Development of Instantaneous Surface Temperature Sensor for Reduction of Heat Losses in Internal Combustion Engines

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***Abstract*— In this research, thin-film temperature sensor (thin-film thermocouple) was directly formed on the surface of combustion chamber of a Rapid Compression and Expansion Machine(RCEM) which imitated the internal combustion engines using a PVD (physical vapour deposition) method, and it aims at high accurate and high response measurement of instantaneous temperature change from a compression stroke to a combustion start timing. In this paper, the newly developed structure and form of thin-film thermocouple was described using one-dimensional numerical calculation in order to reduce the measurement error for real surface temperature. Moreover, the example measurement results of instantaneous temperature using RCEM were reported.**

***Keywords*— Instantaneous Temperature Measurement Method, Thin-Film Thermocouple, Combustion Chamber Wall**

I. Introduction

In recent years, an improvement in thermal efficiency of internal combustion engines have been requested for the correspondence to an environmental problem. Especially engine heat losses over the wall from the combustion gases has big influence on thermal efficiency, reduction of heat losses is very important. In recent years, heat insulation layer is formed on the wall surface of the combustion chamber, and it has been reported that it is possible to reduce the heat losses with control the knocking and improvement the intake efficiency [1][2]. In order to realize the optimization of combustion and to develop the exact numerical model of heat losses, it is important to measure the wall temperature of various places in a combustion chamber with high accurate measurement method and system. In this study, thin-film temperature sensor (thin-film thermocouple) was formed on the engine combustion chamber surface directly by sputtering method, and the sensor which can measure instantaneous temperature with high accuracy and high response.

This paper was reported the newly developed thin-film temperature sensor with respect to the structure and shape of the sensor by using numerical analysis results. Moreover, the example results of measured instantaneous temperature using Rapid Compression Expansion Machine (RCEM) were reported.

II. Shape and Structure of Temperature Sensor and Optimization Using by Numerical Analysis

A. Selection of materials

As for the measurement principle of thin-film temperature sensor, thermocouple method which changes thermal electromotive force was used. In order to measure the instantaneous temperature with high precision and high compatibility, thermocouple materials standardized by Japanese Industrial Standard (JIS) was adopted. Table 1 shows the main JIS standard thermocouple materials, and Table 2 shows their temperature tolerance and limit temperature. R, S and T types have high accuracy and high heat-resistant temperature. However, materials of platinum and copper have lower adhesion strength than the other thermocouple material (especially K type) when platinum and copper are made into thin-film by using PVD (sputtering method). Therefore, thin-film temperature sensor was used K-type thermocouple with having high adhesion strength and high heat resistance.

B. Structure and shape

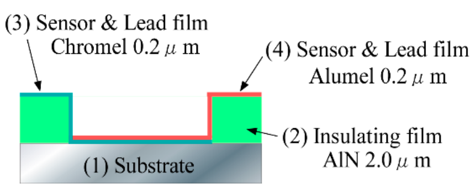
Fig. 1(a),(b) shows the structure and shape of newly developed thin-film temperature sensor. AlN (2) (2μm in thickness) was formed on the substrate (1) in order to insulate between a sensor, lead film and a substrate. After that, the chromel (3) (0.2μm) of primary K-type thermocouple material was formed, and finally the alumel (4) (0.2μm) of secondary material was formed. In order to perform highly accurate instantaneous temperature measurement, the hot junction was formed directly on the substrate surface (ring in RCEM, see figure 10 and 11) without forming the insulating film. The size of hot junction was 50μm×50μm, and insulating film was formed with the minimum line width of 100μm for taking out the signal to the ring (parts of RCEM) outside using lead film.

Table 1 JIS thermocouple materials

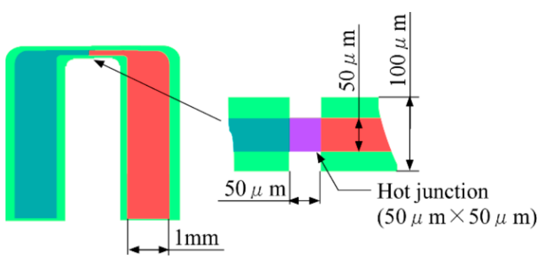
Type	Material (+)	Material (−)
R	Platinum - rhodium alloy (Including 13% of rhodium)	Platinum
S	Platinum - rhodium alloy (Including 10% of rhodium)	Platinum
K	Chromel	Alumel
E	Chromel	Constantan
J	Iron	Constantan
T	Copper	Constantan

Table 2 Accuracy and durability of JIS thermocouple

Type	Temperature tolerance	Limit temperature
R	±1.0K	1400K
S	±1.0K	1400K
K	±1.5K	650K
E	±1.5K	450K
J	±1.5K	400K
T	±0.5K	200K



(a) Structure of thin-film temperature sensor



(b) Sensor form

Fig. 1 Newly developed thin-film temperature sensor

C. Temperature – thermal electromotive force calibration

The ring with thin-film sensors was placed in an electric furnace, the thermal electromotive force with respect to the temperature was measured. As result, 40.5μV/K thermal electromotive force was obtained, and this result was mostly in agreement with conventional JIS K-type thermocouple (41.0μV/K) as shown in Fig. 2.

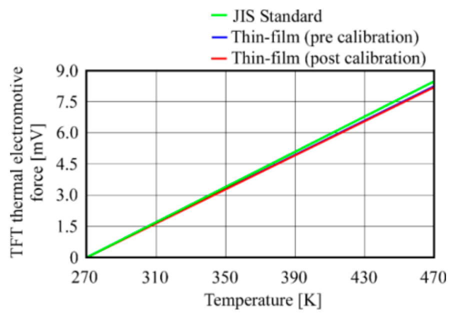


Fig. 2 Temperature – thermal electromotive force calibration

D. Analysis conditions

In order to evaluate the structure and shape of the newly developed thin-film temperature sensor, it was performed numerical analysis of wall temperature distribution. Fig. 3 shows the in-cylinder pressure (P) and the gas temperature (T_g) and the heat transfer coefficient (h_g) of test 4-cycle gasoline engine. T_g was calculated from equation of state of ideal gas, h_g was determined in reference to the equation of Woschni [4]. Table 3 shows the thermal property values of each material used in the analysis [5][6].

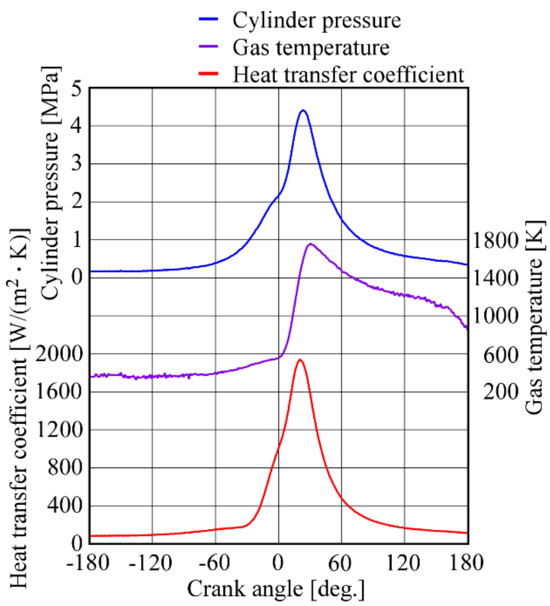


Fig. 3 Analysis conditions

Table 3 Thermal property values

	Thermal conductivity [W/m・K]	Thermal diffusivity [m²/s]
Aluminum alloy	109	40.7×10^{-6}
Chromel	13.8	3.74×10^{-6}
Alumel	29.6	8.27×10^{-6}

E. Analysis method

One-dimensional unsteady heat conduction equation of Fourier (1) was used to determine the wall temperature distribution [7];

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial x^2} \quad (1)$$

If it approximates by difference by fixing a heat physical properties value, the following equation of differential approximation is obtained;

Wall surface (I=1)

$$T(I,J+1) = T(I,J) + \frac{2\alpha\Delta t}{\lambda\Delta x} h_g(J)[T_g(J) - T(I,J)] + \frac{2\alpha\Delta t}{\Delta x^2}[T(I+1,J) - T(I,J)] \quad (2)$$

Wall inside (1<I<N)

$$T(I,J+1) = T(I,J) + \frac{\alpha\Delta t}{\Delta x^2}[T(I+1,J) + T(I-1,J) - 2T(I,J)] \quad (3)$$

Further, the wall temperature at the interface of different properties materials is given by the following equation.

$$T(I,J+1) = T(I,J) + \frac{2\alpha_1\alpha_2\Delta t}{\lambda_1\alpha_2\Delta x_1 + \lambda_2\alpha_1\Delta x_2}[\frac{\lambda_2}{\Delta x_2}T(I+1,J) + \frac{\lambda_1}{\Delta x_1}T(I-1,J) - \frac{\lambda_1\Delta x_2 + \lambda_2\Delta x_1}{\Delta x_1\Delta x_2}] \quad (4)$$

N: Wall back (It was 350K constant.)
$T(I,J)$: Wall temperature in time J and depth I [K]
$h_g(J)$: Heat transfer coefficient at the time J [W/(m^2 · K)]
$T_g(J)$: Gas temperature at the time J [K]
α: Thermal diffusivity [m^2/s]
λ: Thermal conductivity [W/(m · K)]
Δt: Time interval [s] (The time between J and J+1)
Δx: Depth interval [m] (The distance between I and I+1)

This differential approximation equation must satisfy the stability condition (5), because it is explicit equation.

$$\frac{a\Delta t}{\Delta x^2} \leq \frac{1}{2} \quad (5)$$

A stability condition is not satisfied directly although cylinder pressure is recorded every 0.5degree crank angle, therefore Δt was set to satisfy a stable condition by performing a linear interpolation.

F. Analysis model

Fig. 4 shows the number of divisions of the newly developed sensor. The place which should measure temperature is the surface of substrate. Therefore, it was considered as the structure without the insulation film of conventional temperature sensor. For this reason, hot junction of this sensor structure is contact area of the film of chromel and alumel (boundary temperature between chromel and alumel film).

G. Analysis result (the influence of the thickness of the sensor)

The temperature of hot junction by the difference in each film thickness was calculated and it compared with the temperature on the surface of solid plate (true value). The analysis was carried out when the film thickness of alumel and chromel of hot junction part was changed into 0.2, 1, 10, 20, 30μm. Fig. 5 shows the analysis results. According to the increase in film thickness, each error increased as compared with the true value. Moreover, in the case of 30μm film thickness, crank angle of maximum temperature was delayed compared to the solid plate. It can be determined that the delay due to the thermal diffusion of the alumel. On the other hand, the temperature error is reduced by thinning the sensor film thickness. In this experiment considering the durability of the thin film, the sensor film (chromel, alumel) thickness was judged to 0.2μm respectively is reasonable.

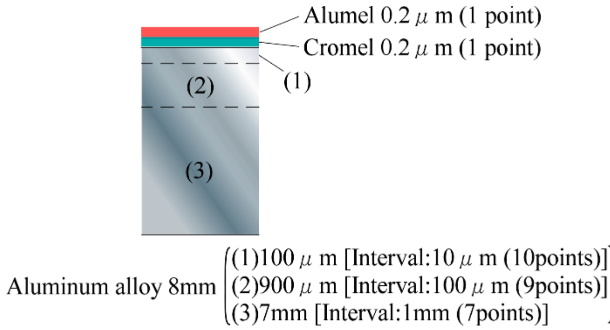


Fig. 4 Analysis model

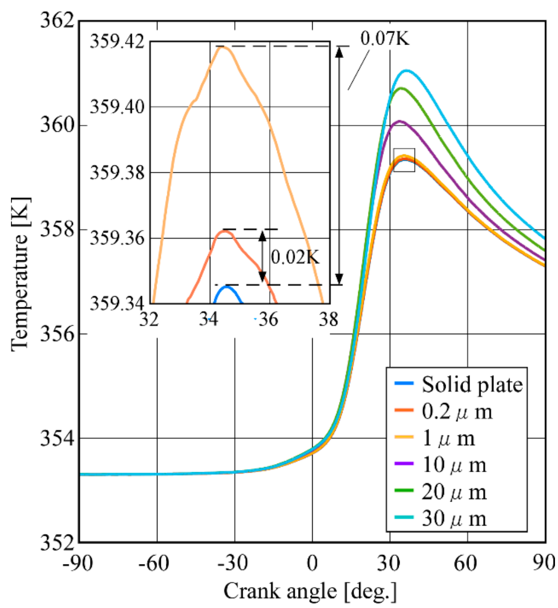


Fig. 5 Wall temperature by sensor film thickness

H. Investigation of thermal property value of thin-film

The thermal conductivity and thermal diffusivity of thin films has been reported to differ from the bulk value [8]. Therefore, the thin film thermal physical properties of chromel and alumel (each 0.2μm) was measured using a thermo-reflectance method. Furthermore, it was also measured physical property values in the case of changing the temperature (290K, 370K, 470K, 570K). Fig. 6 shows the results of thermal conductivity of thin films and bulk of chromel, and Fig. 7 shows the results of their alumel. As the result of these experiment, the thermal conductivity values of chromel and alumel film are higher than that of the bulk properties. It is considered that the crystal structure of materials were changed by sputtering, it is necessary to proceed with these analysis in the future.

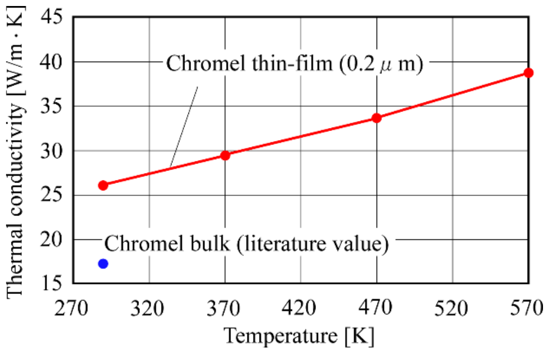


Fig. 6 Thermal conductivity of chromel

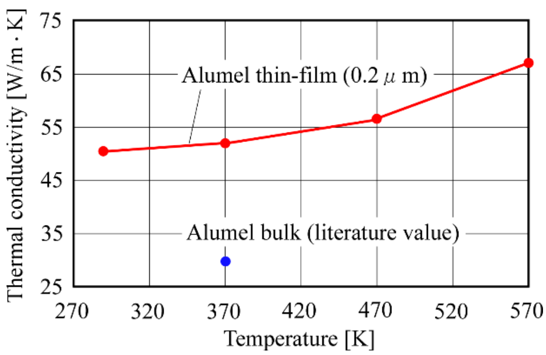


Fig. 7 Thermal conductivity of alumel

I. *Analysis result (the influence of heat conductivity of the thin film and bulk)*

For confirming the effect of the thermophysical properties of the thin film was subjected to numerical analysis by using measurements results. Fig. 8 shows the analysis result of the wall temperature in the case of using the thermophysical properties of bulk and thin film, and the results of wall temperature of the solid plate. In case of using the bulk physical property values temperature error value increased 0.02K in maximum in comparison with the solid plate. On the other hand, in case of using the thin-film physical property values, the temperature error reached 0.05K in maximum temperature error. From this result, it was confirmed that the measurement accuracy is sufficient in heat loss evaluation of this study.

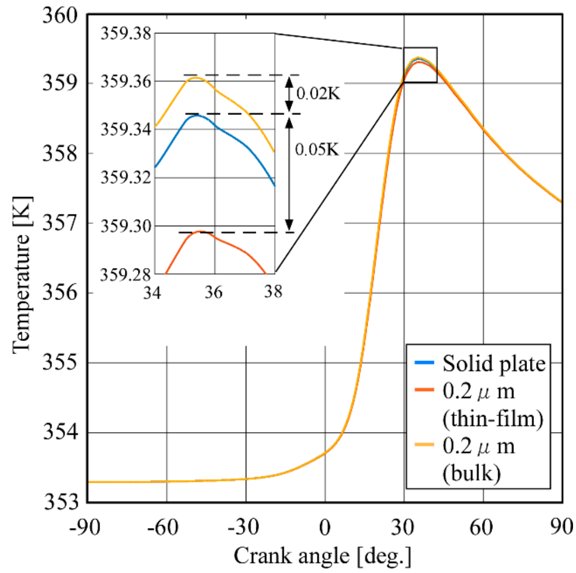


Fig. 8 Wall temperature by heat conductivity of the thin film and bulk

III. The Example Results of the Measurement of Instantaneous Temperature Using RCEM

J. *Experimental device*

Fig. 9 shows the rapid compression expansion machine using in this experiment, Fig. 10 shows configuration diagram of RCEM combustion chamber. This device is testable device of compression and expansion stroke of the engine to drive the piston by hydraulic pressure. Table 4 shows the specifications of this device. The piston was fixed to the top dead center (TDC), after that, constant volume combustion was performed by fuel injection directly into the combustion chamber. A part of the cylinder liner of the combustion chamber(1) is removable ring-shaped part(2), and thin film temperature sensor was formed on the inner surface of the ring. Furthermore, the pressure in the combustion chamber measured by pressure sensor(3) mounted to the bottom of combustion chamber. Ring material was used chromium-molybdenum steel (SCM) in this experiment. For optical measurement of the combustion flame in the combustion chamber, it was possible to do the high-speed shooting of the spray flame by placing the visualization glass(4) set to the head part.

K. *Experimental conditions*

In this experiment, it was the wall temperature of RCEM to 430K constant using the heater (Fig. 10(5)) before the start of the experiment. Injector is attached to the top (Fig. 10(6)) of the combustion chamber, and the injection angle is set to vertically downward. Table 5 shows the experimental conditions. Method of measuring the instantaneous temperature was amplified thermal electromotive force from the thin-film temperature sensor by DC amplifier of response frequency 600kHz, and data were recorded by the logger. For reducing noise from the power supply of the experimental device was driven all the measurement system by uninterruptible power supply battery type (UPS). Its formation positions of the newly developed sensor are 90 ° (1) and 30 ° (2) position with respect to the vertically downward as shown in Fig. 11.

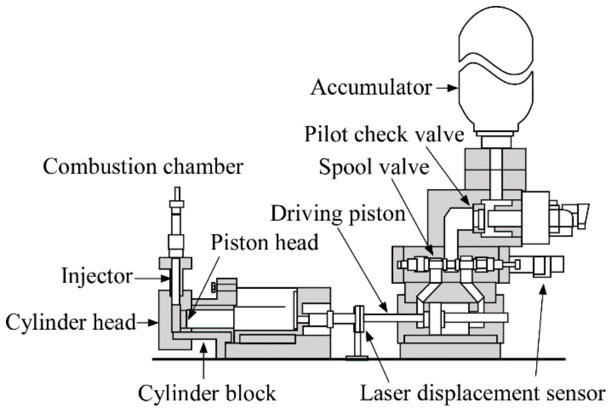


Fig. 9 Schematic of the RCEM

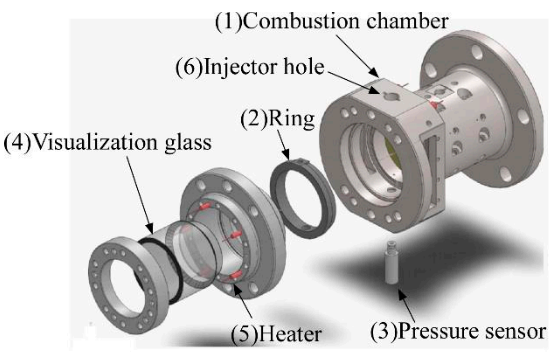


Fig. 10 Configuration diagram of RCEM combustion chamber

Table 4 RCEM specifications

Bore × Stroke [mm]	92 × 151.5
Displacement [cc]	1167
Clearance volume [cc]	160
Compression ratio [-]	7.3:1

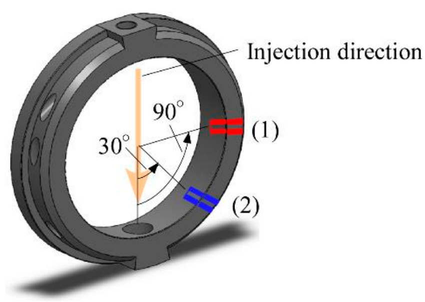


Fig. 11 Measurement position of newly developed thin-film temperature sensor

L. *Experimental results*

Fig. 12 shows the experimental results. The curve(1) and (2) shows the wall instantaneous temperature measured by newly developed thin-film temperature sensor and the bottom curve shows the combustion chamber pressure. As the results of the measurement, the temperature detected by sensor(2) was rising faster than the sensor(1), because the timing of flame reaches to the sensor. With regard to the maximum temperature, sensor (1) reached to15K. On the other hand, sensor (2) reached to 45K. From this result, it was confirmed that new temperature sensor is capable of measuring the instantaneous wall temperature.

Table 5 Experimental conditions

Nozzle diameter [mm]	0.125
Injection pressure [MPa]	150
O2 concentration [%]	21
Equivalence ratio [-]	0.1
Initial pressure [MPa]	0.3
Wall temperature [K]	430
Fuel amount [mg]	17.86
Injection duration [μ s]	2528

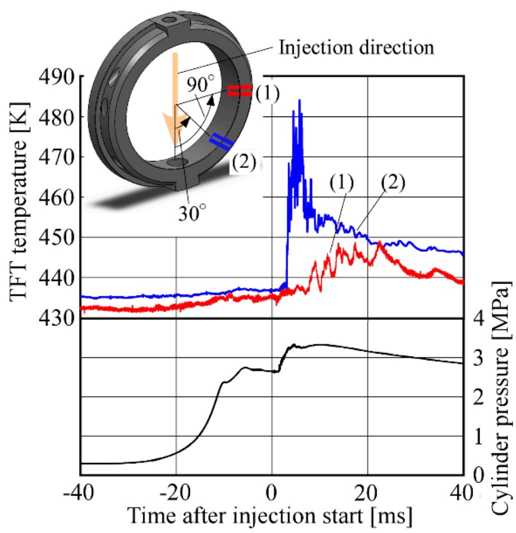


Fig. 12 Wall temperature and cylinder pressure

IV. CONCLUSIONS

(1) Thin-film thermocouple formed on the surface of combustion chamber to measure the surface temperature for investigating the heat losses are successfully developed by using physical vapor deposition (sputtering method).

(2) The temperature-output characteristic of newly developed thin-film thermocouple has good agreement compared with conventional thermocouple of Japanese Industrial Standard.

(3) The temperature of hot junction by the difference in each film thickness was calculated using one-dimensional numerical calculation in order to reduce the measurement error for real surface temperature.

(4) The film thickness of alumel and chromel of hot junction part was changed into 0.2, 1.0, 10,20,30 µm. According to the increase in film thickness, each error increased as compared with the true value.

(5) Thermal physical properties of chromel and alumel film (each 0.2µm) was measured using a thermo-reflectance method. Furthermore, it was also measured physical property values in the case of changing the temperature (290K, 370K, 470K, 570K).

(6) The thermal physical properties of chromel and alumel thin-film (each 0.2µm) were measured using a thermo-reflectance method. As the result of these experiment, the thermal conductivity values of chromel and alumel film are higher than that of the bulk properties.
(7) As the results of the temperature measurement using RCEM, the instantaneous temperature was successfully detected by newly developed thin-film thermocouple.

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