

Laser-Induced Phosphorescence Thermography of Combustion Chamber Wall of Diesel Engine

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ABSTRACT

In order to investigate the mechanism of heat transfer on the chamber wall of direct-injection diesel engines, 2-D temperature imaging and heat flux measurement in the flame impinging region on the chamber wall were conducted using laser-induced phosphorescence technique. The temperature of the chamber wall surface was measured by the calibrated intensity variation of the 355nm-excited laser-induced phosphorescence from an electrophoretically deposited thin layer of $\text{La}_2\text{O}_2\text{S:Eu}$ phosphor on a quartz glass plate placed in a rapid compression and expansion machine (RCEM). Instantaneous 2-D images of wall temperature at different timings after start of injection and time-resolved (10kHz) heat flux near the flame impinging region were obtained for combusting and non-combusting diesel sprays with impinging distance of 23.4mm at different injection pressures (80 and 120MPa). The measured temperature images of the chamber wall for the combusting spray exhibited finely structured temperature distribution, while a smoother temperature distribution was observed for the non-combusting spray. The temperature increase due to spray and flame impingement was observed both for combusting and non-combusting sprays, but observed in a much larger area extending downstream for the combusting spray. The increase of injection pressure advanced and enhanced the heat transfer due to spray impingement.

INTRODUCTION

Diesel engines have been widely used in transportation powertrains for their superior thermal efficiency. However, even in the thermally efficient diesel engines, 20 to 30 percent of the total energy released by fuel combustion is lost as heat loss through the combustion chamber wall. Reduction in the wall heat loss is therefore favorable for the improvement of cycle thermal efficiency, overall system efficiency by possible reuse of the raised exhaust gas enthalpy, and reduction of pollutant emission by more efficient aftertreatment.

Previous researches on heat loss in diesel engines have mostly been performed using real engines^(1,2,3,4), among which recent studies have been probing not only total heat loss but also local heat loss at different locations on the combustion chamber wall. Enomoto et al., for example, developed thin-film thermocouple-based heat flux sensors and used them for extensive quantitative measurements of instantaneous heat flux at different locations on the chamber wall surface^(5, 6). These measurements clarified the amount of heat loss at different locations in direct-injection diesel engines and its dependence on the engine operating conditions. As proved in these measurements, the thermocouple-based heat flux sensors are suitable for quantitative and time-resolved measurement of heat flux at representative measurement points. However, these sensors are not suitable for more detailed investigation of spatial distribution of temperature and heat flux on the wall surface. Infrared thermal imaging using thermographic cameras can produce 2-D images of surface temperature distribution with significantly higher spatial resolution. The temporal resolution, though, of currently available thermographic cameras are less than 100Hz and insufficient for the time-resolved temperature and heat flux measurements in diesel engines which requires a temporal resolution higher than 10KHz.

Laser-induced phosphorescence thermography employed in the present study is a non-intrusive temperature measurement technique based on the temperature-dependent characteristics of fluorescence from rare earth or transition metal doped powdery ceramic phosphors. The use of phosphorescence for thermometry was suggested by Neubert in 1937⁽⁷⁾ and has been applied to the measurements under a variety of harsh environments, as described in an extensive review by Allison et al.⁽⁸⁾ The measurable temperature range covered by different thermographic phosphors extends from cryogenic temperatures to those approaching 2000C. Recent applications of the technique to internal combustion engines include surface temperature measurements of rotating turbine blades of aeropropulsion engines^(9,10), intake/exhaust valves of reciprocating engines^(11,12,13,14), and 2-D gas

temperature measurements in HCCI (homogeneous charge compression ignition) engines^(15, 16). The phosphorescence thermography is applicable to instantaneous imaging using readily available gated CCD cameras with visible spectral range and the temporal resolution in the order of microseconds can be achieved by exciting the phosphors with a pulsed laser. However, instantaneous temperature distribution measurement on diesel combustion chamber wall by this technique, which is expected to provide useful information on the mechanism of heat transfer in diesel engines such as the correlation between the temperature distribution on the chamber wall and the flame distribution in the chamber, has never been reported. There is also a possibility to realize time-resolved heat flux imaging on the chamber wall, if excitation by a high-repetition pulsed laser and imaging by a high-speed video camera are employed.

The present study aims to establish the measurement technique for 2-D temperature and heat flux imaging on the chamber wall of direct-injection diesel engines by laser-induced phosphorescence thermography technique. The present paper briefly describes the measurement theory, preparation of phosphor thin layer on a measurement surface, considerations on the error sources and temporal resolution of the measurement, and the measurement results. The results of instantaneous 2-D imaging of chamber wall temperature for combusting and non-combusting diesel sprays at different injection pressures and also time-resolved (10kHz) point measurements of heat flux near the flame impinging region are presented.

MEASUREMENT THEORY

THERMOGRAPHIC PHOSPHOR

Thermographic phosphor is rare-earth-doped ceramic powder. The electronic energy level of the phosphor is excited to a higher state by exposure to visible or ultraviolet light, including laser light, or x-rays. The electronic energy level returns to the ground state followed by the emission of phosphorescence corresponding to the energy-level difference or by non-radiative relaxation. The probabilities for the radiative and non-radiative transitions depend on temperature, and thus the resulting temperature dependence of the phosphorescence spectrum, intensity and lifetime is used for thermometry.

The thermographic phosphor used in the present study is europium-doped lanthanum oxysulfide ($\text{La}_2\text{O}_2\text{S}:\text{Eu}$) manufactured by Phosphor Technology Ltd., UK and supplied in the form of whitish powder. The size of the phosphor particles was several micrometers. The $\text{La}_2\text{O}_2\text{S}:\text{Eu}$ has a high temperature sensitivity between 100 and 250C, which corresponds to the temperature range of chamber wall of diesel engines under typical operational conditions.

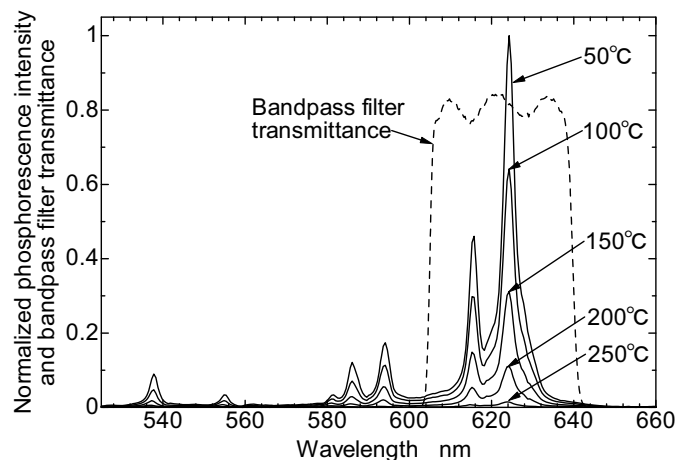


Fig.1 Measured phosphorescence spectrum of $\text{La}_2\text{O}_2\text{S}:\text{Eu}$ at different temperatures

Figure 1 shows the measured laser-induced phosphorescence spectra of $\text{La}_2\text{O}_2\text{S}:\text{Eu}$ excited by the third harmonic of Nd:YAG laser (355nm) and the transmittance of the bandpass filter used in the present study. The phosphorescence spectra were measured by varying the temperature of the phosphor between 50 and 250C in an electric furnace. The spectra show lower phosphorescence intensities at higher temperatures. The phosphorescence peaks around 620nm are prominent and exhibit clear temperature dependence between 50 and 250C. The measurement spectral range, centered at 620nm and FWHM of 35nm, was selected to cover these prominent and temperature-sensitive phosphorescence peaks.

THERMOMETRY METHODS BASED ON PHOSPHORESCENCE INTENSITY AND LIFETIME

In the present study, two different thermometry methods based on the temperature dependent variation of either the intensity or the lifetime of the phosphorescence were employed in order to obtain the wall surface temperature.

Intensity-based temperature measurement

Fig.2 illustrates the principle of the intensity-based temperature measurement. Following the excitation by a laser pulse, the phosphorescence intensity exhibits an exponential decay. The phosphorescence is captured by a gated ICCD camera as an image with a preset gate width of 100μs. The signal intensity corresponds to the hatched area shown in Fig.2, which has a temperature dependence. The signal intensity decreases with increasing temperature of the wall surface. The signal intensity S of the phosphorescence from infinitesimal volume Δv can be expressed as;

$$S(T) = I(T) \cdot C \cdot L \cdot P \cdot O \cdot \Delta v \quad (1)$$

where $I(T)$ is phosphorescence intensity emitted by specific mass of phosphor at temperature T , C is density of phosphor, L is distribution of laser energy on the

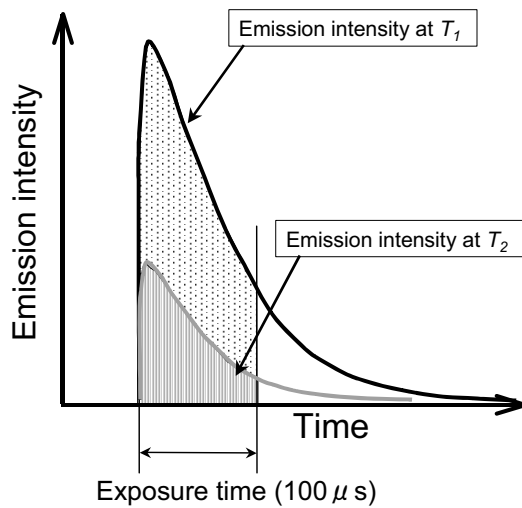


Fig.2 Measurement principle of intensity-based phosphorescence thermometry

irradiated surface normalized by laser pulse energy, P is laser pulse energy, O is efficiency of the collecting optics. By calculating the ratio R of the phosphorescence signal intensity at a measured temperature T_2 to the intensity at a reference temperature T_1 , as;

$$R = \frac{S(T_2)}{S(T_1)} = \frac{I(T_2) \cdot C \cdot L \cdot P_2 \cdot O}{I(T_1) \cdot C \cdot L \cdot P_1 \cdot O} = \frac{I(T_2) \cdot P_2}{I(T_1) \cdot P_1} \quad (2)$$

all the temperature-independent factors except the laser pulse energy P are cancelled out and the wall surface temperature can be obtained. Shot-by-shot fluctuation of laser pulse energy P was measured simultaneously. Note that this thermometry method is applied pixel-by-pixel to the phosphorescence images at the measured and reference temperatures captured by the ICCD camera to obtain the instantaneous 2-D temperature distribution.

In the present study, the temperature dependence of the ratio R was calibrated to different temperatures using an electric furnace. In addition, in-situ calibration of the phosphorescence intensity at a controlled and homogeneous reference temperature of 160°C within the rapid compression and expansion machine (RCEM) explained in a later section was conducted. The calibrations and measurements were conducted using a specially prepared phosphor-coated quartz glass plate explained in a later section. The phosphorescence characteristics could change by coating or deposition processes, impurity diffusion or contamination from the adjacent layers, gas collisions especially by the reactive and high temperature combustion products. To ensure that these issues are negligible, the calibrations and the measurements presented hereafter were all conducted with the same phosphor-coated plate with aluminum protection coating explained in a later section.

Figure 3 shows the calibration plot of the measured signal intensity ratio R at different temperatures obtained

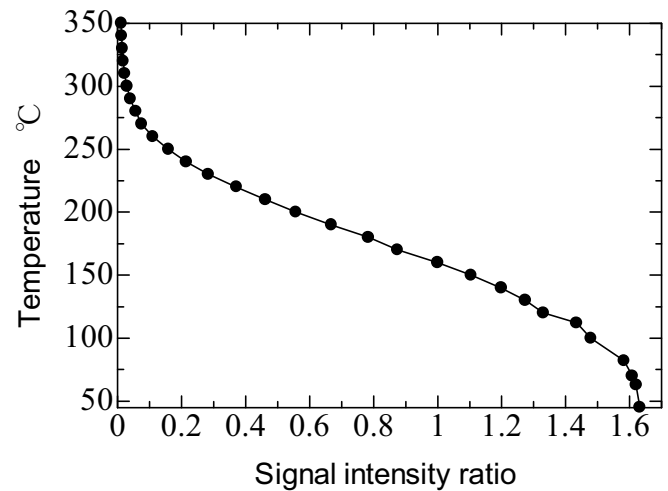


Fig.3 Phosphorescence signal intensity ratio calibrated against temperature

in an electric furnace with the reference temperature of 160°C. The ratio R has a temperature sensitivity adequate for thermometry between 100 and 300°C.

Lifetime-based temperature measurements

In order to obtain the heat flux on the wall surface, time-resolved measurements of wall surface temperature are required. The aforementioned intensity-based imaging using a high-repetition pulsed laser and a high-speed video camera is, theoretically at least, a potential technique to realize time-resolved heat flux imaging on the chamber wall. However, the power and the detection sensitivity of currently available high-repetition pulsed lasers and high-speed video cameras are not sufficient to realize such measurements with acceptable signal to noise ratio. In addition, the intensity-based method requires to simultaneously measure the fluctuation of shot-by-shot laser pulse energy and to correct the signal intensity, considering also the accumulation of phosphorescence resulting from previous laser pulses, which further deteriorates the measurement accuracy. Therefore, in the present study, time-resolved single point measurement of the heat flux on the wall surface was attempted by irradiating the phosphor using a high-repetition Nd:YVO₄ laser beam (3rd harmonic at 355nm) and by detecting the phosphorescence from the laser-irradiated spot with a photomultiplier tube. The temperature of the measurement point was obtained by the thermometry methods based on the variation of phosphorescence lifetime. Fig.4 illustrates the principle of the lifetime-based temperature measurement. The exponential decay of the instantaneous phosphorescence intensity $I(t)$ following the laser excitation can be expressed as;

$$I(t) = I_0 \exp(-t/\tau_T) \quad (3)$$

where I_0 is initial or peak phosphorescence intensity right after the laser excitation, τ_T is the phosphorescence lifetime at temperature T . The time differential of the