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Temperature and Velocity Measurement of a 3-D Thermal Flow Field using Thermo-sensitive Liquid Crystals

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***Abstract*:** It is an important challenge to analyze a three-dimensional thermal flow field in engineering, science, and agriculture. For such an analysis, it is essential to measure physical quantities such as temperature and velocity over the entire thermal flow field.

This paper presents a measurement system based on color image processing for temperature and velocity vector distributions in a three-dimensional thermal flow field. Flow visualization is accomplished by the use of thermo-sensitive liquid crystal tracers.

An algorithm for the color-to-temperature transformation using a multi-layer feed-forward neural network is applied to three-dimensional natural convection in a rotating cylindrical cell. Two-dimensional temperature distributions in a slit plane are obtained by using the algorithm. A three-dimensional temperature distribution is consequently constructed by interpolating the two-dimensional distributions using the B-spline function. In addition, the Spatio-Temporal correlation method is applied to the natural convection to obtain a three-dimensional velocity vector distribution.

***Keywords*:** three-dimensional measurement, color image processing, liquid crystal, velocity vector distribution, temperature distribution.

1. Introduction

It is essential to measure temperature and velocity distributions in order to experimentally analyze thermal flow fields in natural convection. For the measurement, the acquisition of velocity and temperature information is needed. A method most appropriate for flow visualization is the thermo-sensitive liquid crystal suspension method. The movement of a liquid crystal tracer pattern during a constant time interval gives a velocity vector and its color indicates a temperature. Recently, Ozawa & Kimura et al. (1992), and Wozniak et al. (1994) have reported such a two-dimensional measurement system based on color image processing. The system can obtain simultaneously both two-dimensional velocity and temperature fields in thermal flow fields.

For analyzing a more complex thermal flow field, it is essential to measure three-dimensional (abbreviated as 3-D) quantitative information over the entire flow field. The purpose of this study is to expand the 2-D temperature and velocity measurement to a 3-D thermal flow field. A natural convection flow in a rotating cylindrical cell is visualized by using the thermo-sensitive liquid-crystal tracers. The 3-D temperature distribution is obtained from the visualized color images by using the algorithm for color-to-temperature calibration using an artificial neural network reported by Kimura et al. (1993) and the B-spline interpolation. The 3-D velocity vector distribution is measured using the Spatio-Temporal correlation method developed by Kimura et al. (1991).

2. Flow Visualization and Image Processing System

Figure 1 shows a side view of the experimental setup for flow visualization. The test volume (1) is a cylindrical cell 50 mm in radius and 50 mm in height. The top and the bottom walls of the enclosure (2 and 3) are composed of an acrylic resign plate 2 mm in thickness and a copper plate 25 mm in thickness, respectively. Above and below the plates, water jackets (4 and 5) are attached. Constant-temperature water circulates in the water jackets for heating or cooling the test fluid.

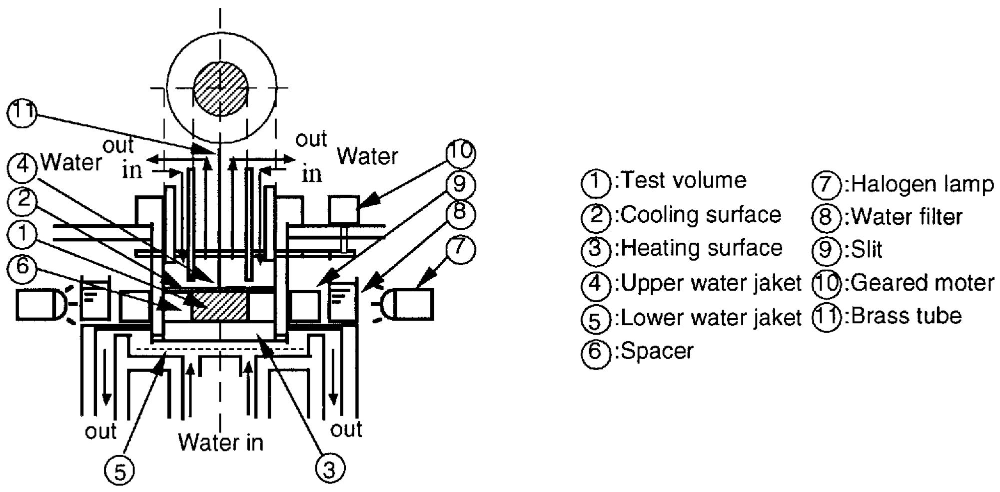


Fig. 1. Experimental setup for flow visualization.

A thermo-sensitive liquid crystal suspension method is adopted for flow visualization. Silicon oil is used as the operating fluid because a combination of silicon oil and the cholesteric liquid crystals gives a very vivid color. Micro-encapsulated cholesteric liquid crystals about 20 μm in diameter (Japan Capsular Products Inc. Type R-20) are used as tracer particles and the concentration of the liquid crystals is about 0.1 weight percent. The thermo-sensitive tracers turn from colorless to red and pass through green and blue before turning colorless again with an increase in the temperature.

The thermo-sensitive tracers are illuminated through slits (9) 7 mm in slit width by halogen lamps (300 W) (7). A water filter (8) is placed in front of each lamp to prevent excessive radiant heat transfer from the lamp to the test fluid. The reflected light is observed by a TV camera (Victor Co., Ltd. KY-17B) installed at right angles to the illuminated sheet. Since the cell is cylindrical, it distorts and deforms the views because of the difference of refractive index between liquid and air. The images are reconstructed in a simple way as follows. A graph paper is placed at the slit plane. The image is geometrically transformed using a simple formula obtained from known point coordinates of the graph paper on both the image and slit planes.

The calibration of color to temperature for the thermo-sensitive liquid crystals is undertaken as follows. First, a thermal stratification is formed in the test volume by heating the upper heating surface (18.3°C) and cooling the lower one (14.7°C) for a few hours. Next, the temperature in the test volume is measured with a Chromel-Alumel thermocouple led through a brass tube (11). The thermocouple is traversed vertically from the top to the bottom in the thermal stratification. The position of the thermocouple and the color of the liquid crystals are recorded by an optical disk recorder.

The experiment is carried out in the following manner. First, the temperatures of the upper and lower walls of the test volume, which is rotating at 10.1 r.p.m. with a geared motor (10), are kept respectively at lower and higher temperatures (15.6°C and 17.9°C). After several hours, a steady natural convection flow is formed in the test section. In this case, the Rayleigh number is 2.55×10^5. Since the test cell rotates while the light sheet is fixed, the illuminated width exposed during a frame time increases with the radius of the cell. The spatial resolution for the measurement is accordingly getting worse at outer radius.

Figure 2 shows a schematic diagram of the image processing. Each color image obtained by the TV camera is separated into R, G, and B (red, green, and blue) images, the size of which is 512×512 pixels, and stored in an image processor. The image data are sent to a workstation for color image processing. Finally, the results are displayed on a graphic display.

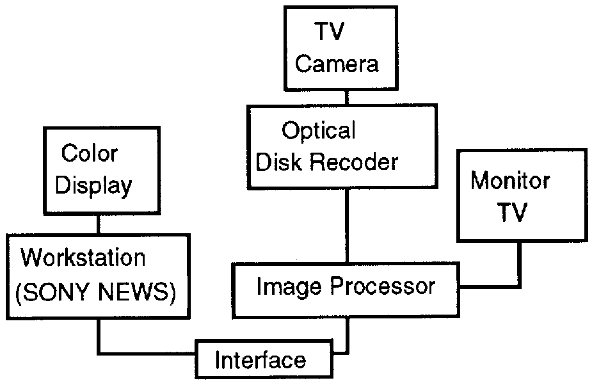


Fig. 2. Schematic diagram of image processing.

3. Transformation of Color to Temperture Using a Neural Network

Since the image lightness depends on the distance from the light sources and the particle density, the color has to be normalized. Figure 3 shows the normalized *r*(red), *g*(green), and *b*(blue) values versus the temperature *Tm*, which is obtained by the calibration of color to temperature. The temperature *Tm* is the values measured with the thermocouple. The normalized *r*, *g*, *b* values are calculated by

$$r=\frac{R}{R+G+B},\ g=\frac{G}{R+G+B},\ b=\frac{B}{R+G+B} \tag{1}$$

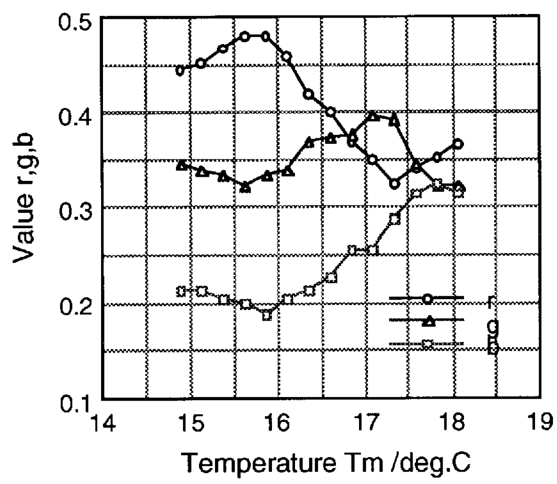


Fig. 3. Relationship between *r,g,b* and temperature *Tm*

Formulating the color-to-temperature relationship has emerged as an important problem because of its strong nonlinearity. To solve the problem, we adopt a four-layer feed-forward neural network shown in Fig. 4. The inputs of the network are *r*, *g*, and *b* values. The output is the temperature *Tn*. The network consists of four layers, namely, an input, first hidden, second hidden, and output layers. The five units in the first hidden layer, three units in the second hidden layer, and one unit in the output layer are neurons. The three units in the input layer are just linear devices. The parameters in the network are determined so that the output *Tn* corresponding to the input (*r*, *g*, *b*) agrees well with the *Tm* measured by the thermocouple. We use the Back-propagation algorithm reported by Rumelhart et al. (1986) for learning. The input data are 14 patterns of (*r*, *g*, *b*) corresponding to the temperature *Tm* measured at every 0.25 K in the range of 14.9-18.1°C and the teaching data are just *Tm*. The number of times for learning is 5,000.

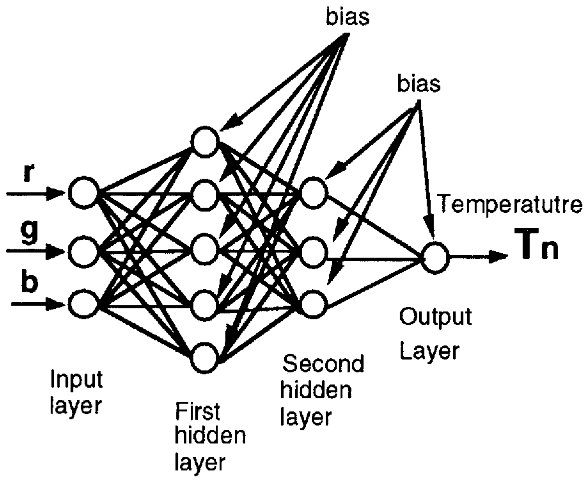


Fig. 4. Neural network structure.

Figure 5 shows the relationship between the measured temperature *Tm* and the network output *Tn* after learning. The *Tn* agrees well with *Tm* almost over the entire range. By using the neural network, the color at each pixel in the images can be transformed into a temperature. Applying the transformation to all the pixels on a visualized image gives a 2-D temperature distribution over the entire field. Some image noises, however, exist in the distribution. In order to eliminate the noises, the Median filter is used.

In the temperature measurement, the main uncertainties arise along with the color-to-temperature calibration.

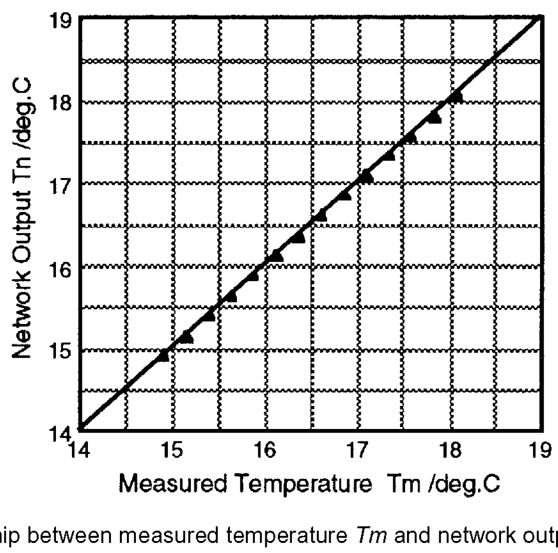


Fig. 5. Relationship between measured temperature *Tm* and network output *Tn*.

4. Velocity Vector Measurement Using Spatio-temporal Correlation Method

The Spatio-Temporal correlation method is used to obtain a 3-D velocity vector distribution. Its principle for the rotating cell is shown in Fig. 6 and the procedure is as follows.

1) Since the cell rotates, a visualized slit image is obtained at every 1/30 sec.
2) A small pixel segment *F*, which consists of $n \times n$ pixels, is set in the image as a standard segment at $t = t_0$.
3) In the same way, another small segment *G*, where there is a time lag $T \pm \alpha$ and the position has been moved, is set in the seven images before and after one rotation as shown in the figure. The *T* is the time required for

one rotation and α is 1/30, 2/30, or 3/30 sec in this case.

4) The normalized cross-correlation function of gray level between these two segments is calculated.
5) If the cross-correlation value reaches the maximum, it means that the tracer particle group in the segment F moved into the segment G during almost the time the cell made one rotation.
6) A 3-D velocity vector at the center point of the segment F is consequently obtained.
7) By applying the above procedure to the entire image, a 3-D velocity vector distribution on a slit plane is measured.

In the velocity vector measurement, the main uncertainties arise along with obtaining the images and the image processing. The accuracy will be improved particularly by a higher pixel resolution and a shorter frame period.

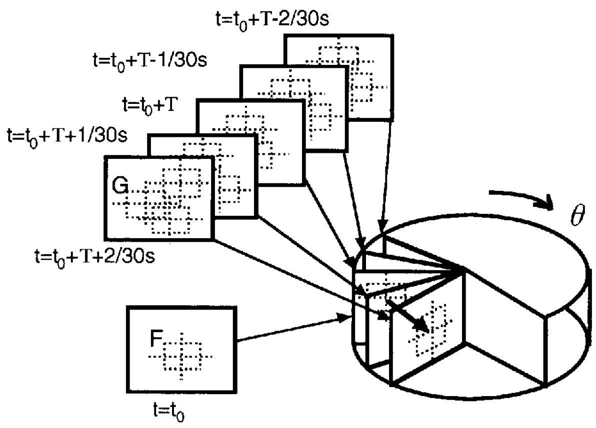
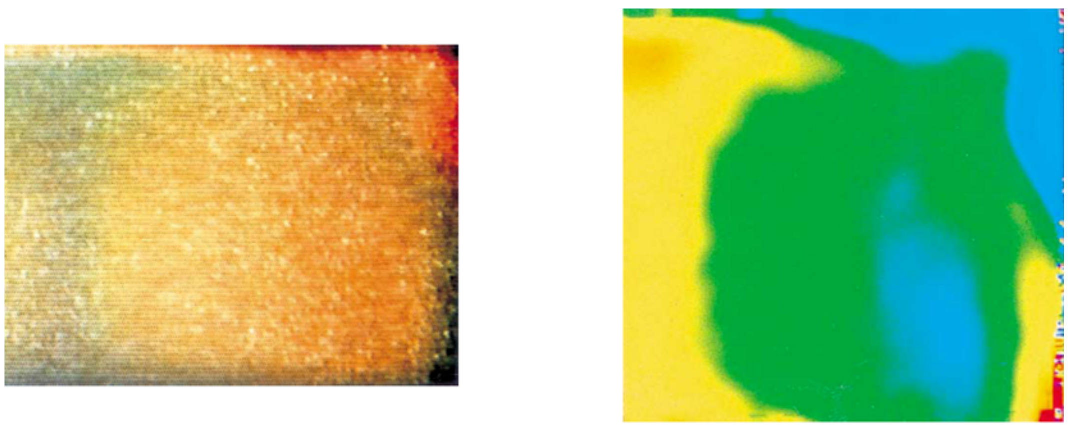


Fig. 6. Spatio-temporal correlation method.

5. Application to a Rotating Natural Convection

5.1 Temperature Distribution

Figure 7 shows an example of the visualized images of the rotating steady natural convection at a slit section and its temperature distribution, which is expressed by using pseudo colors, obtained by the image processing. Since the test volume rotates, 178 such temperature distributions per one rotation are obtained.



(a) (b)

Fig. 7. Visualized image and its temperature distribution at a slit section. (a) Visualized image, (b) Temperature distribution.

From the distributions, such a horizontally sectional view as shown in Fig. 8 is reconstructed. It must be the temperature distribution in a horizontal cross section at the distance Z=25 mm from the top of the test volume. The distribution, however, lacks temperature information in the area between a measured vertical cross section and the next. It must be interpolated accordingly.

Figure 9 (a) shows the temperature distribution obtained by interpolating unmeasured temperatures using the B-spline function from the 178 temperature distributions. The distribution agrees well comparatively with the visualized image in almost the same horizontal cross section (Z=25 mm) shown in the Fig. 9 (b). The fluid in the middle of the test volume has a higher temperature, while in the vicinity of the outer wall the fluid has a lower temperature and partly shows a higher temperature.

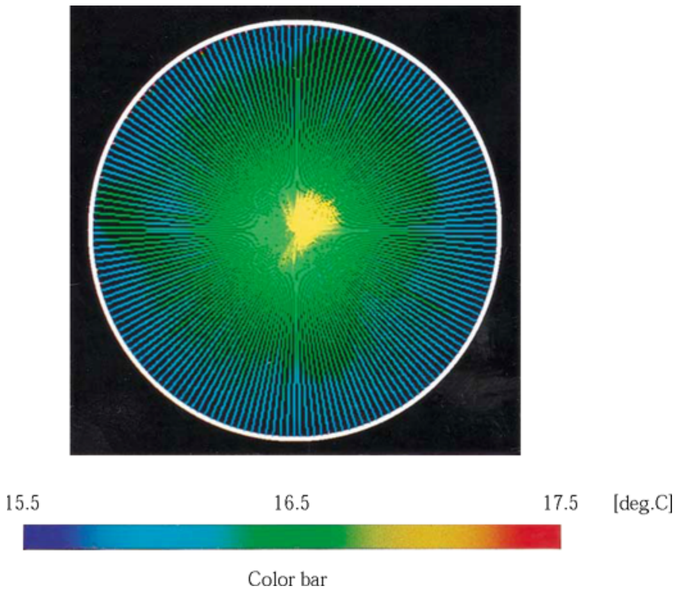


Fig. 8. Horizontal view reconstructed from temperature distributions at a slit section.

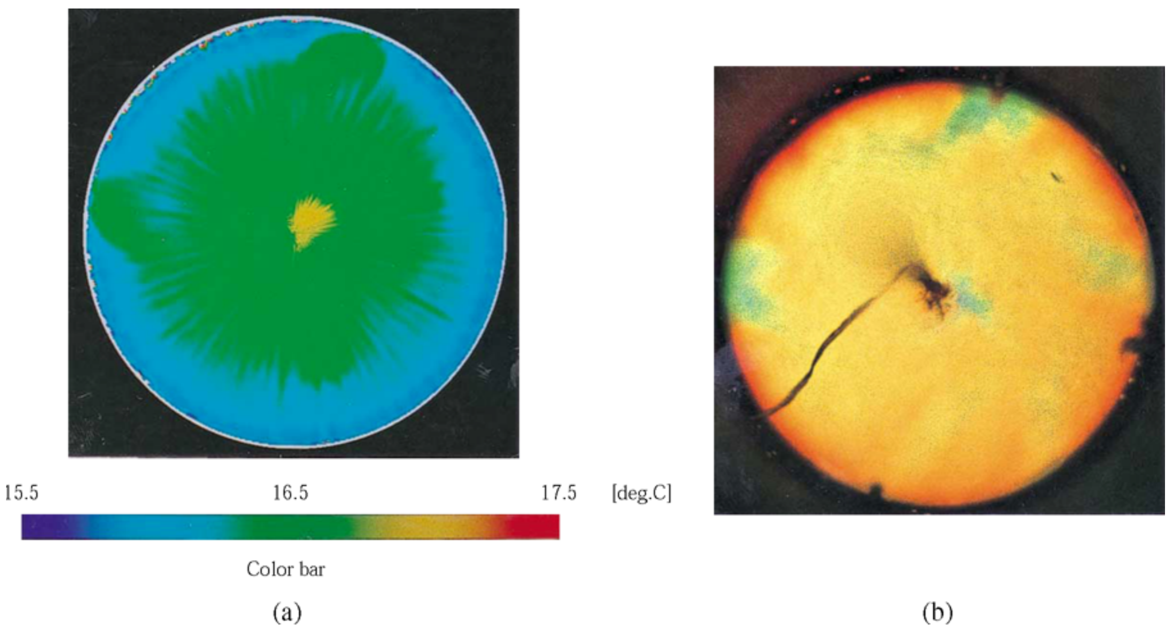


Fig. 9. Comparison of the measured result with its visualized image. (a) Temperature distribution, (b) Visualized image.

Figure 10 shows a set of temperature distributions at six horizontal cross sections, which must be a 3-D representation of the rotating natural convection.

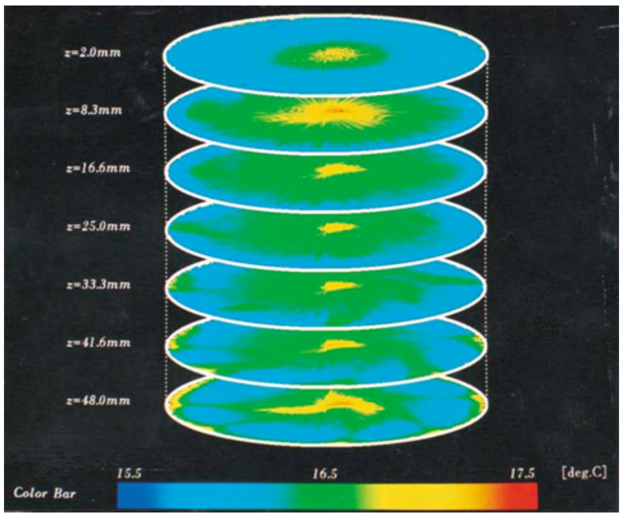


Fig. 10. Three-dimensional representation of temperature distributions.

5.2 Velocity Vector Distribution

Figure 11 shows the 3-D velocity vector distributions at a left half section of the slit in the natural convection in the rotating cell. The segment size for correlation is 19×19 pixels. The upper distribution represents a view from above. The color of vectors indicates a velocity component in the z direction, which is perpendicular to the slit section (x, y). It is possible to obtain 178 such velocity vector distributions per one rotation. Figure 12 shows a set of the 3-D velocity vector distributions at four slit sections. The θ is an angle from a certain standard section. Although some erroneous vectors are found, the flow behavior of the natural convection is made clear.

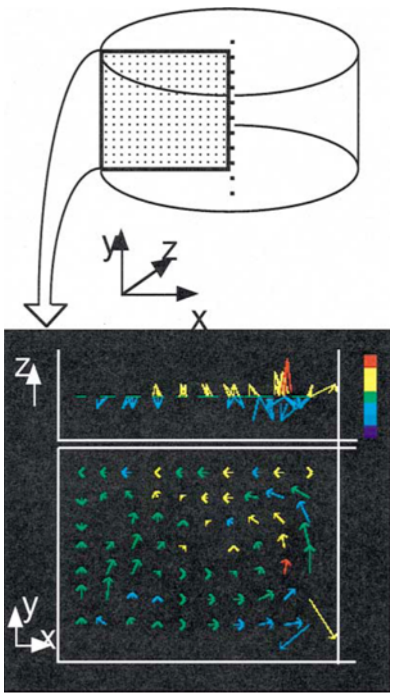


Fig. 11. Three-dimensional velocity vector distribution.

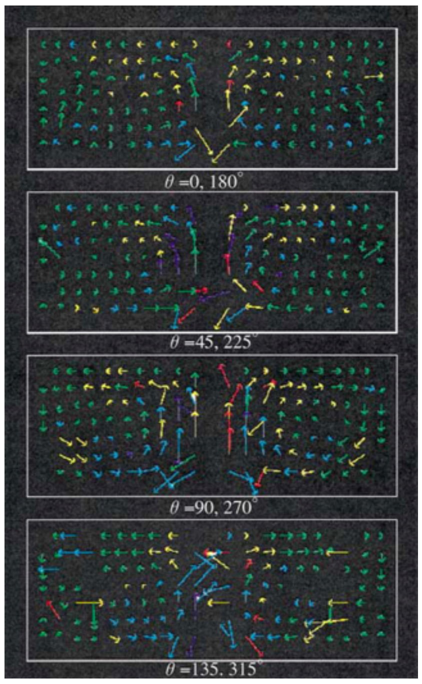


Fig. 12. Three-dimensional velocity vector distributions at four slit sections.

. From the Figs. 10 and 12, the following phenomenon can be derived. The fluid at a higher temperature moves upwards from the bottom to the top in the middle of the test volume. On the other hand, the fluid at a lower temperature moves downwards from the top to the bottom along the side wall. Furthermore, it is assumed that six secondary rolling convections exist in the vicinity of the bottom.

6. Conclusion

We carried out three-dimensional measurements of temperature and velocity vector distributions in a rotating natural convection by applying the color image processing to the images visualized by thermo-sensitive liquid crystal tracers. Consequently, it was confirmed that the measurement system is very useful for experimentally analyzing three-dimensional thermal flow phenomena.

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