

Real-time Piston Temperature Measurement Using Electromagnetic Induction Telemetry

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ABSTRACT

As piston durability is a decisive factor in the limits of engine performance, piston temperatures are useful information for engine development. Because these temperatures are typically available only under constant-speed operating conditions, conventional material hardness measurements can no longer satisfy the diversifying requirements of piston temperature measurement. Therefore, we have developed a piston temperature measurement system that directly measures piston temperatures using a thermistor, which allows the transfer of measurement information at bottom dead center using a light, compact electromagnetic induction system. This measurement system can be applied to motorcycle engines, which are often subjected to high engine speeds, and allows measurement up to 15 300 r/min while ensuring endurance reliability of more than 10 hours.

In this study we introduce some actual examples of piston temperature changes measured by this electromagnetic induction system with the typical parameters altered when the engine is running. The phenomenon that the piston temperatures become less sensitive to changes of parameters under high engine speed conditions is thus explained by the difference in the heat transfer rate of the heat-input side and the heat-release side.

1. Introduction

The “Measurement method of piston temperature for high-speed gasoline engines”⁽¹⁾ by Takamatsu et al., which was announced by the Society of Automotive Engineers of Japan in 1998, involves transferring the signal output from a thermistor recessed in the piston at the location to be measured via a contact in the vicinity of bottom dead center, and converting it into temperature data. This measurement method has the ability to withstand 6 hours of use at a maximum engine speed of 12 000 r/min, and an error of 1% with respect to the temperature measured using a CA thermocouple.

However, because a contact was used to transfer the signal, it is difficult to measure the piston temperature in real-time when the engine is running at high speeds. Therefore, to address such issues, real-time temperature measurement technology using a contactless electromagnetic induction telemetry method was developed, enabling the data to be transferred in the vicinity of bottom dead

center without the use of a contact. This paper reports the results obtained using this technology to measure the effectiveness of the cooling oil jet, and the effect of the air-fuel ratio and ignition timing on the piston temperature, both of which are representative parameters of a running engine.

2. Principle of the Electromagnetic Induction Telemetry Method

Piston temperature measurement technology using the electromagnetic induction telemetry method was reported in 2000 by Matsui et al.⁽²⁾, and in 2002 by Inami et al.⁽³⁾ under the title “Temperature Measurement on an Operating CART Engine,” both at the Society of Automotive Engineers of Japan. Prior to this, Matsuura’s doctorate thesis⁽⁴⁾ included a detailed report^{(5), (6)} on this technology.

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The method described here is basically the same as those mentioned above. Figure 1 shows the configuration of each coil, which is based on the measurement principle used.

The transmitter and receiver coils are fixed to the cylinder block. The resonator coil, which forms a closed circuit with the thermistor, is installed on the piston so that the centers of both coils line up with each other when the piston is near bottom dead center.

When alternating current is passed through the transmitter coil, alternating current of the same frequency flows through the receiver coil as well. To reduce the effect of the relative positions of the coils on the received signal, two sets of transmitter coils and receiver coils are combined with each other.

When the piston approaches bottom dead center, current flows through the resonator coil via electromagnetic induction, causing the current flowing through the resonator coil to decrease. The magnitude of this reduction depends on the resistance of the thermistor, which indicates the piston temperature, thus enabling the piston temperature to be measured.

Figure 2 shows an actual example of the resonator coil and thermistor installed on a piston.

In this example, the recessed depth of the thermistor is 2 mm from the surface at the center of the piston crown.

3. Example of Real-time Measurement

Table 1 shows the main specifications of the engine used in these measurement examples.

Using the hardness method, it was found that the temperature of the third cylinder in a 4-cylinder engine was high, so a thermistor was recessed 2 mm into the surface at the center of the piston in

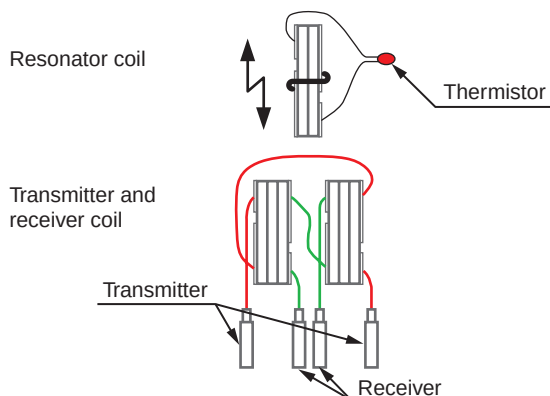


Fig. 1 Construction of electromagnetic telemetry method

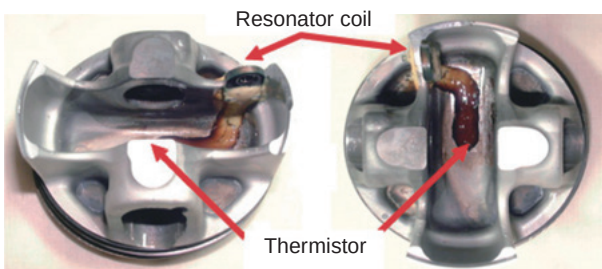


Fig. 2 Illustration of actual piston with measurement device

Table 1 Engine specifications

Engine type		Water cooled, DOHC 4-stroke 4-cylinder, gasoline
Bore × Stroke	(mm)	67 × 42.5
Displacement	(cm ³)	599
Compression ratio		12 : 1
Max. engine speed	(r/min)	15 300
Piston cooling jet	(mm)	φ0.9
Oil pressure	(kPa)	590

this cylinder, and measurement was performed at each set speed after a lapse of about 60 seconds to allow the data to stabilize. A description of the effectiveness of oil cooling of the back of the piston, fuel cooling, and changing of the ignition timing for an actual measurement example is provided below.

3.1. Piston Cooling

The ignition timing was set to minimum spark advance for best torque (MBT) for all engine speeds, the fuel-air ratio was set to the vicinity of 13 to obtain maximum output, and a comparison of the piston temperature with and without the cooling oil jet applied to the back of the piston was performed. The cooling jet had a 0.9 mm diameter nozzle and an oil pressure of 590 kPa. Figure 3 shows the temperature difference measured at this time.

Based on the measurement data, the piston cooling oil jet is very effective, demonstrating a temperature reduction at medium engine speed of 50 °C or more. Conversely, in the high speed region, the difference gradually diminished. One explanation for this is that when the engine is rotating at very high speeds, the lubricating oil at the bottom of the piston is violently agitated in the same way as when the oil jet is applied, even when a cooling jet does not exist.

3.2. Fuel Cooling

The method of lowering the piston temperature by setting the air-fuel ratio to the rich side of stoichiometric and utilizing the latent heat of evaporation of the fuel that is not related to combustion has been used empirically for many years to prevent seizure and melting of the piston due to knocking. When the vehicle is racing under severe conditions, the piston is cooled to help prolong the life of the piston for the duration of the race.

As an example, Fig. 4 shows the piston temperature at engine speeds of 11 700 and 15 000 r/min when the concentration of CO in the exhaust gas, instead of the air-fuel ratio, is changed.

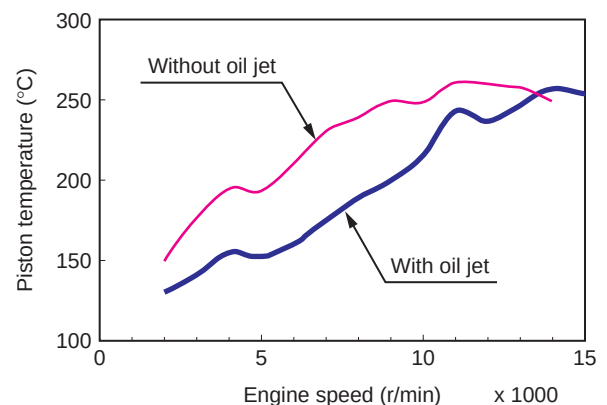


Fig. 3 Effect of piston cooling jet

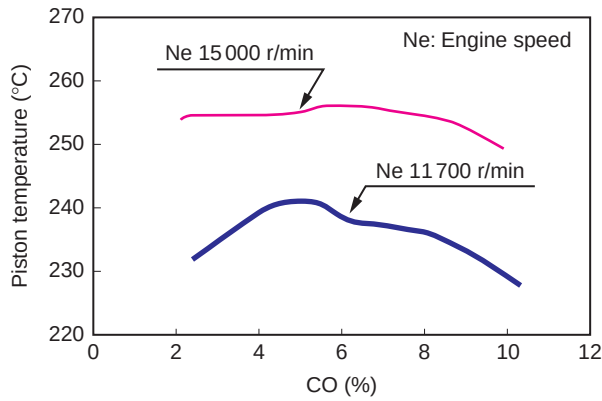


Fig. 4 Piston temperature against CO concentration

It can be seen from Fig. 4 that the temperature of the piston is greatly affected by the CO concentration when the engine speed is a relatively low 11 700 r/min, and is relatively unaffected when the engine speed reaches 15 000 r/min.

These results indicate that the conventional method based on experience, in which the CO concentration was purposely richened to ensure good piston durability, did not have a particularly large effect on the temperature at the center part of the piston at high engine speeds.

Figure 5 shows the data of Fig. 4 expressed in terms of the indicated mean effective pressure (IMEP). The piston temperature rises roughly in proportion to indicated work. When the CO concentration is set to the rich side, the piston temperature drops abruptly at an engine speed of 11 700 r/min, whereas it falls slowly at an engine speed of 15 000 r/min. On the other hand, the piston temperature remains virtually unchanged when the CO concentration is set to the lean side, as seen in the circled area.

3.3. Effect of Ignition Timing

Figure 6 shows the relationship between the maximum in-cylinder pressure and piston temperature when ignition timing is changed at engine speeds of 11 700 r/min and 15 000 r/min as described in Section 3.2.

When the ignition timing is advanced, the crank angle at which the maximum pressure is generated approaches top dead center and the maximum pressure increases. At this time, when the engine speed is an intermediate value of 11 700 r/min, the piston temperature, like the maximum pressure, rises along with the advance angle of the ignition timing. However, when the engine

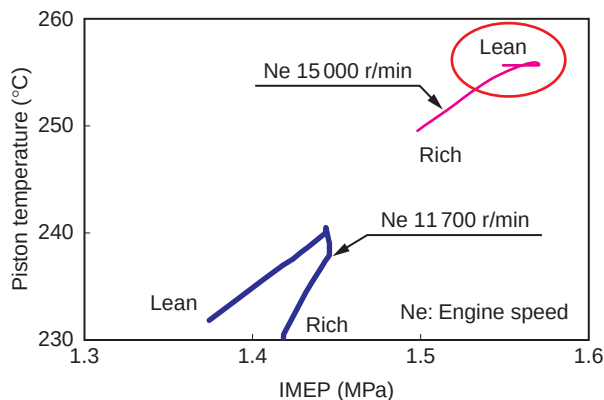


Fig. 5 Fuel cooling effect

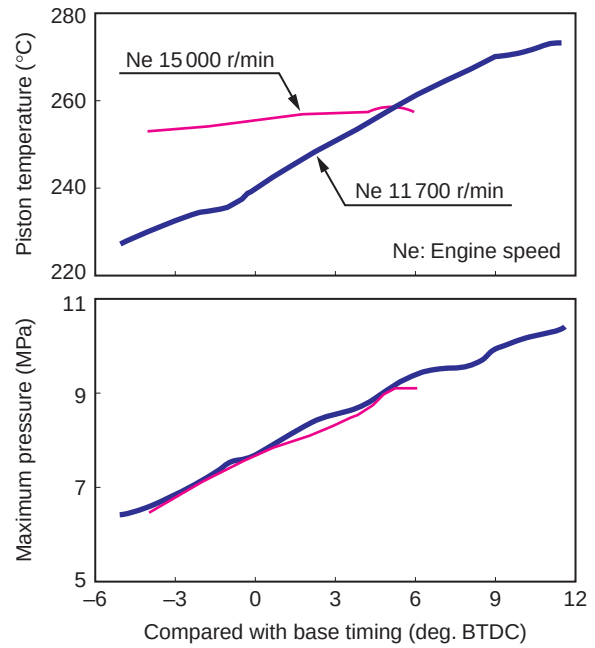


Fig. 6 Piston temperature and maximum pressure against ignition timing

speed is a high value of 15 000 r/min, the temperature is already sufficiently high when the ignition timing is retarded, and even if the ignition timing is advanced further to raise the pressure inside the cylinder, the piston temperature will not rise significantly.

Also, as shown in Fig. 7, the indicated mean effective pressure also changes along with the ignition timing. However, as demonstrated in Fig. 5, the piston temperature exerts relatively little effect on in-cylinder pressure and indicated work.

As mentioned above, the piston temperature is greatly affected by the cooling oil jet, air-fuel ratio and maximum in-cylinder pressure, or the indicated mean effective pressure determined by the ignition timing. However, this applies to an engine speed of around 11 700 r/min, and does not necessarily apply at high engine speeds of about 15 000 r/min. The question of whether this is due to an issue occurring during measurement of the piston temperature at high engine speeds, or whether it occurs unavoidably due to the balance between the heat input to the piston and the heat release from it, will be covered in the following section.

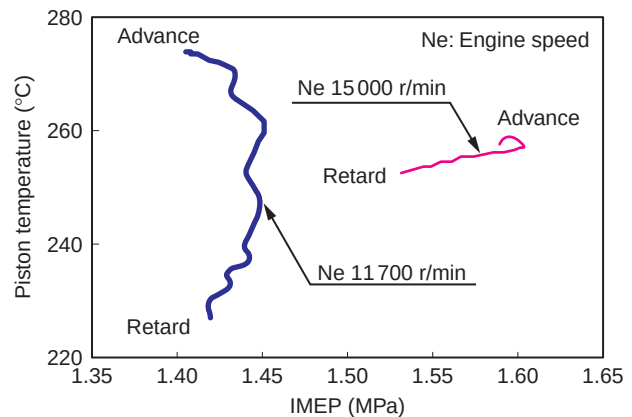


Fig. 7 Piston temperature against IMEP

4. Study of the Balance between Heat Input and Heat Release

Temperature measurement during this development project was carried out 60 seconds after the piston reached a steady-state temperature with each parameter changed. In this condition, heat transfer is also in a steady-state condition, so the total of heat input and heat release to and from the piston is zero. It is thought that when parameters such as air-fuel ratio, ignition timing and engine speed are changed, the heat transfer rate on the heat input side changes along with the in-cylinder temperature.

On the other hand, parameters such as the presence of an oil jet and engine speed can cause the heat transfer rate on the heat release side to change. Figure 8 shows a Microsoft Excel simulation of the change in the piston temperature according to the heat transfer rate difference on the heat input side. Here, the heat transfer rate on the heat release side was assumed to be constant, and the ambient temperature on the heat input side was changed. This demonstrated, of course, that the larger the heat transfer rate is on the heat input side, the more rapidly the piston temperature changes.

Because the piston temperature is determined by the balance between the input heat and the released heat, the piston temperature changes markedly with changes in air-fuel ratio and ignition timing in the medium speed region, but changes relatively slightly in the high speed region. This phenomenon can be explained as follows:

In the medium speed region, torque is increased and heat input time per heat transfer cycle is adequate compared to that of in the high speed region, so the piston temperature changes rapidly in response to changes in input heat. On the other hand, the amount of heat released is affected by the difference between ambient temperature and piston temperature, so it is ultimately determined by the heat transfer rate on the heat input side. Conversely, in the high speed region, torque is reduced and heat input time per cycle decreases, hence the piston temperature is relatively unaffected by changes on the heat input side. Therefore, it is largely determined by the heat transfer rate on the heat release side.

The piston temperature did not rise in the high speed region even when there was no oil jet. Likely, this occurs because the agitation due to the lubricating oil affects piston cooling to the same extent as oil jet cooling. This causes the heat transfer rate on the heat release side to increase and thus largely determine the piston temperature, even when the input heat changed as a result of a slight increase or decrease in engine speed.

5. Conclusion

The authors developed a technology for measuring piston

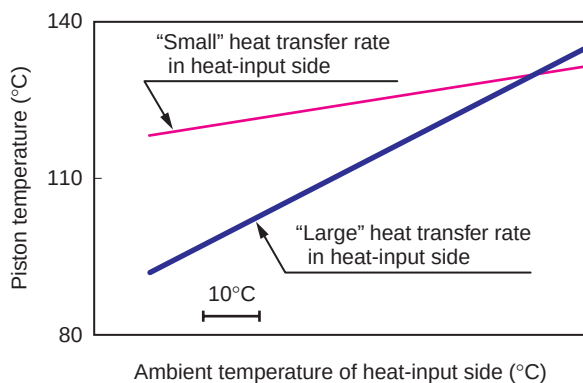


Fig. 8 Piston temperature against heat transfer rate

temperature using a contactless electromagnetic induction telemetry method and used it on motorcycle engines, which are run at high speed. As a result, it was possible to perform measurements up to 15 300 r/min reliably for a period of at least 10 hours. By using this measurement method to perform real-time measurement of piston temperature during actual running of an engine, the following results were obtained:

- (1) It was possible to quantitatively determine the effect of representative parameters, such as the piston cooling oil jet, air-fuel ratio and ignition timing, on the piston temperature.
- (2) In the medium speed range of 11 700 r/min, the temperature measured using this measurement method definitely changed according to changes in each parameter. In contrast, in the high-speed range of 15 000 r/min the temperature did not change very much when each parameter was changed. In other words, it appeared that a temperature saturation condition had been reached.
- (3) Numerical calculation was carried out to establish the cause of this phenomenon. It was found that the heat transfer rate during heat input to the piston and heat release from the piston had both changed. Consequently, the medium speed range can be considered as the range in which the heat transfer rate on the heat input side is dominant, whereas the high-speed range can be considered as the range in which the heat transfer rate on the heat release side is dominant.

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