Heat Losses during Knocking in a Four-Stroke Gasoline Engine*

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Knocking in internal combustion engines causes various problems such as increase in thermal loads, abnormal wear and the deterioration of performance. Even the mechanism of thermal loads alone has not been clarified yet. In this study, therefore, instantaneous temperatures on piston top surfaces of a four-stroke gasoline engine during knocking, caused by changing the spark timing and octane number, have been measured using highly accurate thin-film thermocouples. Conditions of heat losses dependent on the knock intensity have been clarified from the instantaneous heat fluxes and coefficients of heat transfer determined from measurements.

Key Words: Internal Combustion Engine, Gasoline Engine, Heat Transfer, Instantaneous Heat Flux, Knocking, Piston, Heat Transfer Coefficient, Thin Film Thermocouple, Gas Temperature

1. Introduction

Knocking in a gasoline engine is a phenomenon of large pressure waves undergoing reciprocating motions in the combustion chambers, caused by the sudden pressure rise due to the spontaneous combustion of end gas⁽¹⁾. The degree of problems caused by knocking differs according to the knock intensity, but knocking generally results in abnormal temperature rise on the combustion chamber walls⁽²⁾, abnormal wear⁽³⁾ and heat loss^{(4),(5)}, for example. With regard to the heat losses, Woschni and Fieger⁽⁶⁾ arrived at the conclusion that the local heat loss around the knock zone increases only slightly, and that the problems caused by knocking were due to mechanical loads rather than the thermal loads, according to their

experiments carried out with thin-film thermocouples embedded in the cylinder head and to measure the instantaneous wall surface temperatures for the determination of heat transfer coefficients. Harigaya et al.⁽⁷⁾ also measured the effect of knocking on the temperature rise of combustion chamber wall surfaces and the effect of ignition timing on the knock intensity in a side-valve gasoline engine, and reported that the maximum heat flux and time-averaged heat flux hardly changed as long as the knock intensity stayed below a certain value, though the heat flux increased after the knock intensity exceeded such a value.

We previously found, in the measurement of the steady-state temperature of combustion chamber wall surfaces with knocking, that the temperature rise was not only at the local zone but also on all combustion chamber wall surfaces⁽²⁾. It was also found from the unsteady, i.e., instantaneous temperature measurement that the wall surface temperature became higher as the heat transfer coefficient of all wall surfaces became greater, which resulted in a greater amount of heat loss in the working cycle alone^{(4),(5)}. In this study, therefore, the instantaneous temperature on a piston

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top surface of a four-stroke gasoline engine during knocking was measured by means of highly precise thin-film thermocouples^{(8),(9)}, while varying the ignition timing and the octane number of gasoline, in order to determine the relationship between the knock intensity and heat loss characteristics.

2. Test Equipment and Measuring Method

A water-cooled four-stroke engine with four cylinders, bore $\times$ stroke = 83 $\times$ 83.6 mm, total engine displacement = 1 809 cc and compression ratio of 8.8 : 1 (CA 18 S engine made by Nissan) was used as the test engine, and the measurement was performed on the first cylinder piston.

The thermocouples described in Refs. (4) and (5) (Loex-constantan thin-film thermocouples using Loex as the base material) were used in the measurement.

Figure 1 shows the measuring locations on the piston top surface. Locations of the spark plug and intake/exhaust valves on the corresponding cylinder head are shown in the dotted areas. Although the test engine was basically a two-point ignition-type engine, the ignition was induced only by the spark plug shown in the figure, under the full-load condition. The temperature measurement was done at two points: one at the piston top center and the other point 2 in the knocking zone near the cylinder wall away from the spark plug. The engine was always operated at the speed of 2 000 rpm with full throttle (under full load). During the engine operation, the coolant temperature at the engine outlet and the lubricating oil strainer inlet temperature were kept constant at 80°C and 90°C, respectively. Strands of thermocouple wires from the piston were led out of the engine by means of linkage devices⁽²⁾. The thermocouples were shielded for the prevention of electric noise, and the thermoelectromotive force caused by the temperature difference between the hot and cold junctions was amplified by a direct-current amplifier and recorded

by a data recorder. Cold junction temperatures were recorded on dot printers, and the combustion pressure was measured using KISLER-601 A. The knock intensity was defined⁽¹⁾ as the maximum amplitude of pressure vibration caused by knocking. As shown in Fig. 2, the vibrational component of the combustion pressure P was taken out by 2 to 14 kHz band-pass filters, and maximum amplitude was assumed as the knock intensity K_i .

3. Measured Results

Figures 3 (a) and (b) show the effects of ignition timing (test fuel: RON-91) and the octane number (ignition timing: 17° BTDC) on the surface instantaneous temperature T and the combustion pressure P at measuring points 1 and 2 on the piston top, at the engine speed of 2 000 rpm with full throttle. The cold junction temperature T_c and the knock intensity K_i are also shown in the figure. One division is 5 K and 2 MPa, respectively. Looking at the effect of the ignition timing shown in Fig. 3 (a), it is found that the flame of normal combustion propagates in the order of point 1 to 2, and the temperature begins rising also in that order at MBT. In case where the ignition timing lags behind MBT, the surface temperature amplitude becomes smaller. Since the combustion is also delayed in such a case, the start of temperature rise at each measuring point is delayed as well. It is found from the figure that knocking occurs ($K_i=0.13$ MPa) when the ignition timing is advanced by 5° (22° BTDC), and the temperature at measuring point 2 within the knocking zone starts rising as soon as knocking occurs. At measuring point 1 closer to the spark plug, however, the temperature starts rising earlier than the point 2 since the flame of normal combustion reaches there prior to the occurrence of knocking, and the temperature amplitude remains practically the same as in normal combustion even if slight knocking occurs. In the case where the ignition

Fig. 1 Measurement locations on piston

Fig. 2 Combustion chamber pressure and vibration wave under knocking conditions

timing is advanced further by 10° (27° BTDC, $K_i=0.3$ MPa) and 15° (32° BTDC, $K_i=0.8$ MPa), the knock intensity becomes higher and the temperature amplitudes at both measuring points 1 and 2 also become greater in proportion to the knock intensity, as shown in the figure. At 32° BTDC, in particular, where the ignition timing is advanced by 15° , the temperature amplitudes at both measuring points 1 and 2 are about twice greater than those at MBT.

Looking at the effect of the octane number shown in Fig. 3(b), the temperature amplitude becomes greater in proportion to the knock intensity, as in the case of Fig. 3(a). When slight knocking ($K_i=0.15$ MPa) occurs with use of RON-84, the temperature at measuring point 2 rises simultaneously, which is the same as the result at 22° BTDC shown in Fig. 3(a). This tendency becomes more significant with use of RON-77 (0.6 MPa) with a higher knock intensity, and it is confirmed that the temperature at measuring point 1, in particular, rises further with knocking

subsequent to the initial temperature rise caused by the arrival of the normal combustion flame. This phenomenon is also seen at other zones on the wall surface. Looking at the cold junction temperature T_c , it is found that the temperature rises in proportion to the knock intensity, as shown in both (a) and (b) of Fig. 3.

Figure 4 shows the instantaneous heat flux q at measuring point 1. The inside wall temperature distribution is calculated from ΔT_θ and the cold junction temperature T_c at each crank angle with the temperature waveforms shown in Fig. 3, using a differential equation developed by the authors⁽¹⁰⁾ taking account of the temperature dependency of thermal properties of the combustion chamber wall material. The instantaneous heat flux q is then calculated by the following differential equation, according to the calculated values of the temperature $T(2, K)$ at the inner portion from a very shallow depth of Δx from the surface, and the measured values of surface instantaneous

Fig. 3 Results of measurements of instantaneous temperature at points 1 and 2 on piston under each operating condition

temperature $T(1, K)$ (denoted as T in Fig. 3).

$$q(K) = \frac{\lambda_1}{\Delta x} \{T(1, K) - T(2, K)\} + C_1 \rho_1 \frac{\Delta x}{2} \cdot \frac{\{T(1, K+1) - T(1, K)\}}{\Delta \tau} \quad (1)$$

$T(1, K)$: surface temperature at time K

$T(2, K)$: temperature at depth Δx and time K

$T(1, K+1)$: surface temperature after $\Delta \tau$ from time K

$\Delta \tau$: time dividing width (time between K and $K+1$)

Δx : depth dividing width

λ_1 : thermal conductivity between surface and depth Δx

C_1 : surface specific heat

ρ_1 : surface density

Looking at the effect of ignition timing shown in Fig. 4(a), it is found that the peak value becomes greater and q starts rising earlier as the ignition timing is advanced. For the effect of octane number shown in Fig. 4(b), q starts rising nearly at the same timing, and the rising rate is also about the same among different test fuels. In the case of RON-84 and 77, inflection points appear as soon as knocking occurs, and q starts rising again.

Figure 5 shows the test results for measuring point 2. Due to the sharp temperature rise caused by knocking, both the q rising rate and the peak value are higher in Figs. 5(a) and (b) than those at measuring point 1. The drop of q is also smaller. Regarding the effect of ignition timing, it is found that the occurrence of the q peak and the q rise initiation

timing are advanced in proportion to the ignition timing. Results in Figs. 4 and 5 show that the heat flux flowing into the piston wall surface (i.e., heat loss) during the working stroke (from the top dead center to 180°) is increased by knocking.

Figure 6 shows the heat flux flowing into the piston for each stroke and the knock intensity. As for the effect of ignition timing shown in Fig. 6(a), it is found that the heat loss in the compression stroke increases as the ignition timing advances, but the heat loss during the working stroke is greater. At 32° BTDC, the heat loss during the working stroke is greater than the total heat loss during a cycle. As for the effect of octane number shown in Fig. 4(b), it is found that the heat loss during the working stroke increases sharply as the octane number becomes smaller. Since the ignition timing is kept constant (at MBT) in this case, the heat loss during the compression stroke becomes smaller as the knock intensity becomes higher, contrary to Fig. 6(a). With RON-77, the heat loss during the working stroke is greater than the total heat loss during a cycle. It is also found that the effect of the octane number is greater than the effect of ignition timing shown in Fig. 6(a), and the heat loss during the working stroke is greater than the latter, even though the knock intensity is lower.

Figure 7 shows the heat flux flowing into the piston for each stroke and the knock intensity. Although the tendency is similar to that at measuring point 1 shown in Fig. 6, the heat loss during the working stroke and the total heat loss during a cycle

(a) Effect of ignition timing

(b) Effect of research octane number

Fig. 4 Instantaneous heat flux at measuring point 1 (piston center)

are smaller in both Figs. 7(a) and (b). Judging from Figs. 6 and 7, it is found that the heat loss during the working stroke is greater than the total heat loss during a cycle when the knock intensity exceeds a certain value.

Figure 8 shows the combustion gas temperature calculated by a state equation of gas, according to the combustion pressure P measured under the conditions shown in Fig. 3.

The local heat transfer coefficient α_g is calculated

(a) Effect of ignition timing

(b) Effect of research octane number

Fig. 5 Instantaneous heat flux at measuring point 2 (knocking zone)

(a) Effect of ignition timing

(b) Effect of research octane number

Fig. 6 Mean heat flux flowing during each stroke at measuring point 1 (piston center)

by the following equation, from measured values of the surface instantaneous temperature T , instantaneous heat flux q and the combustion gas temperature $T_g^{(11)}$.

$$\alpha_g = q / (T_g - T) \quad (2)$$

Figure 9 shows the local heat transfer coefficient

α_g at measuring point 1 at the piston top center. The mean heat transfer coefficient α_g at crank angles of 30 to 180° is also shown. The highest heat transfer coefficient is found during the working stroke, where high-intensity knocking occurred.

Empirical equations established by Woschni^{(12),(13)}

(a) Effect of ignition timing

(b) Effect of research octane number

Fig. 7 Mean heat flux flowing during each stroke at measuring point 2 (knocking zone)

(a) Effect of ignition timing

(b) Effect of research octane number

Fig. 8 Gas temperature T_g calculated using the ideal gas law

and Eichelberg⁽¹⁴⁾ generally used as reference are also used in this study. Figure 10 shows the respective heat transfer coefficient values where the ignition timing was varied. The coefficient was calculated from the combustion pressure P shown in Fig. 3 and the gas temperature T_g shown in Fig. 8. The effect of ignition timing is clearly seen in each case, and the mean heat transfer coefficient becomes greater as the ignition

timing advances. Since Woschni's equation gives a larger peak value than Eichelberg's equation, the mean value of the former becomes greater. A small peak is found around 120° ATDC in Fig. 10(b), which shows the heat transfer coefficient calculated by Woschni's equation. This peak is due to the inclusion of the gas flow in Woschni's equation, which occurred at the time the exhaust valve was opened.

Fig. 9 Heat transfer coefficient at measuring point 1 (piston center)

Fig. 10 Heat transfer coefficients calculated using Woschni's equation and Eichelberg's equation

Fig. 11 Comparison between measured mean heat transfer coefficient $\bar{\alpha}_g$ and $\bar{\alpha}_g$ calculated using Eichelberg's and Woschni's equations

Figure 11 shows the comparison of mean values $\bar{\alpha}_g$ between the measured local heat transfer coefficient shown in Fig. 9 and those calculated by Woschni's equation and Eichelberg's equation. It is found that the increasing rates of mean heat transfer coefficient $\bar{\alpha}_g$ at measuring points 1 to 2 are much greater than those calculated using Woschni's and Eichelberg's equations against knock intensity. That is, the heat transfer coefficient value increased due to knocking cannot be estimated by those empirical equations.

4. Conclusions

Thin-film thermocouples were embedded on a piston top, and instantaneous surface temperatures and instantaneous heat flux on knocking were measured, where the ignition timing was advanced and the gasoline octane number was varied. As a result, the following conclusions have been reached.

(1) Without knocking: in normal combustion without knocking, the longer the distance of flame propagation from the spark plug becomes, the later is the start of temperature rise at that point.

(2) With knocking: the temperature of the wall surface zone not reached by the normal combustion flame generated by ignition rises as soon as knocking occurs. In the wall surface zone where the tempera-

ture had already begin to rise due to arrival of the normal combustion flame, the temperature is raised further by knocking. The temperature amplitude becomes greater as the ignition timing advances and gasoline octane number becomes smaller. Namely, the amplitude becomes greater in proportion to the knock intensity.

(3) Not only the knock zone on the wall surface, but also the entire wall surface, is subject to temperature rise upon knocking in proportion to the knock intensity.

(4) The heat loss during knocking is greater during the working stroke in proportion to the knock intensity. When the knock intensity exceeds a certain value, the heat loss during the working stroke becomes greater than the total heat loss during a cycle.

(5) As the ignition timing advances, the heat loss during the compression stroke increases, but the heat loss during the working stroke is still greater.

(6) The heat loss increase rate during the working stroke caused by knocking is greater in the case where the octane number is made smaller, than in the case where the ignition timing is advanced.

(7) Comparison of measured values and values calculated by Woschni's and Eichelberg's equations in terms of mean heat transfer coefficient $\bar{\alpha}_g$ shows that

the measured values increase in proportion to the knock intensity, while the values calculated by the empirical equations are hardly change by the knock intensity.

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