

# LAMINAR NATURAL CONVECTION INSIDE A SQUARE ENCLOSURE AROUND ISOTHERMAL HORIZONTAL AND VERTICAL TRIANGULAR PARTITIONS

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## Abstract:

Two dimensional laminar natural convection heat transfer in a square cavity with horizontal and vertical triangular partitions is studied by ANSYS 12.1. The computational procedure based on finite element technique is used to solve equations of continuity, momentum and energy. Two isothermal boundary conditions are considered. The segments of horizontal and vertical walls of the enclosure are maintained at hot temperature, while the triangular partitions surfaces are maintained at cold temperature. Air was chosen as a working fluid with Prandtl number of 0.71. A parametric study is carried out using following parameters: Grashof number from  $10^4$  to  $10^6$ , Dimensionless partition height from 0.2/ to 0.8/ of half height or width of the enclosure. Representative result illustrating the effect of the above parameters on the contours maps of the streamlines and isotherms are reported and discussed. It was found that, the convective heat transfer is greatly influenced by increasing the partitions height. Increasing the partition height causes an increase in heat transfer due to increasing cold surfaces, vise verse, causes decreases in the Nusselt number due to decrease in the flow speed.

**Keywords:** Laminar Flow, Natural Convection, Square Enclosure, Isothermal Partitions, Isotherms, Stream-lines, ANSYS Solutions.

## الخلاصة:

تم دراسة انتقال الحرارة الثنائي الأبعاد بالحمل الطبقي الطبيعي داخل حيز مربع يحوي حواجز أفقية وعمودية مثلثة الشكل باستخدام برنامج "ANSYS 12.1". المعادلات التفاضلية التي تحكم انتقال الكتلة والحركة والطاقة تم حلها عددياً باستخدام تقنية العناصر المحددة. تم اعتماد شرطين حديين ثابتين حرارياً، حيث تم تثبيت درجة حرارة أسطح الطبقة الأفقية والعمودية بدرجة حرارة ساخنة. أما درجة حرارة أسطح الحواجز المثلثة، فقد ثبتت بدرجة حرارة باردة. لقد تم اختيار الهواء كمائع شغل برقم براندتل 0.71. تم تنفيذ هذه الدراسة على مدى واسع لرقم كراشوف من  $10^4$  إلى  $10^6$  وذلك لأرتفاع حواجز بأطوال من 0.2 إلى 0.8 من نصف إرتفاع أو عرض الطبقة. تم عرض نتائج تأثير كل من الأرقام أعلاه على كمتور كل من خطوط الجريان ودرجات الحرارة ومناقشتها. لقد وجد بأن معامل انتقال الحرارة بالحمل يتأثر بصورة كبيرة بكل من إرتفاع الحواجز ورقم كراشوف، وقد تبين بأن رقم نسلت هو دالة تزايدية لرقم كراشوف ودالة تناقصية لأرتفاع الحواجز.

## 1- Introduction:

In the first, the high temperature of electronics equipments inside its containers led to the extensive of micro channel conditioning system to maintain the temperature inside the containers. Secondly, the natural convection heat transfer to arbitrary cross section ducts has many engineering applications, solar collectors, heat exchangers, heating and ventilation of living space and storage of radio-active wastes. However, limited number of studies was concerned with heat transfer in a square cavity with triangular ducts.

Besides the regular geometries such as square or rectangular enclosures, many studies on trapezoidal and triangular enclosures were seen in the literature, with vertical or horizontal partitions connected to vertical or horizontal enclosures walls. These studies can be classified into two categories as the partitions connected to enclosures walls (from reference [1] to [13]) and the partitions or object located inside the enclosure (from reference [14] to [22]).

In the first category, O. Zeiton and M. Ali [1 and 2], studied numerically the natural convection heat transfer from isothermal horizontal rectangular duct with rectangular cross section cylinder, and rectangular and square cross sections, respectively. The results show that increasing Rayleigh number reduces the thermal boundary layer along the vertical and bottom surface of the duct. A thin fin and conductive baffle located horizontally to hot left vertical wall for a square and rectangular enclosures were studied numerically by E. Bilgen [3] and S. Sivasankaran and P. Kandaswamy [4], respectively. They found that Nusselt number is an increasing function of Rayleigh number and the average Sherwood number is a decreasing function of aspect ratio respectively. The investigation of mixed convection in differentially heated square enclosure with partition is explained by S. K. Mahapatra, and et al. [5]. They found that when height of the centrally located partition increases beyond a certain height of 0.3, the heat transfer in case of apposing mixed convection is found to be more than of natural convection for a partitioned enclosure that submitted later by S. K. Mahapatra, and et al. [6]. V. C. Mariani and L. S. Coelho [7] and Y. Varol, and et al. [8], conducted a numerical study to investigate the steady heat transfer and flow phenomena of natural convection of air in rectangular and triangular enclosures respectively, with heat source on the bottom wall at different positions. In view of the results, the position of the heat source influences the fluid dynamics of the air as well as the heat transfer rate in the enclosure. The effect of using solid partitions on the natural convection inside inclined air-filled rectangular enclosure is studied numerically by S. M. El-Sherbing [9]. In that paper the partitions located to the two side's walls. The results show an increasing the partition height and thickness causes a decreases in the Nusselt number. Later A. Ben-Nakhi and A. J. Chamkha [10], applied these two partitions on the bottom wall for the same rectangular inclined enclosure. Finally, they found when the dimensionless partition height increase, the flow speed within the partitioned enclosure decreases resulting in less wall heat transfer. A numerical study has been conducted by F. Moukalled and M. Darwish [11], to examine the effects on heat transfer of mounting of two offset baffles onto upper inclined and lower horizontal surfaces of trapezoidal cavities. Results reveal decreases in heat transfer in the presence of baffles with its rate generally increasing with increase baffle height and

Prandtl number. Y. Duan, et al. [12], studied computationally the effect of insulated and isothermal thin baffles on pseudo steady-state natural convection within spherical containers. It was observed that the Nusselt number strongly depends on the position and length of the baffle and was generally lower than the cases with no baffles. A new approach to suppress the convection currents inside bricks cavities by increasing cell dividers. A numerical study by M. M. Alhazmy [13], on the effect of inserting a folder sheet inside cavities of a hollow building brick is presented. It was obvious from the results that the heat flux through the cavity, decreases as the number of partitions increases.

In the second category, the previous work of P. Kandaswamy, et al. [14], a natural convection heat transfer in a square cavity induced by heated plate located horizontally or vertically, was developed by A. K. Abdul Hakeem, et al. [15], by applying these two (horizontal and vertical) baffles orthogonally. It was observed that the heat transfer becomes more enhanced in vertical situation than in horizontal. But in the developed work, a drop in overall heat transfer was observed whenever one of the baffles is wall mounted. A numerical hybrid lattice-Boltzmann equation finite difference was obtained by A. Mezrhab, et al. [16], to study the radiation natural convection phenomena in a square cavity with partition located vertically. The results obtain show that the radiation produces a rise in the heat transfer. The average Nusselt number increase when the gap width, temperature difference and cavity length get larger. Rotatable baffles were fixed mid way between a vertical stack of a parallelogram enclosure by V. A. F. Costa, et al. [17], or fixed between the glass louvered shades by M. Collins, et al. [18]. They studied numerically the effects of these baffles on laminar natural convection heat transfer, that occurring in a vertical stack and the glass louvered shades enclosures, respectively. Results also show how the thermal performance of an enclosure without shutter is changed by the shutters introduction. M. Famour, and K. Hooman [19], used a FORTRAN code to study numerically the entropy generation for a natural convection with a partitioned cavity, with adiabatic horizontally and isothermally cooled vertical walls. It was theoretically indicated that, the average entropy production rate increases with Nusselt number and dimensionless temperature difference. Z. Altac and S. Konrat [20], performed a natural convection heat transfer from a thin horizontal isothermal plate in air-filled rectangular enclosure. Rayleigh number is varied from  $10^5$  to  $5 \times 10^7$ . The results of the parametric study shows that for increasing Rayleigh number the rate of the heat transfer is increases, and for increasing plate length the Nusselt number decreases by 25%. A numerical investigation of steady state laminar natural convection heat transfer around a horizontal cylinder to its concentric triangular enclosure was carried out by X. Xu, et al. [21]. Base on the presented numerical data, the flow intensity and overall heat transfer are significantly enhanced with increasing Rayleigh number due to more contribution from natural convection. A. Ben-Nakhi and A. J. Chamkha [22], focused on the numerical study of steady laminar, conjugate natural convection around a finned pipe placed in the centre of a square enclosure with uniform internal heat generation. It was concluded that, the finned pipe inclination angle, fin length, and external and internal Rayleigh numbers have a significant effects on the local and average Nusselt number at the enclosure wall-cavity and finned pipe-cavity interface.

The control of natural convection by suitably deciding the geometry of the partition within the enclosure is the object of the present work. Also, it is clear from

this brief review that, the rectangular or square partitions was commonly studied. Then, the partitions considered in the present study were to be triangular. The vertical and horizontal walls segment of the square enclosure were isothermal hot, whereas, the partition surfaces were maintained at isothermal cold temperature. Grashof number, partition height have been studied by using ANSYS 12.1 code to determine their effects on natural convection in this square cavity.

## 2- Mathematical Analysis:

The physical model with its boundary conditions of the system considered in the present study is shown in Fig. (1). It consists of square enclosure containing four horizontal and vertical triangular partitions. The four external walls of the square enclosure are kept at hot temperature ( $T_h$ ) while the walls of the partitions are kept at cold temperature ( $T_c$ ). The governing equations for two-dimensional, steady state, laminar incompressible buoyancy-induced flows with one phase and constant fluid properties which are used in ANSYS 12.1 are;

### Continuity Equation:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \quad (1)$$

### Momentum Equation:

$$u \frac{\partial u}{\partial x} + v \frac{\partial v}{\partial y} = \rho g - \frac{\partial p}{\partial x} + \frac{\partial}{\partial x} \left( \mu \frac{\partial u}{\partial x} \right) + \frac{\partial}{\partial y} \left( \mu \frac{\partial u}{\partial y} \right) \quad (2)$$

$$u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} = \rho g - \frac{\partial p}{\partial y} + \frac{\partial}{\partial x} \left( \mu \frac{\partial v}{\partial x} \right) + \frac{\partial}{\partial y} \left( \mu \frac{\partial v}{\partial y} \right) \quad (3)$$

### Energy Equation:

$$\frac{\partial}{\partial x} (\rho u C_p T) + \frac{\partial}{\partial y} (\rho v C_p T) = \frac{\partial}{\partial x} \left( k \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( k \frac{\partial T}{\partial y} \right) \quad (4)$$

Where  $u$  and  $v$  are the velocity components in the  $x$  and  $y$  direction respectively;  $P$  is the pressure and  $T$  is the temperature. But the fluid properties are assumed to be isotropic.

## 3- Numerical Solution:

The grid system over the computational domain is created using unstructured quadratic element, which are unevenly distribution and concentrated near the four corner of the rectangular enclosure where higher grid densities are desired as in Fig. (2). It provides smooth solution at the interior domain including the corner region. Employing the finite element approach, the governing equations were iteratively solved with the convergence criterion of  $10^{-7}$  for each variable. The set of governing

equations is integrated over the domain using exponential interpolation in the mean flow direction inside the finite element. The ANSYS 12.1 program used the Tri-Diagonal Matrix Algorithm (TDMA) to solve differential equations (Continuity, Momentum and Energy Equations); ANSYS 12.1 program solves the governing equations in dimensional forms. The TDMA method is described in detail in Patanker [23]. The method consists of breaking the problem into a series of tri-diagonal problems where any entries outside the tri-diagonal portion are treated as source terms using the previous values. For a completely unstructured mesh, or an arbitrary numbered system, the method reduces to the Gauss-Seidle iterative method. The set of algebraic equation is solved using Successive Under Relaxation (SUR) technique and 0.1 is taken as under relaxation parameter.

A grid independence test is applied to ensure the accuracy of the numerical results and to determine an appropriate grid density, see Fig. (3).

Since the only concerned fluid here is air ( $Pr=0.71$ ), the effect of the Prandtl number is not studied. However, the effect of Grashof number which is varied from  $10^4$  to  $10^6$  is studied. The natural convection flow within this range of Grashof number is inherently in laminar regime and thus justifies, in general, the steady-state assumption. As mentioned before, isothermal boundary conditions at the walls of the enclosure and the partitions were applied. In addition, no-slip velocity boundary conditions are imposed, i.e.  $u=v=0$  along the walls. In order to investigate the effect of several of parameters on the heat transfer, Nusselt number is selected as an indicator for the heat transfer rate. The film coefficient equation is taken from ANSYS 12.1 program as follow;

$$\{q\}^T \{\eta\} = h(T_h - T_c) \quad (5)$$

Then the Nusselt number is defined as [5];

$$Nu = \frac{hL}{k} \quad (6)$$

Where;  $\{q\}^T$ , heat flux factor,  $\{\eta\}$ , unit outward normal vector,  $h$ , film coefficient and the subscripts  $h$  and  $c$  refers to hot and cold wall respectively.

#### **4- Results and Discussion:**

##### **4-1 Flow and Temperature Fields:**

In the present study, the natural convection phenomenon in a square cavity with triangular partitions is affected by Grashof number and partition height. Analyses of the results were made through obtaining isotherms pattern and streamlines pattern for different Grashof number ( $10^4$  to  $10^6$ ) and partition height ( $0.2l$  to  $0.8l$ ). Because of the presence of four partitions, see Fig. (4), four symmetric vortices about the central vertical direction are formed for all values of Grashof number. These four vortices can be classified into two groups, left hand half group and right hand half group. In the right hand group, the cold air moves up besides the cold walls of the

vertical partitions, impinge to the hot enclosure walls and cold horizontal partition for upper and lower vortices, respectively. Also, turns besides hot vertical or horizontal enclosure walls in clockwise direction. At the same time, upper and lower vortexes are formed in the left hand side group which rotates in counterclockwise direction. With further increase in partition height, clear separation between upper and lower vortices occur and continues until forming four completely separated vortices at  $ph=0.8l$ .

As Grashof number increase ( $10^5$  and  $10^6$ ), Figs. (5) and (6), the motion becomes stronger and the rotation under the horizontal partitions becomes stronger comparing to the one above the partitions. Generally, the values of streamlines increases under the horizontal partitions, and decreases above the mentioned partitions.

From the isothermal lines patterns plots, Fig. (4) at  $Gr=10^4$ , it is observed that at lower partition height ( $ph=0.2l$ ), better penetration of hot isotherms for all region of enclosure, due to higher convective flow. Because of increasing in partition height, ( $0.4l$  to  $0.8l$ ), the crowding of the isotherms near the hot walls has been observed. Then, with increasing in partition height, the hot isotherms are vanished from the center of the enclosure and a cold region appears in the same region. This cold region developed as the natural direction of flow was obstructed by the presence of partitions.

As Grashof number increase ( $10^5$  and  $10^6$ ), Figs. (5) and (6), the convection increases above the horizontal partitions and the isotherms get clustered to hot enclosure walls and the conduction becomes dominate. Because of the convection under the horizontal partitions stronger than one above horizontal partitions as mentioned before, the isotherms have the vigorous mixing and hence, there is severe temperature distribution especially under the horizontal partitions and the convection becomes dominate here.

#### 4-2 Over all Heat Transfer Coefficients:

Variation of surface-average Nusselt number with Grashof number for different partition height is presented in Figs. (7) and (8). Fig. (7) Is given for different partition height. As shown in this figure, the Nusselt number don't change significantly when  $Gr < 10^5$  due to quasi-conductive regime. After that, they increase dramatically with increasing of Grashof number as expected. It is seen from Fig. (8), when  $ph=0.2l$  and  $0.4l$ , the Nusselt number is decreased with increasing of partition height due to the partitions obstructed the flow. But when  $ph > 0.4l$ , the Nusselt number increasing slightly, due to increase in partitions surface area of heat transfer.

#### 5- Conclusions:

The study leads to the following conclusions;

- i. The symmetric flow feature of the fluid in the cavity is retained even in presence of partitions.
- ii. The Nusselt number is an increasing function of Grashof number and a decreasing function of partition height.
- iii. With increase in partition height, heat transfer increases as partitions provides surface area of heat transfer and obstructed the flow.

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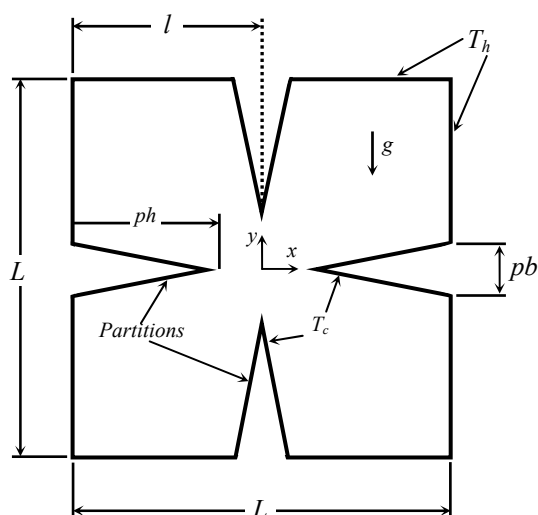


Fig. (1), Schematic Diagram of the Square Enclosure with Horizontal and Vertical Triangular Partitions.

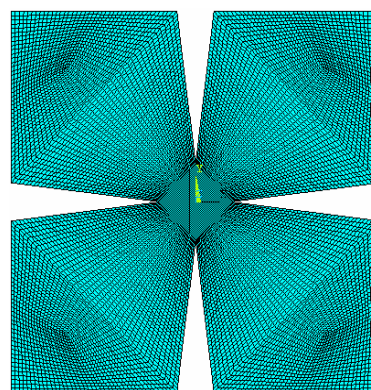


Fig. (2), Schematic Diagram of the Grid System of Square Enclosure with  $ph=0.8L$ .

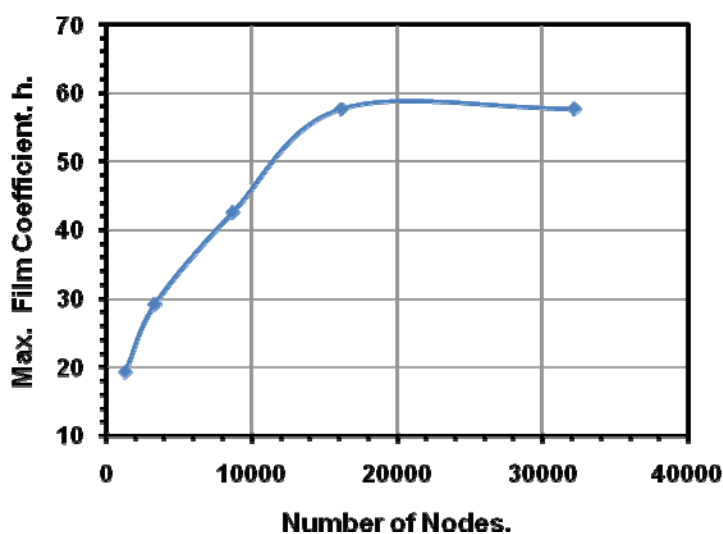


Fig. (3), Variation of Film Coefficient with Different Number of Nodes for  $ph=0.8L$ .

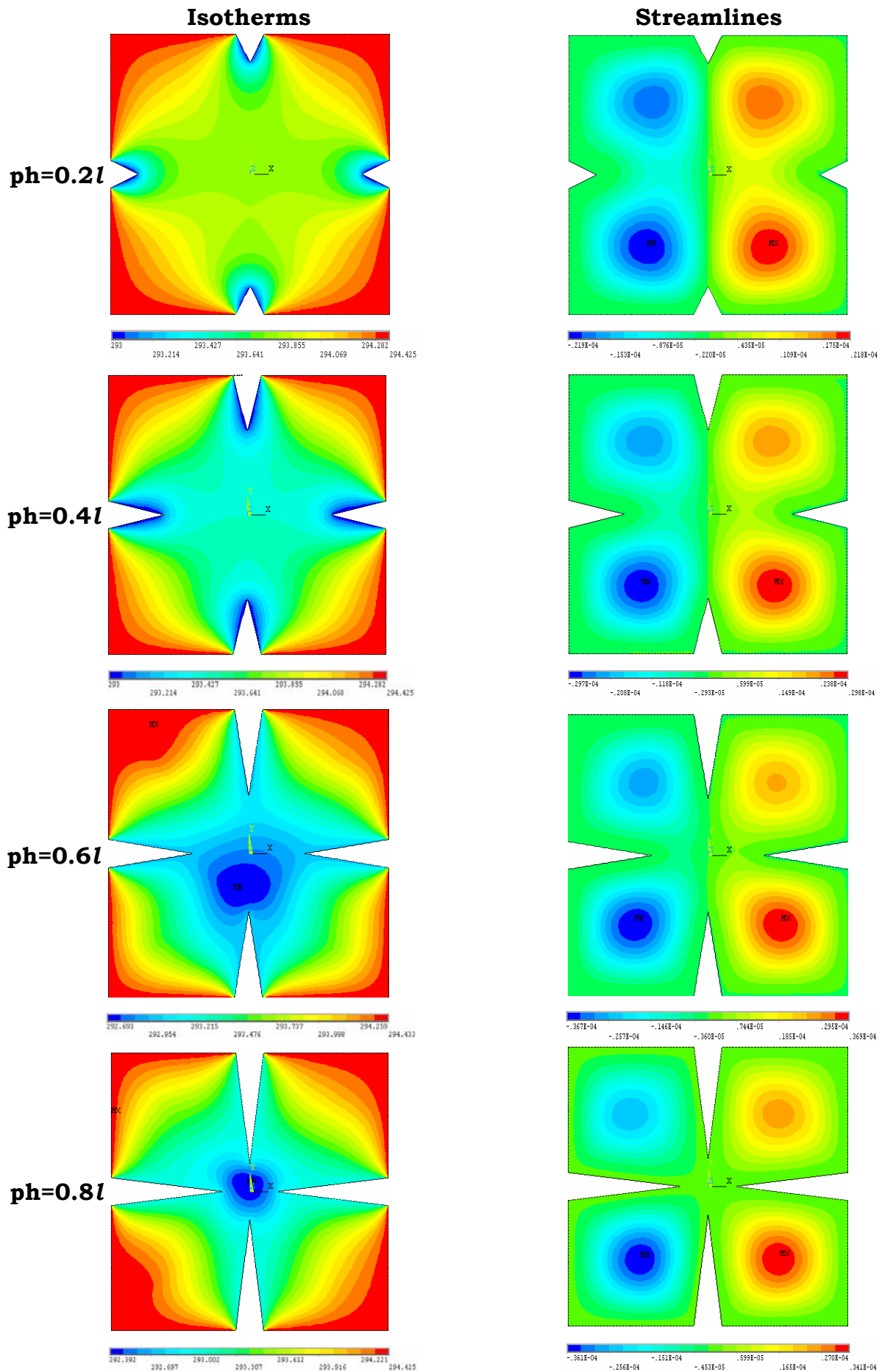


Fig. (4), Variation in Isotherms and Streamlines with Different Partition Height at  $GR=10^4$ .

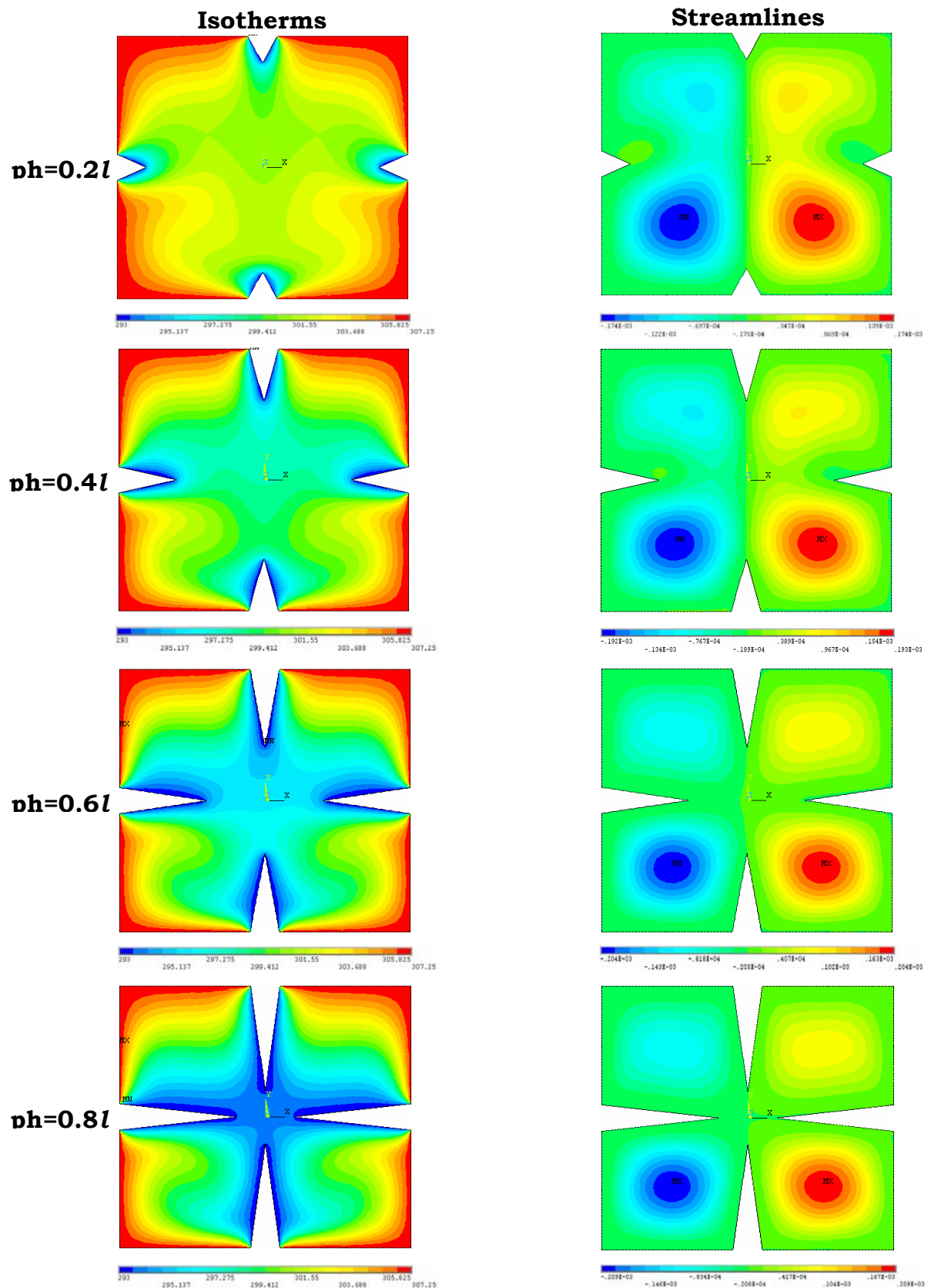


Fig. (5), Variation in Isotherms and Streamlines with Different Partition Height at  $GR=10^5$ .

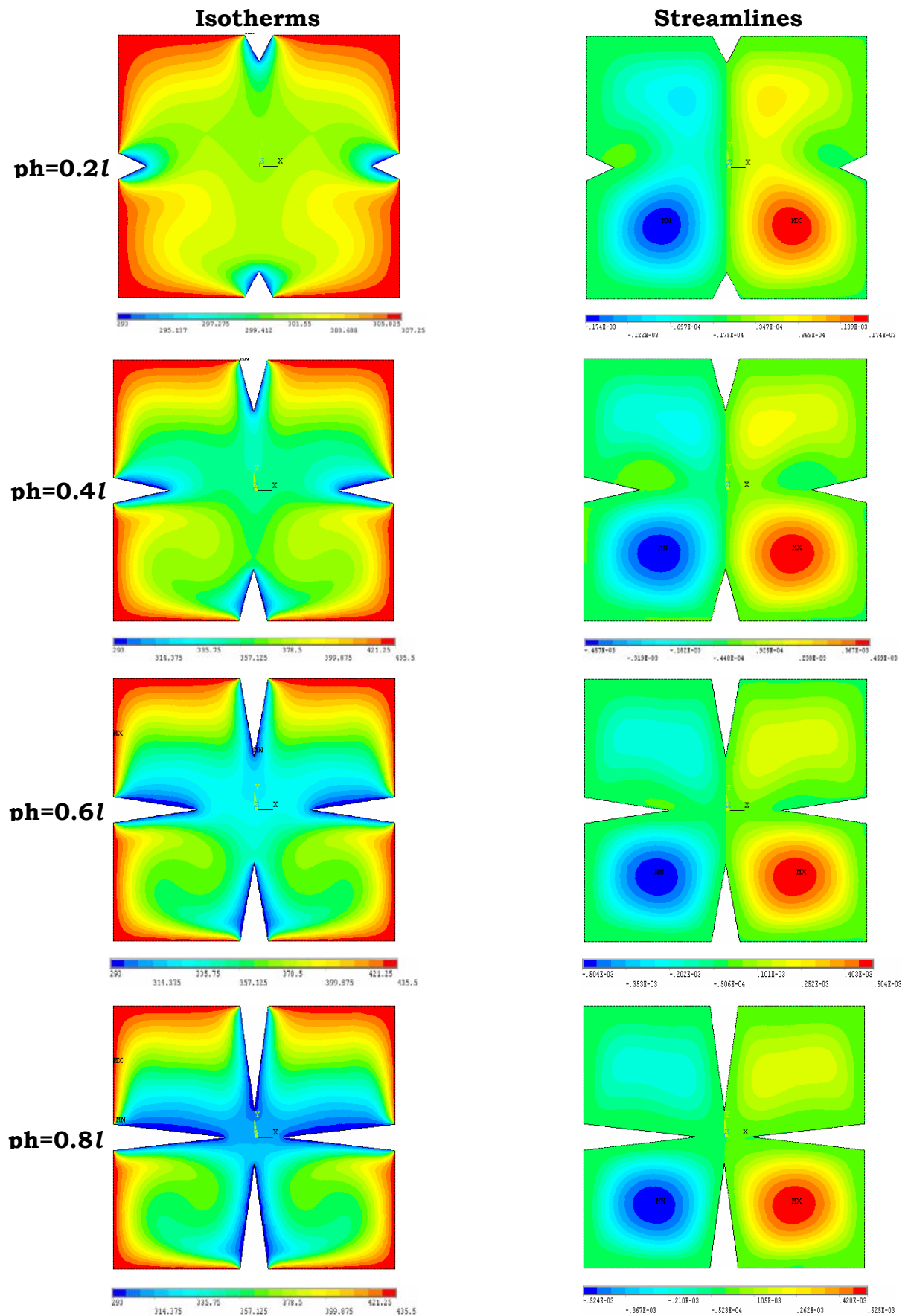


Fig. (6), Variation in Isotherms and Streamlines with Different Partition Height at  $GR=10^6$ .

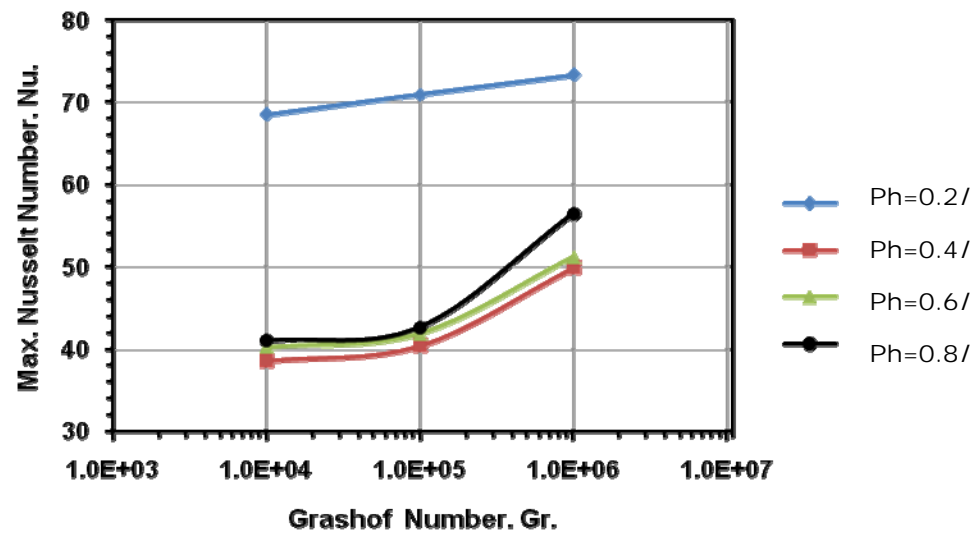


Fig. (7), Nusselt Number as A function of Grashof Number.

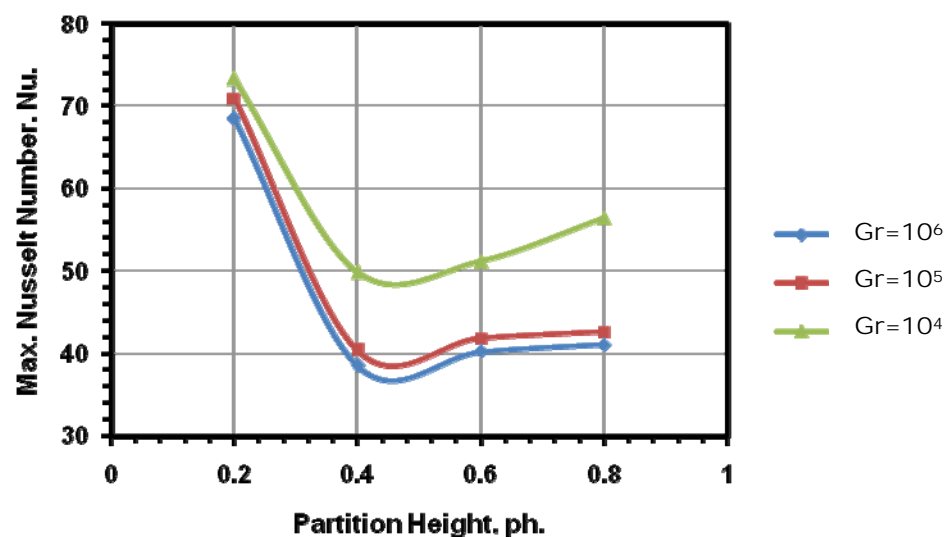


Fig. (8), Nusselt Number as A function of Partition Height.

**Nomenclatures:**

| <b>Symbols</b>                            | <b>Description</b>                           | <b>Unit</b>        |
|---|--|--------------------|
| $Gr = \frac{g \beta \Delta T L^3}{\nu^2}$ | Grashof Number                               | -                  |
| $g$                                       | Gravitational Acceleration                   | m/s <sup>2</sup>   |
| $\beta$                                   | Volumetric Coefficient of Thermal Expansion  | K <sup>-1</sup>    |
| $k$                                       | Thermal Conductivity of Fluid                | W/m. °C            |
| $L$                                       | Side Length                                  | m                  |
| $l$                                       | Half Side Length                             | m                  |
| $Nu$                                      | Local Nusselt Number                         | -                  |
| $p$                                       | Pressure                                     | N/m <sup>2</sup>   |
| $T$                                       | Temperature                                  | °C                 |
| $u$                                       | Velocity Component in x-Direction            | m/s                |
| $v$                                       | Velocity Component in y-Direction            | m/s                |
| $x$                                       | Cartesian Coordinate in Horizontal Direction | m                  |
| $y$                                       | Cartesian Coordinate in Vertical Direction   | m                  |
| <b>Greek Symbols</b>                      |  |                    |
| $c_p$                                     | Specific Heat                                | J/kg. °C           |
| $\mu$                                     | Viscosity                                    | N.s/m <sup>2</sup> |
| $\nu$                                     | Kinematic Viscosity of the Fluid             | m <sup>2</sup> /s  |
| $\rho$                                    | Density of the Fluid                         | kg/m <sup>3</sup>  |
| $\psi$                                    | Stream Function                              | -                  |
| <b>Abbreviations</b>                      |  |                    |
| Fig.                                      | Figure                                       | -                  |
| $pb$                                      | Partition Base                               | -                  |
| $ph$                                      | Partition Height                             | -                  |