RESEARCH OF THE THERMOSOLUTAL NATURAL CONVECTION IN REFLOW OVEN

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Abstract

This study attempts to simulate the phenomenon of thermosolutal natural convection in a horizontal double-opening divided square box with the reflow oven under various boundary conditions and heat offering by performing experiment and numerical methods. To analyze the effects of horizontal divided square box under different temperatures. The fixed buoyancy ratio (N value), the flow field displayed due to the arrangement of plate, the temperature of the liquid inside the box and the varieties of concentration are included as the objectives of this study. A square box made of copper and acrylic sheets with an aspect ratio of 0.5 is used as the experimental apparatus of this study; the horizontal divided plates are placed in the upper and bottom of the interior of the box, while the fluid inside the box will be given in different concentrations. A measuring analysis will be performed to examine the temperature, concentration and mass transmission rate of the current. Finally, the FLUENT (CFD software) will be adopted to conduct numerical simulation on prototype to demonstrate an experiment with temperature variation rate and analyze the errors as contained. To simplify the governing equation of flow filed, the overall coordinate system will be treated as 2D numerical simulation, while visualization will be used to discuss and analyze the physics and results as developed with an attempt to improve the design of reflow oven. The dimensionless parameters as discussed in this study include:
Ar=0.5, Ap=0.33, Pr=7~8, Sc=1700~2500, N=7.53, $Gr_t=8.16\times10^5$, $Gr_m=6.15\times10^6$

Key words: Heat-insulated plate, natural convection, doubled-opening ratio

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RESEARCH OF THE THERMOSOLUTAL NATURAL CONVECTION IN REFLOW OVEN

迴焊爐中有關熱質自然對流探討

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摘要

本研究是以實驗及數值方法探討迴焊爐在各邊界條件及加溫的狀態下，模擬水平雙開口隔板矩形盒之熱質自然對流現象，分析影響不同溫度下的水平式隔板效應。針對固定浮力比（N 值）、隔板位置所展現的流場型態，盒內溶液溫度及濃度的變化情形均是研究的對象。實驗裝置為展弦比等於 0.5 之矩形盒，以銅板及壓克力板構成且分別在盒內上、下間位置放置水平隔板並變化矩形盒內濃度。對流場的溫度及濃度和質傳遞率作量測分析；最後再以 CFD 軟體 Fluent 進行原型數值模擬，以驗證溫度變化率之實驗與分析誤差。為簡化流場統御方程式，整個座標系統視為二維問題行數值模擬；並借由流場可視化來探討其產生的物理現象並分析評估結果。以做為改善迴焊爐設計之要點。本實驗無因次參數研究範圍如後：$Ar=0.5$, $Ap=0.33$, $Pr=7\sim8$, $Sc=1700\sim2500$, $N=7.53$,$Gr_t=8.16\times10^5$,$Gr_m= 6.15\times10^6$

關鍵詞：絕熱隔板、自然對流、雙開口比

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1. Introduction

Germanium (Ge) and Silicon (Si) are the most common element semiconductors used for making transistors; some properties contained within have been approved during the evolution process of these two elements. However, researchers found that compound semiconductors such as GaAs, GaAsP, InP, AgAlAs, InGaP, featuring particular properties, can be adopted as semiconductor materials as well. Jiang et al. [1] used GaAs to examine the thickness distribution of epitaxial film in every possible parameter conditions. Fotiadis et al. [2] focused on MOVPE in vertical reactor to examine the transmission status under different parameter conditions; while Diawarie et al. [3] released a detail describing the operating conditions (size, temperature, etc.) for a MOCVD reflow oven and the thickness of the film as developed eventually.

The occurrence of natural convection in a closed chamber can be classified into two types according to the direction of the change of its density gradient: 1. A change of density in a direction vertical to the gravity direction. 2. An increase of density gradient in a direction in parallel with the gravity direction; in this case, the movement of liquid will not start until the density gradient reaches to a certain level. The two modes may occur at the same time and make things more complicated. Brown and Solvason (1962) [4] once performed an experiment to study the development of "thermosolutal" natural conviction to placing a divided plate with tiny openings on which between two chambers. Nansteel and Greif (1981) [5], (1984) [6] found that the placement of divided plate in a closed chamber may generate recirculation zone and thus reduce the effect of heat transfer. Bejan et al. (1983) [7] used water as working fluid to conduct an experiment exploring the development of natural convection in a closed chamber with divided plate, while the result indicated that the opening ratio played an important role in heat transferring and the development of flow field. Winters (1982) [8] emphasized on the numerical analysis of Rayleigh (10^6~10^{11}), he found that when the number of Rayleigh is low (10^6), the distribution of fluid will occur on the back of the divided plate, while high Rayleigh Number (10^{11}) will have its fluid distribution develop on the front of the divided plate. Chou (1990) [9] used divided plates with and without openings to examine the phenomenon of natural convection; the result as gained showed that the heat transferring rate for plate with openings is higher than which of the plate without openings by 14%~30%, while the size of divided plate did not have obvious influences on the distribution of temperature field and speed field in the lower section. D.A.Olson (1990) [10] reasoning a series of studies investigating the occurrence of natural convection in a closed chamber with and without divided plates, and made comparison on the speed field and temperature field as generated in different locations. The results showed that the heat transferring rate in a closed chamber with divided plates is lower than the one without divided plates by 10%~15%; besides, the divided plate will improve the secondary flow as generated nearby the plate itself. E.Zimmerman (1986) [11] found the intensity of the main flow between the upper and bottom divided plates within a closed box will decrease as the heat transfer of the divided plate increases, and Nu will decrease as there is a divided plate and the heat transfer of the divided plate increases. The afore-mentioned studies were based on numerical simulation or using air as the experiment medium, and most of the experiments were performed under the absolute heat-transfer condition. The heat loss due to heat transfer system and experimental errors as a result of heat transferring were unavoidable; besides, it is impossible to obtain high Ra and Pr in a common heat-transfer experiment. However, the experimental errors due to heat loss may be avoidable in an absolute mass transfer system.

Following the advances of semiconductor technology, the IC chips have been widely applied in man's daily commodities. However, the current standing of semiconductor industry in Taiwan still remains in the phase of manufacturing development, which means it is a pure manufacture business. As a result, the researching, developing and manufacturing of the semiconductor facilities shall be the key matters that keep the industry competitive in a long term. In view of this, this study adopts the MOCVD of reflow oven with horizontal double-opened plate as the study target to function as references for semiconductor business in the manufacturing of reflow facilities and production process as well, so as to increase the productivities while lower the production cost.

2. Experimental Method

2.1 Dimensionless Parameters

Given the basic differential equation for thermosolutal convection in an enclosure with backward-facing steps, the following dimensionless parameters are important in this problem:

$Gr_t \equiv g\beta\Delta CH^3/\nu^2$ thermal Grashof number

$\Pr \equiv \nu/\alpha$ Prandlt number

$Sc \equiv \nu/D$ Schmidt number

$N \equiv \overline{\beta}\Delta C/\beta\Delta T$ buoyancy ratio

where g is the gravitational acceleration; ν denotes the fluid kinematics viscosity; α is the thermal diffusivity, and D is the diffusion coefficient. The annular gap width of the enclosure is H, respectively. ΔT and ΔC are the imposed temperature and concentration differences, respectively. The density variation due to temperature is represented as a volumetric thermal expansion coefficient β. The density variation due to the concentration is presented using the volumetric solutal expansion coefficient $\overline{\beta}$.

The (Gr_t, Gr_m) combination is sometimes used instead of the (Gr_t, N) combination, where Gr_m, is defined as

$$Gr_m \equiv g\overline{\beta}\Delta CH^3/\nu^2 = NGr_t$$

continuity equation:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0$$

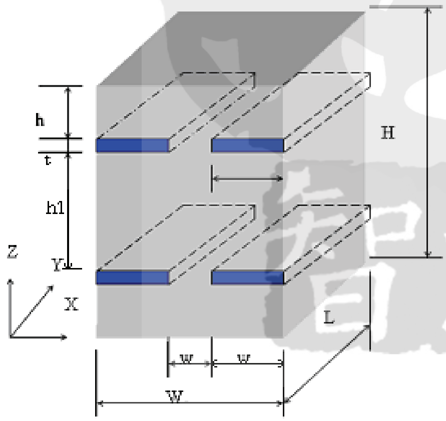
the χ direction of dynamic equation

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=-\frac{1}{\rho}\frac{\partial \rho}{\partial x}+v\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right)+\beta g\left(C-C_b\right)$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}=-\frac{1}{\rho}\frac{\partial \rho}{\partial y}+v\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right)+\beta g\left(C-C_b\right)$$

2.2 Test Apparatus and Test Cell

The temperature gradient of the boundary condition and the square box with an aspect ratio (Ar) of 1.8 as adopted in this study is set up based on the circulator, while the adopting of electro-chemical system is based on the theory of limit current value as stated by Tobias [11] (1953) to generate mass transferring inside the system. The size and circuit diagram are disclosed in **Fig.1**. The shadowgraph is adopted to observe the flow filed.



H	W	w	L	h	h1	t	Ar	
72	36	12	130	10	44	2	0.5	Unit:mm

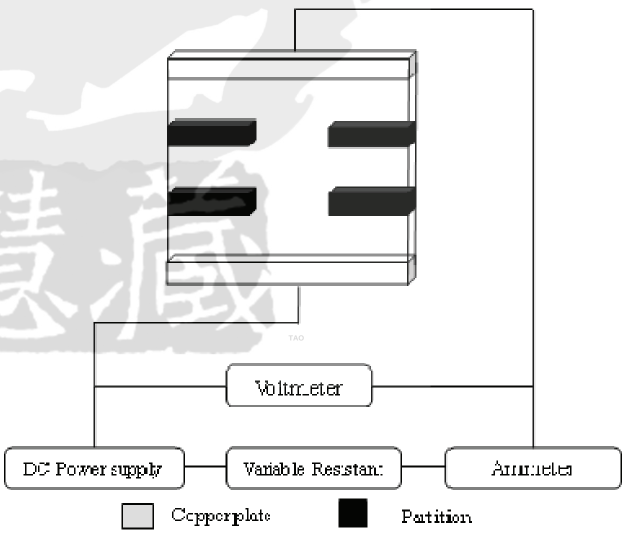


Fig.1 Illustration of test cell and electric circuit

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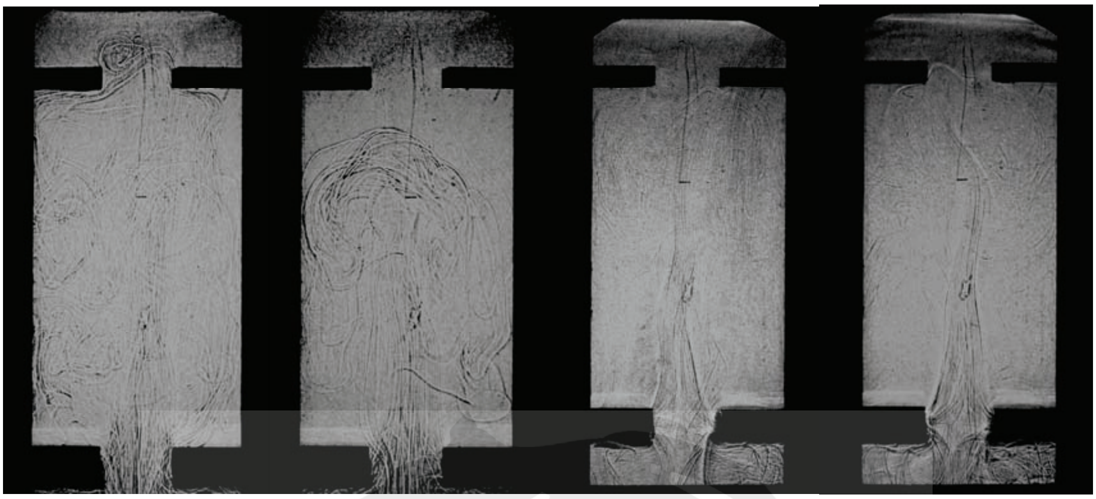
3. Results and Discussion

3.1 The Observation of Thermosolutal flow field

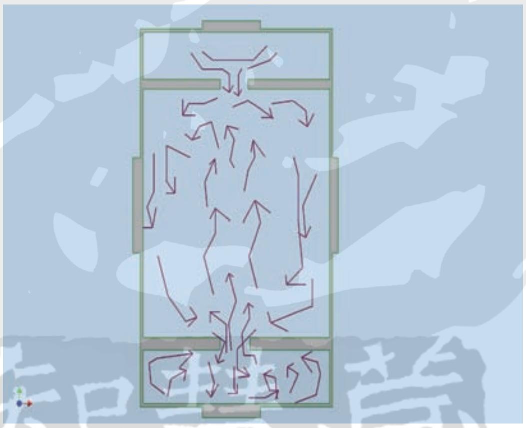
The top and bottom plates are heat plates; the plates placed on the right and left are cool plates. The copper sulfate as adopted is 0.069M, Gr_t=8.16×10^5.

When the pure temperature gradient reaches the heat stable status, the high temperature fluid as occurred from the temperature boundary layer around the top heat plate will pile up on the top plate and in the area around the upper double-divided plates. Whereas the high temperature fluid developed around the bottom plate (heat plate) will rise up along the bottom of the right, left plates inside the bottom double-divided plates as it departs from the temperature boundary layer. As influenced by the low-temperature fluid generated around the right and left cool plates, the flow direction of the main heat flow will be changed as a result (the high-density fluid generated by the cool plate effect will be separated from the cool plate and move toward the bottom divided plate as it is driven by the gravity force after departing from the temperature boundary layer) and move toward the right hand side of the bottom double-divided plate and form a fluid circulation with the uprising fluid within the bottom divided plate, and thus a regional "fluid trap" effect will be developed in the area surrounded by the right, left plates (cool plates) and the upper, bottom plates, whereas two separate flow circulations will also be formed in the space between the bottom plate and bottom divided plate, and the space between the upper plate and the bottom divided plate as well. The heat flow generated from the center of the bottom plate will rise up after departing from the temperature boundary layer and go through the center of the upper and bottom divided plates and reach to the top plate; see **Fig.2 (a)**. When extending the time to 40 minutes, the circulation fluid formed between the upper, bottom divided plates and the right, left plates will move toward the right, left plates, while the less heavier fluid will rise up along the cool plate to the top across the center between the upper divided plate and the two divided plates, and mix with the main flow as generated by the heat flow generated from the center of the bottom plate. See **Fig.2 (b)**. While the mass transfer is added with the top and bottom plates being the heat plates (Negative pole) and the right and left plates being the cool plates (positive pole), and the copper sulfate is 0.069M, Gr_t=8.16×10^5; Gr_m = 6.15×10^6, N=7.53, the bigger the absolute value of N is, the greater the influence of the density effect will be. The high-density fluid generated from the right and left plates will move toward the bottom double-divided plates after departing from the temperature boundary layer, the movement is slower in the higher area yet it is more obvious in the lower area, while a low-temperature high-density fluid will be piled up in a space between the cool plate and the divided plates consequently. The light-heat fluid generated by the bottom heat plate (negative pole) will rise up after departing from the temperature boundary layer, while the heat fluid from both sides will move toward the center of the two divided plates along the down side of the bottom double-divided plates as it is blocked by the bottom double-divided plates. At the same time, the light-heat fluid as generated from the center of the bottom plate will rise up along the center of the double-divided plates and mix up with the fluid as formed along the two sides of the bottom divided plate and keep on going up. Since the high-density fluid generated from the right and left cool plates between the upper and bottom plates will run into the uprising heat flow produced by the double-divided plates in the bottom, the lower fluid will push up the downwards upper fluid while integrating with the right and left cool plates and thus developing into a large circulation system. See **Fig.2 (c)**. The heavier heat fluid as generated from the upper double-divided plates does not descent significantly due to its being pushed up by the uprising fluid in the bottom, and thus a separate small circulation system on both side s is formed as a result.

When the high-density fluid generated by the right and left cool plates below the upper divided plates moves toward the center, it is also influenced by the rising heat flow from the top and the bottom, yet the temperature effect is not strong enough to push up all the high-density fluid, some of which will go down and form a circulation between the cool plates and the upper and bottom divided plates. As time goes by, the circulation movement becomes more evident and the high-density fluid existed between the double-divided plate and the heat plate will continue to develop in the circulating manner. See **Fig.2 (d)**. The main flow in the flow field is disclosed in **Fig.2 (e)**.



(a) t=1min (b) t =120min (c) t =180min (d) t =240min



(e)

Fig.2 Flow pattern in aiding case for At=0.5, Ap=0.33, Gr_t=8.16×10^5, Gr_m=6.19×10^6

3.2 The temperature distribution of forward flow field of the upper and bottom double-divided plates

A 2D positioner is used to fix the T type thermocouple, while the T type thermocouple is putting inside the flow filed to measure the temperature at x/W＝0.3, 0.5, 0.8; z/L＝0.5. The copper sulfate is 0.069M; Gr_t =8.16×10^5; Gr_m = 6.15×10^6.

The top and bottom plates are heat plates (negative pole), with the right and left plates being the cool plates (positive pole). When the pure temperature gradient reaches the heat stable status, the high temperature fluid as occurred from the temperature boundary layer around the top heat plate will pile up on the top plate and the area around the upper double-divided plates. As seen in the temperature distribution diagram, the dimensionless temperature at the point of $\bar{x}$ =0.3, 0.5, 0.8 shows a linear rising state. See **Fig.3**.

When the mass transfer is added, the low-temperature high-density fluid will pile up in the area between the divided plate and the cool plate, making the movement of the fluid in this area more slow. The heat transfer in this area is driven by transmission effect and thus the temperature of the whole area, along with the pure temperature field, is similar to the temperature of the cool plate. When observing the temperature distribution between the upper and bottom divided plates at the point of $\bar{x}$ =0.3, $\bar{x}$ =0.8 and $\bar{x}$ =0.5, we found that when $\bar{x}$ =0.5 and t=0 min, the dimensionless temperature will rise up to about t=240 min0.49; and at the point of $\bar{x}$ =0.3 and $\bar{x}$ =0.8, the dimensionless temperature will be evenly distributed at 0.45 or 0.7.

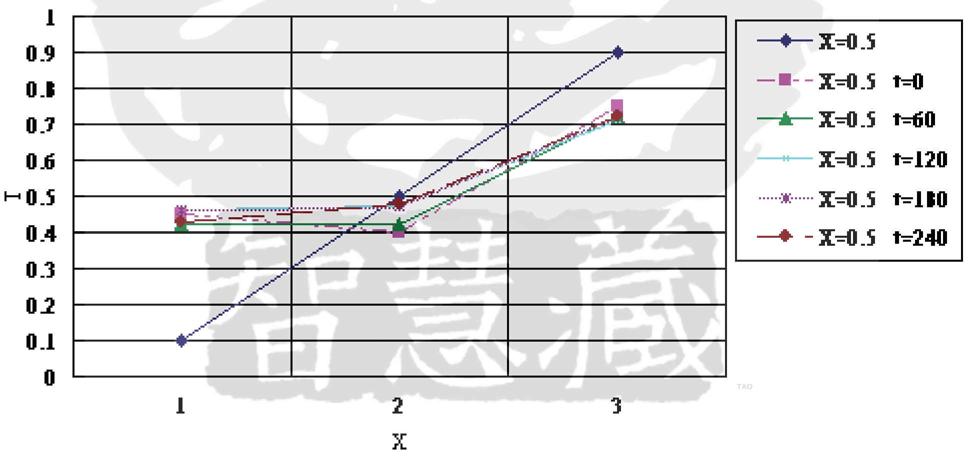


Fig.3 Temperature distribution in aiding case for Ar=0.5, Ap=0.33,

Gr_t=8.16×10^5 , Gr_m=6.19×10^6

3.3 Analysis on Mass Transfer Rate

The value of Gr_m is fixed to examine the relation of Sh, the Sh is higher in forward flow filed than in backward flow field. The result can be seen in **Fig.4**. The main reason is that when the heat and mass exist in a forward field, the temperature differences between the two plates will increase, thus making the rising of the temperature of the fluid while changing the overall convection effect of the fluid. When the mass transfer is added, it will promote the movement of mass transferring and affect the mass transfer rate, and thus the Sh will be determined according to the structure of flow field and the amount of limit current.

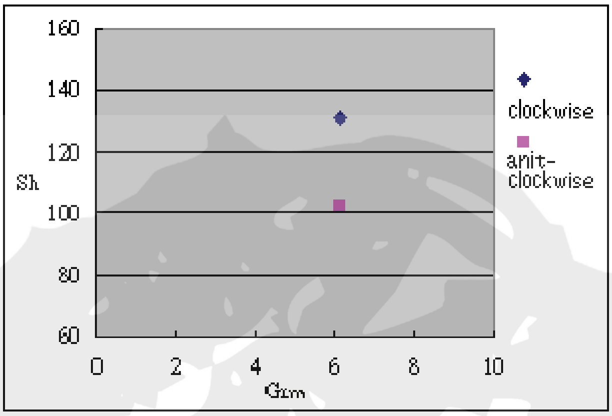
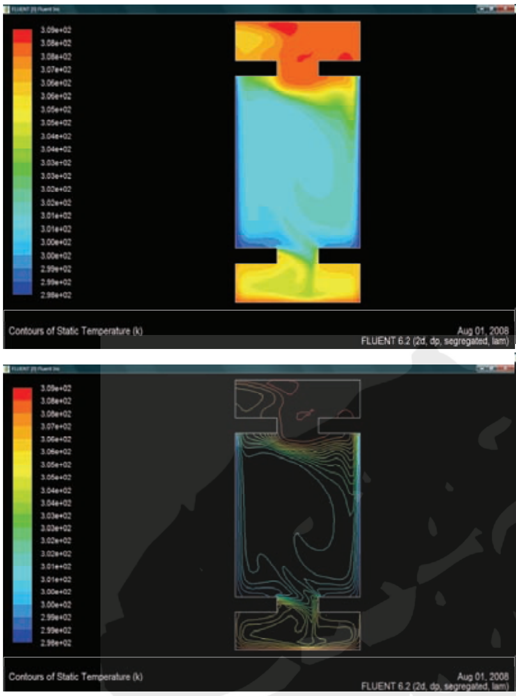


Fig.4 Correlation of Sh with Gr_m（$\times 10^5$）($Gr_t=8.16\times 10^5$)

3.4 Numerical Analysis

Simulation as seen will be conducted with the top and bottom plates being the heat plates and the right and left plates being the cool plates, following a grid of 2557 nodes. As learned from the result, the fluid existed in the top plate will pile up as a result of affecting by the opening ratio of the double-divided plates (upside), while the fluid generated from the bottom plate will develop a heat accumulation inside the double-divided plate under the influences of the cool and heavy fluid as generated from both sides; however, some heavy and heat fluid and light and heat fluid will go through the doubled-divided plates (downside) and enter into the flow field of the cool plate with their temperature rising up. See **Fig.5**. As the heavy and heat fluid and the light and heat fluid flow into the cool field, a maximum velocity of 3.0×103. (m/s) will be measured at the point of x=0.022(m), y=0.2(m) in the double-divided plate (downside); see **Fig.6** that the fluid with similar Fig2. However, the eddy current will develop in the cool field as a result of the dropping of the heavy and heat fluid (see **Fig.7**), an eddy current rotating counter clockwise will form on the right side of the doubled-divided plate (downside) while another clockwise current will develop on the left side of the doubled-divided plate (downside).



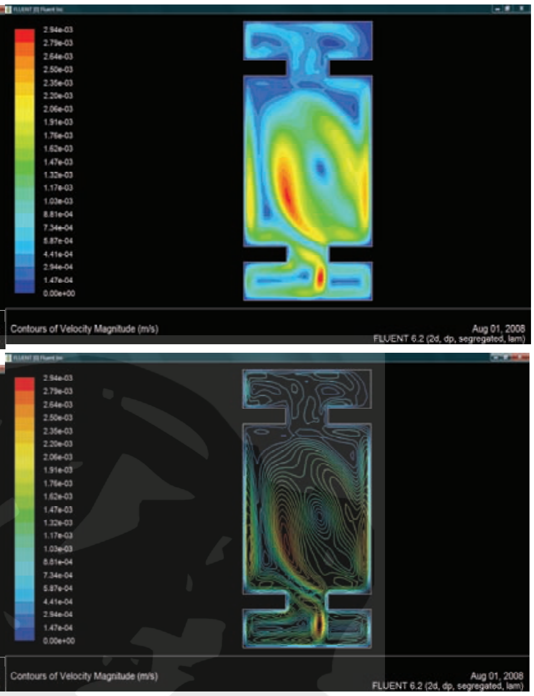


Fig.5 Temperatures distribution
Hot (left) side 308K
Cold (right) side 298K

Fig.6 Velocity distribution
Hot (left) side 308K
Cold (right) side 298K

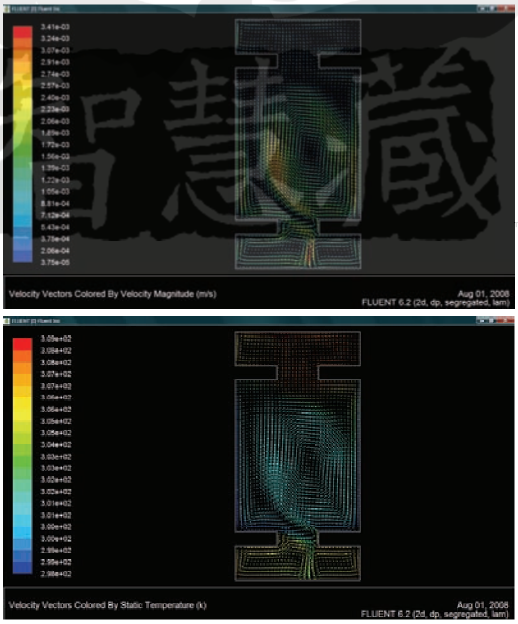


Fig.7 Vector distribution
Hot (left) side 308K
Cold (right) side 298K

4. Conclusions

4.1 The type of flow field

A closed-type square box containing the upper and the bottom doubled-divided plates, a heat accumulation is formed on both sides of the inner part of the upper divided plate during the experiment. After the mass transfer is added, the occurrence of the accumulation of the boundary layer of high-density or low-density mass and the resolution of density surface can still be anticipated.

4.2 The distribution of temperature

When the pure temperature gradient maintains at a stable condition, the temperature between the upper and bottom divided plates will rise up in a linear manner. After the mass transfer is added, the dimensionless temperature at $\bar{x}$ =0.3 appears to be higher in the forward filed than in the backward filed (+0.1).

4.3 The distribution of density

In a theromosolutal forward experiment, the density of fluid existed between the upper and bottom divided plates and the top and bottom plates is high, while which in the center of the flow filed is more stable and close to the substance itself.

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Appendix

Notation

ΔC concentration difference between C_b and C_o

ΔT temperature difference between T_h and T_c

C_b bulk concentration of $CuSO_4$ (g-mole/cm^3)

C_o ion concentration at the cathode

D diffusion coefficient

Gr_t thermal Grashof number $\left(g\beta\Delta H^3/\nu^2\right)$

Gr_m solutal Grashof number $\left(g\bar{\beta}\Delta CH^3/\nu^2\right)$

g gravitational acceleration

H annular gap width ($H=R_o-R_i$)

N buoyancy ratio $\left(\bar{\beta}\Delta C/\beta\Delta T\right)$

Pr Prandtl number $\left(\nu/\alpha\right)$

Sh mass transfer rate

T temperature (℃)

α thermal diffusivity of the fluid (cm^2/s)

β volumetric coefficient of thermal expansion $\left[1/\rho\left(\partial\rho/\partial T\right)_C\right]$

$\bar{\beta}$ volumetric coefficient of thermal expansion $\left[1/\rho\left(\partial\rho/\partial C\right)_T\right]$

ν kinematic viscosity (cm^2/s)