COMBUSTION IN A SUPERCHARGED BIOMASS GAS ENGINE WITH MICRO-PILOT IGNITION - EFFECTS OF INJECTION PRESSURE AND AMOUNT OF DIESEL FUEL

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Abstract

It is one of the solutions to use biomass as fuel in order to realize a sustainable society and to reduce carbon dioxide emission .A single cylinder with supercharged and micro-pilot gas engine operated with four kinds of pyrolysis gas as fuel for cogeneration use. The effects of injection pressure and amount of diesel fuel on engine performance and exhaust emissions were investigated. The combustion periods of initial and main stages were determined from the analysis of mass fraction burned. The combustion process was also visualized with a colour high-speed video camera. Main results obtained in this study are as follows: When the amount of diesel fuel increased in the same injection pressure, smoke was exhausted. However, the smoke was reduced with higher injection pressure. The period of the initial combustion is almost the same even if injection pressure and amount of diesel fuel increases. Therefore, it is enough to ignite the mixture with small amount of diesel fuel. For the case with lower calorific gas, the period of main combustion was shortened owing to the combustion of diesel fuel when the amount of diesel fuel increases. When the mixture contains much hydrogen, the period of main combustion does not become small in higher injection pressure and larger amount of diesel fuel. On the other hand, when the mixture does not contain much hydrogen, the effect of diesel fuel becomes strong.

Keywords: *Internal Combustion Engine, Cogeneration, Pyrolysis Gas, Biomass Gas, Visualization*

1. Introduction

In order to reduce carbon dioxide emission and to realize a sustainable society, one of the solutions for fuel is to utilize biomass resources. The energy generated from woody and waste biomass should be used as fuel. For example, the system, in which woody and/or waste biomass is burned and water vapour is used to generate electricity with a gas turbine, has already operated. This system has an economical advantage in a large scale plant. However, when this kind of cogeneration system is small, the initial cost is relatively high and the thermal efficiency is low. Then, the advantage becomes less. Nowadays, gas engine systems of which fuel is pyrolysis gas generated from biomass through heat decomposition has been studied [1-7]. A relatively small gas engine is suitable for this kind of fuel because of obtaining higher thermal efficiency. A pyrolysis gas includes hydrogen, carbon monoxide and non-activated gas such as carbon dioxide and nitrogen, so that heating value is lower than that of fossil fuel.

There are some kinds of gas engines for cogeneration use. The composition of pyrolysis gas changes due to the condition of raw materials and gasification conditions in the plant. Therefore, a spark-ignition engine is not suitable for this kind of fuel in high load because of the difficulty in stable combustion. Recently, a natural gas engine with a pilot injection is used for cogeneration system. In this dual fuel engine, gaseous fuel is induced from an intake port and diesel fuel is injected into the cylinder near the compression TDC [8]. This engine has an advantage of realizing stable combustion by many ignition sources and high energy for ignition.

In the previous report [9], some kinds of pyrolysis gases were supplied into an intake port, while small amount of diesel fuel was injected into the cylinder with a common rail system. Lean burn can reduce NOx emissions and high intake pressure helps to increase output power. The combustion characteristics and exhaust emissions for four fuel gases were investigated. Moreover, the combustion in the engine cylinder was visualized with a high-speed video camera. At first, diesel fuel is ignited in the mixture of pyrolysis gas and air. Next, the flame develops from several kernels of ignition locations with the structure of wrinkled laminar flame. In this study, the same test engine with single cylinder was used to investigate the effect of injection pressure and amount of diesel fuel on the engine performance and exhaust emissions.

2. Experimental apparatus and procedure

A schematic diagram of the experimental apparatus was shown in Fig.1. As presented in Table.1, a small size, four-stroke cycle, water cooled and single cylinder engine was prepared to investigate the characteristics of combustion fuelled with pyrolysis gas produced from biomass. This engine has bore of 96mm, stroke of 108mm and compression ratio of 16. The combustion chamber is shallow dish type of piston. There are two intake and exhaust valves with no swirl and no tumble. The pressure in cylinder was measured with a pressure transducer and the rate of heat release was determined. The pyrolysis gas was calibrated using pressure method with a small accumulator. The pressure and temperature in the accumulator during a certain period were measured and the mass of the gas was estimated. The pyrolysis gas was injected into the intake pipe with a mass flow controller and mixed with air. The mixture of the pyrolysis gas and air was induced into the cylinder and small amount of diesel fuel was injected into the cylinder near the compression TDC. The injection of diesel fuel was controlled with a common rail system. The pressure in the common rail was 40 and 80 MPa. The amount of diesel fuel, m_{go}, was set to 2 and 10 mg/cycle. The injector had four holes of which diameter were 0.1mm. The injection angle was 140 degrees. The engine speed was 1000rpm. The temperatures of water and lubricant oil were set to 60 °C. The intake air was compressed with a compressor. The intake pressure, P_{in}, was basically 200 kPa of absolute pressure though it was 101kPa (~natural aspirated) in visualization of the combustion. The signals of TDC and every half degree crank angle were detected and used to control the injection timing and period of diesel fuel. Indicated mean effective pressure, P_{mi}, coefficient of variance in P_{mi}, $CV(P_{mi})$ and indicated thermal efficiency, η_i, were determined. The exhaust emissions of NOx, CO, HC and smoke were measured.

The combustion in the cylinder could be visualized when the piston was changed to an elongated piston with a sapphire window. Time series of the flame were recorded with a colour high-speed video camera (nac, K4). The frame speed was 8,000 frames per second.

In this study, four types of artificial gas were prepared by considering the pyrolysis gas produced in the plant from biomass of woody tips and wastes as shown in Table 2. The composition of pyrolysis gas was varied by considering kinds of biomass and operation method for production. This gas is mainly composed by H_2, CO, CO_2 and N_2 with small amount of CH_4 as presented in Table 2. Each gas has a characteristic of the ratio of the component. In the gas of type 1, the ratio of hydrogen is large while the ratio of carbon monoxide is large in the gas of Type 2.

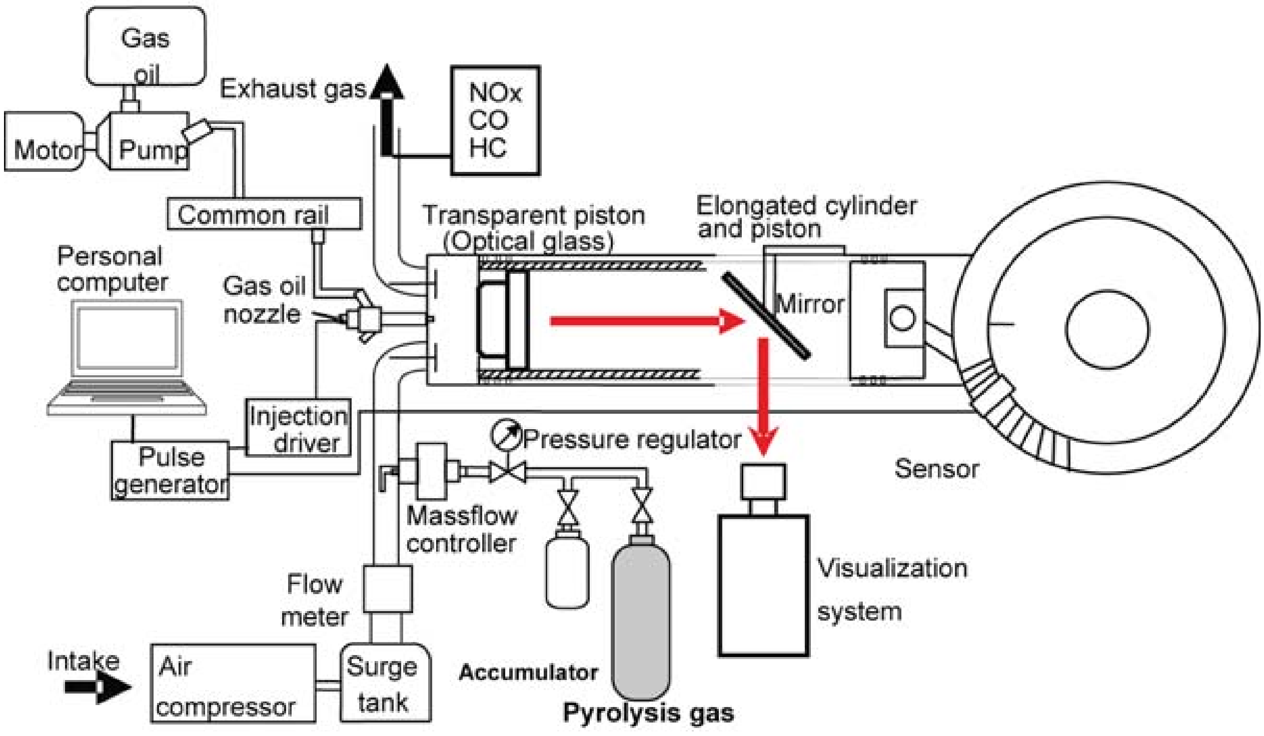


Fig. 1. Schematic diagram of test engine

Tab. 1. Specifications of the test engine

Type	1 cylinder, 4 stroke cycle Water cooled
Bore x stroke	96 x 108 mm
Displacement	781.7 cm^3
Compression ratio	16
Combustion system	Direct injection
Spray	4 holes (d=0.10mm) Spray angle 140°
Injection pressure	P_{inj}=40, 80 MPa
Combustion chamber	Shallow dish
Engine speed	1000 rpm
Amount of gas oil	m_{go}=2, 10mg/cycle

Tab. 2. Composition of pyrolysis gas

	H_2 (%)	CO (%)	CO_2	CH_4 (%)	N_2 (%)	Low hest value (MJ/m^3N)
Type 1	30.4	23.9	36.6	3.1	6	7.4
Type 2	22.3	27.6	23.2	2.7	24.2	6.8
Type 3	13.7	22.3	16.8	1.9	45.3	5.0
Type 4	14.6	19.4	16	28.9	21.1	14.4

The gas of Type 3 is a lower calorific gas and hydrogen is reduced. The gas of Type 4 was added with methane to the gas of Type 2, which is a mixture of pyrolysis gas with natural gas.

3. Visualization of combustion in the cylinder

The combustion process was visualized with a high-speed colour video camera near TDC. Figure 2 shows the flame images with pyrolysis gas for ϕ_t=0.6 in θ_{inj}=8°BTDC and P_{in}=101kPa. Even if the diesel fuel was small amount of 2mg/cycle with injection pressure of 40MPa, it became several locations for ignition source. The injector had four nozzles and ignition occurred in four locations apart from the nozzle exit at almost the same time. It is found clearly that the premixed flames developed from four large kernels produced by auto-ignition of diesel spray.

Anyway, strong and many ignition sources are made by small amount of diesel fuel spray to ignite the pyrolysis and air mixture compared to spark.

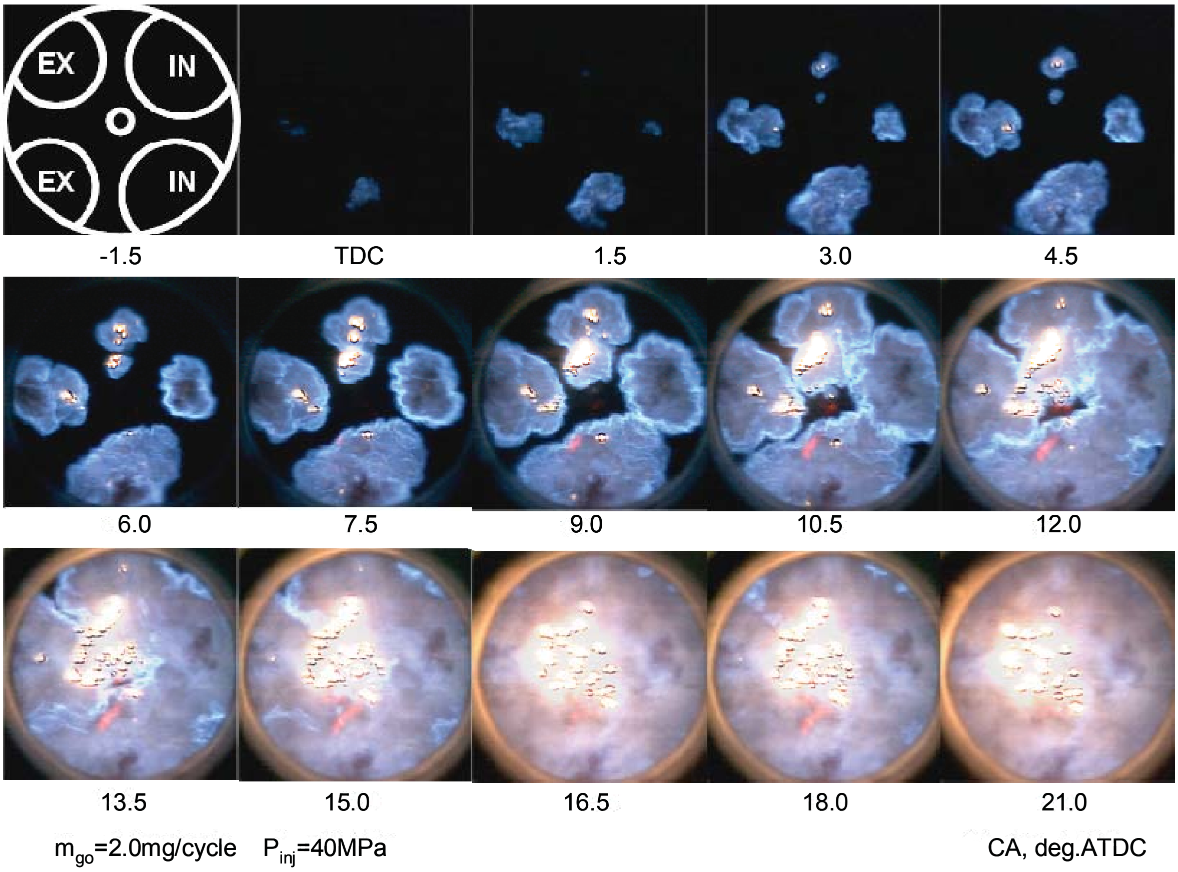


Fig. 2. Time series of combustion process in the cylinder taken with a high-speed color video camera (θ_{inj}=8°BTDC, P_{in}=101kPa, ϕ_t=0.6, biomass gas of Type 2 with diesel fuel of 2mg/cycle)

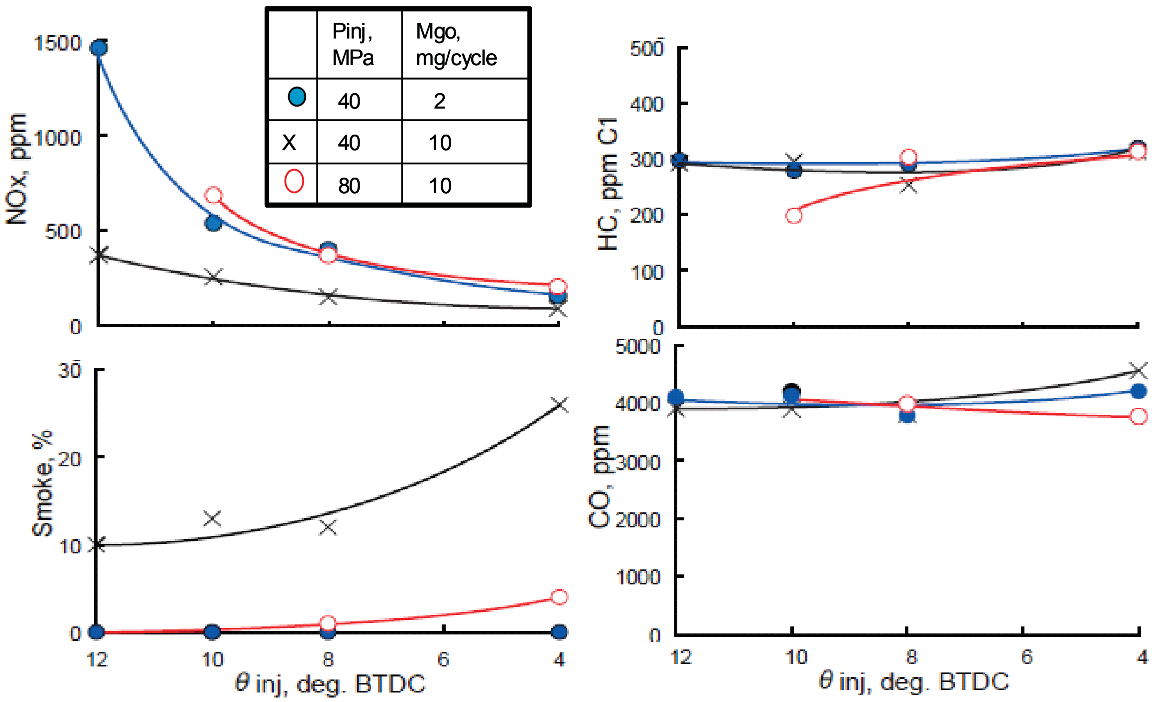


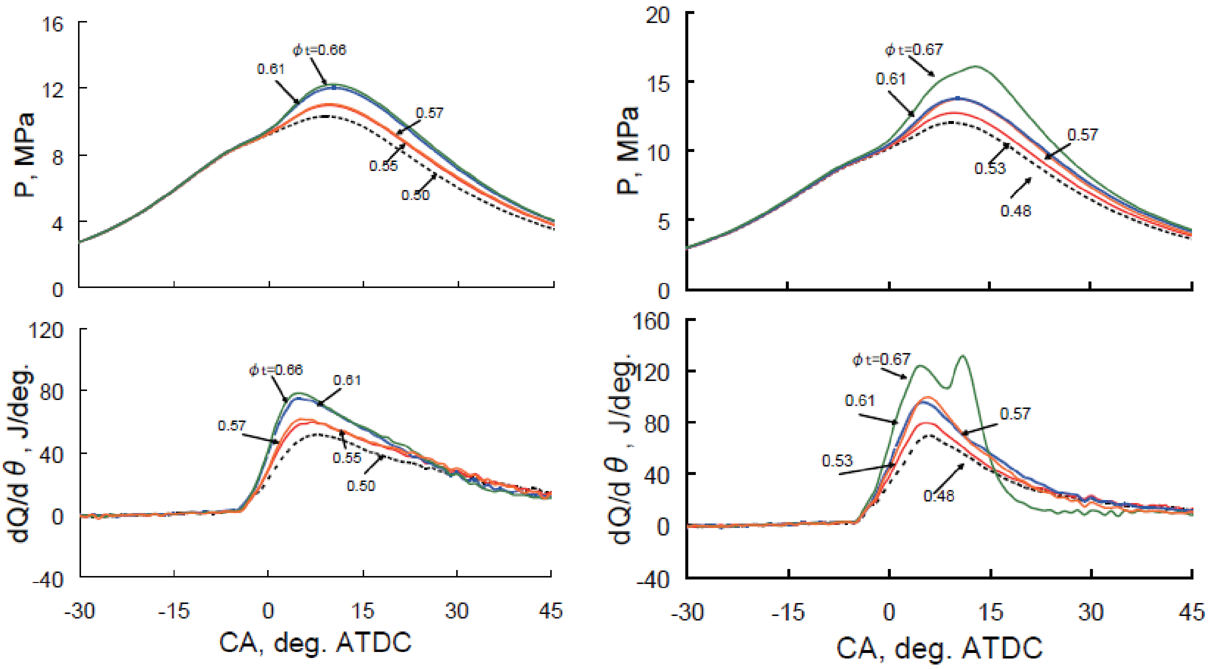
Fig. 3. Exhaust emissions for three conditions of injection pressure and amount of diesel fuel

4. Effects of higher injection pressure and larger amount of diesel fuel on exhaust emissions and rate of heat release

As shown in Fig.3, the engine performance and exhaust emissions were investigated. When the amount of diesel fuel increased from 2 mg/cycle to 10 mg/cycle in the same injection pressure of 40MPa, smoke was exhausted though NOx was reduced. The output power, thermal efficiency, cycle-to-cycle fluctuation, HC and CO emissions were almost the same. And as the injection timing was advanced, NOx was reduced and smoke was increased. There was a relation of trade-off between NOx and smoke. When the injection pressure increased in m_{go}=10mg/cycle, the thermal efficiency increased while almost the same NOx, HC and CO emissions and the same output power in θ_{inj}=8deg.BTDC.

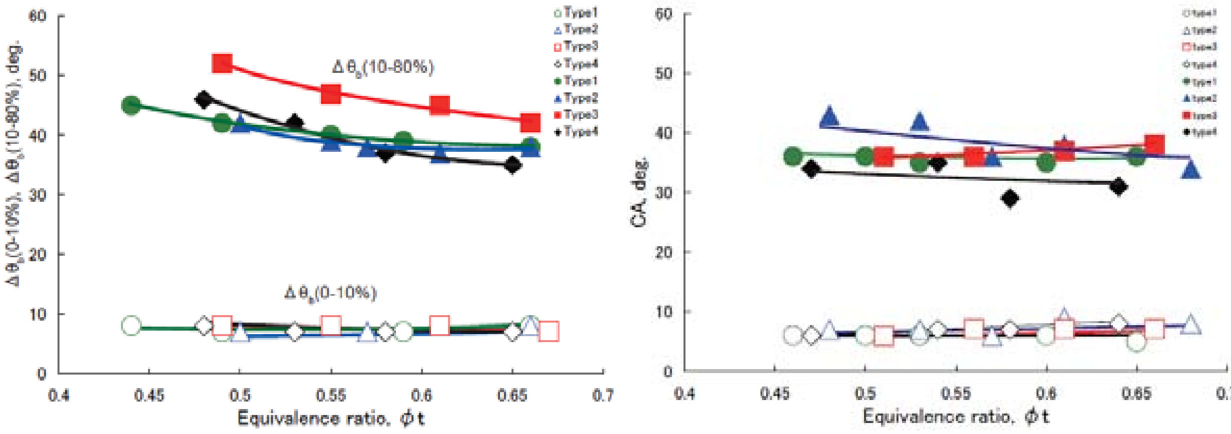
Figure 4 shows pressure history in the cylinder and rate of heat release for two kinds of injection conditions when the equivalence ratio was changed. One is a set of injection pressure of 40 MPa and amount of diesel fuel of 2mg/cycle as shown in Fig.4(a). Another is 80 MPa and 10 mg/cycle as presented in Fig.4(b). When the injection pressure and amount of diesel fuel increased, the pressure increased and the maximum value of the rate of heat release increased, too. In particular, in equivalence ratio of 0.67, the rate of heat release showed two peaks. There was no knock sound and no oscillation in pressure history in each cycle. It may be considered that the second peak is due to relatively slow auto-ignition of pyrolysis gas.

Figure 5 shows combustion periods of initial and main stages for various types of the mixture for two kinds of injection conditions. Here, the initial and main combustion durations, θ_b(0-10%) and θ_b(10-80%) denotes those from 0 to 10% and from 10 to 80% of mass fraction burned, respectively. The initial combustion duration showed almost the same regardless of equivalence ratio and the type of the main fuel. It is considered that the ignition of diesel spray initiates the initial combustion owing to many kernel of ignition source. The period of the initial combustion is almost the same even if injection pressure and amount of diesel fuel increases. Therefore, it is enough to ignite the mixture with small amount of diesel fuel of 2mg/cycle. In leaner conditions, the initial combustion period becomes slightly short.



(a) P_{inj}=40MPa, m_{go}=2mg/cycle (b) P_{inj}=40MPa, m_{go}=10mg/cycle

Fig. 4. Pressure history and rate of heat release (θ_{inj}=8°BTDC, P_{in}=200kPa,)



(a) P_{inj}=40MPa, m_{go}=2mg/cycle (b) P_{inj}=80MPa, m_{go}=10mg/cycle

Fig. 5. Combustion period of initial and main stages (θ_{inj}=8°BTDC, P_{in}=200kPa)

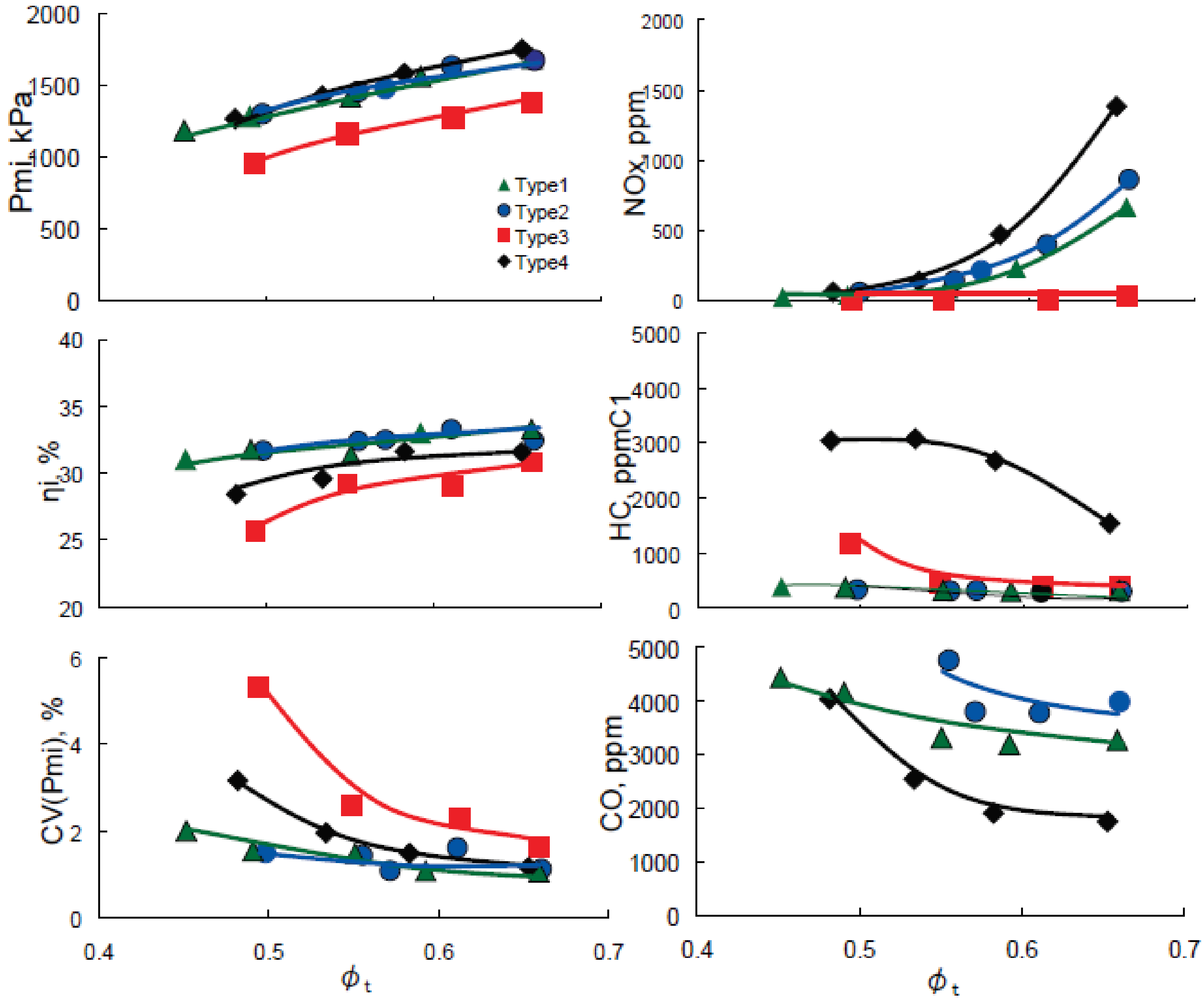


Fig. 6. Effects of equivalence ratio and gas composition on engine performance and exhaust emissions (θ_{inj}=8°BTDC, P_{in}=200kPa, P_{inj}=40MPa, m_{go}=2mg/cycle)

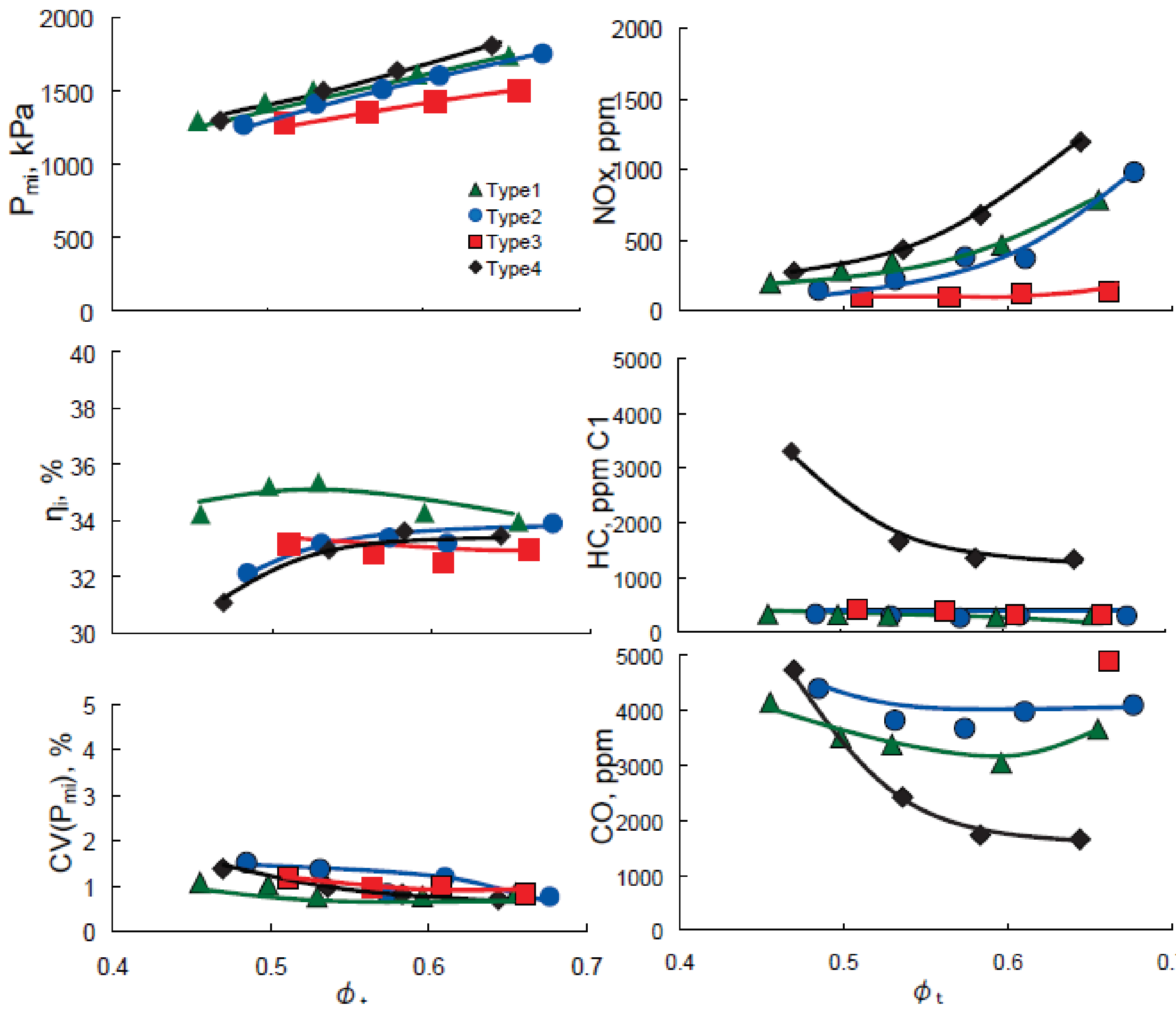


Fig. 7. Effects of equivalence ratio and gas composition on engine performance and exhaust emissions (θ_{inj}=8 °BTDC P_{in}=200kPa, P_{inj}=80MPa, m_{go}=10mg/cycle)

For the case with lower calorific fuel of Type 3, the period of main combustion was shortened owing to the combustion of diesel fuel when the amount of diesel fuel increased as shown in Fig. 5(b). In type 4, there was a similar tendency, too. When the mixture contained much hydrogen as shown in Type 1, the period of main combustion was almost the same. However, as the ratio of the hydrogen in the mixture became small, the effect of diesel fuel became strong. In Type 2, the main combustion period becomes short as the mixture was lean.

Figure 6 shows indicated mean effective pressure, P_{mi}, thermal efficiency, coefficient of variance in P_{mi}, and exhaust emissions (NOx, HC, CO) for P_{inj}=40MPa and m_{go}=2mg/cycle. Figure 7 shows the results for P_{inj}=80MPa and m_{go}=10mg/cycle. The effect of larger injection pressure and amount of diesel fuel is described as follows: Thermal efficiency for Type 1 increased very much in leaner side. In Type 3 and 4, thermal efficiency became large. Even in Type 2, it became slightly good. The cycle-to-cycle fluctuation became smaller in every type of fuel. NOx emissions became large. Hydrocarbons emissions became smaller in Type 3 and 4. CO exhausted was smaller in Type 3 and Type 2 especially in leaner side.

The thermal efficiency in leaner side in Type 1 was considerably improved owing to higher injection pressure and larger amount of diesel fuel although NOx emissions did not increase so large.

5. Summary

A single cylinder micro-pilot gas engine operated with four kinds of pyrolysis gas as fuel. The effects of injection pressure and amount of diesel fuel on engine performance and exhaust emissions were investigated. The combustion process was also visualized with a high-speed video camera.

(1) When the amount of diesel fuel increases in the same injection pressure, smoke is exhausted. However, the smoke is reduced with higher injection pressure.

(2) The period of the initial combustion is almost the same even if injection pressure and amount of diesel fuel increases. Therefore, it is enough to ignite the mixture with small amount of diesel fuel.

(3) For the case with lower calorific gas of Type 3, the period of main combustion is shortened owing to the combustion of diesel fuel when the amount of diesel fuel increases. In type 4, there is a similar tendency, too. When the mixture contains much hydrogen, the period of main combustion does not become small in higher injection pressure and larger amount of diesel fuel. On the other hand, when the mixture does not contain much hydrogen, the effect of diesel fuel becomes strong.

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