Natural Convection Heat Transfer from a Plane Wall to Thermally Stratified Porous Media

Ihsan Y. Hussain
Professor, Department of Mechanical Engineering
University of Baghdad

Basim K. Raheem
MSc. Student, Department of Mechanical Engineering
University of Baghdad

ABSTRACT
The thermal and fluid transport phenomena adjacent to a plane wall in a stable, thermally stratified saturated porous medium is investigated numerically and experimentally in the present work. Glass bead is taken as porous material with diameter (12mm). The temperature distribution and Nusselt number are discussed numerically (Fluent Program) and experimentally for different values of heat flux (150, 250, 500, 750, 1000, 1250 W/m^2), thermal stratification (0,-0.6,-0.8,-1.6,-2,-5,-10) and inclination angles (0,-15, 15, 30, 45deg). It is observed that the temperature distribution is affected strongly by thermal stratification where it increases when thermal stratification decreases and it is unaffected strongly by the inclination angles. Also the results show that the Nusselt number varies linearly with downstream coordinate (X) and increases with decreasing stratification parameter.

Keywords
Natural convection, Thermal Stratification, Porous Media, Experimental and Numerical Study

1. INTRODUCTION
Buoyancy-driven convection in a fluid saturated, density-stratified porous medium has applications in a wide range of areas including geothermal fields and nuclear-waste deposits. The problem had been investigated by many researchers. Some of them studied numerically free convection heat transfer from a plane wall to a porous medium without thermal stratification; see for example Na and Pop [1], Kaviany and Mittal [2], Beithou et al. [3] and Saha et al. [4]. Others studied the natural convection heat transfer from a plane wall to a thermally stratified environment without porous media; see for example Neog and Deka [5], Saha and Hossain [6], Ahmed [7] and Naseem [8]. Some researchers studied numerically the free convection heat transfer from a plane wall to a thermally stratified porous media; see for example Mondal and Chaudhury [9], Angirasa and Peterson [10], Kumar and Shalini [11] and Ching [12]. The present work investigates the natural convection heat transfer from a plane to a thermally stratified porous medium numerically (Fluent Program) and experimentally with wide range of stratification parameter, heat flux and inclination angles.

2. DEFINITION OF THE PROBLEM
The geometry of the problem is shown in figure (1). The geometry consists of a rectangular box contains main and secondary heaters and also contains the porous medium (glass beads). A two dimensional Cartesian coordinate system was considered in this study, where the ***X***-direction represents the direction in which the temperature of the porous medium will be changed in the case of considering the effect of thermal stratification, while the y-direction represents the direction of heat supplied from the plane wall to the adjacent porous media. In the present study, the case of inclination of the plane will be considered, and the inclination angle (φ) was taken between the vertical direction and the plane wall, as shown in figure (2).

3. NUMERICAL SIMULATION
Numerical simulations allow the analysis of a complex phenomenon without resorting to an expensive prototype and difficult experimental measurements. In order to analyze the natural convection heat transfer from vertical and inclined plate to a thermally stratified porous medium, a solution of Darcys' and energy equations are required. In the present work, the mathematical model of the problem was solved numerically using a CFD Code FLUENT 6.3.26 after describing the mesh model using the Gambit 2.2.30. The geometry is generated by using GAMBIT with dimensions of L=100mm, W=100mm and H=200mm. In the present work, a higher order element type hexahedral is used for mesh generation to approximate precisely the geometry interfaces.

4. EXPERIMENTAL WORK
A schematic drawing of the experimental set-up is shown in figure (3). An experimental rig was designed and constructed in the Heat Transfer Lab, at the Mechanical Engineering Department, University of Baghdad. The test section consists of a rectangular box with (200mm x 100mm x 130mm), see figure (1). The box was divided into two parts. The first part with dimensions of (200 x100 x30 mm) made of wood where the heater and the thermal insulator were fixed. The other part made of steel screen mesh with dimensions of (200x100x100 mm) where the porous material (glass beads) are placed adjacent to the vertical heater in the first box and the secondary heater fixed horizontally away from the main heater about (50mm) to obtain the gradient heating of the porous medium. The heaters used in the present study are made from coil with a 0.5mm diameter made from nickel-chrome wire, wrapped around a mica sheet of 0.4mm thick to ensure electrical insulation. The wrapped coils are covered from the top and bottom with mica sheets then covered together with black iron sheet of 0.5mm thick. The number of thermocouples used in the present work was thirty Alumel-Chromel (type K) thermocouples. The ambient stratification in the porous medium was measured continuously by (six) thermocouples. The others thermocouples measure the temperature through the boundary layer as shown in figure (4). All values of S negative because the secondary heater (responsible for stratification) was placed at the bottom of test

section where $T_{\infty,0} > T_{\infty,L}$ to get wide ranges of S and to overcome the difficulties of previous work **(Naseem 2011)**. The following parameters were recorded during the test: heat flux, Angle of inclination and thermal stratification. The ranges of measured variables are shown in **table (1).**

Table 1. Ranges of Measured Variables

Parameters	Values
Downstream Coordinates (X)	50, 100, 150, 200 mm
Angle (φ)	0, 15,-15, 30, 45Degree
Heat Fluxes (q")	150,250,500,750,1000,1250 W/m^2
Time of Testing	6:00 A.M to 4 P.M in April and June
Stratification Parameter (S)	0,-0.6,-0.8,-1.6,-2,-5,-10

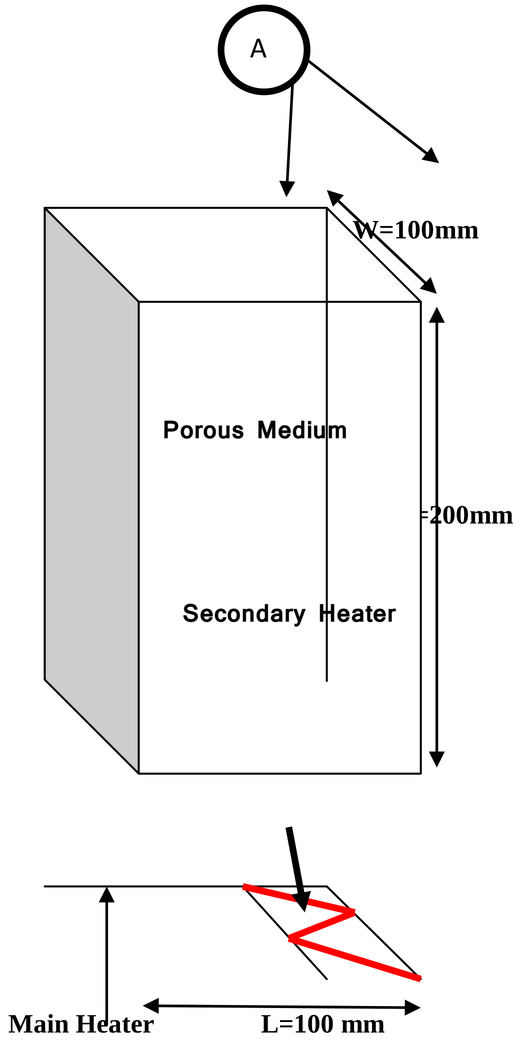
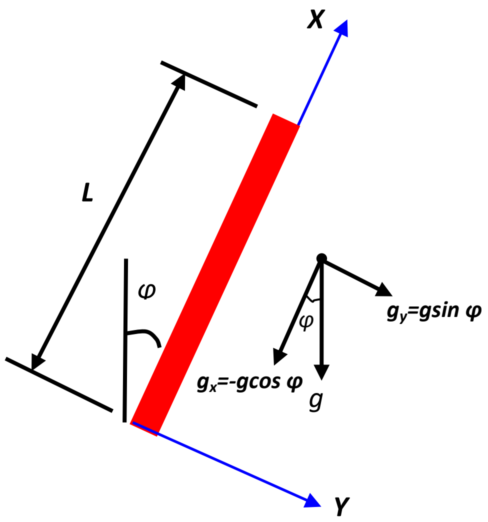
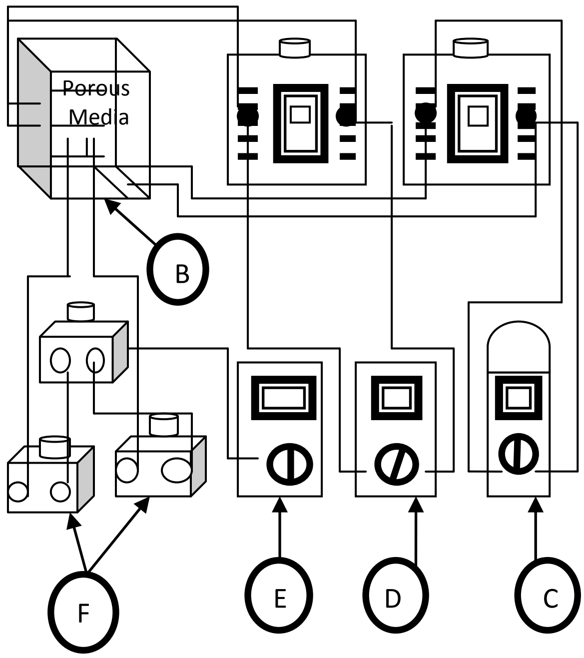


Fig. 1 Model Geometry



Porous Media

Fig. 2 Geometry of the System



A: Variac
B: Test Section
C: Digital Clamp Multimeter
D: Digital Multimeter
E: Reader
F: Selector Switches

Fig. 3 Diagram of Experimental Apparatus

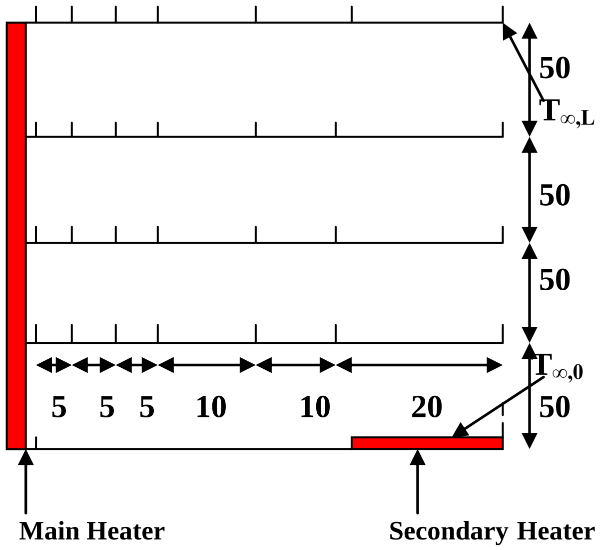


Fig. 4 Thermocouple Location (all dimensions are in mm)

5. RESULTS AND DISCUSSION

5.1 Experimental Results

The temperature profile has been tested with the transverse coordinates (Y=y/L) at different downstream coordinates (X=x/L) at different heat fluxes. The temperature profiles ($\theta = \frac{T-T_{\infty,x}}{T_w-T_{\infty,0}} = \frac{\Delta T_x}{\Delta T_0}$) have been measured at different stratification parameter (S=0,-0.6,-0.8,-1.6,-2,-5and -10). Figure (5) shows the temperature distribution for different values of the stratification level at mid height wall (X=0.5). The temperature profile (ϴ) increases with decreasing thermal stratification $\left(S = \frac{1}{\Delta T_0}.\frac{T_{\infty,L}-T_{\infty,0}}{L}\right)$ because of increasing heat flux for secondary heater at each time (to give different values of stratification parameter) that increases ($T_{\infty,0}$), so the temperature profile increases and thermal stratification decreases according to the equation above. The thermal potential that drives the buoyancy-induced flow in a porous medium increases with decreasing values of the thermal stratification parameter, S. Initially, a conduction regime arises in which fluid adjacent to the wall has been heated by conduction and rises with essentially no effect due to the upstream flow. However, as time elapses at any given location, the flow at the top is at temperature, in the outer region of the boundary layer, which is lower than the local ambient temperature, since the ambient temperature decrease with height because of the position of secondary heater. Therefore, a temperature defect arises downstream and increases with increasing stratification level and this lowers buoyancy. For flow in a porous medium, the presence of a large amount of solid material inhibits the development of temperature defects and slows down the flow and redistributed it well. The influence of inclination angle on the temperature profile has been taken in consideration. Five angles of inclination (0, -15, 15, 30 and 45 degree) have been investigated and compared with situation of vertical plane wall (φ=0º). The figure (6) shows that inclination angles do not affect strongly on temperature profiles. The figures (7) to (9) show a comparison between stratified and unstratified porous medium cases for local Nusselt number. The figures show that the local Nusselt number increases with downstream coordinates (X) in stratified and unstratified porous medium. Also the local Nusselt number (Nu_x) increases with decreasing thermal stratification (S) because the local Nusselt number depends on temperature profile which increases with decreasing thermal stratification as mentioned before. A comparative study of figures (7) to (9) shows the effect of inclination angles on the Nusselt number where the difference between the buoyancy and gravity force acting on a unit volume of fluid in the boundary layer is always in the vertical direction. In the case of inclined wall, this force is resolved into two components, the parallel force drives the flow along the wall and the normal force on the plane wall. The force that drives the motion has been reduced; therefore the convection currents become weaker and the rate of heat transfer is lower relative to the vertical plane case. This is for positive angles. In the case of negative angles the opposite behavior is observed where the rate of heat transfer increases relative to the vertical orientation. The results show that the inclination angles do not affect strongly on the Nusselt number. The average Nusselt number was calculated from an integration of the local Nusselt number (Nu_x) by the method of (Simpsons 1/3 Rule), and has been plotted with the thermal stratification and Rayleigh number for different values of heat flux and inclination angles (φ=0º,-15º, 45º). Figure (10) shows the average Nusselt number increases with decreasing thermal stratification (S). This is a logical result because the (Nu_{avg}) calculated from (Nu_x) and the inclination angles do not affect clearly on average Nusselt numbers**.** Figures (11) shows that the average Nusselt number increases with decreasing Rayleigh number $\left(Ra = \frac{g\,\beta\,\Delta T_0\,K\,L}{\vartheta_f\,\alpha_m}\right)$ (Angirasa 1997) because of increasing ($T_{\infty,0}$) which decreasing (S) that increases Nusselt Number and decreases (Ra) because of decreasing (ΔT_0) where ($\Delta T_0=T_w-T_{\infty,0}$). As a result of studying natural convection problems, the relation between average Nusselt numbers with Rayleigh numbers, angles of inclination and stratification parameters may be represented as a correlation relates these characteristics. These correlations which have been created using STATISTICA program software, release 5.5A, by statsoft Inc., 1999. These correlations have been depicted in figures (12) to (14) for the range of stratification parameter from 0 to -10, angles (0, 15,-15, 30, 45 degree);

1. Average Nusselt number with Rayleigh number and stratification parameter;

$\overline{Nu}= c\,(Ra)^{n}\,(S)^{m}$ (for each φ) Eq. [1]

2. Average Nusselt number with Rayleigh number;

$Nu= c\,(Ra\cos\varphi)^{n}$ (for each S) Eq. [2]

3. Average Nusselt number with Rayleigh Number and stratification parameter;

$Nu=c\,(Ra\cos\varphi)^{n}\,(S)^{m}$ Eq. [3]

5.2 Numerical Results

Figures (15) to (20) show the temperature distribution at different stratification parameter (S), which expresses the heat transfer from a plane wall in thermally stratified porous medium. These figures show how the temperature distribution is affected with stratification parameter (S). The temperature distribution is normal at S=o, but it deforms gradually with changing (S) and reveals strongly at high levels of (S=-5,-10), where the temperature distribution increases with decreasing of stratification parameter (S). Figures (21) to (24) show that temperature distribution does not affected strongly with inclination angles (φ). Experimental analysis show that the temperature profile $\left(\theta = \frac{T - T_{\infty,x}}{T_w - T_{\infty,0}}\right)$ increases with decreasing of stratification parameter. The temperature distribution, which has been found by Fluent, agrees with behavior which has been depicted in experimental work.

5.3 Verification

The experimental and numerical temperature profile results for (q"=150 W/m^2 and φ=0º) has been compared with each other, as shown in figure (25). The experimental data has been used to run the program and obtain numerical results for test case of the experiment. Figure reveals that the numerical temperature profile follows the same behavior as the present experimental results but is approximately with means, maximum and minimum differences of 8.3%, 9.5% and 5.3% respectively. To verify the results obtained from the present study, a comparison was made with the results achieved by previous studies. The present results for the effect of thermal stratification parameter on temperature profile shown in figure (5) agrees with results of Ahmed [7] shown in figure (26) and Angirasa and Peterson [10] shown in figure (27)**.**The present results for Nusselt number shown in figures (7) and (10) agree with the results of Angirasa and Peterson [10] shown in figure (28).

6. CONCLUSIONS

Temperature profile was affected strongly by the thermal stratification parameter especially in the high values of thermal stratification parameter for all studied range of heat fluxes. Temperature profile (Θ) was unaffected strongly by the inclination angle for all studied range of heat fluxes and the inclination angles. Temperature profile (Θ) was unaffected strongly by the inclination angle for all studied range of heat fluxes and the inclination angles. Nusselt number varies linearly with X and increases with decreasing (S). Average Nusselt number was decreased with increasing Rayleigh number for all studied range value of heat fluxes and inclination angles (φ).

6.1 NOMENCALTURE

g	Gravitational Acceleration
K	Permeability
L	Characteristic Length of the Plane Wall
Nu	Nusselt Number
S	Thermal Stratification Parameter
T	Temperature
X	Non-Dimensional Downstream Coordinate
x	Downstream Coordinate
Y	Non-Dimensional Horizontal Space Coordinate
y	Horizontal Space Coordinate

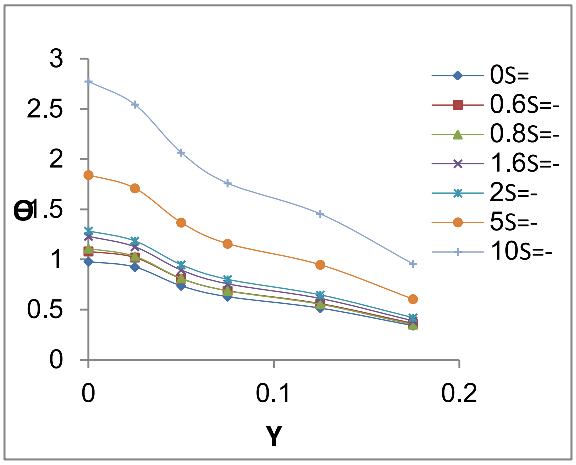
6.2 Greek Letters

α_m	Thermal Diffusivity of Porous Medium
β	Volumetric Coefficient of Thermal Expansion
Δ	Difference
υ_f	Kinematic Viscosity
Θ	Non- Dimensional Temperature

6.3 Subscripts

∞	Location away from the wall outside the boundary layer
∞, 0	Location away from the wall at x=0
∞, x	Location away from the wall at any x
f	Fluid
m	Medium
w	Wall
x	Location in the x-Direction

Fig. 5 Temperature Profile at q"=150 W/m^2 and φ=0º



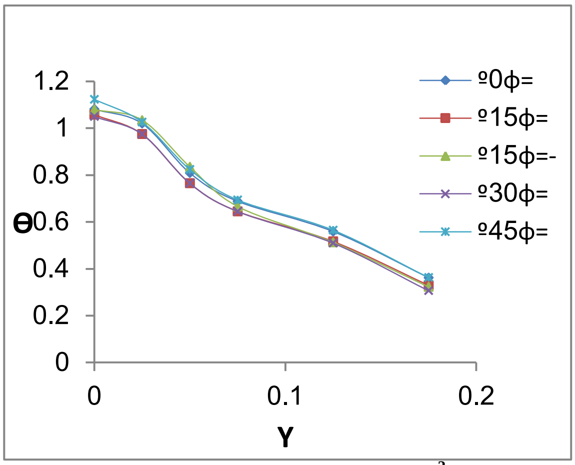


Fig. 6 Temperature Profile at q"=250 W/m^2 and S=-1.6

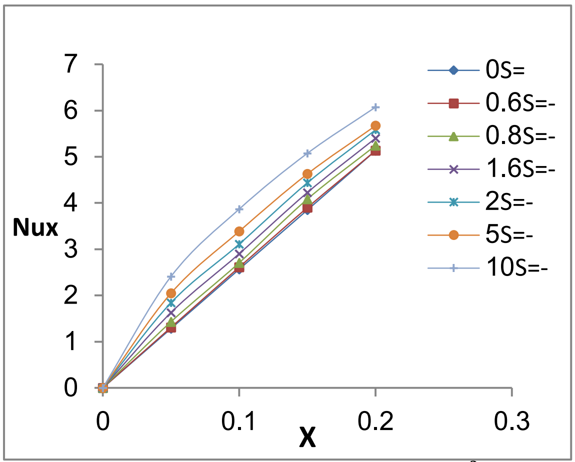


Fig. 7 Local Nusselt Number for q"=150 W/m^2 and φ=0°

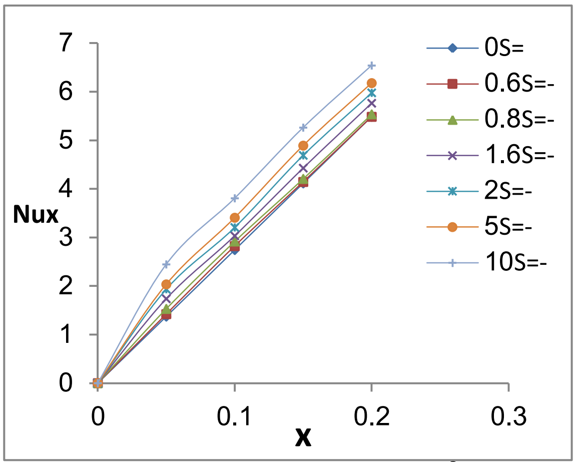


Fig. 8 Local Nusselt Number for q"=150 W/m^2 and φ=45°

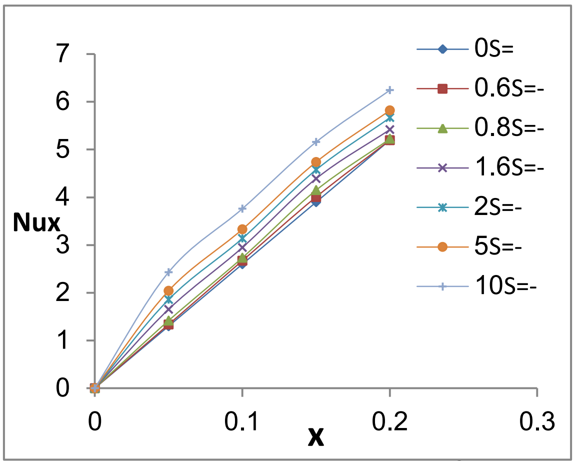


Fig. 9 Local Nusselt Number for q"=150 W/m^2 and φ=-15°

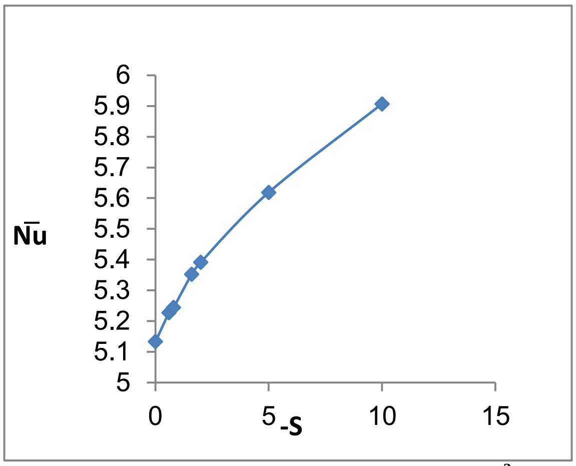


Fig. 10 Average Nusselt Number for q"=150 W/m^2 and φ=0°

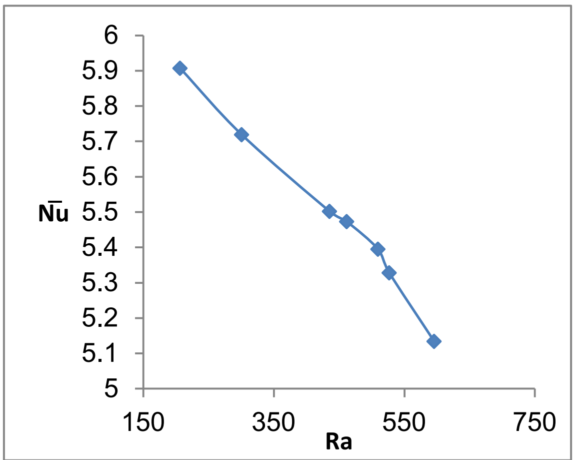


Fig. 11 Average Nusselt Number at q"=150 W/m^2 and φ=0°

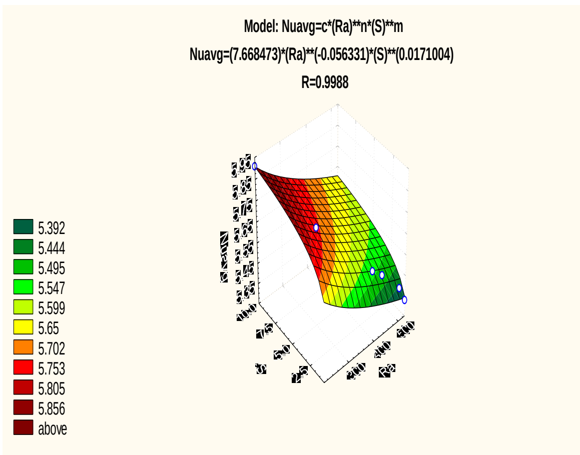


Fig. 12 Nusselt Number vs. Rayleigh Number and Stratification Parameter

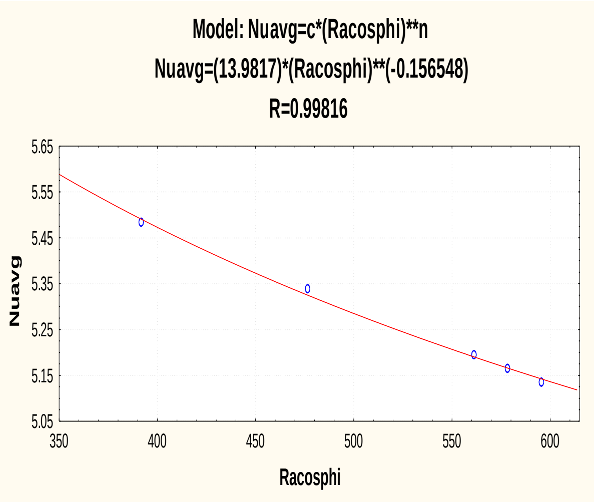


Fig. 13 Nusselt Number vs. Ra cosφ

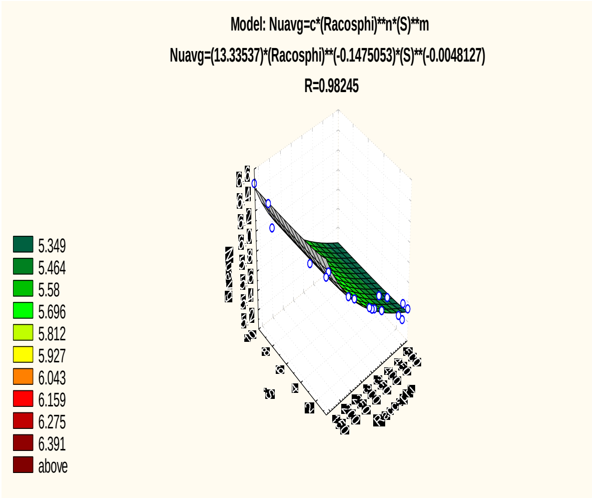


Fig. 14 Nusselt Number vs. Ra cosφ and Stratification Parameter

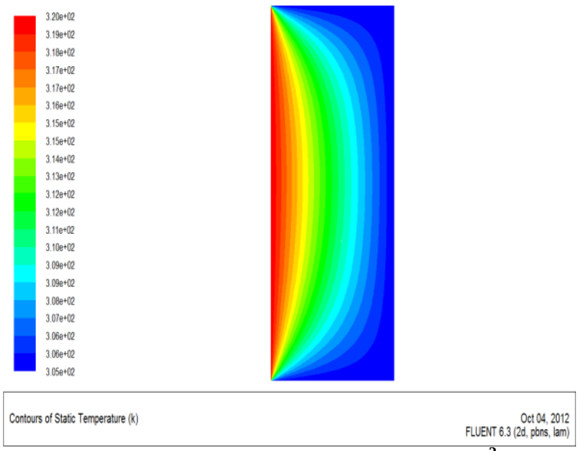


Fig. 15 Temperature Profile at q"=150 W/m^2 and S=0

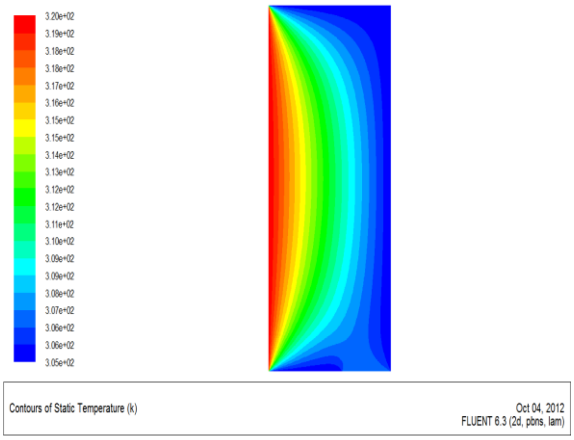


Fig. 16 Temperature Profile at q"=150 W/m^2 and S=-0.8

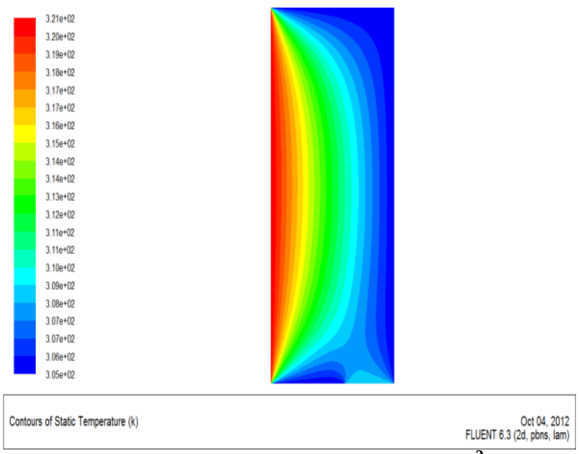


Fig. 17 Temperature Profile at q"=150 W/m^2 and S=-1.6

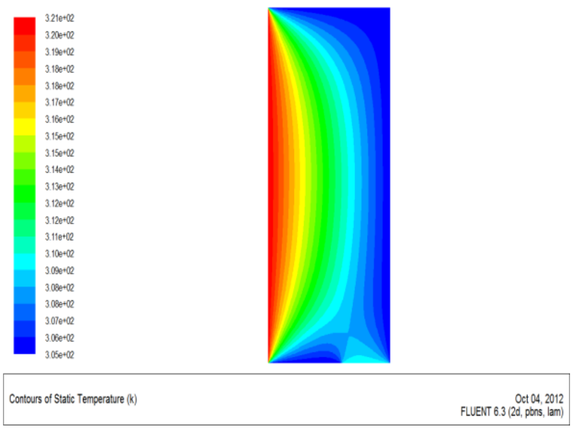


Fig. 18 Temperature Profile at q"=150 W/m^2 and S=-2

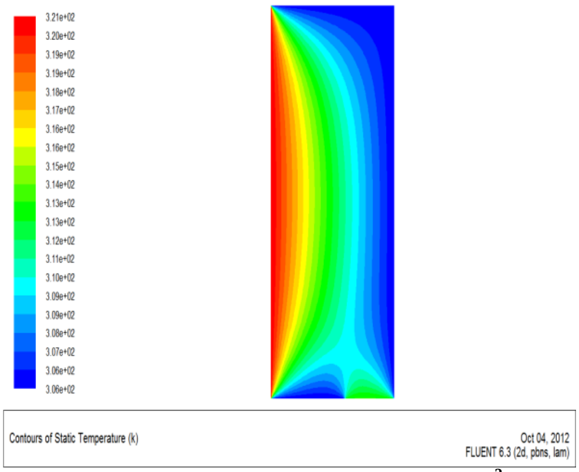


Fig. 19 Temperature Profile at q"=150 W/m^2 and S=-5

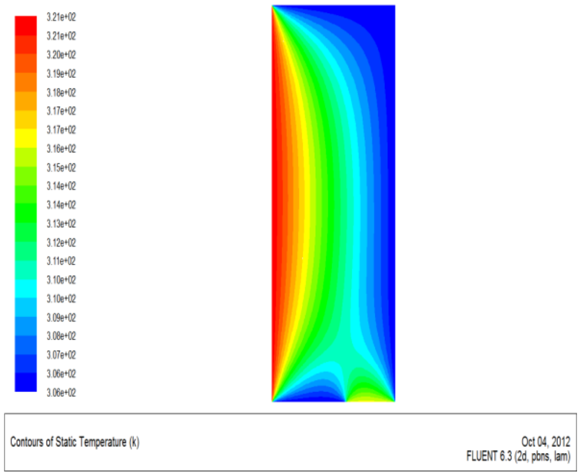


Fig. 20 Temperature Profile at q"=150 W/m^2 and S=-10

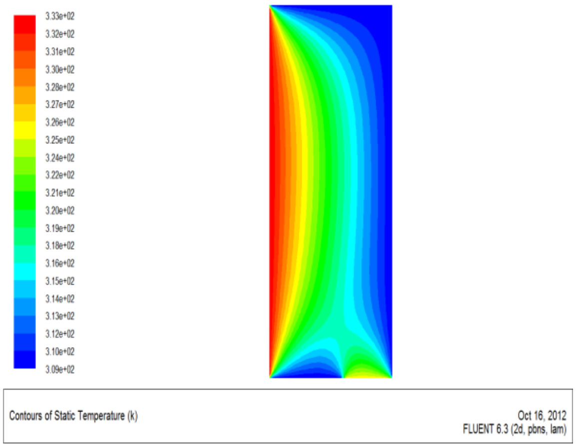


Fig. 21 Temperature Profile at φ=0º

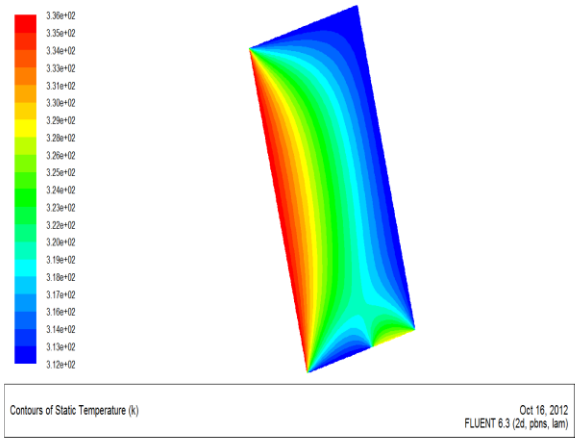


Fig. 22 Temperature Profile at φ=-15º

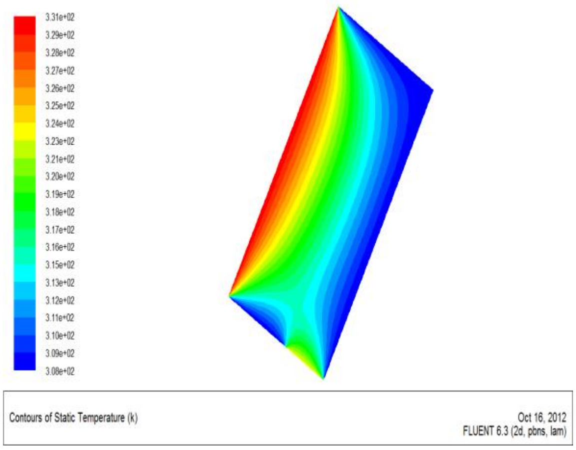


Fig. 23 Temperature Profile at φ=30º

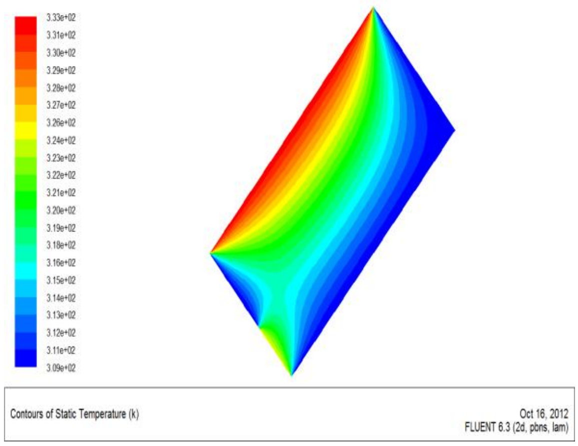


Fig. 24 Temperature Profile at φ=45º

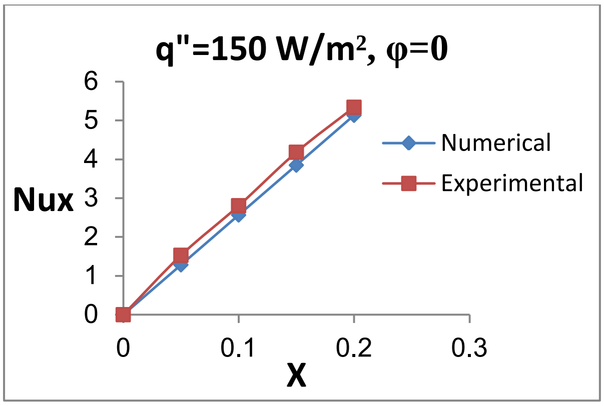


Fig. 25 Comparison of Experimental Temperature Profile with Numerical Results

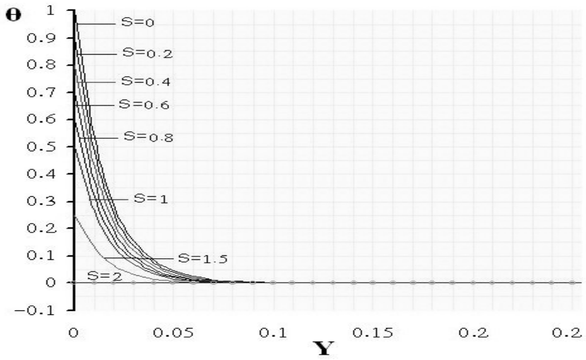


Fig. 26 Temperature Profile (Ahmed 2005)

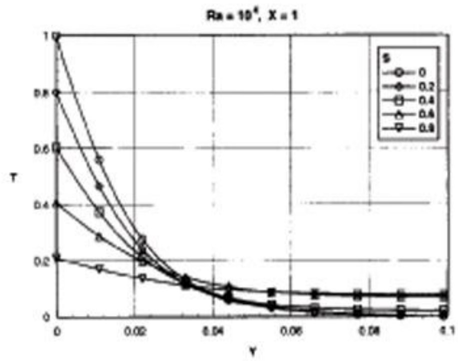


Fig. 27 Temperature Profile (Angirasa and Peterson)

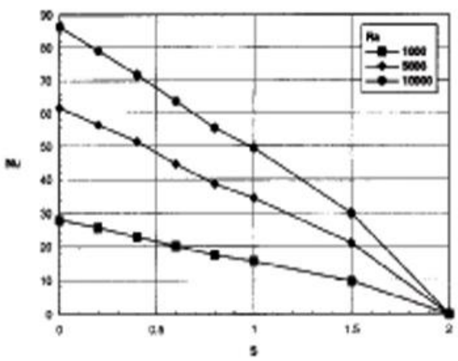


Fig. 28 Nusselt Number (Angirasa and Peterson 1997)

7. ACKNOELEDGMENTS

All praise and thanks are due to my God, the most Compassionate, the most Merciful, and the most Benevolent.

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