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Three-Gate Lifetime Imaging System for Pressure-Sensitive Paint Measurements

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A lifetime imaging system to measure simultaneously pressure and temperature images from a luminescent lifetime decay of pressure-sensitive paint (PSP) has been developed. The dependence of the luminescent lifetime decays on pressure and temperature was clarified by analysis of PtTFPP PSP using a streak camera. The method is proposed to acquire pressure and temperature images from three luminescent images. The three gated times of an intensified charge-coupled device camera were determined, referring to the analysis of streak camera data. The performance of the measurement system was evaluated over the wide range of pressures and temperatures using a PSP-coated coupon. The ratioed lifetime images could be fitted with a smooth function of pressure and temperature. This allowed reconstruction of pressure and temperature images from three luminescent lifetime images. As a verification test, pressure and temperature distributions induced by a sonic-jet impingement flow were visualized. PSP data agreed with pressure tap data, indicating that this lifetime imaging system was a useful tool to measure pressure and temperature fields on an aerodynamic model surface.

Nomenclature

a	=	coefficient of calibration curve for pressure-sensitive paint (PSP)
b	=	coefficient of calibration curve for PSP
D	=	diameter of sonic-jet nozzle
I	=	luminescent intensity, count
I_0	=	peak intensity at beginning of PSP luminescence, count
$L(t)$	=	luminescent decay curve of PSP
P	=	pressure, kPa
q	=	coefficient of multiexponential equation
T	=	temperature, K
t	=	time
τ	=	lifetime of PSP, μs

Subscripts

av	=	average
SD	=	standard deviation

I. Introduction

PRESSURE-SENSITIVE paint (PSP) measurement is a notable technique used to acquire the pressure field on an aerodynamic model surface. This technique provides a way to obtain a simple, inexpensive, full-field image measurement of pressure with high spatial resolution[1,2] compared to conventional pressure field measurement with pressure taps. PSP measurement makes use of a sensor based on a photochemical reaction known as oxygen quenching of luminescent molecules. Recently, a lifetime-based measurement using a luminescent lifetime decay of PSP was spotlighted.[3–5] The advantage of the lifetime-based method is that the relation between lifetime and pressure is independent of illumination intensity, although the measurement accuracy of the intensity-based method is affected by nonuniformity in illumination. Furthermore, the lifetime-based measurement is theoretically insensitive to dye concentration and paint variegation of PSP. Hence, the windoff image (reference image) need not be acquired, and the quality of the processed pressure image is insensitive to misalignment in image registration. In addition, the measurement accuracy is not affected by photodegradation during an experiment.

The lifetime-based method makes use of the dependence of a luminescent lifetime of PSP on pressures. Two methods of measuring time-resolved fluorescence are in widespread use, namely, the time-domain and frequency-domain lifetime methods.[6] In this study, the time-domain lifetime method was applied. A lifetime imaging system is composed of a pulsed laser (or flash lamp) and a charge-coupled device (CCD) camera with a fast shutter. The system acquires the luminescent images during two gates when the luminescence of the dye decays. Pressure can be expressed by a function of intensity ratio of I_1 to I_2, where I_1 and I_2 indicate a luminescent intensity acquired with different two gate times of a CCD camera, respectively. Thus far, this conventional system could be applied only to the pressure field where temperature distribution on a model surface is uniform because PSP is temperature dependent on luminescent decay curves.[7]

In this study, we have developed a lifetime imaging system to measure simultaneously pressure and temperature image from a luminescent lifetime decay of PtTFPP-PSP. The lifetime-based PSP system for measuring pressure and temperature has already been proposed by Davies et al.; however, it is just a point scanning system[8] (SUPREMO), and the details of the measurement technique have still not been clarified.

A streak camera measurement was conducted to understand the basic characteristics of the luminescent lifetime of the PSP. The lifetime decay curves were acquired varying pressure and temperature, and their profiles were analyzed in detail. Based on the streak camera

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data and the error analysis, the method used to obtain pressure and temperature from three gated luminescent intensities was proposed. The three gated intensities of I_1, I_2, and I_3 were acquired during a lifetime decay of the PSP (Fig. 1).

Our lifetime imaging system (LIS) is made up of a pulsed laser and an intensified CCD (ICCD) camera.[9] The three gated times of the ICCD camera were determined with reference to the analysis of streak camera data. The lifetime images of a PSP painted coupon were acquired over various pressure and temperature combinations, and the relationship between pressure, temperature, and gated intensity ratios I_1/I_2 (I_1/I_3) were defined to obtain a pressure and temperature image by solving simultaneous equations. The measurement accuracy of the LIS was also evaluated with calibration data. The precisions of the pressure and temperature image reconstructed from the three lifetime images were calculated. Furthermore, a verification test was conducted to validate the performance of the LIS. The pressure and temperature fields induced by sonic-jet impingement flow were visualized. The obtained PSP data were compared with pressure tap data, and the measurement accuracy of the LIS is discussed.

II. Analysis of Lifetime Luminescent Decay of PSP

A. Experimental Setup for Streak Camera

PtTFPP-PSP is composed of Pt(II)meso-tetra(penta-fluorophenyl) porphyrine (PtTFPP), poly-isobutylmethacrylate-co-trifluoroethylmethacrylate (poly-IBM-co-TFEM),[10] and toluene. The emission peak of PtTFPP was 650 nm, and a green-emitting laser could excite the pressure-sensitive dye. The PSP was sprayed on an aluminum plate covered with white undercoat [Akzo Nobel, Aerodex Finish Matt (lead free) White], which worked as a screen layer to enhance the luminescence of PSP. The lifetime measurement system of a streak camera (Hamamatsu Phonics C5680) is shown in Fig. 2. The streak camera is a device used to acquire ultrafast light phenomena and obtain two-dimensional image data, that is, emission intensity vs time vs position (or wavelength). Time variation of the incident light intensity with respect to the wavelength can be measured in combination with a spectroscope, namely, time-resolved spectroscopy. The system was composed of the pulse laser, spectroscope, streak camera, illumination optics, timing controller, and a personal computer. The PSP pained coupon was set in a pressure- and temperature-controlled chamber and excited at 532 nm by a pulse laser (DS10H-532, Photonics Industries International, Inc.). Pressure in the chamber was controlled by a pressure controller, and the temperature of the coupon was changed by a thermocontroller using a Percier-device. The luminescence was introduced to the monochromator through an optical lens, neutral filters, and a laser-cut filter. After it passed through the monochromator, the emission was detected by the streak camera. Luminescent lifetime decay curves of the PSP were examined by varying pressure and temperature.

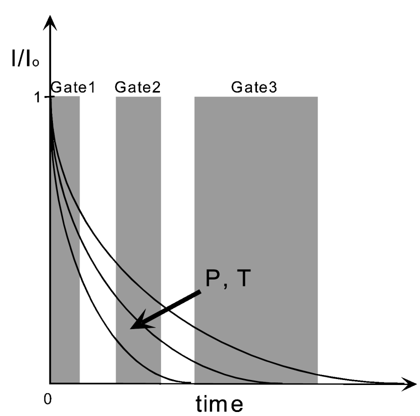

Fig. 1 Luminescent decay curves and three gated times of CCD camera.

B. Pressure and Temperature Dependence of Luminescent Lifetime Decay

The pressure dependence of luminescent decay for the PtTFPP-PSP at 293 K is shown in Fig. 3. Figures 3a and 3b show a linear and a log plot of data, respectively. I_0 indicates the peak intensity of luminescence, and the luminescent intensities were normalized by I_0. The whole shapes of the decay curves strongly depended on pressure, and the luminescent lifetimes decreased with increasing the pressure. The lifetime at 100 kPa was approximately 10 μs. As Fig. 3b shows, the decay curve at the low pressure of 10 kPa was approximately linear. On the other hand, the curves at high pressures became nonlinear, and I/I_0 drastically decreased in the early time region after a pulsed excitation. This transient behavior would be strongly related to the diffusion of an oxygen quencher, as Smoluchowski suggested (see Refs. 11 and 12).

The temperature dependence on the luminescence decay at 10 kPa is shown in Fig. 4. Figures 4a and 4b show a linear and a log plot of data, respectively. The decay curves were sensitive to temperature, and the lifetime decreased with increasing temperature because of thermal quenching. The decay curves in Fig. 4b were almost linear. The drastic fall of I/I_0 after a pulsed excitation was not seen at every temperature. Note, however, that the transient behavior as shown in Fig. 3b appeared at high pressure. The luminescent decay at high pressures included both oxygen and thermal quenching, and it was not easy to discriminate between the pressure and temperature dependence of them.

To comprehend the basic characteristics of the decay curves at high pressures, they were normalized by the luminescent decay at

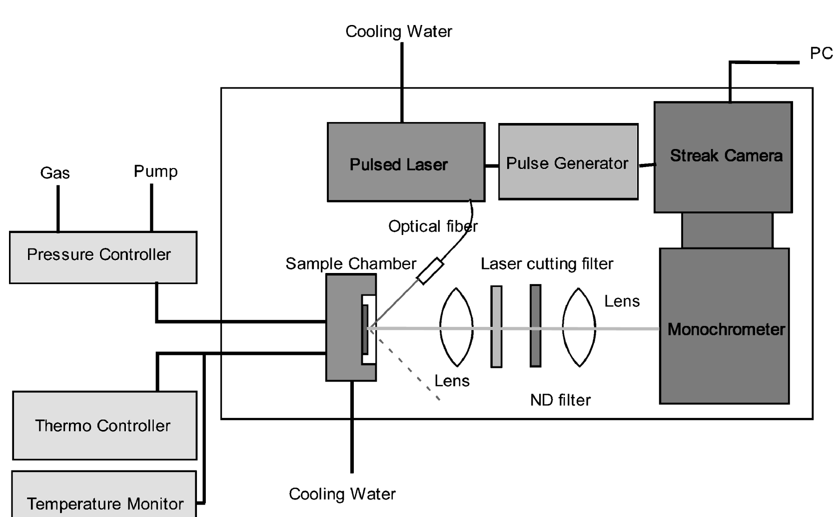

Fig. 2 Streak camera measurement system.

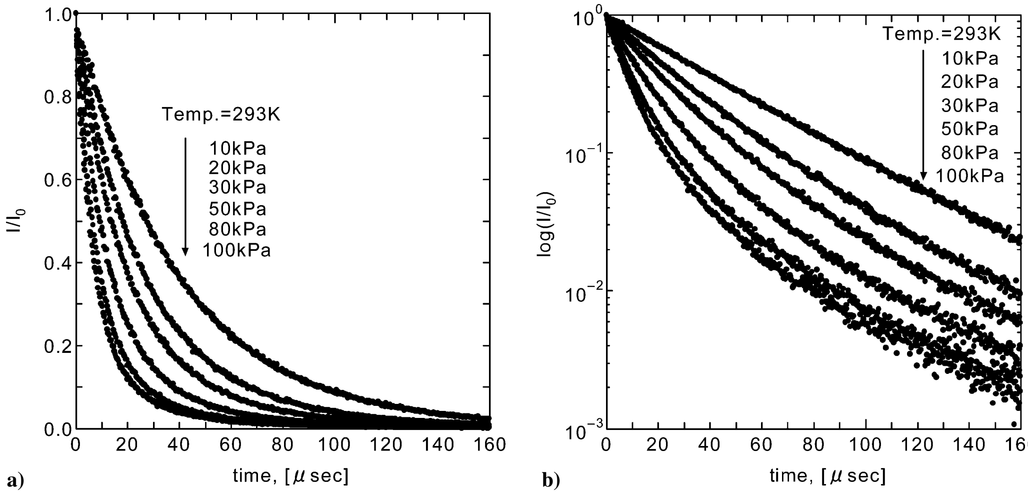

Fig. 3 Pressure dependence of luminescent decay curves of PtTFPP-PSP at 293 K: a) linear scale and b) log scale.

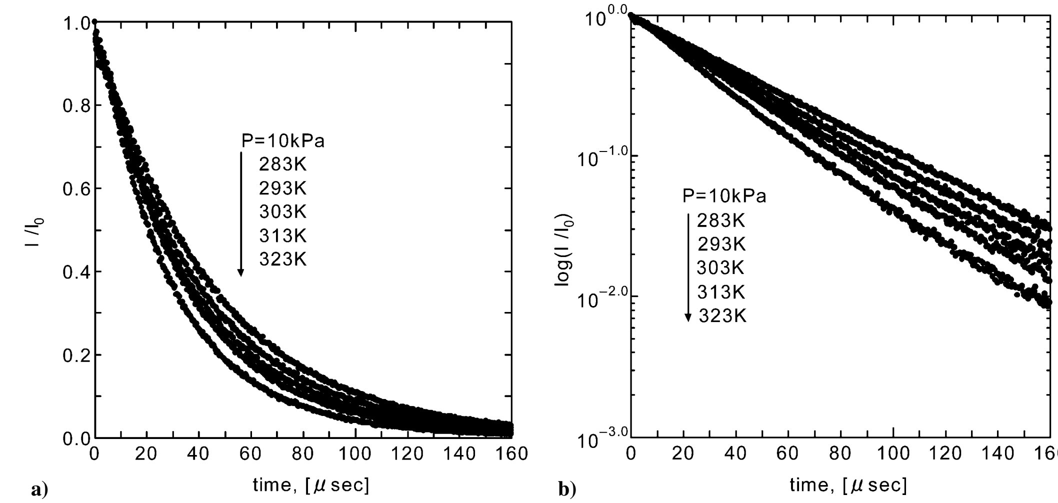

Fig. 4 Temperature dependence of luminescent decay curves of PtTFPP-PSP at 10 kPa: a) linear scale and b) log scale.

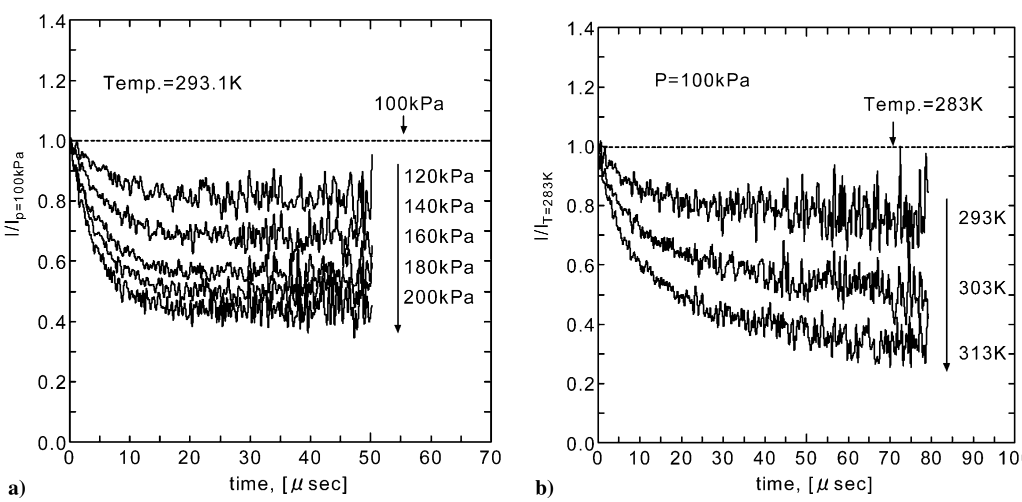

Fig. 5 Calculated ratios of PSP luminescent decay curve: a) pressure dependence and b) temperature dependence.

100 kPa. The calculated ratios ($I/I_{p=100\ \mathrm{kPa}}$) are shown in Fig. 5. The ratios rapidly decreased after the beginning of the luminescent decay and kept almost constant after approximately 15 μs. These profiles showed that pressure sensitivity of $I/I_{p=100\ \mathrm{kPa}}$ was large in the early time region of the decay. The temperature dependence was also investigated. The luminescent intensities at 100 kPa were normalized by the intensity at 100 kPa and 283.1 K. The ratios ($I/I_{T=283\ \mathrm{K}}$) gradually decreased from the onset of the decay. Obviously, the temperature sensitivity of $I/I_{T=283\ \mathrm{K}}$ differed from the pressure sensitivity of $I/I_{p=100\ \mathrm{kPa}}$, showing that the luminescent decay curve of the PSP could be expressed as a function of pressure and temperature.

C. Data Reduction for Obtaining Pressure and Temperature from Luminescent Lifetime Decay of PSP

A method to obtain pressure and temperature from the luminescent lifetime decay of PSP is discussed in this section. Generally, the gated intensity method[4] is used in the lifetime-based measurement.

This method can measure pressure using the relation between the pressure and gated intensity ratio (I_1/I_2). To obtain pressure and temperature, two simultaneous equations on pressure and temperature should be solved. Two gated intensity ratios were required to define the equations. Thus, three or four gated intensities need to be acquired. In the case of our system, three gated intensities of I_1, I_2, and I_3 were used to save time for acquisition lifetime images. The three intensities were calculated by integrating a signal of a lifetime decay curve over three different intervals, that is,

$$I_1 = \int_{\Delta t_1} L(t)\,\mathrm{d}t, \qquad I_2 = \int_{\Delta t_2} L(t)\,\mathrm{d}t, \qquad I_3 = \int_{\Delta t_3} L(t)\,\mathrm{d}t \tag{1}$$

where $L(t)$ and Δt are a luminescent lifetime decay curve and a gated time during a luminescent decay, respectively. To calculate these intensities, the decay curve should be defined by a function of time. However, the physical processes of the luminescent decay were very complicated and have not been theoretically clarified. To express the luminescent decay curves as a function of time, a multi-exponential fitting curve was adapted as follows:

$$L(t) = I_0\left\{\sum_{i=1}^{4} q_i \exp\left(-\frac{t}{\tau_i}\right)\right\} \tag{2}$$

where q_i and τ_i were the coefficients and lifetimes, respectively. These values were calculated by using the nonlinear least-square curve fitting. The curve-fitting models for PSP luminescent decays have been analytically studied by Ruyten.[13]

Based on analysis of streak camera data, the gated times were determined. At first, the gated times of Δt_1 and Δt_3 were deliberately determined, as follows:

$$\Delta t_1 = 0 - 0.8\ \mu\text{s}, \qquad \Delta t_3 = 30 - 82.8\ \mu\text{s}$$

These two gated times were given as I_1 equal to I_3 at 150 kPa and 293.1 K. I_1, which was obtained immediately after the beginning of luminescence, was almost insensitive to pressure and temperature. On the other hand, I_3 was intensively sensitive to both pressure and temperature. Here, we assumed that Δt_2 was between Δt_1 and Δt_3. An initial value of Δt_2 was approximately given as I_2 equal to $I_1(I_3)$ at 150 kPa and 293.1 K. The three gated times were used to calculate the gated intensities of I_1, I_2, and I_3. In this study, the gated intensity ratio of I_1/I_2 and I_1/I_3 were chosen. I_2 and I_3 became small at high pressure and temperature because the lifetime of PSP became short. Thus signal-to-noise ratio (SNR) of I_2/I_3 became low. On the other hand, I_1 was almost insensitive to pressure and temperature, and the SNR of I_1/I_2 (I_1/I_3) was better than I_2/I_3 or I_3/I_2. Therefore, the combination of I_2 and I_3 was not considered in this study. To correlate between pressure, temperature, and the gated intensity ratios, the following fitting model was applied. The least-square method was used to solve calibration coefficients

$$P = \sum_{i,j=1}^{3} a_{i,j} T^{j-1}\left(\frac{I_1}{I_2}\right)^{i-1} \tag{3}$$

$$P = \sum_{i,j=1}^{3} b_{i,j} T^{j-1}\left(\frac{I_1}{I_3}\right)^{i-1} \tag{4}$$

where $a_{i,j}$ and $b_{i,j}$ indicate calibration coefficients. To estimate optimum value of Δt_2, the error analysis was conducted. The $\pm 1\%$ error was deliberately imposed on the intensity ratio of I_1/I_2 and I_1/I_3. Pressure values were calculated by solving these equations, and the difference between reconstructed and targeted pressure was evaluated. The gated time of Δt_2 was iteratively changed until the error value of pressure was minimized. Finally, the estimated Δt_2 was 12–19.4 μs.

The calibration curved planes for I_1/I_2 and I_1/I_3 are shown in Fig. 6. These curved planes were described by a smooth function of pressure and temperature, respectively, and these characteristics were different from each other. This result could provide us the means to obtain pressure and temperature by solving these simultaneous equations. This analysis method could be easily extended to image processing of luminescent lifetime images.

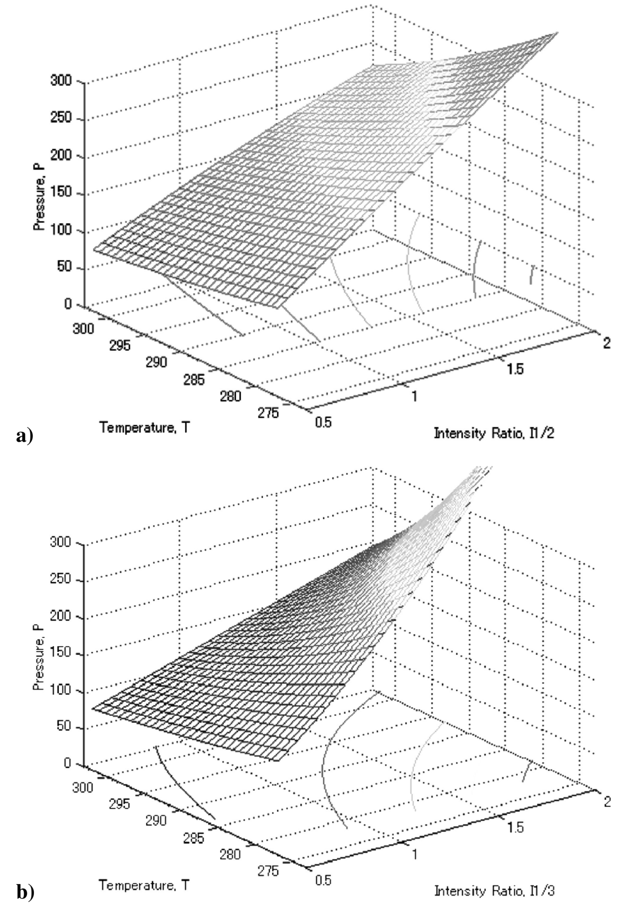

Fig. 6 Calibration curves of I_1/I_2 and I_1/I_3 estimated from streak camera data: a) I_1/I_2 and b) I_1/I_3.

III. LIS for PSP

A. Setup for LIS

The LIS shown in Fig. 7 was composed of a pulsed laser, an ICCD camera, a timing controller, optical components, and a personal computer to control the system. A PtTFPP-PSP coupon was illuminated by a pulsed laser, and the luminescence was acquired by the ICCD camera with a bandpass filter of 650 ± 20 nm. The ICCD camera (Model C8199), which was composed of an image intensifier and a cooled CCD camera, was manufactured by Hamamatsu Photonics. This CCD camera had 512×512 pixel resolution and 12-bit intensity resolution. Long-time exposure was possible due to the very low dark noise of the cooled CCD camera. Therefore, the CCD could obtain a sufficient electron charge by integrating the image several thousand times. The faint luminescence could be imaged by the ICCD camera with the good SNR. A gate time was variable from 20 ns to 10 ms, and gate repetition rate could change up to 200 kHz. Because the lifetime of PtTFPP-based paint was about 10 μs at 100 kPa, this ICCD camera was available for lifetime measurement.

The excitation light source was a laser diode pumped Q-switched Nd:YVO4 laser with a second harmonic generator, Model DS10H-532 from Photonics Industries International, Inc. The pulse width and the energy of the light source at the repetition rate of 1 kHz were 9 ns and more than 0.5 mJ, respectively. The laser beam does not influence the luminescence of PSP because the pulse width was very short compared to the phosphorescent lifetime of PSP. The master trigger source was a DG-535 manufactured by Stanford Research Systems. The trigger signals from the DG-535 control the gating of the ICCD camera and the Q-switching of the laser. An image acquisition sequence was written in an editable file of the image acquisition software. The file included the timing difference between two trigger signals, gate time, image intensifier gain (II gain), and the number of on-chip integration for each image as acquisition parameters. In acquisition, images were successively captured by making reference to the file.

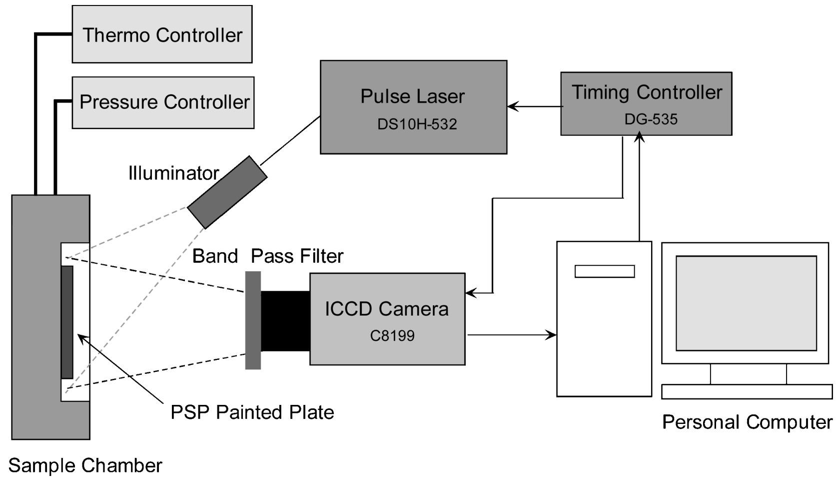

Fig. 7 Lifetime imaging system for PSP.

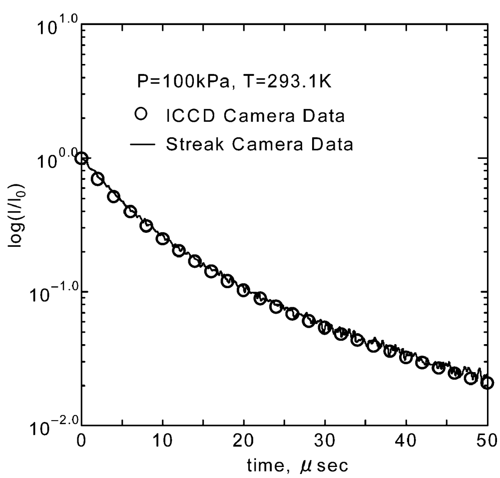

Fig. 8 Luminescent decay curves measured by ICCD camera and streak camera.

B. Measurement Accuracy of LIS

Calibration data were obtained with a PSP-painted coupon for evaluating measurement accuracy of the LIS. The pulsed laser illuminated the PSP plate, and the luminescent image from the PSP was acquired with the ICCD camera. The coupon was set in the pressure- and temperature-controlled chamber, and the luminescent images were examined varying pressure and temperature.

At first, to evaluate the performance of the ICCD camera, a luminescence decay of the PtTFPP-PSP was measured. The decay curve was compared with that acquired by the streak camera. The exposure time of the ICCD was 1 μs, and each delay time was set at the interval of 2 μs. As Fig. 8 shows, the decay curve acquired by LIS was in good agreement with that measured by streak camera, indicating that the characteristics of the streak camera were similar to those of the LIS.

With reference to the analysis of streak camera data, the gated times of I_1, I_2, and I_3 were set to 0–0.8 μs, 12–20.3 μs, and 30–73 μs, respectively. The frequency of laser pulse and the number of integrated times of the ICCD camera were set to 1 kHz and 1000 times, respectively. The curved planes were almost same as those measured by the streak camera. For reference, the coefficients of calibration curved planes are presented in Tables 1 and 2. To understand the characteristics of the curved planes in detail, the pressure and temperature sensitivity of the calibration curved planes are also presented in Figs. 9 and 10, respectively. The pressure sensitivities in Fig. 9 were approximately linear, and the inclinations of them increased with increasing temperature. The pressure sensitivity for I_1/I_3 was larger than that for I_1/I_2. In contrast, the temperature sensitivities were nonlinear and increased with increasing pressure.

Table 1 Coefficient a_{ij} for Eq. (3)

Coefficient $a_{i,j}$	Values ($\times$1000)
a_{11}	−1.082093575
a_{12}	0.006691089
a_{13}	−1.0238E−05
a_{21}	6.086600297
a_{22}	−0.036238136
a_{23}	5.48621E−05
a_{31}	−0.102931422
a_{32}	0.001014336
a_{33}	−2.3142E−06

Table 2 Coefficient b_{ij} for Eq. (4)

Coefficient $b_{i,j}$	Values ($\times$1000)
b_{11}	−2.045045756
b_{12}	0.013918075
b_{13}	−2.34619E−05
b_{21}	5.948070063
b_{22}	−0.037309633
b_{23}	5.94067E−05
b_{31}	8.509885005
b_{32}	−0.055245829
b_{33}	8.95975E−05

Table 3 Pressure reconstructed from calibration data at 293.1 K

P, kPa	T, K	P_{av}	P_{SD}	$P - P_{av}$	T_{av}	T_{SD}	$T - T_{av}$
100.0	293.1	98.7	6.2	−1.3	293.2	3.0	−0.1
125.0	293.1	124.1	5.8	−0.9	293.0	2.3	0.2
150.0	293.1	149.6	6.4	−0.4	292.9	2.2	0.2
175.0	293.1	175.7	8.2	0.7	292.8	2.0	0.4
200.0	293.1	201.8	7.7	1.8	292.7	1.7	0.5
225.0	293.1	226.3	9.8	1.3	292.9	1.7	0.2
250.0	293.1	251.1	8.7	1.1	293.2	1.5	0.0
275.0	293.1	274.0	11.5	−1.0	293.3	1.6	−0.2
300.0	293.1	297.0	11.3	−3.0	293.4	1.5	−0.3

Table 4 Temperature reconstructed from calibration data at 200 kPa

P, kPa	T, K	P_{av}	P_{SD}	$P - P_{av}$	T_{av}	T_{SD}	$T - T_{av}$
200.0	278.1	199.2	12.0	−0.8	278.4	3.3	−0.2
200.0	283.1	198.6	8.4	−1.4	283.5	2.3	−0.4
200.0	288.1	200.2	10.5	0.2	288.2	2.3	0.0
200.0	293.1	201.8	7.7	1.8	292.7	1.7	0.5
200.0	298.1	201.8	9.0	1.8	297.7	1.8	0.4
200.0	303.1	199.8	10.7	−0.2	303.3	2.0	−0.2

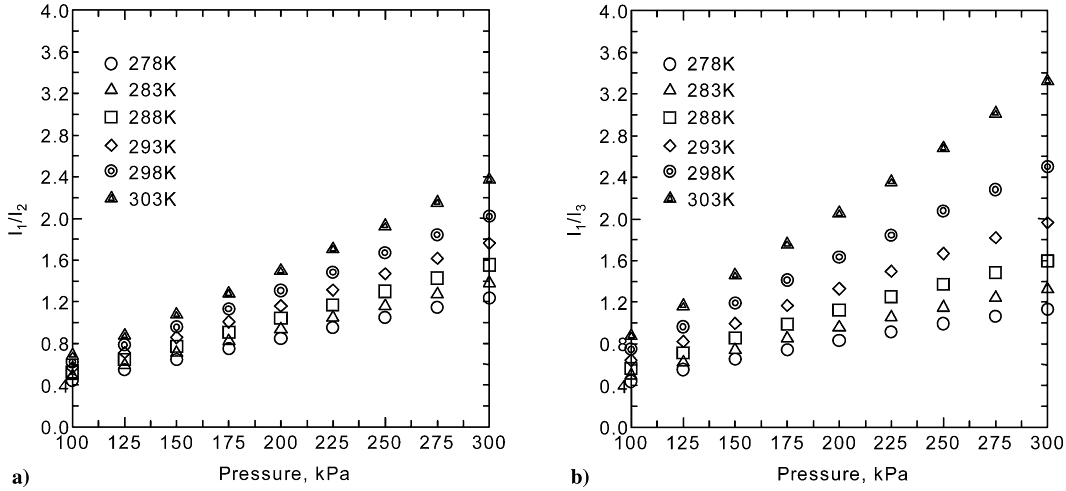

Fig. 9 Pressure dependence of I_1/I_2 and I_1/I_3: a) I_1/I_2 and b) I_1/I_3.

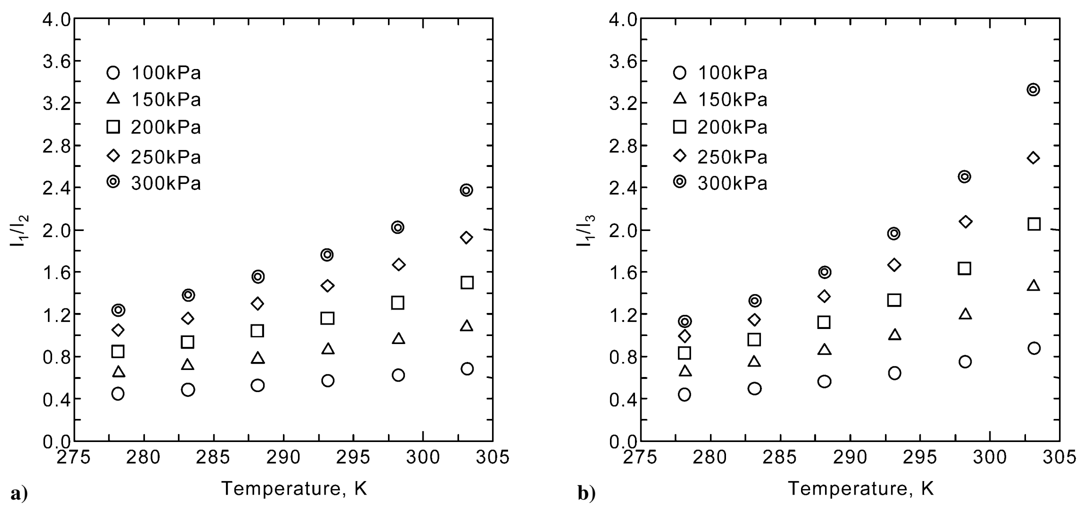

Fig. 10 Temperature dependence of I_1/I_2 and I_1/I_3: a) I_1/I_2 and b) I_1/I_3.

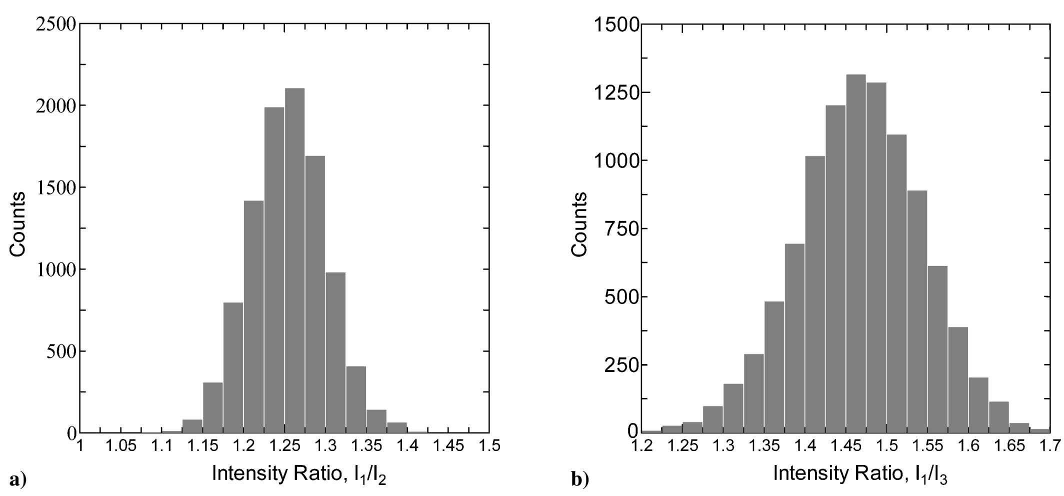

Fig. 11 Histograms for I_1/I_2 and I_1/I_3, P = 200 kPa and T = 293.1 K: a) I_1/I_2 and b) I_1/I_3.

To evaluate the measurement accuracy of this system, pressure and temperature were reconstructed from luminescent lifetime images using calibration-curved planes. The data points of 40,000 pixels (200 pixel × 200 pixels) in the image were examined. The average pressures (P_{av}) and temperature (T_{av}) of the images are presented in Tables 3 and 4, respectively. The error of pressure at 293.1 K was 1.8 kPa for 200 kPa. The difference between T and T_{av} at 200 kPa was 0.5 K.

The characteristic of PSP was almost uniform in these images. However, random error was not negligible. The histograms for intensities of I_1/I_2 and I_1/I_3 at each pixel are shown in Fig. 11. The data spread for I_1/I_3 was somewhat larger than that for I_1/I_2. The random errors estimated from luminescent images are also presented in Tables 3 and 4. The P_{SD} and T_{SD} in Tables 3 and 4 mean the standard deviation of pressure and temperature, respectively. The standard deviation of pressure (temperature) was calculated from difference between P_{av} (T_{av}) and pressures (temperatures) at each pixel. P_{SD} and T_{SD} were 7.7 kPa and 1.7 K at 200 kPa and 293.1 K, respectively. The random error would be due to a laser speckle pattern and the shot noise of the ICCD camera. Therefore, measurement accuracy of the LIS would be greatly improved if these error factors could be eliminated.

IV. Verification

A. Experimental Apparatus for Verification Test

Pressure and temperature fields induced by a sonic-jet impingement were visualized as a verification test. Figure 12 shows the photograph of the experimental setup. The experiment was done at the same optical setup as the calibration test. As shown in Fig. 13, the air jet was generated with a sonic nozzle, and the angle of centerline of nozzle to the PSP painted plate was 45 deg. The distance from the nozzle outlet to the plate is $2D$ (where D indicates a nozzle diameter of 4 mm), and the size of the plate was 25 mm $\times$ 25 mm. The total pressure and temperature in the chamber were 400 kPa and 296.1 K, respectively. The temperature of the PSP coupon before the impingement of the jet was 297.0 K. Pressure tap data were also measured to verify the measurement accuracy of the system.

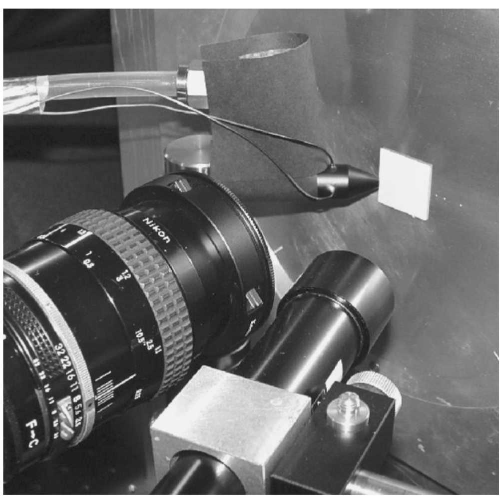

Fig. 12 Photograph of experimental apparatus.

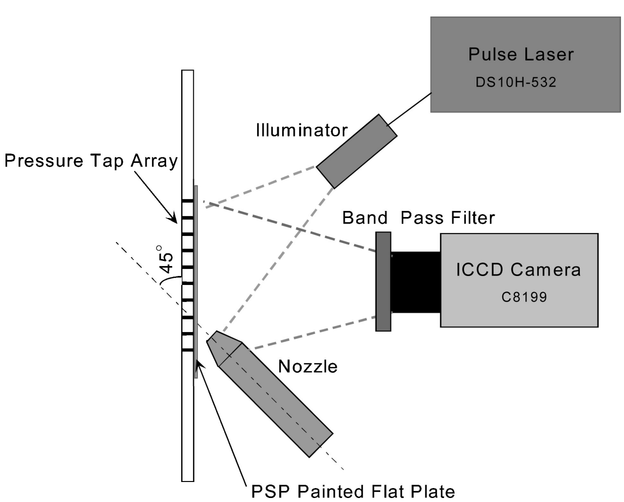

Fig. 13 Sketch of experimental apparatus.

B. Results

Figure 14 shows the images of I_1, I_2, and I_3 acquired in the experiment. The luminescent image of I_1 was fairly different from that of I_2 and I_3 because I_1 was insensitive to pressure and temperature as the streak camera data indicated. On the other hand, the ripple pattern due to photochemical processes of oxygen and thermal quenching was observed in the images of I_2 and I_3. Pressure and temperature image were converted from these three images by using calibration curved planes.

Pressure and temperature image measured by the LIS are shown in Fig. 15. The characteristic pressure image of sonic-jet impingement

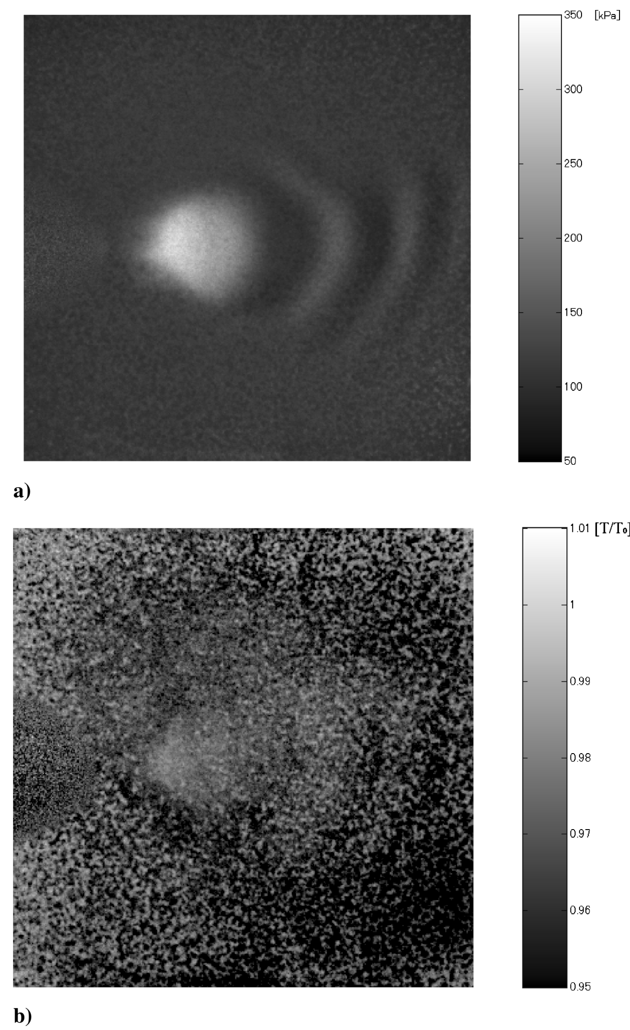

Fig. 15 Pressure and temperature field measured by LIS: a) pressure image and b) temperature image.

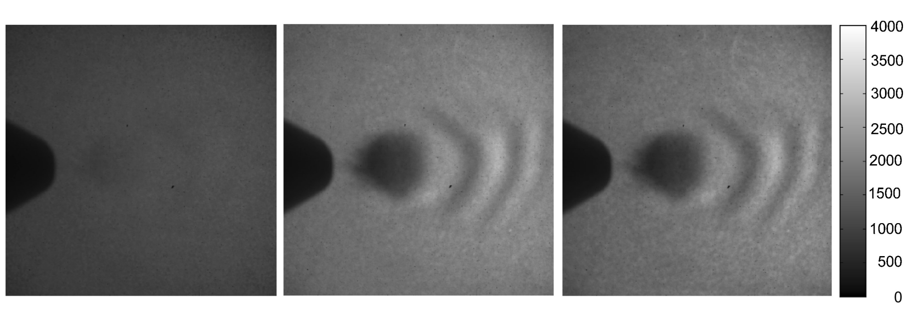

Fig. 14 PSP images acquired at three different gated times: a) gated time 0–0.8 μs, b) gated time 12–20.3 μs, and c) gated time 30–73 μs.

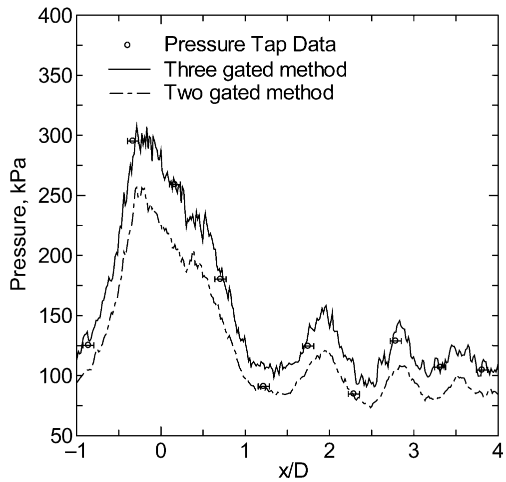

Fig. 16 Comparison of PSP data with pressure tap data.

is clearly visualized. The pressure image showed that the air jet intensively impinged on the flat plate and expanded to the downstream end. The crescent pattern due to the interference between an expansion and compression wave was visualized. The temperature image normalized by T_0 showed that the expanded air jet cooled off the plate. However, the temperature pattern was obscure owing to a low SNR. The plate made of aluminum had high thermal conductance. Thus, the temperature difference on the plate became small.

Pressure taps data were also acquired to estimate the measurement accuracy of the LIS. PSP and pressure tap data are shown in Fig. 16. The precision of pressure scanner (Pressure Systems Model 9010) was approximately 0.3 kPa. The error bars of pressure tap data were derived from size of the taps. The diameter of the tap was 0.5 mm. In Fig. 16, the profile obtained by a conventional lifetime method (two-gated intensity method) is also shown. This method does not include temperature correction of the PSP. It was assumed that the plate temperature was uniform and equal to the temperature just before measurement.

Obviously, significant errors between pressure tap and PSP data obtained by the conventional method were seen due to temperature dependence of PSP. In contrast, PSP data measured by the present method (three-gated intensity method) were close to the pressure tap data. Consequently, these results indicate that the LIS allowed us to measure pressure field regardless of the temperature dependence of PSP. However, a small error was still seen between the PSP and pressure tap data. According to analysis of calibration data, the standard deviation σ of the pressure was approximately within ± 10 kPa. Given twice standard deviation 2σ, the measurement accuracy became approximately ± 20 kPa. The rms difference was estimated from PSP data and pressure tap data. The rms difference was 12.1 kPa and less than 2σ, and pressure tap data were comprised within the measurement accuracy of the LIS. The measurement accuracy of this system would definitely be enhanced if the laser speckle pattern and shot noise of an ICCD camera could be reduced.[14]

V. Conclusions

We have developed an LIS to measure simultaneously pressure and temperature from the luminescent lifetime decay of PtTFPP-PSP. The obtained results are summarized as follows:

1) Analysis of PtTFPP-PSP by a streak camera showed that the luminescent lifetime decays were sensitive to both pressure and temperature. The pressure dependence of the lifetime decays was different from the temperature dependence of them. The rapid decay of the PSP luminescence after a pulsed excitation was sensitive to pressure. This transient behavior would be strongly related to a diffusion of oxygen quenching in a polymer matrix.

2) The method to measure simultaneously pressure and temperature from a luminescent lifetime decay of the PtTFPP-PSP was proposed. Pressure and temperature could be obtained from two-gated intensity ratios of I_1/I_2 and I_1/I_3. The three-gated intensities were determined by using streak camera data and error analysis.

3) We have built an LIS composed of a green-emitting pulsed laser and an ICCD camera. The ratioed lifetime images could be fitted with a smooth function of pressure and temperature, as analysis of streak camera data indicated. This could provide us the means to reconstruct pressure and temperature fields from the luminescent lifetime images.

4) Analysis of the accuracy of the LIS showed that the pressure and temperature images could be well reconstructed from three lifetime luminescent images. The difference between reconstructed and targeted pressure was some kilopascals in the pressure range of 100–300 kPa, and the standard deviation of pressure was approximately 10 kPa.

5) The pressure and temperature field induced by a sonic-jet impingement flow were visualized by using the LIS. PSP data agreed with pressure tap data, indicating that the LIS is a useful tool to measure the pressure and temperature images on an aerodynamic model surface.

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