Observation of Flame Propagation and Knock in a Constant Volume Vessel

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1 Introduction

The control of knock is necessary for further improvement of the thermal efficiency of spark ignition engines by the adoption of higher compression ratio. Knock is considered as the pressure oscillation caused by the auto-ignition in the end gas before the completion of the flame propagation [1]. In order to control the knock phenomena, it is important to understand these successive phenomena well.
The experimental investigations of auto-ignition were carried out using the rapid compression machines and the shock-tubes in detail [2, 3]. The importance of low temperature reactions and negative temperature coefficient region for auto-ignition was shown in a lot of literatures. The auto-ignition process of hydrocarbon was clarified and formulated by the analyses of the detailed chemical kinetics [4]. Knock was also investigated experimentally using constant volume vessels, rapid compression machines and engines [5-12]. Low temperature reaction was found to occurre in the end gas before the occurrence of auto-ignition with the spectroscopic measurement [12, 13].
In this study, flame propagation, consequent onset of knock were investigated at various mixture temperatures from 420 to 520K using a constant volume tube-shaped vessel. The flame initiated by the spark ignition at one end of the chamber propagated towards the opposite end. The behaviors of the propagating flame and the end gas were observed with Schlieren and direct photography using the high speed camera and the pressure history in the chamber was recorded.
Knock occurred at the mixture temperatures at 480K and higher than it. It was most intense at 480K than other higher temperatures. Prior to the knock, the hesitation of the flame propagation, onset of bluish white zone in the vicinity of the propagating flame and its rapid displacement were observed.

2 Experimental Setup

Figure 1 shows the schematic of the constant volume combustion vessel. The tube-shaped combustion chamber has a square cross-section of 14x14mm and a length of 80mm. The volume of the chamber is 15.68cm^3. The initial temperature of chamber wall and mixture was controlled by electric heaters which were embedded in the wall of the vessel. The spark plug was located at the side wall of chamber. The pressure transducer was equipped at the wall opposite to the spark plug.
Table 1 shows the experimental conditions. The experiments were carried out for n-$C_7H_{16}/O_2/Ar$ mixture. The equivalence ratio, ϕ was 1.0. The ratio of O_2 to Ar was set to 21:79 in mole fraction. The initial pressure, P_i was 0.33MPa. Combustible mixture quantities were prepared into the vessel according to the required partial pressure of each component. This mixture preparation took 2 minutes.

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The initial temperature of the mixture, T_i was set to 430, 450, 480, 520 and 550 K. The mixture was ignited 3 minutes after the mixture charge when the mixture flow in the chamber decayed completely. The propagating flame initiated by the spark ignition and the behavior of the end gas were observed with Schlieren and direct photography via quartz windows which were equipped at both sides of the combustion chamber. The Schlieren and direct images were obtained at 100,000 and 50,000 fps respectively. Pressure in the chamber was recorded at the sampling frequency of 1MHz.

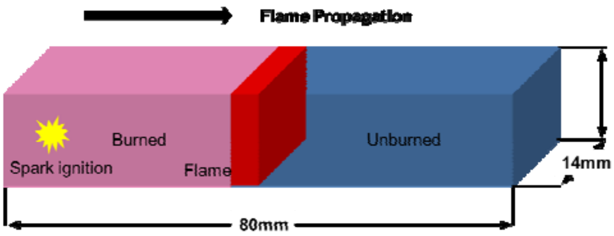

Fig. 1 Schematic of combustion chamber

Table 1 Experimental conditions

Mixture	n-C_7H_{16}/O_2/Ar
Equivalence ratio, ϕ [-]	1.0
Initial Temperature, T_i [K]	430, 450, 480, 520, 550
Initial Pressure, P_i [MPa]	0.33

3 Results and Discussions

Onset of Knock Knock accompanied with pressure oscillation occurred at the initial mixture temperatures of 480K and higher than it. Pressure histories are shown in Fig. 2. Pressure in the chamber increased as the flame propagated and it reached its maximum. At the mixture temperatures of 480K and higher, pressure oscillation was observed. It was most intense at 480K among these temperatures.

Behaviors of Propagating Flame and End Gas Figure 3 shows the histories of pressure, P and pressure increase rate, dP/dt, Schlieren and direct images at the condition of the mixture temperature of 480K. In the middle of the flame propagation, flame became a wedge shape. At the time t =7.70ms after the ignition, pressure increase rate, dP/dt increased suddenly. The flame reduced its propagation speed and it moved backward slightly.

In the Schlieren images from t =7.70 to 7.80ms, some zone due to the density gradient was observed in front of the wedge flame in the end gas. It moved towards the end wall. Weak light emission was observed at this period in the direct images although it is not shown clearly in these figures. This weak light emission might be due to the cool flame according to the spectroscopic analysis [14].

Next period of t =8.42 to 8.48ms, the wedge flame propagated quite rapidly in the end gas changing its color blue to bluish white. At t =8.50ms just before the flame reached the end wall, quite intense light was observed and intense pressure oscillation occurred. Then, yellow-red light was emitted from whole of the chamber.

In order to observe the phenomena after the onset of weak light emission, closeup direct images in the vicinity of the wedge flame to the end gas were obtained at 700,000 fps as shown in Fig. 4. The time indicated at each image was not coincident with that in Fig. 3 because the images in Fig. 4 were taken by another experiment under the same condition as Fig. 3. At t =9.180 and 9.235ms, some bright areas appeared near the upper and bottom chamber walls as shown in (a) and (b) respectively, and they moved towards the end wall at t =9.243ms shown in (c). At t =9.261ms shown in (d), intense light was emitted at the concave area of the wedge flame. It moved very fast to the end wall. At the same time, pressure increased quite rapidly. This intense light emission area reached the end wall at t =9.265ms shown in (e). Then, at t =9.265ms shown in (f) pressure increased very quickly again and intense pressure oscillation occurred.

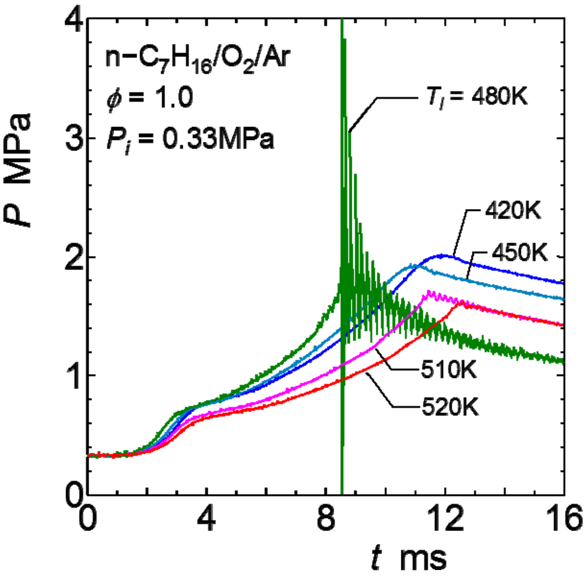

Fig. 2 Pressure histories

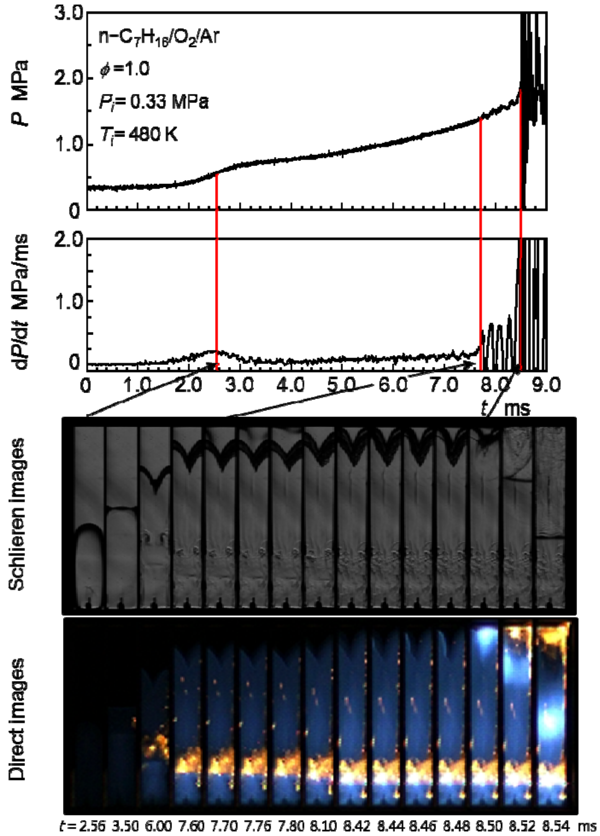

Fig. 3 Pressure history, rate of pressure rise, Schlieren and direct images: ϕ=1.0, T_i=480K

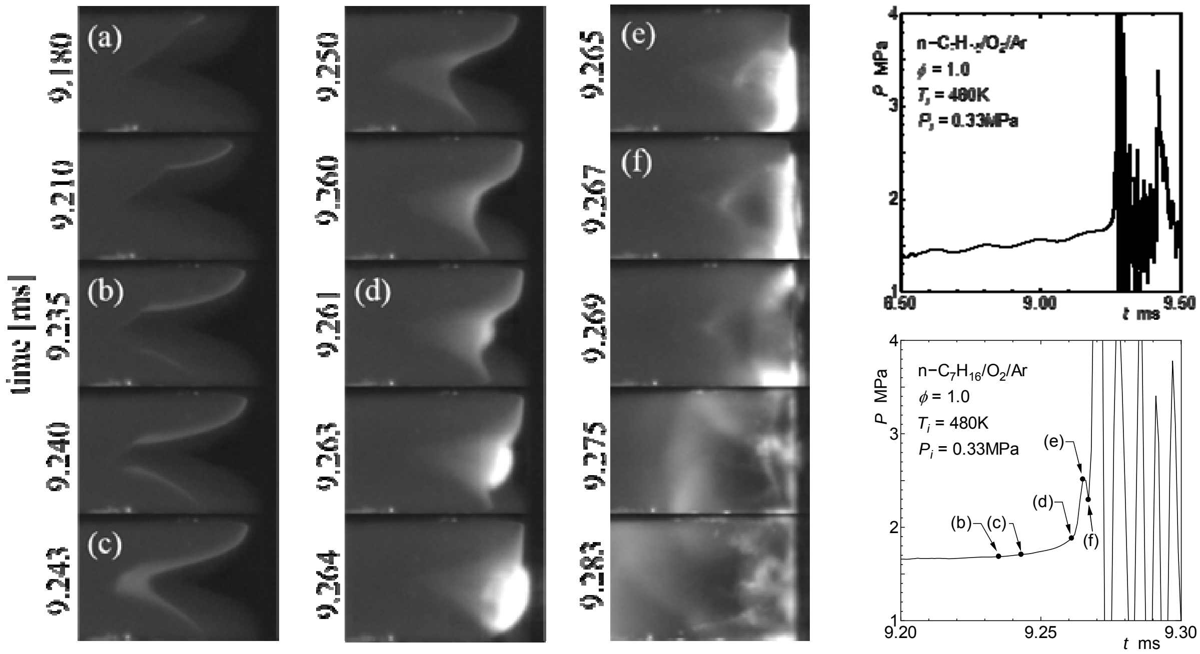

Fig. 4 Closeup direct images and pressure histories: ϕ=1.0, T_i=480K

The propagation speed of the wedge flame initiated by spark ignition was about 7m/s before t =9.180ms. The speed of the bright areas appeared near the upper and bottom chamber walls from 9.180 to 9.243ms was about 50m/s. And it increased to around 400m/s. The speed of intense light emission area observed after 9.261ms was about 1400m/s. Such a fast displacement of light emission zone might cause auto-ignition in the end gas near the end wall due to the rapid pressure increase. The intense pressure oscillation might be occurred by this auto-ignition of the end gas.

4 Conclusions

Flame propagation, consequent auto-ignition in the end gas were observed at various mixture temperatures from 420 to 520K using a constant volume tube-shaped vessel with Schlieren and direct photography. Knock was most intense at 480K among mixture temperatures. Prior to the knock, the hesitation of the flame propagation, onset of bluish white zone in the vicinity of the propagating flame and its rapid displacement were observed.. The intense pressure oscillation might be occurred by this auto-ignition of the end gas.

References

[1] John B. Heywood, Internal Combustion Engine Fundamentals, McGraw-Hill, 1988, p. 457-470.

[2] Ohta, Y. and Furutani, M., Polish Academy of sciences, Vol. 11, No.1-2, p.43-52, (1991).

[3] Furutani, M., Ohta, Y. and Komatsu, K., Trans. Jpn. Soc. Mec. Eng., Vol. 58, No. 559, B, P. 946,(1993).

[4] Ando, H. and Sakai, Y., Universal Rule of Hydrocarbon Oxidation, SAE Paper No. 2009-01-0948 (2009).

[5] Ohta, Y., and Takahashi, H., Progress in Aeronautics and Astronautics, AIAA, Vol. 95, p. 236-247, (1985).

[6] Shiga, S., Kono, M. and Iinuma, K., Trans. Jpn. Soc. Mec. Eng., Vol. 51, No. 465, B, P. 1591, (1985).

[7] Moriyoshi, Y., Kobayashi, S. and Enomoto, Y., Trans. Jpn. Soc. Mec. Eng., Vol. 48, No. 4, B, P. 695, (2005).

[8] Miller, C. D., Olsen, H. L., Logan Jr., W. O. and Osterstrom, G. E., "Analysis of Spark-Ignition Engine Knock as Seen in Photographs Taken at 200,000 Frames per Second", NACA Technical Reports, 857 (1946).

[9] Male, T., 3rd Symposium (International) on Combustion, (1949), p. 721.

[10] Affleck, W. S. and Fish, A., Combust. Flame 12:243 (1968).

[11] Kawahara, N., Tomita, E. and Sakata, Y., Proceedings of the Combustion Institute, Vol. 31, p. 2999, (2007)

[12] Saito, H., Suzuki, R., Kamoshida, S., Iijima, A., Yoshida, K. and Shoji, H., Trans. JSAE, Vol. 41,No. 2, P. 283, (2010).

[13] Gaydon, A. G., The spectroscopy of Flame Second Edition, London, Chapman Hall Ltd. (1974).

[14] Nagano, Y., Koto, T., Iishi, T., Tanaka, S., Kitagawa, T., Proceedings of Japanese Symposium on Combustion, 326-327 (2013).