Analysis of Natural Convection Flow through Square Cavity by Computational Fluid Dynamic Analysis

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Abstract— Laminar natural convection of air into inner rectangular cavity with localized heating from vertical side wall has been investigated by using computation fluid dynamic analysis in ansys. The square cavity consists of two adiabatic top and bottom wall and air filled closed two dimensional geometry. Two stage investigations have been performed to find out the variation in the result between different approaches. The inclination angle of the enclosure was keep constant at 90°, and the effect of heat transfer was investigated over the range 103-Ra-106. Correlations of average Nusselt number based on the CFD results are presented for vertical cases. Solutions are obtained for several Rayleigh numbers with Prandtl number Pr = 0.70 and aspect ratio 1.The Pressure-Velocity Coupling Method used with Non-Iterative Time Advancement (NITA) scheme used to solve the problem. The distribution of temperature and stream function are taken as a function of thermal and geometrical output parameter for given problem.

Keywords: Heat Transfer, Conduction, Computational Fluid Dynamics CFD, Convection, Rayleigh Number, Nusselt Number

I. INTRODUCTION

The natural convection flow and heat transfer in rectangular enclosures are extensively Studied due to its diverse applications. In the vertical position enclosures can acts as insulation for doors and windows of buildings, air conditioning compartment of trains, industrial furnaces, chimney and many heat transfer equipments and in an inclined position it is used in skylights, roof windows, solar collector storage and many other solar applications.

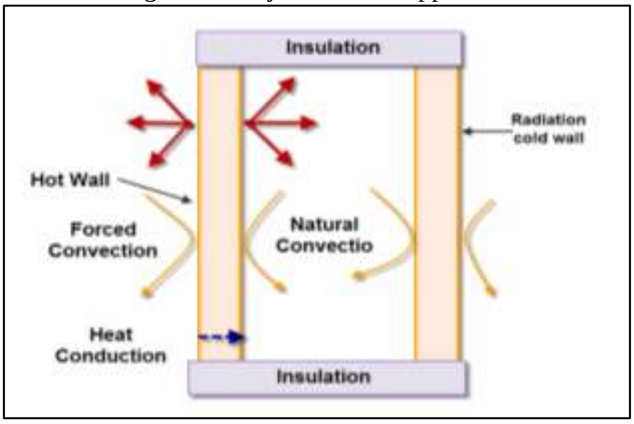

Fig. 1.1: vertical enclosures with two pieces of glass separated by a distance apart

The figure (1.1) shows vertical enclosures with two pieces of glass separated by a distance apart

In the present study a vertical enclosures is considered with side wall heating in which right wall is kept at a higher temperature and left wall is kept at lower temperature or vice-versa and top 2 and bottom walls are kept adiabatic. The space between two glasses is filled with air to reduce the rate of heat transfer.

Heat transfer through vertical enclosures consists of following heat transfer mechanisms shown in figure (1.1):

1) Natural convection in the air trapped inside the enclosure.
2) Forced convection on the outdoor surfaces.
3) Conduction through the solid components of the glass.
4) Radiation from both the indoor and outdoor surfaces.

A. *Convection*

Convection is transfer mode is comprised of two mechanisms. In addition to energy transfer by random molecular motion (diffusion), energy is also transferred by the bulk of macroscopic motion of fluid. The fluid motion is associated with the fact that at any instant large number of molecules are moving collectively. Such motion, in presence of a temperature gradient, contributes to heat transfer. The heat transfer by convection is given by Newton's law of cooling:-

$$Q = h\,A\,(Ts - Tf)$$

1) *Types of Convective Heat Transfer*

a) Natural Convection

When a surface is maintained in still fluid at temperature difference higher or lower than the fluid a layer of fluid is heated or cooled by the effect of surface temperature. A density difference is created between layers and still fluid that surrounds it. The density difference gives buoyant force which causes flow of fluid near the surface heat transfer is such conditions is known as Natural Convection or free convection. No external means required to flow here.

b) Forced Convection

When a fluid is forced to flow along the surface by external means such as fan, pumps or by stirring which artificially induced convection current which causes flow. It is known as forced convection.

II. PROBLEM FORMULATION

A. *Problem Identification*

The present study deals with two-dimensional natural convection taking place inside enclosed Space. The enclosed cavity has differentially heated side walls and adiabatic top and bottom wall. In this problem the cavity is filled with air and the effect of conduction and radiation is neglected.

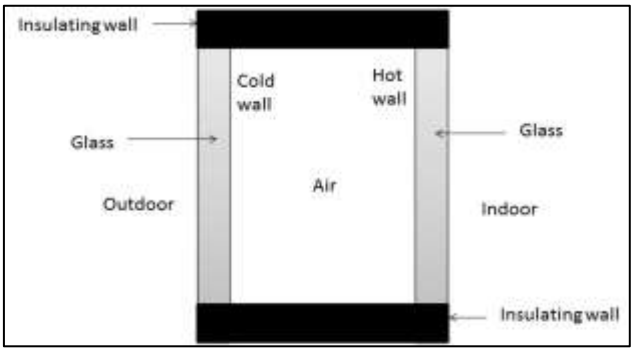

Fig. 2.1: Schematic representation of vertical cavity

In the above Fig 2.1, H is the height of the cavity and L is length of the cavity along which the heat transfer takes place. Th is the hot-wall temperature and Tc is the cold-wall temperature and the upper wall and the lower wall are assumed to be adiabatic.

B. Assumptions

The following assumptions are made in the present work:

1) Flow is steady laminar natural convection.
2) Flow is two -dimensional.
3) The fluid properties are constant except that the variation of density with temperature is accounted for in the formulation of buoyancy term (Boussinesq approximation).
4) The effect of conduction and radiation effects are neglected.

Range of Parameters Investigated
Rayleigh number = 10^3,10^4, 10^5, 10^6
Aspect ratio A = 1,2.5, 5, 7.5, 10
Inclination θ = 90^0
Prandtl number (Pr) = 0.7

III. METHODOLOGY

A. Geometry

The geometry of cavity is created using Ansys 15 software by using geometry generation workbench for different Rayleigh number varying from 10^3 to 10^6 and aspect ratio constant at 1.aspect ratio 1 means we are using the square geometry for analysis. The heat transfer analysis is carried out using Ansys (Fluent).

The geometry of the enclosed space, meshing and boundary identification is carried out in Ansys software.

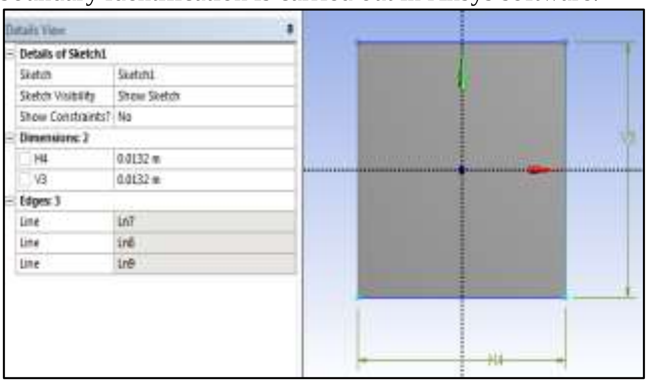

Fig. 3.1: Geometry of Square enclosed space

B. Mesh Generation

After creating the geometry it is required to divide the control volume into smaller number of Nodes and element of finite size, therefore it is called finite volume method. The method of splitting the Control volume into small finite size volume is known as meshing of the control volume. As Geometry is simple structured grid is preferred as it gives better results as compared to unstructured grid. Here we were using the minimum size of node 1e-04 m for mesh generation of square cavity.

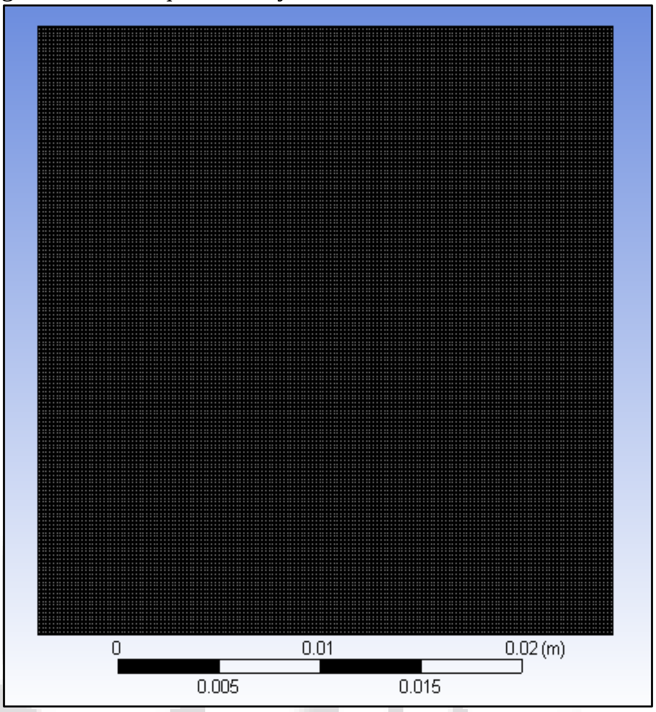

Fig. 3.2: meshing of Square enclosed space

C. Selection of Scheme

1) Space - Two- Dimensional
2) Solver - Pressure based
3) Time - Steady
4) Viscous - Laminar
5) Energy - On
6) Gravity – On

D. Boundary Condition

The enclosed cavity has differentially heated side walls and adiabatic top and bottom wall which is shown in table 3.1 below.

BOUNDARY	TYPE	VALUES
Side wall	Isothermal	T=308 K
Rigth wall	Isothermal	T=303 K
Top wall	Adiabatic	q= 0 W/m2
Bottom wall	Adiabatic	q= 0 W/m2

Table 3.1: Boundary condition of square cavity

E. Solution Method

In order to solve the given boundary condition in ansys fluent workbench we were using the Pressure-Velocity Coupling Method. ANSYS Fluent provides four segregated types of algorithms: SIMPLE, SIMPLEC, PISO, and (for time-dependant flows using the Non-Iterative Time Advancement option (NITA) Fractional Step (FSM). These schemes are referred to as the pressure-based segregated algorithm. Steady-state calculations will generally use SIMPLE or SIMPLEC, while PISO is recommended for transient calculations. PISO may also be useful for steady-state and transient calculations on highly skewed meshes. In ANSYS Fluent, using the Coupled algorithm enables full pressure-velocity coupling, hence it is referred to as the pressure-based coupled algorithm.

IV. RESULT & DISCUSSION

A. Validation of Present Results

The thermal conditions and dimensions of the enclosures are permit to cover wide range of Rayleigh number varying from 103 to 106. The temperature difference between side walls was kept at constant for all the cases. The property of air is obtained at mean temperature of hot wall and cold wall. The computed results of heat transfer for average Nusselt number are obtained by using commercial Computational Fluid Dynamics software and compared with results available in the literature shown in the table 4.1.

S No	Rayleigh Number Ra	Present Study (Nu)	Byong-Hoon Chang [1] (Nu)	De Vahl [8] (Nu)
1	10^3	1.17	1.118	1.118
2	10^4	2.08	2.241	2.243
3	10^5	4.48	4.532	4.519
4	10^6	8.86	8.848	8.799

Table 4.1: Validation of results for square enclousure

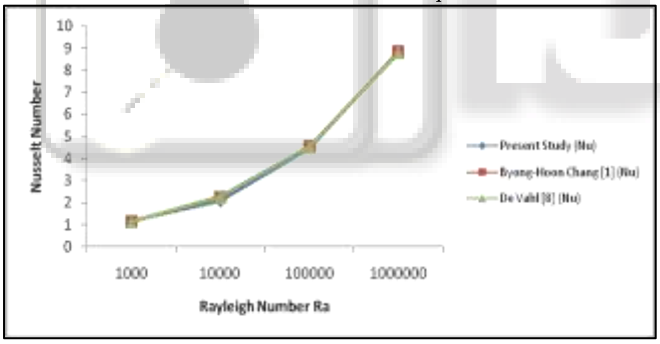

Fig. 4.1: Validation of Nusselt number for square enclosure at different Rayleigh number

B. Result of Heat Transfer for Square Cavity and Different Rayleigh No.

In order to find out the result in ansys fluent we perform 200 iteration for each combination of aspect ratio and Rayleigh No. Fluent provide wide range of solution in terms of continuity, energy, and velocity in x and y direction with respect to the time. On the basis of each result we calculate the average nusselt number by maximum and minimum range by using user defines function. The result tabulated below in table 4.2

Rayleigh number	Nusselt Number (Nu)
10^3	1.17
10^4	2.08
10^5	4.48
10^6	8.86

Table 4.2: Nusselt number of Square cavity for different Rayleigh number

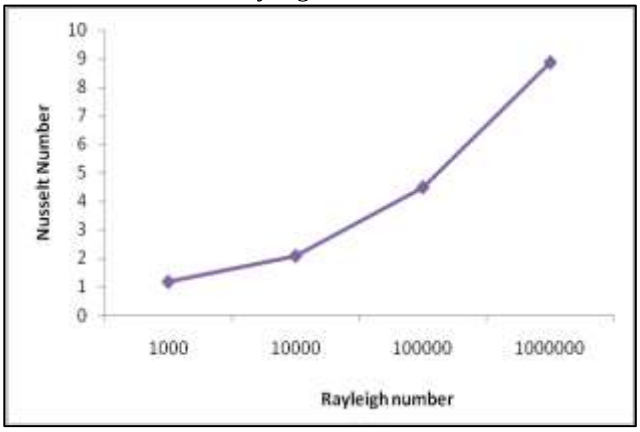

Fig. 4.2: Variation of Nusselt number with Rayleigh number at A=1

C. Comparison of Present Correlations for Medium Aspect Ratios and Lower Rayleigh Number

The present correlation for heat transfer in enclosed spaces for medium aspect ratios (2.5≤A≤10) and lower Rayleigh number ($10^3 \leq Ra \leq 10^6$) is validated with the correlations given by Byong-Hoon Chang [1] and is shown in table (12) to (15). The present correlations under predict the correlations given by Byong-Hoon Chang [1] and deviates by about 1 to 10 %. The deviations seems to be quite high but the heat transfer correlations are only best possible curve fit of large amount of data. The fig. 4.3 to 4.6 shows the variation of Nusselt number with Aspect ratio for different Rayleigh number i.e. 10^3, 10^4, 10^5, 10^6.

Aspect ratio (A)	Nusselt Number (Nu) Present Work	Nusselt Number (Nu) Byong-Hoon Chang [1]
1	1.07	1.34
2.5	1.14	1.21
5	1.08	1.13
7.5	1.06	1.08
10	1.04	1.04

Table 4.3: Comparison of Present correlation at $Ra=10^3$ and A= 1 to 10

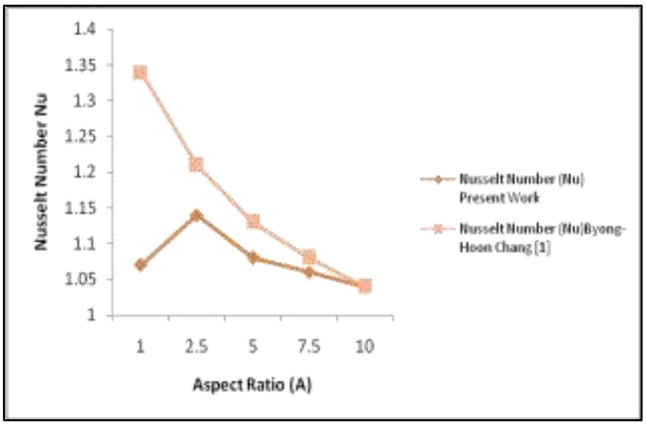

Fig. 4.3: Comparison of Present correlation for different aspect ratios at $Ra=10^3$

Aspect ratio (A)	Nusselt Number (Nu) Present Work	Nusselt Number (Nu) yong-Hoon

		Chang [1]
1	2.03	2.45
2.5	2.25	2.21
5	2.03	2.05
7.5	1.82	1.96
10	1.69	1.89

Table 4.4: Comparison of Present correlation at $Ra=10^4$ and A= 1 to 10

Fig. 4.4: Comparison of Present correlation for different aspect ratios at $Ra=10^4$

Aspect ratio (A)	Nusselt Number (Nu) Present Work	Nusselt Number (Nu) Byong-Hoon Chang [1]
1	4.52	4.44
2.5	4.18	4.02
5	3.74	3.73
7.5	3.45	3.56
10	3.2	3.45

Table 4.5: Comparison of Present correlation at $Ra=10^5$ and A= 1 to 10

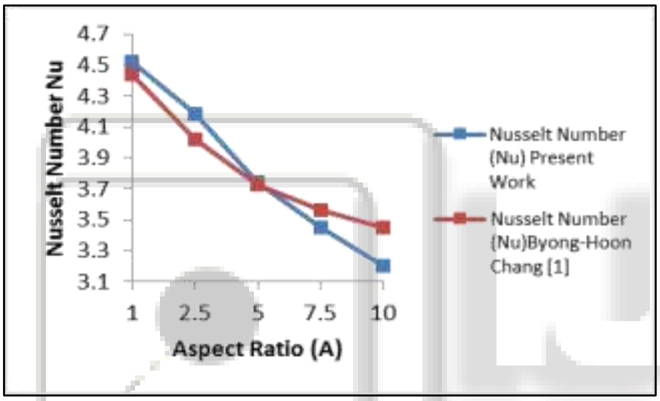

Fig. 4.5: Comparison of Present correlation for different aspect ratios at $Ra=10^5$

Aspect ratio (A)	Nusselt Number (Nu) Present Work	Nusselt Number (Nu) Byong-Hoon Chang [1]
1	8.89	8.1
2.5	7.6	7.32
5	6.65	6.78
7.5	6.21	6.49
10	6	6.28

Table 4.6: Comparison of Present correlation at $Ra=10^6$ and A= 1 to 10

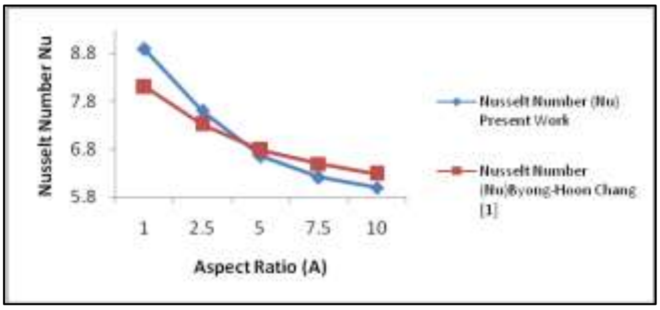

Fig. 4.6: Comparison of Present correlation for different aspect ratios at $Ra=10^6$

V. CONCLUSION

The important conclusion can be summarized as follows:-

- It is observed that the Nusselt number increases with increase in Rayleigh number.
- It is investigated from stream function plot that for all Rayleigh number, circulation pattern exist and number of circulation cells increase with an increase in Rayleigh number.
- The temperature distribution of air inside enclosed spaces is obtained with the help of temperature contours.
- The present results of heat transfer for two-dimensional, laminar, steady natural convection flow is obtained by using Computational Fluid Dynamics Software and compared with the results of Byong-Hoon Chang [1]. The present results show very good agreement with results of Byong-Hoon Chang.
- Based on computational results of Nusselt number obtained by Computational Fluid Dynamics software, the correlations of heat transfer is proposed using least square curve fitting for Small aspect ratio or square cavity and lower Rayleigh number.
  $Nu=0.1225 (Ra)^{0.31}$
  For Medium aspect ratios and lower Rayleigh number
  $Nu=0.23 (Ra)^{0.2625}(A)^{-0.159}$

VI. FUTURE SCOPE

1) The present work is concerned with two-dimensional flow inside square enclosed space. The work can be further extended for three-dimensional Flow.
2) In the present work air is used as working fluid. The work can be extended for different fluid.
3) The present work is concerned with laminar natural convection flow. The work can be further extended for Turbulent Flow.
4) In the present work the dependency of Rayleigh number is taken into consideration. The work can be further extended for varying aspect ratio, Prandtl number and inclinations of plate.
5) In the present work the natural convection flow inside enclosed space is considered and the effect of radiation and conduction are neglected.
6) The present work is concerned with aspect ratios one means for a square cavity. The work can be further extended for large Rayleigh number.
7) The present work is concerned with vertical air cavity. The work can be further extended for various inclinations.

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