Journal of KONES Powertrain and Transport, Vol. 17, No. 4 2010

VISUALIZATION OF AUTO-IGNITION OF END GAS REGION WITHOUT KNOCK IN A SPARK-IGNITION NATURAL GAS ENGINE

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Abstract

It is important to increase thermal efficiency in a spark-ignition engine for reducing carbon dioxide gas in exhaust emissions. One of the solutions is to increase the compression ratio of the engine. Then, knock is a barrier in increasing in compression ratio because of higher pressure and unburned gas temperature in the end gas region. Therefore, there have been many studies on knock. However, there was an interesting phenomenon under some conditions in a gas engine. There is no pressure oscillation in the end stage of combustion and rate of heat release increased. It is considered that the auto-ignition in the end gas region occurs without knock. In this study, the combustion behavior in the end gas region was visualized with an ultra-high-speed camera. In normal combustion case, the flame propagates in the end gas region. In the knock case, the auto-ignited part burns suddenly and leads pressure oscillation. Under the critical conditions, some shows knock and some shows normal flame propagation. However, in some cases, even if auto-ignition occurs, pressure wave is not produced. Then there is no pressure oscillation, that is, mild auto-ignition without knock can be confirmed. And the rate of heat release shows two peaks. The first peak is due to flame propagation and the second peak is due to auto-ignition in the end gas region. The combustion near the end stage become short and thermal efficiency is expected to be increased because of increase in degree of constant-volume.

Keywords: *Knock, Spark-Ignition Engine, Homogeneous Mixture, Visualization, Natural Gas, End Gas Region*

1. Introduction

It is very important to increase thermal efficiency in a spark-ignition engine to reduce carbon dioxide in exhaust emissions. One of the ways to increase thermal efficiency is to increase compression ratio. However, when the compression ratio is increased, knock occurs in the end gas region because of higher pressure and temperature [1]. Therefore, knock is one of the barriers for increasing thermal efficiency in a spark-ignition engine. If knock is avoided under some conditions, thermal efficiency is expected to be increased. Knock is defined as the phenomena that pressure oscillation in a cylinder occurs due to pressure wave. The shock wave starts from auto-ignition of the end gas region. There have been done much works on knock, such as pressure oscillation, auto-ignition timing, visualization experimentally since at least the 1930s [2-4] and chemical reactions in low temperature for numerical simulation [5].

In previous study using a specially designed compression expansion machine, knock in the end gas region in a homogeneous mixture was visualized and how a part in the end gas region is auto-ignited and pressure wave is produced with a ultra high-speed camera [6, 7]. The location and timing of end-gas auto-ignition were investigated using the high-speed images.

In my laboratory, the combustoin and exhaust emissions in a natural gas engine ignited with a pilot diesel fuel have been investigated [8-11]. The mixture of natural gas and air was induced from an intake port and homogeneous mixture was ignited with a diesel fuel under lean condition to achieve highrt thermal efficiency and lower NOx emissions. When the injection timing of the diesel fuel is advanced, mean effective pressure is increased, however, knock occurs. However, under some conditions, knock with pressure wave does not occur. The rate of heat release shows two peaks. The first peak is due to flame propagation and the second peak appears in the end of combustion. When the second peak appears, the thermal efficiency increases due to shorter combustion duration with lower hydrocarbons and lower carcon monoxide. Under this condition, it is considered that auto-ignition of the end gas does not induce the knock in a natural gas and air mixture in an engine judging from the pressure because there is no pressure oscillation. But in this engine, the end gas region was not visualized.

Therefore, the auto-ignition phenomena in the end gas region should be visualized with another experimental apparatus of a compression-expansion machine. The behavior of auto-ignition is captured with an ultra high-speed camera and the process of auto-ignition is discussed.

2. Experimental apparatus and experimental method

In this study, a specially designed compression-expansion machine was used. A schematic diagram of this experimental apparatus is shown in Fig.1 [6, 7]. The phenomena of one cycle without residual gas can be achieved. The engine had a bore and stroke of 78 and 85 mm, respectively, and the compression ratio was 9.0:1. The combustion chamber in this engine is pancake type. The engine cylinder was connected to a mixture tank through a pipe. Initially, a homogeneous mixture composed of natural gas, oxygen and argon was introduced into the tank and the cylinder through an open valve with the piston set at top dead center (TDC). The engine was driven by an electric motor while the valve was left open. After a given time, the valve was closed when the piston was at bottom dead centre (BDC). The gas was then compressed and ignited by an electric spark at a selected crank angle. The gas was introduced without swirl so that the flame is not bended by gas flow. The engine was operated at 600 rpm, and spark timing was 15 degrees before TDC. The pressure in the cylinder, interference intensity, crank angle, TDC, BDC and valve closure were recorded by the A/D converter. The cylinder and mixture tank were initially charged with a homogeneous natural gas, oxygen and argon mixture (equivalence ratio= 1.0).

In this study, a small quartz window is installed in the cylinder head as shown in Fig. 2. The diameter of measurement region is 32mm. The ignition location is set at opposite side of this optical window so that the combustion phenomena in the end gas region of auto-ignition can be observed. We used an ultra high-speed camera (Shimadzu, Hyper vision HEX-108; Maximum frame speed is one million frames per second) In this study, the camera speed was se to be 64.000 frames per second during 1.6 ms (5.7 degrees of crank angle) because this camera has only 102 successive frames per one experiment. The resolution of the image is 312x260 pixels even if the frame speed is changed.

3. Results and discussion

3.1. Pressure history and rate of heat release

Figure 3 shows examples of pressure history and rate of heat release for the case with knock and mild auto-ignition without knock. As shown in Fig. 3(a), the pressure oscillation was seen after 2 or 3 degrees after the top dead center of the compression and the rate of heat release shows a steep peak after ordinary premixed combustion in a spark-ignition engine. This is not a strong knock but a slight knock. The main frequency of the oscillation is about 7 kHz according to Fast Fourier Transform (FFT) analysis. In Fig. 3(b), there is no pressure oscillation in pressure history. After the first peak that is caused due to normal flame propagation, another mild peak, that is, the second peak could be seen in rate of heat release. However, after the mild peak, the rate of heat release decreased rapidly compared to the normal combustion. The combustion near the end stage become short and thermal efficiency is expected to be increased because of increase in degree of constant-volume. These facts have been already confirmed in a dual fuel lean burn gas engine and exhaust emissions of hydrocarbons and carbon monoxide were decreased although NOx were increased [10, 11].

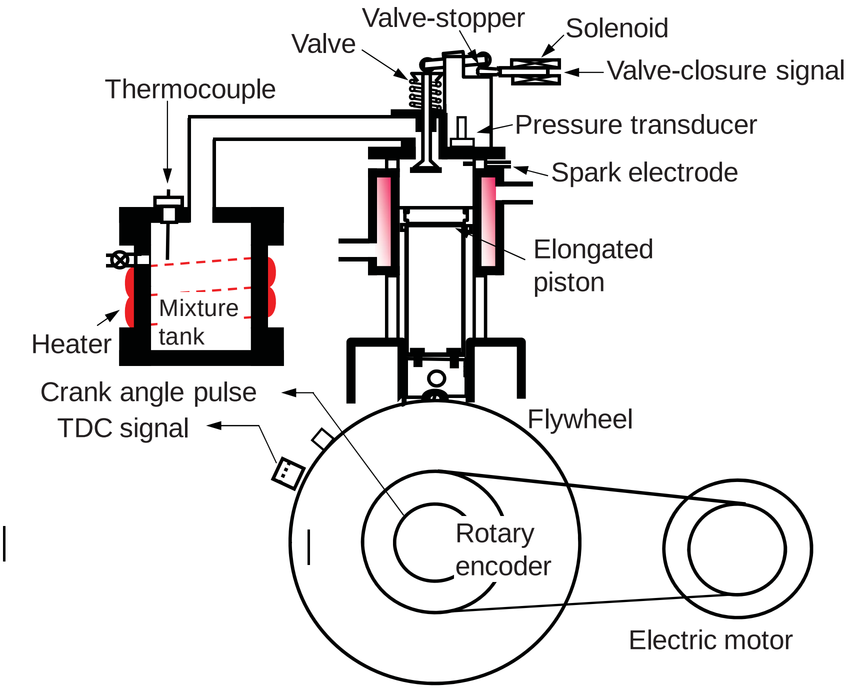


Fig. 1. Schematic diagram of experimental apparatus (compression-expansion machine)

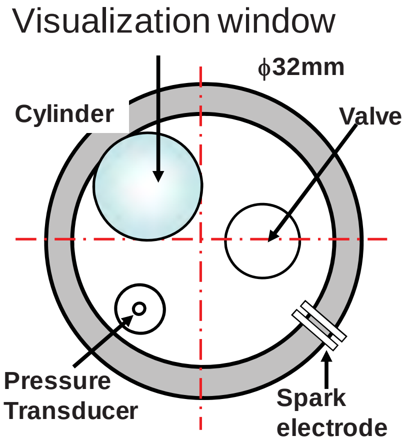
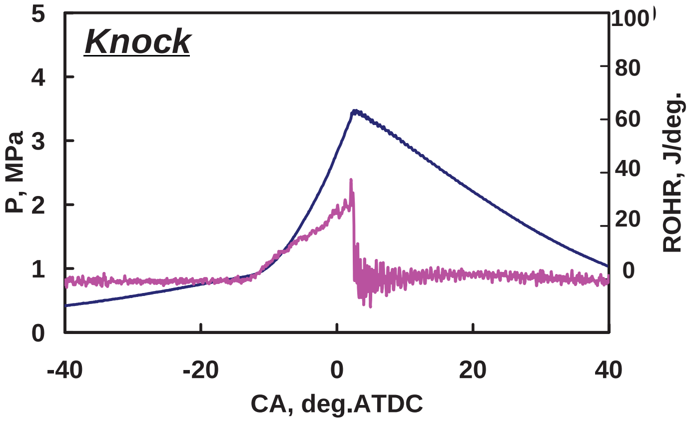


Fig. 2. Visualization setup and location of optical window

3.2 Visualization of behaviour of auto-ignited mixture

In this study, the frame speed of this high-speed camera was selected as 64,000 frames per second. Therefore, the images were obtained in every 15.625 microsecond. This camera has only 102 images so that this camera can records the phenomena during 1.6ms, that is to say, 5.7 degrees crank angle. Fig. 4 presents a time series of images of the combustion in the end gas region. A flame propagates from the right and bottom side where is far from the optical window to left and upper side near the cylinder wall because the location of the spark is right and bottom side of Fig. 4 as shown in Fig. 2.

(a) Knock with pressure wave



(b) Mild auto-ignition without pressure wave

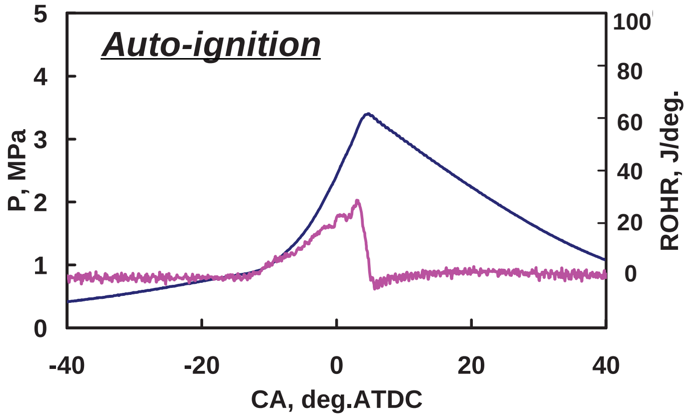


Fig. 3. Pressure history and rate of heat release

a) Knock with pressure wave

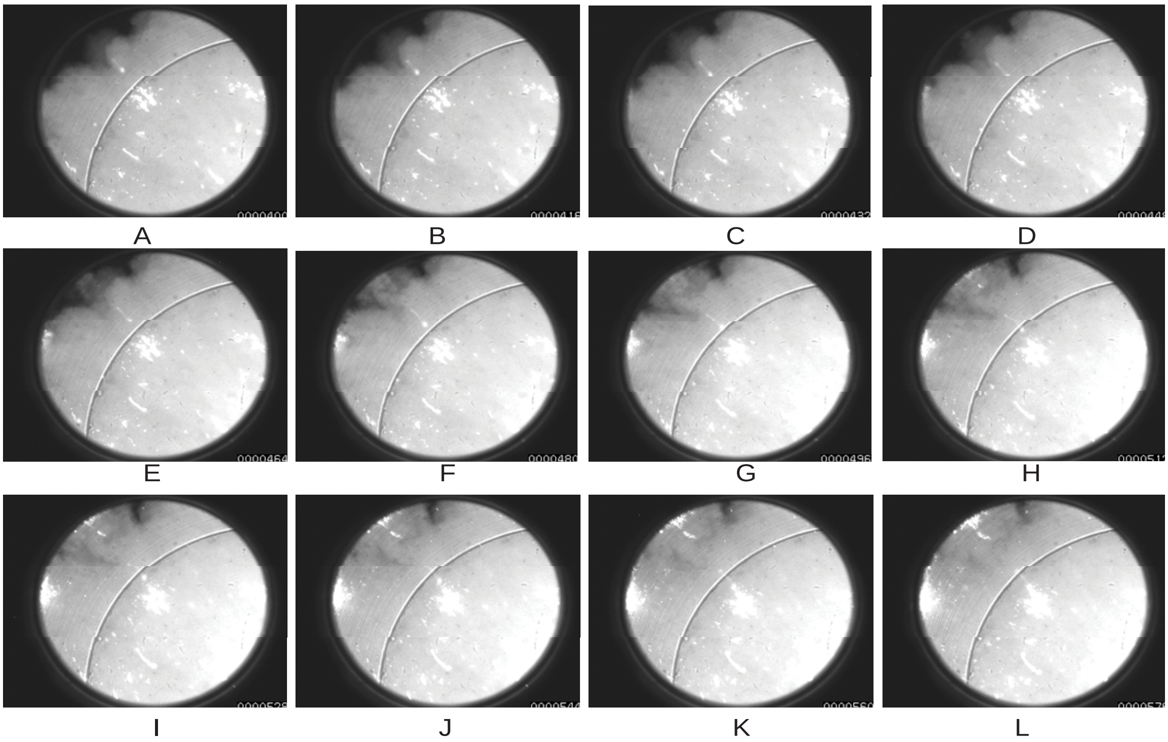


Fig. 4. Combustion behaviour in the end gas region (every 15.625 s)

(b) Mild auto-ignition without pressure wave

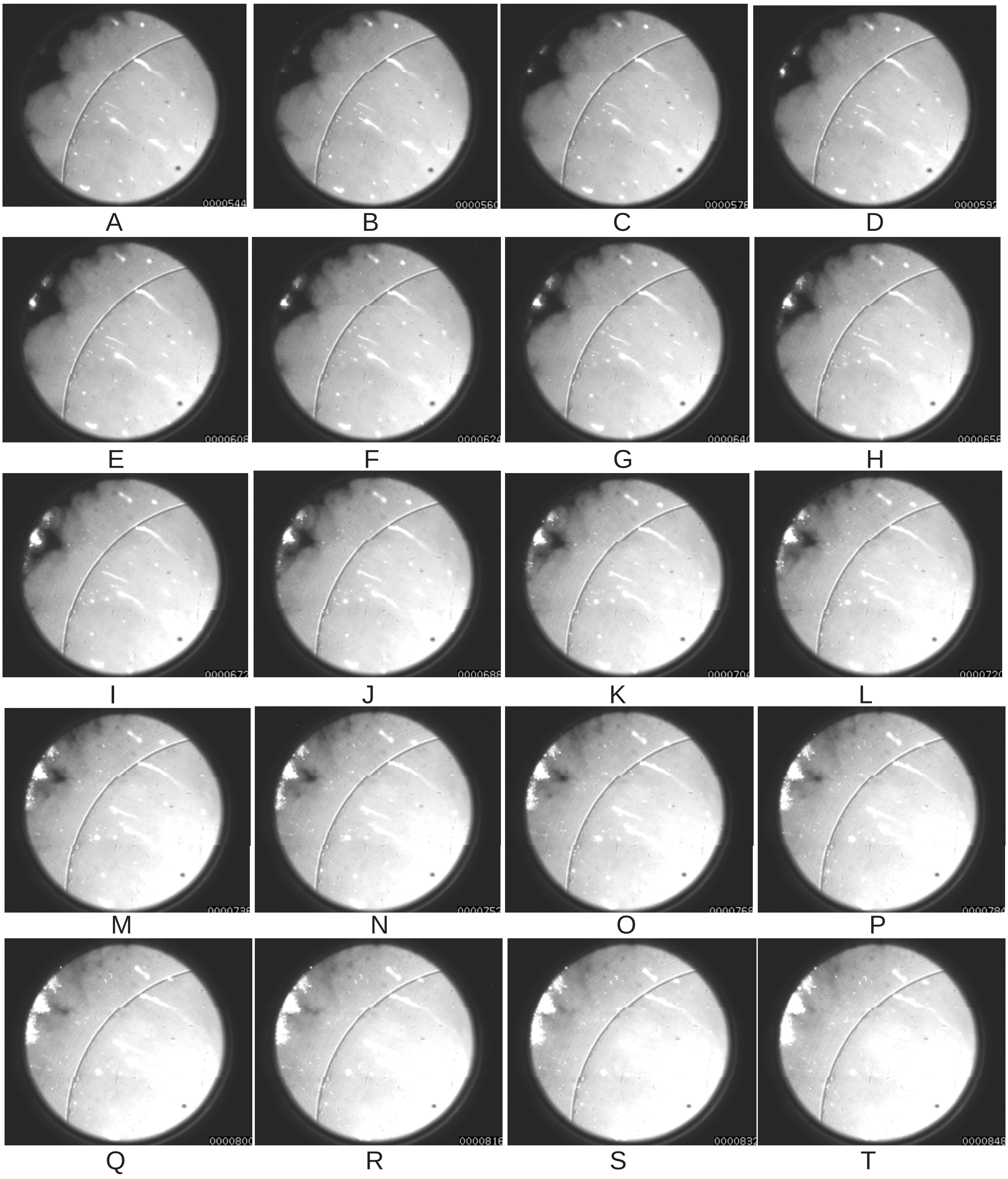


Fig. 4. Combustion behaviour in the end gas region (every 15.625 s)

Figure 4(a) shows an example of time series of images for the case with knock. After auto-ignition in the end gas region at the timing of E, the whole of end gas region burned out soon at the timing of I. A pressure wave is produced by sudden burning of the end gas region. Thereafter, pressure oscillation could be seen in pressure history. Although still images do not present well, it could be easily understood that the gas moves according to the pressure wave by watching the movie. In knock case, the end gas region is always burned out suddenly regardless of knock intensity because the pressure wave occurs.

However, as shown in Fig. 4(b), for the case with mild auto-ignition without knock, the auto-ignition part in the end gas region at the timing of B expands slowly such as normal flame propagation. At the timing of T, the burned gas covered the end gas region. It took about 0.3 ms, which is very long. It is not clear whether this is a flame propagation or successive auto-ignition. Furthermore, after the mild auto-ignition, another part was auto-ignited and led to pressure oscillation, that is to say, knock in some cases.

In this study, completely homogeneous mixture was used so that there is no effect of inhomogeneity of the fuel concentration. However, it is considered that there are some distributions in unburned gas temperature. Probably, this is the reason why some parts in the end gas region are auto-ignited and other parts are not. Another question is why the mild auto-ignition occurs in some cases and why knock occurs in some cases.

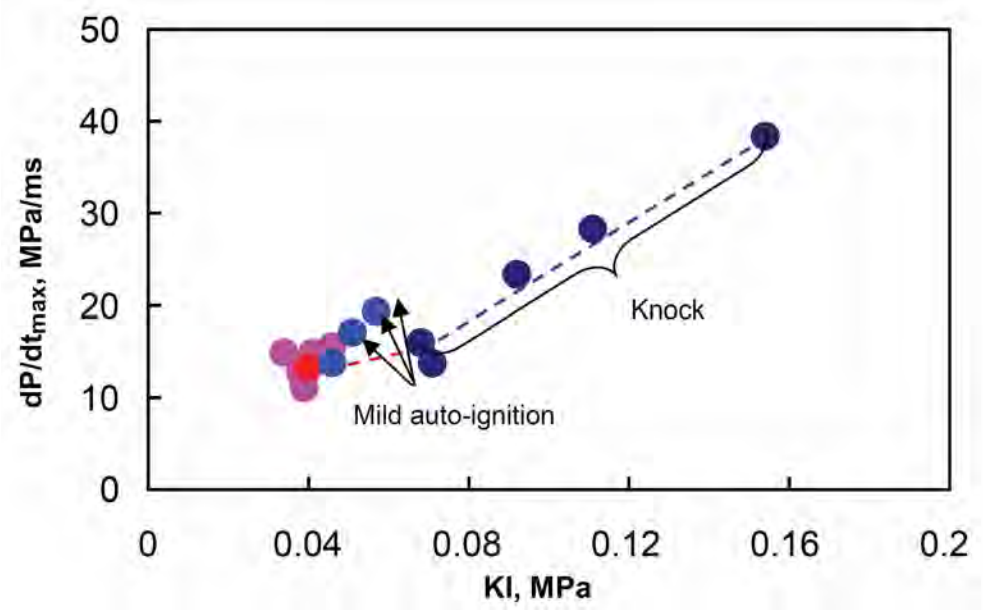


Fig. 5. Relation between dP/dt$_{max}$ and KI

3.3. Discussion

Figure 5 shows the relation between dp/dt$_{max}$ and knock intensity, KI. The KI value was determined from the maximum value after passing through high-pass-filter of 1 kHz. The limitation of detecting KI value was about 0.05. Under this value, the noise could not be distinguished from oscillation signal. When the knock intensity was large, the maximum value of dP/dt was also increased. When the auto-ignition without knock occurs, the maximum value of dP/dt was almost the same as that in weak knock. Sometimes, after auto-ignition occurred without knock, knock occurred from other parts. Even in this case, the maximum value of dP/dt was almost the same as in normal flame propagation.

However, it is not clear whether the combustion after auto-ignition without knock is a flame development or successive auto-ignition. Anyway, the end gas region produces many auto-ignition spots and they develop under the critical cases. We have to clarify what happen in these regions.

4. Summary

In this study, auto-ignition in the end gas region in a compression-expansion machine was visualized with a high-speed video camera. Under the critical conditions, some shows knock and some shows normal flame propagation. However, in some cases, even if auto-ignition occurs, pressure wave is not produced. Then there is no pressure oscillation, that is, mild auto-ignition without knock can be confirmed. And the rate of heat release shows two peaks. The first peak is due to flame propagation and the second peak is due to auto-ignition in the end gas region. The combustion near the end stage become short and thermal efficiency is expected to be increased because of increase in degree of constant-volume.

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