

Simultaneous Measurement Technique for Temperature and Velocity Distribution in Flow Field using Thermographic Phosphor



KOHEI KAWAZOE*1

HIROYUKI NAKAHARAI*2

HIROSHI MASHIMA*3

YUICHI KANEMAKI*4

AKIRA YAMADA*5

SATOSHI SOMEYA*6

In many of the product lines of Mitsubishi Heavy Industries, Ltd. (MHI), fluids such as liquid and air are used. Therefore, understanding the behaviors and characteristics of velocity and temperature distribution in a flow field by actual measurement is the key to improving product performance. One of the technologies for responding to this need is Phosphorescent PIV, for which MHI has been developing applicable technology to product development testing with the cooperation of the National Institute of Advanced Industrial Science and Technology. This method is PIV using thermographic phosphor, which enables the simultaneous measurement of two-dimensional distribution of velocity and temperature. The measurement procedure was verified using a test flow channel and the correlation between the distribution of flow velocity and temperature was evaluated.

1. Introduction

We have designed and manufactured many products using heat exchange. In order to improve their performance and reliability, it is important to properly evaluate the heat transport volume from the heat transfer surface. As it is generally known that heat transport is promoted at the place where the flow is fully disturbed, the flow field (momentum transport) and the temperature field (heat transport) have a correlation. Therefore, in discussing heat transport, it is indispensable to evaluate the flow field in the vicinity of the heat transfer surface. As an actual measurement method, PIV (Particle Image Velocimetry) has been used. It is considered, however, that in the future, in order to establish a higher-precision analysis and evaluation method, it will be necessary to measure the temperature field in the vicinity of the heat transfer surface and the flow field at the same time, and to evaluate the correlation of the temperature field and the flow field, and conventional PIV is not sufficient for this need.

Therefore, we have been developing a product measurement method using phosphorescence PIV that enables the simultaneous measurement of the flow field and temperature field with high precision and in two dimensions. This is a method using thermograph phosphor with temperature dependence on fluorescence or phosphorescence emission instead of seed particles used in common PIV, and combining it with PLIF (Planar Laser-Induced Fluorescence) in which fluorescence or phosphorescence is generated by a laser beam to obtain and measure images. The flow field is evaluated by conventional PIV analysis, while the temperature field is evaluated based on the difference in phosphorescence emission characteristics by temperature. Since images taken by the same camera can be used for the evaluation of velocity and temperature, it also has the advantage that no individual measurement systems are required.

This technique is expected to become an important measurement technique for measuring actual phenomena in the development of our products. This article describes the measurement results in the simplified test flow channel for the establishment of the Phosphorescent PIV technique.

*1 Chief Staff Manager, Electricity & Applied physics Research Department, Research & Innovation Center

*2 Heat Transfer Research Department, Research & Innovation Center

*3 Chief Staff Manager, Electricity & Applied physics Research Department, Research & Innovation Center

*4 Manager, Heat Transfer Research Department, Research & Innovation Center

*5 Research & Innovation Center

*6 The National Institute of Advanced Industrial Science and Technology

2. Phosphorescent PIV

2.1 Thermographic phosphor

When an electron in a molecule receives energy corresponding to the energy level gap in the molecule, it is excited to an upper level. An excited electron emits light (a photon) with energy according to the level gap when it transfers to the original level. This photon emission is fluorescence, and that with a long emission duration of microseconds or milliseconds is called phosphorescence. Thermographic phosphor has temperature dependence on fluorescence (phosphorescence) intensity, spectral characteristics, duration, etc., and exhibits temperature sensitivity characteristics as a result of changes in the absorption efficiency of the excitation light and the energy level related to excitation or the transition of electrons caused by temperature. Dye such as rhodamine and fluorescein are examples of organic thermographic fluorescent substances, and organic metal complex ions are examples of thermographic phosphorescent substances. Among inorganic matter, there are many thermographic phosphorescent substances containing rare earth metals, such as BAM (barium magnesium aluminate) and YAG (Yttrium Aluminum Garnet)⁽¹⁾. In addition, there are materials that can be applied at temperatures exceeding 1000°C, and we have also been developing a method of measurement in the high temperature region using them.

2.2 Phosphorescence PIV

In this measurement method, thermographic phosphor particles are dispersed in the flow field, and the area in which the flow field and the temperature field to be measured or visualized is irradiated with a sheet laser beam. This enables data to be obtained only for the necessary cross section. The spatial distribution and temporal change of laser fluorescence or phosphorescence from the particles are imaged using a high-speed camera, and based on the images, the velocity and temperature distribution are analyzed and evaluated.

In this method, the velocity distribution is analyzed in the same way as normal PIV, based on the amount and direction of particle movement between selected two images. On the other hand, in the analysis of the temperature distribution, an appropriate method among several is used according to the characteristics of thermographic phosphor and the field to be measured. Generally, the methods of fluorescence or phosphorescence intensity, ratio of two wavelength components or change of lifetime decay by temperature are used. In the verification in this article, the fluorescence intensity method was used.

In this method, a pulse laser with a high peak power was used because the exposure time of a high-speed camera needs to be reduced depending on the velocity of the flow field, and in order to obtain clear images by making the particles dispersed in the flow field emit fluorescence at a high intensity.

3. Verification of the measurement method

To examine the applicability of Phosphorescent PIV to our product development, the flow velocity and temperature distribution in a simplified flow channel with ribs were measured, and the relationship between the generated vortex and the water temperature was evaluated.

3.1 Test device

The aluminum flow channel with ribs with the shape shown in **Figure 1** was used. This flow channel with ribs was incorporated into part of a water circulation system consisting of a reservoir tank, a pump, a flow regulating valve, a cooling jacket and other components. A sheet laser was irradiated through the window facing the surface with ribs and the light emission of the thermographic phosphor particles was imaged through the window on the side of the flow channel. Particles were provided by adsorbing rhodamine B to resin beads, and accordingly, the second harmonic generation (wavelength: 532 nm) of a YAG laser was used for the excitation light source. From the fluorescence emitted after laser irradiation, components 560 nm or greater were selected through an optical filter and imaged by a high-speed camera. Then through the image processing, the flow velocity and temperature distribution were evaluated. A heater was set on the back of the flow channel, and the temperature of the water flow was changed by heating. The flow rates of 1.5 and 4.5 l/min were used. The measurement conditions are shown in **Table 1**.

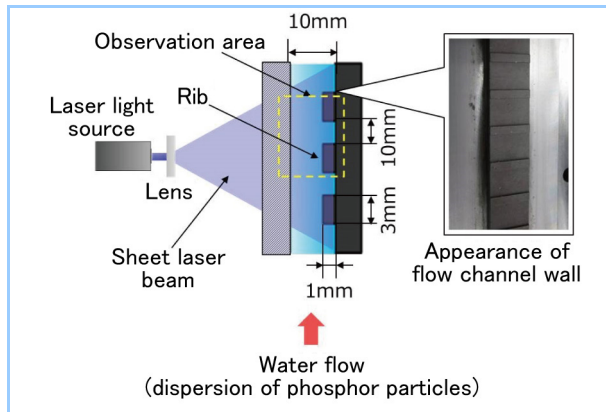


Figure 1 Flow channel with a rib

Table 1

Item	Condition
Flow rate	1.5, 4.5ℓ/min
Phosphor	Rhodamine B
Laser wavelength	532 nm
Phosphorescence observation wavelength	560 nm or more
Measurement area	11×18 mm

3.2 Verification results

(1) Measurement results for fluid velocity and temperature distribution

The results of the velocity and temperature distribution in the flow channel obtained by this method are shown in **Figures 2(a)**, **2(b)**. The results were obtained under the conditions of a rib height of 1.0 mm, a flow rate of 1.5 l/min. In **Figure 2(a)**, the white line drawn in the vicinity of the flow channel wall indicates the velocity of 0 mm/s. This shows that the fluid flows backward on the downstream side of the rib and a vortex region has been formed. In addition, on the upstream side of the rib, a small vortex is generated. A comparison of the flow velocity distribution and the temperature distribution in **Figure 2(b)** shows that the downstream region of the rib has a high temperature and meets the vortex region. This is considered to occur because the fluid stays in the vortex region, causing the inhibition of heat transport to the main flow.

Next, the results of the measurement with the increased flow rate of 4.5 l/min are shown in **Figures 3(a)**, **3(b)**. Compared to the measurement with the condition of 1.5 l/min, the vortex region was reduced. In addition, it shows that the high temperature region on the downstream side of the rib was also reduced, the maximum temperature was changed from 32°C to 26°C and the temperature range was lowered.

From these results, it was found that the measurement of a flow field by phosphorescence PIV using thermographic phosphor particles allows the quantification and visualization of the velocity and temperature distribution at the same time. As a result, the effect of the flow channel shape on the flow line and the relationship with the temperature field at the moment can be understood and evaluated in detail.

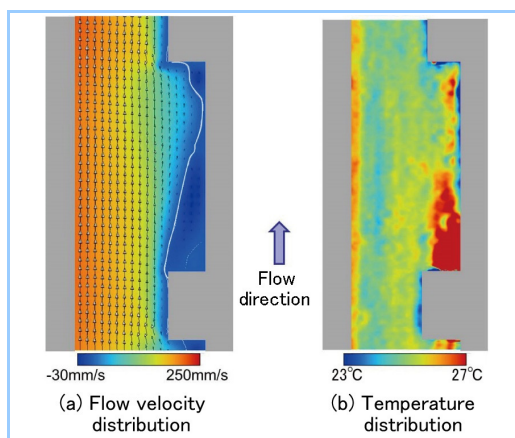


Figure 2 Measurement results with a flow rate of 1.5 l/min

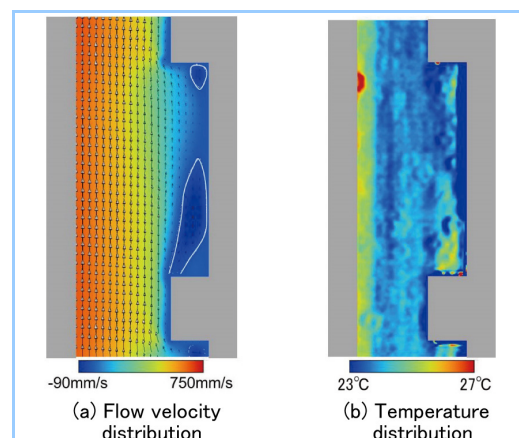


Figure 3 Measurement results with a flow rate of 4.5 l/min

(2) Results of the temperature distribution measurement on the flow channel heating wall

In addition to the measurement of the fluid in the flow channel, the surface temperature was measured on the flow channel wall surface with thermographic phosphor layer applied thereto. Since infrared rays are absorbed under the presence of water flow, it is impossible to measure the temperature of the flow channel wall through water flow using an IR camera. But with thermographic phosphor layer, both the excitation light and phosphorescence emissions pass

through water, enabling measurement.

For this measurement, a flow channel with a phosphor layer was used, and the excitation beam shape was changed and irradiated in such a manner as to cover the flow channel wall surface. In addition, the camera was placed at a position facing the wall surface to image its phosphorescence emissions.

The measurement results are shown in **Figure 4**. The conditions such as flow channel shape, flow rate and heating are the same as those in Figures 2 and 3. The results show that, similarly to the fluid temperature distribution, the wall surface temperature in the vortex generating region of the downstream of the rib was high, which led to an increase in water temperature. This is considered to occur because the vortex inhibited the heat transport from the wall surface. (The sparsely existing spots in the figure where the temperature is lower than the surrounding area were caused by air bubbles generated on the surface.)

From the above results of 3.2 (1) and (2), it is found that through the measurement method using thermographic phosphor particles, the relationship of heat transfer between the heat transfer surface and fluid and the relationship of velocity and temperature in the flow field can be obtained. Therefore, it is expected that this method can be applied to or produce effects in the development and design verification of heat exchangers used in various forms in our products.

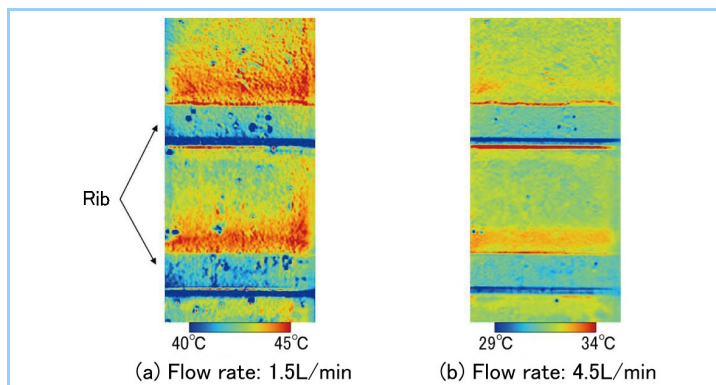


Figure 4 Measurement results of the temperature of the flow channel wall surface

4. Conclusion

The development of phosphorescent PIV by which the two-dimensional distribution of temperature and velocity of the flow field in a heat exchanger, etc., can be simultaneously obtained was described. This method is expected to contribute to a more detailed understanding of the actual phenomena in the flow field of liquid or gas in our products, resulting in improvements in design quality, product development capability and competitiveness. Toward the application of this technique to product development testing, measurement testing was conducted using a simplified form of a flow channel and the phenomena in the flow field were visualized and evaluated. The measurement was conducted in a heated flow channel with a rib on wall surface. As a result, it was found that a vortex was generated at the rear of the rib, where the temperature was higher, allowing the evaluation of the correlation between the flow field and the temperature field. In addition, it can be expected that the fluid and temperature behaviors obtained by this measurement can be used in the verification or improvement of turbulence models in CFD (Computational Fluid Dynamics) analysis.

In the future, we will expand the use of this method to the measurement of high temperature gas and promote application to development testing for products such as engine and turbocharger to contribute to the improvement of their performance.

In the development of this method, we received significant advice and cooperation from the Energy Saving Research Division in the Department of Energy and Environment of the National Institute of Advanced Industrial Science and Technology. Here, we express our deep gratitude to them.

Reference

1. Alden, M. et al., Thermographic phosphors for thermometry: A survey of combustion applications, *Progress in Energy and Combustion Science*, 37 (2011) p.422-461