MEASUREMENT OF HIGH TEMPERATURE FIELD BY USING THERMOGRAPHIC PHOSPHORS AND LIFETIME ANALYSIS METHOD

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ABSTRACT : *The phosphor thermometry was applied to measure the temperature field of a hot plate. The rare earth fluorescence material (MFG: Mg_4FGeO_6:Mn) was used for the thermographic phosphor to measure high temperature(higher than 300 ℃) on the surface by the optical method. The MFG dye was coated on the aluminum plate and it was placed on the hot plate, which can be controlled up to 450 ℃. A pulsed UV-LED light source to exciting the MFG dye was adopted for lifetime based measurement with 385 nm wavelength. The CMOS high speed camera (Photron Fastcam SA1.1) was used to acquire images, and the surface temperature of aluminum plate was monitored by K type thermocouples. The 590 nm long-pass filter was installed on the 50mm lens to filtering the whole light except luminescence light. To analyze the temperature field, a lifetime based calibration was applied and the decay time was calculated from the measured images using the MATLAB program. The pulse frequency of UV-LED was 10 Hz, and the frame rate of the high speed camera was 8000 fps. After starting impinging air jet cooling, the images were obtained for 10 second. According to the result, the temperature of hot plate was decreased from 750 K to 450 K after starting impinging air jet cooling and the temperature field was quantitatively visualized.*

1 Introduction

To analyze various phenomena of the fluid machinery or other engineering flows, the measurement of physical parameter is the first step for analysis. Temperature is one of the important physical parameters in the flow phenomena with velocity and pressure, and the measurement technique for these parameters has been developed rapidly for last decades. The PIV (Particle Image Velocimetry) technique had made it possible to measure the velocity field, while PSP (Pressure sensitive paint) technique was developed to measure pressure field [1-3]. Temperature is also available to measure field information by the thermal paint and the phosphor thermometry techniques. However, because of the disadvantage of thermal paint which is expensive, requires skill and experience, many researchers are focused on the improvement of phosphor thermometry technique [4].

Thermographic phosphors have tried to measure temperature since at the late 1930s, phosphor thermometry have been adopted to a variety of application field. Kontis et al.[5] and Heyes et al.[6] investigated a transient heating with impinging turbulent flame on the ceramic and metal surface. Noel et al. [7] suggested a method to measure the temperature of turbine engine with phosphor thermometry in 1986 and Seyfried et al. [8] measured the surface temperature of the afterburner of turbine engine. Phosphor thermometry techniques were also applied for the temperature measurement of internal combustion engine and single droplet [9-11]. Because of the advantage of phosphor thermometry that has the global spatial resolution of temperature, continuous temporal resolution, the application field of phosphor thermometry is various and it could be more advanced. For the phosphor thermometry, the phosphor dye and data analysis method are important parameters because the specification of light source is determined by these two parameters. Many previous researchers are used Y_2O_3:Eu, YAG:Dy, La_2O_2S:Eu or $MgFGeO_6$:Mn dye and Nd:YAG laser in the third (355 nm) or fourth harmonics (266 nm) or nitrogen lasers (337 nm) for the lifetime based calibration. However these laser systems are expensive and have a limitation at wavelength. The UV-LED system is inexpensive and the wavelength could be changed with LED specification.

In this research, a UV-LED light source was adopted for exciting $MgFGeO_6$:Mn dye coated on the aluminum plate and we analyzed an impinging air jet cooling phenomenon on the hot aluminum plate with the lifetime based calibration method. A high-speed camera was used to measure the decay time of $MgFGeO_6$:Mn dye with temperature.

2 Background of lifetime based analysis and calibration

Phosphor thermometry is the technique to exploit the fluorescence dependence along the temperature. The decay time known as lifetime is one of the fluorescence characteristics that changes with temperature. When the illumination source gives a pulse light, the emission light of fluorescence dye is decreased with time, and it is different with temperature condition. The decay time relation with temperature is defined as:

$$I = I_0 \exp(-\frac{t}{\tau}) \tag{1}$$

where I_0 is the initial intensity at t=0, and τ is the decay time.

We used $MgFGeO_6$:Mn which is a rare earth dye for the phosphor thermometry. Brubach et al. [12] measured decay time of $MgFGeO_6$:Mn from 300 K to 1000 K with an optically accessible tube furnace. According to their data, the decay time of $MgFGeO_6$:Mn is around 4.5 millisecond at 300 K, around 1.8 millisecond at 600 K, and after 700 K, the slope of decay time is higher than lower temperature. In our research, we made a semi-closed heating system for the calibration and experiment.

3 Calibration for lifetime analysis

3.1 Experiment and calibration setup

For the experiment and calibration about the hot plate cooling phenomenon by impinging air jet cooling system, the experimental apparatus is shown in Figure 1. The 95 mm by 55 mm area on the center of 160 mm by 120 mm aluminum plate was coated with the MFG solution. The MFG solution was made by $MgFGeO_6$:Mn dye and HPC binder, and the MFG solution was coated on the aluminum plate by a compressed air spray system evenly. For drying and thermal treatment of MFG solution, the aluminum plate was kept for 3 hours at room temperature, then put into a 300 ℃ oven for 2 hours and cooled for 2 hours at room temperature again. The aluminum plate coated with MFG solution was placed on the hot plate that could control temperature up to 550 ℃ and a K type thermocouple was installed on the aluminum plate for monitoring the temperature of the target plate. The glass chamber made with tempered glass was installed to cover the hot plate which prevents the effect of ambient air flow to the aluminum plate. In addition, the glass chamber is a pentagon shape that has a slope on one side for installing the high speed camera. To illuminate the MFG dye, a UV-LED which has 385 nm wavelength and 700 mW power was used for the light source and the illumination frequency of UV-LED was 10 Hz for the lifetime analysis. A high speed camera (Photron SA 1.1, 8000 fps) was employed to capture the fluorescence image from MFG dye on the aluminum and a function generator was used to control UV-LED and the high speed camera by generating external trigger signal. Figure 2 describes the timing chart of the UV-LED, the high speed camera and the external trigger signal generated by the function generator. If there is the external trigger signal, the UV-LED started the pulse illumination with 50 ms duration after delaying 50 ms. The high speed camera obtained the images with 8000 frames per second after the external trigger signal, and the images after turning off the UV-LED were analyzed to calculate the delay time.

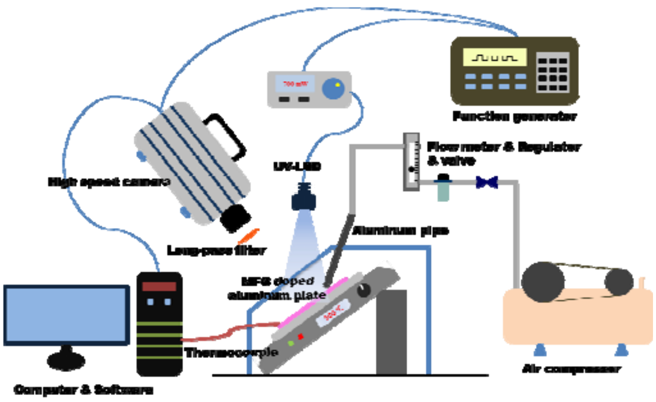

Figure 1 Experiment and calibration apparatus

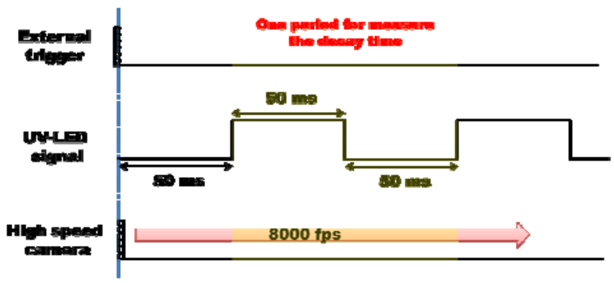

Figure 2 Timing chart of UV-LED, high speed camera and function generator

3.2 Calibration result for lifetime analysis

To acquire calibration data which is the temperature dependence of MFG dye, the hot plate was heated to 770 K and while cooling the aluminum plate, the decay time was measured between 300 K and 770 K. Figure 3 shows the decrease of phosphorescence captured by CMOS sensor over time. The y-axis means a normalized intensity value that was calculated by dividing instantaneous intensity value (I) with the intensity at t=0 (I_0) after removing noise level intensity then we confirmed that the phosphorescence at low temperature remains longer than that of high temperature condition. Figure 4 represented the decay graph of initial phosphorescence when time in logarithmic scale, and one can see that the whole data lines (at six point temperature) depict linear decay rates and the decay gradient is much higher if the temperature is higher. Figure 5 shows the averaged MFG decay time along the temperature from 300 K to 770 K. The averaged MFG decay time was calculated with decay time data of number of 56 pixels for each temperature, and the standard deviation was presented with the error bar in Figure 5. The decay time is decreased when temperature is increasing, and we confirm that the decay time and temperature has a linear relation. The linear calibration curve was calculated from the calibration data, and then it was applied to experimental data to calculate the temperature.

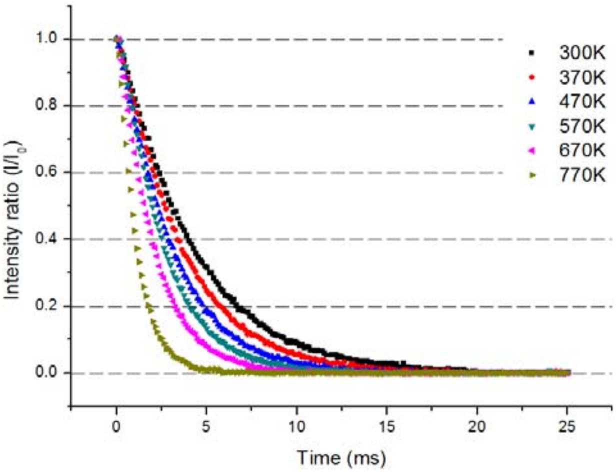

Figure 3 Normalized intensity ratio of phosphorescence

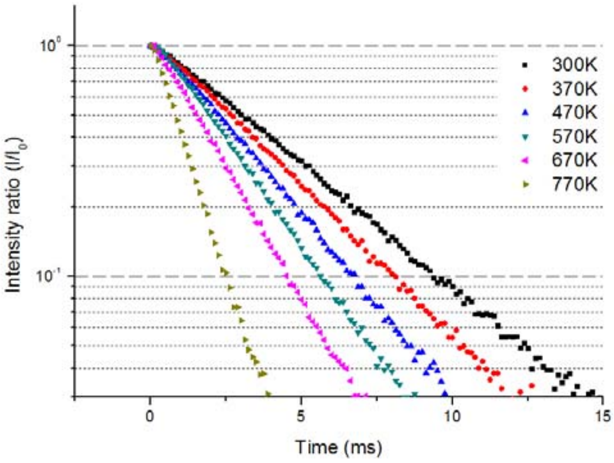

Figure 4 Initial decay gradient of phosphorescence along the temperature

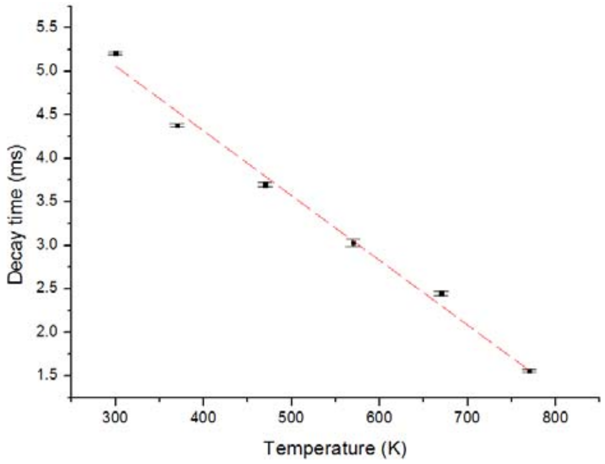

Figure 5 Averaged MFG decay time

4 Experiment of impinging air jet cooling system

To investigate the hot plate cooling phenomenon by the impinging air jet cooling system, the experiment was executed at the similar setup with the calibration test. The compressed air of 25 ℃ was injected on the hot plate through the 30° tilted aluminum pipe, whose inner diameter was 5mm. The UV-LED illuminated the dye on the aluminum plate with 10 Hz frequency same as the calibration test, and the emission images were captured with the high speed camera with 8000 frame per second. The decay time was obtained from the measured images by MATLAB program, and the temperature was calculated by applying the experimental decay time of the calibration curve.

Figure 6 shows the temperature field of hot plate at intervals of 2 seconds, which is obtained by adopting calibration curve, and we can see that the temperature of aluminum plate had being lowered by in progress of continuous impinging air jet cooling. The initial temperature of aluminum plate before starting air jet cooling was 750 K, and the temperature of plate was lowered to 450 K after 8 seconds. Figure 7 represented the temperature variation of one point on the aluminum plate by the impinging air jet cooling, and the temperature is decreased linearly since the beginning of the cooling. We have successfully visualized the hot plate cooling phenomenon by the impinging air jet using the phosphor thermometry technique.

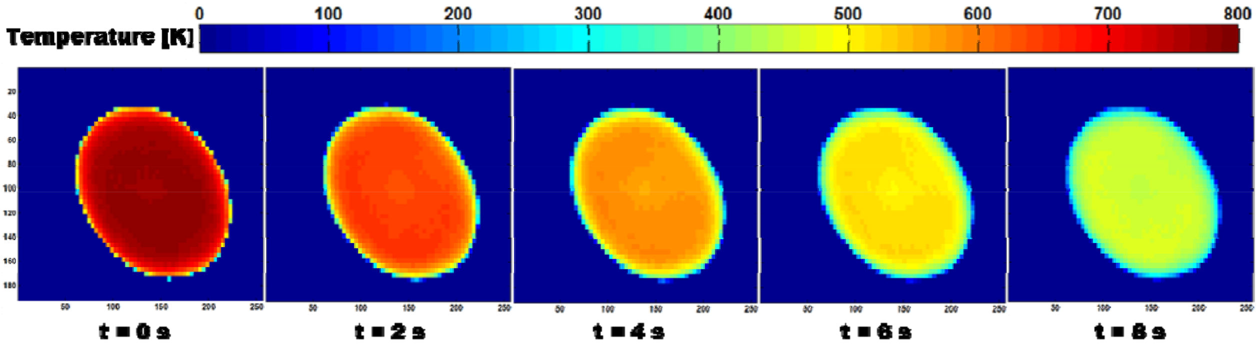

Figure 6 Temperature field of hot plate

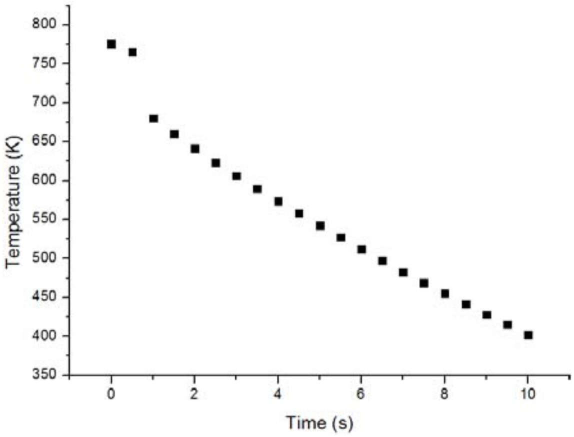

Figure 7 Surface temperature of aluminum plate

5 Conclusions

To investigate the hot plate cooling phenomenon by the impinging air jet cooling system, the phosphor thermometry technique was applied with $MgFGeO_6$:Mn dye with the lifetime analysis method. The UV-LED pulse light source with 10 Hz illumination frequency and the high speed camera were used for the lifetime analysis, and decay time was calculated with the MATLAB program. The temperature dependence of MFG dye had a linear relation with the temperature, and we applied the calibration curve to the experimental result. The hot aluminum plate was cooled by the impinging air jet, and we found that the temperature of aluminum plate was lowered from 700 K to 450 K after 8 seconds.

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