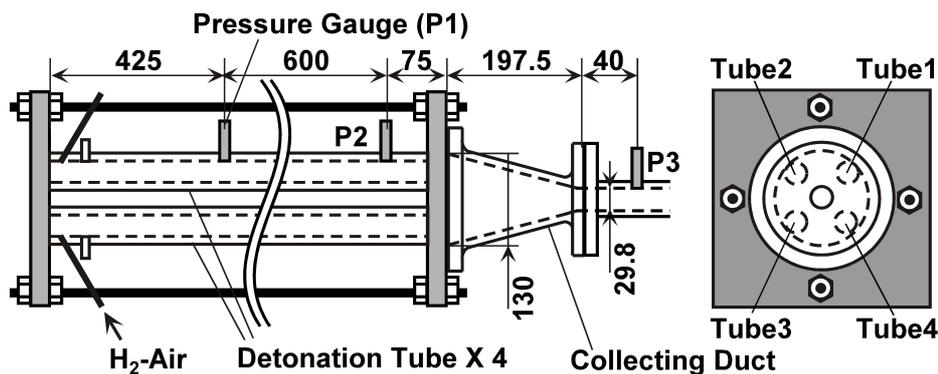


Fig.1 Schematic diagram of four-tube pulse detonation engine

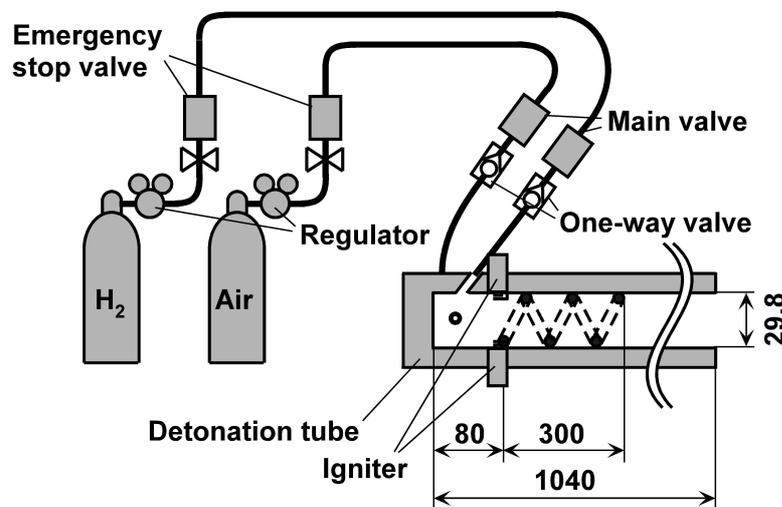


Fig.2 Piping diagram of hydrogen and air feeding system for one detonation tube.

3. Results and discussion

Table 2 shows the experimental conditions. The signal output duration for hydrogen and air injection was kept constant as 11ms in any experiments. However, the physical gaseous injection duration must be delayed compared to the controlling signal duration because of the delay of about 5ms for opening and closing motion of MAC valve. The optimum ignition timing for generating the detonation is 14 ms after the end of gaseous injection signal, which must be affected by the delay of valve system and others. The ignition timing was also kept constant independently of experimental conditions. In addition, it was confirmed in the preliminary experiment that the purge process, which is generally required to prevent the unintended ignition, was not required if the operational cycle was less than about 5 cycle. Thus, all of the experiments were carried out without purge process. Fig.3 shows the symbols for the injection signal and the ignition timing of each tube. The figures of the present report include these symbols to indicate the operational time chart of each experiment.

3.1 Single tube operation

All tubes were tested individually as single pulse operation and multiple cycle operation. Results of the 1st tube among them are shown in this section. Fig.4 shows the pressure histories of P2 and P3 in the case of single-pulse operation. It should be noted that the waveform of P2 was shifted for easier recognition. In this experimental

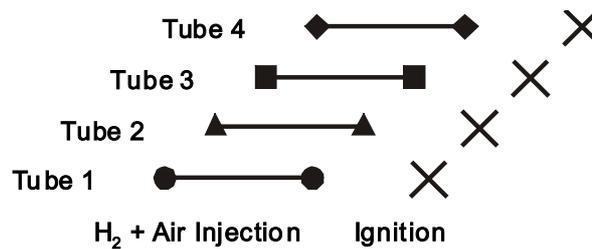


Fig.3 Notations for duration of hydrogen-air injection and ignition timing

Table1 Details of multi-tube PDE

Number of tubes	4
Target maximum frequency per tube	30 Hz
Charged mixture	H2 and Air
Maximum flow rate per tube	H2 : 18.4 L/s Air : 37.5 L/s
Dimensions [mm]	
Detonation tube	φ29.8 x 1040
Collecting duct	Inlet: φ130
	Exit : φ29.8
	Length : 220
	Taper angle :15deg.
Dimensions in total size	Width : 320
	Height : 320
	Length : 1260

Table2 Experimental conditions

Mixture fill fraction in tube section	0.74-0.94
Equivalence ratio of mixture	1.21-1.58
Neuman and CJ pressure	Neuman P: 2.8 MPa CJ P: 1.5 MPa
Injection signal duration	11 ms
Ignition timing	14 ms after end of injection signal
Supply pressure	H2: 0.7 MPa Air: 0.7 MPa
Accuracy of volumetric gaseous supply (Standard deviation)	H2: 5.6% Air: 5.2%
Purging	Non
Accuracy of ignition timing	Less than 1 ms

condition, the border of detonable mixture and inert air or burnt gas exists around the pressure gauge P2. Therefore, the detonation is assumed to start attenuating around the measuring point P2. The pressure spike could be found at about 2ms after the ignition. This pressure spike indicates the arrival of detonation or attenuated shock wave at P2. Although the peak pressure of P2 was 2.3MPa, which is slightly lower than Neuman pressure, the fully developed detonation must be generated in the tube..

At the exit of the collecting duct (P3), the arrival of shock wave was found about 1 ms after the detonation arrival at P2. Since the detonable mixture did not exist in the collecting duct, detonation was rapidly attenuated and the steep pressure peak, which was found at P2, did not appear. The peak pressure at P3 was 0.6MPa. In the experiments of multiple-cycle operation with single-tube or multi-tube, the conditions of detonation generation was estimated by comparing the pressure history of P3 in this experiment.

Figure 5 shows that the pressure histories at P2 and P3 under the operational conditions of 8Hz and 30Hz. The repetition of operation cycle was three times. The operational frequency of 8Hz is the maximum frequency, which satisfies the condition at four-tubes operation that the exhaust from any other tube does not affect the gaseous filling process. The frequency of 30Hz is the stable and maximum operation frequency that the 4th tube, which is the worst in the high frequency operation, is able to operate. It was confirmed that the maximum operational frequency of the 1st tube was 40Hz.

Except the 3rd cycle of 8Hz

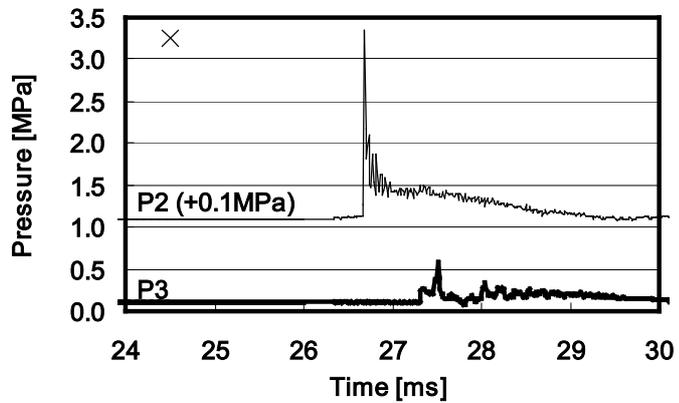
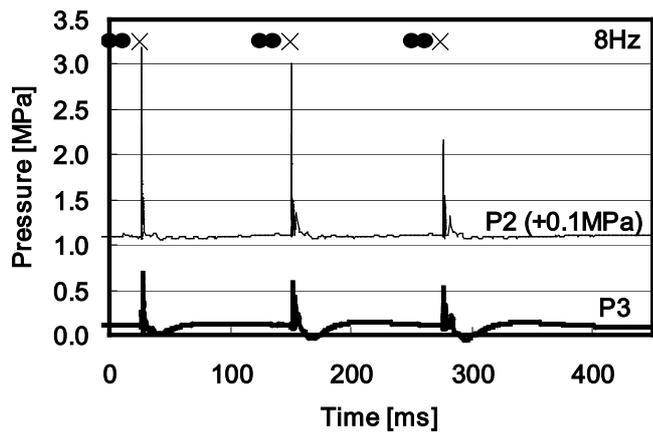
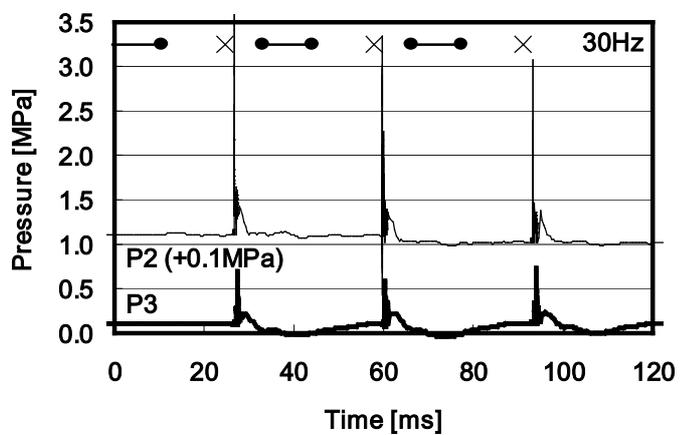


Fig.4 Pressure histories in a detonation tube at single-pulse operation with single tube



(a) 8Hz



(b) 30Hz

Fig.5 Pressure histories in a detonation tube at multi-cycle operation with single tube

operation, peak pressure at P2 was higher than 2MPa, which indicates that well developed detonation was generated. Although the pressure peak of 3rd cycle was slightly lower than other cycle, the peak pressure at P3 in this cycle was the same level with that of single-pulse operation shown in fig.4. Thus, it was confirmed that the detonation was stably generated in all tested cycle with single tube. In addition, the periods of pressure peaks at P2 and P3 were within the range of about $\pm 0.5\text{ms}$ against the operational periods. In the preliminary experiment, it was confirmed that the accuracy of ignition timing was less than 1.0ms. Therefore, it could be assumed that the deviation of DDT time from cycle to cycle in each tube was negligible.

3.2 Multi-tube operation

Figure 6 shows the pressure histories at P2 and P3 in the multi-cycle operation with four tubes. Tested operational frequency was 8Hz and 30Hz for each tube (32Hz and 120Hz in total system frequency). As mentioned before, 8Hz is the maximum frequency that the exhausts from other tubes do not affect the gaseous filling process, and 30Hz is the maximum frequency that the present system is able to operate. In the figure, operation time chart, including gaseous injection signal and ignition timing, was also indicated. The order of ignition was just three cycles from the 1st tube in case of 8Hz. In case of 30Hz, two cycles of ignition started from the 4th tube was carried out, and the 1st tube was ignited subsequently.

In the case of 8Hz operation, the pressure history at P2, which is installed vicinity of the 1st tube exit, has the pressure spikes of about 1MPa when the 1st tube was ignited. On the contrary, when the other tubes were ignited, small pressure peaks of 0.2-0.3MPa, which were caused by the ingress of exhausts from other tubes, were observed. When the 1st tube was ignited, the peak pressure of P2 was lower than that of single pulse operation with single tube shown in fig.4. However, the peak pressures at P3 were the same level with that of fig.4, it can be assumed that the well-developed detonation was generated in all cycle.

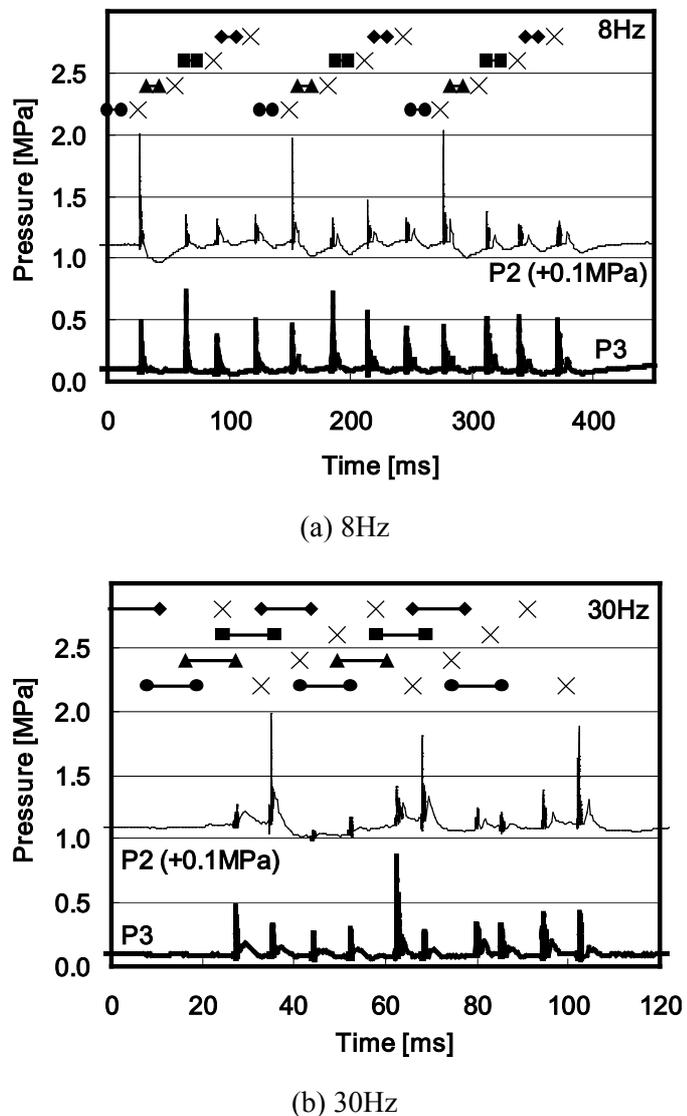
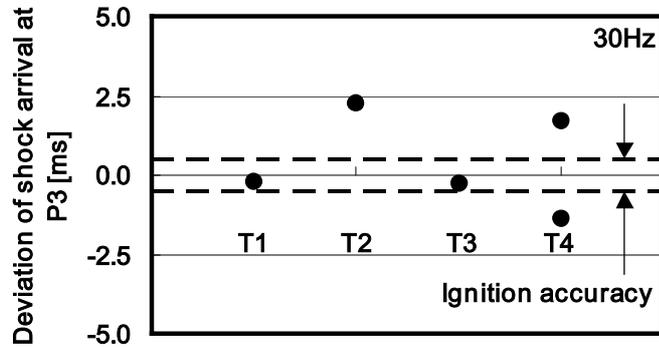


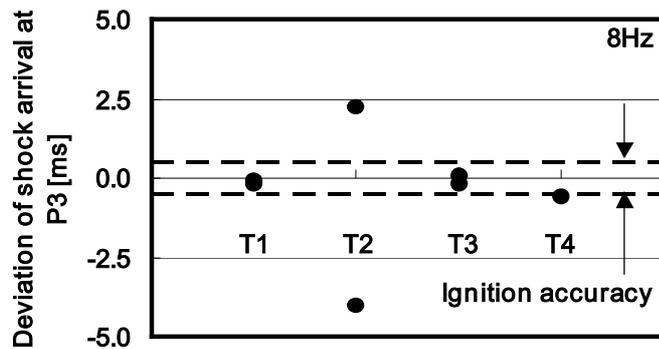
Fig.6 Pressure histories in a detonation tube at multi-cycle operation with four tube

In the case of 30Hz operation, pressure peaks at P3 were 0.3-0.4MPa, which was lower than that of the case in single-pulse operation with single tube shown in fig.4. In addition, the irregularity of pressure-peak period also got remarkable. Fig.7 indicates the period in each tube, which is from the shock arrival caused by one tube to the next shock arrival by the same tube. The values in the figure are the deviation from the operational period. As compared to the case of single-pulse operation with single tube, of which the deviation of shock arrival period is the same level with the accuracy of ignition timing, it can be found that the deviation of shock-arrival period is larger than ignition-timing accuracy. The same level of the deviation is found in the result of 8Hz operation as shown in fig.7(a), of which the gaseous filling process is not affected by the exhaust from other tube. Since the fraction of the deviation gets larger at the higher operational frequency, the irregularity of the shock-arrival periods seems more remarkable in case of 30Hz than that of 8Hz. In addition, the both deviations of advance and delay can be found in the same tube. This fact indicates that the cause of the deviation is the random factor, and it assumed that the interference of exhaust affects the DDT processes.

The precise investigation of shock ingression to the detonation tube was carried out, which must cause the deviation of DDT time and the reduction of peak pressure at P3. The 2nd tube, the 3rd tube and the 4th tube were ignited in turn. Operational timing was based on the 30Hz, and single-pulse operation in each tube was carried out. Fig.8 shows that the pressure histories of P1 and P2, which were installed in the 1st tube. In the pressure history at P2 nearby the



(a) 8Hz



(b) 30Hz

Fig.7 Period of shock arrival at P3 for each tube. Values were the deviation from the operational period.

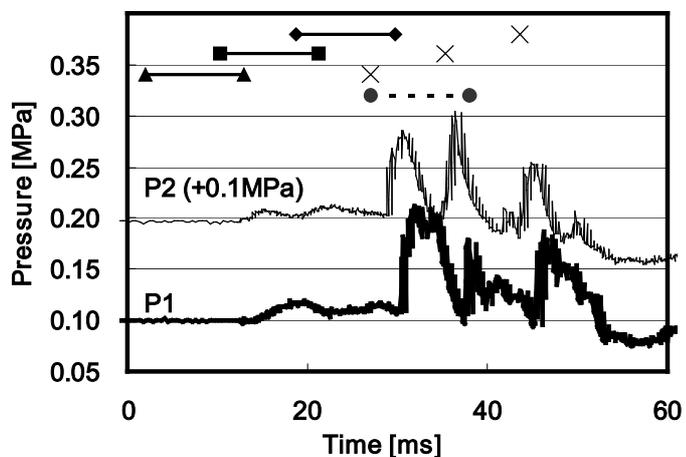


Fig.8 Pressure histories in the 1st detonation tube affected by exhausts from other tubes.

collecting tube, there are three pressure peaks of 0.1-0.2MPa, which were caused by ingression of shock waves from other three tubes. The second peak pressure from the 3rd tube was highest among the three peaks at P2. Thus, the effect from the opposing corner tube is largest at the point P2. On the contrary, the pressure history at P1 just behind the end of spiral has also three pressure peaks, but the second pressure peak, which was caused by the exhaust from opposing corner tube, decreased dramatically as compared to P2. In the actual operation at 30Hz, the gaseous filling of the 1st tube is carried out at the dotted line in the figure. This indicates that the gaseous filling process at 30Hz is strongly affected by first pressure peak of P3 caused by the 2nd tube, or an adjacent tube. It is assumed that the fill fraction of mixture to the detonation tube was decreased because the backpressure was raised from 0.1MPa to the order of 0.2MPa. Since the shock wave had to propagate in the longer inert section and is attenuated farther, the peak pressure at P3 was decreased.

4. Conclusion

Four-tube pulse detonation engine with hydrogen-air mixture has been developed to investigate the inter-tube exhaust interference. The experimentally operated maximum frequency was 30Hz in each tube, which is 120Hz in the system total frequency. When the operational frequency gets higher, the following matter becomes remarkable. The deviation of the period of detonation generation gets larger compared to the single tube operation. In addition, the pressure in the detonation tube was kept higher because of the exhaust interference. The reduction of the peak pressure at the exit of collecting tube suggests that the mixture fill fraction to the detonation tube was reduced by higher backpressure in the detonation tube.

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