Journal of the Korean Society of Marine Engineers, Vol.28, No.2, pp.277~284, 2004(ISSN 1226-9549)

Flow Visualization and Measurement of Velocity and Temperature in Parallel Plates

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(Manuscript : Received OCT 30, 2003 ; Revised DEC 7, 2003)

Abstract : This paper describes the influence of through-flow on the mixed convection in a parallel plates with the upper part is cooled and the lower part heated. When forced convection is imposed on natural convection, it is found that the flow pattern of mixed convection in the parallel plates can be classified into three patterns which were affected by Reynolds number. In such a mixed convection, the flow pattern plays an important role in the heat transfer process. In this study, thermo-sensitive liquid crystal suspension method is employed, then the visualization image acquired through the above method is processed by the color image processing technique and the two-dimensional velocity vector and temperature configuration are measured simultaneously.

Key words : Mixed Convection, Natural Convection, Liquid Crystal, Neural Network

1. Introduction

The measurement of the temperature and velocity of the flow caused by the temperature gradient takes an important role in the study of media of heat conduction. As a new technique to measure temperature, liquid crystal is widely applied, which shows the advantages, such as no-interference, instantaneity, being able to measure the temperature of the whole field, and so on compare to the conventional temperature method. Recently, with the development of the experiments of the flow being visible, to measure the flow of the whole field has become achievable. The liquid crystal can reflect various temperatures with various colors, therefore, the temperature distribution of the flow field can be obtained by the color versus temperature relationship graph, and getting the flow field velocity becomes possible due to the particles characteristics, that the particle has sensitive scattering for the light and the ability to track fluid exactly. With help of liquid crystal, Ozawa etc make the flow

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field and the temperature field of the natural convection in Hele-Shaw cell quantitative visible[1]. Anmen etc have studied the change of the mixed flow in Hele-Shaw cell[2]. Bae etc have quantitative studied the velocity field and temperature field about the bubble flow [3]. However, most of them have done the numerical analysis or the study of natural convection, so there is little study published about the mixed convection.

The purpose of the present study is to visualize and analyze the complex structures of the flow and temperature patterns of the mixed convection between two parallel plates simultaneously using liquid crystals.

2. Experiments

2.1 Experimental apparatus

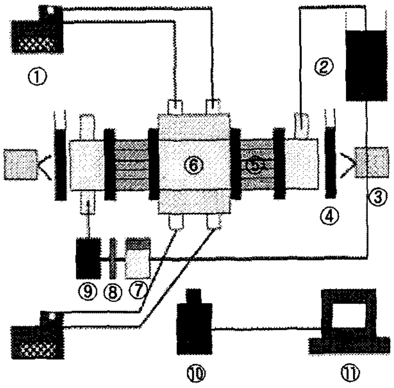
Figure 1 shows a schematic diagram of experimental apparatus. The apparatus mainly consists of nine parts: test section, two constant temperature baths, two halogen lights, two water filters, tank, pump, temperature regulator, digital video camera and computer.

The test section consists of 15mm thick transparent acrylic resin to facilitate flow visualization. The test section is a rectangular channel with heated lower wall and cooled upper wall of the width W=140mm, the height H=15mm and the depth D=10mm. Honeycombs are installed on the both ends of the test section, so that a uniform flow at the inlet is provided. Upper and lower walls, which are cooling and heating surfaces, respectively, consist of copper plates of 15mm thickness. The temperature of heating and cooling surfaces can be controlled by circulating water from thermostats through water jackets installed in the test section was control and kept constant by temperature regulator installed on left side of the test section. The pulse dampener is installed in the left side of the test section, so that a continued flow at the inlet is provided. The test section is illuminated by two halogen lights located at both smaller sides of the test section, and used water filters. The reflected flow field in the test section is observed by digital video camera installed at right angle to the light sheet formed in the test section. The test section is placed in the thermally insulated box for controlled to retain the predetermined temperature. The predetermined temperature level of the box was set at the mean value between the upper and lower wall temperatures of the test section.

Table 1 Properties of silicon oil at 25.

Silicon oil(viscosity, ν)		100cSt
Density	ρ[kg/m^3]	963.1
Specific heat	Cp[J/kg.K]	1507
Thermal conductivity	λ[W/m.K]	0.16
Expansion coefficient	β[K^{-1}]	$9.5 * 10^{-4}$
Thermal diffusivity	α[m^2/s]	$1.1 * 10^{-7}$
Prnumber	Pr	909.1

Shin-Etsu Silicon Oil KF-96-100cSt was used at the test fluid. Table 1 shows properties of silicon oil at 25℃. For the flow visualization, a powder of micro-capsules filled with a liquid was mixed as tracers into the silicon oil. The liquid



① constant temperature bath
② tank
③ halogen light
④ water filter
⑤ honey combs
⑥ test section
⑦ step dos pump
⑧ pulse dampener
⑨ temperature regulator
⑩ digital video camera
⑪ computer

Fig. 1 A schematic diagram of experimental apparatus.

crystals used in this experiment were the thermo-sensitive cholesteric liquid crystal of type "RM-2830"(Japan Capsular products INC.). The concentration was about 0.1 weight percent.

2.2 Experimental procedures

The experiments were carried out in the following manner. At first, the test fluid was filled in the test section, and the test section was heated from below and cooled from above. After a few hours, the liquid crystal tracer mixed with the silicon oil was introduced very slowly into the test section by the pump. After the tracer was well mixed in the whole region of the test section, the pump was stopped and the wall temperatures at the upper and lower boundaries were kept at the same value. Then the test section was cooled from below and heated from above. Then the wall temperatures at the upper and lower boundaries were kept at the same value again. After a few hours, the test section was heated from below and cooled from above again. After the natural convection was fully developed, the through-flow by using the pump was imposed on the fluid in the test section. Then the flow phenomena were recorded by digital video camera after the mixed convection was fully developed.

3. Measurement of velocity

In order to make visualization of the flow field, liquid crystal is used as a tracer particle. Calculation of velocity field is made with gray-level cross correlation algorithm. R G B values obtained from the color original image of liquid crystal is changed to brightness value Y of YIQ system. In this study, Thinkers eyes (TNTech Co. Ltd) software was used to visualize velocity field quantitatively.

4. Transformation of color to temperature using a neural network

Figure 2 shows the normalized *r*, *g* and *b* 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* and *b* values are calculated by

$$r=\frac{R}{R+G+B}\quad g=\frac{G}{R+G+B}\quad b=\frac{B}{R+G+B}\qquad(1)$$

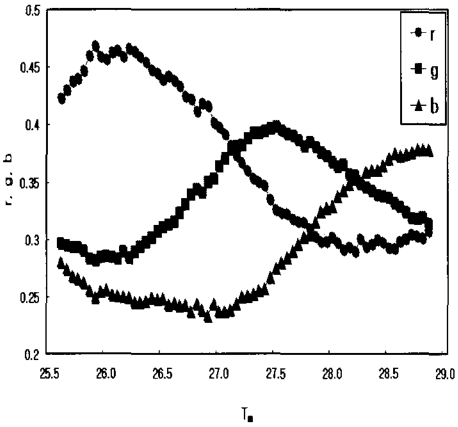


Fig. 2 Relation between r, g, b and temperature T_m

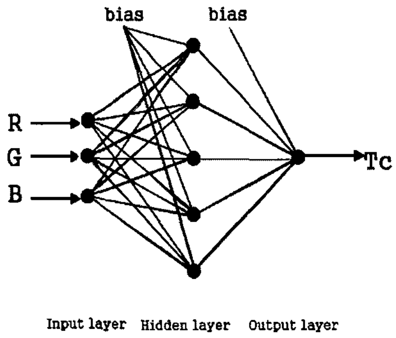


Fig. 3 Neural network structure.

Formulating the color-to-temperature relationship has emerged as an important problem because of its strong nonlinearity. To solve the problem, we adopt a three-layer neural network as shown in Figure 3. The method proposed first by Kimura [4]. The inputs of the network are *r*, *g* and *b* values. The output is the temperature *Tn*. The network consists of three layers, namely, an input, hidden, and output layers. The five units in the hidden layer, 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 for learning.

Figure 4 shows the relationship between the measured temperature *Tm* and the network output *Tc* after learning. The *Tn* agrees well with *Tm* almost over the entire range when the number of times for learning is 300,000. 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.

5. Experimental results

Figure 5 shows the visualized original image of liquid crystal and result of original image calibration. Upper and lower wall temperatures are 25.8deg.C and 28.8deg.C, respectively. Figure 5(a) is original image of the vertical temperature distribution with no fluid motion for temperature calibration, (b) is the result of color to temperature transformation using a neural network. The color changed from red, yellow, green and to blue with increasing fluid temperature. The red shows the low temperature, and the blue shows the high temperature.

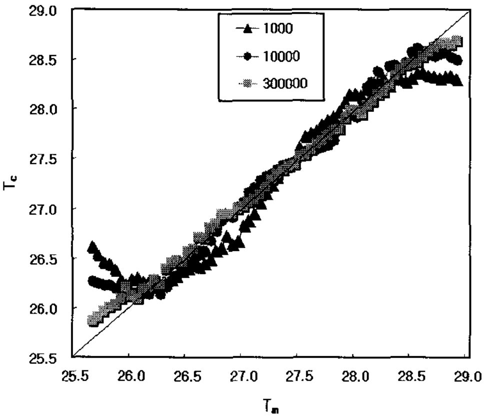
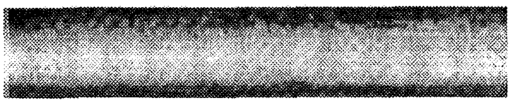


Fig. 4 Results of neural network calibration and evaluated temperature distribution.

(a) Visualized image



(b) Evaluated temperature

Fig. 5 Visualized image of liquid crystal tracers.

Photo 1 shows the natural convection patterns. When the temperature difference, i.e. the Rayleigh number is relatively low, unstable 10 rolls with axes parallel to the smaller side of the test section are observed (photo 1a). An increase in the temperature difference induces stable 10 rolls as can be seen in photo 1b. When the temperature difference increases further, stable 10 rolls and one smaller roll on the left edge of the test section is observed (photo 1c). This represents typical flow patterns in a relatively slender parallel plate channel.

(a) ΔT=1.2, Ra=170

(b) ΔT=3, Ra=349

(c) ΔT=8, Ra=931

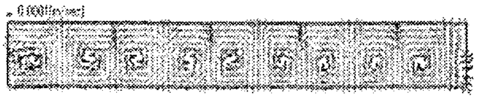
Photo. 1 Natural convection pattern.

Figure 6~8 show the temperature and velocity patterns when the through-flow is imposed from the left end of the test section on the natural convection at T=3deg.C(upper and lower wall temperatures are 25.8deg.C and 28.8deg.C respectively, Ra=349).

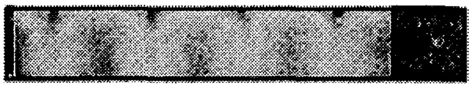
When the through-flow inlet velocity is u=1.6mm/min (Re=$4.0 * 10^{-3}$) is imposed, the structure of natural convection is hardly disturbed by the through-flow as shown in Figure 6.

Figure 7 shows the convection patterns at the through-flows u=5.2mm/min (Re=$1.3 * 10^{-2}$). In this pattern, we found that the tracers rising and descending are flowing into the roll next to the right at about half height of the test section, and the flow becomes the sinusoidal type. The flow in the region at the left end, however, retains stratified flow. This phenomenon becomes typical with an increase in the inlet velocity.

When the through-flow at u=11.7mm/min (Re=$2.9 * 10^{-2}$) is imposed as shown in Figure 8, the effect of through-flow is dominant on the fluid motion in the test section so that the roll like convection is suppressed. Moreover, in the entrance part the flow near the entrance region is stratified, and the vertical velocity components in the downstream region decrease.

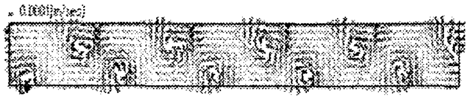


(a) Velocity vector

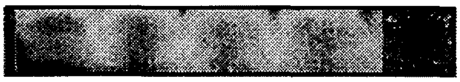


(b) Evaluated temperature

Fig. 6 Experimental results at ⊿T=3, U=1.6[mm/min], Re=4.0 * 10^{-3}, Ra=349

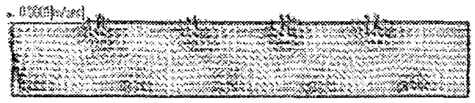


(a) Velocity vector

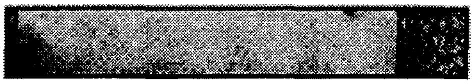


(b) Evaluated temperature

Fig. 7 Experimental results at ⊿T=3, U=5.2[mm/min], Re=1.3 * 10^{-2}, Ra=349



(a) Velocity vector



(b) Evaluated temperature

Fig. 8 Experimental results at ⊿T=3, U=11.7[mm/min], Re=2.9 * 10^{-2}, Ra=349

Figure 9 shows the u-velocity profiles at the center line of height of the test section for various inlet velocities. When the mean inlet velocity is 0 mm/min, cell that direction is opposite each other is formed by natural convection consecutively, then flow pattern of typical Rayleigh-Bernard convection that u-velocity changes periodically is shown. But, as the entrance velocity increases, flow pattern of Rayleigh-Bernard convection is destroyed. When the inlet velocity is higher than u=5.2mm/min, all of the u-velocity have + values because of increasing of the effect of forced convection at the center line. Although U-velocities have + values, the flow patterns of U-velocity are still sinusoidal type. It is due to effect of natural convection that is occurred near the top and bottom surfaces.

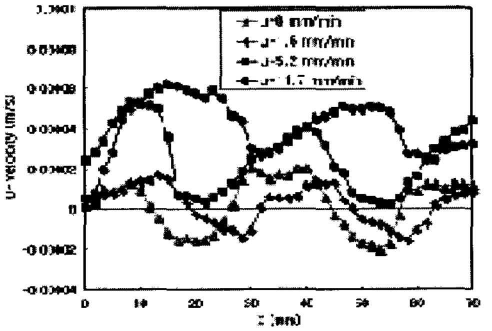


Fig. 9 U-velocity profiles for various instants.

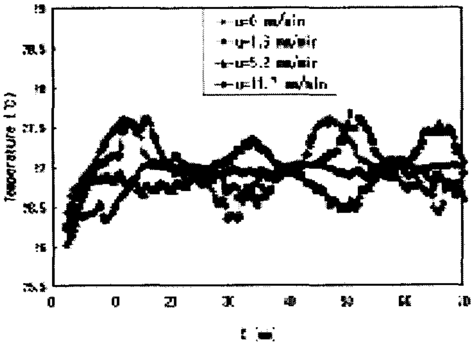
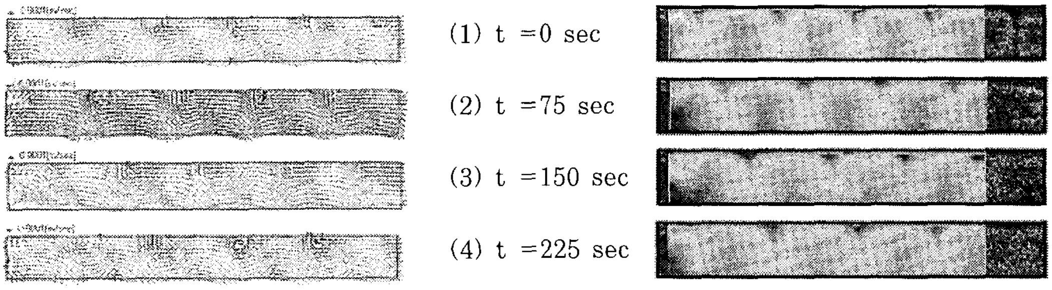


Fig. 10 Temperature profiles for various instants.

Figure 10 shows temperature profiles at the center line of height of the test section for various inlet velocities. As the inlet velocity increases the amplitude of temperature is decreased, when the inlet velocity u=11.7mm/min the temperature is almost same in the whole region except near the entrance region. It is due to the inlet fluid of which temperature is mean temperature and the strong effect of forced convection near the center line.

The through-flow divide the flow occurred by natural convection into two parts, upper and lower flow are still affected by natural convection, as shown in Figure 7. As the inlet velocity increases, the effect of natural convection is decreased, thus the temperature of fluid near the center line becomes the mean temperature of upper and lower surface temperature.

When the inlet velocity is u=9.0mm/min ($Re=2.3*10^{-2}$), temperature and velocity patterns at four different instants are shown in Figure 11. Figure 11(a) shows velocity vectors, and Figure 11 (b) shows temperature distribution painted by full color after applying color to temperature transformation to the original image. As shown in this figure, velocity pattern shows a periodic motion. This phenomena of mixed convection between the parallel plates is shown more clearly in Figure 11(b). As the time is passed, the



(a) (b)

Fig. 11 The temperature distribution and velocity vector of U=9.0mm/min, $\Delta T=3$, $Re=2.3*10^{-2}$, Ra=349.

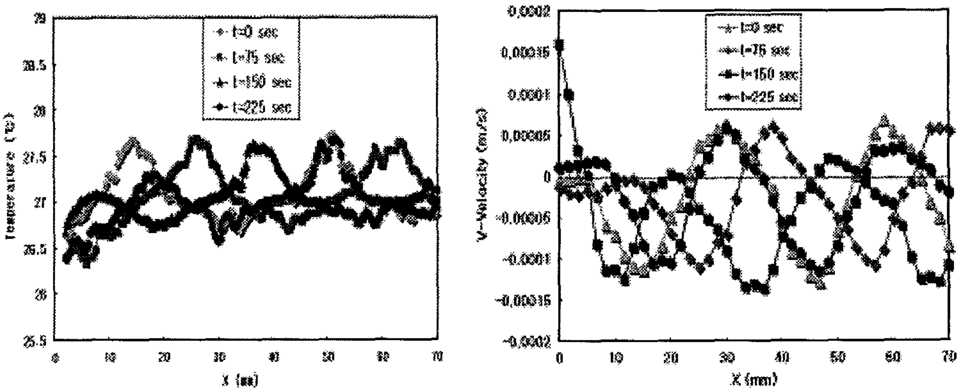


Fig. 12 Temperature and V-velocity profiles for various instants.

through-flow push the rolls formed by natural convection to upward direction consecutively, and the new roll is formed near the entrance region by the effect of natural convection at the end of a period. This result is shown in Figure 12 quantitatively. In this figure, we can confirm that temperature and velocity profiles at t= 0 second agree well with those at t=225 seconds after a period.

6. Conclusions

This work was conducted to develop measuring system using liquid crystals. The developed method was applied on the study of mixed convection between the parallel plates with opposed horizontal isothermal surfaces at different temperature. The following conclusions can be drawn from the present study.

1) We can develop the simultaneous measuring system of temperature and velocity field using liquid crystals successfully.

2) By applying this method on the mixed convection between parallel plates, we can visualize the temperature and velocity field between parallel plates quantitatively.

3) Three flow-patterns were observed with increasing inlet velocity in the mixed convection between parallel plates as follows:

(1) Natural convection flow pattern

(2) Sinusoidal flow pattern in a whole region

(3) Stratified flow pattern in the upstream, and sinusoidal flow pattern in the downstream

4) Periodic flow pattern in the mixed convection between parallel plates was found in experiment.

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