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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Received: Date? Accepted: Date?

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 103 ≤ Ra ≤ 106 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.

1. **Introduction**

Natural convection heat transfer in a square cavity has been investigated by many researchers due its wide variety of application such as heat treatment, electronic cooling, building heating and cooling, internal combustion engine, solar collectors and heat exchangers etc. Davis [1] investigated the effect of natural convection in a two dimensional square cavity with differentially heated side wall and other walls were kept at constant temperature which is lower than heated wall. Mobedi [2] investigated the effect of heat conduction in horizontal walls in a square cavity numerically. They studied the effect of variation of Rayleigh number and thermal conductivity ratio on heat transfer rate with finite conjugate wall thickness. 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 [3] investigated an inverse problem in a two dimensional 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. [4] investigated the effects of conjugate natural convection of Al2O3 – 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 102 ≤ Ra ≤ 106. 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. [5] studied the effect of various thermal boundary conditions on natural convection in a trapezoidal cavity with linearly heated side wall. 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 ≤ 5x103 with linearly heated side wall and for Ra ≤ 3x103 in case of left and cold walls. Sathiyamoorthy et al. [6] presents steady natural convection flow in square cavity filled with porous medium. The bottom wall heated uniformly 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 106 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 [7] 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.

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| --- | --- |
| C:\Users\USER\Desktop\DIA_1.PNG | C:\Users\USER\Desktop\DIA_2.PNG |

Figure1. (a) Top and Bottom walls are adiabatic (b) Conjugate top and bottom wall

1. **Governing equations**

The governing equations for the present are as follow:

|  |  |  |
| --- | --- | --- |
| Continuity: |  | (1) |
| X-Momentum: |  | (2) |
| Y-Momentum: |  | (3) |
| Energy: |  | (4) |

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

, ,

, Pr = 0.71

Where g is acceleration due to gravity (9.81 m2/s), Gr is Grasshoff Number (Gr = gβΔTL3/υ2), k is thermal conductivity (W/mk), kf is thermal conductivity of fluid (W/mk), ks is thermal conductivity of solid (W/mk), L is dimension of square cavity (m), d is thickness of solid block (m), p is pressure vector (pa), Pr is prandtl number (υ/αf), q is heat flux (W/m2), Ra is Rayleigh number (Gr.Pr), T is Temperature (k), U is dimensionless velocity in x-direction, u is velocity component in x-direction (m/s), V is dimensionless velocity in y-direction, v is velocity component in y-direction (m/s), Φ is dimensionless temperature, ρ is density of the fluid (kg/m3).

**3. 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 = Th at X = 0, and T = Tc at X = L

at y = 0 and y = L

u = 0 and v = 0 at x = 0 and y ϵ (0, L), Pr =0.71

(b) Conjugate top and bottom walls

|  |  |
| --- | --- |
|  | (5) |

q = c1 + c2y at x=0 and d≤ y ≤ L+d

at y = d and y = L+d and 0 ≤ x ≤L

Where ks and kf are thermal conductivities of the solid and fluid, respectively.

, at y = d and y = L+2d and 0 ≤ x ≤ L

, at x = 0 and x = L, L+d ≤ y ≤ L+2d

u = 0, v = 0 at x = 0 and y ϵ (0, L)

u = 0, v = 0 at x = L and y ϵ (0, L), Pr = 0.71

**4. 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 c1 and c2 for the calculation of Rayleigh number. ANSYS Fluent 15 is used to solve the governing equations with uniform meshing. The simple algorithm is selected to solve the pressure – velocity coupling and second order upwind scheme is used for momentum and energy equations. Converging criteria for continuity, momentum and energy equations is 1x10-3, 1x10-3 and 1x10-6 respectively.

**5. 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 which is defined as:

|  |  |
| --- | --- |
|  | (6) |

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Fig. 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 1x103

|  |  |  |
| --- | --- | --- |
| Grid size | Average Nusselt Number | Percentage Nusselt number variation between successive grids |
| 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 isotherms and streamlines of 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 104 to 1 x 106. It is observed that from the streamline, the circulation is symmetrical at Rayleigh number 1 x 104 and afterwards getting distorted at higher values of Rayleigh number. This is due to linear heat flux, the mass flow rate of air is higher towards the top side wall and the circulation starts in the clockwise direction.

|  |  |
| --- | --- |
| Isotherms | Stream lines |
| C:\Users\USER\Desktop\104T1.PNGC:\Users\USER\Desktop\104 T.PNG | C:\Users\USER\Desktop\104V1.PNGC:\Users\USER\Desktop\104V.PNG |
| (a) Ra = 1 x 104 | |
| C:\Users\USER\Desktop\105T1.PNG C:\Users\USER\Desktop\105T.PNG | C:\Users\USER\Desktop\105 V1.PNGC:\Users\USER\Desktop\105V.PNG |
| (b) Ra = 1 x 105 | |
| C:\Users\USER\Desktop\106 T1.PNG C:\Users\USER\Desktop\106 T.PNG | C:\Users\USER\Desktop\106 V1.PNG C:\Users\USER\Desktop\106V.PNG |
| (c) Ra = 1 x 106 | |

Fig. 3. Isotherms and streamlines in the cavity for different Rayleigh Numbers

The variation of Nusselt number with Rayleigh number for both aluminum 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 aluminum 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 5%L and 10%L are behaving the same in terms of average Nusselt number but the thickness ratio of 15%L 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 5%L and 10%L gives better results for the present range of Rayleigh number studied.

|  |  |
| --- | --- |
| C:\Users\USER\Desktop\Graph2.tif  (a) | C:\Users\USER\Desktop\Graph9.tif  (b) |

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

**6. 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 5%L and 10%L gives similar results compared to 15%L.
* For low Rayleigh number, circulation of the fluid inside the cavity is not disturbed whereas for high Rayleigh the flow pattern is distorted and circulation starts shifting towards the left wall.

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