Natural Convective Heat Transfer in an Inclined Open Porous Cavity with Non-Uniformly Heated Wall

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Abstract: -

Theoretical and experimental investigations of free convection through a cubic cavity with sinusoidal heat flux at bottom wall, the top wall is exposed to an outside ambient while the other walls are adiabatic saturated in porous medium had been approved in the present work. The range of Rayleigh number was $(3500 \leq Ra \leq 125000)$ and Darcy number values were$(Da = 3.88 \times 10^{-4}, 9.\times 10^{-4} and\ 18 \times 10^{-4})$.

The theoretical part involved a numerical solution while the experimental part included a set of tests carried out to study the free convection heat transfer in a porous media (glass beads) for sinusoidal heat flux boundary condition. The investigation enclosed values of Rayleigh number (5845.6, 8801, 9456, 15034, 19188 and 22148) and angles of inclinations (0, 15, 30, 45 and 60 degree).

The numerical and experimental results showed the effect of Rayleigh number and angles of inclinations on the temperature profile besides local Nusselt number. The temperature distribution values were unaffected strongly by the inclination angle for all studied range of values of Rayleigh number.

Comparison was made between the present experimental and numerical results. The experimental and numerical temperature profile and Nusselt number follows the same behavior but is approximately with mean differences of 11.5%and 15.6% respectively.
Key Words: Natural Convective, Porous Medium, Sinusoidal Heating, Square Cavity

1. Introduction

Natural convection is a kind of heat transfer, within the fluid motion is not formed by an exterior cause but it happens because density changes in the fluid due to temperature grades. In free convection, fluid near a heat source becomes hot, thus reducing its density and rise then cooler fluid replace it. Subsequently this cooler fluid is heated then return the process, generating convection current, at this processes heat energy is transfer from the base to top. The problem had been investigated by many researchers. In early 1987, Moya et al. [11] investigated numerically natural convective flow in an inclined rectangular fully saturated porous medium. Darcy type was adopted to write governing equations. They concluded that for zero inclined angle and Darcy-Rayleigh number $< 4\pi^2$, the heat transfer was just conductive, while for Darcy-Rayleigh number $> 4\pi^2$ the convection was considered main heat transfer type. Al-Amiri 2002 [3] investigated numerically an incompressible two dimensional laminar flow and heat transfer inner the enclosure full with saturated fluid porous media. Both the base and top walls of enclosure stayed isolated but the left and right walls were kept respectively at different cold and hot temperatures. Their results were examined over a range of the Darcy number values $(10^{-5} - 10^{-1})$ and Grashof number from $(10^4 - 10^6)$. Mahdi et al. 2006, [9] investigated steady state two dimensional flow natural convection heat transfer in the rectangular cavity fully with porous media heated from bottom with horizontal wells heated to a uniform but different temperatures and adiabatic sides. The governing equations were wrote using Darcy model. A detailed parametric study had been presented for the Darcy-Rayleigh number $(Ra \leq 500)$ and aspect ratio $(0.5 \leq Ar \leq 5)$. This analysis displayed that the Nu was a strong function of the porous Ra, and the geometry of the cavity was represented by aspect ratios. Dawood and Ismaeel, 2007, [7] performed numerically free steady flow convection for porous medium inside the inclined square cavity. They employed governing equations based on Darcy model. Results for modified Rayleigh numbers were obtained between 0 and 300 and tilt angle between 0° and 90°. The amount of heat transfer was found a strong function of Darcy-Rayleigh number and tilt position. Revnic et al. 2009, [14] examined numerically the steady state free convection heat transfer in sloped square cavity packed with the porous media. They employed the governing equations based on Darcy model. It was found that the isotherms, streamlines and the average Nusselt numbers were affected meaningfully by the slope of cavity and the Ra. The Under-Relaxation explicit technique was adopted by Ahmed K. H. 2010, [2] to predict the free convection characteristics of laminar isothermal flow over an inclined rectangular porous cavity. It was seen that intensity of circulation rises with increasing the angle of tilted. Also, the larger circulation reasons more heat to be dispersed in the cavity central region. Oztop et al. 2012, [13] solved numerically the governing equations dimensionless written by using Forchheimer-Brinkman model by using the finite volume method by applying open boundary conditions in only side. The opposite side of the cavity was below non-isothermal boundary conditions. The vertical wall was adiabatic. It was found that tilt angle is the significant factor on the field of flow and temperature. Hussain and Raheem 2013, [8] presented Numerical and experimental investigations of free heat transfer convective from the plane wall to a thermally stratified porous medium. The material of porous was glass bead with diameter (12mm). The results show that the profile of temperature was unaffected strongly by the inclinations. Mashkour et al. 2013, [10] presented an experimental search of the natural convection for laminar steady flows in a cubic cavity packed with saturated porous medium. The bottom wall was heated via an electrical heater, the other walls were thermally adiabatic. Experimental results displayed that the inside temperature of the cavity rises as the Rayleigh number raises. Also, the local Nusselt number rises with the increasing of the Rayleigh number for the first three values of the heat flux, then it drops after heat flux ($1146.67\,W/m^2$) for the control of the conduction on convection heat transfer. Abbas et al. 2015, [1] simulated numerically a laminar two dimensional free convection heat transfer in the enclosure packed with porous media. The right wall was kept a cold temperature and the left wall was kept a warm temperature. The horizontal walls were maintained adiabatic. They concluded that for the Grachof number increasing with constant Darcy number, the convection increases and by way of a result the heat transfer and flow velocity increase. Siddiki et al. 2016, [15] demonstrated numerically laminar unsteady state free convection heat transfer in the two dimensional packed with porous media. The bottom wall had local heating with heat flux, while the insulated top wall and regular cooling from the sides. The analysis exposed that the isotherm and the flow field are laminar up to$Ra = 10^3$. At $Ra = 10^4$ the temperature and flow fields are not symmetric. The increases in Rayleigh number enhance the heat transfer, then reduce the rate of heat transfer for increasing heat source size. Alwan et al. 2017, [4] performed an experimental investigation of the unsteady free convection heat transfer parameters through porous media. Subjected to heat flux at the lower surface as boundary condition. It was found that increasing the heating time and the dimensions of the solid and liquid layers of the sample depended on heat transfer coefficients (h, Nu and Ra).

In the present work, the natural convection heat transfer in an inclined cubic cavity has been studied experimentally and numerically. The side walls of cavity was adiabatic saturated in porous media and heated from bottom wall while the top wall that is exposed to an outside ambient. The effect of Rayleigh number and angles of inclinations on streamlines and isotherms are presented, as well as on the rate of heat transfer from the heated wall of the cavity are discussed and presented by graphically.

2. Mathematical model

The Physical problem consists of a square cavity occupied with the porous media, uniform porosity and permeability. The two dimensional square cavity under investigation is with dimensions of $(L \times L)$, inclined at an angle (φ) and filled with fluid saturated porous medium (air-glass beads).The cavity is insulated except the top wall that is exposed to an outside ambient and the bottom wall is heated see **Fig. 1**.

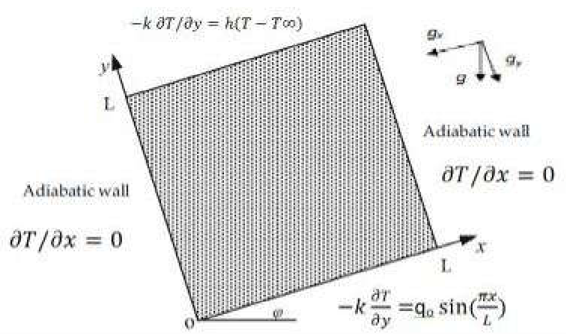


Fig. 1 Schematic Diagram of the Physical Problem and Coordinates System.

In the porous medium, Darcy's law is assumed to hold, and the fluid is assumed to be a normal Boussinesq fluid. The viscous drag and inertia terms in the governing equations are neglected. In convection heat transfer, the convection process in porous medium is governed by the basic conservation principles of mass, momentum (Darcy law), and energy equations. Therefore, the general governing equations are given as shown by (Nield and Bejan 2006, [12]):

Continuity Equation

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

Momentum Equations

$$u = -\frac{K}{\mu}\left[\frac{\partial p}{\partial x} + \rho g \sin\varphi\right]$$
(2)

$$v = -\frac{K}{\mu}\left[\frac{\partial p}{\partial y} + \rho g \cos\varphi\right]$$
(3)

Energy Equation

$$u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \alpha\left[\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right]$$
(4)

The equation of state under the Boussinesq approximation is assumed to be:

$$\rho = \rho_o[1 - \beta(T - T_o)]$$
(5)

Where ρ_o and T_o are respectively the density and the temperature in the reference state, β the coefficient of thermal expansion.

In accordance with the present problem, the above governing equations are subjected to the following boundary conditions:

$$u = 0, v = 0 \frac{\partial T}{\partial x} = 0 \text{ at } x = 0,\ 0 \le y \le L \quad (6)$$

$$u = 0, v = 0 \ \frac{\partial T}{\partial x} = 0 \ at\ x = L,\ 0 \le y \le L \quad (7)$$

$$u = 0, v = 0 \ -k\frac{\partial T}{\partial y} = h(T - T_\infty) \ \ at \ y = L,\ 0 \le x \le L \quad (8)$$

$$u = 0, v = 0,\ -k\frac{\partial T}{\partial y} = (q_o + a\ sin(\pi x)) at\ y = 0,\ 0 \le x \le L \quad (9)$$

3. Numerical Analysis

In present work, numerical solution by using finite volume based on finite difference method is presented for steady state, two dimensional flow free convection heat transfer in the square filled with porous medium. The convective fluxes at the cell interface are discretized by employing the Quadratic Upwind Interpolation for Convective Kinematics (QUICK) scheme. The governing equations solved by a tri-diagonal matrix algorithm (TDMA). A computer program is built using (MATLAB R2013a) to instrument the solution of the discretized governing equations.

4. Grid Independency Test

The numerical grid size in the present study was tested by using dissimilar number of grid points in (x and y) directions. **Fig. 2** displays the effect of number of grids points on the average Nusselt number for steady state. It is clear that as the grid becomes to be better, the results convergence becomes better. A 70 x 70 grid size appears sensible and was used in the present study.

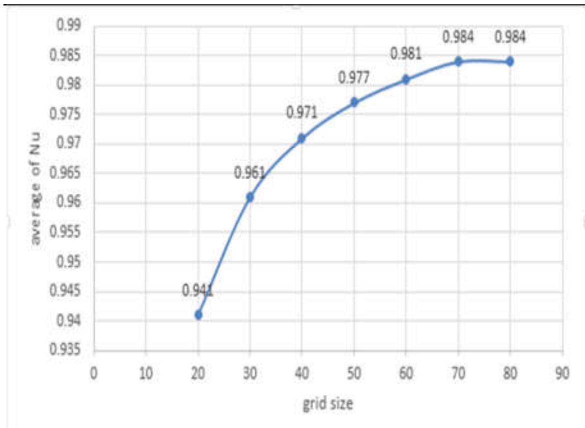


Fig. 2 The Effect of Grid Fineness on the Average Nusselt Number.

5. Computer Program Description

For the sake of performing the preceding formulated numerical solution, a computer program was constructed in (MATLAB R2013a) software. This program contains the chief program and a TDMA solver subroutine for both stream and temperature field. The flow chart of the constructed computer program is showed in **Fig. 3** in the first part of the main computer program, the stream field calculations and the corresponding velocity distribution are observed while the second part is devoted to carry out the temperature distribution computation. Then, the program estimates the average Nusselt number values. Lastly, the remaining part of the program is assigned to arrange the output results in order to print out these results and save them in specific files for further manipulation.

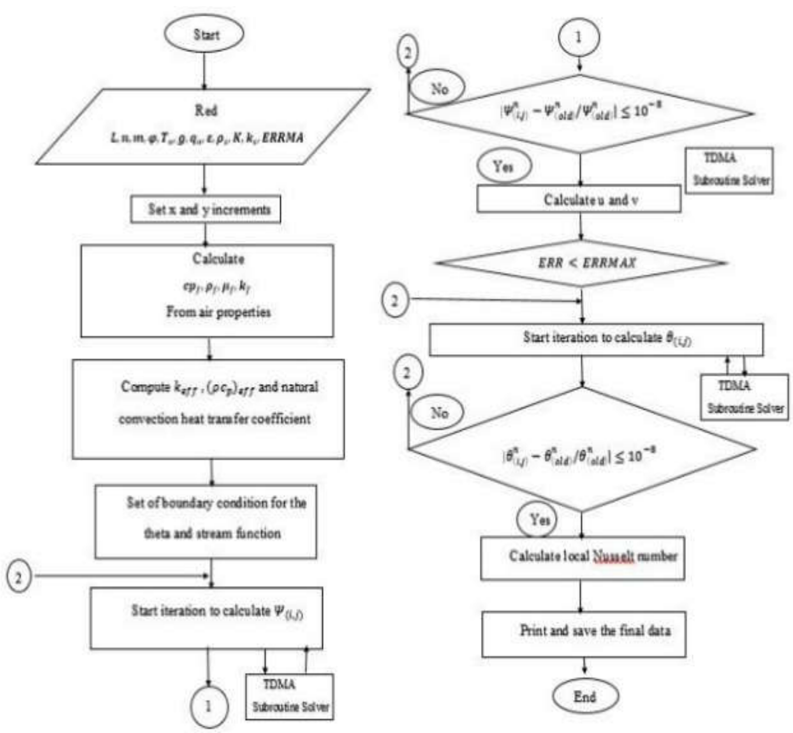


Fig. 3 Flow Chart for the Computer Program

6. Experimental Work

An experimental rig was designed and constructed in the Heat Transfer Lab, at the Mechanical Engineering Department, University of Baghdad. The cubic has sinusoidal heat flux at bottom walls, the top wall that is exposed to an outside ambient while the other walls are adiabatic. The experimental model used in the present study is a cubic box with equal width, high and depth of $(300\ mm)$ filled with spherical glass beads with diameter $(12\ mm)$, these balls are used in this diameter because they are available in the market and fulfill the research requirements. The properties of glass beads are given in **Table 1**.

Table. 1 Properties of Porous Media

Parameters	Values
Porosity (ε)	0.572
Permeability (K)	$3.5\ x\ 10^{-5}(\ m^2)$
Density (ρ)	$2512.38\ (\ kg/m^3)$
Thermal Conductivity (k)	$0.87(W\ /m.℃)$
Specific Capacity (C_P)	$670\ (J/kg\ .℃)$

All the vertical walls and the base of the box are constructed from a mica of thickness $(10\ mm)$. The rig covered with a kaowool insulation of $(50\ mm)$ thickness and $(25\ mm)$ thickness of a glass wool insulation to reduce the heat loss. On the lower side of the rig, a non-uniformly heating is provided by means of electric strip heater. The heater made from strips Nickel Chrome covered from outside with a kaowool insulation of $(50\ mm)$ thickness and $(25\ mm)$ thickness of a glass wool insulation see **Fig. 4**.

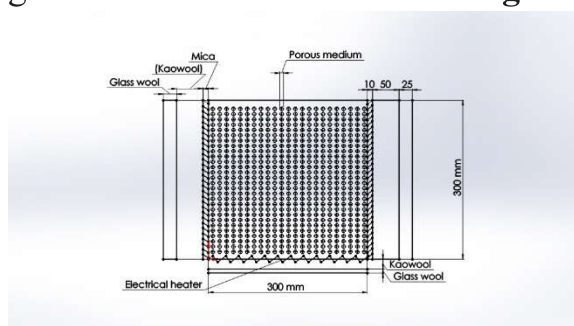


Fig. 4 Schematic of the Test Suction.

The support base of the plywood can be supported on one side in order to give the desired degree of inclination angle from the horizontal axis in the range (0 ° - 60 °) , as shown in **Fig. 5.**

Fig. 5 Photograph of Experimental Apparatus.

Thirty thermocouples type-k were used to measure the distribution of temperature within the porous cubic cavity. A (30) thermocouples was divided into six groups in six levels by fixing on rake. The levels were separated by uniform vertical distance of (6cm) along the test section. The horizontal distance between the thermocouple was (6cm), which was chosen to cover up the change in temperature profile. Four thermocouples were fixed on the upper wall inside the cubic box. Finally, to measure air temperature at the exit, there was another thermocouple as shown in **Fig. 6**.

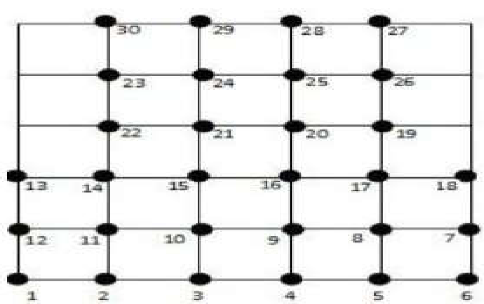


Fig. 6 Thermocouples Distribution

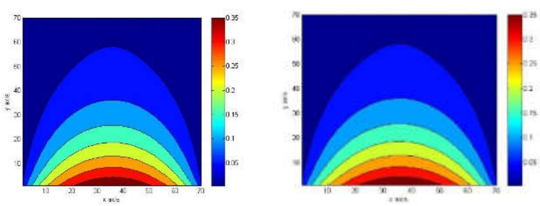
7. Results and Discussion

7.1 The Numerical Results

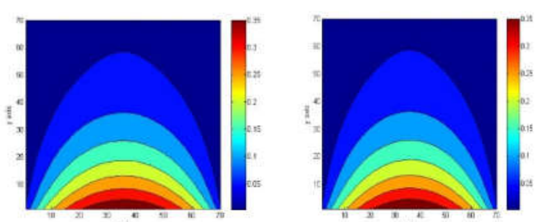
The objective of the current numerical study is to simulate the fluid flow and heat transfer characteristics of the porous cavity by employing the experimental boundary conditions and to deduce information about the temperature distribution, streamline, and average Nusselt number.

Temperature Distribution

The range of Rayleigh number $(3500 \leq Ra \leq 125000)$, Darcy number $(Da = 3.88 \times 10^{-4}, 9.\times 10^{-4} \, and \, 18 \times 10^{-4})$and the inclination angles (φ= 0, 15, 30, 45 and 60 degree) are theoretically studied. The temperature distribution inside the cavity for different values of sinusoidal heat flux is displayed in **Fig. 7**.



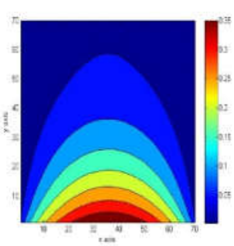
(a): $Ra = 5854.6$ (b): $Ra = 8801$



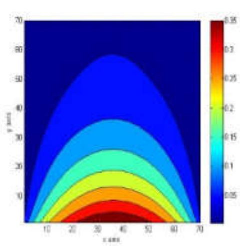
(c): $Ra = 15034$ (d): $Ra = 22148$

Fig. 7 Temperature Contours at Different Rayleigh Numbers ($Da = 3.88 \times 10^{-4}$, $\varphi = 0$ Horizontal Position)

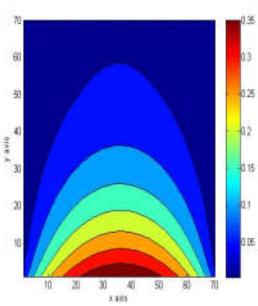
Fig. 7 shows how the temperature distribution inside the cavity is affected with the Rayleigh number. It is obvious from these figures that the temperature field is not strongly influenced by the different Rayleigh number value because of the Darcy number which used is large, so the conduction property is more controlled than the convection property. In other words, the resistance of the glass beads act as a strong impediment to the convection property. The explanation is clear when the Darcy number is changed. **Fig. 8** shows the temperature distribution inside the cavity at different inclination angles (φ= 15, 30, 45 and 60 degree).



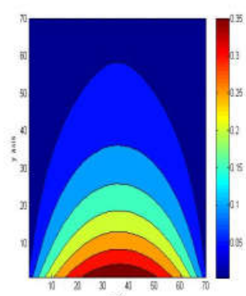
(a): $\varphi = 15$



(b): $\varphi = 30$



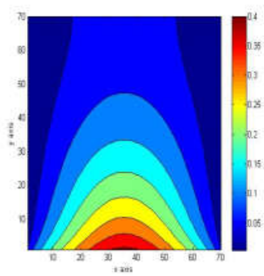
(c): , $\varphi = 45$



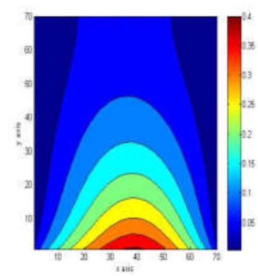
(d): , $\varphi = 60$

Fig. 8 Temperature Contours at Different Inclination Angles ($\boldsymbol{Da = 3.88 \times 10^{-4}}$ *and* $\boldsymbol{Ra = 22148}$)

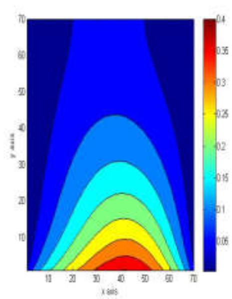
It is clear from these figures above that the temperature field is not strongly affected with inclination angles when the Rayleigh number is small values. **Fig. 9** shows the theoretical temperature distribution inside the cavity at different inclination angles (φ= 0, 15, 30, 45 and 60 degree).



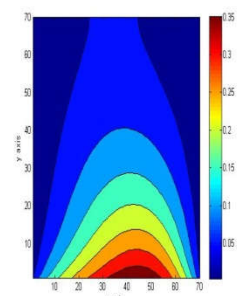
(a): $\varphi = 0$



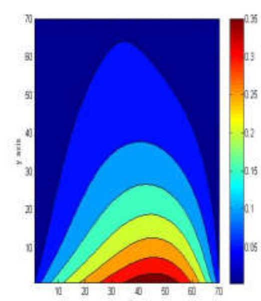
(b): $\varphi = 15$



(c): $\varphi = 30$



(d): $\varphi = 45$



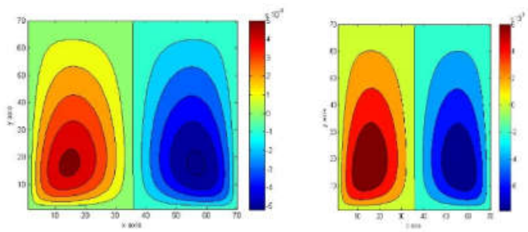
(e): , $\varphi = 60$

Fig. 9 Temperature Contours at Different Inclination Angles ($\boldsymbol{Da = 3.88 \times 10^{-4}}$ *and* $\boldsymbol{Ra = 122460}$)

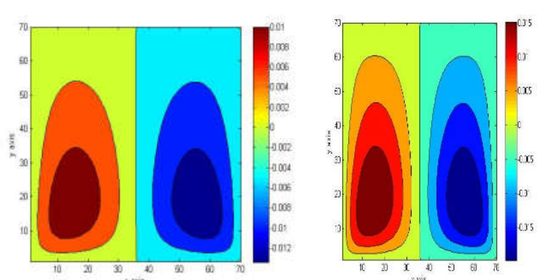
It can be seen that the effect of the inclination angles is clearly displayed in the values of the high Rayleigh number. Furthermore, it can be concluded from **Figs. 7** to **9** that the Darcy number plays a large role in the form of the contour of temperature distribution. In other word, when the Darcy number is small, the effect of the inclination angle on the transfer of heat through the porous medium does not appear clearly only when increase the Rayleigh number to large values.

Streamline Distribution

As seen from the streamlines in **Fig**. **10**, two symmetrical cells are formed into the cavity and at different directions.



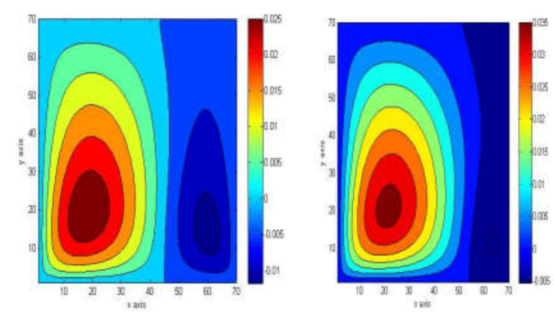
(a): $Ra = 5854.6$ (b): $Ra = 8801$



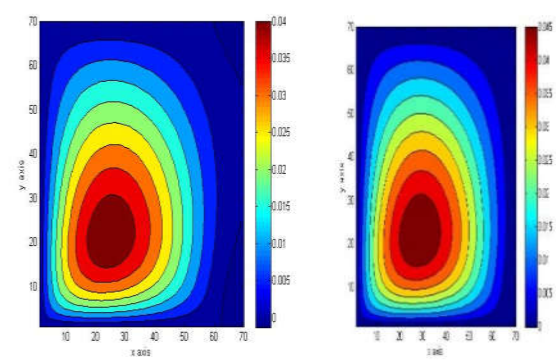
(c): $Ra = 15034$ (d): $Ra = 22148$

Fig. 10 Streamline at Different Rayleigh Number ($Da = 3.88 \times 10^{-4}, \varphi = 0$)

The negative sign of stream function denotes the clockwise circulation. Also, from the streamline schemes, the value of stream function is directly proportional to the Rayleigh number. The inclination angle is the important dominate factor for flow field in a cavity packed with porous media **Fig. 11** and **Fig**. **12** showed that the intensity of circulation increases with the increasing of the angle of inclination.

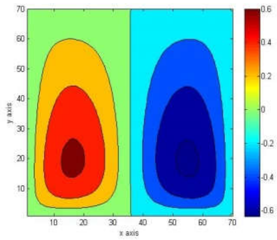


(a): $\varphi = 15$ (b): $\varphi = 30$

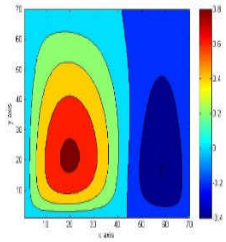


(c): , $\varphi = 45$ (d): , $\varphi = 60$

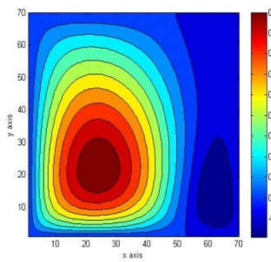
Fig. 11 Streamline at Different Inclination Angle ($Da = 3.88 \times 10^{-4}, Ra = 22148$)



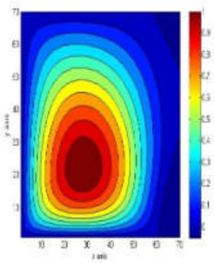
(a): $\varphi = 0$



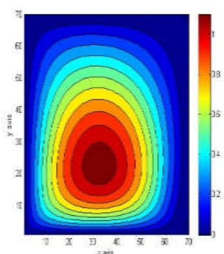
(b): $\varphi = 15$



(c): $\varphi = 30$



(d): $\varphi = 45$



(e): $\varphi = 60$

Fig. 12 Streamline at Different Inclination Angle ($\boldsymbol{Ra = 22148, Da = 18 \times 10^{-4}}$)

The stream functions are nearly circular when the Rayleigh number is small. It can be observed that, the flow circulation inside the cavity is larger nearby the center and smallest nearby the wall with reason no slip boundary conditions.

Local Nusselt number

The Nusselt number is the ratio of convection to conduction heat transfer inside the boundary layer. Therefore, it is an important factor to estimation the improvement in heat transfer. The local Nusselt number is inversely proportional with the width of heat source. So, the local Nusselt number had been calculated along the width of heat source. **Fig. 13** displays the inclination angle which does not affect hardly the surface Nusselt number.

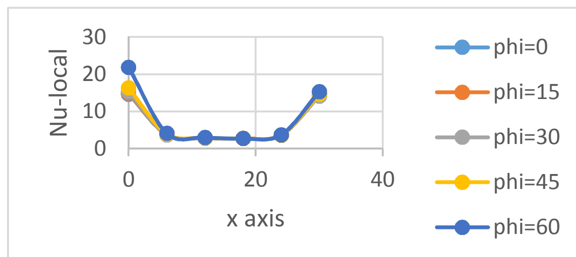


Fig. 13 Local Nusselt Number ($\boldsymbol{Ra = 2.2148 \times 10^{4}}$ and $\boldsymbol{Da = 3.88 \times 10^{-4}}$)

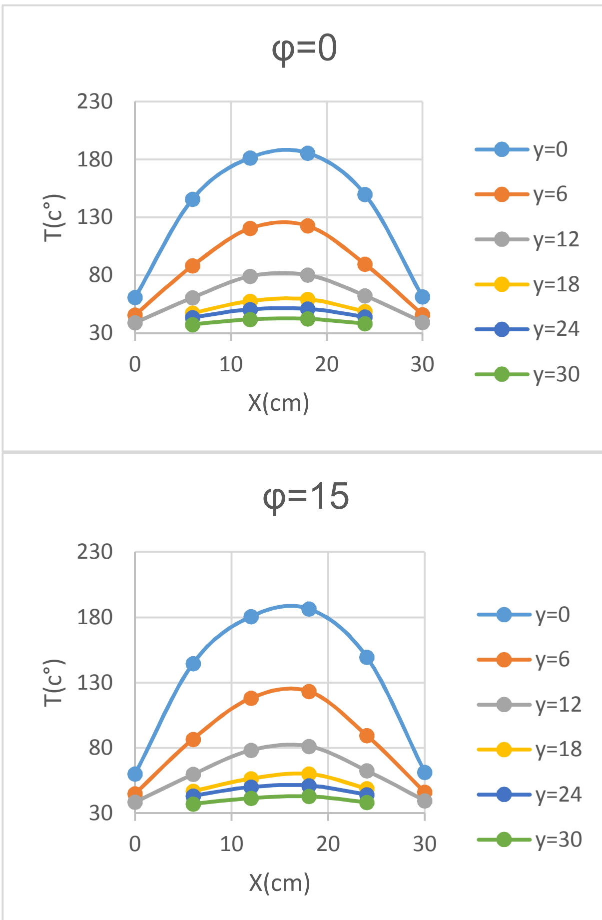
The behavior of Nusselt number in the theoretical results is agreed with that of experimental results.

7.2 The Experimental Results

Temperature Distribution

The temperature profile has been verified with inclination angles (φ=0, 15, 30, 45 and 60 degree), Rayleigh number($Ra = 5854.6,\ 8801,\ 9456,\ 15034, 19188$ and 22148) and Darcy number($Da = 3.88 \times 10^{-4}$).

The direct reading of temperature distribution with axial distance for different Rayleigh number values is schemed in **Fig. 14**. When Rayleigh number increases, the temperature gradients in this region increase.



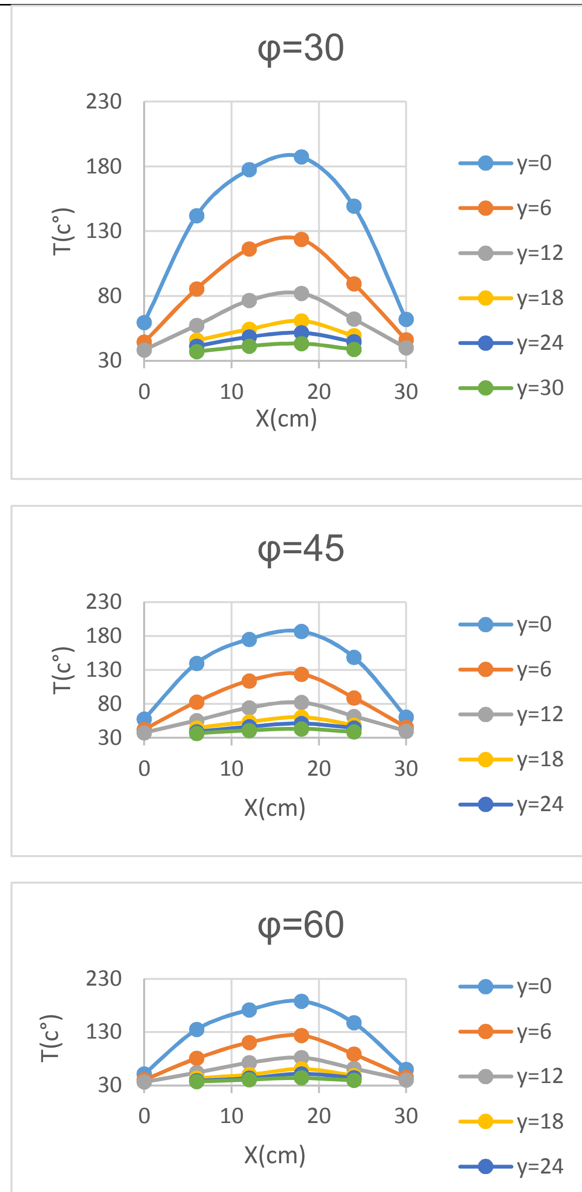
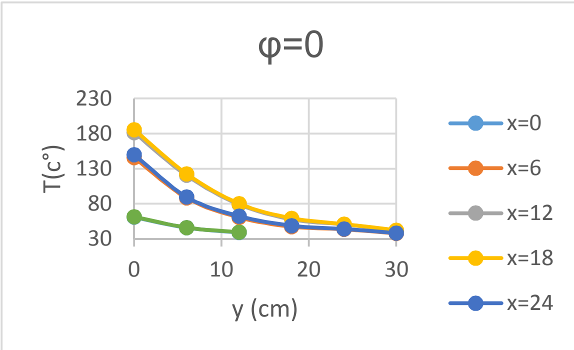
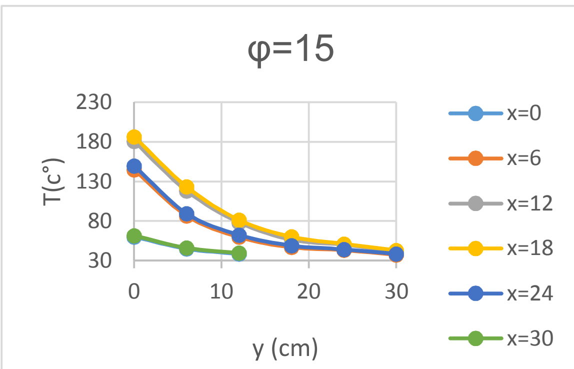
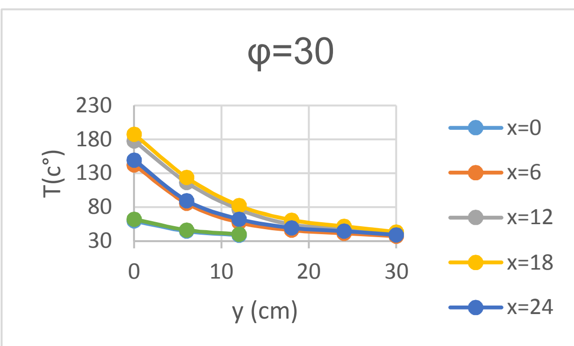


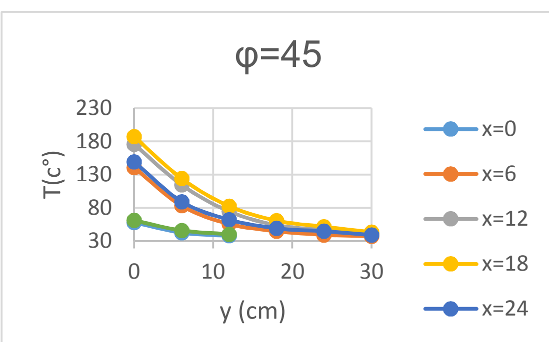
Fig. 14 Experimental Temperature Distribution with Axial Distance for ($\boldsymbol{Ra} = \mathbf{22148}$)

The distribution of temperature decreases within the box along the y-direction. By moving upward, the heat resistant increases producing a reduction in the temperature values. This is for the low value of the glass beads effective thermal conductivity that reduces the heat transfer effect as shown in **Fig. 15**.









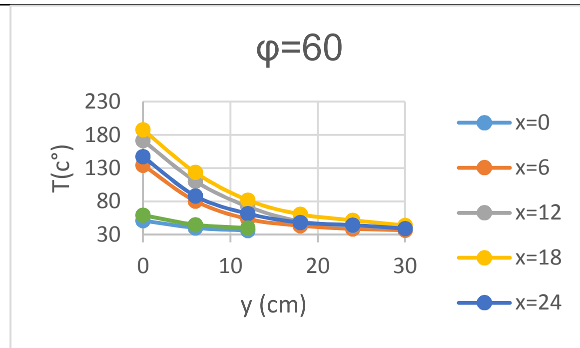


Fig. 15 Experimental Temperature Distribution with Normal Distance for($\boldsymbol{Ra} = \mathbf{22148}$).

The temperature distribution values increase about (1-9%) when the inclination angle changes from φ=0º to 60º.

Average Nusselt Number

The relationship between average Nusselt number and Rayleigh number is shown in **Fig.16**. The average Nusselt number is directly proportional with the Rayleigh number for the first two values of Rayleigh number, but it decreases then since of domination of the conduction heat transfer on convection heat transfer.

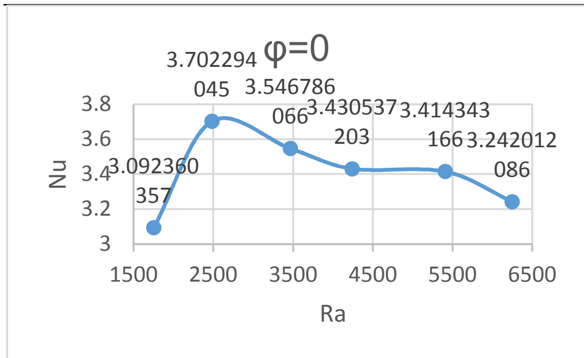


Fig. 16 Experimental Average Nusselt Number with Rayleigh Number

Fig. **17** illustration that the inclination angle does not affect clearly the average Nusselt numbers.

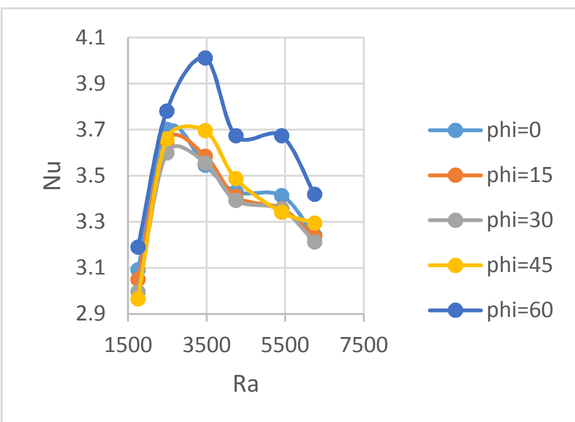


Fig. 17 Experimental Average Nusselt Number with Rayleigh Number at Different Inclination Angle.

8. Comparison with Previous Results

In fact, there are no cases similar to the cases discussed in the present work, so they were chosen as close as possible to the working conditions of the present work to compare in terms of the shape of behavior.

The numerical results of (Bask et al. 2006, [5]) and (Bask et al. 2007, [6]) are compared with the results of the present work as shown in **Fig**. **18** and **Fig**. **19** respectively.

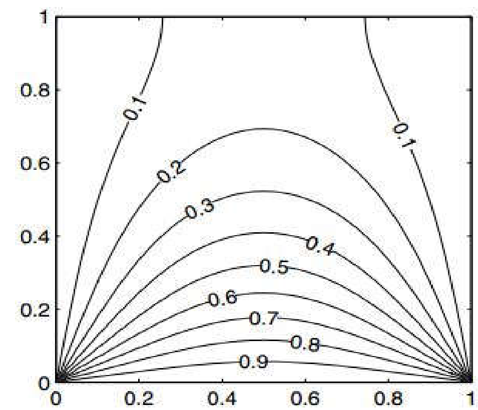


Fig. 18. (a). Comparison Temperature Distribution between the Present Work and Bask et al. 2006, Work's [5].

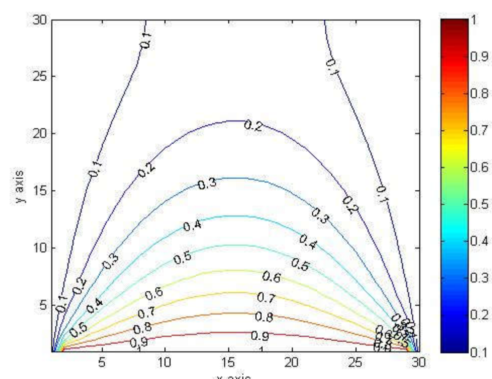


Fig. 18. (b). Comparison Temperature Distribution between the Present Work and Bask et al. 2006, Work's [5].

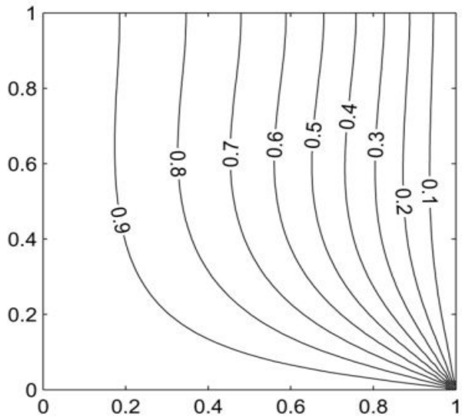


Fig.19. (a). Comparison Temperature Distribution between the Present Work and Bask et al. 2007, Work's [6].

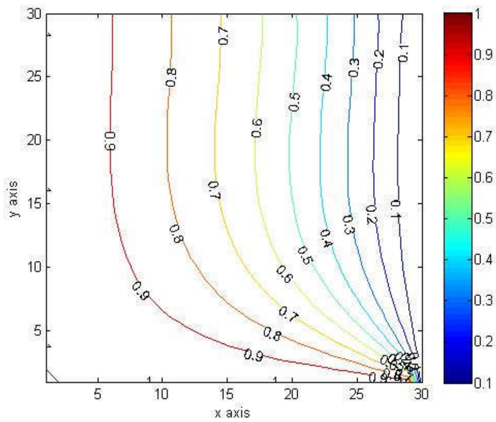


Fig. 19. (b) Comparison Temperature Distribution between the Present Work and Bask et al. 2007, Work's [6].

9. Conclusions

- The intensity of circulation increases with increasing of the angle of inclination from ($\varphi = 0°$) to($\varphi = 60°$).
- The value of stream function increases from 0.002 at $\boldsymbol{Ra} =$ 3500 to 0.92 at$\boldsymbol{Ra} =$ 125000.
- The average Nusselt number directly proportional with Rayleigh number for the first four values of Rayleigh number (Ra=3500, 4750, 5854.6 and 8801) but it decreases after Rayleigh number reach approximately Ra=9000 because of domination of the conduction heat transfer on convection heat transfer.
- For all studied range value of Rayleigh number, the average Nusselt number decrease with increasing inclination angles.
- For high values of Rayleigh number, the rate of natural convection heat transfer is inversely proportional with Rayleigh number.

Nomenclature

Da: Darcy number, Da $= K/l^2$.

g: Gravitational Acceleration (m/s^2).

h: Heat Transfer Coefficient $(w/m^2\,.\,°C)$.

K: Permeability (m^2) .

l: Length (m).

Nu: Nusselt number, $\mathrm{Nu} = \frac{h\,l}{k_{eff}}$.

P: Pressure (N/m^2).

q_o: Constant heat flux (w/m^2).

Ra: Rayleigh number, $= \frac{g\,\beta\,K\,q\,l^2}{k_{eff}\vartheta_f\alpha_m}$.

T: Temperature (°C).

u: Velocity in x-Direction (m/s).

v: Velocity in y-Direction(m/s).

x: Horizontal Coordinate (m).

y: Vertical Coordinate (m).

Greek Symboles

α_m: Thermal Diffusivity (m^2/s).

β: Volumetric Coefficient of Thermal Expansion $(1/k)$.

ε: Porosity.

φ: Angle of inclination (degree).

ρ: Density (kg/m^3).

ρ_o: Density at temperature T_o (kg/m^3).

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انتقال الحرارة بالحمل الحر في تجويف مائل مسامي مفتوح مع تسخين غير منتظم

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الخلاصة

يقدم البحث الحالي دراسة نظرية وعملية لأنتقال الحرارة بالحمل الحر في حيز محدد مائل ذو وسط مسامي محصور و مشبع بالمائع و مسخن بفيض حراري ذو دالة جيبية ويكون من الاعلى معرض كليا الى المحيط الخارجي بينما الجدران العموديه معزوله حراريا , معدل رقم رالي لهذه الدراسه يكون $3500 \leq Ra \leq 125000$) ورقم دارسي ($Da = 3.88 \times 10^{-4}, 9.\times 10^{-4} and\ 18 \times 10^{-4}$). الدراسه النظريه تضمنت الحل العددي. بينما الجانب العملي تم بناء مكعب مملوء بوسط مسامي (كرات زجاجيه) و يتكون من نفس الظروف الحديه الموجوده في الدراسه النظريه, و تضمن اجراء عدة تجارب بتطبيق قيم مختلفه من الفيض الحراري. وكانت القيم المأخوذه لرقم رايلي هي (22148 , 19188 ,15034 ,9456 ,8801 ,5845.6) وقيم زاويه الميلان كانت (0 , 15 , 30 , 45 , 60 درجه).النتائج النظريه والعمليه اظهرت مقدار تأثير رقم رايلي وزاوية الميلان على توزيع درجات الحراه وعلى رقم نسلت الموقعي. وكانت النتائج تشير الى ان تغيير الزاويه ليس لها تأثير قوي على اختلاف مقدارتوزيع درجات الحراره لكل الحالات التي تم دراستها عمليا. تم أجراء مقارنة بين الدراسه العملية والنظريه للبحث الحالي من خلال توزيع درجة الحرارة ورقم نسلت وكانت النتائج تشابه في السلوك بين الدراسة العمليه والنظرية مع معدل فرق بحدود 11.5% و 15.6% على التوالي.

الكلمات المفتاحية: الحمل الحر، وسط مسامي، تسخين جيبي، حيز مربع الشكل.