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A Computational Assessment of Different Materials and Variations in Thickness Ratio of Solid Blocks in a Square Cavity – A Conjugate Heat Transfer Analysis

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Abstract: *This paper presents the numerical study of a conjugate heat transfer for two dimensional square cavity with two different materials. The analysis mainly focuses on variation in thickness ratios of solid blocks, which are attached to the top and bottom walls of the cavity, under natural convection. The range of the Rayleigh number is $10^3 \leq Ra \leq 10^6$ in which the length of the square cavity is kept constant. Conjugate heat transfer in a square cavity is modeled with a linear heat flux at one side wall, the opposite wall is assumed to be cold wall at a constant temperature and other two walls are maintained adiabatic. The effects of stream line do not show any variation at low Rayleigh number; on the other hand, some substantial changes are seen with high Rayleigh number. The results of Nusselt number are better for copper compared to aluminum in the conjugate square cavity and the same increases with increasing Rayleigh number. The variation of thickness ratios is also studied for aluminum square cavity and found that the Nusselt number is betters for smaller thickness ratios.*

Keywords: conjugate natural convection, linear heat flux, thickness ratio and Nusselt number.

I. INTRODUCTION

Many researchers considered heat transfer in a square cavity by natural convection due its wide variety of applications such as heat treatment, electronic cooling, building heating and cooling, internal combustion engine, solar collectors and heat exchangers etc. Davis (1983) studied the natural convection effect in a two dimensional square cavity with differentially heated side wall and other walls were kept at isothermal condition which is lower than heated wall.

Mobedi (2008) numerically studied the effect of heat conduction in horizontal walls in a square cavity. The effect on heat transfer due to the variation of Rayleigh number and ratio of thermal conductivity with finite conjugate wall thickness are studied. For high Rayleigh number and low values of thermal conductivity ratio, the heat transfer through natural convection from the cavity reduces with increase in ratio of thermal conductivity is almost constant. Kumar and Balaji (2010) investigated an inverse problem in a 2-D conjugate natural convection by principal component analysis and neural network based non iterative method. As a result, they determined the boundary the heat flux at the heated side wall.

Alsabery et al. (2018) investigated the effects of conjugate natural convection of Al_2O_3 – water as nano-fluids in a square cavity with a concentric solid insert using Buongiorno’s two-phase model. The heater placed on the left bottom corner while right top corner maintained cold at constant temperature and other remaining walls are kept adiabatic. The study includes the variation of volume of fraction of nano-particles and thermal conductivity ratio of solid blocks while Rayleigh number varies from $10^2 \leq Ra \leq 10^6$. The heat conduction is dominated at low Rayleigh number and increase in heat transfer was found with the increase of nanoparticles volume fraction.

Natarajan et al. (2007) studied the natural convection through trapezoidal cavity for various thermal boundary conditions. They observed a symmetry flow pattern at linearly heated side wall whereas the secondary circulation was observed at linearly heated left and cold right walls. The conduction heat transfer dominates at Ra ≤ 5x10^3 with linearly heated side wall and for Ra ≤ 3x10^3 in case of left and cold walls. Sathiyamoorthy et al. (2007) carried out steady natural convection in square cavity filled with porous medium. The uniform heating is assigned to the bottom wall and side wall heated linearly where as other walls are adiabatic. They studied parameters such as Rayleigh number, Darcy number and Prandtl number. The average Nusselt numbers are almost constant in the range of Rayleigh number up to 10^6 and Darcy number up to 10^{-5}. The conduction mode of heat transfer is dominant when there is increase in Rayleigh number and Darcy number.

Kartas and Derentli (2017) investigated the natural convection in a rectangular cavity with one vertical wall active and other four walls are adiabatic. They performed experiments by changing the six aspect ratios of the rectangular cavity. The temperature distribution was presented for six cavities.

With respect to the above literature, there seems to be a window in which the effect of Nusselt number can still be studied by varying the thicknesses of the top and bottom walls for different thermal conductivities. Henceforth, in this work, a square cavity has been modelled that accounts for the heat transfer through top and bottom walls and the variation in stream line due to different thicknesses and thermal conductivities for enhancement of heat transfer.

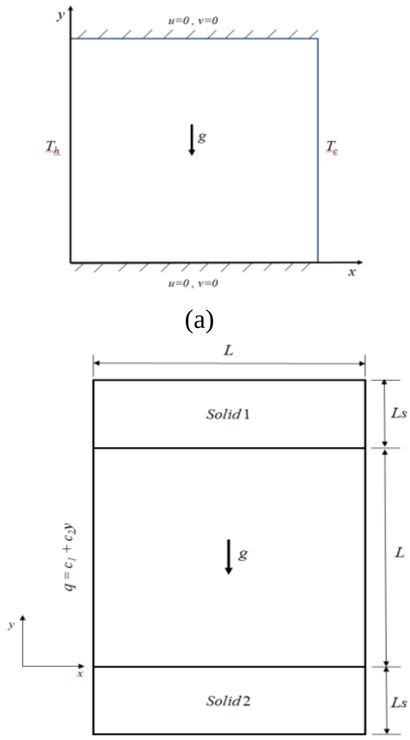

Figure 1: (a) Adiabatic top and bottom walls (b) Conjugate top and bottom wall

II. GOVERNING EQUATIONS

The governing equations for the present are as follow:

Continuity:
$$\frac{\partial U}{\partial X}+\frac{\partial V}{\partial y}=0 \quad (1)$$

X-Momentum:
$$U\frac{\partial U}{\partial X}+V\frac{\partial U}{\partial Y}=\frac{Ra}{Pr}\Phi+\frac{\partial^2 U}{\partial X^2}+\frac{\partial^2 U}{\partial X^2} \quad (2)$$

Y-Momentum:
$$U\frac{\partial V}{\partial X}+V\frac{\partial V}{\partial Y}=\frac{\partial^2 V}{\partial X^2}+\frac{\partial^2 V}{\partial X^2} \quad (3)$$

Energy:
$$U\frac{\partial \Phi}{\partial X}+V\frac{\partial \Phi}{\partial Y}=\frac{1}{Pr}\left(\frac{\partial^2 \Phi}{\partial X^2}+\frac{\partial^2 \Phi}{\partial Y^2}\right) \quad (4)$$

The above equations are non dimensional by introducing the following relation into the Navier-stokes and energy equations as below

$$X=\frac{x}{L}, \quad Y=\frac{y}{L}, \quad U=\frac{uL}{v_f},$$
$$V=\frac{vL}{v_f}, \quad P=\frac{P}{\rho\left(\frac{v_f}{L}\right)^2}, \quad \Phi=\frac{T-T_c}{\Delta T},$$
$$Gr=\frac{g\beta\Delta T\,L^3}{\upsilon^2}$$

$$\mathrm{Pr}=\frac{\upsilon}{\alpha_f}, \quad Ra=GrPr, \quad \mathrm{Pr}=0.71, \quad d=\frac{L_s}{L}$$

where g is gravitational acceleration (9.81 m/s^2), Gr is Grasshoff number (Gr = gβΔTL^3/υ^2), k_f and k_s are thermal conductivity of fluid and solid (W/mk) respectively, L is dimension of square cavity (m), Ls is thickness of solid block (m), p is pressure vector (pa), Pr is Prandtl number (υ/α_f), q is heat flux (W/m^2), Ra is Rayleigh number (Gr.Pr), T is Temperature (k), U and V are dimensionless velocity in X and Y directions, ‘u’ and ‘v’ are velocity component in X and Y directions (m/s), Φ is dimensionless temperature, ρ is density of the fluid (kg/m^3), d is the thickness ratio.

III. BOUNDARY CONDITIONS

The following boundary conditions are applied for the computational domain selected in the present study.

(a) Top and bottom wall are adiabatic

$T = T_h$ at x = 0, and $T = T_c$ at x = L

$-k\frac{\partial T}{\partial y} = 0,$ at y = 0 and y = L

u = 0 and v = 0 at x = 0 and y ϵ (0, L), x = L and y ϵ (0, L)
y = 0 and x ϵ (0, L), y = L and x ϵ (0, L)

(b) Top and bottom walls (conjugate)

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} = 0 \quad (5)$$

$q = c_1 + c_2 y$ at x=0 and $L_s \leq y \leq L + L_s$

$-k_s\frac{\partial T_s}{\partial y} = -k_f\frac{\partial T_f}{\partial y}$ at $y = L_s$ and $y = L + L_s$ and $0 \leq x \leq L$

Where k_s and k_f are thermal conductivities of the solid and fluid, respectively.

$-k_s\frac{\partial T_s}{\partial y} = 0,$ at y = 0 and $y = L+2L_s$ and $0 \leq x \leq L$

$-k_s\frac{\partial T_s}{\partial x} = 0,$ at x = 0 and x = L, $0 \leq y \leq L_s$ and $L+L_s \leq y \leq L+2L_s$

u = 0, v = 0 at x = 0 and x = L, y ϵ (L_s, $L+2L_s$)
y = 0 and $y = L+L_s$, x ϵ (0, L)

IV. NUMERICAL SIMULATION

Air is considered to be working fluid in the square cavity. The linear heated square cavity is modelled as conjugate heat transfer with Boussinesq approximation to account for the natural convection. The linear heat flux is varied by varying the values of c_1 and c_2 for the calculation of Rayleigh number. The governing equations are solved for uniform mesh generated for the computational domain using ANSYS Fluent 15. The pressure and velocity in the computations are coupled using popular SIMPLE scheme and second order upwind scheme is used for convective terms. Convergence criteria for continuity, momentum and energy equations are 1×10^{-3}, 1×10^{-3} and 1×10^{-6} respectively.

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V. RESULTS AND DISCUSSION

5.1. Validation of the Numerical Model

A grid size of 41 x 41 was considered for the known values of temperature of hot and cold at left and right vertical wall of square cavity. The results are validated with available literature. The Nusselt number is defined as:

$$Nu = \frac{\overline{q}(x=0)}{(T_h - T_c)}\frac{L}{K_f} \quad (6)$$

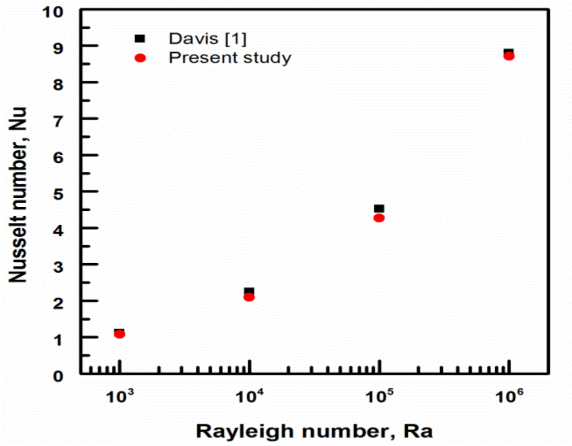


Figure 2: Validation of the present study

5.2. Grid Independence Test

Similar grid independence test was carried out to choose the optimal grid size for conjugate natural convection square cavity of uniform meshing with constant heat flux at left vertical wall and other vertical wall is kept cold at constant temperature.

Table1: Grid independence study with constant heat flux for Rayleigh Number 1×10^3

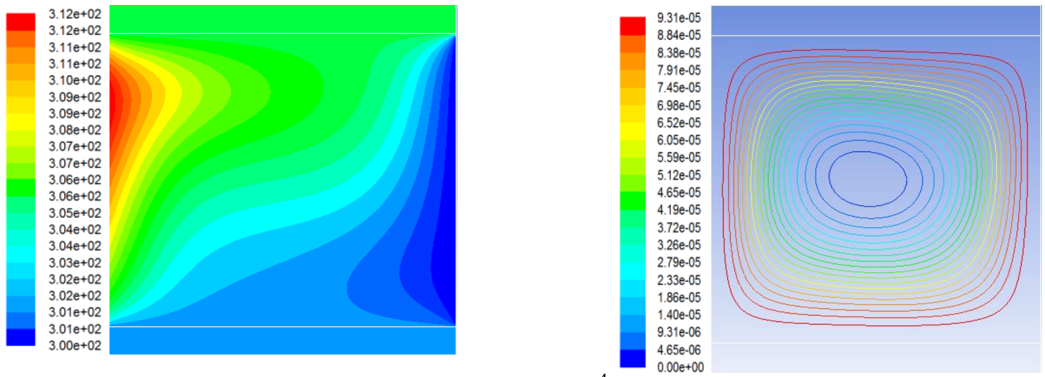
Number of nodes	Average Nusselt Number	Nusselt number variation between consecutive grids in percentage
41 x 41	2.443	-
61 x 61	2.507	2.6
81 x 81	**2.548**	**1.6**
101 x 101	2.577	1.12

From the above grid sensitivity results the grid size of 81 x 81 is selected as the optimum grid for further numerical computations to save time and space.

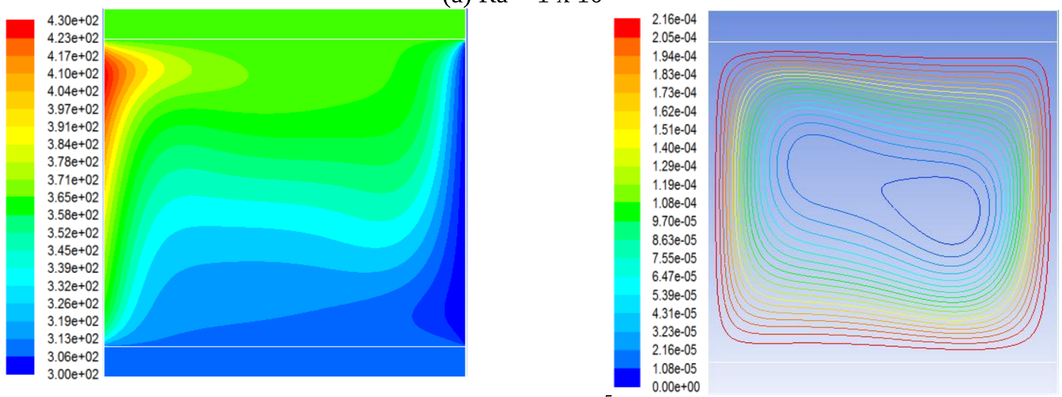
5.3. Temperature and Velocity Contour

Figure 3 shows the variation of isotherms and streamlines in the cavity for different Rayleigh numbers. The contour plots are used to study the temperature distribution of air in the conjugate square enclosures for different Rayleigh number varying from 1 x 10^4 to 1 x 10^6. It is observed that symmetrical circulation at Rayleigh number 1 x 10^4 from the streamline plot and afterwards getting misshape at higher values of Rayleigh number. This is because the left wall is assigned linear heat flux hence, the flow rate of air is higher towards the top side wall and the circulation starts in the clockwise direction.

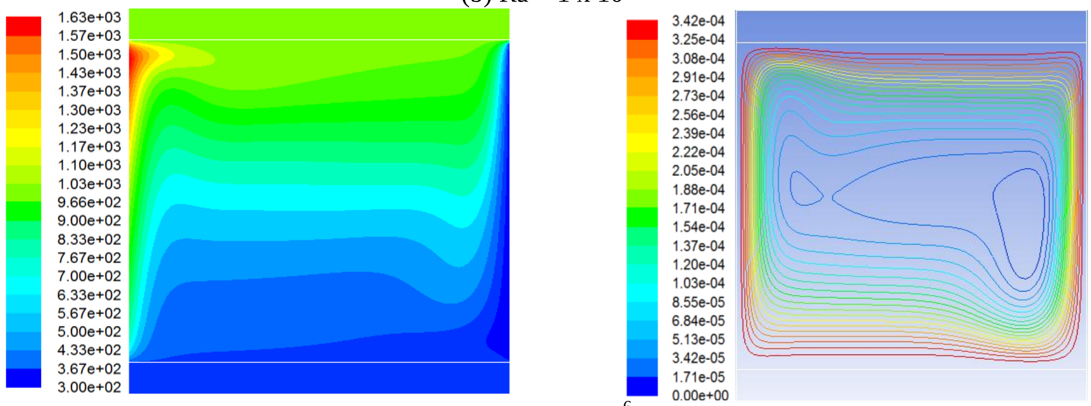
Isotherms **Stream lines**



(a) Ra = 1 x 10^4



(b) Ra = 1 x 10^5

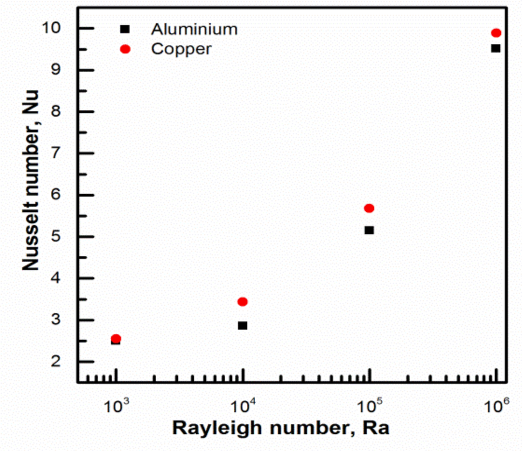


(c) Ra = 1 x 10^6

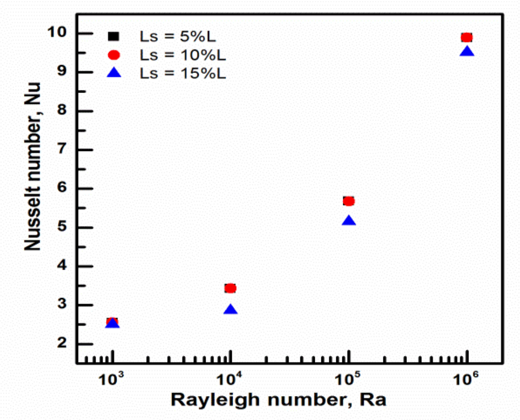
Figure 3: Variation of isotherms and streamlines in the cavity

The Nusselt number variation with Rayleigh number for both aluminium and copper solid domains of square cavity is shown in Fig. 4 (a). The Nusselt number shows a general increase with increase in the Rayleigh number for both aluminium and copper solids. Whereas square cavity with copper solid shows higher heat transfer rate compared to aluminium solid. This is because of copper possesses higher thermal conductivity compared to aluminium.

Furthermore, numerical analysis is carried out on aluminium solid walls by changing the thickness of top and bottom walls. As a representative case, three different thickness ratios are considered in the present study and presented in Fig. 4 (b). From the results, it has been observed that the thickness ratios of 0.05 and 0.1 are behaving the same in terms of average Nusselt number but the thickness ratio of 0.15 shows slight decrease in average Nusselt number due to increase in conduction resistance when the thickness of the walls are increased. Hence, from the results the thickness ratios of 0.05 and 0.1 gives better results for the present range of Rayleigh number studied.



(a)



(b)

Figure 4: Variation of Nusselt number (a) For aluminium and copper solid walls (b) effect of thickness ratio

VI. CONCLUSIONS

The present study considers the effects of linear varying heat flux on conjugate free convection in a square cavity filled with air and heated from the left vertical side wall. A two dimensional numerical computation is performed using commercial ANSYS FLUENT15. The computation was carried out for conjugate square enclosures of aluminium and copper. The following are the findings from the present analysis:

- Nusselt number increases with increase in Rayleigh number for both the materials considered.
- Nusselt number is higher in case of copper in comparison with aluminium due to its high thermal conductivity.
- The thickness ratios of 0.05 and 0.1 gives similar results compared to 0.15.
- For low Rayleigh number, circulation of the fluid inside the cavity is not disturbed whereas for high Rayleigh number the flow pattern is distorted and circulation starts shifting towards the top left corner.

Conflict of Interest

All authors declare that there is no conflict of interest for this publication.

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