Combined velocity and temperature measurements of natural convection using temperature sensitive particles

Satoshi Someya¹, Kaoru Tominaga², Yanrong Li³, Koji Okamoto⁴

1: Graduate School of Frontier Science, The University of Tokyo, Kashiwa & Energy Technology Research Institutes of AIST, Tsukuba, Japan, some@k.u-tokyo.ac.jp
2: Graduate School of Frontier Science, The University of Tokyo, Kashiwa, Japan, tominaga@vis.k.u-tokyo.ac.jp
3: Graduate School of Frontier Science, The University of Tokyo, Kashiwa, Japan, yanrong@vis.k.u-tokyo.ac.jp
4: Graduate School of Frontier Science, The University of Tokyo, Kashiwa, Japan, okamoto@k.u-tokyo.ac.jp

Abstract This paper proposes a combined method for two-dimensional temperature and velocity measurement in liquid and gas flows using temperature sensitive particles (TSPs), a pulsed ultraviolet laser, and a high-speed camera. TSPs respond to temperature changes in the flow and can also serve as tracers for the velocity field. The luminescence from the TSPs was recorded at 15,000 frames per second as sequential images for a lifetime-based temperature analysis. These images were also used for the particle image velocimetry calculations. The temperature field was estimated using several images, based on the lifetime method. The decay curves for various temperature conditions fit well to exponential functions, and from these the decay constants at each temperature were obtained. The proposed technique was applied to measure the temperature and velocity fields in natural convection driven by a Marangoni force and buoyancy in a rectangular tank. The accuracy of the temperature measurement of the proposed technique was ±0.35–0.40°C. The proposed approach can be applied to the flow of any working fluid by selecting a suitable base-sphere. The approach can be applied also to the combined measurement of oxygen concentration and velocity distribution by incorporating an oxygen-sensitive dye.

1. Introduction

Optical sensors are often used for evaluating the physical and chemical properties of multidimensional fields. Rapid development in the field of image sensors has made it possible to perform multidimensional measurements. Particle image velocimetry (PIV) is a well-established technique for the evaluation of multidimensional velocity fields with high temporal and spatial resolution (Stanislas et al. 2008). However, velocity measurements alone are insufficient in many applications. Combined or simultaneous measurement of the velocity field and a scalar quantity, such as temperature or concentration, is valuable for understanding fluid dynamics and for validating numerical models.

Laser induced fluorescence (LIF) measurements can be used to determine the temperature distribution in a liquid (Crimaldi 2008). For this purpose, the fluorescence intensity of rhodamine B is sufficiently sensitive to temperature, e.g., −1.54%/°C (Coppeta and Rogers 1998), and is sufficiently high to be detected using short exposure times. However, this intensity is affected by nonuniformity of the excitation light intensity and of the dye concentration. To counter these effects, it is necessary to introduce a temperature-insensitive dye and an additional camera into the LIF system, which is then referred to as the two-color LIF or dual-emission LIF (DeLIF) method (Sakakibara and Adrian 2004; Someya et al. 2005a).

Several studies have been carried out concerning simultaneous LIF/PIV measurement techniques (Funatani et al. 2004; Hoffmann et al. 2006; Cardenas et al. 2007). However, in most cases, these strategies have necessitated the use of a separate light source and several cameras, especially when seeking to carry out simultaneous DeLIF and PIV measurements. In addition, the applications of DeLIF are very limited, especially in oil and gas flows.

Phosphor thermometry is another option to visualize a temperature field. Luminophors, including phosphors, are typically rare earth-doped ceramics that emit light when suitably excited.
Luminophors have been investigated in several studies. The intensity and the lifetime of the emitted light are both dependent on temperature. For example, Alaruri et al. (1993) reported that the luminescent lifetime of Y$_2$O$_3$:Eu excited at 266 nm decreased from 897 to 0.049 µs when the temperature varied from 510 to 1,103ºC. To eliminate errors caused by nonuniformity of the excitation light intensity and of the dye concentration, a two-color method such as DeLIF or a lifetime approach should be applied.

Lifetime is an intrinsic property of luminophors, and is theoretically unaffected by variations in excitation light intensity and dye concentration. Lifetime-based methods have been used by Zelelow et al. (2003) and Hradil et al. (2002). Zelelow et al. (2003) performed one-dimensional measurements of temperature and pressure using a photomultiplier tube. Hradil et al. (2002) used a cooled CCD camera equipped with a microchannel plate. They used a multi-gated camera to capture time-averaged images, and thus the transient fluid flow could not be captured. Holst et al. (1998, 2001) also adopted the multi-gated approach, resulting in time-averaged superimposed images. Allison et al. (1997) and Kholid et al. (2008) reviewed phosphor thermometry in detail, especially for measurements at high temperatures.

There has been little research into the combined measurement of temperature and velocity distributions. Omrane et al. (2008) proposed simultaneous velocity and temperature measurements, using a method that required a stereoscopic intensified camera and a pulsed UV laser for the thermometry, in addition to a second double-shutter camera and a double-pulsed laser for the PIV. Molecular tagging thermometry and molecular tagging velocimetry (MTT/MTV) (Hu and Koochesfahani 2006) is a combined temperature-and-velocity measurement method, though it cannot be applied to oil. The use of liquid crystals (Dabiri 2009) is also a well-developed combined method. Liquid crystals are sensitive to temperature changes and only a color camera and a white light source are needed. However, this method can not be applied to a gas flow and the practical temperature range is only about 10ºC in many cases.

There have been no reports of combined measurement of velocity and temperature fields within a flow using a high-speed camera by the simultaneous use of PIV and luminescence-lifetime measurements. In this paper, a technique for combined measurement of velocity and temperature is proposed using only a single non-intensified high-speed camera and a single-pulsed UV laser. A temperature-dependent luminophor is incorporated into ion-exchanged spherical particles with diameters of 15 µm. These particles are small enough to accurately follow the fluid flow. Therefore, the particles can be used not only as a temperature indicator for the lifetime-based temperature measurements, but also as tracer particles for the PIV measurements (Astarita et al. 2009). The PIV analysis can be carried out using images common to the lifetime-based temperature measurements. The proposed approach can be applied to the flow of any working fluid by selecting a suitable base-sphere. The approach can be applied also to the combined measurement of oxygen concentration and velocity distribution by incorporating an oxygen-sensitive dye such as PtTFPP (platinum tetrakis(pentafluorophenyl)porphyrin), PdTFPP (palladium tetrakis(pentafluorophenyl)porphyrin), PtOEP (platinum(II) 2,3,7,8, 12,13,17,18-octaethylporphyrin), Ru(bpy)$_3^{2+}$ (tris(2,2-bipyridine) ruthenium(II)) and so on. The new approach is used to measure the velocity and temperature distribution in natural convection driven by a combination of a Marangoni force and buoyancy in a rectangular tank.

2. Experiments
2.1 Preparation of Temperature Sensitive Particles
The TSPs were prepared as follows: A mass of 100.0 mg of Eu(TTA) was dissolved in 20.0 ml of ethanol. A mass of 20.0 g of ion-exchange spheres was dipped into the solution and sintered gradually at a relatively low temperature, i.e., 6 h at 60.0ºC. Thus, it can be seen that the application of the dye to the ion-exchange spheres is quite easy. The base particles are standard spheres, such as those used for PIV. Their sizes are widely selectable from 3 µm to a few hundred µm, and their
density is usually around 1.01–1.03 g/cm\(^3\), which makes them suitable for use as tracers for liquid (oil/water) flow. For a gaseous flow, a hollow porous sphere made of SiO\(_2\) (e.g., Godball B-6C, Suzukiyushi Co., Ltd.) can be used as the base-sphere, with a true density of 2.1 g/cm\(^3\) and a bulk density of 0.22–0.40 g/cm\(^3\). The size of Godball is also widely selectable. In this study, ion-exchanged spheres (MCIGEL, Mitsubishi Chemical Co., Ltd.) with a mean diameter of 15 µm were selected.

The present TSPs do not include any binder material. Eu(TTA) dye does not elute to the oil, the working fluid in the present study. Rare-earth metal complex dyes, including Eu(TTA), have often been used in a dried condition as a temperature sensitive paint in aerodynamic research (McLachlan et al. 1995; Kavandi et al. 1990; Wade et al. 2003; Heyes et al. 2006; Mitsuo et al. 2006). Thus, the TSPs are painted particles without any binder which can work as functional tracers. The luminescence of Eu(TTA)-doped TSPs exhibits a high intensity and a lifetime of sufficient duration to enable detection by a high-speed camera without an image intensifier. An image intensifier system suffers from an intrinsic delay time of its own, and the luminescent screen in front of the image sensor exhibits inhomogeneous and nonlinear behavior. The luminescence lifetime of the screen material is generally long (>20 µs), except in the case of P46 material, and the decay time of the image intensifier system increases with total incident light intensity, i.e., the total intensity of luminescence from the TSPs. Since the luminescent lifetime measured using an image intensifier system may show a dependency on the excitation intensity, such devices are not appropriate for measurement of a transient temperature field, and are used primarily for time-averaged measurements.

In this study, a high-speed CMOS camera without an image intensifier was selected. The present EuTTA-based TSPs can be used between 0 to 120°C with a non-intensified high-speed camera (Photron SA1.1, Photron Co., Ltd. (HighSpeedStar6, LaVision Co., Ltd.); MicroNikkor 105 mm, Nikon Co., Ltd.).

### 2.2 Combined Measurement using TSPs and a High-Speed Camera

The concept of this novel TSP method is presented in Fig. 1. Time is indicated on the horizontal axis, and the vertical axis shows the relative intensity of luminescence normalized by its initial value. The gray columns in Fig. 1 indicate the integrated luminescence intensity for each image frame. The luminescence at the moment of excitation is not included in any of the frames in order to avoid noise caused by fluorescence from other materials in the system. Each image frame was recorded using a high-speed camera, and the dead-time between frames was 100 ns.

In the TSP method, we set the interrogation window as in the PIV method. In the PIV method, it is assumed that the particles in the interrogation window move with the flow, while maintaining the same pattern. The spatially-averaged displacement of particles in the interrogation window is then calculated. For the temperature analysis, the TSP method assumes that the temperature in the interrogation window is uniform and constant during the exposure time of the sequential images. At high temperature, the image intensity in the interrogation window decreases quickly. The lower the temperature is, the longer the decay time of the intensity is.

Pulsed excitation light was used for the lifetime measurements, where the decay constant was simply estimated from the intensity ratio between two or more time-sequential image frames within the luminescence decay period associated with one pulse. The luminescence intensity is given by Eq. (1), where \(\tau\) is the decay constant, and \(I_0\) is the initial intensity in the first image of a sequence of images.

\[
I = I_0 e^{-t/\tau}
\]

The decay constant is a function of temperature. As shown in Fig. 1, the temperature in each interrogation window area can be estimated from the decay constant after each excitation. The ratio of the intensity change is calculated using the mean intensity in each interrogation window.

The particle image pattern in each interrogation window is also analyzed by PIV. When the velocity is too small to detect any displacement of particles in images recorded during a single decay period,
as for Pattern A in Fig. 1, PIV analysis is carried out by comparing the first images recorded immediately after successive excitations. The temperature changes with the flow and the movement of particles due to convection; therefore, Pattern A is the simplest case. The dynamic range can be controlled separately for the temperature and for the velocity measurement. When the velocity is sufficiently large that significant particle movement occurs during a single decay period, as shown in Pattern B in Fig. 1, the velocity is measured by comparing the first image following the excitation pulse to the first of the subsequent images to show a 1-3 pixel movement. Highly time-resolved PIV can also be carried out, in which the velocity field is calculated from a few images (e.g., 1st, 5th and 9th) for a single excitation pulse. The amount of particle movement between two sequential images should be negligible (i.e., less than 1.0 pixel). During temperature measurements, small particle displacements were ignored in the calculations, although it is better to track the particles in order to more accurately measure the decay constant. The technique developed here makes it possible to evaluate the velocity and temperature fields simultaneously while using only one camera. Moreover, in the approach of Pattern B, it offers the advantage that highly time-resolved PIV can be carried out without the use of a high-pulse-frequency laser. Thus, the combined PIV-TSP method is not only suitable for time-averaged measurements, but also for simultaneously obtaining time-series data for temperature and velocity. In the present study, we chose the simplest case of natural convection, as exemplified by Pattern A in Fig. 1.

Fig. 1 Basic concept of the TSP method for combined measurement of temperature and velocity

2.3 Experimental Setup
Figure 2 shows a schematic diagram of the experimental apparatus. In this study, we carried out the experiments in a simple system comprising a rectangular quartz cavity. The working fluid was silicone oil, 10 cSt (KF96-10, Shin-Etsu Chemical Co., Ltd.). The thermo-physical properties of
such oil are well known and are very stable. The surface tension gradient of the oil, $\gamma_t$, was previously measured to be $-0.0765 \times 10^{-3}$ Nm$^{-1}$K$^{-1}$, and its surface tension was $19.595 \times 10^{-3}$ Nm$^{-1}$ at 25°C (Someya et al. 2005a, 2005b). In such a situation, the Marangoni and Rayleigh numbers are defined as $Ma=\gamma_t \Delta TH/\mu \kappa$ and $Ra=g\beta \Delta T(H)^3/\nu \kappa$, respectively. Here $\mu$ is the dynamic viscosity, $v$ is the kinematic viscosity, $\kappa$ is the thermal diffusivity, $\beta$ is the thermal expansion coefficient, $g$ is the gravitational acceleration, $H$ is the height of the oil layer, $\Delta T$ is the temperature difference, $\gamma_t$ is the absolute value of the surface tension gradient with respect to temperature, and $\lambda$ is the thermal conductivity. The thermo-physical properties are summarized in Table 1.

Table 1 Thermophysical properties of silicone oil

<table>
<thead>
<tr>
<th></th>
<th>$\rho$</th>
<th>$v \times 10^{-6}$</th>
<th>$\lambda$</th>
<th>$c_p$</th>
<th>$\beta \times 10^{-3}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>KF96-10</td>
<td>935</td>
<td>10</td>
<td>0.14</td>
<td>1674</td>
<td>1.06</td>
</tr>
</tbody>
</table>

The experiments were carried out with a cavity with a fixed width and height of $W=20$ mm and $H=20$ mm, respectively. The length of the cavity was 100 mm. All walls were coated with a fluorocarbon resin that was oil-repellent, thus minimizing the meniscus at the interface between the silicone oil and the wall. The flow was assumed to be two dimensional. Thermal radiation from the front walls was neglected. The heater and the cooler were made of copper, and the temperatures $T_h$ and $T_c$ were controlled by temperature regulator baths. The temperature difference, $T_h-T_c$, was maintained at zero during calibration of the TSP method and was varied systematically during the experiments. The temperature in the oil layer was also monitored by two thermocouples, which were set at the center of the cavity at depths of 5 and 15 mm from the surface. The natural convective flow within a 2-D vertical cross-section of the cavity, 15 mm from the front glass wall, was visualized by illuminating with a laser light sheet. The traceability of the TSP particles was considered to be high because their Stokes number is quite small (Visualization Society of Japan 2002). The laser light source was a pulse-laser (third YAG harmonic, 355 nm, 10 mJ, 25 Hz, Newwave Research Co., Ltd.). The laser light sheet was formed using a cylindrical lens. A harmonic filter was placed in front of the lens to cut off leaking visible light (532 nm) due to the second harmonic of the YAG source. The thickness of the laser sheet was less than 1 mm. The field of view of the camera was approximately 22 mm×22 mm. Its frame rate was set at 15,000 frames per second (fps) and its spatial resolution was 512×512 pixels.

The laser and the high-speed camera were controlled by a pulse generator. The timing chart of the TSP measurement system is shown in Fig. 3. Thirty image frames were captured sequentially in an
interval of only 100 ns, and six of these images were used for the analysis. Exposure of the first frame began 1.0 µs after the excitation pulse in order to avoid noise that occurred immediately following excitation due to reflection or fluorescence emitted from the particle base resin or from dust or other ambient materials. The exposure time of each frame was 66 µs.

3. Results and Discussion

3.1 Calibration procedure

The relation between the intensity ratio, $I/I_0$, and the elapsed time, $t$, was investigated in the calibration test using the oil-filled cavity shown in Fig. 2 and the high speed camera. The temperature difference, $T_p-T_c$, was maintained at zero during calibration. The temperature of both walls was changed from 22 to 52°C at intervals of about 3°C. Sequential images were captured five minutes after the temperature of the oil (which was monitored by the thermocouples) became constant and uniform. As mentioned above, thirty sequential images were captured at 15,000 fps, beginning 1 µs after each excitation pulse. Figure 4 shows an example of an image captured at 26.0°C. Illumination was from the bottom of the container, and the excitation intensity decreased gradually towards the free surface due to absorption by the TSPs and the oil. The particle images were somewhat blurred at the free surface due to reflection and the presence of a residual meniscus at the walls.

The decay constant was evaluated as follows:

1) The spatially-averaged intensity ratio, $I/I_0$, was calculated within each interrogation window of $16 \times 16$ pixels with a 50% overlap of each ambient interrogation window.
2) The relation between elapsed time and the spatially-averaged intensity ratio was fitted to an exponential curve using a least-squares method, and the local decay constant for each interrogation window was determined. The six images used in the analysis corresponded to a combined time duration of 396 µs, during which almost no particle movement occurred.
3) Steps 1 and 2 were repeated for different temperature conditions and the temperature dependence of the decay constant was determined.

The relationship between the elapsed time and the intensity ratio in an interrogation window at the center of the image is shown in Fig. 5 for temperatures of 26.0–46.2°C. The mean intensity in the interrogation window was found to decrease by a factor of $1/e$ in about 280–222 µs. The solid lines were calculated by the least-squares method using six sequential images. The experimental data, however, could not always be well fit to Eq. (1), which corresponds to a first-order reaction. Over a wider range of temperatures, the experimental data may depart from this simple relation. It has been reported that a double-exponential function or an empirical function is sometimes required to produce good fits (Brubach et al. 2009; Bai et al. 2008; Albelda et al. 2003; Mills et al. 2006).
However, in the current study, it was found that the data could be well represented by a single exponential curve if an additional constant, $C$, was included, as shown in Eq. (2). The values of $C$ required to produce the fits shown in Fig. 5 were in the range 0.989–0.992, which are close to 1.0. $C$ is referred to as the “offset coefficient”, and has been applied for lifetime measurements using phosphor thermometry (Brubach et al. 2007).

\[ \frac{I}{I_0} = C e^{-\frac{t}{\tau}} \]  

(2)

Fig. 5 Relation between time and intensity ratio

The decay constant, $\tau$, was found to decrease with increasing temperature, and was 284.5 µs at 22.3°C, and 217 µs at 49.0°C, which yields a temperature sensitivity of -2.53 µs/°C. The curve-fitting coefficients for the least-squares approximation in Fig. 5 were 0.999 for all temperatures. The decay constant, $\tau$, and the constant, $C$, were calculated for each temperature and for each interrogation window, from thirty-three sets of sequential images. The residuals of the measured values of the intensity ratio from the calculated decay curves ranged from 0.0001 to 0.0003 for all temperatures and interrogation windows.

The relationship between temperature and the decay constant at different pixel positions is shown in Fig. 6. The upper left corner of Fig. 4 represents the (0,0) position and (256,256) corresponds to the center of the image. As shown in Fig. 6, the relation between temperature and the decay constant showed a slight dependence on pixel position, and could be approximated by Eq. (3). Here, $a$, $b$ and $c$ are constants calculated by least-squares fitting. The solid and dotted lines in Fig. 6 show...
examples of the obtained fitting curves. The maximum residual of the calculated equation was 4.1~4.5×10^{-3} among all interrogation windows. The curve fitting constants were greater than 0.998 for all interrogation windows. The value of the function \( \ln(1/\tau) \) of the decay constant was 8.182 at 26.0°C, and 8.411 at 46.2°C, yielding a temperature sensitivity of -11.34×10^{-3}/°C, at the position (256,256). The residual, 4.1×10^{-3}~4.5×10^{-3}, corresponded to 0.35~0.40°C. Figure 7 shows the calculated temperature distribution using the calibration images at 46.2°C. At each calibration-referenced temperature, we obtained back-calculated temperature maps and the maximum error range was less than ±0.4°C.

\[
\ln \left( \frac{1}{\tau} \right) = a T^{-2} + b T^{-1} + c \tag{3}
\]

\[
k_{\text{all}} = k_0 + k_1 e^{-\varepsilon/kT} \tag{4}
\]

\[
\ln \left( \frac{1}{\tau} \right) = T^{-1} \tag{5}
\]

It has been previously shown (Coyle and Gouterman 1999; Nagl et al. 2009) that, for most luminescence-based temperature sensors, the temperature dependence of the decay constant can be modeled by an Arrhenius equation, as shown in Eq. (4), which has the form of a single exponential decay. Here, \( k_{\text{all}} \) is the total observed rate constant, which is the inverse of the observed decay constant, \( \tau \). The quantity \( k_0 \) is the radiative rate constant, and \( k_1 \) is the non-radiative rate constant. \( k \) is the Boltzmann constant. Eq. (5) has been used to describe the temperature dependence of the decay constant. However, as shown in Fig. 5, in the present case it could be well modeled by Eq. (3). As is the case for Eq. (1), Eqs. (4) and (5) are satisfied only when the emission is either a first-order process or is at least dominated by a single long-period decay process.

As long as reasonably clear particle images can be recorded, the lifetime method is fundamentally unaffected by nonuniformity of the laser illumination or variations in the concentration of particles. However, the signal/noise ratio does depend on the signal intensity. If the constants \( a, b, \) and \( c \) in Eq. (3) are determined locally, however, the measurement system would become robust to optical noise.

3.2 Combined Measurement of Natural Convection

Figure 8 shows a contour map of the temperature distribution found for natural convection. The temperature at the hot wall was set at 50.0°C and that at the cold wall was 24.0°C. The Marangoni number was calculated to be 4.822×10^4 and the Rayleigh number was 2.451×10^6. Under these conditions, both the driving force due to the surface tension and the buoyant force were large. The grey scale represents the temperature range 29.0 to 47.0°C, and the contour lines are drawn at 2.0°C intervals. Figure 8 was produced from individual sequential images and was not time-averaged. The calibration and temperature estimations were each carried out in a 16×16 pixels region with a 50% overlap. No additional spatial averaging or interpolation was performed. The spatial resolution of the captured image was 43 µm/pixel, and that of the temperature estimation was 344 µm.
As mentioned in the previous section, the displacement of particles during the period of luminescence decay was not taken into account for the temperature estimations. In fact, no particle movement could be detected in the sequential images recorded at a frame rate of 15,000 fps. As seen in Fig. 4, it was difficult to obtain well-focused images for temperature measurement near the free surface and the walls, due to reflection and the presence of an unexpected residual meniscus. Therefore, the thin boundary layer with the high temperature gradient could not be clearly visualized. However, the temperature seems to have been successfully estimated in other regions of the container. A high-temperature region appears near the upper part of the hot wall, and an extended cold region near the lower part of the cold wall. These temperature distributions are caused by the buoyancy driven flow. Just below the free surface, a thin layer of hot liquid with a relatively large temperature gradient exists. Beneath this layer lies a colder layer followed by another hot region. Such circulating flow near a free surface is typical of Marangoni convection in a relatively deep cavity, and has been previously reported by Someya et al. (2003, 2005a, 2005b). Thus, this situation corresponds to a combination of two types of natural convection, the first characterized by a large-scale circulating flow within the main body of the fluid, and the second by a thin circulating flow region near the surface, due to a combination of large Ma and Ra numbers.

The velocity distribution was also calculated using the PIV method between the first images of different sequential image sets, as illustrated by Pattern A in Fig. 1. The calculated velocity map is presented in Fig. 9, which was produced using a recursive PIV method. The size of the interrogation window was reduced from 32×32 pixels to 8×8 pixels. Due to the Marangoni force, the velocity and the velocity gradient at the free surface were large in the present natural convection. No particles were observed to have moved in any six sequential images recorded at 15,000 fps. At this frame rate, a 1-pixel movement corresponds to a velocity of about 750 mm/s at the present spatial resolution. However, the velocity in the oil was much smaller than this. At the center position, just below the free surface, the particles moved about 2.4~2.5 pixels between images recorded at 25 fps, i.e., between the first images after each excitation pulse.

Consistent with the temperature distribution, there was a large circulating flow pattern driven by the buoyancy in the entire cavity, and a thinner circulating flow near the free surface driven by the surface tension. The point of confluence of these two flow regions was near the top of the hot wall. The downward flow near the top of the cold wall divided into two different circulating flows – downward flow along the wall and the returning flow below the free surface. In the latter case, the stream of cool liquid returning to the hot wall gave rise to the low temperature region below the free surface, as seen in Fig. 8. This is a typical feature of Marangoni convection and has been previously reported by Someya et al. (2003, 2005a, 2005b). Thus, the measured temperature and velocity distributions were consistent with a system exhibiting combined natural convection.

3.3 Limitations and advantages

These results indicate that the TSPs have potential as useful tracers in hybrid-measurement systems for temperature and velocity. In addition, only a single camera is required for such measurements. The working fluid used in this study was oil; however, due to their small sizes and the range of base-particle types available, TSPs could also be applied to the study of gaseous or water flow patterns.

As mentioned in Section 2.1, the Eu(TTA) dye does not elute to the oil. Eu(TTA) incorporated into ion-exchange material also elutes very little to water. TSP particles with Eu(TTA) can be used with oil, water and gas at any temperature less than the decomposition temperature of Eu(TTA) and the melting point of the base-particles. However, there are many other kinds of temperature sensitive luminescent dyes. For example, PtTFPP is insoluble in ethanol and water but, unlike Eu(TTA), it is soluble in toluene. Ru(bpy)$_3^{2+}$ is also an option and the luminescent lifetimes of PtTFPP, PdTFPP and Ru(bpy)$_3^{2+}$ also depend on the oxygen concentration. Therefore, there are many choices when selecting a suitable luminescent dye. Godball is often used as a tracer in gas flow studies. It is also a highly adsorbent base-particle. For very-high-temperature flows, inorganic phosphor particles can
be used. Thus, the proposed TSP particle method has the potential to be applied to all kinds of working fluids.

The measurements reported in this paper correspond to the situation shown in Pattern A in Fig. 1, and no temporal averaging was involved. Using the approach shown in Pattern B, highly time-resolved combined measurements can be carried out using a laser with a relatively low repetition rate. This method is similar to that for highly time-resolved PIV, and has the advantage of requiring only a single low-pulse-rate laser. Application of this approach to an unsteady flow is currently underway and will be presented in a future report.

There are also problems remaining to be solved. The multi-exponential factors should be considered in order to develop a more accurate and powerful measurement technique. However, as shown in Fig. 5 and described in Section 3.1, the simple approximation worked well for the range of experimental conditions used in the present study. In situations where single-exponential decay characteristics prevail, the approximation of a single exponential curve can be used with suitable fitting parameters. The fitting parameters should be the same for the data obtained at unknown temperatures and all calibration data.

For the case of Pattern A used in the present study, images immediately following consecutive excitations were used to analyze the velocity. The velocity was calculated by a cross-correlation based recursive PIV method. In the case of Pattern B, as mentioned in Section 2.2, the amount of particle movement between two sequential images following a single excitation pulse should be negligible. The velocity is measured by comparing the first image following the excitation pulse to the first of the subsequent images to show a 1-3 pixel movement. In such a situation, it is possible that the intensity decrease may introduce some errors in the PIV results, and this is something that should be investigated in a future study.

The TSP method described in this paper is a “combined” technique for velocity and temperature measurement. However, although temperature and velocity are calculated from common images, strictly speaking the measurements are not simultaneous. The frame rate of camera can be freely varied so long as clear images can be recorded. In order to estimate temperature, we do not need to use all the images recorded during a single decay period. The number of images used to calculate the temperature depends on the image quality and the required time resolution. Since the signal-to-noise ratio becomes poor at lower image intensity, the number of images used for the temperature measurement should be optimized to reduce the effect of noise. When the required time resolution of the temperature measurement is \( t_a \) [µs], the camera speed should be faster than \( 4 / t_a - 2 / t_a \times 1000000 \) fps. In addition, the decay time of the luminescent dye should be longer than \( t_a \). A common high-speed camera has a trade-off between spatial resolution and time resolution. Thus, the applicability and limitations of the proposed technique depend on camera specifications such as sensitivity, spatial resolution, frame rate, and pixel linearity.

4. Conclusion

The aim of this study was to develop a combined measurement method to determine instantaneous temperature and velocity distributions, which can be applied to liquid and gas flows over a relatively wide temperature range.

Temperature-sensitive particles were developed as tracer particles, prepared from ion-exchange spheres treated with a dye without a binder material. Since temperature is known to affect the luminescence lifetime of these particles, the decay in light intensity was captured by a high-speed camera without an image intensifier. The normalized intensity was represented by a single exponential function of elapsed time, and the relationship between the temperature and the decay constant was represented by an empirical function. The temperature coefficient was calculated for each local position with an accuracy of \( \pm0.35-0.4°C \). Simultaneously, the velocity field was calculated by the PIV method. The proposed combined technique was applied to the study of natural convection in a liquid. The measured temperature and velocity distributions were found to
be consistent with each other, thus confirming the effectiveness of this method.

**Acknowledgement**

This work was supported by Grant-in-Aid for Young Scientists (B) 20760129

**References**


