Special Feature: Challenges of Internal Combustion Engines for Achieving Low-carbon Society

Research Report

Verification of Thermo-swing Temperature Cyclic Fluctuation by Laser-induced Phosphorescence Thermometry

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ABSTRACT This study aims to validate “thermo-swing” temperature fluctuations on the combustion chamber wall. The surface temperature of the thermo-swing insulation coating follows the gas temperature transiently. This reduces the temperature difference between the gas and the surface, causing a reduction in heat loss. To verify the swing phenomenon, we developed a technique to measure the temperature at a diesel spray flame impingement point, where a large heat loss reduction would be expected. The lifetime of laser-induced phosphorescence (LIP) was measured to determine the surface temperature, which has a high responsiveness. First, we confirmed that the sensitivity and response of this technique were sufficient for the investigation. Then, this technique was applied to a diesel spray flame impingement point. To reduce the occurrence of bright flames during optical measurements, we chose an oxygen-containing fuel in the place of normal diesel fuel. The temperature measurements of the insulation coating revealed a steep temperature rise during the combustion period and a temperature drop during the intake stroke. The swing width of the temperature in one cycle was approximately 140 K. On the other hand, the swing width with a non-insulation coating was about 45 K. The results showed a clear difference between the insulation and non-insulation coatings, which confirms the temperature swing phenomenon of the insulation coating. When these measured values were compared with the calculation results for one-dimensional heat conduction, the values were mostly consistent.

KEYWORDS Internal Combustion Engine, Temperature Measurement, Heat Insulation, Laser-induced Phosphorescence

1. Introduction

To improve the thermal efficiency of an internal combustion engine and achieve a low-carbon society, ceramics have been applied to reduce the heat loss from the cylinders. This approach focuses on the low thermal conductivity and high heat resistance of ceramics. However, because the heat capacity of ceramics is so large, the wall temperature increases through the whole engine cycle. This reduces the charging efficiency and causes knocking in gasoline engines. To overcome these problems, thermal insulation that does not raise the gas temperature during the intake stroke has been proposed. To achieve this, we developed the “SiRPA” (silica-reinforced porous anodized aluminum) thermo-swing insulation coating, which has low thermal conductivity and low thermal capacity. This reduces the heat flux from the combustion chamber into the cooling water by making the wall temperature follow the gas temperature as much as possible during the expansion and exhaust strokes. During the intake and compression strokes, heating of the intake air is prevented because the wall temperature does not increase. The temperature cyclic fluctuation within a single cycle is referred to as the “temperature swing”.

Existing techniques to measure the surface temperature of the combustion chamber have used a thin-film thermocouple. However, the heat capacity of thermocouple materials is not small enough relative to that of the insulation coating used in this study, which makes it difficult to measure the temperature swing with a thermocouple. There is also concern regarding the durability of a thermocouple junction and wire when it is installed on the moving parts of an engine. Thus, a noncontact measurement technique...
has been developed whereby a radiation thermometer is used for the in-cylinder measurement.\(^\text{(13)}\) To measure the temperature accurately, a blackbody spray should be applied to the surface of the object to be measured. There may be problems if a blackbody spray, which absorbs heat easily, is applied to an insulation coating with low thermal capacity. In this study, we focused on a temperature measurement technique that is based on the dependence of the phosphorescent lifetime on temperature. Although laser-induced phosphorescence (LIP) has already been applied to the surface of an engine combustion chamber,\(^\text{(14,15)}\) this technique is limited to applications in which the temperature change within one cycle is small. In other words, a technique is needed for cases in which the surface temperature follows the gas temperature very responsively, as in the case of the newly developed SiRPA insulation coating. The area of greatest interest is near the diesel spray impingement point because the flow of the flame is intense, and a large heat loss reduction can be expected. However, optical temperature measurement methods that use phosphorescence have been reported as being difficult to apply because of the influence of the luminous flame.\(^\text{(16)}\) In this study, we attempt to clarify the swing phenomenon at the spray impingement point.

We first confirmed the responsiveness of this measurement technique before applying the insulation coating. It proved possible to measure the temperature swing by reducing the effect of the luminous flame, which presents a problem during temperature measurement. Our results indicated that the temperature thermometry we developed demonstrated a swing phenomenon of 140 K for the SiRPA coating. For the base aluminum, however, the measured swing was only about 45 K. Therefore, a clear difference was confirmed in the swing phenomenon for these two cases.

2. Establishment of Laser-induced Phosphorescence Thermometry

2.1 Principle of Laser-induced Phosphorescence Thermometry

The lifetime of laser-induced phosphorescence (LIP) depends on temperature. This temperature dependence of phosphorescence has long been used to measure temperature in many fields.\(^\text{(17,18)}\) Since the temperature sensitivity differs depending on the phosphor, excitation wavelength, and observation wavelength, optimization of the combination of these parameters is important. The phosphor La\(_2\)O\(_2\)S:Eu has been reported to have a high temperature sensitivity in the range to be measured (approximately 373–573 K).\(^\text{(19)}\) We selected an excitation wavelength of 355 nm and an observation wavelength of 620 nm.

2.2 Acquisition of Calibration Curves for the Temperature and Lifetime

We measured the phosphorescence lifetime \(\tau\) at different temperatures by changing the heater temperature, and then obtained a calibration curve using the polynomial approximation shown in Fig. 1.

Phosphor was applied to the ceramic heater with a binder, and the signal from the phosphor was measured with a photomultiplier tube (PMT) through a bandpass filter. We measured the phosphorescence decay curve with an oscilloscope.

\[
\frac{I(t)}{I_0} = C \times \exp\left(-\frac{t}{\tau}\right). \tag{1}
\]

The phosphorescence intensity and decay waveform at time \(t\) can be approximated with Eq. (1) by using the initial intensity \(I_0\), constant \(C\), and lifetime \(\tau\). Here, the initial intensity \(I_0\) was assumed to be the intensity after 10 \(\mu\)s of laser incidence to reduce the effects of noise on the incident laser.

![Fig. 1 Calibration curve for temperature and lifetime.](image)
2.3 Interface Between the Phosphor Film and Base Material

With this measurement method, we measured the surface temperature through the phosphor film attached to the object being measured. The phosphor was mixed with cellulose-based organic matter acting as a binder. It was then applied to the surface with an airbrush. The measured surface temperature of the phosphor must follow the surface temperature of the measurement object. Therefore, we observed the interface between the phosphor film and the surface by scanning electron microscopy (SEM). Figure 2 shows an obtained SEM image. For these measurements, we observed a cross-section of the phosphor film. Although the phosphor particles were a few microns in diameter, we confirmed that they contacted the test pieces without any gap. Thus, we assumed that this represents an ideal state for measuring the surface temperature. The phosphor film should ideally be as thin as possible to reflect the surface temperature, but the signal-to-noise ratio (S/N) decreases for thinner films. Therefore, the thickness of the phosphor film was set to between 10 and 15 µm. The influence of the film thickness on an engine will be described later.

2.4 Confirmation of the Transient Responsiveness

For the developed SiRPA coating, we estimated that there would be a rapid temperature rise upon spray flame collision. A temperature rise of 20 K or more in 1 ms during the combustion stroke was expected from the simulation results. Therefore, we checked the responsiveness of LIP thermometry before applying it to an engine. Figure 3 shows the experimental apparatus. Both sides of an aluminum foil of 20 µm in thickness were coated with blackbody spray (emissivity: 0.94). A phosphor film was then applied on one side. By irradiating the back of the aluminum foil with focused light, a steep temperature rise could be attained. Prior to this, a halogen lamp was used to raise the surface temperature to at least 473 K before the pulsed laser irradiation. The temperature of the aluminum foil surface was measured with a radiation thermometer having a high temporal resolution (10 µs) and was obtained as the phosphorescence signals were being measured with the PMT. Figure 4 shows the temperature results according to the LIP and the radiation thermometer. The horizontal axis shows the time after pulsed laser irradiation, and each measurement point was averaged to produce consistent
time results. We confirmed the repeatability of the temperature rise of the aluminum foil using the radiation thermometer. The figure clearly confirms that the temperatures measured by the radiation thermometer and the phosphor were in good agreement. Because the emissivity of the surface of the blackbody spray ($\varepsilon = 0.94$) changed when the phosphor was applied, the emissivity of the radiation thermometer was set to 0.85 so that the temperatures would agree in the steady state. The rate of the temperature rise in this case was greater than or equal to 20 K/ms. Therefore, we confirmed that the temperature measurement technique using the phosphor can be applied to a temperature field with a rapid rise.

2.5 Specifications of the Optical Engine

Table 1 lists the main specifications of the optically accessible engine$^{(20)}$ used in this experiment. Figure 5 shows the experimental apparatus. The temperature

<table>
<thead>
<tr>
<th>Engine</th>
<th>Optically accessible single-cylinder diesel engine</th>
</tr>
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<tbody>
<tr>
<td>Displacement volume [cm$^3$]</td>
<td>557</td>
</tr>
<tr>
<td>Bore [mm] × Stroke [mm]</td>
<td>86 × 96</td>
</tr>
<tr>
<td>Compression ratio</td>
<td>15.83</td>
</tr>
<tr>
<td>Number of valve</td>
<td>Intake: 2, Exhaust: 1</td>
</tr>
<tr>
<td>Piston cavity shape</td>
<td>Bathtub type</td>
</tr>
<tr>
<td>Nozzle diameter × Hole number</td>
<td>0.09 mm × 9 holes</td>
</tr>
</tbody>
</table>

Table 1  Engine specifications.

- Third harmonic YAG laser, Spectra Physics PRO290-10, 355 nm
- Band-pass filter, MZ0620; Asahi Spectra Co., Ltd.
- PMT, R2228; Hamamatsu Photonics
- Mirror
- Sapphire glass
- Measuring point
- Enlonged piston
- Bore
- Cavity

Fig. 5  Experimental setup.

measurement point was in the vicinity of the spray flame impingement in the cavity on the piston surface. The pulsed laser irradiated the measurement point through a sapphire window mounted on the engine head side, while the phosphorescence signal was extracted coaxially. The measurement points are also shown in Fig. 5 ((a) aluminum, (b) SiRPA coating). The SiRPA insulation coating was formed on the aluminum piston. The physical properties of SiRPA will be described later herein (Table 2). A thermocouple was mounted to a depth of 200 µm on the piston (base aluminum material) to enable comparison of the temperature with that indicated by the phosphor.

2.6 Engine Operating Conditions for Removing the Luminous Flame

As mentioned in the introduction, removal of the luminous flame is important in LIP thermometry. The thermo-swing temperature fluctuation was measured at the spray flame impingement point because this was regarded as exhibiting a large reduction margin for the heat flux when the insulation coating was used. For this method, the phosphorescence signal at around 620 nm was measured. However, in this wavelength region, the broad spectrum of the luminous diesel flame is taken at the same time and superposed onto the signal from the phosphor. This was a major obstacle when measuring the temperature. Thus, the fuel was changed to diethylene glycol dimethyl ether (DGM), which has been reported to emit a smaller luminous flame than diesel fuel.$^{(21)}$ To confirm the brightness of the DGM flame,
we captured combustion images with a high-speed camera (FASTCAM SA1.1; Photron Co., Ltd.) having a frame rate of 20000 fps. Table 3 lists the experimental conditions. Figure 6 shows the obtained results. The top of the figure shows typical images of the luminous flame, and the lower part shows the luminous flame brightness with respect to the crank angle.

In Case 3, which was measured under motoring and firing conditions using the optical system. The crank angle in Fig. 7 was set to 10° after top dead center (ATDC) to compare the timing when the luminous flame was bright according to the visualization results. In motoring operation, only the base noise was observed. In firing operation, the luminous flame was superimposed on the base noise. The brightness of the luminous flame fluctuated with cycle variations, so this noise level was likely to change during the phosphorescence measurement.

If the luminous flame overlaps only in the initial phosphorescent stage, the slope of the decay increases, and the obtained phosphorescence lifetime is short. In this case, the temperature will be overestimated. Conversely, if the luminous flame overlaps only in the final phosphorescent stage, the slope of the decay decreases, and the phosphorescence lifetime is overestimated. In this case, the temperature will be underestimated. However, this noise level was sufficiently low compared with the intensity of the phosphorescence, so the error in the temperature calculation caused by the luminous flame was estimated to be about ±5 K. The above results confirmed that we could measure the piston surface temperature at the instant of spray flame collision by using the oxygenated fuel and reducing the oxygen

<table>
<thead>
<tr>
<th>Table 2</th>
<th>Physical properties of aluminum and SiRPA coating.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Aluminium</td>
</tr>
<tr>
<td>Thermal conductivity [W/mK]</td>
<td>125</td>
</tr>
<tr>
<td>Specific heat at constant volume [kJ/mK]</td>
<td>2700</td>
</tr>
<tr>
<td>Density [kg/m³]</td>
<td>2700</td>
</tr>
<tr>
<td>Thickness [μm]</td>
<td>—</td>
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<table>
<thead>
<tr>
<th>Table 3</th>
<th>Combustion conditions.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Case1</td>
</tr>
<tr>
<td>Engine speed [rpm]</td>
<td>1200</td>
</tr>
<tr>
<td>Fuel</td>
<td>DGM (Diethylene glycol dimethyl ether)</td>
</tr>
<tr>
<td>Coolant temperature [°C]</td>
<td>80</td>
</tr>
<tr>
<td>Rail-pressure [Mpa]</td>
<td>60</td>
</tr>
<tr>
<td>Pilot injection (timing [° ATDC]/period [ms])</td>
<td>−20/0.26</td>
</tr>
<tr>
<td>Main injection (timing [° ATDC]/period [ms])</td>
<td>−3/0.93</td>
</tr>
<tr>
<td>Injection quantity [mm³/st]</td>
<td>38.8</td>
</tr>
<tr>
<td>Oxygen concentration [% (N₂ diluted)]</td>
<td>21.0</td>
</tr>
</tbody>
</table>

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phosphor film thicknesses of about 10–15 µm and 55–60 µm were prepared. The film thickness was measured with a charge-coupled device (CCD) laser displacement meter (LK-G3000V; Keyence Corporation). Figure 10 shows the temperature measurement results for a 5-s cycle before and after firing operation. The crank angle measured by LIP was fixed to 15° ATDC. The horizontal axis represents time. There were 30 cycles between 1 and 4 seconds during firing operation. The thermocouple measured the temperature of the metal part at a depth of 200 µm from the surface, as shown in Fig. 5. When the operation switched from motoring to firing, the temperature rise was confirmed with the thermocouple on a cycle-by-cycle basis. According to LIP, the surface temperature changed suddenly before and after firing operation. From the Fig. 10, the temperature during the motoring period with the phosphor was equal to that obtained with the thermocouple for a phosphor thickness of 10–15 µm. When the thickness was 55–60 µm, however, the temperature was higher than that measured with the thermocouple. As the phosphor film thickness increased, the peak temperature became higher. Figure 11 shows the mean and standard deviation of the temperature for each crank angle during the 30-cycle firing operation shown in Fig. 10 and the in-cylinder bulk gas temperature obtained from the gas state equation. For the thicker film case of 55–60 µm, the peak temperature is higher than that of 10–15 µm and the peak timing was delayed (10° ATDC for 10–15 µm, 30° ATDC for 55–60 µm). This may be because the phosphor film itself functioned as an

3. Results

3.1 Measurement Variations During Motoring Operation

The variation over 100 consecutive cycles during motoring operation was measured with an aluminum piston. The measured condition was in-cylinder pressure of 4.1 MPa at 15° ATDC. Figure 9 shows the measurement temperature for the 100 consecutive cycles. The standard deviation of the measurement temperature was 3.8 K. During motoring operation, the temperature fluctuation was relatively small, and the measurement variation was about ±4 K. Note that the temperature measured by the LIP was higher than that obtained by the thermocouple by about 7 K. This is considered to be caused by the fact that the thermocouple was positioned at a depth of 200 µm from the surface.

3.2 Influence of the Phosphor Film Thickness

The effects of the phosphor film thickness were evaluated with an aluminum piston. Two different

![Fig. 7 Influence of luminous flame on signal.](image-url)
insulation coating. Although the bulk temperature decreases at +5° ATDC when the film thickness was 10–15 µm, the surface temperature also decreased. This indicates that the measured values for the phosphor temperature followed the gas temperature. Therefore, in order for the phosphor to follow the surface temperature, the film thickness of the phosphor needs to be reduced as much as possible. In this study, it proved difficult to reduce the thickness to 10 µm or less because of the low S/N ratio. Therefore, a phosphor film with a thickness of 10–15 µm was used in the following experiment.

3.3 Comparison of Aluminum and Insulation Coatings

As shown in Fig. 10, the thermocouple showed that the piston surface temperature continued to rise during firing operation. To suppress the influence of this temperature rise and the residual gas in the following experiments, the engine operating conditions were set to one firing operation per four cycles (skip firing), and the temperature was measured while the crank angle was shifted (e.g., −30° ATDC for the first firing, −20° for the second, −10° for the third, etc.). In this study, we used the SiRPA coating as insulation. This

![Fig. 8](image)

**Fig. 8** Cylinder pressure and heat release rate.

![Fig. 9](image)

**Fig. 9** Temperature measurement results (motoring conditions).

![Fig. 10](image)

**Fig. 10** Influence of the phosphor film thickness (time series).

![Fig. 11](image)

**Fig. 11** Influence of the phosphor film thickness (average result).
is a porous alumina that can be formed by anodizing
the cast aluminum alloy piston. Many pores with
a size of several tens to several hundreds of nanometers
are formed in the coating thickness direction. These
pores contribute to the thermal insulation effect. The
pores penetrate inwards from the surface. Thus, there
is concern that the thermal insulation effect would
be adversely affected if the high-temperature and
high-pressure gas penetrates the inner membrane.
Therefore, a silica coating of several microns in
thickness was added to the porous alumina. Details of
the insulation coating are given in Ref. 6. Figure 12
shows the temperature measurement results under
the base (aluminum) conditions and with the SiRPA
coating. A steep temperature rise from near the TDC
was confirmed for both the base aluminum and the
SiRPA coating. For the SiRPA coating, a swing width
of about 140 K or more was measured: 400 K for the
intake stroke, and 540 K for the expansion stroke.
On the other hand, a swing width of about 45 K was
measured for the aluminum. Thus, a clear difference
in the swing phenomenon for the two cases was
confirmed. During the intake stroke, the temperature
was almost the same for both cases, and there was no
increase in the piston surface temperature. Therefore,
as described in the introduction, there is no concern
regarding a decrease in charging efficiency with this
insulation coating. For both the aluminum base and
SiRPA coating, the measurement variation was large
at crank angles of 10°–30° ATDC. This large variation
may mainly be caused by the flame behavior of the
luminous flame in the cavity.

4. Comparison with the One-dimensional Heat
Conduction Calculation

To validate the temperature swing phenomenon,
the experimental results for the SiRPA coating, as
shown in Fig. 12, were compared with the calculated
results. We assumed an infinite flat plate to simulate
the piston with an insulation coating formed on the
flat plate. One-dimensional heat transfer calculations
were performed for the wall in the vertical direction. The
heat transfer coefficient and the gas temperature
obtained by a 3D computational fluid dynamics (CFD)
simulation as a function of time were assigned at the
temperature measurement position. The temperature at
the rear of the piston was measured with the embedded
thermocouple. Two cases describing the physical
properties of the insulation coating were considered in
order to estimate the density.

Case 1: Bulk density
The density was determined from the volume (with
the open pore part being regarded as contributing to the
volume), which was calculated from the dimensions
and weight of the film.

Case 2: Apparent density
The density was determined from the volume (with
the open pore part not being regarded as contributing to
the volume), which was determined by the Archimedes
method and the weight of the film.

Table 3 lists the respective physical properties of the
aluminum and the SiRPA coating. Figure 13 shows the
measurement results (same as the results of the SiRPA
coating shown in Fig. 12) and the calculated results.
Generally, the calculated values tended to match the

![Fig. 12](result_of_temperature_swing_measurement.png)
![Fig. 13](experimental_and_calculation_results.png)
measured values. The measurement results were close to Case 2 at the peak temperature and close to Case 1 when the temperature dropped during the expansion stroke. This suggests that gas may enter the insulation coating during the rapid pressure rise from combustion. Although the SiRPA coating was coated with silica, the gas seal may be incomplete. Based on these results, we can conclude that we can further enhance the heat insulation effect by improving the seal.

5. Conclusions

To verify the concept of a thermo-swing temperature coating that conforms to the gas temperature, we developed a temperature measurement technique based on the lifetime of laser-induced phosphorescence (LIP) for application to an optical engine, and obtained the following results.

(i) The highly responsive temperature thermometry we developed demonstrated a swing phenomenon of 140 K for the SiRPA coating. For the base aluminum, however, the measured swing was only about 45 K. Therefore, a clear difference was confirmed in the swing phenomenon for the two cases.

(ii) The temperature measurement technique based on the phosphor lifetime was confirmed to be highly responsive to temperature change, even with our developed insulation coating.

(iii) To reduce the luminous flame, which is a problem with temperature measurements at the spray flame impingement point, where a large heat loss reduction can be expected as a result of adding the SiRPA coating, we changed the diesel fuel to oxygen-containing fuel (DGM) and decreased the in-cylinder oxygen concentration. In this way, we realized a combustion condition whereby almost no luminous flame is emitted.

(iv) The temperature calculation error due to the luminous flame at the spray flame was no more than ±5 K in this experiment.

(v) The swing temperature width measured by LIP depended on the thickness of the phosphor. In this measurement, the thickness of the phosphor film was set to 10–15 µm, and we reduced the swing effect of the phosphor itself.

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References


Figs. 1-13 and Tables 1-3
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