Chapter 1

INTRODUCTION

1.1 Research Background

The study of heat transfer and fluid flow behaviour in porous medium has received much attention from researchers during the last few decades due to numerous industrial, engineering and physical science applications. Several prominent applications include oil recovery techniques in petroleum industries, transpiration cooling, and storage of radioactive nuclear waste materials, separation processes in chemical industries, solar heating systems and thermal insulation of buildings (Kaya, 2011). A thorough understanding of the heat transfer mechanism as well as heat and mass transfer is of primary importance to the scientific community, which has led to the intensive research during the last few decades, as evidenced by the myriad number of research articles published in this field. Porous media models are chiefly applied for liquid metal flow through the dendritic structures in alloy castings (Streat and Weinberg, 1976), (Lee et al., 2001), flows through packed and fluidized beds (Sun et al., 2013) as well as in the analysis of fluid flow through turbo-machinery (Gregory et al., 2002). The insight of the subject and various aspects of transport in porous media were well documented by Nield (Nield, 2002).

The three modes of heat transfer in matter are conduction, convection and radiation. Natural convection is a heat transfer mechanism in which the fluid motion is not generated by any external source such as pumps, fans and suction devices rather; the fluid motion is induced by difference in the fluid density due to temperature gradients. The fluid within the vicinity of the heat source receives heat, which reduces the density of the fluid and therefore the fluid rises upwards. The surrounding cooler fluid moves downwards in replacement of the warmer fluid then moves to replace it. The cooler fluid then receives heat and the process continues forming convective currents. Studies on natural convection have received considerable attention over the years due to its presence in nature as well as in engineering applications such as in the formation of microstructures during cooling of molten metals and in shrouded fins and solar ponds. However, detailed studies which address more specific aspects convection such as free, forced and mixed convection have gained significance due to their vast range of real world applications. This study aims to elaborate heat transfer as well as heat and mass transfer phenomena due to natural and mixed convection specifically in square porous and vertical cylindrical annular geometries respectively.

A porous material is a solid matrix impermeated by an interconnected network of pores (voids) filled with a fluid (liquid or gas). Usually both the solid matrix and the pore network (also known as the pore space) are assumed to be continuous so as to form two interpenetrating continua such as in a sponge. Many natural substances such as rocks, soils, biological tissues (e.g.bones), and man-made materials such as cements, foams and ceramics are examples of porous material. A typical porous medium structure is shown in the Figure 1 (Schrefler, 2002).

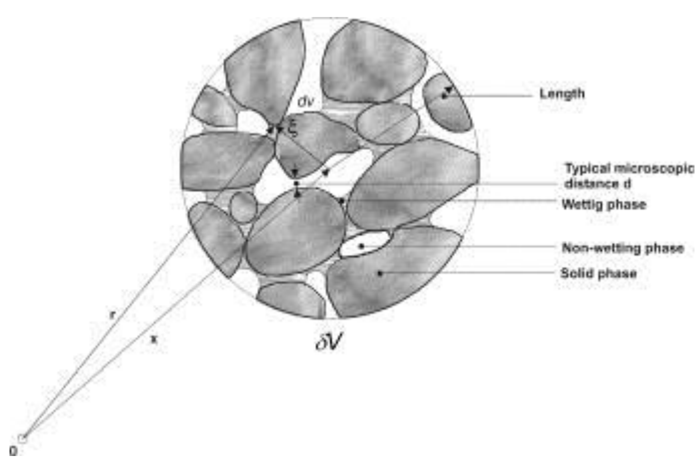

Figure 1.1: Schematic representation of a porous medium (Schrefler, 2002)

1.1.2 Flow through porous medium

A fundamental study on flow though porous media was first carried out by French civil engineer, Henry Darcy, in 1856. Experiments were carried out on vertical water filtration through sand beds to demonstrate the flow through porous medium (Niessner and Hassanizadeh, 2009). He formulated the Law that governs the flow through porous medium, which is known as the Darcy's Law. This law serves as the fundamental guideline to many researchers when addressing post Darcy problems in order to investigate the various aspects of flow through porous media. The Darcy law in its simple form can be expressed mathematically as (Tiab and Donaldson, 2012).

$$\upsilon = -\frac{k}{\mu}\frac{dp}{dx}$$

where

υ = apparent fluid flowing velocity

k = permeability of the porous rock, darcy

μ = viscosity of the flowing fluid, centipoise

$\frac{dp}{dx}$ = pressure gradient in the direction of flow, atm/cm

x = distance in the direction of flow, always positive, cm (Tiab and Donaldson, 2012)

It shall be noted that the Darcy Law accounts for major aspects of flow through porous media and is regarded as the basic law that governs the flow of fluid in porous media. Forchheimer and Brinkman extended the Darcy law to account for the high-velocity flows which incorporates high-velocity inertial effects and viscous shear stress parameter, respectively.

1.1.3 Convective heat transfer in porous medium

The convective heat transfer in porous medium is considered as the most complex phenomenon compared to the conductive and radiative heat transfer due to the simultaneous combined effect of conduction (heat diffusion) and advection (heat transfer by bulk fluid flow). Furthermore the combined heat and mass transfer, in which matter or heat is transported by the larger-scale motion of currents in the fluid increases the complexity of the phenomenon. The need to understand the heat transfer characteristics and the flow behaviour in the finite porous enclosure becomes inevitable due to its varied applications such as high performance insulations in buildings, air conditioning ducts, and porous heat exchangers to name a few (Sankar et al., 2011). The research articles published during the last few years demonstrate the practical applications related to the convective heat transfer in porous square enclosures, such as; melting process (Wang et al., 2010), heat exchangers (Persoons et al., 2011), electronic cooling (Bednarz et al., 2009). The various aspects of the convective heat transfer such as conjugate heat transfer, conjugate heat and mass transfer, effect of viscous dissipation on the rate heat transfer rate are the important areas whereby plentiful research is being concentrated to explore the potential applications in this specific area. The conjugate heat transfer is an important process whereby prevalence of the variation of the temperature within the solids and fluids is seen due to the interaction between the solids and fluids. Several applications related to the micro channel-based heat sink for electronic packaging is primarily based on this process (Fedorov and Viskanta, 2000). The conjugate heat transfer in vertical annulus is an important aspect to deal with, owing to its innumerable applications in industries such as; electronic packaging, combustion, gas turbines and spent nuclear fuel casks (Venkata et al., 2010). In the context of heat and mass transfer the term "convection” refers to the sum of advective and diffusive transfer. Apart from the natural and forced convection phenomena the practical applications of mixed convection in several areas such as solar collectors, double-layer glass, building insulation, electronic cooling, food drying and sterilization has been witnessed in recent research work (Goodarzi et al., 2014).

1.1.4 Convective heat transfer in square and cylindrical porous annulus

The convective heat transfer analyses in various geometries have been reported with significant thrust with the relevance to square and cylindrical geometries in recent years due to the wide applications in industry as well as in the research areas. The applications such as; mechanism for the transport of water from the ground to upper branches of tall trees, engineering devices like finger pumps and roller pumps and also in most physiological processes such as urine transport in the ureter involve the same structure (Vajravelu et al., 2007). Even more generally the porous media approach was adopted by aerospace, automotive, and electronics industries to achieve efficient and effective thermal management system to anticipate the increased heat dissipation rates and reduced temperature gradient (Hatami and Ganji, 2014). The applications related to the square geometries have been reported in many research articles specifically as in case of mold industry (Lavers, 1983). The important thermal energy storage application as melting of phase-change material in a square annulus shows the specific square annular geometrical application in research (Li et al., 2010). Furthermore the cylindrical geometries as well found to have abundant industrial applications witnessed by recent research articles (Karim et al., 1986). The oil recovery techniques in petroleum industry is well known application (Patel et al., 2013). Thus the significance of the square and vertical cylindrical geometries in several applications motivates in depth research and thorough understanding the heat transfer and heat and mass transfer phenomena along with the nature of the fluid flow in the square and vertical cylindrical annuls fixed with porous medium. The schematic representations of the square and vertical cylindrical geometries are shown in the figure1 and 2.

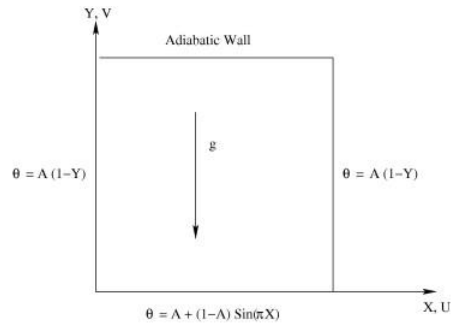

Figure 1.2: Schematic representation flow model and physical coordinate system (Ramakrishna et al., 2013)

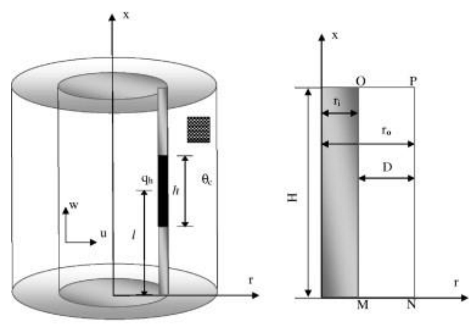

Figure 1.3: Physical configuration and co-ordinate system of vertical porous annulus

(Sankar et al., 2011).

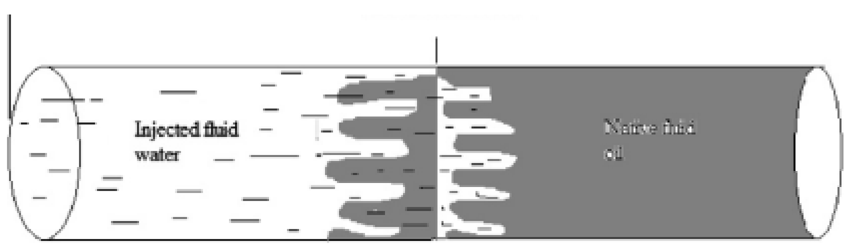

Figure 1.4: Counter-current imbibition in cylinder (Patel et al., 2013).

1.2 Mathematical Formulation

Mathematics is the base for scientific and engineering developments which have led to the advancements in many fields of human life. Mathematics can be used to imitate any physical phenomenon without having to build the physical structure accomplishing the phenomenon. Mathematical modeling requires the basic laws of science to be written, arranged and operated with the help of mathematical rules to finally come up with a single or multiple equations which can predict the behaviour of the physical system under study. There are two distinct advantages of using mathematical modeling over experimental studies. Firstly, it avoids the heavy cost involved in building the prototype of physical system. Secondly it compresses the time required to study a system by many folds as compared to that of experimental studies. The beauty of mathematical modeling lies in the fact that it can answer many questions about the behaviour of system in very short period of time. Analytical and numerical studies in recent times have become very popular due to accuracy within required range, fast, inexpensive due to the advanced computer technology. Thus the present study is fairly justified.

1.2.1 Modelling in porous medium

The fundamental governing equations for the fluid flow in porous medium are continuity, momentum and energy equations. These governing equations are partial differential equations which are difficult to solve analytically. Generally it is assumed that the fluid and the solid porous material are in the thermal equilibrium state and it requires only one energy equation to be solved. But in some of the real world applications, where the characteristic time of flow is small compared to that of mass or energy transfer or where the amount of interfacial areas separating the phases are low, there exist the discrepancies in the temperature between the solid and fluid phase of the porous medium (Niessner & Hassanizadeh, 2009). In such situations there has to be suitable modifications which can accommodate separate energy equations for solid as well as for fluid. The mass transfer along with the heat transfer adds up more complexity and to account for the thermosolutal transport, the concentration equation along with the energy equation is required.

Present study is carried out by considering both thermal equilibrium and thermal non- equilibrium approach to analyze the heat transfer in square porous annulus and heat transfer and as well as heat and mass transfer in vertical porous cylinder. The governing partial differential equations for the specific boundary conditions are formulated. The well-known finite element method is employed to solve the transformed set of algebraic equations. The effect of various physical and geometrical parameters such as Rayleigh number *Ra*, Radiation R_d, aspect ratio *Ar*, width ratio *W*, on heat transfer characteristics are investigated. The square porous annulus and vertical annulus are modeled and solved for solution variables such as temperature $\overline{T}$ and stream function $\overline{\psi}$, are solved to analyze the heat transfer and fluid flow behaviour in porous domain.

1.3 Problem Statement and Objectives

The increased and intense research carried out so far in the area of flow through porous media, exemplifies the application and importance of the research related to the flow through porous media in various geometries. Despite this exhaustive and in-depth research, the important applications related to porous ducts (human thermal comfort and food preservation applications) and also hot fluid transported through ducts (petroleum refineries, fruit ripening applications) has received greater interest towards the analysis of various aspects of heat transfer and fluid flow through porous medium. Furthermore the use of porous material to increase the insulation and /or to enhance the heat transfer has been the important aspect among the researchers. This motivated the investigation of the heat transfer and fluid flow behaviour in cylindrical geometries which are mainly used in the petroleum industries (Eow and Ghadiri, 2002). The specific applications pertaining to the conjugate heat transfer which is chiefly employed in electronic packaging and microelectronic cooling is also an area of high demand due to its applications in microelectronic cooling systems (Fedorov and Viskanta, 2000). Thus the one of the objective of the study is to determine the conjugate heat transfer with the emphasis on, porous material inserted between conducting surfaces, used as an external insulation for the conducting spherical surfaces. The effect of heat flux on specific location in cylindrical geometries also has greater importance in various engineering applications such as fusion power plant application (Raffray and Pulsifer, 2003). Similarly the various applications pertaining to the mixed convection demand an in-depth investigation of the effect of viscous dissipation and thermal non-equilibrium modeling applied in case of cylindrical geometries (Lai and Kulacki, 1991; Saeid, 2004). Thus the current study is the outcome of the significance of the problem under investigation which has innumerable applications in industries as well as in science and research and development field.

The present study deals with the natural and mixed convection heat transfer analysis. The fluid behaves as steady, laminar and compressible flow. Thus below are the objectives of the current research.

- To study heat transfer analyses in a square porous Annulus (inner hot and inner cold)
- To study conjugate heat transfer in porous annulus (single and double wall)
- To study conjugate heat and mass transfer in a vertical porous cylinder

- Investigation of the effect of length and location of heater in a vertical cylinder: thermal non equilibrium approach
- Study of mixed convection in an annular vertical cylinder filled with saturated porous medium subjected to discrete heating, using thermal non-equilibrium model.

1.4 Scope of the study

The study predominantly deals with the convective heat transfer and fluid flow analysis in square and cylindrical porous annulus with focus on the heat transfer and heat and mass transfer. The entire research is dedicated towards the in-depth study of the effect of viscous dissipation on heat transfer and flow behaviour, conjugate heat transfer with inserted porous material between two conducting surfaces, mixed convection and effect of heat flux on the heat transfer and fluid flow patterns in the porous medium fixed within the geometry. Both thermal equilibrium and thermal non-equilibrium models are applied to study the effects of geometrical and physical parameters on the heat transfer and fluid flow behaviour. The area of the study is wide and its applications in various fields are even more vast such as geophysical sciences, engineering, industries and research and development and many more.

1.5 Thesis structure

This thesis is organized into five chapters which systematically explain convective heat transfer in square and cylindrical annulus. A brief description of each chapter is given as follows:

The background of the research is presented in Chapter1, whereby the applications of the research in various areas of science, industry as well as, in research and development (R&D) are described. Fundamental research and recent development in porous media are highlighted, with special emphasis on the key contributions eminent researchers in addressing the emerging problems in the field. A brief description of the porous medium modelling and the methodology implemented in this study is also provided in this chapter, followed by the research objectives and scope of the study. A comprehensive literature review pertaining to the convective heat transfer is presented in Chapter 2, with special emphasis on specific phenomena and geometry.

The methodology adopted in this study is elaborated in detail in Chapter3, comprising the fundamental governing equations for fluid flow in porous medium, mathematical formulation and solution procedure adopted including the general representation of the geometry considered and the boundary conditions applied. The detailed description of the Finite Element Method is discussed.

The results for each case study are presented and described in detail in Chapter 4. Validation and comparison are also discussed, wherever applicable. Lastly, the conclusions of this study and recommendations for future research are presented in Chapter 5.