VISVESVARAYA TECHNOLOGICAL UNIVERSITY

JNANA SANGAMA BELAGAVI-590018

A Project Report on

STUDY OF HEAT AND FLUID FLOW THROUGH POROUS CAVITY

Submitted in partial fulfilment of the requirement of Seventh Semester

BACHELOR OF ENGINEERING

IN

MECHANICAL ENGINEERING

Submitted by

DEVANSHU PANDEY	**1BI21ME016**
PRAJWAL KUMAR	**1BI21ME039**
RAHUL	**1BI21ME046**
UDAY KUMAR	**1BI22ME494**

Under the Guidance

Dr. HONNE GOWDA

Assistant Professor

Department of Mechanical Engineering

Bangalore Institute of Technology Bangalore-560004

DEPARTMENT OF MECHANICAL ENGINEERING
BANGALORE INSTITUTE OF TECHNOLOGY
K.R.ROAD, V.V.PURA BANGALORE -560004, KARNATAKA, INDIA
2024-2025

DEPARTMENT OF MECHANICAL ENGINEERING
BANGALORE INSTITUTE OF TECHNOLOGY
K.R.ROAD, V.V.PURA BANGALORE -560004, KARNATAKA, INDIA

CERTIFICATE

Certified that the project work entitled **STUDY OF HEAT AND FLUID FLOW THROUGH POROUS CAVITY** is a bonafide work carried out by, **DEVANSHU PANDEY(1BI21ME016), PRAJWAL KUMAR(1BI21ME039), RAHUL(1BI21ME046), UDAY KUMAR(1BI22ME494),** the Bonafide students of Bangalore institute of technology in partial fulfillment for the award of 7th semester of Bachelor of Engineering in Mechanical Engineering of Visvesvaraya Technological University, Belagavi during the year 2024-2025. It is certified that all the corrections/suggestions indicated for the internal assessment have been incorporated in the report. The Project has been approved as it is satisfied the academic requirement in respect of project prescribed for the Bachelor of Engineering Degree in mechanical Engineering.

Signature of Guide
Dr. HONNEGOWDA,
Assistant Professor,
Department of Mechanical Engineering,
BIT, Bengaluru-560004

Signature of HOD
Dr. ASWATHA,
Professor and Head,
Department of Mechanical Engineering,
BIT, Bengaluru-560004

Signature of Principal
Dr. ASWATH M U,
Principal,
Bangalore institute of Technology,
Bengaluru-560004

Name of the Examiners: Signature:

i.

ii.

DECLARATION

We, **Mr. DEVANSHU PANDEY**, bearing the University Seat Number **1BI21ME016**, **Mr. PRAJWAL KUMAR**, bearing the University Seat Number **1BI21ME039**, **Mr. RAHUL**, bearing the University Seat Number **1BI21ME046**, **Mr. UDAY KUMAR**, bearing the University Seat Number **1BI22ME494**, of VII Semester B. E in Mechanical Engineering, Bangalore Institute of Technology, Bangalore do hereby declare that the work being presented in this Project Work entitled **STUDY OF HEAT AND FLUID FLOW THROUGH A POROUS CAVITY**, is an authentic record of the work that has been carried out independently by us during our VII Semester B. E in Mechanical Engineering at Bangalore Institute of Technology, Bangalore, under the supervision of our guide, **Dr. HONNE GOWDA**, Assistant Professor, Department of Mechanical Engineering, Bangalore Institute of Technology, Bangalore. The work contained in this report has not been submitted in part or full to any other university or institution or professional body for the award of any degree or diploma or any fellowship.

Date: 04/02/2025

Place: Bengaluru

NAME	**USN**	**SIGNATURE**
DEVANSHU PANDEY	**1BI21ME016**	
PRAJWAL KUMAR	**1BI21ME039**	
RAHUL	**1BI21ME046**	
UDAY KUMAR	**1BI22ME494**	

ACKNOWLEDGEMENT

The satisfaction and euphoria that accompany the successful completion of any task would be incomplete without the mention of the people who are responsible in completion of the project because its epitome of hard work, perseverance, undeterred missionary zeal, steadfast determination. So, with gratitude we acknowledge all those whose guidance and encouragement served as “Beacon Light” and crowned our efforts with success.

We have taken this opportunity to express gratitude to our project guide **Dr. HONNE GOWDA**, Assistant Professor, Department of Mechanical Engineering, Bangalore Institute of Technology, Bangalore for providing all help and guidance needed for the successful completion of the final year project.

We would like to thank, **Dr. ASWATHA**, Professor and Head, Department of Mechanical Engineering, Bangalore Institute of Technology, Bengaluru for his help and guidance throughout our academic career.

We would like to thank, **Dr. ASWATH M U**, Principal Bangalore Institute of Technology, Bengaluru for his continued support towards successful completion of the course.

There have been a lot of hardships and dead ends that we faced while carrying out the work therefore special thanks to coordinator, **Mr. V C RAVI**, Assistant Professor, Dept. of Mechanical Engineering, has come to our aid and has shown me how to proceed further. I am very grateful to him for the time and patience he has given me.

We also extend our sincere thanks to all faculty members of Department of Mechanical Engineering, BIT, Bengaluru who have encouraged us throughout the course.

1. **DEVANSHU PANDEY** **1BI21ME016**
2. **PRAJWAL KUMAR** **1BI21ME039**
3. **RAHUL** **1BI21ME046**
4. **UDAYKUMAR** **1BI22ME494**

ABSTRACT

This study explores the behavior of heat and fluid flow within a porous cavity, emphasizing the effects of natural convection and different boundary conditions. The research uses numerical simulations and the Finite Element Method (FEM) to analyze how temperature changes and fluid movement interact within the cavity. Key parameters such as the Rayleigh number, boundary heating conditions, and cavity geometry are varied to understand their influence on heat transfer efficiency and flow patterns. The results indicate that as the Rayleigh number increases, convective heat transfer becomes stronger, leading to enhanced thermal circulation. Different heating configurations, including uniform and non-uniform heating of walls, significantly impact fluid motion and temperature distribution. The study also highlights how thermal insulation and cavity design affect energy efficiency. These findings provide valuable insights for optimizing thermal management in engineering applications, such as cooling systems, heat exchangers, and energy storage devices. This research contributes to improving the design of systems that use porous materials to enhance heat dissipation and overall efficiency.

TABLE OF CONTENTS

TABLE OF FIGURES

Chapter - 1

INTRODUCTION

1.1 Importance of Free Convection

Fluid flow and heat transfer analysis in uniformly and non-uniformly heated porous media has become a separate topic for research in last three decades in view of its importance in various applications such as power plant waste in nuclear power plants, fiber insulations solar collectors etc.

The interest in the study of different aspects of porous medium has increased to many folds in recent decades. This immense amount of interest has resulted into myriad research papers addressing the wide range of problems involving porous medium such as understanding of structure of porous medium, deformation of porous medium, natural convective heat transfer etc. The study of porous medium is one of the classical subjects in science. There are various definitions of porous medium but, it can be defined in simple terms as a medium which allows the fluid to flow through itself.

Our aim in this study is to investigate the effect on natural convection in porous cavity in different Rayleigh number.

Natural convection flow caused by buoyancy are classified in to two; internal flows and external flows. Free convection analysis involves simultaneous solution of flow and temperature fields.

Typically, a porous medium we mean a material consisting of a solid matrix with an inter connected void. We suppose that the solid matrix is either rigid (which is the usual situation) or it undergoes small deformation. The interconnectedness of the void (the pores) allows the flow of one or more fluids through the material. In the simplest situation (“single phase flow”) the void is saturated by a single fluid. In a two-phase flow gas and a liquid share the same void space. The porosity φ of a porous medium is defined as the fraction of the total volume of the medium that is occupied by void space.

$$\varphi = \frac{V_V}{V_T}$$

V_V is the volume of void-space (such as fluids) and V_T is the total or bulk volume of material, including the solid and void components. In defining φ in this way we are assuming that all the void space is connected. If in fact one has to deal with a medium in which some of the pore space is disconnected from the remainder, then we have to introduce an “effective porosity”, defined as the ratio of connected void to total volume. For natural media, φ does not normally exceed 0.6. For man-made materials such as metallic foams φ can approach the value 1.

Natural convection in porous media has wide applicability in various natural and industrial processes e.g. fluid flow in geothermal reservoirs, dispersion of chemical contaminants through water saturated soil, petroleum extraction, migration of moisture in grain storage systems, building thermal insulations, catalytic reactions for this reason, this mode of heat transfer has been extensively studied experimentally as well as analytically and numerically for different flow aspects. Porous media is used mainly,

- As its dissipation area is greater than the conventional fins that enhances more heat convection.
- The irregular motion of the fluid flow around the individual pores mixes the fluid more effectively.

In a natural porous medium the distribution of pores with respect to shape and size is irregular. On the pore scale (microscopic scale) the flow quantities (velocity, pressure etc.) will be clearly irregular. But in typical experiments the quantities of interest are measured over areas that cross many pores, and such space-averaged (macroscopic) quantities change is a regular manner with respect to space and time, and hence are amenable to theoretical treatment. How we treat a flow through a porous structure is largely a question of distance, which is the distance between the problem solver and the actual flow structure. When the distance is short, the observer sees only one or two channels, or one or two open or closed cavities. In this case it is possible to use the conventional fluid mechanics and convective heat transfer to describe what happens at every point of fluid and solid-filled spaces. When the distance is large so that there are many channels and cavities in the problem solver’s field of vision, the complications of the flow paths rule out the conventional approach. In this limit, volume-averaging and global-measurements (ex: permeability, conductivity) are useful in describing the flow in simplifying the description. As engineers focus more and more in designed porous media at decreasing pore scales, the problems tend to fall between the extremes noted above. In this intermediate range, the challenge is not only to describe coarse porous structures, but also to optimize flow elements and to assemble them. The resulting flow structures are designed porous media. The usual way of deriving the laws governing the macroscopic variables is to begin with the standard equations obeyed by the fluid and to obtain the macroscopic equations by averaging over volumes or areas containing many pores.

1.2 Applications of porous medium

Porous medium is involved in numerous applications covering a large number of engineering disciplines. Some of these applications are:

1. Combustion processes
2. Heat exchanger applications
3. Solar energy collectors
4. Refrigerators and recuperators
5. Insulation of buildings and other mechanical devices etc.
6. Packed and circulating bed combustors and reactors.
7. Energy storage and conversion methods
8. Containment transport in groundwater and exploitation of geothermal resources.
9. Drying problems such as vegetable, grains, ceramic, wood, brick etc.
10. Flow through different organs of animal body for example lungs.
11. Problem involving nuclear energy such as heat removal from packed bed nuclear reactors, multi shield structures used in the insulation of nuclear reactors, nuclear waste disposal etc.
12. Seepage of water through river bed.
13. Migration of pollutants into the soil and aquifer.
14. Study to know the solidification of alloys.
15. Heat transfer and fluid flow in bio-digesters.
16. Chemical reactors and petroleum recovery processes catalytic reactors etc.
17. Flow of moisture through porous insulating materials.

Porous media approach is becoming popular in approximating the flow behavior in many other phenomena such as flow through turbo machinery and liquid metal flow in alloy casting etc. Understanding of heat and fluid flow behavior in the porous medium will help to design the system in a better way so as to increase the efficiency of systems involving porous medium

1.3. Mathematical modeling and simulation study

As in other fields, the study of various problems related to porous media can either be carried out by experimental setup or by mathematical modeling and simulations. The mathematical modeling and thus simulation study have many advantages over experimental study. For instance, the experimental setup requires a huge amount of investment which many times becomes a deciding factor whether to carry out the study or abandon it. As far as the time is concerned, the experimental study requires an epoch. Contrary to experimental study, the time required for simulation study is substantially low. The great thing about simulation is that it compresses the time and thus allows investigating the different operational conditions and answers the many "what if" scenarios which otherwise becomes impossible in experimental study for various reasons. Simulation study also avoids the need of human being exposed to various hazardous environments, which are part and parcel of experimental study.

1.4 Heat transfer in porous medium

The phenomenon of natural convection in an enclosure is as varied as the geometry and orientation of the enclosure. Judging from the number of potential engineering applications, the enclosure phenomena can be organized into two classes:

(1) Enclosures heated from the side.

(2) Enclosures heated from below.

The fundamental difference between enclosures heated from the side and enclosures heated from below is that in enclosures heated from the side, a buoyancy-driven flow is present as soon as a very small temperature difference (T_h-T_c) is imposed between the two sidewalls. By contrast, in enclosures heated from below, the imposed temperature difference must exceed a finite critical value before the first signs of fluid motion and convective heat transfer are detected. In this study, heat transfer by natural convection across porous media- filled enclosure is considered. In such flow, in porous media there is a buoyancy-driven flow which is entirely enclosed by a solid wall along which differential heating is applied, the resulting temperature difference leading to the generation of buoyancy force which causes the flow. We find enclosures heated from the side in the cooling systems of industrial-scale rotating electric machinery. Enclosures heated from below refer to the functioning of thermal insulations oriented horizontally, for example, the heat transfer through a flat-roof attic space. The study of both flow classes is also relevant to our understanding of natural circulation in the atmosphere, the hydrosphere, and the molten core of the earth.

The characteristics of heat transfer through a horizontal enclosure depend on whether the hotter plate is at the top or at the bottom. When the hotter plate is at the top, no convection currents will develop in the enclosure, since the lighter fluid will always be on top of the heavier fluid. Heat transfer in this case will be by pure conduction, and we will have Nusselt number equal to 1. When the hotter plate is at the bottom, the heavier fluid will be on top of the lighter fluid, and there will be a tendency for the lighter fluid to topple the heavier fluid and rise to the top, where it will come in contact with the cooler plate and cool down. Until that happens, however, the heat transfer is still by pure conduction and Nu=1.

1.4.1 Radiation

Radiation heat transfer in the porous media plays an important role when natural convection is relatively small. The keen observation through the available literature reveals that the radiation heat transfer has received little attention as compared to natural convection heat transfer. One reason for this can be understood in a way that the inclusion of radiation term in the governing energy equation of the porous medium increases the complexity of partial differential equations. But when we look at the realistic aspects of heat transfer, then one can find that there are various applications wherein radiation heat transfer takes place and thus cannot be ignored. For instance, the combustion processes, high temperature heat exchangers, solar energy collectors, the radiative drying of papers and other porous materials, manufacturing systems that use laser to melt the powder etc. In these and many such applications, the porous medium either absorbs or emits the radiant energy. Therefore, it is of great importance to study the heat transfer behavior in the porous medium bounded by different geometries and thus predict the influence of natural convection and radiation heat transfer. Thus, the effect of radiation heat transfer is investigated in this study.

1.4.2 Partially Divided Enclosures

Real-life systems such as buildings, lakes, and solar collectors rarely conform to the single-enclosure model used in much of the natural convection literature. A very basic model for the study of natural convection in such systems is the association of two enclosures communicating laterally through a doorway, window, or corridor or over an incomplete dividing wall. The new flow feature caused by the presence of a vertical obstacle inside the cavity is the trapping of the fluid on one side of the obstacle. For example, if the partial wall is mounted on the floor of the cavity, the fluid on the cold side of the obstacle becomes trapped and inactive with respect to convection heat transport. Relative to convection in a box without internal flow obstructions, where the flow fills the entire cavity, the presence of sizable pools of inactive fluid has a significant effect on the overall heat transfer rate between the far ends of the cavity. The partition is a control parameter for flow field and temperature distribution. Number of eddies is an independent parameter from all effective parameters. However, their turns or changes in their rotation depend on the parameters.

1.4.3 Thermal Management in Electronic Cooling

Natural convection cooling of components attached to printed circuit boards, which are placed vertically and horizontally in an enclosure, is currently of great interest to the microelectronics industry. Natural convection cooling is desirable because it doesn't require energy source (such as a forced air fan) and it is maintenance free and safe. Microelectronic systems can take several forms, ranging from the large cabinets found in mainframe computers or telecommunications equipment which contains several shelves of circuit boards to small personal computers with a single board and optional plug-in expansion cards. Common to each of these systems is a need-to-know fluid temperatures and velocities as well as maximum board temperatures in order to accurately determine 'hot spots' on the circuit boards which could lead to reliability problems. Modern telecommunications equipment is often designed using a modular approach, implementing natural convection cooling in place of its noisier and more costly forced convection counterpart. In a system module, typically contain 2 - 10 printed circuit cards suspended parallel to one another, thereby creating vertical channels cooled via buoyancy induced flow. In order to impede electro-magnetic interference between the module and other equipment, perforated metal screens are positioned at the fluid inlet and exit points.

1.5 Numerical Methods

Numerical methods like FEM are based on discretization of integral form of equation. Basic theme of all numerical methods is to make calculations at only limited number of points and interpolate the results for entire domain (surface or volume). Even before getting the solution, we assume how the unknown is going to vary over a domain. Say for example, when meshing is carried out using linear quadrilateral elements, assumptions made is linear variation of displacement over the domain and for 8-noded quadrilateral element, assumptions made is parabolic variation. This may or may not be case in real life and hence all numerical methods are based on an initial hypothetical assumption. After getting the results there are several ways to check numerical as well as practical of field result correlation accuracy and minimization of errors. The following numerical methods are generally used for solving engineering problems:

1. Finite difference method

2. Finite element method

3. Control volume or finite volume method

4. Boundary element method

Finite difference scheme expresses the derivatives of the governing differential equation, in terms of the variables at the selected grid points using truncated Taylor series expansion. The computational domain is filled up with number of grids and grid points selected at the center of the corresponding grids. Finite difference scheme has the following disadvantages.

a) Specification of boundary conditions for irregular geometries

b) Incorporation of complex material properties

Finite element method is a popular computer aided numerical method based on the discretization of the domain, structure or continuum into number of elements and obtaining the solution.

Control volume analysis or finite volume method formulates the discretized equations at each grid point of the domain by integrating the terms of the differential equations over the control volume and assuming the variation of the unknown variable between grid points. This method is mainly used for fluid flow problems.

Boundary element method is based on the boundary integral equation formulation of the problem. It needs only a boundary discretization in contrast to domain methods. This method has not become popular compared to finite difference, finite element and control volume formulations.

1.5.1 FINITE ELEMENT METHOD (FEM):

Finite element method is a numerical technique for finding approximate solutions to boundary value problems. It uses variational methods to minimize an error function and produce a stable solution. Analogous to the idea that connecting many tiny straight lines can approximately create a larger circle, FEM encompasses all the methods for connecting many simple element equations over many small sub domains, named finite elements, to approximate a more complex equation over a larger domain

The method originated from the need to solve complex elasticity and structural analysis problems in civil and aeronautical engineering.

The basis of the finite element method is summarized below:

- Subdivide the structure into small finite elements.
- Each element is defined by a finite number of node points.
- Assemble all elements to form the entire structure.
- Formulation of Governing equations.
- General solution for all elements results in algebraic set of simultaneous equations.

1. Subdivide the structure into small finite elements: In this step the continuum is divided into several finite elements with each element represented by a set of equations by the original problem.

2. Each element is defined by a finite number of node points: In this step each element is represented by nodes which are the points where different boundary conditions arise and are used to apply them in the equations obtained.

3. Assemble all elements to form the entire structure: In this step all the separated elements after analyzing them for the individual boundary conditions and loads acting on them are assembled to form the original structure.
4. Formulation of Governing equations: After assembling the elements, the individual values obtained in the elements are applied to obtain a set of governing equations which on solving them will give the approximate behavior of that element under that load and boundary condition.
5. General solution for all elements: Now after obtaining the individual behavior of the elements, just as how the elements are assembled the governing equations are also added to obtain the overall behavior of the structure or continuum.

Advantages of FEM:

- Irregular shaped bodies can be modeled easily.
- Several loading conditions can be handled easily.
- Bodies composed of different materials can be modeled.
- Unlimited number of boundary conditions can be handled.
- Unlimited types of boundary conditions can be handled.
- Element size can be varied.
- Finite element model can be altered easily.
- Non-linear behavior can be handled.
- The basic procedure of FEM is that a system of matrix equation governing the behavior can be formed automatically and solved efficiently irrespective of the complexities of practical design condition.
- The mathematics of FEM is simple & understandable and procedure is easy to use.
- Successful application of FEM in practice depends on availability of general-purpose FEA software implemented on digital computer.

1.6 Closure

In the present chapter, the importance of natural convection in porous medium and its applications are observed. Further FEM technique and its applications are discussed. In the present research, an attempt is made to model natural convection of porous medium in a trapezoidal cavity with the help of MATLAB programming. The heat transfer results obtained by simulation from the code are then compared with results already published in the literature. The details of these are discussed in the further chapters. The organization of the entire thesis is depicted below.

1.7 Organization of Thesis

The present thesis is structured into five chapters, viz.,

1. Introduction,
2. Literature review,
3. Numerical investigation
4. Results and discussions
5. Conclusions and Scope for future work.

The work is supported by 20 referred references selected from international journals and conferences.

Chapter - 1 gives a brief background and the relevant importance of heat transfer in porous medium. the different boundary conditions. Importance of cavities subjected to different boundary conditions in industrial applications, science and technology have been discussed in this chapter. This chapter concludes with the types of boundary conditions

In Chapter - 2, a thorough literature review has been carried out by referring to related numerical research work of international caliber. The literature review has been organized to highlight the effect of various identified parameters on the flow and heat transfer characteristics of cavities. The discussions on the current developments, the gap in literature and the need for current investigation have been highlighted. Based on these observations, aim and objectives have been derived.

In Chapter - 3, deals with verifying the present methodology. The present methodology is verified in terms of temperature contours, stream functions, heat lines , local and average Nusselt number. The above parameters are investigated using the present methodology and is found to be in good agreement with those available in the current literature.

Chapter - 4, deals with the numerical investigations to analyze the flow and heat transfer characteristics in cavities during the course of the present research. It highlights the influence of different types of boundary conditions, different types of variations of boundary conditions, Rayleigh numbers on the flow and heat transfer characteristics in cavities.

In Chapter - 5, the summary and conclusions of the present work and scope for future work are presented. This is followed by references.

CHAPTER - 2

LITERATURE REVIEW

2.1 Introduction

As stated earlier, the study of heat and fluid flow in a saturated porous media is one of those subjects in which research has been going on for 150 years. This chapter is aimed at providing some of the related information regarding the research being carried out pertaining to heat transfer in porous media by different researchers across the globe.

It is noteworthy to start the literature review with the work of Henry Darcy whose research is considered to be milestone in this field. Darcy conducted experiments in France to understand more about water filtering. He used silica sand as the filtering media for experimental purpose. His experimental setup was comprised of a simple vertical column where he could measure the flow rate of water and pressure difference in the vertical column. The experimental results were presented in terms of water flow rate and the pressure difference across the silica sand. Based on these experimental results Darcy proposed a relation that relates the flow rate with the pressure difference, length of the porous media, cross sectional area and a constant. Darcy's relation has been used extensively since its emergence, to predict the flow characteristics in the porous medium. The monograph on convection in porous media by Nield and Bejan [1] provides elaborate exposition of research in natural convection configuration for several decades.

Due to its numerous uses in the fields of design and operation of solar collectors, micro channels, agriculture, geothermal energy, medicine, and biological sciences, buoyant flow in porous media has attracted a lot of attention. Examples include managing radioactive waste, storing grains, ground water contamination, food technology, and specific biological materials. [2-3]. within a rectangular, permeable enclosure, buoyant energy was quantitatively examined by Prasad and Kulacki [4]. Their findings show that raising the aspect ratio causes the heat transfer rate to increase. In a cavity filled with a non -Darcian porous media, natural convection is examined statistically by Beckerman et al. [5]. Brinkman
-Extended Darcy Equations are used to represent the flow, and the importance of non- Darcian effects is shown. There are several different Rayleigh numbers and aspect ratios. Bilgen et al [6] investigated free convection in a cavity filled with uniformly heat-

generating, saturated porous media and concluded energy transfer is more uniform heating case.

Saied [7] conducted a computational analysis of buoyant flow with maximum density in a porous cavity filled with water and subjected to sinusoidal temperature boundary conditions and found that heat transfer rate is less compare to linear temperature boundary conditions. In a porous chamber, the effect of different positioning of heating on natural convection was mathematically studied by Saied and Pop [8] and concluded that the flow and heat transfer properties are significantly influenced by the discrete heater's position.

2.2 Heat transfer in porous cavities.

In the following pages a concise review of research carried out with respect to the heat transfer in porous cavities is presented. In this type of geometry, the porous medium is completely confined inside a close chamber having solid boundaries. This situation arises in some of the building insulation, geothermal and oil extraction applications etc. Bayats and Pop [9] have analyzed the free convection in an oblique enclosure filled with porous medium. Their results suggest that at sharp corners of the cavities, the flow breaks down into series of vertices and the sub vertices system grown in size with increased Rayleigh number and the inclination angle.

2.2.1 Square cavity

Natural convection flows in a square cavity filled with porous matrix has been studied numerically using penalty finite element method for uniformly and non-uniformly heated bottom wall, and adiabatic top wall maintaining constant temperature of cold vertical walls by Tanmay Basak [10].

The numerical results are presented in terms of stream functions, temperature profiles and Nusselt numbers. Non-uniform heating of the bottom wall produces greater heat transfer rate at the center of the bottom wall than uniform heating case for all Rayleigh numbers but average Nusselt numbers shows overall lower heat transfer rate for non- uniform heating case. For convection dominated regimes the power law correlation between average Nusselt number and Rayleigh numbers are presented. Revnic et al. [11] studied the steady free convection flow in a square enclosure filled with a bidisperse porous medium (BDPM).

M. Sathiyamoorthy et.al [12] have published the study regarding steady natural convection flows in a square cavity with linearly heated side walls. This numerical study deals with natural convection flow in a closed square cavity when the bottom wall is uniformly heated and vertical walls are linearly heated whereas the top wall is well insulated. Non-linear coupled PDEs governing the flow have been solved by penalty finite element method with bi-quadratic rectangular elements. Results are presented in the form of streamlines, isotherm contours, local Nusselt number and the average Nusselt as a function of Rayleigh number. K. Al-Farhany [13] studied numerically the steady conjugate double- diffusive natural convective heat and mass transfer in a two-dimensional variable porosity layer sandwiched between two walls. A finite volume approach has been used to solve the dimensionless governing equations. The model has been validated with the available experimental, analytical/computational studies. Prasanth Anand et al [14] numerically investigated fluid flow and thermal characteristics associated with natural convection heat transfer in a porous enclosure containing high temperature heat sources placed on top and bottom walls of a square cavity. The effect of heat sources on flow pattern, entropy generation and temperature distribution are studied for different Darcy numbers, porosities and Rayleigh numbers. Mathematical simulation of unsteady natural convection modes in a square cavity filled with a porous medium having finite thickness heat-conducting walls with local heat source in conditions of heterogeneous heat exchange has been carried out [15]. The influence scales of the defining parameters on the average Nusselt number have been detected. Nield et al [16] investigated the onset of convective instabilities in a porous layer with a horizontal basic flow by including the effects of viscous dissipation and pressure work in the energy balance. Extended Oberbeck-Boussinesq approximation i.e., the model based on the enthalpy formulation of the energy balance is adapted

2.2.2 Other enclosures – Triangle or Rectangle

Yasin Varol et. al. [17] investigated natural convection heat transfer in a porous media filled and non-isothermally heated from the bottom wall of a triangular enclosure is analyzed using finite difference technique. Darcy law was used to write equations of porous media. Dimensionless heat function was used to visualize the heat transport due to buoyancy forces. Three different boundary conditions were applied for the vertical and inclined boundaries of triangular enclosures as i) both vertical and inclined walls were isothermal, ii) vertical wall was adiabatic and inclined one was isothermal, iii) vertical wall was isothermal and inclined wall one is adiabatic. The study was performed for different aspect ratios ($0.25<Ar<1.0$) and Darcy modified Rayleigh numbers ($100<Ra<1000$). It was observed that heat transfer enhancement was performed when vertical and inclined walls were isothermal while bottom wall was at non-uniform temperature. Heat transfer from bottom wall did not vary when the value of aspect ratio was higher than 0.5.

Turbulent natural convection in a rectangular enclosure having finite thickness heat conducting walls at local heating at the bottom of the cavity provided that the convective radiative heat exchange with an environment on one of the external borders have been numerically studied by Tanmay Basak [18]. The special attention was paid to the effects of Grashoff number $10^8<Gr<10^{10}$, the transient factor $0< \tau <1000$ and the thermal conductivity ratio. Detailed results including streamlines, temperature profiles and correlations for the average Nusselt number in terms of Grashoff number have been obtained.

Genizy et.al [19] simulated numerically turbulent natural convection in a rectangular enclosure having finite wall thickness. Mathematical simulation has been carried out in terms of dimensionless Reynold's averaged Navier-Stokes (RANS) equations in stream function-vorticity formulations. The formulation comprises the standard two equations k-€ turbulence model with wall functions along with Boussinesq approximation. Pakdee.W et al [20] studied unsteady effects on natural convective heat transfer through porous media in a rectangular cavity due to top surface partial convection. The formulation of differential equations is non-dimensionalized and then solved numerically under appropriate initial and boundary conditions using the finite difference method. Unsteady effects of associated parameters were examined. It was found that the heat transfer coefficient, Rayleigh number and Darcy number considerably influenced characteristics of flow and heat transfer mechanisms. Aniruddha et al [21] studied numerically two-dimensional natural convection in fluid-superposed porous layer heated locally from below. The effects of five-dimensional parameters on overall Nusselt number are investigated. Nusselt number increase with a decrease in heater length and height ratio and increase with Darcy number.

2.2.3 Bottom Wall / Side Wall Heating

Kirkpatrick and Bohn [22] conducted an experiment to study the natural convection in a cubical (AR = 1) enclosure of differentially heated and cooled vertical and horizontal surfaces at high Rayleigh numbers. In their study all the experiments were variations of the heating from below case. The results reported in this study indicated that the heated floor promoted mixing in the enclosure and reduced the thermal stratification. Also it showed that for the boundary conditions of the experiment, the heat transfer from the horizontal surfaces was not strongly affected by the presence of a horizontal temperature gradient. It is seen that the variations of heating conditions and aspect ratio have not been discussed.

2.3 Motivation for the Present Study and the Objectives

Although natural convection of porous media in cavities is studied in the past, the open literature available on non-uniform temperature boundary condition is limited to temperature cases only. Also, the correlations between the average Nusselt numbers versus Rayleigh number required to design an effective heat transfer cabinets are very much limited in the current literature. Thus, in the present study, cavity considered for study is of regular shape. This type of geometry finds application in Compact Linear Fresnel Reflectors and for heat storage underground. Computations have been performed to analyze the flow and heat transfer for sinusoidal and linear variation of temperature for Rayleigh number ranging from 100 to 500. All these aspects motivated the present investigation.

Thus, the aim of the present study is to numerically investigate the flow and heat transfer characteristics of a regular cavity for varied boundary conditions.

The objectives of the present research work are as follows;

- Selection of geometry and boundary conditions.
- To formulate the problem with governing equations of fluid flow and heat transfer.
- To set up numerical procedure to solve the defined problem of fluid flow and heat transfer in enclosed cavities.
- To validate the numerical procedure against available numerical results.
- To carryout parametric studies with various types of boundary conditions and to suggest suitable correlations.

2.4 Closure

The numerous publications on natural convection of porous media in cavities reported in the literature is taken into consideration and the objectives of the present work are laid in the literature review. It is observed that very few researchers have carried out heat transfer investigations in cavities with Rayleigh number up to 500 with non-constant boundary conditions at the bottom wall. Thus, the aim of the present research is laid down. In the present work, investigations will be carried out for left side wall subjected to linearly varying temperature boundary conditions. In convection dominated regions, correlations between average Nusselt number and Rayleigh number are presented for non-uniform temperature and heat flux boundary conditions

CHAPTER - 3

NUMERICAL INVESTIGATIONS

3.1 Introduction

The better understanding of temperature distribution, magnitude and location of concentration of stream function cells, heat energy transport, identification of the location of maximum and minimum values of local Nusselt number and averaged value of Nusselt number for different thermal boundary conditions on natural convection in cavities needs extensive study. Hence, it is felt that the study of these parameters available in the form of numerical results in the literature is very useful to validate the present methodology. It is seen that the transition from conduction to convection for a discrete heat source does not occur at a specific value of the Rayleigh number instead, within a range of values.

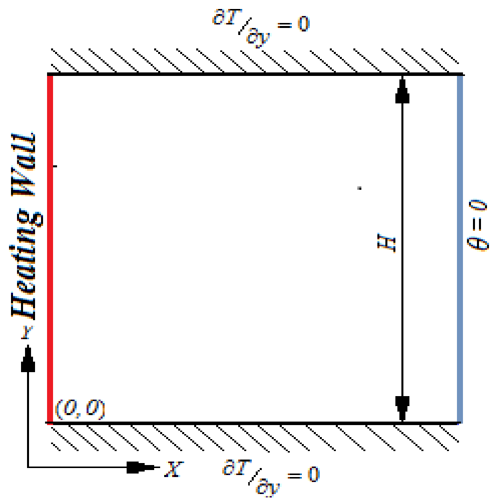


Fig 3.1. Schematic diagram of physical model

A Physical system as illustrated in Fig. 3.1 is used in the present study for simulating natural convective flow and heat transfer characteristics. The cavity of length (L) and height (H) has a side wall with hot constant / linearly varying/ sinusoidal temperatures, top and bottom walls are adiabatic and the right-side wall is at constant temperature T_c. The gravitational force is acting downwards. A buoyant flow develops because of thermally induced density gradient. Heat is transferred from the hot wall to cold wall.

3.2 Mathematical Formulation

The governing equations for steady two-dimensional natural convection flows in the porous cavity using conservation of mass, momentum and energy are written as follows

Continuity: $$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \qquad (3.1)$$

Momentum: $$\frac{\partial v}{\partial x}-\frac{\partial u}{\partial y}=\frac{Kg\beta}{\upsilon}\frac{\partial T}{\partial x} \qquad (3.2)$$

Energy: $$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\alpha\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right) \qquad (3.3)$$

Where x and y are the dimensional co-ordinates along horizontal and vertical directions respectively: the fluid is assumed to be Newtonian and its properties are constant. Only the Boussinesq approximation is invoked for the buoyancy term. No-slip boundary conditions are specified at all walls. Introducing stream function ψ as $u=\frac{\partial\psi}{\partial y}$ $and\ v=-\frac{\partial\psi}{\partial x}$ and the following non-dimensional parameters, defined as

$\theta=\frac{T-T_c}{T_h-T_c},\psi=\frac{\Psi}{\alpha},Y=\frac{y}{L},X=\frac{x}{L},$ non- dimensional equations for the fluid saturated porous medium is reduced to

$$\frac{\partial^2\psi}{\partial X^2}+\frac{\partial^2\psi}{\partial Y^2}=-Ra\frac{\partial\theta}{\partial X} \qquad (3.4)$$

$$\frac{\partial\psi}{\partial Y}\frac{\partial\theta}{\partial X}-\frac{\partial\psi}{\partial X}\frac{\partial\theta}{\partial Y}=\frac{\partial^2\theta}{\partial X^2}+\frac{\partial^2\theta}{\partial^2 Y} \qquad (3.5)$$

$Ra=\frac{Kg\beta\Delta TL}{\upsilon\alpha}$ is the modified Rayleigh number or Rayleigh number of the porous medium.

3. 3 Numerical Procedure

In the present investigation, we predominantly used finite element method to solve partial differential equation, which describes the heat and fluid flow behavior in the vicinity of porous medium. There are various numerical methods available to achieve the solutions of these equations, but the most popular numerical method are finite difference method, finite volume method and the finite element method. The selection of these methods is an important decision, which is influenced by variety of factors amongst which the geometry of domain plays a vital role. The computation is terminated when all of the residuals are less than 10^{-5}. The calculations are carried out using MATLAB own code

3.4 Stream Function and Nusselt Number

3.4.1 Stream Function:

Eq. (3.4 and 3.5) with boundary conditions are solved numerically using Galerkin's Residual finite element method. Numerical results for streamlines and isotherms for natural convection were obtained for Ra numbers. The no-slip boundary condition is valid at all boundaries. Positive sign of ψ denotes anti-clockwise circulation and clockwise circulation is represented by negative sign of ψ.

3.4.2 Nusselt Number:

The local heat transfer coefficient is defined as $h_y = \dfrac{q''}{T_S - T_C}$ at a given point on the heat source surface, where T_S is the local temperature on the surface. Accordingly, the local Nusselt number is obtained as $Nu = \dfrac{h_y L}{k}$. The trapezoidal rule is used for numerical integration to obtain the average Nusselt number.

In order to determine the local Nusselt number, the temperature profiles are fit with quadratic (three nodal points are considered near the wall), cubic and bi-quadratic polynomials and their gradients at the walls are determined. It has been observed that the temperature gradients at the surface are almost the same for all the polynomials considered. Hence only a quadratic fit is made for the temperature profiles to extract the local gradients at the walls to calculate the local heat transfer coefficients from which the local Nusselt numbers are obtained. Integrating the local Nusselt number over each side, the average Nusselt number for each side is obtained as

1

On Left side wall, $Nu_{avg} = \int_0 Nu \; dX$

On Right side wall, $Nu_{avg} = \frac{1}{LX} \int_0^{LX} Nu \; dX$

3.5. Solution Methodology and Convergence Study

The computations are undertaken for 41 X 41 grid based on a grid refinement study. A Galerikin's Residual FEM is used for solution of the dimensionless governing equations. In order to determine the buoyant heat transfer parameters in the non-square cavity, Eqn. (3.1) is to be solved.

The grid independency against $\overline{Nu}$ for various mesh size of 11×11, 21×21 31×31, 41×41, 51×51 and 61× 61 of a porous square cavity for regular mesh with triangular element have been investigated using Finite Element Method. Table shows grid independence study of the average Nusslet numbers with *Ra =500* for left side is wall uniform heating. Average Nusselt number is increases from 11 X 11 to 31 X 31 and constant at 41 X 41,51 X 51,61 X 61 Grid size , hence 41 X 41 grid is used for all further computations**.**

Grid independence Test

Grid Dimension	Average Nusselt No ($\overline{Nu}$)
11 X 11	4.2351
21 X 21	4.9222
31 X 31	5.7252
41 X 41	6.4222
51 X 51	6.4234
61 X 61	6.4251

Table. 1: ***Mesh convergence study*****.**

3.6 Validation of Numerical Results

During the course of present research, the present methodology is verified in terms of temperature contours, stream functions, local and average Nusselt numbers. In order to validate the predictive capability and accuracy of the present methodology.

The flow model is based on the following assumptions,

i) The fluid is Newtonian.

ii) The fluid properties are constant with the exception of the density in the body force term of the momentum equation.

iii) The Boussinesq approximation is invoked for the fluid properties to relate density changes to temperature changes, and so to couple in this way the temperature field to the flow field.

iv) The flow is to be laminar.

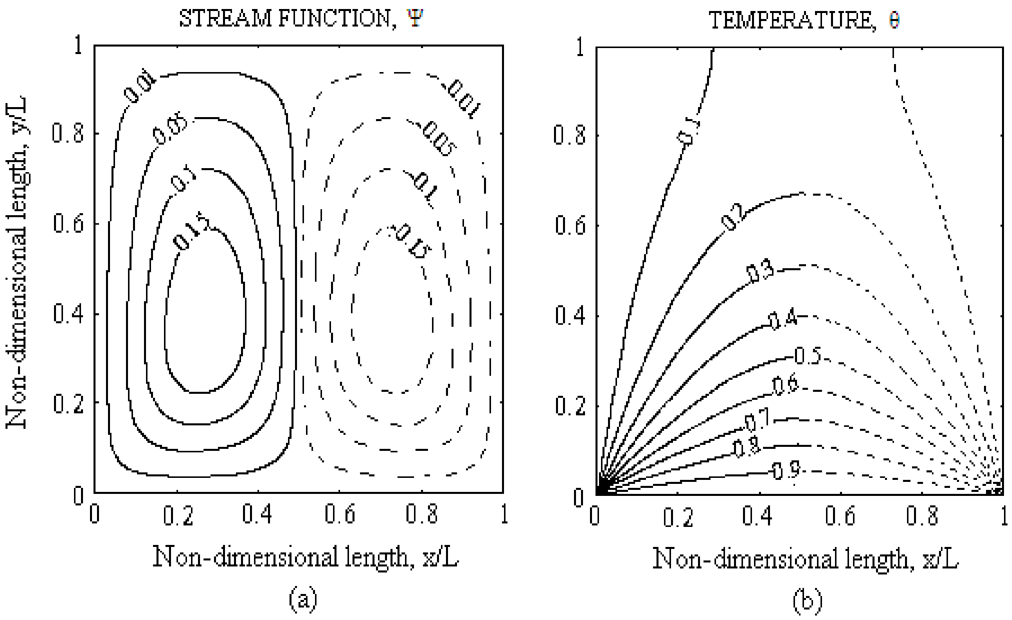


Fig. 3.2 (a) streamlines and (b) temperature profiles for constant temperature on bottom wall for Ra = 10^3, present study (—) and Basak [8] ( ).

Fig. 3.2 shows the streamline and temperature profiles for the case of constant temperature at the bottom wall for Ra = 10^3. In Fig. 3.2(a) the left portion shows the results of Basak [8] whereas right side shows the present results. There is good agreement between the two. Fig. 3.2(b) shows the temperature profiles for the same case which also show good agreement.

CHAPTER - 4

RESULTS AND DISCUSSION

4.1 Introduction

As outlined in the previous chapter, various flow and heat transfer characteristics like temperature contours, stream functions, local and average Nusselt numbers have been verified with numerical results published in the literature. The present methodology is verified in the previous section and the agreement is found to be excellent.

During the course of present research, the numerical investigations have been carried out for different boundary conditions. In the first set, the temperature boundary conditions like constant temperature, linearly varying and sinusoidal temperatures along the Left side wall with insulated top and bottom walls and Right-side wall as cold is considered. The investigations have been carried out for Rayleigh number ranging from 100 to 1000 and cavity aspect ratio of 1. The transition from conduction to convection is dealt for various boundary conditions.

4.2 Temperature Boundary Conditions

The cavity illustrated in Fig. 4.1 is chosen for simulating natural convective flow and heat transfer characteristics in porous media. In this study the constant, linearly and sinusoidal varying temperature has been investigated at the Left side wall. The top and bottom walls are adiabatic with a cool right-side wall.

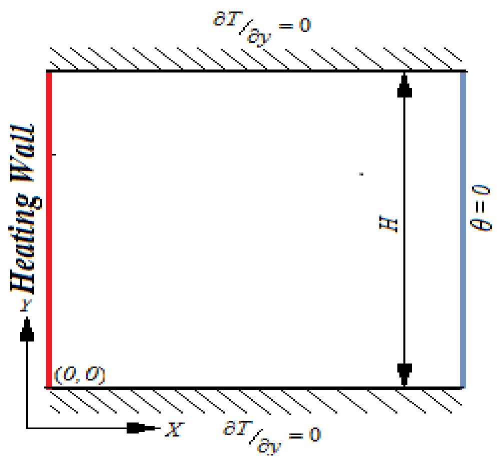


Fig.4.1: Geometry of the cavity

The aspect ratio of the cavity is defined as AR = H/L. Rayleigh number ranging from 100 to 1000 for an aspect ratio of 1. The gravitational force is acting downwards. The results highlighting the effect of different temperature boundary conditions are presented and discussed.

Using Galerkin's approach, the relevant boundary conditions are discredited together with the aforementioned governing equations. Simple triangular elements with three nodes are used in the present investigation. For more accuracy, cubical equations were used to fit the temperature contours. According to the current investigation, the governing equations above are subject to the following boundary conditions:

$\theta = 1, U = V = 0 \; at \; Y = 0 \; at \; 0 \leq X \leq 1$ On bottom wall; (4.1)

$\theta = 0, U = V = 0 \; atX = 0 \; and \; 0 < Y < 1$ on top wall; (4.2)

$\frac{\partial \theta}{\partial n} = 0, U = V = 0 \; at \; 0 < X < 1 \; and \; 0 < Y < 1$ on inclined walls. (4.3)

During the course of present research, the numerical investigations have been carried out for different boundary conditions. In the first set, the temperature boundary conditions like constant temperature, sinusoidal and linearly varying temperatures along the side wall with symmetrically cooled top and bottom walls (with same temperature) and right-side wall as cold is considered. The investigations have been carried out for Rayleigh number ranging from 100 to 1000 and cavity aspect ratio 1. The transition from conduction to convection is dealt for the range of AR studied and for various boundary conditions.

4.3 Effect of Rayleigh Number

The cavity used for the analysis is subjected to constant temperature at the bottom wall. Computations are carried out for Rayleigh number ranging from 100 to 1000. Fig. 4.2 illustrates the movement of the fluid inside the cavity for aspect ratio 1 with the bottom wall exposed to constant temperature environment. Fluid rises up from middle portion of the bottom wall and flows down along the two vertical walls, forming two symmetric rolls with clockwise and anti-clockwise rotations inside the cavity.

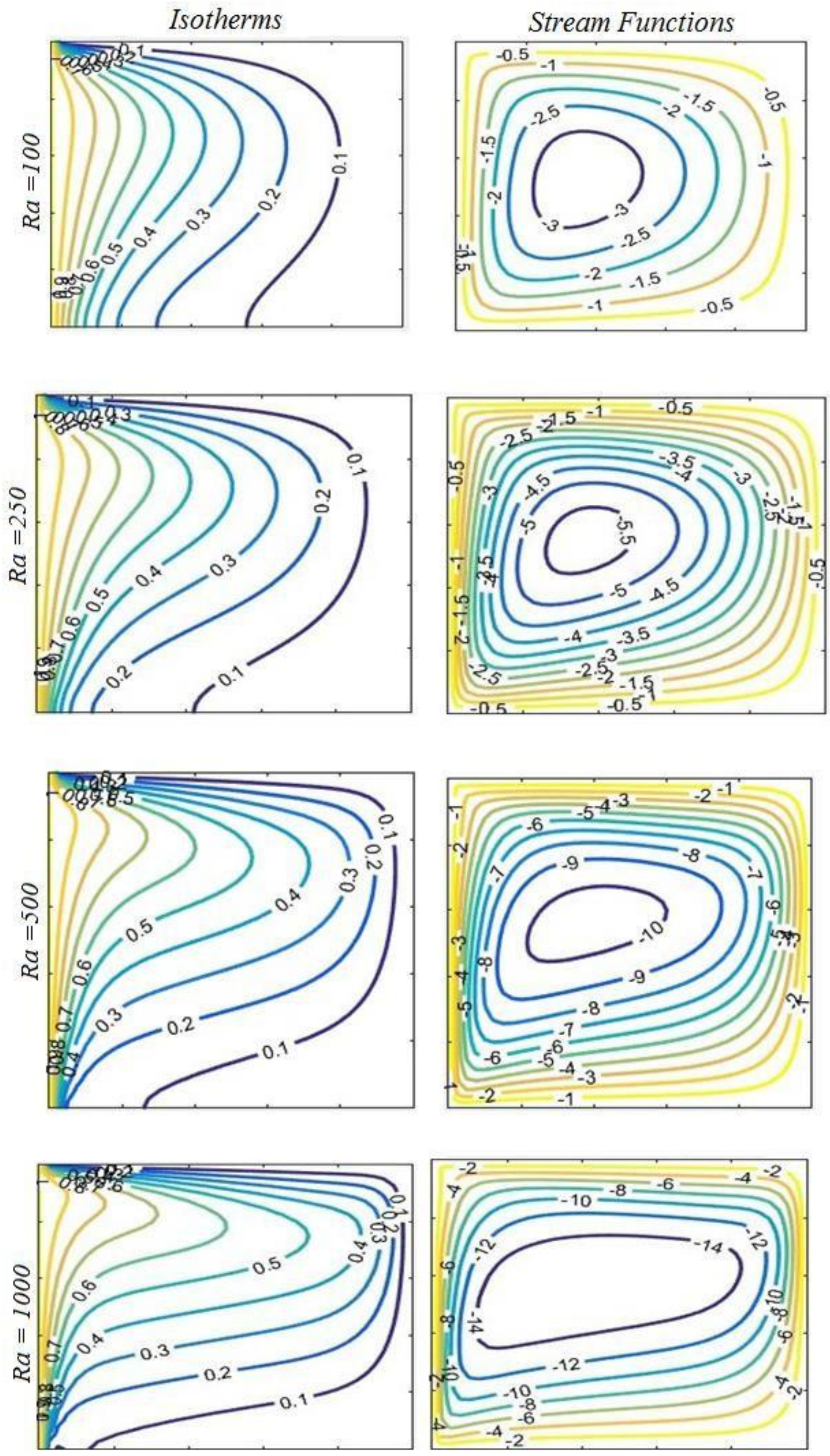


Fig. 4.2: Contour plots for uniform side wall heating with different Rayleigh number

Ra = 100,250,500 and 1000.

The contours of stream function and isotherms of computational solutions for different Rayleigh numbers ranging from Ra = 100 to 1000 and AR = 1, when the left vertical wall is heated uniformly for case 1 is illustrate in Fig. 4.2. As expected, due to uniform heating and cooling of vertical walls, the fluid starts to rise up from bottom end to top end of the heating wall and flow downward direction along the constantly cooled right vertical wall. The presence of partitions at the top reduces the magnitude of the flow of fluid and deflects in the downward direction. Again, fluid flows upward as soon as it comes to lower end of the partition and then reaches to the upper end of the cold surface. Due to the existence of partition at the lower side of the cavity, the cold fluid coming out of the cold wall moves up and down before it reaches to hot wall forming rolls with clockwise rotation. At $Ra = 10^3$, the values of the flow field is very small and the heat transfer occurs primarily by conduction dominated mode. Due to symmetry in partitions, the flow fields are symmetry with respect to horizontal and vertical symmetry lines with hither magnitudes at the outer one and stagnant ($\psi = 0$) at core. The core starts deformed horizontally, due to the existence of partitions at the upper and lower ends of the cavity.

The isotherm contours which are very close to the hot wall ($\theta = 0.9$) and cold surface ($\theta = 0.1$) are almost parallel to the vertical wall. However, the isotherm contours, θ ($0.8 \geq \theta \geq 0.2$) are smooth curves and surround the partitioned walls. The isotherm contours (which are not shown) are not varying with Rayleigh number up to $Ra < 100$. The circulations become stronger at the extreme outside the core of center of rotations and consequently, the isotherm contour of $\theta = 0.1$ is smooth curve with top portion shifting towards the partition and lower portion near the hot wall. The upper portion of isotherms with values $\theta \geq 0.5$ is deformed towards cold wall. As Rayleigh number increases to 10^5, the convection current caused by buoyancy force inside the cavity, the values of the flow of fluid increases. The central core is bifurcated into two eyes and is placed at the center of the two halves of the cavity. Consequently, due to the presence of partition at the bottom, isotherm contours $\theta \leq 0.7$ distorting against the top portion of the cold surface. In contrast, the lower partition causes $\theta \geq 0.2$ deformed towards the lower portion of the hot wall. At $Ra = 500$, the convection current is more dominated and hence the values of stream functions are doubled to that of $Ra = 1000$. The stratification of the isotherm contours is more and more and covers 80% of the vertical walls. The central portion of the contours is almost horizontal. The portion of stream function contours placed in the left half of the enclosure starts deforming upward direction and same thing happening downward in the right half of the cavity. However, due to higher stratification rate of isotherm contours near the vertical walls and strong convective mode of heat transfer the central core reunite and starts bulging inclined with left end lower and upper at the other.

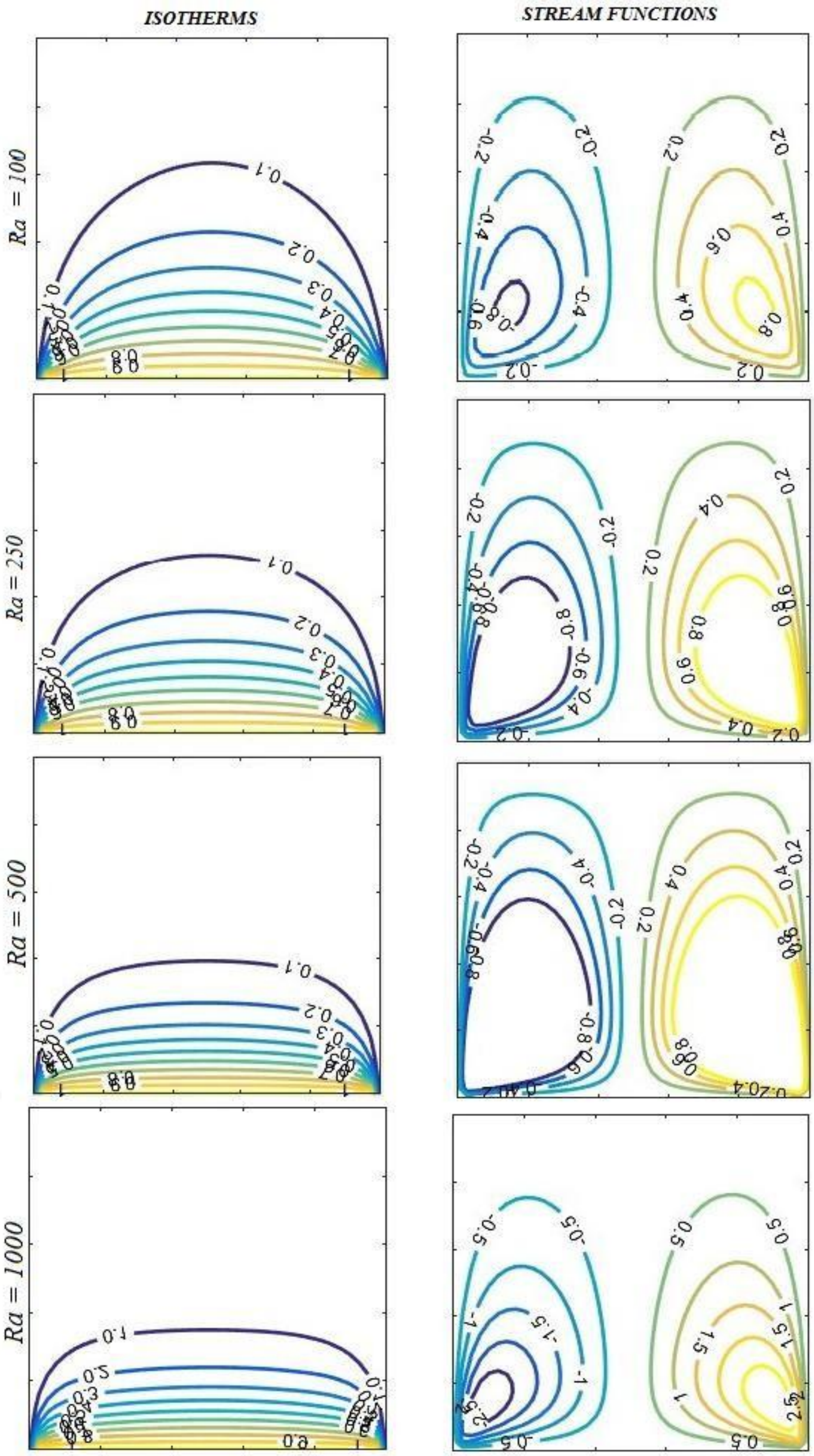


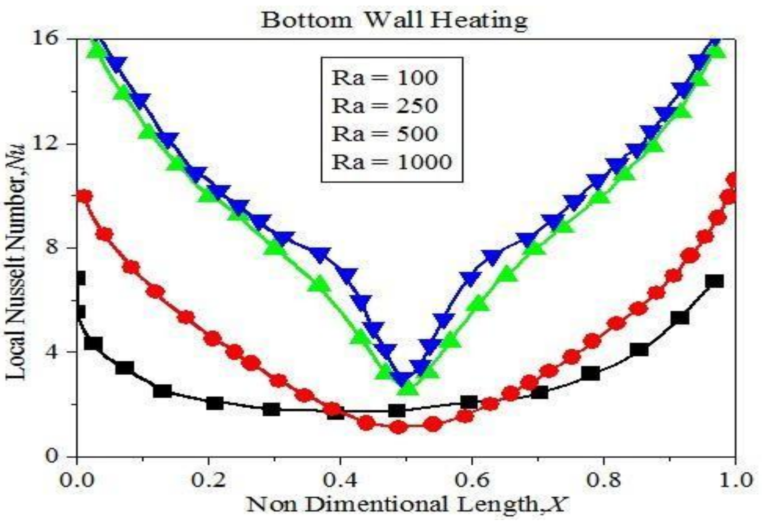
Fig. 4.3: Contour plots for uniform bottom wall heating with different Rayleigh number

Ra = 100,250,500 and 1000.

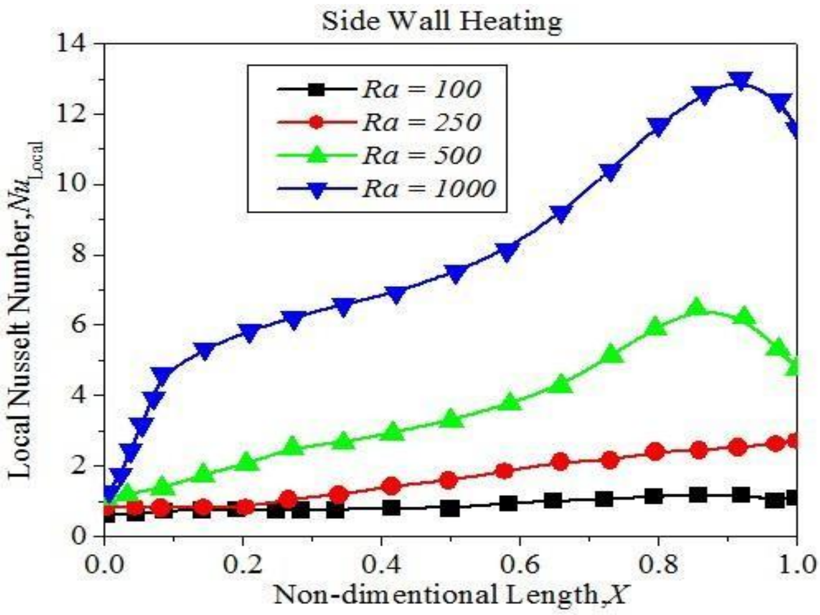
In the second case, the bottom wall is uniform heating boundary condition, top wall is cold and other two vertical walls are adiabatic as shown in Fig.4.3. The contours of stream function and isotherms of computational solutions for different Rayleigh numbers ranging from *Ra = 100 to 1000* and *AR* = 1, Fig. 4.3, illustrates the stream function and isotherm contours of aspect ratio 1 for Ra = 500 with the bottom wall exposed to constant temperature environment. It has been observed that for Ra = 10^3 the magnitudes of stream function are very low (ψ = 0.4 to 0.8) and the heat transfer is primarily due to conduction.

During conduction dominant heat transfer, the temperature contours are similar and occur symmetrically. The temperature contour θ = 0.1 is opened and occurs symmetrically. The temperature contours, θ = 0.2 and above are smooth curves and are generally symmetric with respect to vertical center line. Discontinuities occur at bottom corners of the cavities. The temperature contours remain invariant up to Ra < 1000. However, it is observed from the Fig. 4.3 that, the magnitude of stream function increases with increase of Rayleigh number. For Ra = 1000 central cell is smaller in size than other. For Ra = 500 and above the size of the central cell increased. It is seen in the Fig. right side that, the stream functions for Ra = 1000 are forming circular cells at the top half of the vertical walls. Portions of the stream function contours near the cold walls are parallel to vertical cold walls. The middle top corners are concentrating at the middle of the top adiabatic wall bottom corners are dragging of the bottom wall.

4.4 Effect of Local Nusselt Number



(a) Bottom wall



(b) Side wall

Fig. 4.4: Variation of local Nusselt numbers (AR = 1) for bottom wall subjected to constant temperature (a) bottom wall and (b) side wall.

Figs. 4.3(a) and (b) shows the variation of local Nusselt number for both bottom wall and side walls for AR = 1. The investigations have been carried out for Rayleigh number ranging from 100 to 1000 for the constant temperature case. As the Rayleigh number increases the local Nusselt number at the bottom wall also increases. As expected, the local Nusselt number at any given location increases with Rayleigh number. Fig. 4.3(a) shows the variation of local Nusselt number for bottom wall.

Fig. 4.3(a) and (b) shows the effect of *Ra* on the local Nusselt number at the bottom and side walls (Nu_b, Nu_s) for AR = 1. For uniform temperature of the bottom wall, the heat transfer rate of Nu_b is high at the edges of the bottom wall due to discontinuities present in the temperature boundary conditions (Fig. 4.1) at the edges, reduces towards the center of the bottom wall with minimum value at the center.

Fig. 4.3(b) illustrate the variation of Nu_s for Ra = 100 (corresponds to predominantly conduction case). Nusselt number monotonically decreases from bottom to the top of the side wall. However, for Ra =1000 convection currents starts and hence the reversal is observed after Y = 0.6. For values beyond 100 convection dominates and hence local Nusselt number goes on increasing up to point Y = 0.75 and then shows a decreasing trend as flow velocity reduces near the corner.

4.5 Effect of Average Rayleigh Number

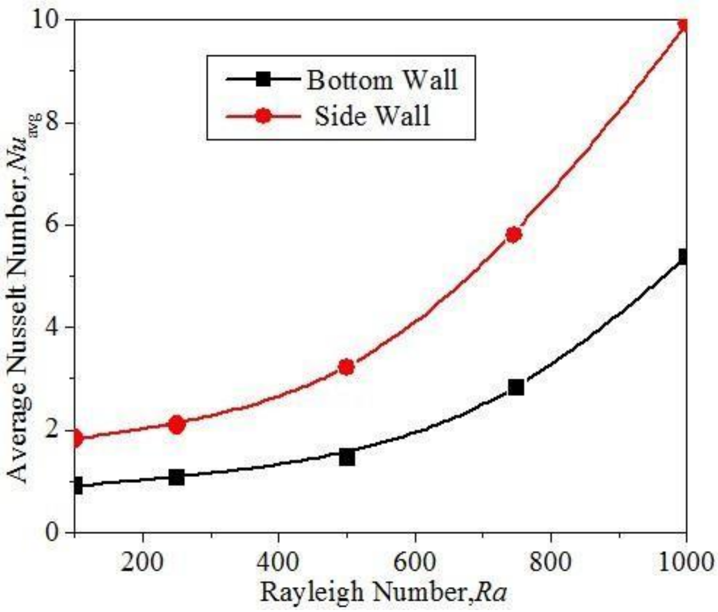


Fig. 4.5 Variation of average Nusselt numbers for bottom wall subjected to Different Rayleigh Numbers

Fig. 4.4 shows the variation of average Nusselt number for the case of constant temperature for bottom wall and side walls respectively. It can be observed that the average Nusselt number increases with Rayleigh number as expected. It has been also observed from Fig. 4.4 that the average Nusselt number for bottom wall is twice that for side wall for a given Rayleigh number, as expected.

CHAPTER - 5

CONCLUSIONS AND SCOPE FOR FUTURE WORK

5.1 Summary of Numerical Work

The primary object of the present research is to investigate the flow and heat transfer characteristics in cavities. The cavities used are bounded with adiabatic top wall, symmetrically cooled vertical cold walls maintained at same temperature and bottom wall subjected to temperature, heat flux and convective boundary conditions. To full-fill this goal, the following variations have been made at the bottom wall in the temperature and heat flux boundary conditions.

- Temperature boundary conditions
  - Constant temperature
  - Sinusoidally varying temperature
  - Linearly varying temperature

The temperature variations along the bottom wall were plotted while studying the heat flux and convective boundary conditions. The numerical results were able to throw light on the effect of several parameters of cavities like,

- Type of boundary conditions used
- Variation of boundary condition
- Rayleigh number

The flow and heat transfer characteristics of cavities are studied in the following terms.

- Distribution of temperature along the bottom wall for different Rayleigh numbers cases.
- Local Nusselt numbers
- Average Nusselt numbers

It is observed that the numerical results agree well with the numerical results available in the current literature. It is observed that constant boundary conditions were capable of transferring more heat than other variations.

In the first phase of numerical work, an effort has been made to investigate the flow and heat transfer characteristics in cavities when the side wall is subjected to temperature boundary conditions like uniform, sinusoidal and linearly varying temperature.

When bottom wall is subjected to constant temperature, the following points have been observed for the range of Rayleigh number and Aspect ratios studied.

- Magnitudes of stream function are increased with increase of Rayleigh number.
- For constant temperature, discontinuities occur at the corners of the bottom wall.
- As Rayleigh number increases, the temperature contours (with low values) indicate the increase of convection activity.
- It is seen from the local Nusselt numbers that, the heat transfer is least at the center of the bottom wall and monotonically increases towards cold side walls.
- It is observed that the average Nusselt number is increased monotonically with increase of Rayleigh number along both bottom and side wall.

In the second phase of numerical work, our attention is focused to investigate the flow and heat transfer characteristics in cavities, when the bottom wall is subjected to the different boundary conditions like constant, sinusoidal and linearly varying cases.

The following conclusions have been written for the range of Rayleigh number and Aspect ratio studied during the study of different heat flux boundary conditions at bottom wall.

- The temperature along the bottom wall decreases with increase of modified Rayleigh number.
- Magnitudes of stream function are increased with increase of modified Rayleigh number.
- As modified Rayleigh number increases, the temperature contours (for low θ values) are raised from bottom wall and split at the top and moving towards the cold walls. Rest of the contours is concentrated near the bottom wall.
- For $Ra \leq 500$, 50% of the contours are continuous curves, however, for Ra > 500 and above the temperature contours tend to concentrate towards bottom hot wall.

- The local Nusselt numbers are least at the center of the bottom wall and monotonically increases towards cold side walls for Ra* up to 500. However, for Ra* = 1000 the local Nusselt numbers are linearly increased from center of cavity to cold side walls.
- For side walls, the local Nusselt numbers are decreasing, increasing and again decreasing trends have been observed for Ra* = 100 and 500. But, for Ra* = 1000 the local Nusselt numbers are increased and decreased at Y = 0.8.

5.2 Scope for Future Work

Through there are sufficient number of publications on flow and heat transfer in closed cavies are available, a comprehensive analysis involving both the Rayleigh numbers ranging from 100 to 3000 and cavity aspect ratio 0.1 to 5 for 2D heat transfer is still not available. Further such analytical models require experimental validation. The following specific areas can be considered for continued research work on closed cavities which could result in improved performance levels for electronic cooling and other technological applications.

- The majority of works in the literature dealing with convection in enclosures is restricted to the cases of simple geometry, e.g., rectangular, square, cylindrical, and spherical cavities. However, the configurations of actual containers occurring in practice are often far from being simple. Therefore, the flow and heat transfer analysis may be extended to energy efficient cooling of buildings and cooling of complicated cavities.
- The analysis can be extended to heat flow and heat flux lines in cavities.
- The analysis can be carried out with different opening ratios in the cold and adiabatic walls.
- The investigations can also be performed for different orientations of the cavity.
- 2D analysis can be performed with discrete heat sources at bottom wall for different aspect ratio and orientations.

CHAPTER – 6

REFERENCES

1. D.A.Nield,A. Bejan, Convection in Porous Media, 3rded.,Springer, NewYork,2006.
2. .K.Vafai,Hand book of Media,Seconded.,Taylor&Francis,BocaRaton,FL,2005.
3. .K.L.Walker,G.M. Homsy,Convection in a porous cavity,J. Fluid Mech. 87(1978) 449–474.
4. V. Prasad, F.A. Kulacki, Convective heat transfer in a rectangular porous cavity—effect of aspect ratio on flow structure and heat transfer, J. Heat Transfer 106 (1984) 158–165.
5. C. Beckermann, R. Viskanta, S. Ramadhyani, A numerical study of non-Darcian natural convection in a vertical enclosure filled with a porous medium, Numer. Heat Transfer A 10 (1986) 557–570
6. Z.-G. Du, E. Bilgen, Natural convection in vertical cavities with internal heat generating porous media, Heat Mass Transfer 27 (1992) 149–155
7. N.H. Saeid, Maximum density effects on natural convection in a porous cavity under thermal non-equilibrium conditions, Acta Mech. 188 (2007) 55–68.
8. N.H. Saeid, I. Pop, Natural convection from a discrete heater in a square cavity filled with a porous medium, J. Porous Media 8 (2005) 55–63.
9. Baytas A.C and Pop.I, "*Free convection in oblique enclosures filled with a porous medium*, Int Journal of Heat and Mass Transfer, Vol 42, 1999, pp1047-1057.
10. Basak. T., Roy, S, and Balakrishnan A.R., " *Natural convection in a square cavity filled with a porous medium: Effects of various thermal boundary conditions"*, Int. Journal of Heat and Mass Transfer, Vol 49, 2006, pp 1430-1441.
11. C. Revnic, T. Grosan, I. Pop , D.B. Ingham*," Free convection in a square cavity filled with a bidisperse porous medium",* Int. Journal of Thermal sciences, Vol 48, pp 1876-1883.
12. M. Sathiyamoorthy, Tanmay Basak, S. Roy, I. Pop, "*Steady natural convection flows in a square cavity with linearly heated side wall(s)",* Int. Journal of Heat and Mass Transfer, Vol 50, 2007, pp 766-775.
13. K.Al-Farhany, A.Turan, "*Non-Darcy effects on conjugate double-diffusive natural convection in a variable porous layer sandwiched by finite thickness walls",* Int. Journal of Heat and Mass Transfer, Vol 54, 2011, pp 2868-2879.

14. Prasanth Anand Kumar Lam, K.Arul Prakash, " *A numerical study on natural convection and entropy generation in a porous enclosure with heat sources",* Int. Journal of Heat and Mass Transfer, Vol 69, 2014, pp 390-407.
15. Inna A. Aleshkova, Mikhail A.Sheremet, "*Unsteady conjugate natural convection in a square enclosure filled with a porous medium",* Int. Journal of Heat and Mass Transfer, Vol 53, 2010, pp 5308-5320.
16. D.A.Nield, a.Barletta, "*Extended Obereck-Boussinesq approximation study of convective instabilities in a porous layer with horizontal flow and bottom heating",* Int. Journal of Heat and Mass Transfer, Vol 53, 2010, pp 577-585.
17. Yasin Varol, Hakan F.Oztop, Asaf Varol, "*Free convection in porous media filled right-angle triangular enclosures",* Int. communications in Heat and Mass Transfer, Vol 33, 2006, pp 1190-1197.
18. Tanmay Basak, S. Roy, D.Ramakrishna and I.Pop," *Visualization of heat transport due to natural convection for hot materials confined within two entrapped porous triangular cavities via heatline concept",* Int. Journal of Heat and Mass Transfer, Vol 53, 2010, pp 2100-2112.
19. Geniy.V.Kuznetsov, Mikhail.A.Sheremet*,"Numerical simulation of turbulent natural convection in a rectangular enclosure having finite thickness walls",* Int Journal of Heat and Mass Transfer, Vol 53, 2010, pp 163-177.
20. W. Pakdee, P. Rattanadecho, "*Unsteady effects on natural convective heat transfer through porous media in cavity due to top surface partial convection", Applied Thermal Engineering* , Vol *26*, 2006, pp.2316-2326.
21. Aniruddha Bagchi, F.A.Kulacki, "*Natural convection in fluid-superposed porous layers heated locally from below",* Int. Journal of Heat and Mass transfer, Vol 54, 2011, pp 3672-3682.
22. Kirkpatrick, A. T., Bohn, M., "*An Experimental Investigation Of Mixed Cavity Natural Convection in the High Rayleigh Number*", Int. J. Heat Mass Transfer. Vol. 29, No. 1, 1986, pp 69-82.