Application of Pulsed Flame Jet to Compression Ignition Premixed Charge Engine

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INTRODUCTION

In diesel engines, most of the fuel is burned in a diffusion combustion phase, which inherently leads to the formation of excessive amount of soot and NOx emissions. In order to decrease soot and NOx emissions simultaneously, the concept of lean premixed compression ignition engine has been proposed (Takeda *et al*., 1996, Yanagihara *et al*., 1997, Furutani *et al*., 1998). The onset of the combustion of the engine depends on the autoignition of the fuel, so it is quite difficult to control the ignition timing (Furutani *et al*., 1998, Tsujimura, 2000). On the other hand, it has been revealed that *Pulsed Flame Jet* (PFJ) has a great potential to enhance ignition reliability and burning rate in lean mixtures (Oppenheim *et al*., 1990, Wolanski *et al*., 1997, Murase *et al*., 1995, 1996, 2000). In PFJ, the combustion is initiated in the jet issuing from the igniter, that is, the combustion is initiated volumetrically. This volumetric combustion initiation must behave as a trigger for the autoignition of the fuel in the combustion chamber. This paper describes the preliminary experimental study of the application of PFJ to the ignition timing control of the compression ignition premixed charge engine.

EXPERIMENTAL APPARATUS

Rapid Compression Machine

In order to create a high pressures and high temperatures environment, a compact rapid compression machine (RCM) (Murase, 1995) as shown in Fig. 1 was used. The RCM consists of a driving air reservoir, a cam driving piston, the cam, the compression piston, and

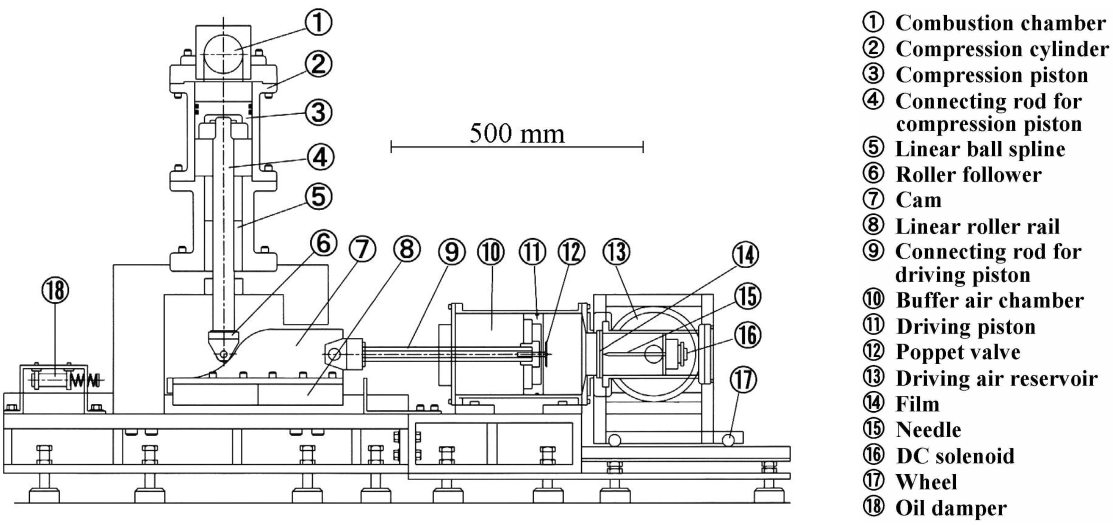


Fig. 1 Rapid compression machine

the combustion chamber. Compressed air at a pressure of 0.39 MPa (gauge) was accumulated in the driving air reservoir. When the diaphragm (three sheets of 35 μm thickness cellophane films) between the reservoir and the driving cylinder was ruptured by a needle actuated by a DC solenoid, the driving piston (160 mm in diam.) was pushed to the left in Fig. 1 by the compressed air. The cam was mounted on a linear roller rail, and it was connected to the driving piston by a push rod. The compression piston (115 mm in diam.) was pushed upward by the rod following the cam shape, and the gas in the combustion chamber was compressed. When the roller follower ran into the plateau of the cam, the compression was terminated and the piston was brought to rest. The cam length was 220 mm and the cam lift, governing the piston stroke, was 95 mm. The disc-shaped combustion chamber used in the tests is shown in Fig. 2. It was a cylinder 50 mm in diameter and 28.9 mm in width, and optical glass windows fitted at both ends. The compression ratio can be changed from 13.5 to 22.4, and in the tests, the compression ratio was adjusted to 14.7. The PFJ igniter was located at the top of the chamber. The combustion chamber and the cylinder were wrapped in the flexible tube in which the heated oil at the designated temperature was circulated. So the gas in the combustion chamber before compression was at atmospheric pressure and the designated temperature. The fuels used in the tests were *n*-butane/air mixtures. The timing of the events such as actuation of the DC solenoid was computer controlled.

Pulsed Flame Jet (PFJ)

The schematic of the PFJ system and detail of its cavity are shown in Fig. 3. The PFJ igniter is of the same size and shape as the conventional spark plug, and it contains a small cavity and an orifice. Rich fuel-air mixture was injected by the fuel injector, and it was introduced into the cavity via an insulator, a hollow center electrode (2.0 mm outer diam. and 1.5 mm inner diam.), and two inlet ports (each 1.0 mm in diam.). After injection of the rich mixture, a conventional spark discharge took place between the center electrode and the ground electrode. Thus the rich mixture in the cavity was ignited and a jet of incomplete combustion products was issued from the orifice to form a turbulent jet plume in the combustion chamber. The cavity was made of a ceramic and the cavity volume used was Vp = 500 mm^3 and two orifice diameters (d = 4.0 mm and 2.5 mm) were used. As the vapor pressure of *n*-butane is low (0.2 MPa at 293 K), methane/air mixture was used in PFJ. The

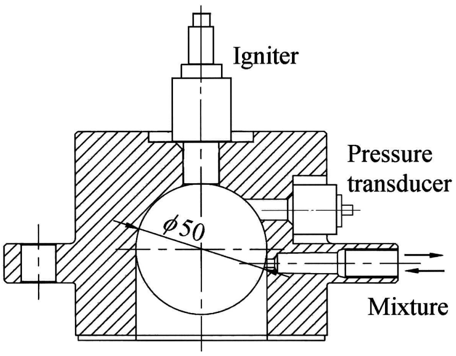


Fig. 2 Combustion chamber

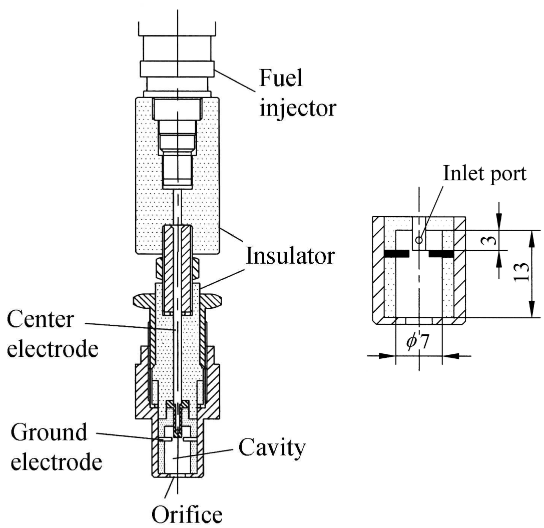


Fig. 3 PFJ igniter and detail of its cavity

autoignition temperature of methane is higher than n-butane, so the gas overflows from the cavity of PFJ will not shorten the ignition delay of n-butane.

EXPERIMENTAL RESULTS AND DISCUSSIONS

Autoignition characteristics in RCM

Autoignition characteristics of n-butane in the RCM were investigated first. Typical examples of pressure diagrams in the combustion chamber at different initial temperatures, T_1, and different equivalence ratios, ϕ, are presented in Fig. 4. The temperatures at the end of compression, T_c, are also indicated in Fig. 4. Here, T_c was derived from the ideal gas law applied to initial and final compression conditions, which is thought to be a spatially averaged compression temperature. When the initial temperature was at room temperature, T_1 = 289 K (T_c = 583 K), autoignition did not occur at these equivalence ratios (ϕ=0.1~ 0.4). As it appears from Fig. 4, autoignition occurred in ϕ = 0.4, 0.3, and 0.2 mixtures at raised initial temperatures, and the shorter ignition delay and the faster pressure rise were attained in ϕ = 0.4 than in ϕ = 0.3, or 0.2. The ignition delay was also shorter in higher temperatures of T_c, which indicates that the final compression conditions in the RCM correspond to the positive temperature dependence region (Griffiths *et al.*, 1993). Light emissions were also detected in some tests by the use of photomultiplier and two different color glass filters: a blue glass filter (360 nm ~ 540 nm) and a red glass filter (620 nm ~). The light emission through the blue glass filter corresponds to that of "cool flames" which comes from the deactivation of CH_2O*, and the light emission through the red

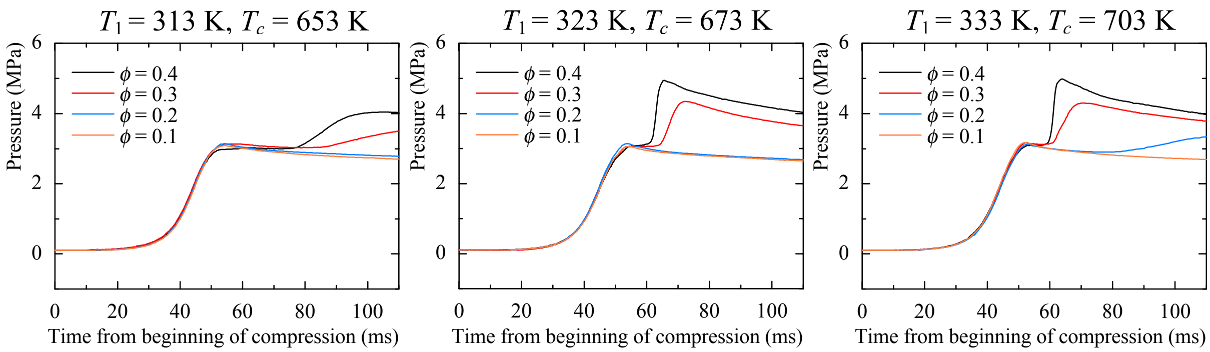
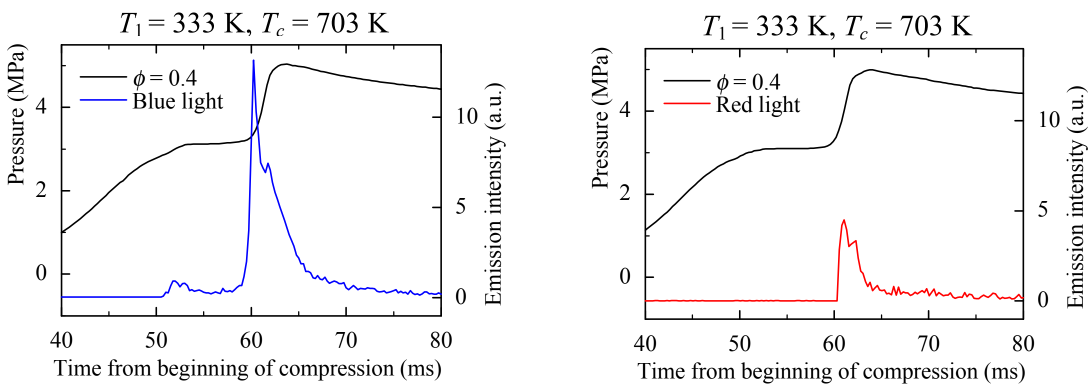


Fig. 4 Pressure diagrams of compressed n-butane/air mixture in RCM

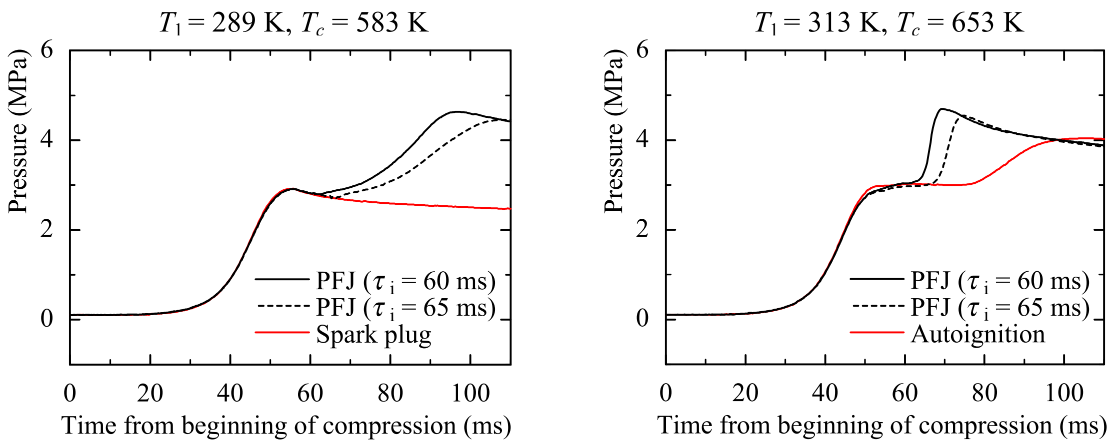


(a) Blue glass filter (b) Red glass filter

Fig. 5 Light emissions from compressed n-butane/air mixture glass filter corresponds to that of "hot flames" (Furutani *et al.*, 1998). Figure 5 depicts the example of the result of the light emissions. According to Fig. 5(a), blue light emission, which corresponds to the cool flames, appeared first where a small pressure rise was observed. The second peak in the blue light emission was observed close to the occurrence of the red light emission, which corresponds to that of "blue flames" (Ohta *et al.*, 1991). Then the peak of red light emission occurred close to the maximum pressure rise as shown in Fig. 5(b). The appearance of the low temperature flames, such as cool flames and blue flames, was typically observed in piston compressed *n*-butane mixtures at relatively low gas temperatures (Griffiths *et al.*, 1993, Ohta *et al.*, 1991).

Ignition timing control by PFJ

Figure 6 demonstrates the pressure diagrams of combustion initiated by PFJ. Figure 6(a) shows the pressure diagrams at an equivalence ratio of $\phi = 0.4$, where the initial temperature was at room temperature, T_1 = 289 K (T_c = 583 K). In this condition, autoignition did not occur at all, and autoignition could not be initiated by a spark discharge of an ordinary spark plug as shown in Fig. 6(a). On the other hand, the large pressure rise was observed in PFJ case. In PFJ, the orifice diameter used was d = 4.0 mm, and the methane/air mixture at an equivalence ratio of ϕ_c=3.0 was injected at a pressure of 4.4 MPa (gauge) with the injection duration of $\Delta\tau_i$=17.5 ms. Here, the injected mixture was beyond the rich flammability limit at atmospheric pressure and room temperature. However, the temperature and the pressure in the cavity at the time of spark discharge were increased, and the charge in the cavity must have been diluted by the lean mixture in the combustion chamber as it was pushed into the cavity during compression. Consequently, the combustion in the cavity was initiated at this equivalence ratio. Two ignition timings of PFJ were chosen, i.e. τ_i= 60 and 65 ms (τ_i is the time from the beginning of compression). From Fig. 6(a), the onset of large pressure rise, namely the beginning of combustion in the combustion chamber was observed, and the onset time was corresponded to the ignition timing of PFJ. Figure 6(b) shows the pressure diagrams with the initial temperature of T_1 = 313 K (T_c = 653 K), where the injection duration and the orifice diameter were changed to $\Delta\tau_i$=12 .5 ms and d = 2.5 mm respectively. According to Fig. 6(b), autoignition occurred late at about 75 ms in this test condition. The large pressure rise corresponding to the ignition timing of PFJ was also observed in advance of the autoignition. As apparent from



(a) (b)

Fig. 6 Pressure diagrams of combustion initiated by PFJ

Figs. 6(a) and 6(b), the beginning of the combustion in the combustion chamber has changed appropriately with varying the ignition timing of PFJ. Therefore, it was obvious that the jet issuing from the PFJ igniter must behave as a trigger for the autoignition of the fuel in the combustion chamber, and it was revealed that PFJ has a potential for the ignition timing control of the compression ignition premixed charge engine.

CONCLUSIONS

(1) The appearance of low temperature flames was observed in autoignition of *n*-butane in the RCM used here, and it was realized that the final compression conditions in the RCM correspond to the positive temperature dependence region.
(2) Shorter ignition delay and faster pressure rise were attained at $\phi = 0.4$ than at $\phi = 0.3$, or 0.2.
(3) It was obvious that the jet issuing from the PFJ igniter must behave as a trigger for the autoignition of the fuel in the combustion chamber, and it was revealed that PFJ has a potential for the ignition timing control of the compression ignition premixed charge engine.

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