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JSAE 20159104
SAE 2015-01-1891

Simultaneous Observation of Combustion in Optical Rotary Engine by Bottom View and Side View

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ABSTRACT

Combustion behavior in Rotary Engine (RE) is quite different from that in conventional reciprocating engines. Therefore, it is important to observe the combustion in RE. In the previous studies, an optical RE was developed, which enabled the observation of the flame propagation in the rotor rotating direction (side view). In the present study, modification was made to the optical RE so that the observation of the flame propagation in the rotor width direction (bottom view) became possible. By using two high-speed cameras, the combustion in RE was observed by bottom view and side view simultaneously. Consequently, it was found that the flame propagation in the rotor width direction is also important for better engine performance as well as that in the rotor rotating direction.

INTRODUCTION

The structure of Rotary Engine (RE) is very simple (Fig. 1), and therefore RE is lightweight and compact compared with conventional reciprocating engines [1]. In addition, RE makes less noise and vibration because it has no reciprocating part [2]. However, combustion efficiency and thermal efficiency of RE are lower. Combustion behavior in RE is quite different from that in conventional reciprocating engines because of its flat-shaped combustion chamber and extremely strong unidirectional mixture flow. Therefore, it is important to observe the combustion in RE to improve its combustion efficiency and thermal efficiency.

In the previous studies [3-7], an optical RE (Fig. 2) was developed for the observation of combustion in RE. One of the side housings was replaced with a sapphire glass window, and thus the observation of the flame propagation in the rotor rotating direction (side view) became possible. Thereby, the effects of several experimental conditions on flame propagation were examined [4-7]. However, the flame propagation in the rotor width direction was still unclear, and local burning behavior could not be evaluated in detail.

In the present study, modification was made to the optical RE. An eccentric shaft, the output shaft of RE, was replaced with a hollow one, and a sapphire glass window was attached to one of three recesses of the rotor. Through a borescope inserted in the hollow eccentric shaft, the observation of the flame propagation in the rotor

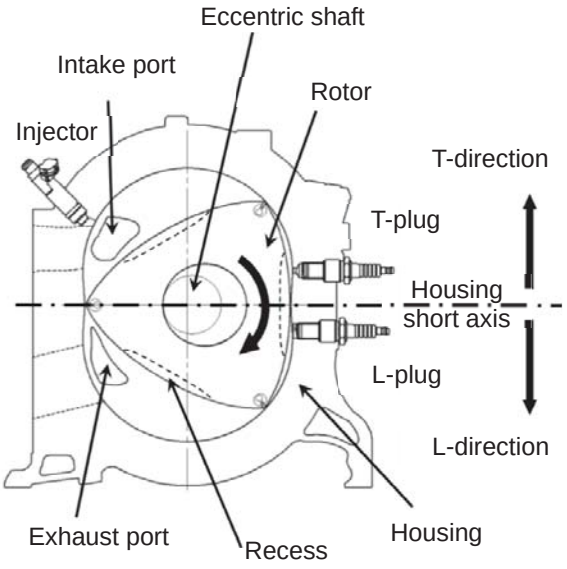


Figure 1 Rotary Engine (RE)

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width direction (bottom view) became possible. By using two high-speed cameras with the new optical RE, the combustion in RE was observed by the bottom view and the side view simultaneously. Fuel injection period and ignition timing were varied, and it was examined how their effects are detected through the simultaneous observation.

EXPERIMENTAL SETUP AND PROCEDURE

Figure 3 shows the schematic of the experimental setup. For the observation of the combustion, an optical RE, a borescope and two high-speed cameras were used.

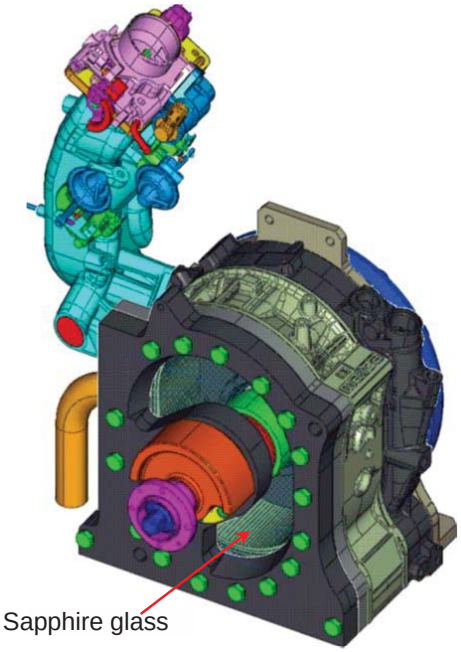


Figure 2 Optical RE

The optical RE is a single rotor RE, and was remodeled from a production two-rotor RE. Displacement is 0.654 Liter. Compression ratio is 10. Fuel is injected by port injection system. As shown in Fig. 1, the rotor has three hollows on its surface called “recesses”. Each recess and the housing form a combustion chamber. In general, RE has two spark plugs [2]. The spark plug on the upper side of the housing short axis is called “Trailing plug” (“T-plug”), and the other is called “Leading plug” (“L-plug”). The electrodes of the two spark plugs are located inside the cavities of the housing called “plug holes”. This is because the electrodes would interfere with the rotor movement otherwise. Here, the authors define the directions regarding the rotor movement for later discussion. The direction from the housing short axis to T-plug is defined as “T-direction”, and the opposite direction is defined as “L-direction” as shown in Fig. 1.

Figure 4 shows the previous rotor and the new rotor developed for the visualization by bottom view. One of three recesses of the rotor was replaced with a sapphire glass. Figure 5 shows the newly developed eccentric shaft. The new eccentric shaft is hollow, and has an opening at the eccentric part (the part where the rotor is attached to). A borescope was inserted into the hollow eccentric shaft. The borescope has a mirror at its end, and reflects the light from the combustion chamber to the shaft axis direction. Through the borescope and the sapphire glass recess of the rotor, the inside of the combustion chamber can be observed from the inside of the rotor as shown in Fig. 6. However, the observation area of the bottom view is

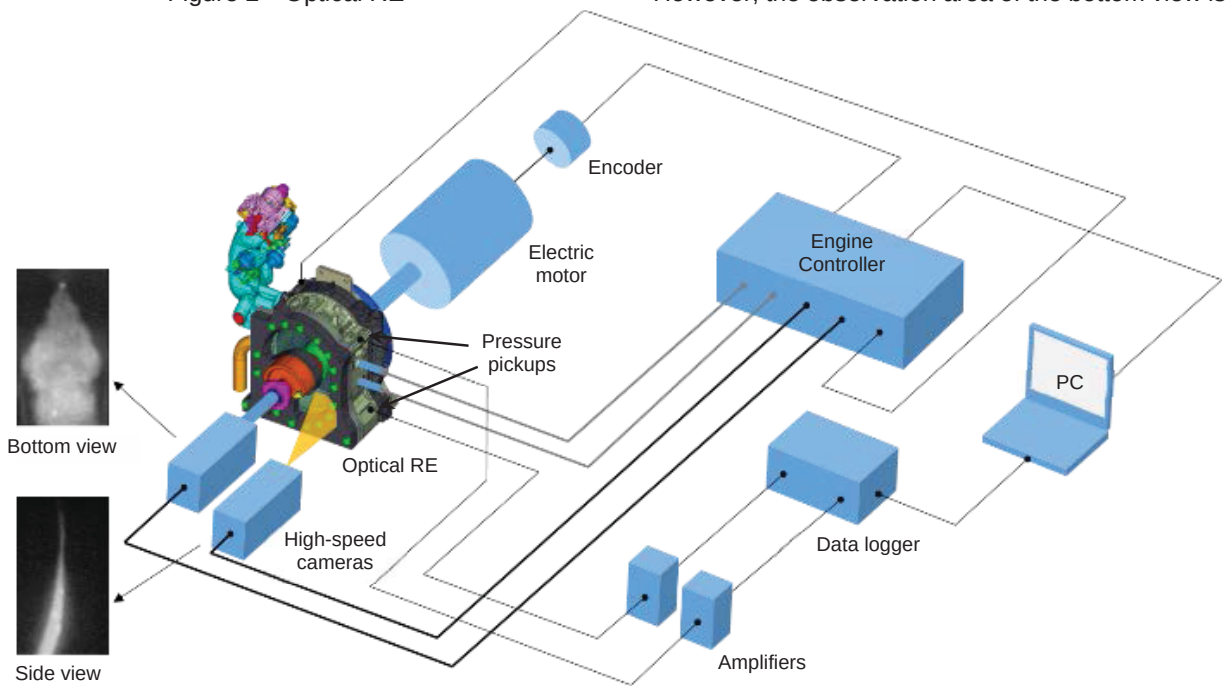
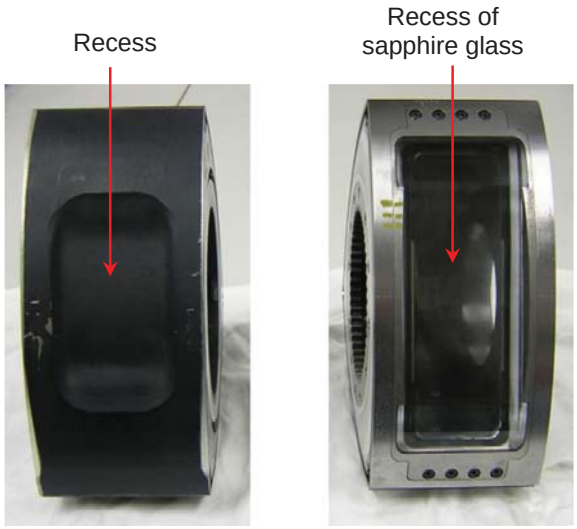


Figure 3 Schematic of experimental setup

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limited by the fields of view of the rotor, the eccentric shaft and the borescope. Figure 7 shows the view angle of the borescope. The borescope is fixed on a supporting device outside the optical RE, and does not rotate with the rotor or the eccentric shaft. The field of view of the rotor is limited by the size of the sapphire recess, and that of the eccentric shaft is limited by the opening angle (90 deg.) of the shaft. The rotor and the eccentric shaft rotate with the RE operation. For these reasons, the observation area of the bottom view varies with the rotation of the rotor and the eccentric shaft. Figure 8 shows the observation areas at three representative output-shaft angles.



(a) Previous rotor (b) New rotor

Figure 4 Previous rotor and new rotor



Figure 5 Hollow eccentric shaft

For the simultaneous observation of the combustion by bottom view and side view, two high-speed cameras were used. One (Vision Research, Phantom V4-i) was used for the side view, which has an image intensifier inside. The other (nac, MEMRECAM GX-1) was used with an image intensifier (Invisible vision, UVi 1850-100) for the bottom view. The frame rates of two cameras were 10,000 fps.

The optical RE was not continuously operated. It was first driven externally by an electric motor without firing so that a desired engine speed would be maintained. Then, fuel injection and spark discharge were carried out by an engine controller for about 100 cycles. Fuel was high-octane gasoline. The pressure history in the combustion chamber was also obtained.

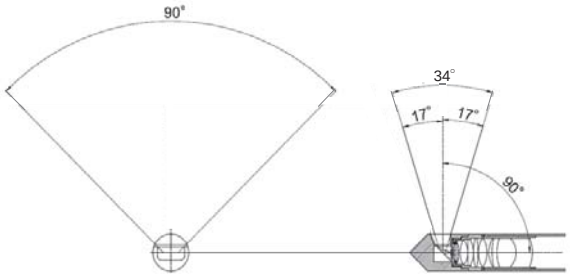


Figure 7 View angle of borescope

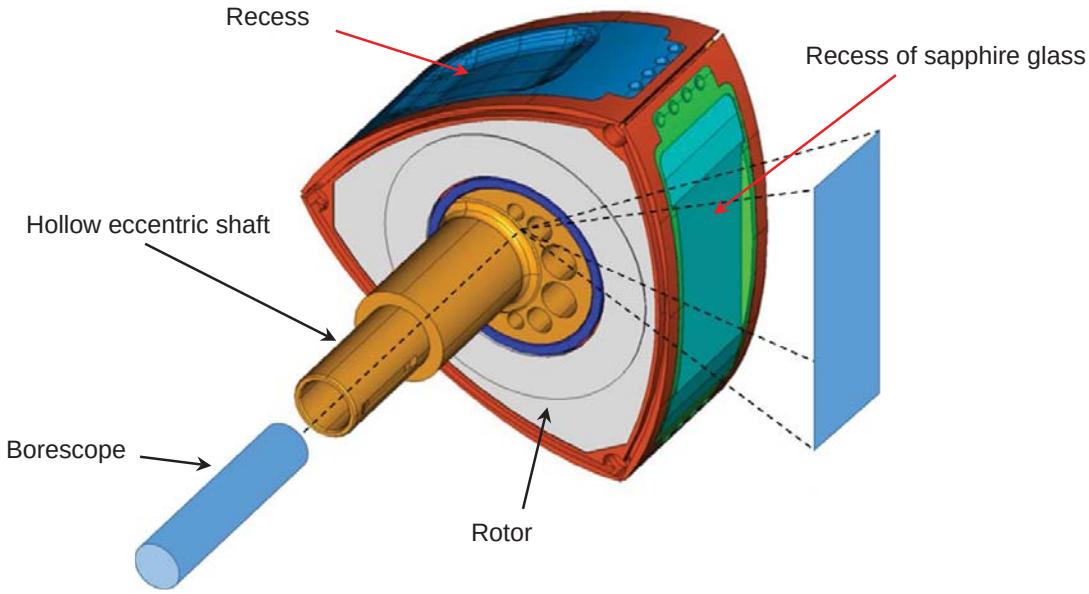


Figure 6 How to realize the bottom view

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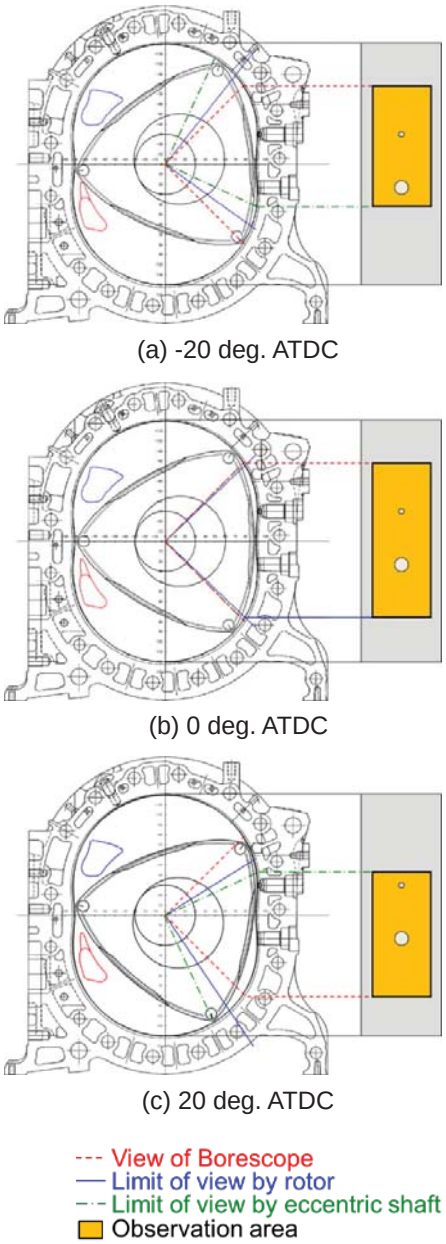


Figure 8 Observation area of bottom view (Output-shaft angle: -20, 0, 20 deg.ATDC)

RESULTS AND DISCUSSION

EFFECTS OF FUEL INJECTION PERIOD ON FLAME PROPAGATION AT 820 RPM

First, the effects of fuel injection period (τ_{inj}) on the flame propagation were examined at 820 rpm. Table 1 shows the experimental conditions. Intake manifold pressure, fuel injection timing and ignition timing were fixed. These conditions correspond to idling.

Figure 9 shows the pressure histories in the combustion chamber for τ_{inj} = 4.0, 4.4 and 4.8 ms. Figure 10 shows the images of the high-speed cameras at several output-shaft angles. Here, the ignition timings of T- and L-plugs are expressed as "T/L=x/y" when ignition timings of T- and L-plugs are x and y deg. BTDC, respectively. In Fig. 10, the locations of T- and L-plugs are indicated by red lines. In bottom view, an upper small red circle indicates T-plug hole, and a lower large red circle indicates L-plug hole. Also in side view, T- and L-plug holes are described. In Fig. 10, the images by bottom view show that the flame from T-plug was narrower compared with that from L-plug. This was probably caused by the difference between two plug holes. T-plug hole has a narrow orifice, while L-plug hole does not [2]. The images both by bottom view and by side view show that the flame propagation to T-direction was extremely slow. This is due to the strong unidirectional mixture flow in the rotor rotating direction, which is unique to RE.

Table 1 Experimental conditions for effects of fuel injection period at 820 rpm

Engine speed	820 rpm
Intake manifold pressure	43.3 kPa
Fuel injection pressure	400 kPa
Fuel injection timing	43 deg. BTDC
Ignition timing for T/L-plugs	20/15 deg. BTDC
Fuel injection period, τ_{inj}	4.0, 4.4, 4.8 ms

In Fig. 9, the combustion pressures were higher in the cases of τ_{inj} = 4.4 ms and 4.8 ms than in the case of τ_{inj} = 4.0 ms. It seems that the equivalence ratios of air-fuel mixture were preferable for τ_{inj} = 4.4 ms and 4.8 ms. This difference can be recognized in Fig. 10. Bottom view and side view in Fig. 10 clearly show the fact that the flame propagations from L- plug in the case of τ_{inj} = 4.4 ms and 4.8 ms were faster both in the rotor rotating direction and rotor width direction than in the case of τ_{inj} = 4.0 ms. In Fig. 9, however, the pressures of τ_{inj} = 4.4 ms and

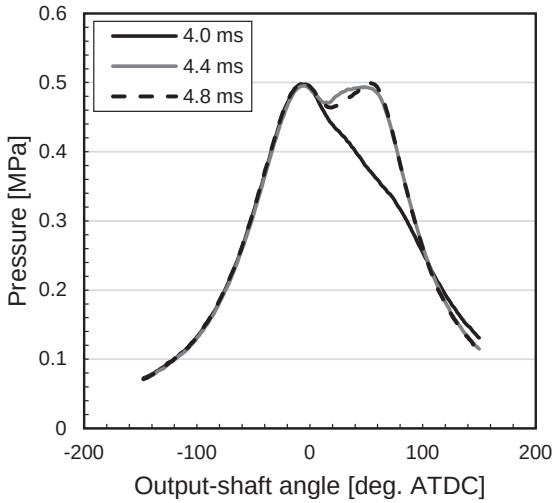
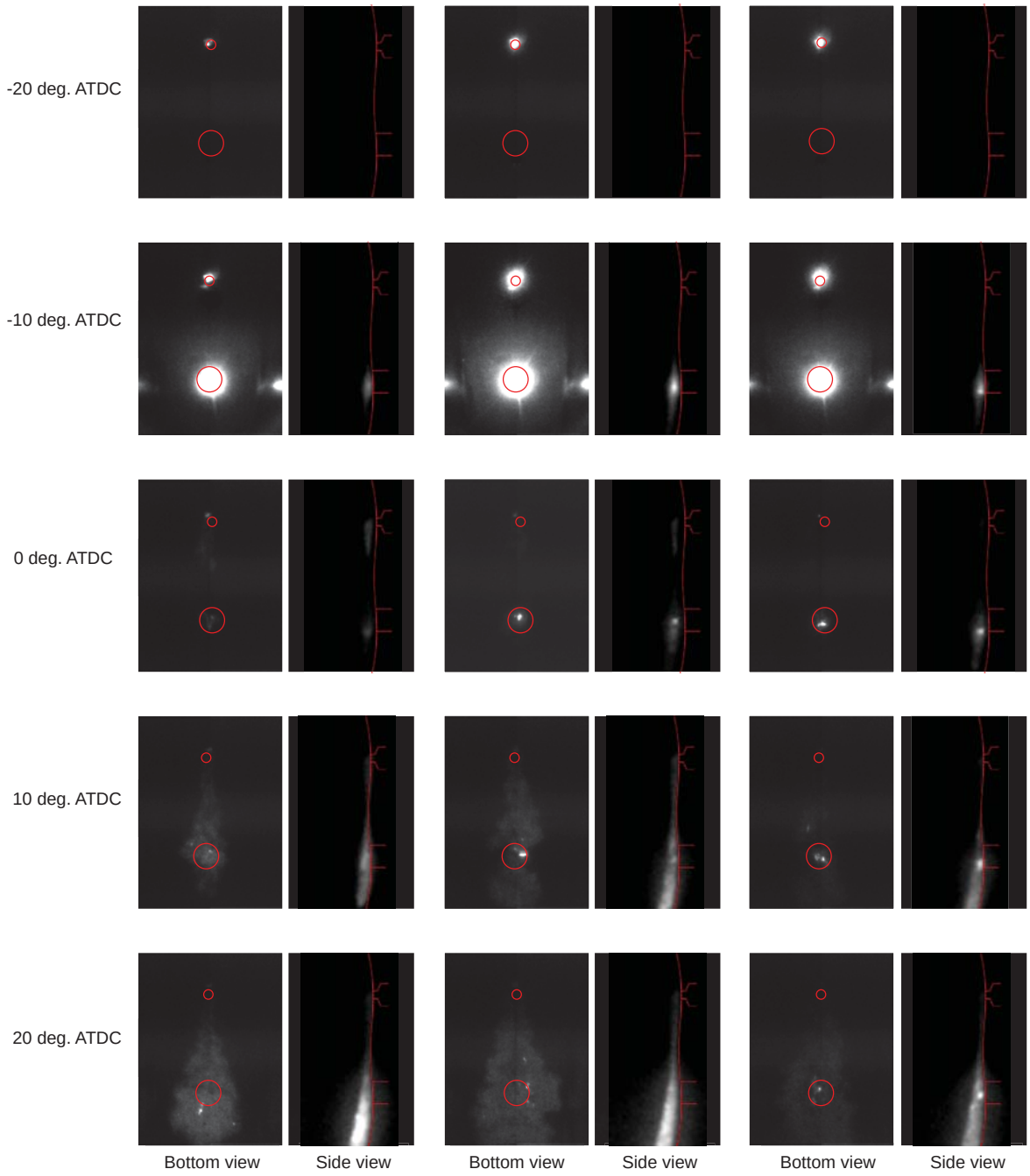


Figure 9 Pressure versus output-shaft angle for ignition timing T/L=20/15 at 820 rpm (fuel injection period: 4.0, 4.4, 4.8 ms)

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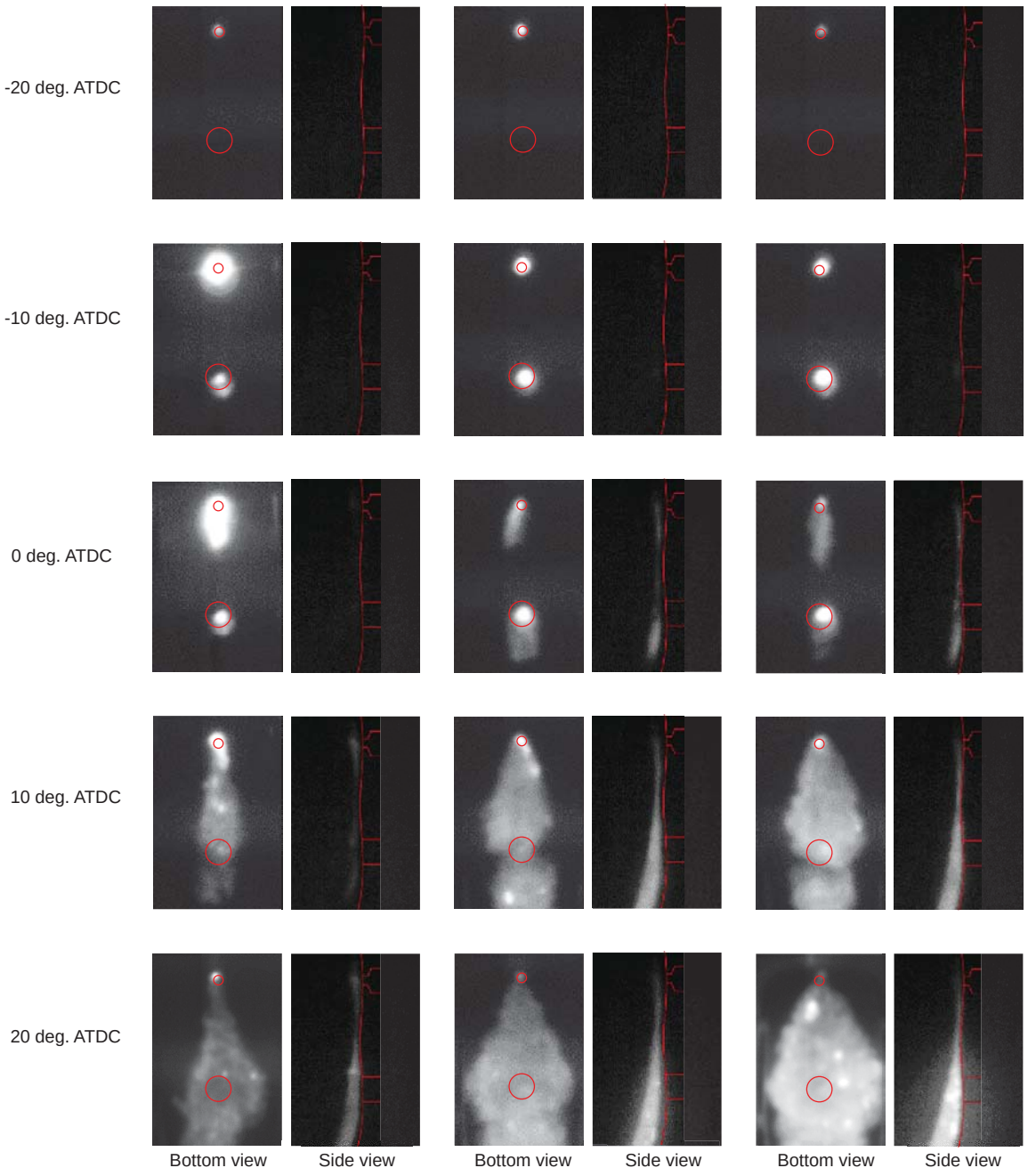
(a) τ_{inj} = 4.0 ms (b) τ_{inj} = 4.4 ms (c) τ_{inj} = 4.8 ms

Figure 10 Images of flame propagation for ignition timing T/L=20/15 at 820 rpm (Fuel injection period: 4.0, 4.4, 4.8 ms)

4.8 ms after around 100 deg. ATDC were lower than that of τ_{inj} = 4.0 ms. This is probably because of heat loss. Please note that the RE was first in the cold state and then fired only for about 100 cycles. Besides, the surface volume ratio of the combustion chamber of RE is larger than that of conventional reciprocating engines [8]. Thus higher temperature inside the combustion chamber for τ_{inj} = 4.4 ms and 4.8 ms led to larger heat loss.

Looking to the flame propagation from T-plug in Fig. 10, that of τ_{inj} = 4.4 ms is almost the same as that of τ_{inj} = 4.0 ms unlike the flame propagation from L-plug. This can be understood through the property of RE. In a low speed rotation range, fuel tends to be amassed in T-direction of the combustion chamber, and local equivalence ratio there becomes rich [8]. For this reason, the air-fuel mixture around T-plug became too rich and

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(a) τ_{inj} = 5.0 ms (b) τ_{inj} = 5.6 ms (c) τ_{inj} = 6.0 ms

Figure 12 Images of flame propagation for ignition timing T/L=20/15 at 1500 rpm (Fuel injection period: 5.0, 5.6, 6.0 ms)

the burning velocity there was low in the case of τ_{inj} = 4.4 ms.

Comparing the combustion pressure in Fig. 9 between τ_{inj} = 4.4 ms and τ_{inj} = 4.8 ms, the pressure increase was faster for τ_{inj} = 4.4 ms though the maximal pressure was slightly higher for τ_{inj} = 4.8 ms. In the case of τ_{inj} = 4.8 ms, the flame from T-plug was scarcely observed at -10 and 0 deg. ATDC in Fig. 10. Furthermore, the flame propagation of τ_{inj} = 4.8 ms in the rotor width direction was slower even at 10 and 20 deg. ATDC as shown in the bottom view. Probably the air-fuel mixture was even richer in T-direction side of the combustion chamber in the case of τ_{inj} = 4.8 ms because of the peculiarity of RE described before. As a result, the flame propagation in the rotor width direction became slow.

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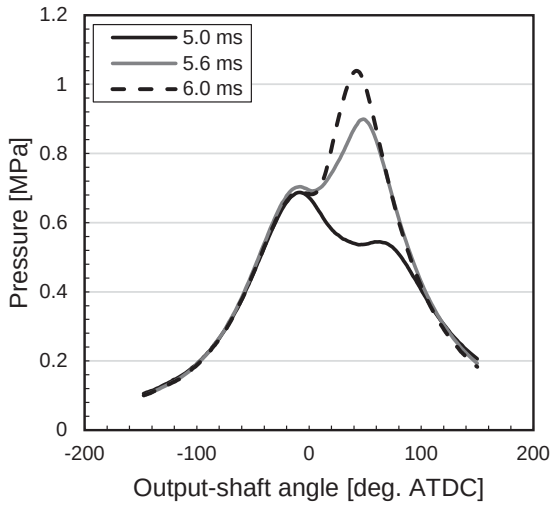


Figure 11 Pressure versus output-shaft angle for ignition timing T/L=20/15 at 1500 rpm (fuel injection period: 5.0, 5.6, 6.0 ms)

EFFECTS OF FUEL INJECTION PERIOD ON FLAME PROPAGATION AT 1500 RPM

Next, the effects of τ_{inj} on the flame propagation were examined at 1500 rpm. Table 2 shows the experimental conditions. These conditions correspond to partial load.

Table 2 Experimental conditions for effects of fuel injection period at 1500 rpm

Engine speed	1500 rpm
Intake manifold pressure	55.3 kPa
Fuel injection pressure	400 kPa
Fuel injection timing	43 deg. BTDC
Ignition timing for T/L-plugs	20/15 deg. BTDC
Fuel injection period, τ_{inj}	5.0, 5.6, 6.0 ms

Figure 11 shows the pressure histories in the combustion chamber for τ_{inj} = 5.0, 5.6 and 6.0 ms. Figure 12 shows the images of the high-speed cameras at several output-shaft angles. Figure 11 shows that longer τ_{inj} simply led to larger combustion pressure. The difference between τ_{inj} = 5.0 ms and τ_{inj} = 5.6 ms in Fig. 11 can be clearly recognized in Fig. 12 both by side view and bottom view. The flame propagation of τ_{inj} = 5.6 ms was faster both in the rotor rotating direction and the rotor width direction. Comparing τ_{inj} = 5.6 ms and τ_{inj} = 6.0 ms in Fig. 12, the difference in side view is unclear unlike the difference in Fig. 11. At 10 deg. ATDC, the images by side view of 5.6 ms and 6.0 ms are almost the same. However, the flame propagations in the rotor width direction by bottom view are quite different. The flame propagation from T-plug was faster in the case of 6.0 ms than in the case of 5.6 ms. Thus, the rise of combustion pressure is strongly related to the flame propagation especially in the rotor width direction.

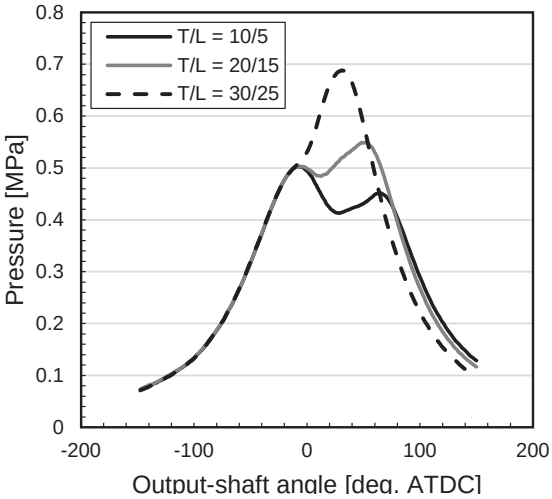


Figure 13 Pressure versus output-shaft angle for fuel injection period 4.4 ms at 820 rpm (ignition timing T/L=10/5, 20/15, 30/25)

EFFECTS OF IGNITION TIMING ON FLAME PROPAGATION AT 820 RPM

The effects of fuel ignition timing on the flame propagation were examined at 820 rpm. Table 3 shows the experimental conditions. Intake manifold pressure, fuel injection timing and τ_{inj} were fixed.

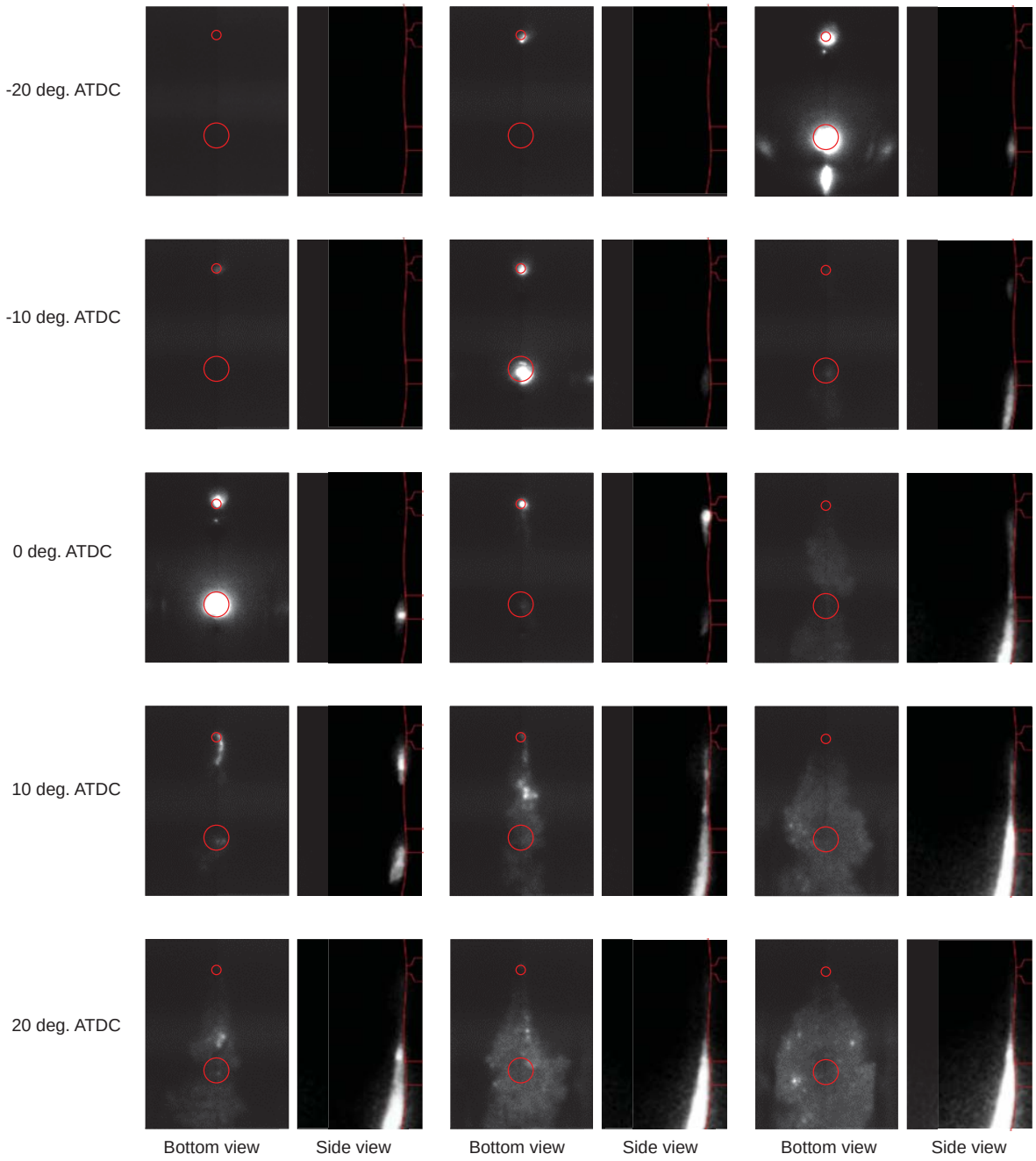
Table 3 Experimental conditions for effects of ignition timing at 820 rpm

Engine speed	820 rpm
Intake manifold pressure	43.3 kPa
Fuel injection pressure	400 kPa
Fuel injection timing	43 deg. BTDC
Ignition timing for T/L-plugs	10/5, 20/15, 30/25 deg. BTDC
Fuel injection period, τ_{inj}	4.4 ms

Figure 13 shows the pressure histories in the combustion chamber at ignition timing T/L = 10/5, 20/15 and 30/25. Figure 14 shows the images of the high-speed cameras. In Fig. 13, the peak of combustion pressure increased along with the ignition timing advance. Higher maximum pressure led to lower pressure in the latter part of the expansion stroke. This can be explained thorough the heat loss as explained for Fig. 9.

In Fig. 14, faster flame propagation both from T-plug and L-plug with earlier ignition timing can be recognized both by side view and bottom view. There is a remarkable difference among the three conditions especially in the images by bottom view at 20 deg. ATDC. Although the images by side view show a relatively small difference, the images by bottom view clearly show that the flame propagation in the rotor width direction was faster as the ignition timing was earlier. In this way, it is

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(a) T/L = 10/5 (b) T/L = 20/15 (c) T/L = 30/25

Figure 14 Images of flame propagation for τ_{inj} = 4.4 ms at 820 rpm (ignition timing T/L = 10/5, 20/15, 30/25)

very important to observe the combustion by bottom view also for understanding the RE combustion more in detail.

CONCLUSION

Simultaneous observation of the combustion in RE by bottom view and side view has been carried out for the first time. Under the conditions examined in the present study, the followings were found.

1. At 820 rpm, the flame propagation from L-plug became faster both in the rotor rotating direction and the rotor width direction by lengthening fuel injection period. However, the flame propagation from T-plug became slower.

2. At 1500 rpm, the flame propagation became faster especially in the rotor width direction by lengthening fuel injection period.

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3. At 820 rpm, advancing ignition timing made the flame propagation from T-plug and L-plug faster both in the rotor rotating direction and the rotor width direction.

In conclusion, it was confirmed that the simultaneous observation by bottom view and side view is significant for better understanding of combustion in RE.

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ISSN 0148-7191