CFD ANALYSIS OF NATURAL CONVECTION IN DIFFERENTIALLY HEATED ENCLOSURE

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

Master of Technology
in
Mechanical Engineering

By

Santhosh Kumar M.K

Department of Mechanical Engineering
National Institute of Technology
Rourkela
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Under the guidance of
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CERTIFICATE

This is to certify that the thesis entitled, **"CFD ANALYSIS OF NATURAL CONVECTION IN A DIFFERENTIALLY HEATED SQUARE ENCLOSURE"** submitted by **Mr. Santhosh Kumar M.K** in partial fulfillment of the requirements for the award of Master of Technology Degree in **Mechanical Engineering** with specialization in **Thermal Engineering** at the National Institute of Technology, Rourkela (Deemed University) is an authentic work carried out by him under my supervision and guidance.

To the best of my knowledge, the matter embodied in the thesis has not been submitted to any other University/ Institute for the award of any degree or diploma.

Date:

Prof. SWARUP KUMAR MAHAPATRA
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I am extremely fortunate to be involved in an exciting and challenging research project like "CFD analysis of natural convection in a differentially heated enclosure". It has enriched my life, giving me an opportunity to work in a new environment of Fluent. This project increased my thinking and understanding capability as I started the project from scratch.

I would like to express my greatest gratitude and respect to my supervisor Prof. Swarup Kumar Mahapatra, for his excellent guidance, valuable suggestions and endless support. He has not only been a wonderful supervisor but also a genuine person. I consider myself extremely lucky to be able to work under guidance of such a dynamic personality. Actually he is one of such genuine person for whom my words will not be enough to express.

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I would like to thank all whose direct and indirect support helped me completing my thesis in time.

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CONTENTS

ABSTRACT

The thermal control in many systems is widely accomplished applying natural convection process due to its low cost, reliability and easy maintenance. Typical applications include the heat exchangers, cooling of electronic equipment and nuclear reactors, solar chimneys and Trombe walls in building industry, etc.

Numerical and experimental studies of natural convective flows in two dimensional channels, opened to ambient conditions at both end sections, are extensively reported in the literature but most of them are treated severely idealized situations. CFD code of natural convection with variable properties and slip condition are presented in the present work. The 2D, laminar simulations are obtained by solving the governing equations using a Fluent 6.2.16. It is considered that the temperature variations are not so high and the Boussinesq approximation is applied. The latter leads to the simplification of the system of equations. The computed results for Nusselt number, velocity and temperature profiles and heat transfer rate are directly compared with those proposed in the bibliography letting therefore the validation of the employed numerical procedure.

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Abbreviation and acronyms

A constants for polynomial approximation

C_p specific heat of air J/kgK

g acceleration due to gravity m/s^2

k thermal conductivity of air W/mK

L length of enclosure in meter

Nu Nussult number of air

Pr Prandtl number of air $Pr = (\nu/\alpha) = (\mu\, Cp)/k$

Ra Rayleigh number of air $Ra = (g\beta\Delta T L^3)/(\alpha\gamma)$

t temperature in Kelvin

q heat flux W/m^2

u velocity in x-axis

v velocity in y-axis

x,y coordinates along x-axis and y-axis

Greek symbols

α thermal diffusivity m^2/s

β thermal coefficient of expansion K^{-1}

γ kinematic viscosity of air m^2/s

ρ density of air kg/m^3

μ dynamic viscosity of air kg/ms

τ shear stress at the wall

η slip coefficient

λ mean free path

σ momentum accommodation coefficient

Subscripts

m mean

h hot

c cold

s slip

Δ change

1, 2, 3 notation

CHAPTER – 1

INTRODUCTION

1.1 Introduction

A considerable portion of heat loss from a typical residence occurs through the windows. The problem is finding an insulating material that is transparent. An examination of the thermal conductivities of the insulating materials reveal that air is a better insulator than most common insulating material. Besides, it is transparent. Therefore, it makes sense to insulate the windows with layer of air. Of course we need to use another sheet of glass to trap the air. The result is an *enclosure*. Other examples of enclosures include wall cavities, solar collectors and cryogenic chambers involving concentric cylinders or spheres.

Enclosures are frequently encountered in practice, and heat transfer through them is of practical interest. Heat transfer in enclosed spaces is complicated by the fact that fluid in the enclosure, in general, does not remain stationary. The fluid adjacent to the hotter surface rises and the fluid adjacent to the cooler one falls, setting a rotionary motion within the enclosure that enhances heat transfer through the enclosure.

1.2 Motivation of work

Natural convection heat transfer in cavities has been a topic for many experimental and numerical studies found in the literature. From practical and industrial point of views, the interest is justified by its many applications, which include heating and cooling of buildings, energy drying processes, solar energy collectors, etc. Most of the published works covering natural convection in enclosures that exist today can be classified into two groups: differentially heated enclosures and enclosures heated from below and cooled from above (Rayleigh Bénard problems). Benchmark solutions related to differentially heated enclosures can bee found in many numerical investigations. However, CFD benchmark solutions related to the simplest case of 2D differentially heated enclosure are less encountered in the literature.

1.3 Variable properties of air

Most fluids fluids, however, have temperature-dependent properties, and under circumstances where large temperature gradients exist across the fluid medium, fluid properties often vary significantly. Under many conditions, ignoring such variations may cause inaccuracies in estimating heat transfer rates. The thermophysical properties that appear in the governing equations include thermodynamic and transport properties that appear in the governing equations. Thermodynamic properties define the equilibrium state of the system. Temperature, density and specific heat are such properties. The transport properties include the diffusion rate coefficients such as the thermal conductivity and viscosity.

1.4 Slip boundary condition

In many practical applications, the particle adjacent to a solid surface no longer takes the velocity of the surface. The particle at the surface has a finite tangential velocity; it "slips" along the surface. The flow regime is called the slip-flow regime and this effect can not be neglected.

In recent years, considerable attention has been given because it plays an important in numerous applications such as crystal growth from melts , droplet migration in nonuniform temperature fields (Subramaniam, 1981) and flame spreading over a pool of liquid fuel (Sirigano, 1972).

1.5 Literature overview

Natural convection problem, involving buoyancy driven flow in a cavity, was first suggested as a suitable validation test case for CFD codes by Jones [1]. The boundary condition for the problem involved two vertical walls which differ in temperature leading to a thermal gradient across the solution domain. This thermal gradient leads to the buoyancy forces varying between the walls giving rise to flow. Adiabatic conditions are assumed on the remain boundaries

1.5.1 Variable properties of air

Natural convection flows in a rectangular enclosure subject to a horizontal temperature gradient have been extensively studied by numerical means (e.g. Polezhaev, 1967, Macgregor and Emery, 1969, Rubel and Landis, 1970, Mallinson and de Vahl Davis [2], 1973 and 1977). Only three of these have treated variable fluid properties. Macgregor and Emery (1969) used the Boussinesq approximation and a variable viscosity while Rubel and Landis (1970) used a linearized approach and reported results for moderate Rayleigh numbers. Polezhaev (1967) solved the complete equations, including the continuity equation, for a square cavity and for one value of non-dimensional temperature difference between hot and cold walls.

The study of fully developed free convection between parallel plates at constant temperature has been initiated by Ostrach [3]. Sinha [4] studied this problem using as working fluid water at low temperatures where the relation between density and temperature is nonlinear. However the other water properties (viscosity and thermal conductivity) have been considered constants. The first exact solutions for free convection in a vertical parallel plate channel with asymmetric heating for a fluid with constant properties was presented by Aung [5]. Vajravelu and Sastri [6] reconsidered the problem treated by Sinha using a more accurate relation between water density and temperature, ignoring again the variation of other water properties with temperature. Vajravelu [7], in a subsequent paper, treated the same problem using water and air as working fluids and considering all fluid thermophysical properties (ρ, μ, k, cp)_ as linear functions of temperature. However, the results are valid for room temperatures between 10 and 25°C. Chenoweth and Paolucci [8] presented exact solutions for a perfect gas using the Sutherland law for viscosity and thermal conductivity and considering the ambient fluid temperature equal to the reference temperature (mean temperature of the two plates).

Chenoweth and Paolucci [9] extended the previous work to cases where the ambient fluid temperature is different from the reference temperature. The presented results in both works are valid for the temperature range between 120 K and 480 K.

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1.5.2 Slip boundary condition

Chen and Weng [10] recently presented analytical investigations on fully developed natural convection in open–ended vertical parallel plate microchannels, by taking the velocity slip and temperature jump effects into account. An important conclusion from their study is that for fully developed free convection flows with symmetrically heated walls, the Nusselt number turns out to be zero. These conclusions, however, were made by neglecting the momentum and heat transfer characteristics in the developing region of the microchannel. Appreciating the fact that the transport phenomena in the developing region might influence the characteristics of the fully developed natural convection in vertical microchannels in a rather profound manner, Biswal et al. [11] have recently executed a comprehensive computational study on free convection heat transfer in the entrance region, followed by that in the fully developed region, in long vertical microchannels, for different values of Knudsen number and Rayleigh number. In their study, special implications of accommodating the effects of the developing region in the heat transfer analysis were discussed in details and some important conclusions based on the same were pinpointed. Haddad et al. [12] have reported implicit finite difference simulations of the developing natural convection in an isothermally heated microchannel filled with porous media. Chen and Weng [13], in a subsequent study, have emphasized the importance of thermal creep and high order slip/jump conditions for modeling developing natural convection problems, by employing a marching implicit procedure.

1.6 Thesis outline

The aim of this thesis is to propose two dimensional CFD code related to natural convection in a square enclosure heated differentially with variable properties of air and slip boundary condition which comprises electronic equipment for cooling purposes. The buoyancy-induced air flow depends on the difference in air density between the faces of the enclosure. The fluid under consideration is air (Prandtl = 0.71) and the Rayleigh number is taken in the range $10^4 \leq Ra \leq 10^6$. Our numerical method is based on a finite volume formulation and a PRESTO scheme with second order upwind acceleration. In the present investigation, relatively fine grids corresponding to 110x110 nodes were used. Predicted velocity and temperature profiles are presented for the different cases. Important parameters such as average Nusselt number, Temperature and velocity profiles are calculated and compared with the proposed one from bibliography.

CHAPTER – 2

PROBLEM FORMULATION

2.1 Introduction

A schematic representation of the system under investigation is shown in Fig. 2.1, where L is the dimension of the enclosure which is calculated depending on the Rayleigh number. Refer Table for other parameters for calculation. The gravity vector is directed in the negative y coordinate direction. A general analysis is now presented for transport from vertical isothermal surface allowing for the variation of all the fluid properties. The pressure and viscous dissipation terms are neglected.

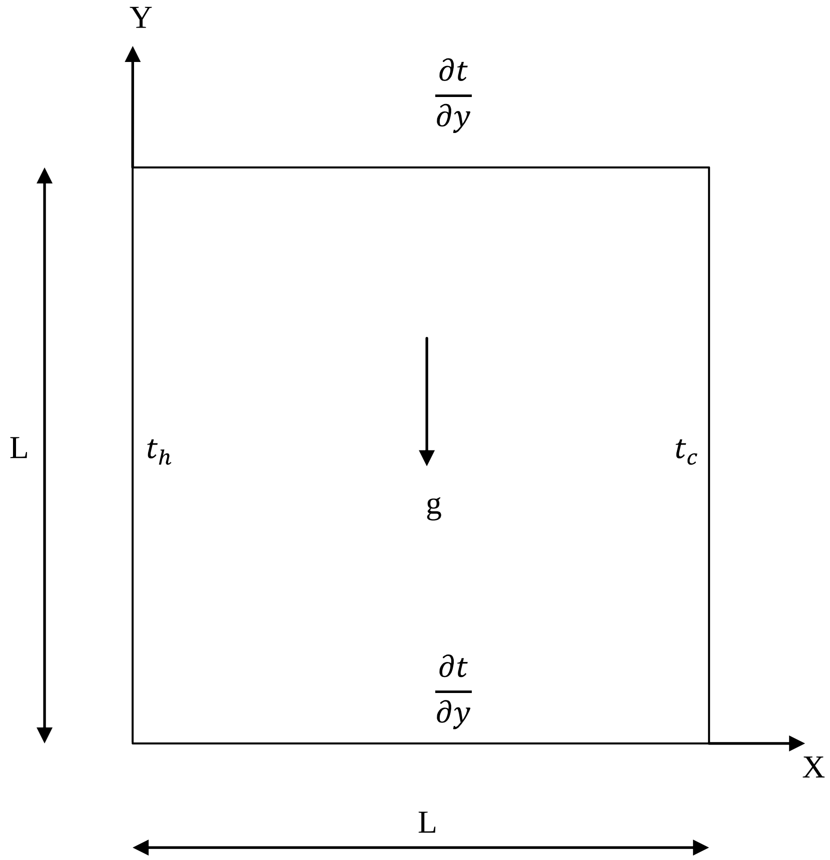


Fig 2.1

2.2 Governing Equations

With the boundary layer approximations the governing equations for convection are as follows

Continuity Equation

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

Momentum Equation

$$\rho\left(u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y}\right) = g(\rho_\infty - \rho) + \frac{\partial}{\partial y}\left(\mu\frac{\partial u}{\partial y}\right)$$

Energy Equation

$$\rho c_p \left(u \frac{\partial t}{\partial x} + v \frac{\partial t}{\partial y} \right) = \frac{\partial}{\partial y} \left(\mathrm{k} \frac{\partial \mathrm{t}}{\partial \mathrm{y}} \right)$$

Rayleigh Number

$$Ra = \frac{g\beta \Delta t L^3}{\alpha \gamma}$$

Nusselt number

$$Nu = \frac{k \left(\frac{\partial t}{\partial x} \right)}{k_m \left(\frac{t_h - t_c}{L} \right)}$$

2.3 Boundary conditions

For the above domain, left wall is considered hot wall which is maintained at 100°C and right wall is considered cold wall which is maintained at 50°C. The other two walls, i.e. top and bottom are considered to adiabatic walls i.e. heat flux $\dot{q} = 0$. Refer Table 2.1 Rayleigh number calculation based on dimension of domain and assuming constant properties.

2.3.1 For variable properties of air

Here we assume that fluid velocity at all fluid–solid boundaries is equal to that of the solid boundary i.e. no slip condition and fluid temperature at all fluid–solid boundaries is equal to that of the solid boundary wall temperature i.e. no jump condition. The vertical walls are maintained at uniform surface temperature.

Velocity:

- $u(x,0) = 0$, $v(x,0) = 0$,
- $u(x, L) = 0$, $v(x, L) = 0$.
- $u(0, y) = 0$, $v(0, y) = 0$,
- $u(L, y) = 0$, $v(L, y) = 0$

Temperature:

- $t(x, 0) = t_h = 100°C$,
- $t(x, L) = t_c = 50°C$,
- $t(0, y)$ *and* $t(L, y)$ where $\partial t / \partial y = 0$

In the constant property analysis the buoyancy force term is replaced by a temperature difference, assuming that ρ, μ, C_p and k are constant. Here instead the following properties are assumed to be temperature dependent:

ρ = ρ (t)   μ= μ (t)   k=k (t)

2.3.2 Slip boundary condition

To account for slip-flow regime, the Navier-Stokes equations are solved in conjunction with the slip-velocity boundary condition

$$\tau_s = \eta u_s$$

where u_s is the slip-velocity at the wall, τ_s is the shear stress at the wall and η is the slip coefficient. Schaaf and Chambre [14] have shown that the slip coefficient can be related to the mean free path as follows:

$$\eta = \frac{\mu}{\left(\frac{2-\sigma}{\sigma}\right)\lambda}$$

where σ is the momentum accommodation coefficient (MAC) and λ is the mean free path. The MAC is introduced to account for gas-surface interactions at the wall. For a perfectly elastic smooth surface, the angles of incidence and reflection of molecules colliding with the wall are identical and therefore the gas cannot exert any stress. This is referred to as *specular reflection* and results in perfect slip at the boundary

($\sigma \rightarrow 0$). Conversely, in the case of an extremely rough surface, the gas molecules are reflected at totally random angles and lose, on average, their entire tangential momentum: a situation referred to as *diffusive reflection* ($\sigma = 1$).

Combining both equations and rearranging we get

$$u_s = \left(\frac{2-\sigma}{\sigma}\right)\frac{\lambda}{\mu}\tau_s$$

This slip velocity is implemented where the boundary wall undergoes slip boundary condition.

Table 2.1 Properties of air for Rayleigh number calculation

Description	Symbol	Value			Units
Gravitational acceleration	g	9.801	9.801	9.801	m/s^2
Density	ρ	1.0137	1.0137	1.0137	kg/m^3
Specific heat	Cp	1007.5	1007.5	1007.5	J/kgK
Thermal conductivity	k	0.02917	0.02917	0.02917	W/mK
Dynamic viscosity	μ	0.00002074	0.00002074	0.00002074	kg/ms
Mean temperature	t_m	3.48E+02	3.48E+02	3.48E+02	K
Kinematic viscosity	γ	2.05E-05	2.05E-05	2.05E-05	m^2/s
Beta	β	2.87E-03	2.87E-03	2.87E-03	K^{-1}
Delta T	Δ t	5.00E+01	5.00E+01	5.00E+01	k
Length	L	2.00E-02	4.00E-02	8.00E-02	m
Thermal diffusivity	α	2.856E-05	2.856E-05	2.856E-05	m^2/s
Prandtl number	Pr	7.16E-01	7.16E-01	7.16E-01	
Rayleigh number	Ra	1.93E+04	1.54E+05	1.23E+06	

CHAPTER – 3

CFD MODELING

3.1 Introduction

Based on control volume method, 2-D analysis of fluid flow and heat transfer for the square enclosure is done on fluent software. The geometry for the same done using preprocessor gambit.

3.2 Gambit part

As per the length according Rayleigh number obtained square enclosure is modeled in Gambit 2.2.30 with grid size 110x110 as shown in Fig 3.1. The mesh nearby to walls is fine meshed to cope-up the thermal and velocity boundary layer formation and at the centre it is coursed meshed.

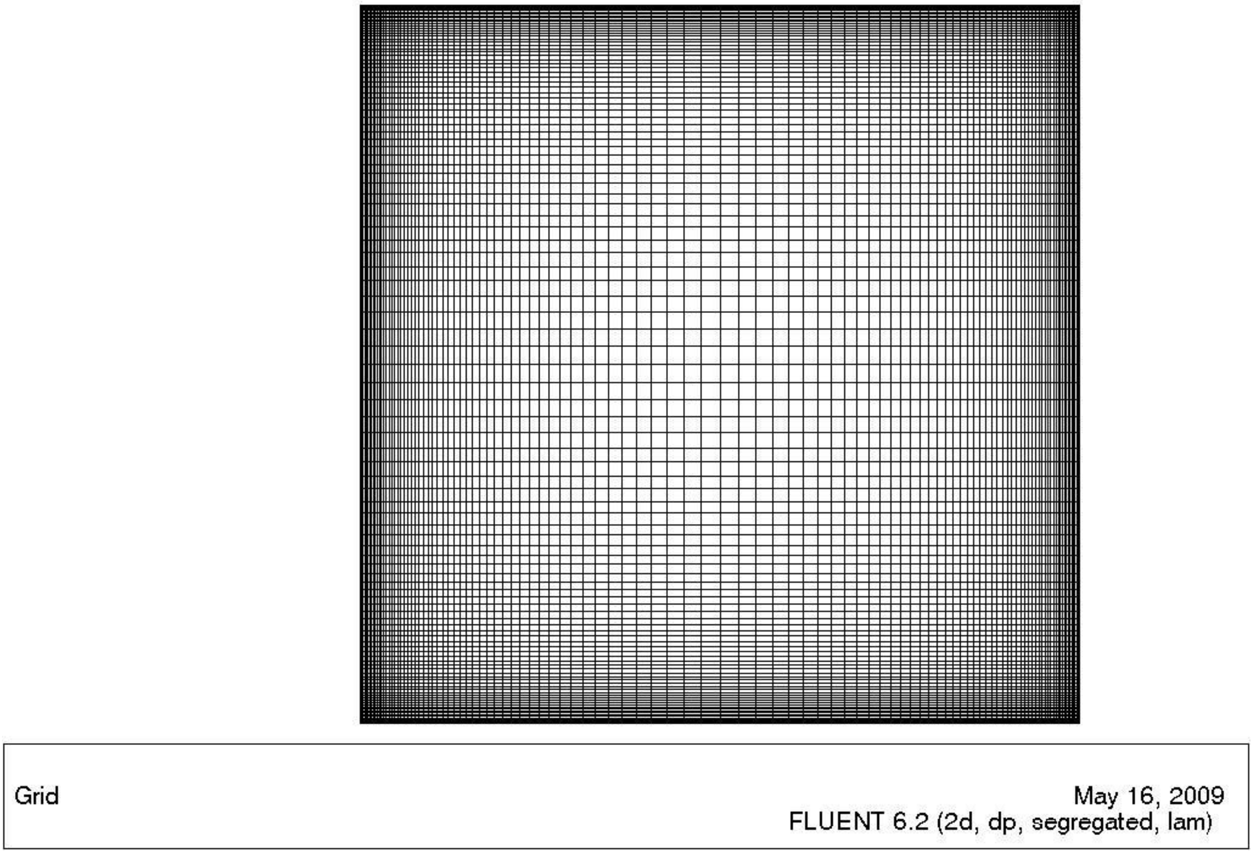


Fig 3.1

3.3 Fluent part

Analysis is carried out with simple algorithm and Presto for pressure discretization, second order upwind scheme for momentum and energy. Relaxation factors are taken to be default values. Refer Table 3.1 for values. Convergence criterion set for 10^{-3} for continuity, x-momentum and y-momentum and 10^{-6} for energy. Constant properties of air is considered and results for average Nusselt number temperature and velocity profiles are matched with paper [15].

Table 3.1 Relaxation factors to be taken

Pressure	Density	Body force	Momentum	Energy
0.3	1	1	0.7	1

3.3.1 Variable properties of air

Variable properties of density, viscosity and thermal conductivity are applied with piecewise linear and polynomial method.

Refer Table 3.2 for properties of density, thermal conductivity and dynamic viscosity for the temperature range 50°-100° for piecewise linear approximation.

Fluent uses the approximation

$$\varphi(t) = \varphi_n + \frac{\varphi_{n+1} - \varphi_n}{t_{n+1} - t_n}(t - t_n)$$

where $1 \leq n \leq N$ and N is the number of segments

Table 3.2 properties of density, thermal conductivity and dynamic viscosity

Temperature	Density	Thermal Conductivity	Dynamic Viscosity
323.0	1.0920	0.027350	1.9630E-05
328.0	1.0755	0.027715	1.9855E-05
333.0	1.0590	0.028080	2.0080E-05
338.0	1.0435	0.028445	2.0300E-05
343.0	1.0280	0.028810	2.0520E-05
348.0	1.0137	0.029170	2.0740E-05
353.0	0.9994	0.029530	2.0960E-05
358.0	0.9856	0.029885	2.1175E-05
363.0	0.9718	0.030240	2.1390E-05
368.0	0.9588	0.030595	2.1600E-05
373.0	0.9458	0.030950	2.1810E-05

For polynomial method, we consider properties of air are function of temperature of the order of 2 with 3 coefficients for input i.e.

$$\varphi(t) = A_1 + A_2 t + A_3 t^2$$

Refer Table 3.3 for values of coefficient to input for polynomial approximation

Table 3.3 Values of coefficients

	A_1	A_2	A_3
Density	3.039	-8.715E-03	8.320E-06
Thermal conductivity	2.387E-04	9.427E-05	-3.200E-08
Viscosity	1.692E-06	6.587E-08	-3.200E-11

3.3.2 Slip model

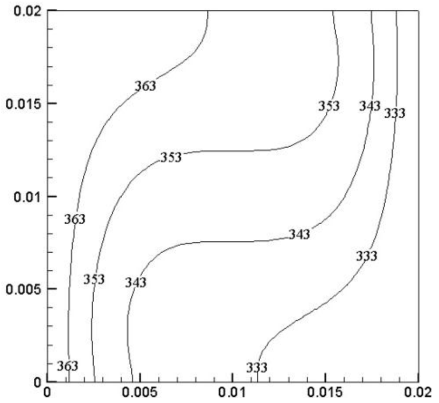
In this section the effect of slip has been discussed considering shear stress to be zero at different walls. The effect has been shown through streamline and isotherm pattern (fig 4.3) The table 4.3 presents effect of slip boundary condition on Nusselt number.

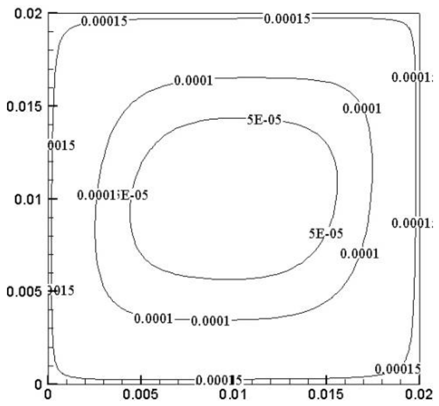
CHAPTER- 4

RESULTS AND DISCUSSION

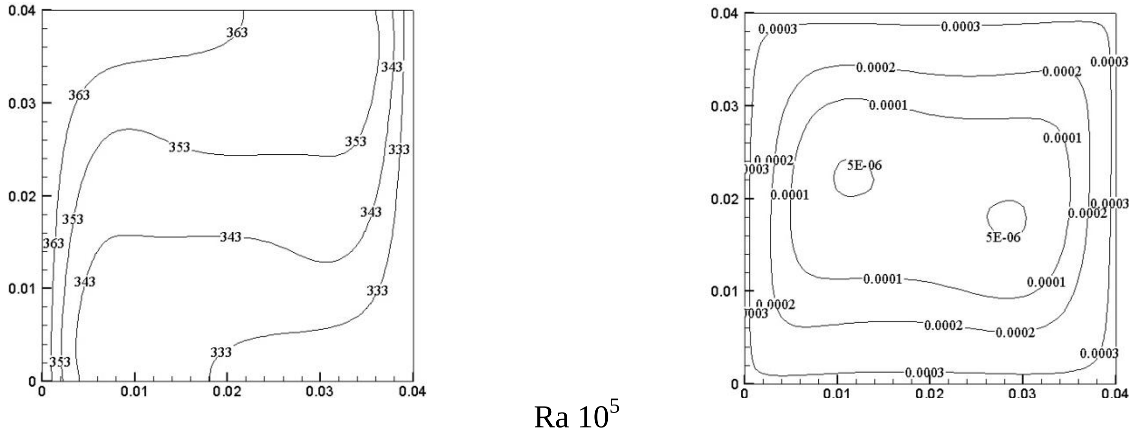
4.1 **Constant property analysis**

In this section the effect of variable property has been delineated. The flow phenomenon has revealed through isotherm and streamline pattern. The Rayleigh number has been varied from 10^4 to 10^6. The flow phenomenon is examined for Ra= 10^3 as the matter fact it is seen that flow features is conduction dominated and therefore it has not been presented here. In the beginning effect of constant property has been described in order to sense the effect of variable properties. Normally the properties are assumed constant in order to avoid additional non linearities because of variable properties in the complex N-S equation. Here flow is considered to be laminar and 2-D. It is observed from fig 4.1(a), (b), (c), (d) that flow is clockwise inside the cavity. The energy received by the fluid at the hot wall is delivered at the cold wall. The insulated horizontal walls behave as energy corridors for the fluid flow. As Rayleigh number increase the flow becomes stronger, there is a formation of very thin strong shear jet layer adjacent to active walls. The secondary vertices are also formed for higher Rayleigh number so this feature somewhat makes the energy transfer less effective. The isotherms pattern reveals that as Rayleigh number increases, the packing of isotherms near the active walls become prominent implying rise in Nusselt number. The isotherms are orthogonal at the insulated walls ensuring zero heat transfer. The stratification in isotherm pattern across the cavity has become a feature for higher Rayleigh number.

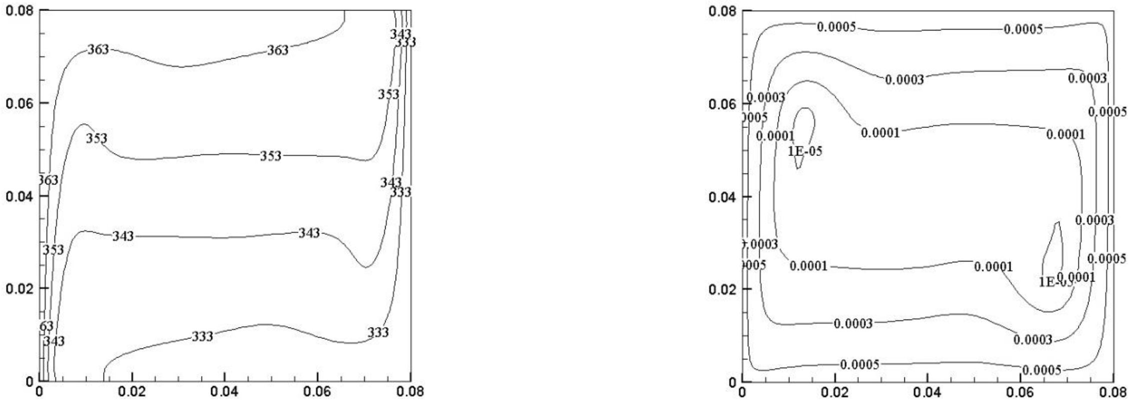




Ra=10^4



Ra 10^5



Ra = 10^6

Fig 4.1 Isotherms and streamlines for Ra= 10^4, 10^5, 10^6

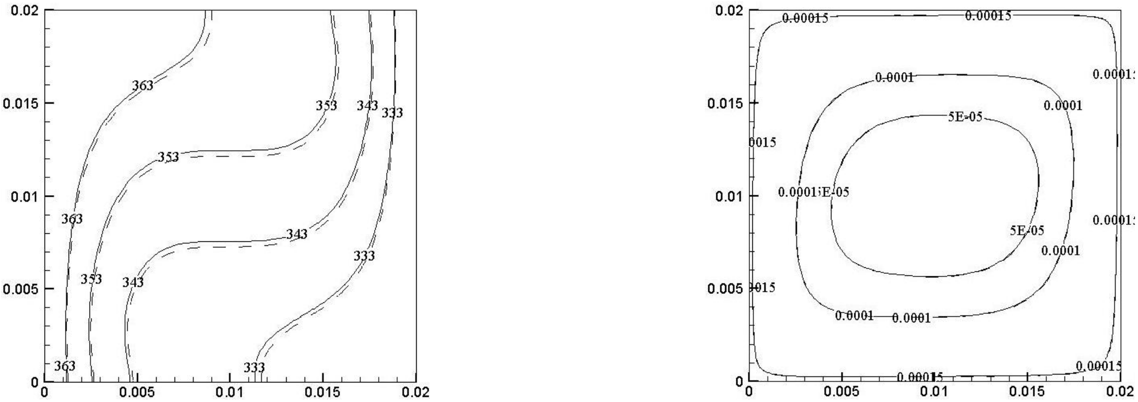
Table 4.1 Values of Nusselt number for different Rayleigh number

Rayleigh number	Nu
10^4	2.188
10^5	4.529
10^6	8.823

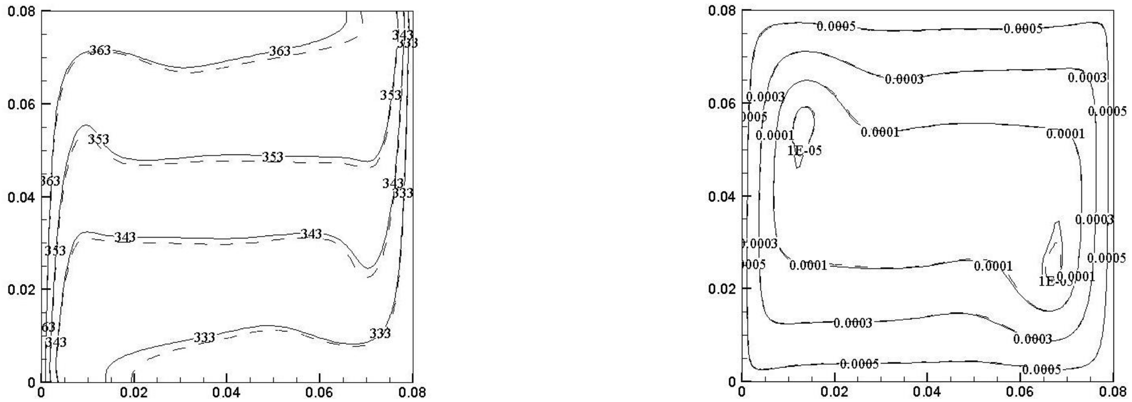
4.2 Effects of Variable Properties

4.2.1 Variable Thermal conductivity

The thermal conductivity has been varied with temperature adopting piecewise linear approximation and polynomial approximation, the results have been presented in the table 4.2.1. It is observed that the Nusselt number does vary even though the relationships between thermal conductivity and temperature are different. It is also observed there is no difference in both isotherm pattern and flow pattern. Therefore, the isotherm pattern and flow pattern have been depicted in the fig 4.2.1 considering the variation of thermal conductivity as piecewise linear for both Ra= 10^4 and Ra= 10^6. It is observed that Nusselt number decreases with varying thermal conductivity which also clearly observes from the isotherm pattern. The change in Nusselt number (i.e. comparing with table 4.1) more or less same order (6% decrease) for different Rayleigh numbers



(a) Ra=10^4 (b)



(c) Ra=10^6 (d)

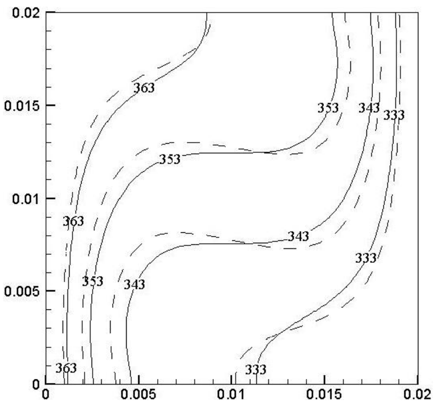
Fig 4.2.1 Effect of variable thermal conductivity on isotherm pattern and flow pattern (Ra=10^4 and Ra=10^6) (‘constant property _____ ‘ ‘variable thermal conductivity -------‘)

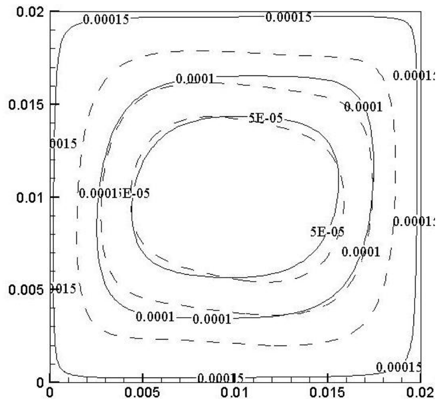
Table 4.2.1 Effect of variable thermal conductivity on Nusselt number

Rayleigh number	Nu	
	Piecewise wise linear approximation	Polynomial approximation
10^4	2.050	2.048
10^5	4.235	4.231
10^6	8.269	8.272

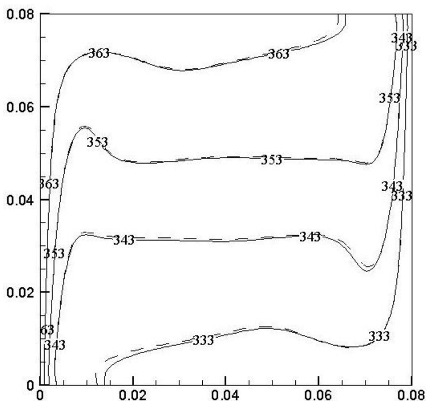
4.2.2 Variable density

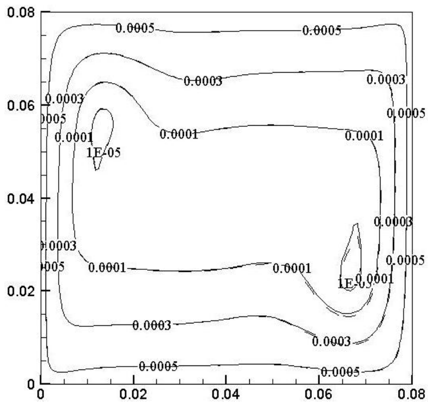
The density has been varied with temperature adopting piecewise linear approximation and polynomial approximation, the results have been presented in the table 4.2.2.It is observed that the Nusselt number does vary even though the relationships between density and temperature are different. It is also observed there is no difference in both isotherm pattern and flow pattern. Therefore, the isotherm pattern and flow pattern have been depicted in the fig 4.2.2 considering the variation of density as piecewise linear for both Ra= 10^4 and Ra= 10^6. It is observed that nusselt number increases with varying density. The change in Nusselt number (i.e. comparing with table 4.1) is more for Ra=10^4 and not much variation is seen for Ra=10^6.





(a) Ra=10^4 (b)





(c) Ra=10^6 (d)

Fig 4.2.2 Effect of variable density on isotherm pattern and flow pattern (Ra=10^4 and Ra=10^6) (

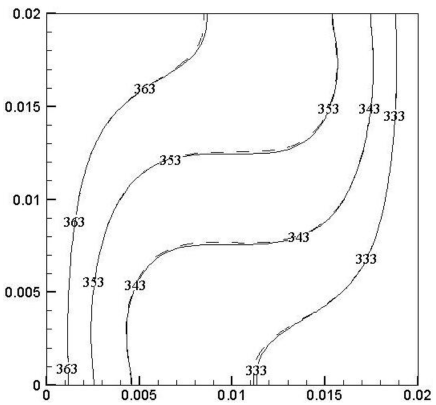
‘constant property _____ ‘ ‘variable density -------‘)

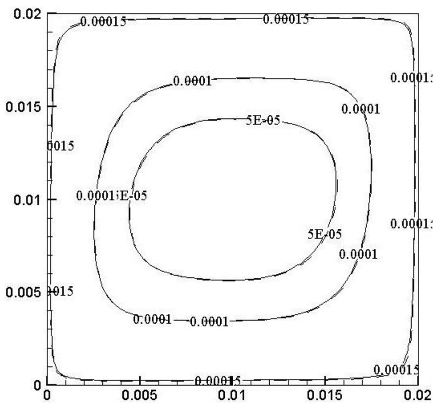
Table 4.2.2 Effect of variable density on Nusselt number

Rayleigh number	Nu	
	Piecewise wise linear approximation	Polynomial approximation
10^4	2.692	2.694
10^5	5.082	5.086
10^6	9.258	9.265

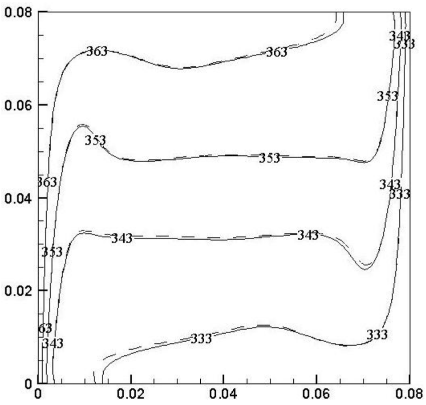
4.2.3 Variable viscosity

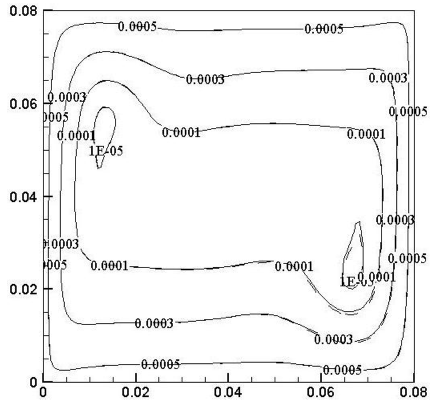
The viscosity has been varied with temperature adopting piecewise linear approximation and polynomial approximation, the results have been presented in the table 4.2.2. It is observed that the Nusselt number does not vary even though the relationships between viscosity and temperature are different. It is also observed there is no difference in both isotherm pattern and flow pattern. Therefore, the isotherm pattern and flow pattern have been depicted in the fig 4.2.2 considering the variation of viscosity as piecewise linear for both Ra= 10^4 and Ra= 10^6. The variation in nusselt number is not noticeable with varying viscosity for different Rayleigh number.





(a) Ra=10^4 (b)





(c) Ra=10^6 (d)

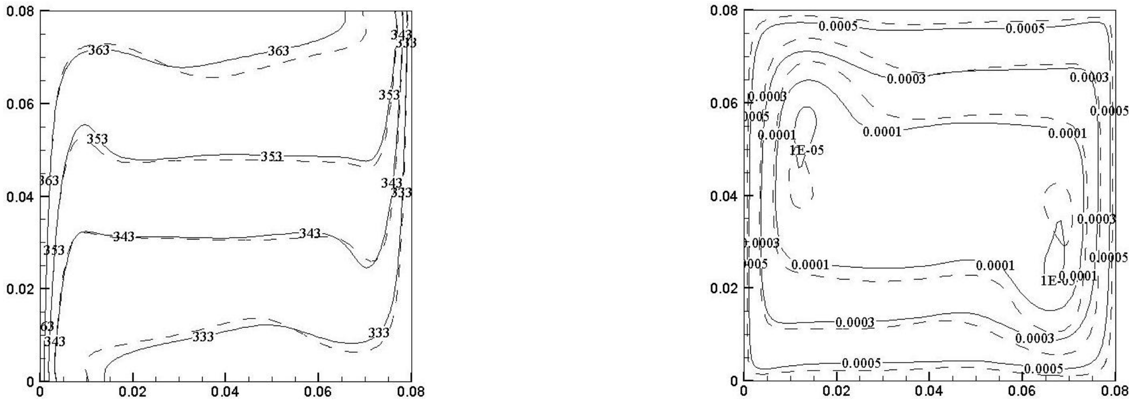
Fig 4.2.3 Effect of variable viscosity on isotherm pattern and flow pattern (Ra=10^4 and Ra=10^6) (‘constant property _____ ‘ ‘variable density -------‘)

Table 4.2.3 Effect of variable viscosity on Nusselt number

Rayleigh number	Nu	
	Piecewise wise linear approximation	Polynomial approximation
10^4	2.201	2.200
10^5	4.552	4.552
10^6	8.913	8.913

4.2.4 Combined effect of varying properties

In this section the combined effect of varying properties i.e. thermal conductivity(k), density(ρ) and viscosity(μ) has been explained through variation in Nusselt number and both isotherm pattern and flow pattern Fig 4.2.4 The flow features presented through isotherm pattern and flow pattern is meant for Ra=10^6. It is observed from table 4.2.4 that the effect of varying viscosity does not influence the phenomena and hence the Nusselt number. The combined effect of thermal conductivity and density counters each other. At low Rayleigh number effect of varying density dominates over effect of thermal conductivity and thus results increase in Nusselt number by 15%.(comparing Table 4.1 table and Table 4.2.4). However at higher Rayleigh number as density does not have pronounced effect because of varying thermal conductivity, the Nusselt number decreases by 1.5%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0
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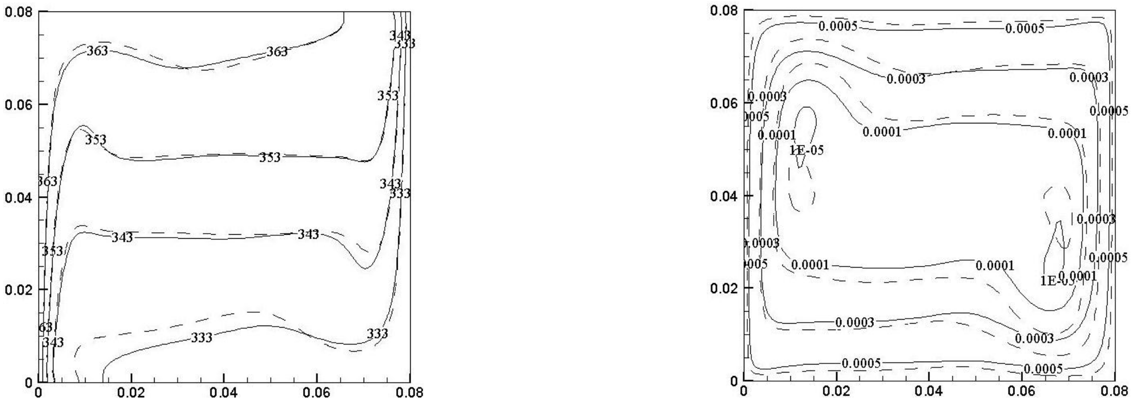
343
333
0.0005
0.0003
0.0001
1E-05

(a)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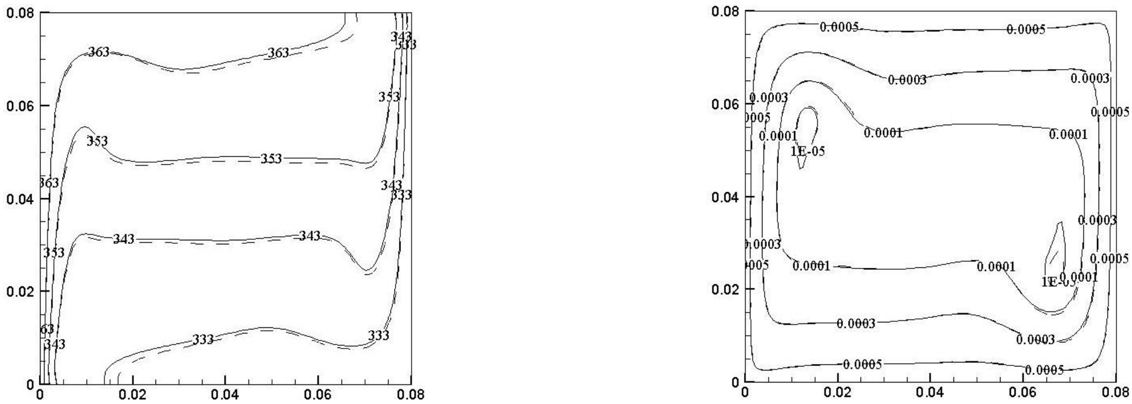
0.0001
1E-05

(b)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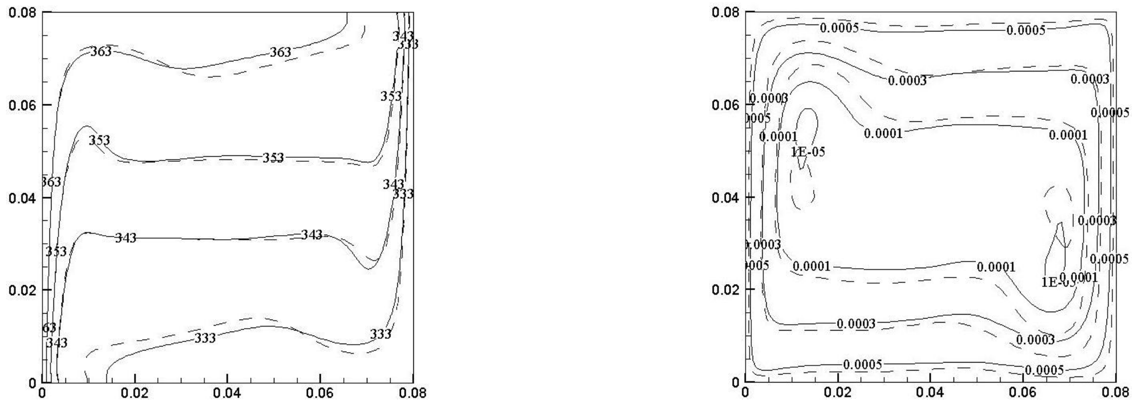
(c)

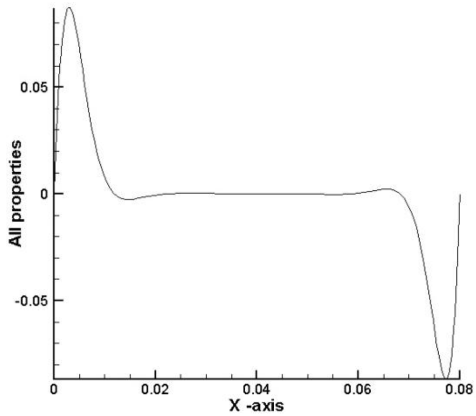


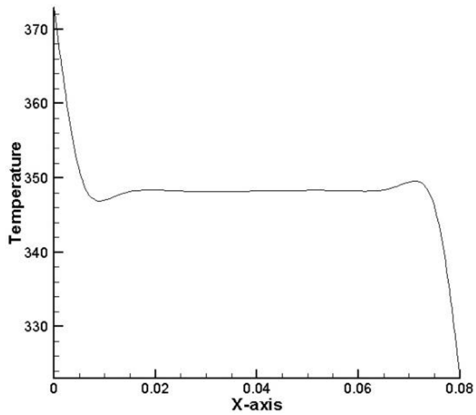
(d)

Fig 4.2.4 Combined effect of varying properties on Isotherm pattern and flow pattern for Ra=10^{6}. (a) Thermal conductivity and viscosity (b) density and viscosity (c) Thermal conductivity and viscosity (d) density, thermal conductivity and viscosity

Table 4.2.4 Combined effect of varying properties on Nusselt number

Varying properties	Ra	Nu	
		Piecewise linear	Polynomial
k , ρ	10^4	2.523484	2.52925
	10^5	4.76552	4.774166
	10^6	8.692294	8.705205
ρ, μ	10^4	2.684873	2.69107
	10^5	5.06445	5.073386
	10^6	9.228832	9.241427
k, μ	10^4	2.060268	2.059778
	10^5	4.265834	4.264918
	10^6	8.366097	8.364594
k , ρ, μ	10^4	2.52509	2.530543
	10^5	4.767239	4.775087
	10^6	8.693941	8.705383



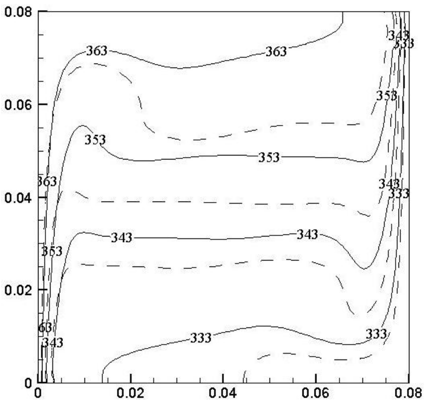


(a) Ra=10^6 (b)

Fig 4.2.5 (a) Midplane velocity for all properties variable (b) Midplane temperature for all property variable

4.3 Effect of Slip Boundary condition

In this section the effect of slip boundary condition i.e. left, right, top, bottom and altogether has been explained through variation in Nusselt number and both isotherm pattern and flow pattern Fig 4.3 The flow features presented through isotherm pattern and flow pattern is meant for Ra=10^6. It is observed from table 4.3 that the effect of slip boundary condition on active walls influence the phenomena and hence the Nusselt number. The combined effect of slip boundary condition on all walls leads to max. heat transfer between active walls. At low Rayleigh number effect of slip on active walls, less variation is seen and thus results increase in Nusselt number by 6%.(comparing Table 4.1 table and Table 4.3.). However at higher Rayleigh number, have pronounced effect and is more influential than variable properties hence the Nusselt number increases by 22%. When we consider for all wall slip, the fluid particles is not obstructed by boundary walls and heat from hot wall is delivered to cold wall leading to max. heat transfer rate, hence increase in Nusselt number by 67%.



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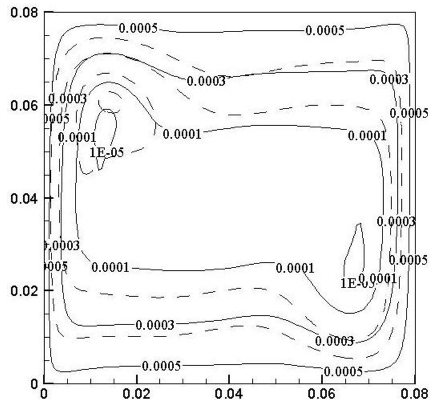
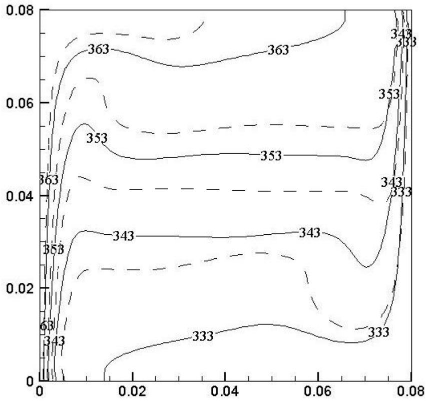
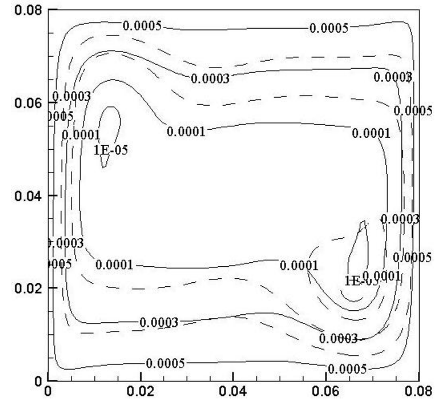


(a) (b)

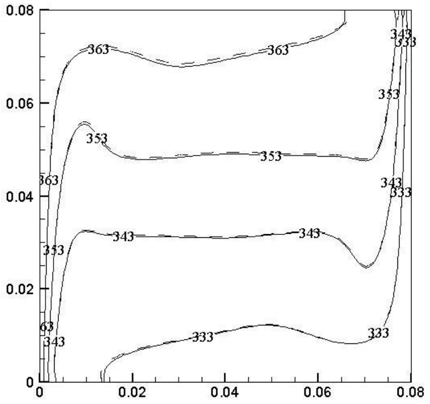


Right

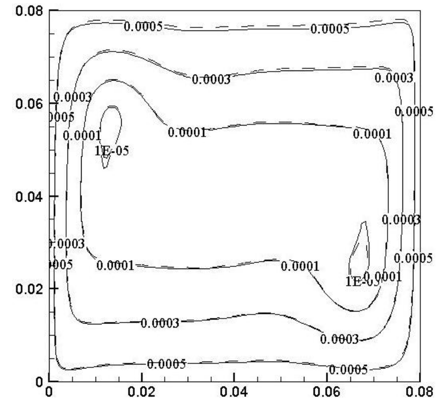


(c)

(d)

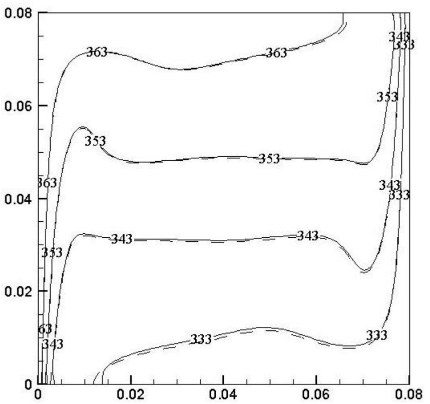


Top

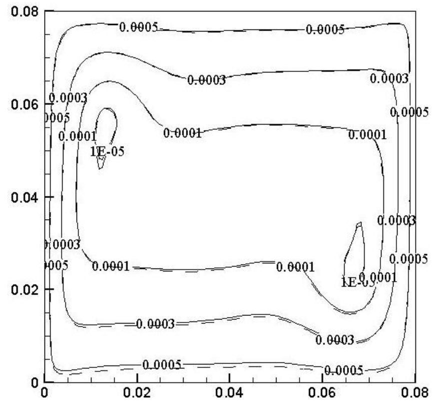


(e)

(f)

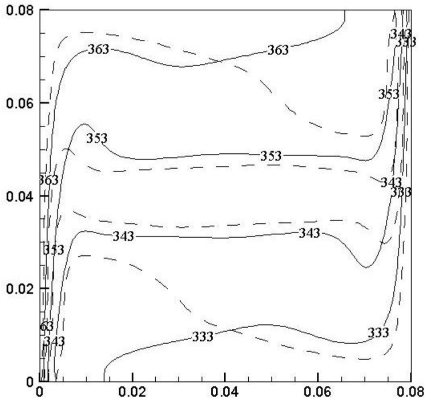


Bottom

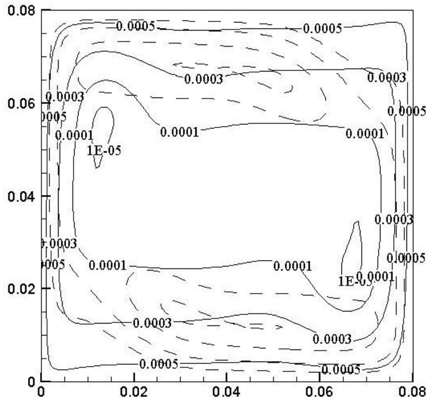


(g)

(h)



All Wall Slip



(i) (j)

Fig 4.3 Isotherms and streamlines for left, right, top and bottom and all wall slip for Ra=10^6.

Table 4.3 Effect of slip on Nusselt number

Slip boundary condition at	Ra	Nu
Left wall	10^4	2.324
	10^5	5.066
	10^6	10.846
Right wall	10^4	2.322
	10^5	5.073
	10^6	10.871
Top wall	10^4	2.197
	10^5	4.552
	10^6	8.876
Bottom wall	10^4	2.196
	10^5	4.551
	10^6	8.870
All walls	10^4	2.813
	10^5	6.687
	10^6	14.808

CHAPTER- 5

CONCLUSIONS AND FUTURE WORK

5.1 Conclusions

CFD analysis of natural convection is done using varying properties and varying boundary conditions. From the analysis following conclusions are made.

- Nusselt number decreases because of varying effect of thermal conductivity compared to constant value of thermal conductivity.
- Nusselt number is independent of varying effect of viscosity
- Effect of variation in density is quite influential, which prohibits the assumption of constant density in the governing equations.
- Constant property assumption for higher Rayleigh number fairly holds good.

- Heat transfer rate increases with slip boundary condition
- Increase in Nusselt number is more pronounced at higher Rayleigh number with slip boundary condition
- Assumption of slip boundary condition at active isothermal walls yields higher heat transfer compared to same slip boundary condition at insulated walls.

5.2 Future study

As the effect of slip is influential and crucial under certain situations, therefore, it gives room for the study of effects of slip along with temperature jump condition for different domains and Rayleigh number.

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