

An Experimental Investigation of Unsteady Mixed Convection in a Horizontal Channel with Cavity Using Thermo-Sensitive Liquid Crystals

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Abstract : An experimental study is performed to investigate unsteady mixed convection in a horizontal channel with a heat source. Particle image velocimetry (PIV) with thermo-sensitive liquid crystal (TLC) tracers is used for visualization and analysis. This method allows simultaneous measurement of velocity and temperature fields at a given instant of time. Quantitative data of the temperature and velocity are obtained by applying the color-image processing to a visualized image, and neural network is applied to the color-to-temperature calibration. It is found that the periodic flow of mixed convection in a cavity appears at very low Reynolds numbers ($Re < 0.4$), and the period decreases with increasing Reynolds numbers and increases with increasing aspect ratio.

Key words : Cavity, Experimental, Mixed convection, Liquid crystal, Unsteady

Nomenclature

AR	: aspect ratio, W/H
H	: cavity height
W	: cavity width
Ra	: Rayleigh number, $g\beta\Delta TH^3/\alpha\nu$
Re	: Reynolds number, $U_{in}H/\nu$
U_{in}	: inlet velocity
t	: time

1. Introduction

The convective flow and heat transfer in cavities have received considerable attention by many researchers. The attention stems from the importance of such geometry in cooling electronic components and compact heat exchangers. Most of the studies about this geometry have been concerned with the natural and forced convection. However, mixed convection is important

for both theoretical and practical points of view. It may play at low forced velocities which are appropriate for the cooling systems with relatively weak power dissipation.

In the past decade, there has been considerable work showing that unsteady mixed convection flows are complex[1-4]. However, these studies mainly adopted numerical method to treat the problem. Recently, the new experimental technique using liquid crystal tracers as indicators of velocity and temperature was introduced. This method allows simultaneous measurement of velocity and temperature in the whole flow field at a given instant of time. So, it is very useful experimental method for analyzing unsteady thermal flow phenomena.

Ozawa et al.[5] and Kimura et al.[6] applied the new technique to the natural

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2.2 Measurement of velocity and temperature field

In order to make visualization of the flow field, liquid crystal is used as a tracer particle. Calculation of velocity field is done by gray-level cross-correlation algorithm. RGB 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.

In order to obtain quantitative thermal flow, the calibration of color to temperature for the liquid crystals is undertaken in the stratified temperature field[7]. The results of the calibration experiment are the relationship between r (red), g (green), and b (blue), and the measured temperature shows a strong nonlinear characteristic. This makes it difficult to obtain an exact equation for color-to-temperature transformation. In this study, a neural network is employed to formularize the color-to-temperature relationship.

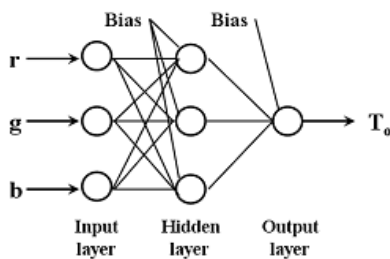


Figure 2: Neural network structure

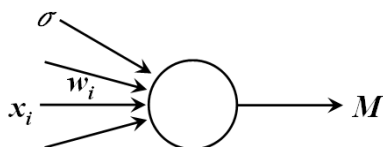


Figure 3: Neuron model

Figure 2 shows the structure of a three-layer feed-forward neural network. The inputs of the network are r , g and b values. The output is the temperature T_o . The network consists of three layers, namely, an input, a hidden, and an output layer. The three units in the input layer are linear devices and the three units in the hidden layer and one unit in the output layer are neurons. A simple neuron model is shown in Figure 3. This is the basic unit of neural network, which performs a nonlinear transformation of the sum of weighted inputs to produce the output of the neuron. The sum of weighted inputs X is given by

$$X = \sum_{i=1}^n w_i x_i + \sigma \quad (1)$$

Where x_i is an input to the neuron, w_i is the connected weight, and σ is the bias. The output M is expressed as

$$M = f(X) = \frac{1}{1 + \exp(-X)} \quad (2)$$

and this is termed a sigmoid function. Learning the neural network is carried out in order to agree with the output T_o corresponding to the inputs of r , g and b patterns with the measured temperature T_m . Therefore, it can be said that learning is to seek the values of the connected weight w_i and the bias σ to minimize the following error function E .

$$E = \frac{1}{2} \sum (T_o - T_m)^2 \quad (3)$$

3. Results and discussion

Figure 4 shows the visualized original image of liquid crystal and the result of original image calibration. The temperature difference between top and bottom surfaces is 3.0°C ($28.8\text{--}25.8^{\circ}\text{C}$). Figure 4(a) shows the original image that the vertical temperature gradient is established in the fluid, and it corresponds to the state of heat conduction. There is no fluid motion and the thermal boundary layer grows by pure conduction. After applying the color-to-temperature transformation to the original image, temperature distribution is painted by 24 bit full color as shown in Figure 4(b). The color of the original image changes from brown to blue as the temperature rises, namely, the brown indicates the low temperature and the blue indicates the high temperature. However, the order of colors is reversed in the image painted by full color as usual.

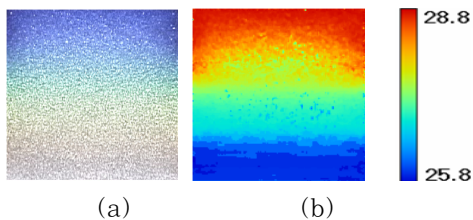


Figure 4: Visualized image of liquid crystal tracers and evaluated temperature distribution

Figure 5 shows evaluated temperature distributions and velocity vectors at different instants of a flow cycle for $Ra = 6.86 \times 10^4$, $AR = 1$ and $Re = 0.05$. Figure 5a shows the through flow runs almost parallel and the small secondary cell is formed at the left corner of the cavity by

natural convection. During the evolution of the cycle, the main flow is displaced downstream until it mixes with secondary cell (Figure 5b). For the rest of the cycle, the secondary cell increases in size (Figure 5c), and then it turns back to its initial form (Figure 5d). Considering the temperature patterns in Figure 5, the low temperature flows from the entrance of the channel permeates into the cavity slowly. The natural convection caused by temperature difference and the forced flow that introduced from the entrance of the channel influence each other. As a result, the complex change of the cell forms, which can be observed periodically and the period is 180 seconds. By progressively increasing Re , the forced flow occupies more and more space in the domain. This behavior is illustrated in Figure 6a-d, which shows evaluated temperature distributions and velocity vectors at selected instants of the flow cycle obtained for $Ra = 6.86 \times 10^4$, $AR = 1$ and $Re = 0.1$. Two secondary cells appear at the cavity bottom by natural convection (Figure 6a). However, the natural convection cells are destroyed by the penetrated forced flow (Figure 6b-c). Later, the main through flow continue to be carried until the beginning of a new cycle (Figure 6d).

The period of the periodic flow decreases to 120 seconds from 180 seconds with increasing Reynolds numbers. By further increasing Re , the main forced flow which occurs by natural convection at the bottom disappears. Thus, the forced convection dominates the whole space above the block inducing a recirculating vortex in the cavity and the flow becomes steady.

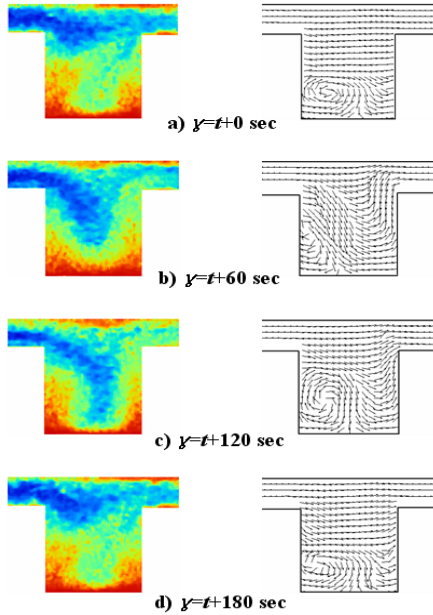


Figure 5: Evaluated temperatures and velocity vectors at different instants of a flow cycle for $Ra = 6.86 \times 10^4$, $AR = 1$ and $Re = 0.05$

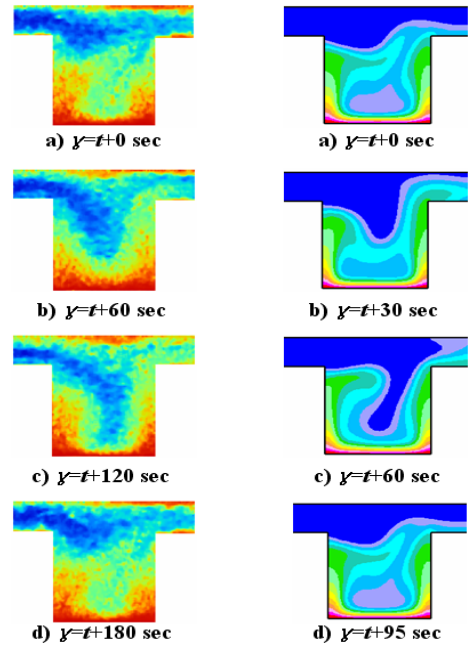


Figure 7: Comparison of experimental and numerical results at $Ra = 6.86 \times 10^4$, $AR = 1$ and $Re = 0.05$

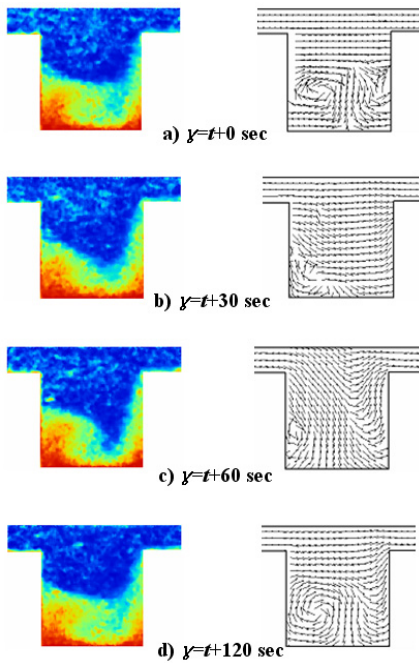


Figure 6: Evaluated temperatures and velocity vectors at different instants of a flow cycle for $Ra = 6.86 \times 10^4$, $AR = 1$ and $Re = 0.1$

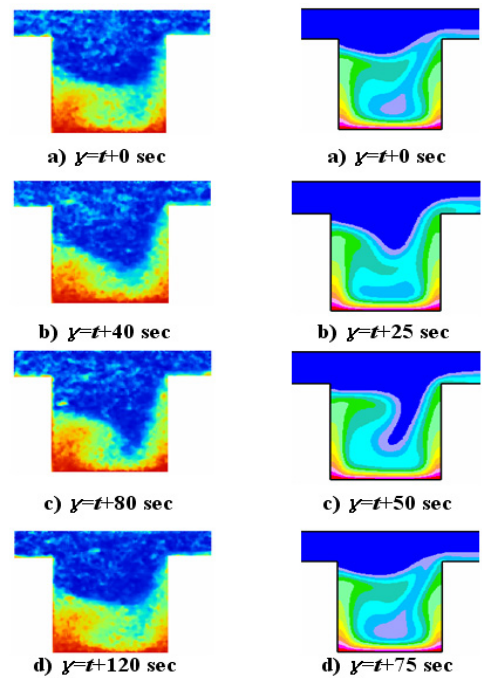


Figure 8: Comparison of experimental and numerical results at $Ra = 6.86 \times 10^4$, $AR = 1$ and $Re = 0.1$

Figure 7 and Figure 8 show the results of experiment and numerical simulation in a period of the periodic flow at $Ra = 6.86 \times 10^4$, $AR = 1$, $Re = 0.05$ and at $Ra = 6.86 \times 10^4$, $AR = 1$, $Re = 0.1$, respectively. The experimental results of the velocity and temperature distribution are in accord with numerical calculation. Although the period values obtained in the experiment are longer than those of numerical calculation, these pictures show that we have successfully achieved the visualization of periodic flows in cavity experimentally in this study.

4. Conclusions

In this study, Particle image velocimetry (PIV) with thermo-sensitive liquid crystal (TLC) tracers is used for visualization and analysis. By applying this method to the unsteady mixed convection in a horizontal cavity with heat source at the bottom, we can visualize the temperature and velocity field of the unsteady mixed convection in the cavity quantitatively. It is found that the periodic flow of mixed convection in a cavity is shown at very low Reynolds numbers and the period decreases with increasing Reynolds numbers.

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