Moving-Component-Free Pulse-Detonation Combustors and Their Use in Ground Applications

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1 Introduction

A pulse-detonation combustor (PDC) is a combustor in which detonable gas is repetitively burned as detonations. A cycle of PDC operation is shown in Fig. 1. Because of higher burning temperature in detonation compared with other combustion mode, it is expected that internal combustion engines will become more efficient by PDCs [1]. Furthermore, a PDC is expected to be used as a compact high-power energy source for, e.g., thermal spraying because high-temperature high-speed jets are easily obtained from a PDC [2].

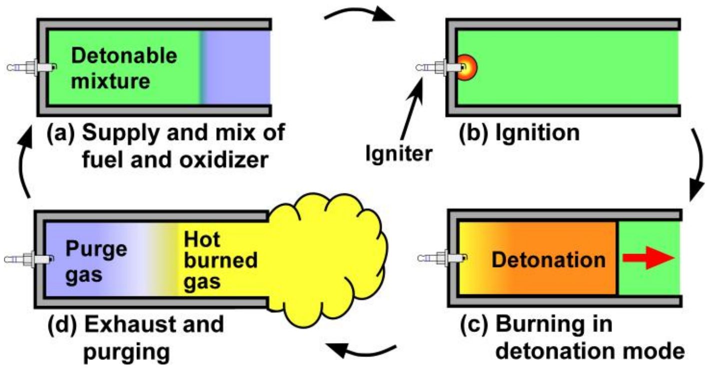

Figure 1. A cycle of PDC operation.

For realization of compact high-power PDCs, we developed a technology by which high-frequency operation of a PDC became possible. In this operation mode, valves for gas supply, by which the operation frequency of a PDC is usually restricted, are kept opened all the time of operation. That is, we developed moving-component-free PDCs. By this technology, PDCs become highly powerful and durable. In the following, we explain the principle of the valve-opened mode of PDC operation first. After that, a demonstration experiment for this technology is described. Finally, we present some experimental results on thermal spraying and turbine drive, as examples of ground applications of the developed PDCs.

2 Principle of Valve-Opened Mode of PDC Operation

As shown in Fig. 1, after the burning of detonable gas, sufficient purge gas has to be supplied to a PDC prior to the supply of fuel and oxidizer. Otherwise, the supplied fuel and oxidizer will start to be

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burned by contact with the residual hot burned gas without ignition spark, and it will be impossible to operate the combustor as a PDC. That is, the key to high-frequency operation of a PDC with all valves kept opened is how to supply purge gas properly.

Figure 2 schematically shows the developed gas-supply method to a PDC with all valves kept opened. When fuel, oxygen as oxidizer, and inert gas as purge gas are separately supplied, the gas-supply method shown in Fig. 2(a) is adopted. A typical pressure history near the closed end of a PDC (p_{PDC}) is shown in the upper half of Fig. 2(a). After the initiation of a detonation, a retonation reaches the closed end, and pressure near the closed end shows a high peak. This pressure peak relaxes soon, and a pressure plateau follows. This pressure plateau terminates when a rarefaction wave from the open end of the PDC reaches the closed end, and then pressure gradually decays [3]. In order to supply fuel, oxygen, and inert gas to the PDC properly, we adjust the gas-supply pressures for fuel, oxygen, and inert gas so as shown by p_{F}, p_{O}, and p_{Inert} in the upper half of Fig. 2(a), respectively.

The principle of this gas-supply method is simple. When pressure in the PDC near the gas-supply port is higher than the gas-supply pressure, the gas is not supplied. On the other hand, when pressure in the PDC near the gas-supply port is lower than the gas-supply pressure, the gas is supplied. We adjust the gas-supply pressures so that $p_{\mathrm{F}} = p_{\mathrm{O}} < p_{\mathrm{Inert}}$. When p_{PDC} is higher than p_{F}, p_{O}, and p_{Inert} just after the detonation initiation, no gas is supplied. When p_{PDC} relaxes to p_{Inert}, only inert gas starts to be supplied, and only the inert-gas supply goes on while $p_{\mathrm{F}} \left(= p_{\mathrm{O}}\right) < p_{\mathrm{PDC}} < p_{\mathrm{Inert}}$ as shown in the lower half of Fig. 2(a) where Q denotes the gas-supply flow rate. When p_{PDC} relaxes to $p_{\mathrm{F}} \left(= p_{\mathrm{O}}\right)$, fuel and oxygen start to be supplied, and the supply of fuel, oxygen, and inert gas goes on until the next detonation initiation. Thus, once the PDC operation is started, the operation is governed by the ignition sparks only. By the delay of the supply of fuel and oxygen relative to that of inert gas, the residual hot burned gas is automatically purged by the inert gas. The quantity of the supplied inert gas effective for purge is shown by the filled region in the lower half of Fig. 2(a). By adjusting the gas-supply pressures p_{F}, p_{O}, p_{Inert}, and the flow resistance of gas-feeding pipes, we can control, to some extent, the supplied quantities of purge gas and detonable gas, and the composition of detonable gas mixture. The flow resistance of a gas-feeding pipe can be adjusted by the diameter of an orifice installed in a gas-feeding pipe or by the diameter of a gas-feeding pipe itself.

When air is used not only as oxidizer but also as purge gas, the gas-supply pressures of air p_{Air} and fuel

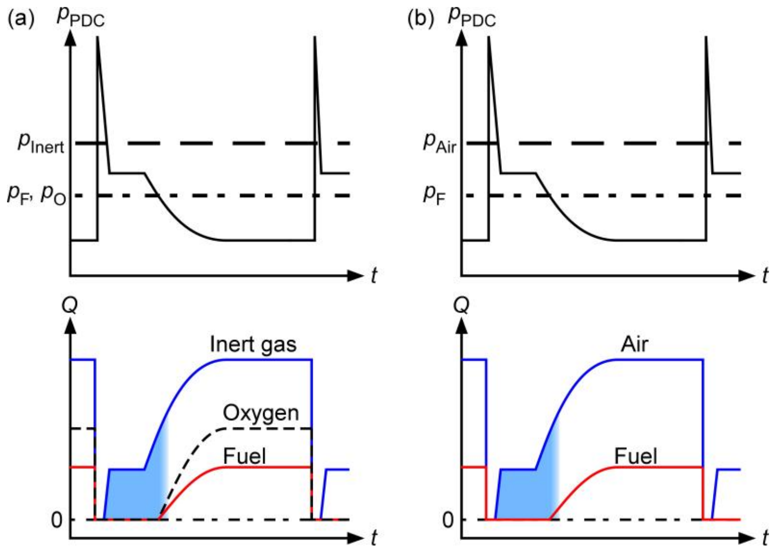

Figure 2. Gas-supply method to a PDC with all valves kept opened.
(a) A case where fuel, oxygen as oxidizer, and inert gas as purge gas are separately supplied.
(b) A case where air is used not only as oxidizer but also as purge gas.
Upper half: Pressure history near the closed end of a PDC and gas-supply pressures.
Lower half: Flow rates of supplied gases.

p_F are adjusted so that $p_F < p_{Air}$ as shown in the upper half of Fig. 2(b). In a case where $p_F = p_O$ as shown in Fig. 2(a), the equivalence ratio of the detonable gas mixture is almost constant because the effective gas-supply pressures of fuel and oxygen behave so that $p_F - p_{PDC} = p_O - p_{PDC}$ and therefore the ratio between the flow rates of fuel Q_F and oxygen Q_O is almost constant. However, in a case shown in Fig. 2(b), the equivalence ratio of the detonable gas mixture varies with time especially in the early phase of fuel supply because the effective gas-supply pressures of fuel and air, i.e., $p_F - p_{PDC}$ and $p_{Air} - p_{PDC}$, vary with time in different manners and therefore the ratio between the flow rates of fuel Q_F and air Q_{Air} varies with time. The advantage of the gas-supply method shown in Fig. 2(b) is the simpleness and cheapness of the gas-feeding system.

3 Demonstration Experiment for Valve-Opened-Mode PDC Operation

In order to demonstrate high-frequency PDC operation by the above-mentioned gas-supply method, we developed a PDC shown in Fig. 3 where "P" denotes a pressure transducer. The inner diameter and length of the PDC are 16 mm and 401 mm, respectively. Ethylene (C_2H_4), oxygen (O_2), and argon (Ar) were used as fuel, oxidizer, and purge gas, respectively. In order to adjust the flow resistance of gas-feeding pipes, we installed flow-rate adjusters as shown in Fig. 3, where the gas-flow rate was adjusted by varying the diameter ϕ_{FRA}. The vibration sensor shown in Fig. 3, installed for an emergency stop system, picks up the vibration of the PDC. If the operation of the PDC becomes failed by some reasons and its vibration amplitude becomes small, the feeding of C_2H_4 and O_2 will be instantaneously stopped for safeness by closing the magnetic valves installed in the gas-feeding pipes, which are usually operated only when the operation is started and stopped.

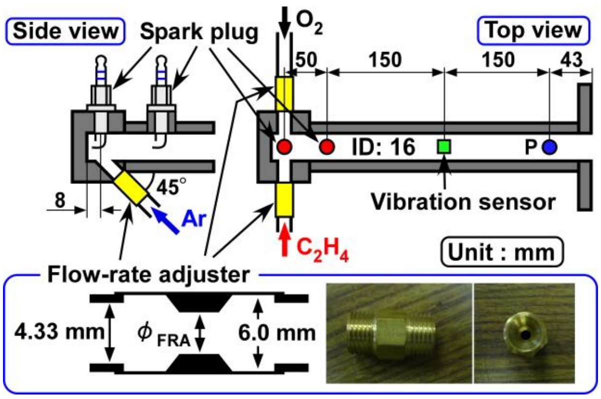

Figure 3. PDC used in the demonstration experiment.

In order to adjust the operation conditions, we first measured the gas-flow rate of each gas by varying the gas-supply pressure and ϕ_{FRA}, where a water-displacement method under atmospheric pressure was adopted. In the measurement, the gas quantities for the valve-open durations of 30 ms and 50 ms were measured, and the gas-flow rate was calculated dividing their difference by 20 ms. Based on this preliminary measurement, we determined the diameters of the flow-rate adjusters so that ϕ_{FRA} = 5.0 mm for Ar, ϕ_{FRA} = 7.0 mm for O_2, and ϕ_{FRA} = 1.8 mm for C_2H_4. Figure 4(a) shows the measured gas-flow rates for these diameters of the flow-rate adjusters. Figure 4(b) shows the estimated equivalence ratio as a function of the gas-supply pressure for C_2H_4 and O_2. As mentioned above, the equivalence ratio is not sensitive to the variation of the gas-supply pressure for the same gas-supply pressures for C_2H_4 and O_2. Based on the preliminary gas-flow-rate measurement

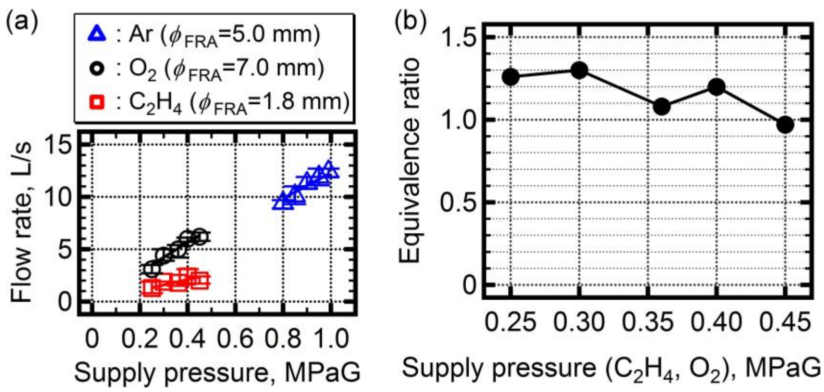

Figure 4. (a) Measured gas-flow rate as a function of gas-supply pressure.
(b) Estimated equivalence ratio as a function of gas-supply pressure.

Table 1: Conditions of the demonstration experiment for valve-opened-mode PDC operation

Gas-supply pressure (MPaG)			Operation frequency (Hz)	Operation cycle	Composition of the detonable gas (estimated)	Fill-fraction of the detonable gas (estimated)
C_2H_4	O_2	Ar				
0.36	0.36	0.99	200	75 (0.375 s)	$1.1C_2H_4+3(O_2+2.5Ar)$	approx. 100% of the PDC

mentioned above, the operation conditions were determined as shown in Table 1. Figure 5 shows the pressure history measured at "P" in Fig. 3. If we judge the pressure peaks undoubtedly lower than p_{CJ}, where p_{CJ} is the Chapman-Jouguet pressure of a detonation, as unsuccessful events for detonation initiation, the 20th, 26th, 31st, 38th, 40th, 42nd, 45th, 48th, 62nd and 71st cycles are the unsuccessful events, that is, 87% of the operation cycles were successful. This result shows that the valve-opened mode of PDC operation we developed is effective.

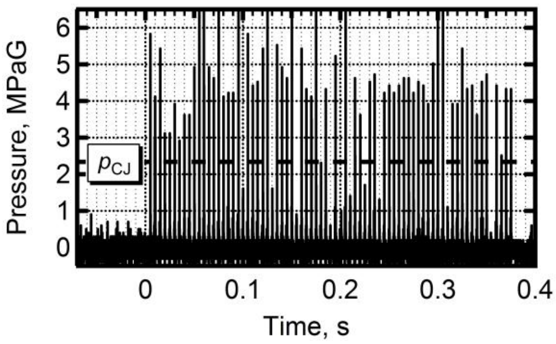

Figure 5. Pressure history measured at "P" in Fig. 3.

4 Ground Applications of Moving-Component-Free PDC

4.1 Thermal Spraying

Thermal spraying is a technology for thick surface coating (coating thickness is usually several tens micrometers or more) in which melted or highly heated materials are sprayed onto a surface with high speed. Detonation has long been used as the energy source for thermal spraying. Especially, D-Gun™ [4] is a well-known coating device using detonation, which was invented by Union Carbide. Although the developed moving-component-free PDC can be operated at frequencies more than 100 Hz, the operation frequency of D-Gun™ is usually less than 10 Hz. Therefore, the thermal-spraying process using the developed high-frequency PDC can become another thermal-spraying process using detonation as the energy source. As the first step, we carried out an experiment on thermal spraying using the developed moving-component-free PDC in order to examine the stability of the PDC when we feed fine solid powders into the PDC.

Figure 6 shows the experimental arrangement. We modified the PDC used in the experiment described in the previous section. We installed a nozzle, whose inner diameter was 1.2 mm, for feeding solid powders into the PDC, which is shown by "PN" in Fig. 6. In addition, an extension barrel, which was 200 mm in length, was added at the exit of the PDC. Further, the vibration sensor for the emergency stop system was moved to the closed end of the PDC, and the diameters of the gas-feeding pipes were enlarged. A test piece for thermal spraying, which was a blast-treated flat plate of hot-rolled sheet steel (SS400), was placed at 100 mm from the exit of the extension barrel. Table 2 summarizes the operation conditions of the PDC, and Table 3 summarizes the conditions and results of the thermal spraying. When solid powders were fed into the PDC, the PDC was able to be

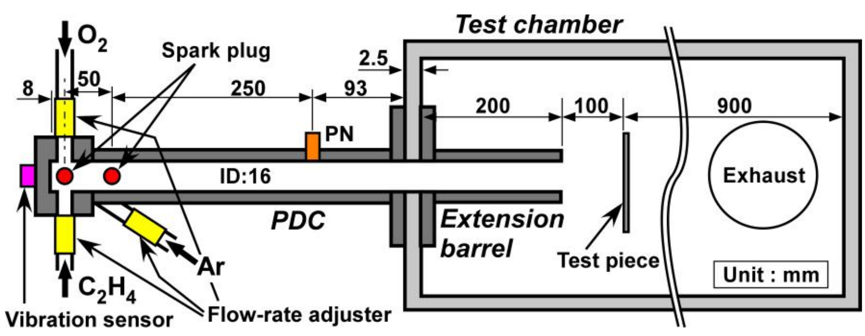

Figure 6. Arrangement of experiment on thermal spraying.

Table 2: Operation conditions of the PDC for experiment on thermal spraying

Gas-supply pressure (MPaG)			Operation frequency (Hz)	Operation time (s)	Composition of the detonable gas (estimated)	Fill-fraction of the detonable gas (estimated)
C_2H_4	O_2	Ar				
0.38	0.38	0.99	130	15	$1.1C_2H_4+3(O_2+2.3Ar)$	approx. 70% of the PDC

Table 3: Conditions and results of thermal spraying

Time for thermal spraying (s)	Powder feed conditions				Results		
	Species	Size (μm)	Carrier gas (pressure)	Feed rate (g/min)	Porosity (%)	Oxide content (%)	Peak thickness (μm)
10	80Ni-20Cr*	10-44	Ar (0.8 MPaG)	19	0.3	0.3	768

* melting point: approx. 1400 ^{o}C

stably operated at 130 Hz. Figure 7 shows the photograph of a cross section of the coating viewed by a metallurgical microscope. The coating was successfully processed with low porosity and low oxide content. This result shows the possibility that the developed moving-component-free PDC will be a new compact powerful energy source for thermal spraying.

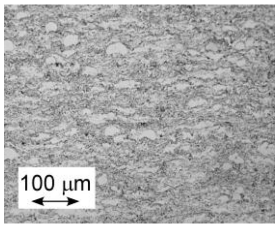

Figure 7. Photograph of a cross section of the coating.

4.2 Turbine Drive

So far, applications of PDCs have been pursued not only for aerospace propulsion [5] but also for turbine drive [6,7]. We also tried to apply a developed moving-component-free PDC to turbine drive. A moving-component-free PDC is expected to be operated long term without trouble.

For turbine-drive experiments, we prepared two types of experimental systems shown in Fig. 8. In these systems, each gas-feeding pipe had an orifice for adjusting the gas-flow rate, an emergency stop system for fuel supply based on the sonic noise of detonations picked up by a microphone was used, and air was supplied from a compressor driven by a separate diesel engine. Type A was a fully-water-cooled system, whereas only the PDC was water-cooled in Type B. In the turbine-drive experiments, we used air not only as oxidizer but also as purge gas, i.e., the gas-supply method shown in Fig. 2(b) was adopted. The operation conditions of the PDCs are summarized in Table 4. The output (compressor work) and energy balance obtained in the experiments are shown in Fig. 9. The input energy was calculated by using the lower heating value of H_2 and the flow rate of H_2, which was evaluated by the pressure difference of the cylinder of H_2 between before and after each experiment. On the turbine-drive performance, the isentropic efficiency of the turbocharger was experimentally estimated to be about 0.6, which was almost in agreement with the theoretical value based on a preliminary measurement of the isentropic efficiency by using steady air flows.

The pressure at the turbine inlet in the idling phase was measured to be about twice the atmospheric pressure. Hence, the theoretical thermal efficiency is estimated to be about 0.35, which means that the maximum thermal efficiency for the systems we prepared is about 0.2 because the isentropic efficiency of the turbocharger was about 0.6. Although the measured thermal efficiency was lower

Table 4: Operation conditions of the PDCs for experiments on turbine drive

Gas-supply pressure (MPaG)		Operation frequency (Hz)	Operation time (min)	Equivalence ratio (estimated)	Fill-fraction of the detonable gas (estimated)
H_2	Air				
0.28 (Type A) 0.32 (Type B)	0.54	60	10	1.1	74-93% of the PDC (Type A) more than 93% of the PDC (Type B)

than 0.2, it became closer to 0.2 in the lower-heat-loss case (Type B).

5 Summary

Moving-component-free pulse-detonation combustors (PDCs) were developed, which were able to be operated at high frequencies with all valves kept opened. The developed PDCs were successfully usable in thermal-spraying and turbine-drive experiments. The developed PDCs are expected to be compact high-power durable combustors.

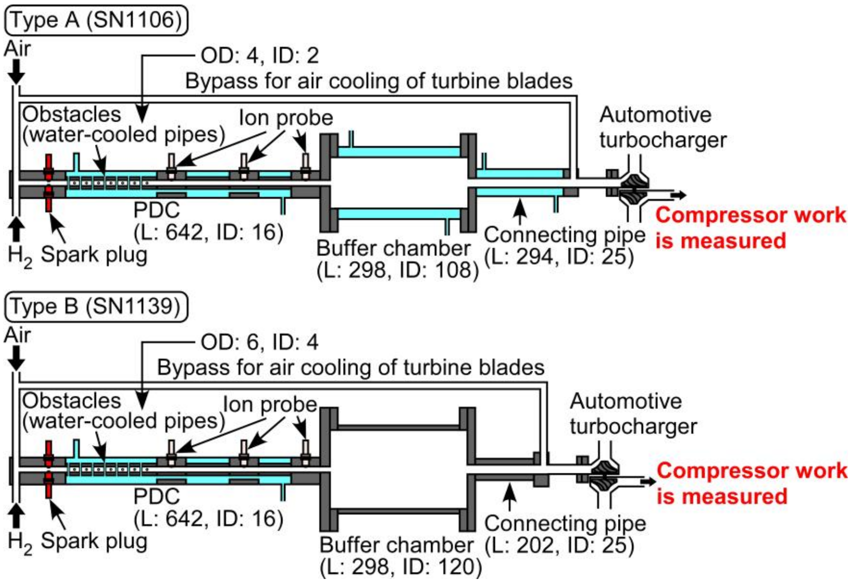

Figure 8. Systems for turbine-drive experiments.

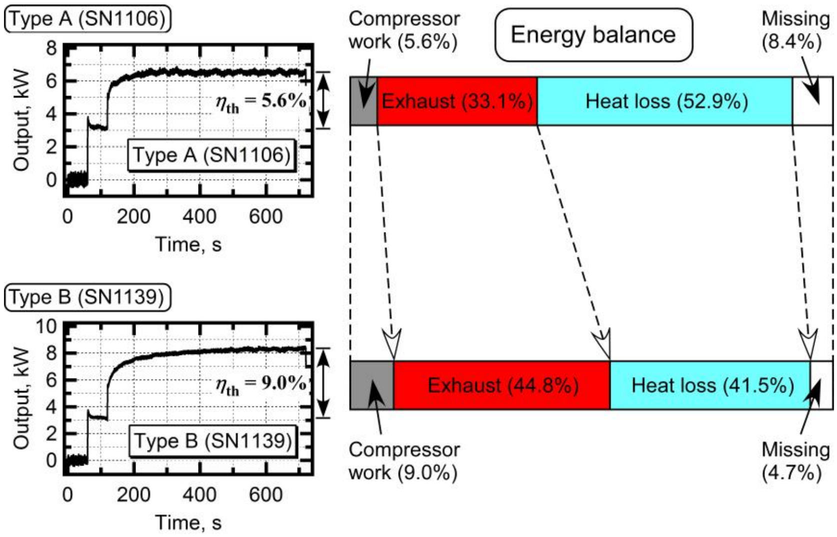

Figure 9. Output and energy balance obtained in turbine-drive experiments.

Acknowledgment

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