# Simultaneous Velocity and Temperature Measurements inside Suspended Droplet in Hot Air Flow using TSPs & PIV


| | | | |
|---|---|---|---|
| 東京大学 | 周　騫 | Qian ZHOU | Member |
| 東京大学 | | Nejdet ERKAN | Member |
| 東京大学 | 岡本　孝司 | Koji OKAMOTO | Member |



Abstract: Containment spray cooling is a part of nuclear reactor safety system, which can condense the steam into liquid within the containment structure to realize depressurization and temperature decrease during a reactor accident. In order to investigate the space spray mechanism, which is the heat and mass transfer between falling droplets and surrounding gas, 2-D temperature distribution and velocity field inside a suspended water droplet in upward hot air stream was measured using combined temperature-sensitive particles (TSPs) and particle image velocimetry (PIV). EuTTA dyed particles were adopted as phosphorescence sensors of temperature and as tracers for the PIV. Calibration experiments were conducted to obtain the correlation between water temperature and phosphorescence decay constant for measurement. As a result, internal flow circulation induced by Marangoni convection and air flow shear force was observed inside the droplet. Due to water mixing enhancement caused by this circulation, the droplet temperature was kept about 40℃ and the evaporating time was about 1 minute.



**Keywords**: TSPs, PIV, Phosphorescence, Measurement, Droplet, Internal Circulation


## 1. Introduction

A containment vessel is a reinforced steel structure enclosing a nuclear reactor. It is designed, in any emergency, to contain the escape of radiation to a maximum pressure in the range of 410 to 1400 kPa, as the fourth and final barrier to radioactive release.

In case of a severe accident in a LWR, a probable pipe failure, therewith coolant leakage, may result in a high temperature and pressure circumstance inside the containment. [1]

The thermal-hydraulic plays a crucial part in Nuclear Engineering research and power plants design. For experimental researches related to fluid mass and heat transfer, a feasible technique of simultaneous measurement of temperature and velocity with high spatial accuracy and sensitivity will be very helpful to a better understanding of heat and mass transfer mechanism by experimental research. During a containment spray cooling process, temperature decrease and depressurization is realized by heat and mass transfer between falling spray water droplets and surrounding gas mixture.

In our research, TSPs technique for temperature measurement was developed for fluid, which can be available for simultaneous velocity measurement using PIV.


連絡先: 周騫、〒113-8654 東京都文京区本郷７丁目３－１、東京大学工学系研究科、原子力専攻
E-mail: qzhou@vis.t.u-tokyo.co.jp


Optical sensors are widely used for temperature and pressure measurements in multidimensional fields. Luminescence sensors under pulsed laser excitation for temperature measurements mainly include two kinds of measuring methods, intensity based laser induced fluorescence (LIF) [2, 3] and lifetime based phosphor thermometry [4]. In our research, Europium (III) thenoyltrifluoroacetonate (EuTTA) dyed 10 μm particles were adopted as sensors of temperature and as tracers for the PIV. Combined method for 2-D temperature and velocity measurements was used for suspended droplet evaporating investigation. Similar experimental research was conducted by Someya et al. in 2011 with silicone oil as applied fluid. [5] In previous research, calibration to obtain the correlation between decay constant and local fluid temperature was conducted in the same device with measuring test section.

## 2. Experimental

### 2.1 Temperature-sensitive particles

The PIV-TSP method for simultaneous velocity and temperature measurements has been developed and investigated in the past decade. Since the particles with temperature-sensitive dye adopted as sensors are smaller than common PIV particles, the measurement can achieve a higher spatial resolution. Similar investigation has already been conducted in silicone oil, which does not elute EuTTA dye [5]. In order to employ the method for measurement inside water droplet, 25mg dyed particles with 10μm mean diameter were added into 8ml distilled water, and about 0.3ml ethanol were added as cosolvent to reach a homogeneous state. Considering elution, precipitation and agglomeration, after ultrasonic treatment, the water with particles can stay in balance that is available for PIV-TSP measurement for about half an hour. During calibration and measurement test, the sample water was diluted with distilled water in varying proportions.

## 2.2 Experimental setup for PIV-TSP analysis

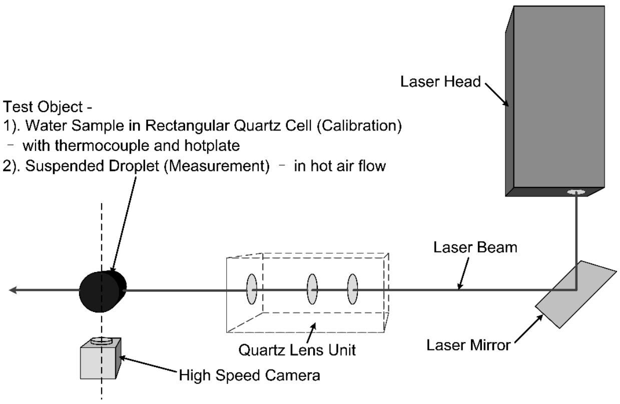



**Fig.1 Schematic view of PIV-TSP system**

Fig. 1 is a schematic view of experimental system for PIV-TSP calibration and measurement. The correlation curve between decay and temperature is considered to be related to the type of fluid, therefore calibration is necessary in the study. Since it is difficult to ensure controllable temperature field inside suspended droplet, experiments were carried out offsite in a rectangular quartz cell during calibration for relationship between phosphorescence intensity decay constant and local fluid temperature, which is shown in Fig. 2. For testing, a capillary tubing suspended water droplet was taken into measurement, heated by a hot upward airstream about 100℃.

Uniform temperature was assumed inside the target region considering its small size. A hot plate was used to reach different water temperature inside quartz container. The calibration error can be defined as the discrepancy between thermocouple measuring temperature and calculated temperature obtained by TSPs analysis, and the deviation in analysis results of same temperature indicated the accuracy of measurement.

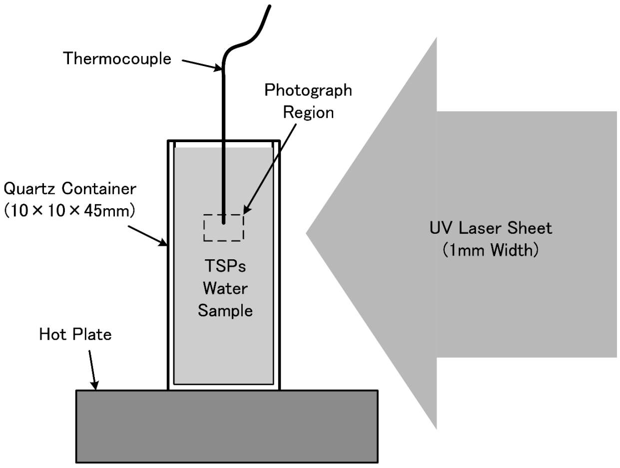



**Fig. 2 Calibration test section**

Phosphoresces sensors were excited by pulsed ultraviolet (UV) laser sheet of 532nm wavelength. A double head laser system was used to generate the pulsed UV laser at a rate of 100Hz, and two laser heads were working with a 1ms delay for PIV analysis. The generated laser sheet was located in a direction perpendicular to axis of the lens unit and test object, reflected by a high energy Nd:YAG laser mirror with high reflectivity (> 98.5% - 99.5%) at the 532nm wavelength for 45° angle of incidence (AOI). Through the lens unit consist of three quartz lenses, round-section laser sheet was distorted into slender shape with a width of approximately 1mm, concentrated at the center of the quartz cell or water droplet. Little energy loss and laser stability can be ensured by using optical instruments made of quartz with good UV light transmission and a great temperature resistance.

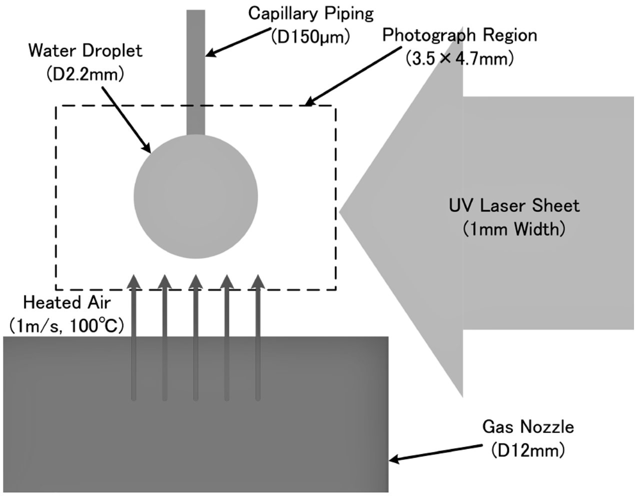



**Fig. 3 Measurement test section**

Fig. 3 shows the measurement test section of suspended droplet. Water droplet with TSPs particles was formed by micro-syringe and its size was controlled. Hot air was generated by an air compressor and heated up through an air heater to reach about 100℃ with on-off control. Images were recorded and the target region included the whole droplet, and then using TSPs and PIV analysis, temperature distribution and velocity field were measured inside the droplet.

A high-speed-camera was used to record the decay frames, working at a frame rate of 20,000 frames per second. The camera was located in front of the test object, and the photographic direction line was at a right angle to lenses-object axis.

### 2.3 Sample calibration

Decay frames were recorded with the water temperature changing at intervals of about 5℃ from room temperature to about 80℃. The mean decay constant was calculated from each phosphorescence decay under laser flashes. Referring to the temperature measured by thermocouple, the relation between T and τ was obtained.

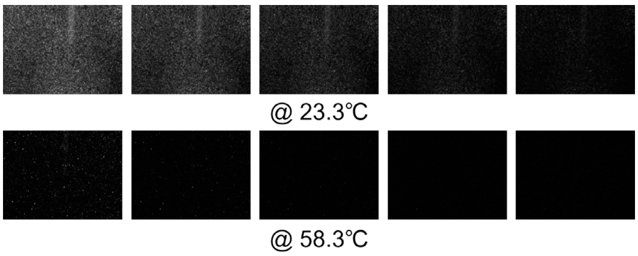



**Fig. 4 Sequences of decay frames recorded inside water sample**

Fig. 4 shows sequences of decay frames recorded at 23.3℃ and 58.3℃. Faster decay and lower phosphorescence intensity can be observed from the images at higher temperature. Laser was from the right of the container, and the intensity under excitation appeared to be uniform at low particle density, while decreasing from the right side to the left in high density situation due to absorption by particles.

Using sequences of decay frames, local intensity exponential decay constant was computed spatially by image processing and analysis. The images were recorded in PNG format of 16 bits high quality, which means that the intensity of pixels is in the range of 0-65,535. The computational procedure was conducted in each interrogation window of 32×32 pixels.

## 3. Data analysis and Results

### 3.1 Temperature and decay constant correlation

Phosphorescence intensity varying as time was evaluated in logarithmic relative values. The momentary intensity of phosphorescence is given as follow:

$$I_t = I_0 \times e^{-t/\tau}$$

Where $I_0$ is the initial intensity obtained from the first decay frame, and $\tau$ is the decay constant. According to this equation, in order to estimate the decay constant, the values of relative logarithm $ln(I_t / I_0)$ were plotted with decay frame number as x-coordinate.

Consequently, this value of frame number 0 (the first frame) is constant value 0, then the following values linearly decrease in negative territory. Considering the exposure time of each frame, the relative value of intensity and elapsed time was fitted by the least-square method, and the decay constant τ was determined from the linear slope for each interrogation window. The reliability of the aforesaid computation process was ensured by correlation coefficient of the data fitting, acceptable when over 0.999. The relation between intensity relative value and elapsed time in a certain interrogation window at image center is shown in Fig. 5 for several recorded temperatures.

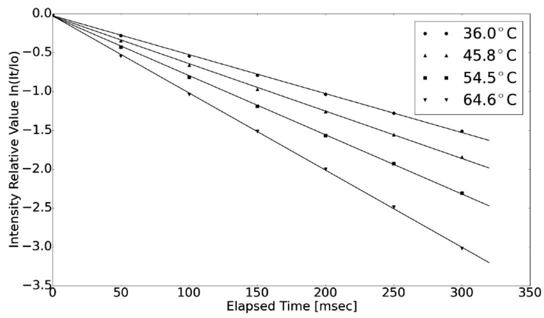



**Fig. 5 Relation between time and intensity relative value**

Local decay constant obtained from each interrogation window appeared to be location-varying, which was considered to be caused by local fluid condition and optical noise. This effect can be automatically avoid when calibration was conducted onsite. However, it must be considered during offsite calibration. The initial intensity of the decay, varying with local particle density and laser power, was found to affect the local decay constant as a coefficient of sigmoid function, which is shown in Fig. 6.

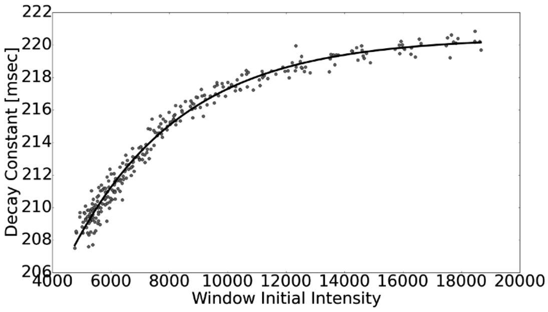



**Fig. 6 Initial intensity varying local decay constants**

Considering this effect, a correlation curve between temperature and exponential decay constant was fitted by least-squares method. In principle, luminescence lifetime based temperature sensors can be estimated according to the Arrhenius equation [6, 7]. According to Arrhenius equation, $ln(1/\tau)$ should be linearly correlated to the inverse value of absolute temperature $1/T$. The obtained correlation between temperature and decay constant is shown in Fig. 7.

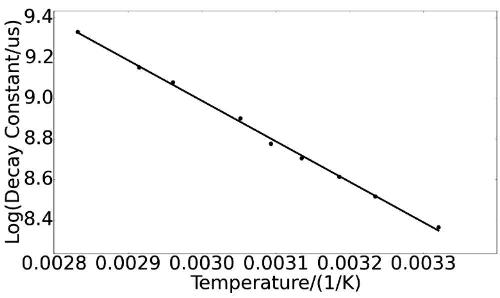



**Fig. 7 Relation between temperature and decay constant**

Local water temperature can be calculated using the obtained T- $\tau$ correlation function. With the computed decay constant in each interrogation window, local temperature was calculated. Fig. 8 shows the inverse-calculated temperature distribution in each interrogation window of the calibration decay frames at 45.8℃. At this temperature, the arithmetic mean value of calculated temperature was 45.4℃, which means that the measurement error was 0.4℃, and the standard deviation was ±0.19℃. The obtained inverse calculated temperature maps indicated that the error became larger with temperature increasing, and as an example, the error was 0.9℃ with a standard deviation ±1.03℃ at 69.9℃. Considering the indicator accuracy of thermocouple using for water temperature measurement, error of TSPs calibration results were within acceptable range.

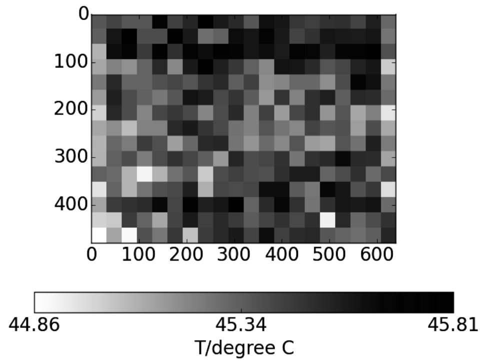



**Fig. 8 Inverse-calculated temperature distribution at 45.8℃**

### 3.2 Temperature and decay constant correlation

Focusing on measuring test section, temperature distribution and velocity field were obtained inside the heated suspended droplet using TSPs and PIV measurements described above. Fig. 9 shows a sequence of phosphorescence decay frames of the suspended droplet recorded at room temperature.

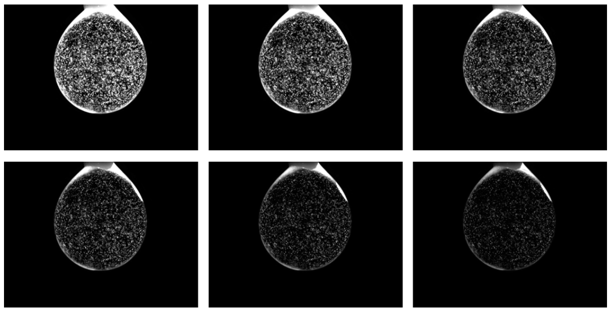
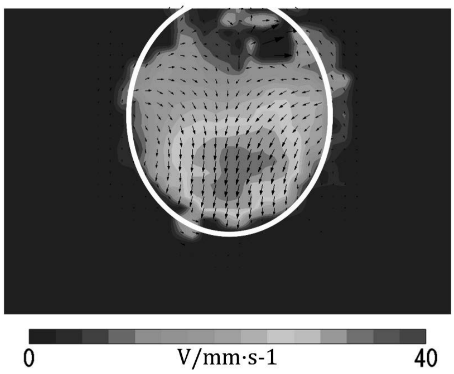


**Fig. 9 Sequence of phosphorescence decay frames of the suspended droplet**

The obtained distribution images of temperature and velocity are displayed in Fig. 10. As the results, internal flow circulation was observed inside the heated droplet, and the droplet temperature was steadily around 40℃ during about 1 minute evaporation.



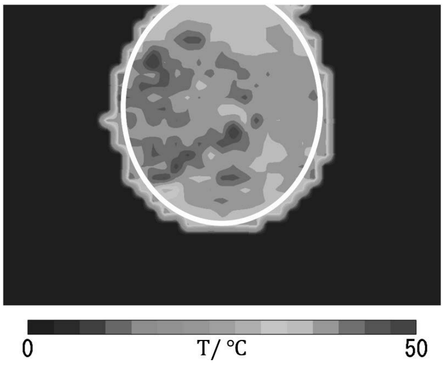



**Fig. 10 2-D temperature & velocity distribution inside the droplet**

The internal flow circulation is considered to be induced by two effects, Marangoni convection and shear force of the air flow on surface, shown in Fig. 11. This circulation may enhance the droplet internal water mixing and heat transfer. Consequently, temperature difference inside the droplet kept small in the evaporation process and high heat flow rate between droplet and hot air was ensured.

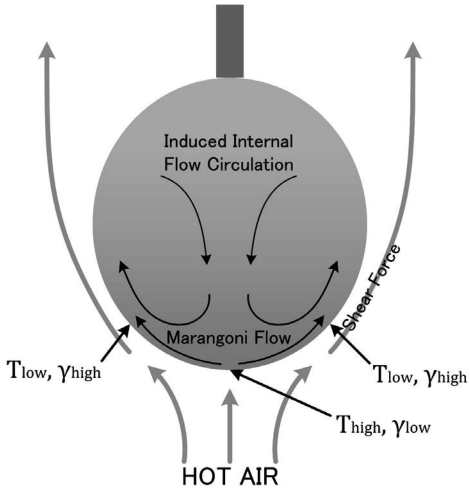



**Fig. 11 Internal circulation induced by Marangoni convection and shear force**

## 4. Conclusions

Phosphorescence decay rate based simultaneous velocity and temperature measurement technique was used to investigate a suspended droplet in upward hot air stream. By offsite calibration experiments and image analysis, a correlation curve between temperature and exponential decay constant was obtained referring to Arrhenius, considering the initial intensity effect on decay constant.

Temperature distribution & velocity field was measured inside the target water droplet. As results, internal flow circulation was observed inside the droplet, which was induced by Marangoni Effect and shear force, and droplet internal water mixing was enhanced by this circulation, which may result in a high heat flow rate between gas and fluid.

Further research on heat and mass transfer mechanism of spray droplets will be conducted with experimental TSPs and PIV analysis.

## References

[1] Lemaitre, Pascal, and Emmanuel Porcheron, "Study of heat and mass transfers in a spray for containment application: Analysis of the influence of the spray mass flow rate", Nuclear Engineering and Design, Vol.239(3), 2009, pp.541-550.

[2] Stanislas, Michel, et al., "Main results of the third international PIV challenge", Experiments in Fluids, Vol.45(1), 2008, pp.27-71.

[3] J. Coppeta, and C. Rogers, "Dual emission laser induced fluorescence for direct planar scalar behavior measurements", Experiments in Fluids, Vol.25(1), 1998, pp.1-15.

[4] Zelelow, Biniam, et al., "Dual luminophor pressure sensitive paint: II. Lifetime based measurement of pressure and temperature", Sensors and Actuators B: Chemical, Vol.96 (1), 2003, pp.304-314.

[5] Someya, Satoshi, et al., "Combined two-dimensional velocity and temperature measurements of natural convection using a high-speed camera and temperature-sensitive particles", Experiments in Fluids, Vol.50(1) , 2011, pp.65-73.

[6] Liebsch, Gregor, Ingo Klimant, and Otto S. Wolfbeis, "Luminescence Lifetime Temperature Sensing Based on Sol‐Gels and Poly (acrylonitrile) s Dyed with Ruthenium Metal‐Ligand Complexes", Advanced Materials, Vol.11(15), 1999, pp.1296-1299.

[7] Nagl, Stefan, et al., "Method for simultaneous luminescence sensing of two species using optical probes of different decay time, and its application to an enzymatic reaction at varying temperature", Analytical and bioanalytical chemistry, Vol.393(4), 2009, pp.1199-1207.