23 Analysis of Auto-Ignition in a Rapid Compression Machine Using Two-Wired Thermocouples

Seung-Hwan CHOI[1], Yasuo MORIYOSHI[1], Takafumi TSUNEKAWA[1], Young-June CHANG[2]

[1] Chiba University, Japan, [2] The Pusan Natinal University, Korea

In order to examine the auto-ignition phenomenon, which plays an important role in HCCI and knock phenomenon, information on local gas temperature in combustion chamber is one of the most important factors. Thermocouple is useful to measure local gas temperature even in the vicinity of wall. However, a traditional thermocouple is not adaptable to measure the in-cylinder gas temperature due to slow response. The issue of response can be overcome by two-wired thermocouple. The two-wired thermocouple is consisted of two thermocouples in different diameter and it is possible to determine the time constant using the raw data from each thermocouple. In this study, measurements such as local gas temperature inside a constant-volume combustion chamber, pressure and visualization were achieved under with and without auto-ignited conditions. As a result, negative temperature coefficient was found to mostly affect auto-ignition in this experimental condition. To discuss more in engine-like conditions, RCM (Rapid Compression Machine) was designed and built. As a preliminary result, local gas temperature inside the combustion chamber under compression without combustion was measured to examine the accuracy of two-wired thermocouple.

***Keywords*: Temperature, Two-wired Thermocouple, Constant Volume Combustion Chamber, RCM**

1. INTRODUCTION

In order to reduce exhaust gas emissions from Diesel engines, HCCI (Homogeneous Charge Compression Ignition) is widely studied. Meanwhile, in order to improve thermal efficiency of spark ignition engines, control of knock is the most important issue. In both engine systems, “auto-ignition” is a key word. Control of auto-ignition is a key technology to accomplish low exhaust gas emissions and fuel economy. Thereby, the study of auto-ignition with fuel-air mixture has been carried out by many researchers [1-3]. Recently, analysis of auto-ignition is widely carried out theoretically using a chemical reaction code such as “CHEMKIN”. Experimental analysis is also achieved by some techniques such as visualization, chemical species measurement using LIF, temperature measurement using CARS and so on. Among them, local gas temperature measurement is the most important factor to analyze the auto-ignition although it is very difficult.

In spark-ignition engines, knock phenomenon has been examined as a subject of auto-ignition. Recently, the study of knock has been made using rapid compression machines (RCM) or shock-tube. Here, detailed knock phenomenon in a real engine should be analyzed under a condition where flame propagation exists during the auto-ignition induction period. On the other hand, the analysis using a real engine causes a difficulty to remove the effects of temporal changes in pressure and temperature by the piston movement.

Thereby, in this study, knock phenomenon was realized in a constant-volume chamber as the first step where ignition was made by a spark plug and flame was initially propagated. Instantaneous local gas temperature measurement has been required to investigate the knock phenomenon because the gas temperature in the unburned region greatly affects the chemical reactions and it is an indispensable factor to make quantitative comparisons with calculated results. CARS is possible to do this [4], but has problems in the accuracy, complexity of setup and difficulty in measurement near walls. The authors introduced a two-wired thermocouple [5-6] that can attain an instantaneous measurement of local gas temperature. Also, an endoscope was used to visualize the combustion process. By combination of local temperature detection, visualization and pressure analysis, influencing factors on knock phenomenon were examined.

As a second step, experiments using RCM should be made under engine-like conditions. Thereby, design and built of RCM was carried out. The details of structure and preliminary test results of local gas temperature measurement under compression without combustion are also reported.

2. TWO-WIRED THERMOCOUPLE

The structure of two-wired thermocouple is illustrated in Fig. 1. Relatively thin and thick thermocouples are closely set using four struts in ϕ0.6 mm. Two wires of K-type (Chromel/Alumel) with thicknesses of 50 and 100 µm were used to have a clearance of 0.1 mm between the two hot-junctions, corresponding to the thickness of the relatively thick thermocouple. This standard for the clearance length was examined in the authors’ paper [6]. The thinner the thermocouple is, the shorter the time delay becomes, but thin wires less than 50 µm cannot be used due to burn-off. Each thermocouple was made by using a percussion welding to make a hot-junction. Only inspected thermometers were used that have no deviation of wire centers and the same size of hot-junction as that of wire.

The basic equation of thermocouple is Eq. 1, where Tg, T and τ are gas temperature, hot-junction temperature and the time constant, respectively.

$$T_g = T + \tau \frac{dT}{dt} \tag{1}$$

An unknown quantity is only τ in the right-hand-side of Eq. 1 and there are several methods to estimate that. Two wires were used as τ can be directly estimated. The principle is that measuring one true temperature by using two sensors that have different thermal inertia so as to attain the same temperature by adjusting the two time constants. The details are available in other papers [5-6], where one can find a method to obtain the instantaneous gas temperature in the end-gas region accompanying flame propagation. Here, the theory is briefly introduced.

The basic equations for estimating the gas temperature are shown in Eq. 2, where the subscripts 1 and 2 denote the thin and thick thermocouples.

$$T_{g1} = T_1 + \tau_1 \frac{dT_1}{dt} \qquad T_{g2} = T_2 + \tau_2 \frac{dT_2}{dt} \tag{2}$$

Although T_{g1} and T_{g2} should be identical ideally, the difference between T_{g1} and T_{g2} exists actually. Thus in this concept, time constants, τ_1 and τ_2, are determined by minimizing the value of **e** using the least square method, as shown in Eq. 3.

$$e = \frac{1}{N} \sum_{i=1}^{N} \left(T_{g1}^{i} - T_{g2}^{i} \right)^2 \tag{3}$$

,where N is the number of samples for each thermocouple.

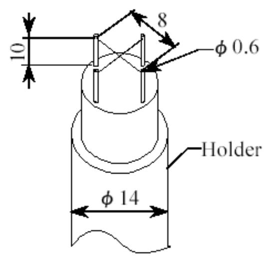

Fig. 1 Structure of two-wired thermocouple

3. EXPERIMENTAL APPARATUS USING COMBUSTION CHAMBER

3.1 COMBUSTION CHAMBER AND VISUALIZED AREA

Figure 2 shows the schematic of a combustion chamber employed in this study. The chamber is pancake shaped in ϕ120 x height 20 mm (volume 226 cc) and equipped with electric heaters in upper and lower parts and wall periphery to control initial wall and gas temperatures up to 600 K. To cause auto-ignition in the end-part of the chamber, a spark plug is located in the position shifted by 45 mm from the center of the chamber. The thermocouples are located at two positions of the center of chamber (CNT) and the end-part (END) as illustrated in Fig. 3 that designates settings of sensors viewed from the top of the chamber. CNT thermocouple is located 45 mm left from the spark plug while END thermocouple is 97 mm left from the spark plug. The position in height is fixed just in the middle of the chamber.

In this study, it is required to keep the wall and gas temperatures around the low-temperature reaction region (~600 K) to examine the effect of negative temperature coefficient (NTC) region. This prevents from setting a large optical window in the wall. Instead, an air-cooled endoscope (AVL MO0117, ϕ4, Hopkins linear lenses) was used with a wide field-view angle of 80 deg. Also, a water-cooled piezo-type pressure transducer (Kistler 601B) was equipped near the spark plug.

The initial temperature and pressure of charged mixture can be controlled by controlling both the wall temperature and the charging pressure. Followed by mixture charging, the spark ignition was made. As the flame propagation inside the chamber causes a compression of unburned gas, leading to increases in pressure and temperature of end-gas, the initial gas temperature and pressure were controlled to bring with a scheduled temperature of the end-gas. Preliminary experiments were carried out to achieve an auto-ignition at the end-gas and the experimental conditions are listed in Table 1. By using Ar gas as a diluent instead of N_2 to decrease the gas specific heat, the effect of raising gas temperature was enhanced. In this study, as the charging pressure was fixed, the mass of charged mixture was decreased with increasing the wall temperature.

3.2 EXPERIMENTAL METHOD

The prescribed mixture was prepared using a tank with a rotating fan, where fuel, oxygen and diluent are mixed and well stirred. The tank was kept warm to enhance the fuel evaporation and prevent from condensation. The wall temperature of the combustion chamber was controlled and the chamber was evacuated to charge the mixture up to the prescribed pressure. Spark-ignition was made to propagate the flame and compress unburned gas in the end-gas region. The temporal variations of pressure and outputs from two thermometers were recorded with a digital oscilloscope. The digitized data were transferred to a PC for analyses. Using the pressure value, the bulk temperature and apparent rate of heat release were estimated. The repeatability was confirmed by making three runs in each experimental condition.

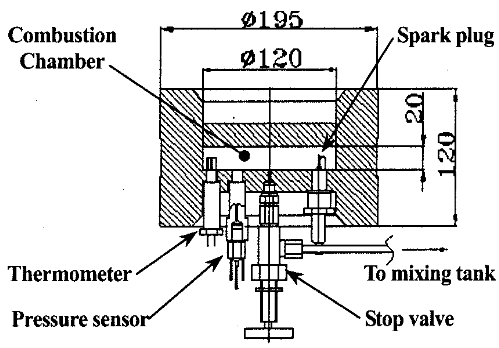

Fig. 2 Schematic of combustion vessel

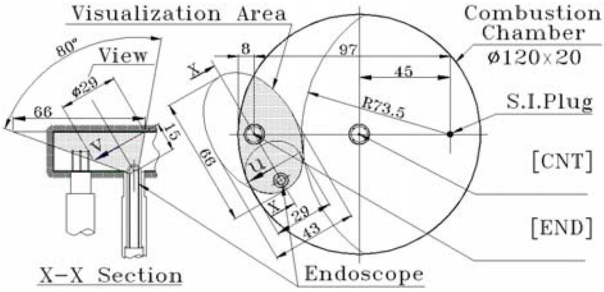

Fig. 3 Thermometer locations and visualized area through endoscope

Table 1　Experimental conditions

Fuel	n-Pentane
Oxidizer	O_2
Dilution Gas	Ar
O2 / Ar (vol. ratio)	40%
Equivalence ratio	0.35
Mixture State	Pre-mixed charge
Wall Temperature	307,323,373,423, 443,463,473,483, 493,503,513,518,[K]
Charge Pressure	0.3 [MPa]

4. DESIGN OF RCM

RCM (Rapid Compression Machine) enables to simulate engine combustion only once for compression stroke. This can cause easy measurements of physical properties by using sensors and optical visualization techniques. So far, many kinds of RCM are designed and built. In this study, Murase's system at Kyusyu university [7] was employed.

4.1 PRINCIPLE OF RCM OPERATION

The outline of RCM is shown in Fig. 4. RCM comprises main five units of pressure reservoir, driving, cam, compression and combustion. For operation, firstly, compressed air is charged in the reservoir tank. Secondly, a sharp pin operated by a solenoid smashes a barrier membrane. Thirdly, a piston in driving unit is driven by compressed air and the cam moves quickly. And then, another piston in compression unit is driven by rod that contacts the cam surface to realize a rapid compression of combustion chamber.

In RCM, the piston must start and stop quickly at TDC precisely with reproducible motion. To realize this, most RCMs employ very big power supply, but this RCM does not require big power supply because it has two moving directions as indicated in Fig. 4. The horizontal motion requires just a quick moving, while the vertical motion can be controlled by the profile of cam. Therefore, as any special mechanism to keep TDC position, which sometimes causes impulsive force and sound, is not needed, this RCM is superior to other systems in compactness.

For combustion analysis, dead volume should be decreased as small as possible because mixture in the dead volume causes strange affect on combustion pressure and visualized image. Thus, attaching a rotary valve in the passage reduced the dead volume of connecting passage between combustion chamber and mixture tank.

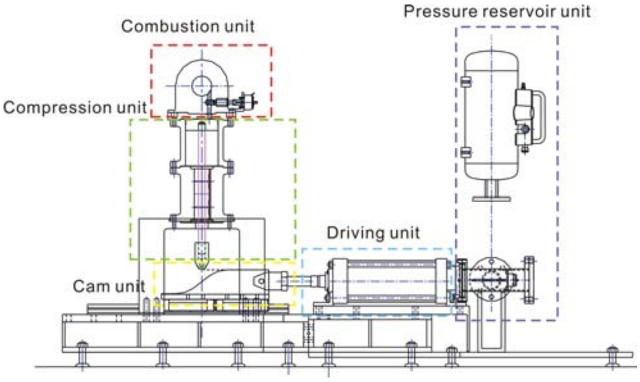

Fig. 4　Rapid compression machine

4.2 SPECIFICATIONS

The specifications are listed in Table 2. Figure 5 shows schematics of experimental apparatus. The piston position of combustion chamber is measured using a laser displacement meter. The gas pressure inside the chamber is detected using a piezoelectric sensor. The local gas temperature inside chamber was measured using three two-wired thermocouples including near wall location. Fuel and air are mixed using a tank with heater. The mixture is introduced to the combustion chamber.

Combustion period including compression period is 100 ms at most. In this duration, sequential operations such as smash of barrier membrane, onset of spark and closing connecting passage between combustion chamber and mixture tank and so on.

Table 2　Main specifications of RCM

Combustion chamber	φ80ｍｍ×16ｍｍ
Compression ratio	13
Compression cylinder	φ130mm×95ｍｍ
Compression cylinder for driving	φ160mm×330ｍｍ
Volume of reservoir tank	16Ｌ
Max pressure of reservoir tank	~ 0.5MPa

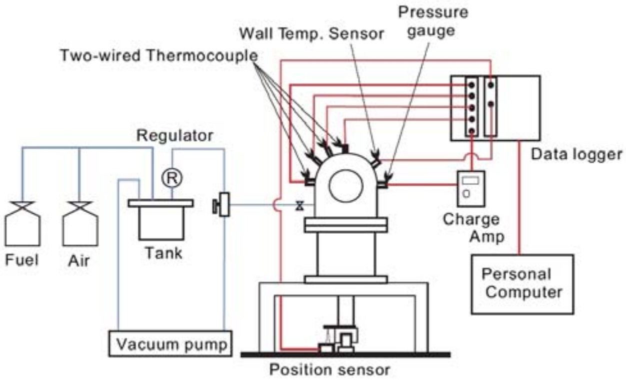

Fig. 5　Schematics of RCM apparatus

5. EXPERIMENTAL RESULTS USING CONSTANT-VOLUME CHAMBER

5.1 EFFECT OF INITIAL WALL TEMPERATURE ON PRESSURE WAVE

Experiments were performed by raising the wall temperature as indicated in Fig. 6(a). The combustion period becomes decreased as the initial temperature is increased. The reference time of zero in Fig. 6 is the spark-ignition timing. The combustion noise is indistinct sound, but it changes to an intense sound with raising the wall temperature. When the initial wall temperature was set at between 503 and 518 K, the pressure oscillation was observed with a frequency of 3.9 kHz. When the oscillation occurs, the pressure drop after the peak becomes large due to an increase in heat loss. Thus, knock was realized in a constant-volume chamber with flame propagation without piston compression. Moreover, increasing the initial wall temperature above 518 K caused auto-ignition before spark-ignition.

Here, the bulk temperature can be presumed using a pressure value assuming an adiabatic compression.

$$T_{bulk} = T_0 \, (P_0 \, / \, P \,)^{1/(\kappa\text{-}1)} \qquad (4)$$

The specific heat ratio, κ was set at 1.45. The estimated bulk temperature is indicated in Fig. 6(b). The effect of the initial wall temperature on pressure and bulk gas temperature can be observed in Figs. 6(a) and (b).

5.2 OBSERVATION IN KNOCK CONDITIONS

Figure 7 shows the results of pressure and temperature at a condition (wall temperature at 503 K) with knock. The estimated local temperatures at CNT and END are indicated in the upper figure. The measured local temperature accuracy after the flame passes by may become deteriorated as the gas velocity becomes small. Thereby, some part of the measured data is drawn in broken lines where the accuracy is estimated low. The pressure, bulk temperature and rate of heat release are shown in the lower figure. High-speed video images (8bit, 256x256 resolution, 4500 fps, with I.I. gated in 100 μs) are shown in Fig. 8. The view field of the endoscope is designated in Fig. 3 (X-X section). In each frame, the symbol ('a' to 'o') indicates the corresponding temperature and pressure in Fig. 7. Also, the number in parentheses indicates the time after spark timing in ms.

The local temperature at END sharply rises at 19.6 ms 'c', leading to a rapid increase from 700 to 3240 K. Pressure oscillation is observed and the first appearance of the peak coincides with that in temperature signal at 23 ms. This means that auto-ignition occurred in the end-gas region and that it was detected by both pressure and temperature. Before the flame propagation is completed, strong luminescence is observed from 20.7 ms. Rapid reactions seem to occur and the peak of heat release indicates a high value of 87 kJ/s.

In previous studies, "hot spot" is observed in the unburned region by LIF measurement of CH_2O [8], leading to the chance of auto-ignition before knock initiates. In this study, identification of CH_2O cannot be made, but highly illuminated spots in images ('j', 'k' and 'l') are probably equivalent to the "hot spot" in [8]. These spots disappear at 25.6 ms as soon as the heat release completes.

5.3 HEAT RELEASE PATTERN BY AUTO-IGNITION AT END-GAS REGION

In order to examine the effect of initial wall temperature on the combustion period and the heat release pattern, temporal variations of heat release are indicated in Fig. 9. When the wall temperature exceeds 520 K, instantaneous combustion occurs before spark-ignition as soon as the mixture is charged. Thereby, the maximum wall temperature was limited to 520 K where auto-ignition occurs in one minute or longer without spark-ignition after the mixture charge completed. The result with 530 K is shown in the figure for a reference.

The combustion period was 70 ms with the wall temperature of 307 K, while it was reduced to 24 ms with increasing the wall temperature to 503 K, leading to a steep heat release with knock (shown as 'a' in Fig. 9). According to a previous report using a production engine [9], reducing the knock intensity causes a drop of the heat release peak and also a double-humped heat release curve. This means that the first hump is due to the flame propagation while the second one is due to the auto-ignition.

In this study, the same tendency was found at 'c' and 'd' in Fig. 9 with the wall temperature of 463 K. When the initial wall temperature was set at between 373 and 518 K, the second peak due to the auto-ignition is found, but knock is detected only with a relatively high wall temperature of between 503 and 518 K. This result agrees with a previous study that auto-ignition does not necessarily induce knock [9].

5.4 RELATIONSHIPS BETWEEN UNBURNED GAS TEMPERATURE AND AUTO-IGNITION TIMING

The initiation of auto-ignition was defined as the time when the local temperature starts rising. The relationship between the unburned gas temperatures estimated by pressure and the initiation time of auto-ignition are plotted on the graph of Fig. 6(b). Black circles indicate results with knock while white ones do without knock. With increasing the wall temperature, the initiation timing of auto-ignition is once advanced, but then retarded. This shows that the temperature at the initiation time of auto-ignition has an upper limit. That is reasonable because other experimental or theoretical results show that hot flame appears at almost the same temperature.

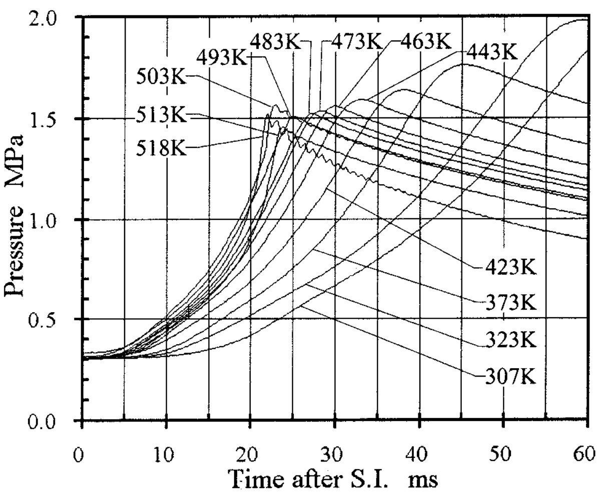

Fig. 6(a) Pressure histories in various wall temperatures

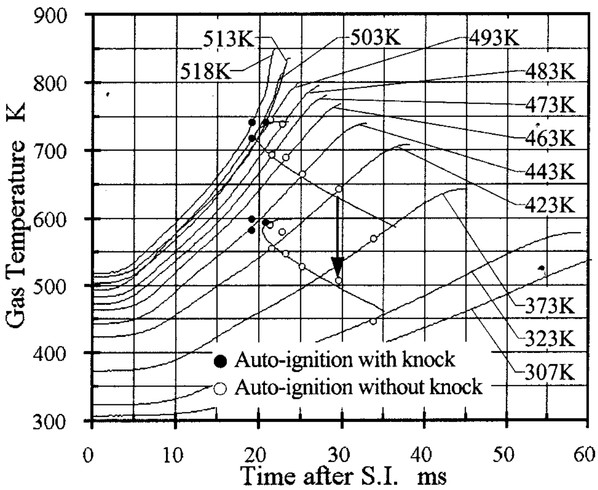

Fig. 6(b) Unburned gas temperature history in various wall temperatures

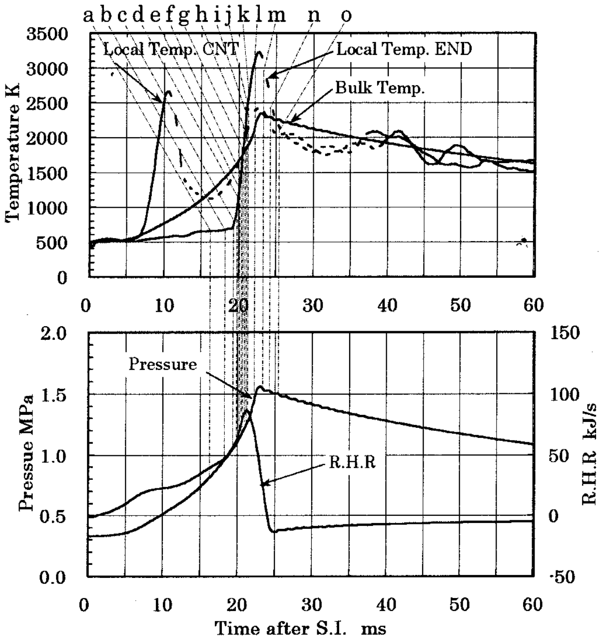

Fig. 7 Local gas temperature and pressure histories in knock condition (Wall Temp. 503 K)

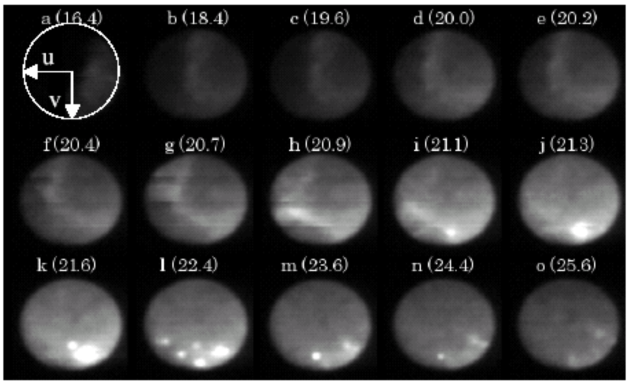

Fig. 8 High-speed photographs through endoscope observing in the end gas region with knock (Wall Temp. 503 K)

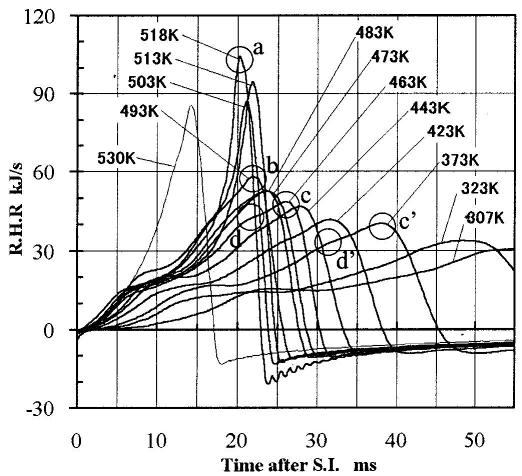

Fig. 9 Rate of heat release histories in various wall temperatures

Regarding the temperature at the initiation time of auto-ignition, the definition in this study is different from other results using RCM or shock-tube as auto-ignition occurs during compression accompanying with flame propagation in this study. Thereby, a mean gas temperature from the spark-ignition timing to the initiation of auto-ignition was estimated by integrating the instantaneous temperature along the time and then, dividing the value by the past time. Here, it might not be appropriate to use this "mean gas temperature" because chemical reactions are non-linear, but it is possible to examine the qualitative tendency. As a result, the mean gas temperature is almost 150 K less than that of the instantaneous temperature at auto-ignition as shown in Fig. 6(b) with an arrow. The tendency between the two was found almost the same.

Figure 10 indicates a relationship between the mean gas temperature and the initiation time of auto-ignition. A simulation result [10] is also plotted in this figure. The simulation definitely indicates that NTC is apparent using n-pentane as a fuel. From this figure, raising the mean gas temperature between 580 and 600 K, a delay of auto-ignition is observed, corresponding to NTC. In this study, knock occurred at 582 ~ 598 K. In this region, auto-ignition without knock was also observed. It should be noted that when knock occurs, the auto-ignition time seems slightly early compared to the results without knock. As the high-speed images and previous studies showed, several "hot spots" were randomly found in the end-gas region before auto-ignition occurs. The initiation time earlier in knock conditions is due to that many hot spots, namely higher inhomogeneity, cause early initiation of auto-ignition stochastically, leading to spatially many auto-ignition points one after another and increasing the pressure and temperature very rapidly with a synergic effect of having a higher volume ratio of unburned mixture.

6. PRELIMINARY RESULTS USING RCM

As a preliminary experiment, rapid compression was made without combustion. Local gas temperature measurements were carried out at three locations 2 mm left from the wall. The results are indicated in Fig. 11. Raw temperature data from two thermocouples, an estimated temperature which was deduced from two raw data by estimating the time constant, a corrected temperature [11] which was compensated by considering ambient gas velocity and its density and bulk temperature which was estimated from pressure value are plotted. Also, pressure data is plotted in the figure. The timing of maximum temperature of estimated, corrected and bulk is almost the same, but that of raw date is delayed due to slow response.

Regarding the maximum temperature, only corrected one indicates almost the same value as the bulk temperature. It was found that the estimated temperature using two-wired thermocouples is not enough to estimate real gas temperature because the gas temperature around the thermocouples is different to that without thermocouples. That is, the gas temperature is changed due to an existence of thermocouples as solid thermocouples absorb a large quantity of heat from the ambient gas.

As the next step, measurements of local gas temperature, pressure and visualization will be carried out in non-knock and knock conditions to clarify the effect of NTC region on knock occurrence.

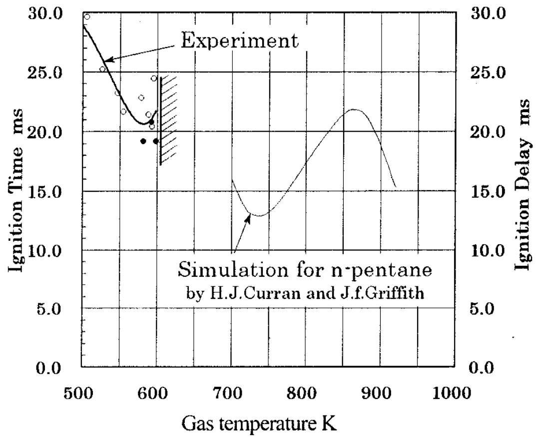

Fig. 10 Temperature dependence of ignition time (this work) and ignition delay (theoretical study)

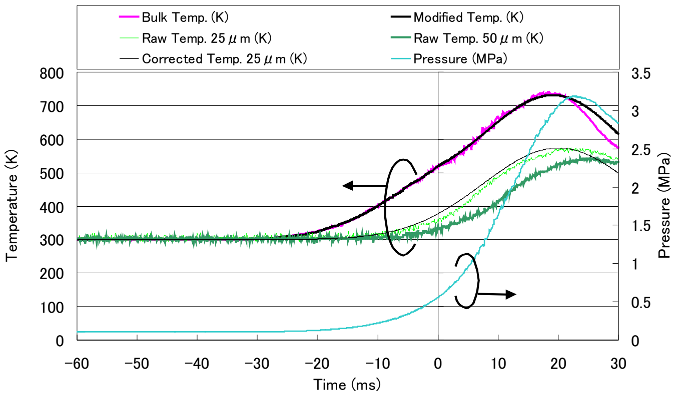

Fig. 11 Temporal variations of temperature and pressure in RCM

7. CONCLUSIONS

1. By controlling the initial wall temperature of a constant-volume chamber at between 307 and 518 K, combustion of n-pentane, oxygen, and argon mixture was examined. As a result, auto-ignition with knock was realized in a pancake chamber with flame propagation by adjusting spark plug location, mixture component and initial wall temperature at between 503 and 518 K.

2. Auto-ignition was detected at the end of combustion period with initial wall temperature at between 373 and 518 K. The initiation of auto-ignition does not necessarily cause knock phenomenon as some additional conditions are required. There found a relationship similar to "negative temperature coefficient" between the initiation times of auto-ignition and mean gas temperature when the mean gas temperature was between 580 and 600 K.

3. As the next step, combustion tests under engine-like condition are required. To meet this, RCM was designed and built. Local gas temperature measurement without combustion was carried out at three locations 2 mm left from the wall. As a result, the estimated temperature using two-wired thermocouples is not enough to measure real gas temperature because the gas temperature around the thermocouples is different from that without thermocouples. Only corrected temperature, which was compensated by considering ambient gas velocity and its density could show a good agreement with the bulk temperature estimated from pressure value.

ACKNOWLEDGEMENT

The authors would like to appreciate Mr. S. Kobayshi's experimental work and also to thank the staff of Enomoto Lab., at Musashi Inst. of Tech. who gave useful help to make thermometers and also the related companies who supplied mechanical parts and measurement devices.

REFERENCES

(1) Halstead, M. P., Kirsch, L. J., Prothero, A., and Quinn, C. P., Proc. Roy. Soc. London ,A346 (1975), p.515.
(2) Y.Ohta and M.Furutani, Polish Academy of Sciences, vol.11, ,No.1-2 (1991),p.43-52
(3) Senda et al, Trans. of the JSAE, Vol.29, No.3 (1998), pp.11-15.
(4) Borje Grandin, Ingemar Denbratt, SAE Paper No. 2000-01-2831
(5) Tagawa,M.,Okuda,M.,Ohta,Y., Trans. Jpn. Soc. Mech. Eng, Vol.62B, No.598 (1986), p.2506-2512.
(6) Kobayashi,S., Moriyoshi,Y., Enomoto, Y., "Auto-ignition of Premixed Mixture Using a Constant Volume Vessel", Prepr. of 17th Sympo. of the Int. Comb. Eng. (2002), p.89-94.
(7) Murase, E., Performance of Pulsed Combustion Jet in a Rapid Compression Machine, Archivum Combustionis Vol.15, No.3-4 (1996) pp.173-185
(8) J.Warnatz, Combustion, Springer, p.217-218.
(9) B Grandin, Int J Engine Reserch, Vol3, No4 (2002), p.209-221.
(10) C.K.Westbrook, Kinetic modeling of hydrocarbon autoignition at low and intermediate temperature in a rapid compression machine,3rd Workshop on Modeling of Chemical Reaction Systems (1996).
(11) Choi, S., Moriyoshi, Y., JSAE No. 20055451