

Chapter 2

LITERATURE REVIEW

2.1 Introduction

The vast research pertaining to the heat transfer and flow through porous medium during the last few–decades shows its importance as evidenced by exhaustive research carried out by eminent researchers. This section deals with the comprehensive literature review relevant to various aspects of heat transfer and flow through porous medium with emphasis on some specific phenomena with respect to porous annular geometries.

It is worth to be mentioned here that the research relevant to the flow through porous medium was first demonstrated by Henry Darcy, a French scientist, as mentioned in the Chapter 1 section 1.1.2. In 1856 Henry Darcy investigated the fluid flow in a porous medium. Experiments were carried out in Dijon to demonstrate the water filtration process that served as fundamental guidelines for further research in flow through porous medium. This law is popularly known as the Darcy law. Until today his law serves as the basic guidelines for predicting fluid behaviour in the porous medium. Apart from Darcy, Forchheimer and Brinkman have contributed to this field by extending the Darcy law. Forchheimer introduced the thermal flow resistance term in Darcy's equation, while the 'viscous shear stress' term was introduced by Brinkman. Contributions made by these early researchers still serve as the fundamental laws for further research.

The literature pertaining to various aspects of heat and mass transfer and flow behaviour in the porous medium has been well documented (Nield and Bejan, 1999; Nield and Bejan, 2006; Vafai, 2000; Vafai, 2005; Pop and Ingham, 2001). The research carried out by these researchers is considered as benchmark results in this field.

2.2 Convective heat transfer in porous cavities and ducts

It is a well known fact that the industrial applications of porous cavities or ducts and its applicability in the research and development field are vast. The emerging problems in the industries as well as in research and development that are influenced by the physical and geometrical parameters have motivated to find the fruitful solution. Barletta and Storesletten (Barletta and Storesletten, 2011) investigated the onset of convective rolls in a circular porous duct for various values of the Biot number. The determination of the neutral stability and critical values of the wave and Rayleigh numbers were studied for the different Biot numbers. The Galerkin finite-element method was used to solve elliptic governing equations. They reported that, on increasing the length-to-radius aspect ratio, there was a transition from a two-dimensional to a three-dimensional pattern of instability at the onset of convection.

A numerical investigation of the forced convection in a channel, using control volume method, was reported by Ould-Amer et al. (Ould-Amer et al., 1998). The inertia, drag and boundary effects were evaluated by using the Darcy-Brinkman-Forchheimer equation. The effects on the flow pattern and heat transfer for the parameters of the Darcy number, the dimensions of the blocks and the thermal conductivity ratio were analyzed.

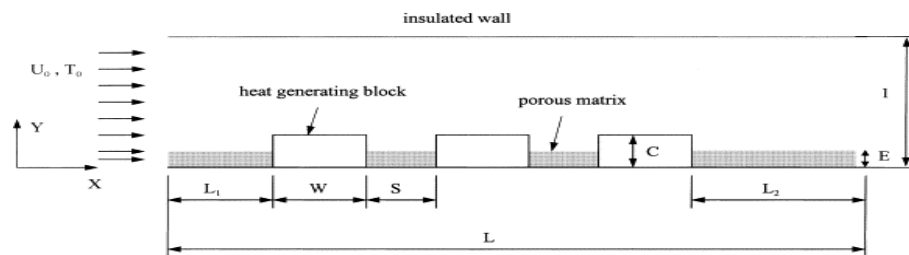


Figure 2.2.1: Schematic of the physical domain. (Ould-Amer et al., 1998)

The enhancement of radiative and convective heat transfer by the insertion of porous medium was presented by Chen and Sutton (Chen and Sutton, 2005). They concluded that the effect of enhancing the Darcy number of a porous insert is significant on

the enhancement of heat transfer. They considered a circular geometry with an inner layer occupied by the porous medium and outer layer by the fluid. A similar trend of accomplishing the augmented heat transfer by inserting the porous material was reported by Zhang et al. (Zhang et al., 1996). In addition to the enhancement in the heat transfer, they introduced a new technique, the Convection to Radiation (CRC) technique, by inserting the porous ceramic materials. They found that, it not only increases the convective heat transfer but also enhanced radiative heat transport. The system was considered to be effective for the gas medium and weak emanate with slower velocity and lower wall temperatures.

The vertical ducts/channels are important structures which find numerous applications, such as in electronic equipment cooling, residential/commercial building air conditioning. An attempt was made to study the problem of a fully developed laminar mixed convection through a vertical annular duct embedded in a porous medium. by Kou and Huang (Kou and Huang, 1997). They found that the temperature distribution depends on thermal boundary conditions and the inner to outer radii ratio. They further concluded in their study that the presence of the porous particles would increase wall friction and decrease the heat carried away by the fluid.

Pop et al. (Pop et al., 2004) investigated the mixed convection flow in a narrow vertical duct filled with a porous medium. Analytical and numerical analyses showed a very good agreement with each other in this study. It was fairly demonstrated that the interaction between the heat transfer and the fully developed flow has significant effects on the governing parameters.

Jecl and Škerget (Jecl and Škerget, 2003) applied the boundary element method (BEM) to study the natural convection in a non-Newtonian, fluid-saturated, square porous cavity and results were in agreement with that obtained by the finite difference method. It

was reported that enhancement of the heat transfer rate with the decrease in the power law index was seen in the vertical walls of the cavity.

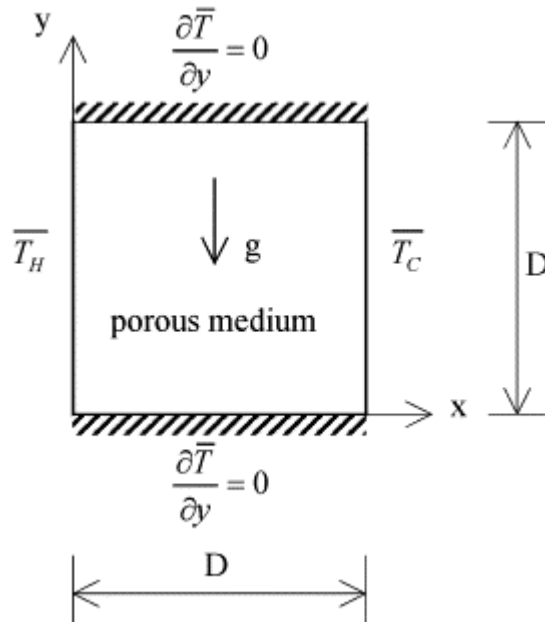


Figure 2.2.2: Geometry and boundary conditions for the porous cavity (Jecl and Škerget, 2003).

Amahmid et al. (Amahmid et al., 1999) considered the boundary layer flows in a vertical porous enclosure induced by opposing buoyancy forces. They carried out the analytical and numerical investigation to determine the convective heat transfer in a vertical porous layer submitted to constant fluxes of heat on the vertical sides. They obtained different results from the studies reported earlier for a boundary layer regime of the buoyancy ratio $N < 0$ and for the aiding buoyancy forces $N > 0$.

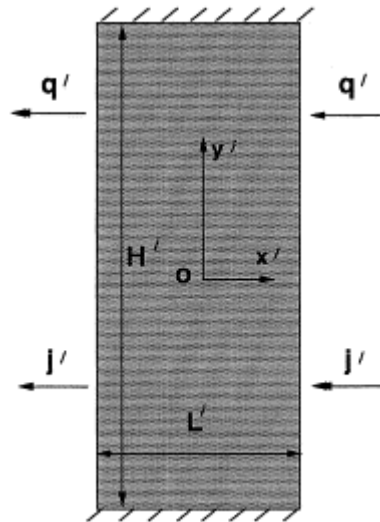


Figure 2.2.3: Schematic vertical porous enclosure. (Amahmid et al., 1999)

The effect of finite heat source at the bottom wall of the anisotropic porous cavity was considered by Krishna et al. (Krishna et al., 2009). They concluded that the velocity and the temperature gradients close to the heat source surface were enhanced in the Darcy regime due to an increase in the Rayleigh number. It was found that, in the non-Darcy regime, convective mixing occurred in the interior region due to higher permeability whereas in the Darcy regime the convective mixing occurred in the lower portions of the cavity due to lower permeability. The effect of the natural convection in a porous enclosure with a partial heating and salting element was analyzed by Zhao et al. (Zhao et al., 2008). The Nusselt and Sherwood numbers obtained in the results furnished the necessary details for locating the heating and salting segment. The effect of the Lewis and Darcy numbers on the double diffusive convection was investigated and it was found that decreased Darcy number was having a flow retardation effect and that suppressed the overall heat and mass transfer in the enclosure.

Sathiyamoorthy et al. (Sathiyamoorthy et al., 2007) analyzed the steady natural convection flow in a square cavity filled with a porous medium for linearly-heated side

walls. They found that in the case of a linearly heated left wall, the oscillation in local Nusselt number occurs at the bottom wall due to secondary circulations at $Da = 10^{-3}$. Badruddin et al. (Badruddin et al., 2006; 2007) investigated heat transfer in square porous cavities using Finite Element Method to determine the effects of physical and geometrical parameters.

2.3 Convective heat transfer in cylindrical geometries

A numerical investigation of transient free convection in a vertical cylindrical annulus filled with a fluid-saturated porous medium with the inner wall heated to a uniform temperature, the outer wall cooled to a uniform temperature while the top and bottom surfaces are maintained adiabatically, was reported by Shivakumara et al. (Shivakumara et al., 2002). The effect of radius ratio on the temperature and velocity profile was discussed and they found that at a high Rayleigh number, the curvature effect on the heat transfer is not significant. The heat transfer rate was found to be increased substantially with the radius ratio. A finite difference implicit method was used to determine the upwind differencing for nonlinear convective terms, whereby the successive line over relaxation (SLOR) method for convergence was used to solve the coupled nonlinear governing equations. The effects of the Darcy number, radii ratio, viscosity ratio and Rayleigh number on the temperature and velocity fields were studied.

Rashad and EL-Hakim (Rashad and EL-Hakim, 2007) investigated the effects of both free convection and radiation with non-linear Forchheimer terms from a vertical cylinder embedded in a fluid-saturated porous medium on fluid. The fluid viscosity was assumed to vary as an inverse linear function of temperature. The boundary-layer equations governing flow were solved numerically by using the second-level local

nonsimilarity method, which was used to convert the nonsimilar equations into a system of ordinary differential equations. Numerical results for dimensionless velocity, temperature profiles and the local Nusselt number were presented.

The phenomenon of natural convection in a right-angle triangular enclosure filled with a porous matrix was studied numerically by Basak et al. (Basak et al., 2008). A penalty finite element analysis with biquadratic trapezoidal elements was used for solving the Navier-Stokes and energy balance equations. The detailed study was carried out in two cases, depending on various thermal boundary conditions: (1) the vertical wall was uniformly or linearly heated, while the inclined wall was cold isothermally and (2) the inclined wall was uniformly or linearly heated, while the vertical wall was cold isothermally. In all cases, the horizontal bottom wall was adiabatic and the geometric aspect ratio was considered to be 1. Varol et al. (Varol et al., 2008) conducted a study on steady state two-dimensional natural convection heat transfer in triangular enclosures filled with porous media at different boundary conditions. Six different cases were tested based on all possibilities of temperature boundary conditions on vertical, bottom and inclined walls of enclosure. Solutions of governing equations and linear algebraic equations were performed by the central difference and the successive under-relaxation method, respectively. It was observed that when a heater was located at the bottom wall, multiple vortices were formed and the highest heat transfer was obtained according to the mode of other cases.

Minkowycz and Ping (Minkowycz and Ping, 1976) studied the natural convection in a vertical cylinder embedded in a saturated porous medium. It was assumed that the temperature of the wall varies along the height of the cylinder in a power law fashion. Prasad and Kulacki (Prasad and Kulacki, 1984) analyzed the steady free convection in a vertical annulus, filled with saturated porous medium. The vertical

walls were maintained at variable temperature, whereas the horizontal surfaces were insulated. They found that the velocity of the fluid in the upper half of the annulus was higher than that of the velocity in the lower half.

Bossom and Rees (Bassom and Rees, 1996) carried out their research pertaining to free convection from a heated vertical cylinder in a fluid-saturated porous medium. The power law temperature values were extended from the Merkins work. The Keller box method was used in their study. Kumari et al. (Kumari et al., 1985) investigated free convection on a vertical cylinder embedded in a saturated porous medium by using finite difference method and improved perturbation solution. A numerical study was performed by Havstad and Burns (Havstad and Burns, 1982) to analyze the convective heat transfer in a vertical annulus filled with porous medium. They found that the results obtained in their study were fairly in agreement with the results of others. They also showed some interesting findings with respect to the aspect ratio. Similar study was carried out using Finite Element method by Rajesh et al. (Rajesh et al., 1995). They investigated convective heat transfer in a vertical annular cylinder embedded with porous medium whereby the effect of the aspect and radius ratios of the annulus on the heat transfer rate was discussed. The study pertaining to interaction of natural convection and radiation on boundary layer flow along a thin vertical cylinder was carried out by Hossain and Alim (Hossain and Alim, 1997) to predict the heat transfer rate by means of the temperature and velocity profiles, and Nusselt number. The effects of the parameters such as the radiation parameter, R_d , the surface temperature parameter θ_w , Prandtl number Pr , on temperature and velocity profiles was evaluated and graphically presented. It was found that the increment in the radiation or temperature parameters resulted in the augmentation of the local heat transfer rate.

Reda (Reda, 1986) reported the experimental investigation on finite vertical cylinder. The study was based on the nuclear waste isolation in which the inner heat source along the length of the cylinder was maintained whereas the outer cylinder was maintained at constant temperature. The radial temperature drop across the annulus was found to be systematically deviated from the finite length cylinder conduction solution as heater power was increased.

Natural convection in a vertical cylinder with porous medium was studied using finite difference method with Keller Box scheme by Yih (Yih, 1999b). The Rosseland approximation was employed to incorporate the radiation term. It was found that the thermal boundary layer increased with radiation. Later heat transfer in a porous, heat-generating horizontal annulus was analyzed by Khanafer and Chamkha (Khanafer and Chamkha, 2003). The annulus was heated at the inner surface of the cylinder whereas the outer surface of the cylinder was cooled. The effect of Reynolds and Richardson numbers on the flow patterns and the heat transfer inside the annulus was analyzed. It was concluded that it had a significant effect on the heat transfer characterization in the annulus. They also found that the increase in the Reynolds number had a significant effect on the flow patterns with respect to two-eddy, one-eddy and no-eddy flows.

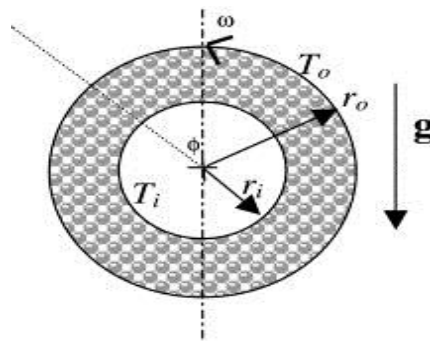


Figure 2.3.1: Schematic of porous heat-generating horizontal annulus. (Khanafer and Chamkha, 2003)

Non-Darcy natural convection heat and mass transfer in a vertical cylinder was considered by Hossain et al. (Hossain et al., 1999). The study was carried out by using two different methods, the finite difference and local non- similarity method. It was noticed that the boundary layer thickness increased with the curvature parameter.

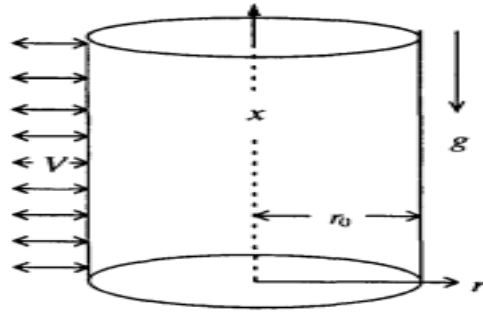


Figure 2.3.2: Physical model of vertical cylinder (Hossain et al., 1999)

Yih (Yih, 1998a) studied the combined heat and mass transfer phenomenon in a mixed convection domain. The governing equations were solved by using the Keller box and implicit finite difference methods. It was found that the local Nusselt number and Sherwood numbers decreased initially up to a certain minimum point and then increased gradually when the natural convection changed to forced convection. He showed that the increment in the curvature parameter resulted in the corresponding increment in local Nusselt and Sherwood numbers. Yih (Yih, 1998b) extended the study to investigate heat and mass transfer over a wedge with variable wall temperature. It was found that increased temperature or concentration exponent on the wall led to increased Nusselt and Sherwood numbers. He investigated the same phenomenon in the horizontal cylinder and concluded that the temperature and concentration profiles were showing declination with the non-dimensional circumferential coordinates.

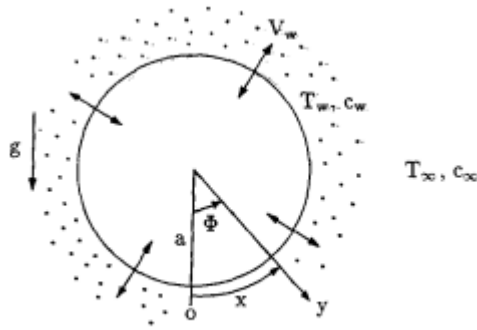


Figure 2.3.3: Flow model for heat and mass transfer over a wedge (Yih, 1998b)

Kwendakwema and Boehm (Kwendakwema and Boehm, 1991) investigated the mixed convection in concentric cylinders. They found that the local Nusselt number varies with the variation in the Reynolds numbers. They also reported the correlations of the average Nusselt number against the Grashof, Peclet, and Darcy numbers for various radius ratios.

Duwairi (Duwairi, 2006) reported numerical solutions for the effect of thermal radiation on mixed convection of optically dense viscous fluids about a non-isothermal cylinder and sphere. The governing equations were transformed by using a set of non-similarity variables and solved by using the Keller box method. Numerical results for the dimensionless velocity and temperature profiles and local Nusselt number for the mixed convection parameter, the power index of temperature variation, the radiation-conduction parameter and the surface temperature parameter were presented.

Natural convection in a porous horizontal circular cylinder was studied by Storesletten and Tveitereid (Storesletten and Tveitereid, 1991). The cylinder wall was non-uniformly heated to establish a linear temperature in the vertical direction, with the end sections perfectly insulated. At $L > 0.86$, a unique three-dimensional flow was determined at the onset of convection. For short cylinders ($L < 0.86$) the convection was two-dimensional. In this case there existed two different, steady solutions at

supercritical Rayleigh numbers, consisting of two and three rolls, respectively. It was proven that both flow structures and any composition of these structures were stable. However, introducing thermal forcing in the applied temperature, the flow became uniquely determined.

The heat transfer and fluid flow patterns in the mixed convection regimes for the double circular cylinders arranged transverse to the vertical air stream were presented by Chang-Joon and Keun-Shik (Chang-Joon and Keun-Shik, 1991). It was found that the Karman vortex street breaks down behind the double heated cylinders in a transient manner for a certain Richardson number range due to the buoyancy effect and vortex interaction, in contrast to the sudden breakdown applicable to a single heated cylinder.

Ho and Lin (Ho and Lin, 1991) presented a combined numerical and experimental study on the natural convection inside a horizontal concentric cylindrical annulus, partially filled with cold water encompassing the density inversion. A holographic interferometry system was employed to map the temperature distribution in the water layer, and a laser shadowgraph system was used to measure the local heat transfer coefficient on the water-wetted inner cylinder of the annulus. Both the numerical and the experimental results obtained in their study unveiled an interesting coupling between the natural convection of the air layer and that of the cold water bulk in the presence of the density inversion effect. The predictions were in good agreement with the experimental results.

The unsteady laminar natural convection flow from a heated horizontal cylinder under diverse surface boundary conditions was investigated numerically by Wang et al. (Wang et al., 1991) using the spline fractional step method. Some characteristics of the boundary layer obtained with a scale analysis were compared with the numerical results. The development of the plume region as well as the surface heat transfer and local

flow field were evaluated. Qualitative comparisons between the present results and flow visualization experiments partially verified the numerical results.

Kumar and Kalam (Kumar and Kalam, 1991) reported the numerical investigation of natural convective heat transfer of a fluid in vertical cylindrical annuli. The inner wall maintained at a higher temperature than the outer wall. The top and the bottom plates were insulated. Perfectly conducting horizontal walls were also considered for comparison of heat transfer results. Numerical results of heat transfer rates and flow fields for $10RaL10^6$, $1k$ 15 and $0.3 A$ 10 were reported. Discrepancies in the existing numerical and experimental data were noted and discussed. New correlations for heat transfer rate were presented.

Bu-Xuan and Xing (Bu-Xuan and Xing, 1990) presented a numerical study on three-dimensional, steady natural convection in liquid-saturated porous media enclosed between concentric, inclined cylinders. The inner cylinder was kept at constant heat flux or was isothermal, while the outer cylinder was maintained isothermally and the end plates insulated. Numerical studies range for: Rayleigh number, Ra 10^3 ; radius ratio 1 $|R_O|$ 10 ; aspect ratio 1 $|A|$ 15 ; angle of inclination ϕ from 0° to 90° . Numerical results showed that there existed a critical aspect ratio, for which the angle of inclination had no effect on the heat transfer. Good agreements between numerical results and experimental values ascertained for mean Nusselt number Num .

McLeod and Bishop (McLeod and Bishop, 1989) explained the heat transfer by natural convection of helium between horizontal isothermal concentric cylinders at cryogenic temperatures. As whole heat transfer rates, profiles of the time-averaged temperature and its fluctuations were measured for different Rayleigh and different expansion numbers. An equation was presented which correlated the heat transfer data

in terms of the expansion and Rayleigh numbers based on the inner and outer cylinder diameters. The influence of the Rayleigh and expansion number on time-averaged temperature profiles and temperature fluctuations were reported. The nature and extent of turbulence in the convective flow, as reflected in the fluctuations of temperature, were also documented.

Hirata and Nishida (Hirata and Nishida, 1989) investigated the process of a phase change material (PCM) inside an isothermally heated horizontal cylinder. It was shown that melting rates show good agreement with the experimental data for a wide range of Rayleigh numbers. Also the effect of the natural convection on the melting process can be negligible for $Ra_D < 10^5$.

Mixed convection in laminar boundary layer flow along a slender vertical cylinder was analyzed by Heckel et al. (Heckel et al., 1989). The local Nusselt number was found to be increased with surface curvature. The correlation between the local and average Nusselt numbers was also discussed.

Muralidhar (Muralidhar, 1989) presented the analysis of mixed convective flow and heat transfer in the annular region between concentric cylinders filled with fluid-saturated porous material. The results were shown for various parameters such as Peclet and Rayleigh numbers.

Numerical analysis on a natural convection in isosceles triangular enclosures with inclination angles (φ) filled with a fluid-saturated porous medium was reported by Varol et al. (Varol et al., 2009). It was reported that both the inclination angles and Rayleigh numbers had a profound effect on natural convective heat transfer, fluid flow and entropy generation. Similarly Kaiser et al. (Kaiser et al., 2009) studied numerically the natural

convective flows, for high Rayleigh numbers, in a sloped converging channel. Two-dimensional, laminar, transitional and turbulent simulations were carried out by solving the fully elliptic governing equations using Fluent and Phoenics. An application of the numerical correlation in two experimental prototypes was presented.

Harsini and Ashjaee (Harsini and Ashjaee, 2009) demonstrated the variation of natural convection heat transfer from an isothermal horizontal cylinder confined between two adiabatic walls of constant height. They employed Mach-Sender interferometry technique and the cylinder's local and average Nusselt numbers were determined for ratio of vertical position to its diameter ranging from $Y/D = (0 \text{ to } 10)$, for the Rayleigh number ranging from 3.5×10^3 to 1.4×10^4 . It was showed that the value of the optimum vertical position was increased with ascending Rayleigh numbers.

Varol et al. (Varol et al., 2008) investigated the buoyancy-driven flow and heat transfer in an inclined trapezoidal enclosure filled with a fluid-saturated porous medium heated and cooled from inclined walls. The results showed that the angle of inclination had a profound effect on the heat transfer and flow strength than that of the side wall inclination angle. At 90° Bénard regime was observed.

Natural convection in the enclosed space between two concentrically positioned vertical cylinders having different finite heights was reported by Sparrow and Myrum (Sparrow and Myrum, 1987). Parametric vibrational study was carried out for the height of the fluid-fluid interface and for the Rayleigh number. Comparisons were made between the experimental results and predictions obtained from numerical solutions.

Tian-Yih and Kleinstreuer (Tian-Yih and Kleinstreuer, 1988) studied the steady laminar forced convection of micro-polar fluids past two-dimensional or axisymmetric bodies

with porous walls and different thermal boundary conditions. They concluded that the effects of material parameters, wall mass transfer, the Prandtl number and the distinct thermal boundary conditions on the local skin friction coefficient and heat transfer coefficient were the key findings in their study.

An experimental and numerical investigation of the transient free- convection flow in the annulus between horizontal concentric cylinders was investigated by Castrejon and Spading (Castrejon and Spading, 1988). The numerical simulation was carried out by using finite domain method using the interface tracking technique. The experimental and numerical results were compared using an interface-tracking technique.

2.4 Conjugate heat transfer in cylindrical geometries

A study on conjugate natural convection in two-dimensional vertical porous layer sandwiched between two equal-thickness walls was presented by Saeid (Saeid, 2007). The Darcy model was used in the mathematical formulation for the porous layer and finite volume method was employed to solve the dimensionless governing equations. The parameters such as the ratio of the wall thickness to its height, the wall to porous thermal conductivity ratio and the Rayleigh number were analyzed. The results were presented to show the effect of these parameters on the heat transfer and fluid flow characteristics. Similarly Kaya (Kaya, 2011) investigated the mixed convection heat transfer of a vertical slender hollow cylinder. The effects of the porosity on buoyancy and conjugate heat transfer were analyzed. It was found that an increase in the conjugate heat transfer parameter tends to decrease the velocity and the temperature gradient. This in turn, decreased the dimensionless interfacial temperature distribution, the local skin friction and the local heat transfer parameters.

Conjugate heat transfer in porous medium with uniform heating was reported by

Lopez et al. (Lopez et al., 2012). They presented the detailed discussions for an array of inline and staggered square rods. In another study Cha and Chien-Hsin (Cha and Chien-Hsin, 1990) investigated the conjugate convection-conduction analysis in the case of a vertical plate fin embedded in a variable porosity medium. They concluded that due to the near-wall porosity variation, the heat transfer rate is greatly increased. Similarly the conjugate heat transfer for different parameters and in different scenarios explained the phenomenon (C.-H. Chen and Chiou, 1994; Gill and Minkowycz, 1988; Higuera, 1997; Higuera and Pop, 1996; Liu and Minkowycz, 1986; Tao et al., 2005; Wu et al., 2004).

2.5 Convective heat and mass transfer in porous medium

Double diffusive non-Darcy natural convection flow along a permeable vertical cylinder embedded in a saturated porous medium was reported by Hossain et al. (Hossain et al., 1999). The effects of various key parameters on the velocity, temperature and species concentration profiles were presented graphically. A combined heat and mass transfer analysis in MHD non-Darcy non-Newtonian natural convection adjacent to a horizontal cylinder in a saturated porous medium was investigated by El-Kabeir et al. (El-Kabeir et al., 2008). The distinctive features of the pertinent parameters were discussed such as the effects of a magnetic parameter M , Ergun number Err , power law (viscosity) index n , buoyancy ratio N , radiation parameter R_d , Prandtl number Pr and Lewis number Le on the velocity, temperature fields within the boundary layer, heat and mass transfer were presented graphically.

A coupled heat and mass transfer by natural convection from a cylinder in porous media was analyzed by Singh and Chandarki (Singh and Chandarki, 2009). They found that the local Nusselt number was found to be decreased while the local Sherwood number increased with Lewis number Le for positive values of buoyancy ratio N . The effects of the

curvature, the buoyancy parameter and the Lewis number on the temperature, concentration and flow fields were investigated in a study carried out by Yücel (Yücel, 1990). The combined heat and mass transfer analysis of natural convection along a vertical cylinder in a saturated porous medium was studied. In another study the combined heat and mass transfer characteristics of free convection about a permeable horizontal cylinder embedded in porous media was reported by Yih (Yih, 1999a). The coupled effects of thermal and mass diffusion were analyzed numerically with respect to the horizontal cylinder embedded in porous media. He also investigated the mixed convection phenomenon in the case of the vertical cylinder. It was found that the density gradients that provided the driving buoyancy effect were induced by the combined effects of temperature and concentration in a porous medium (Yih, 1998a).

2.6 Convective heat transfer in cylindrical geometries using thermal non-equilibrium approach

Most of the studies in porous medium were carried out by considering the local thermal equilibrium conditions where, the solid and fluid phases are assumed to be at the same temperature locally. In applications using porous media such as thermal energy transport, cooling of electronic devices, chemical reactors, the thermal non-equilibrium approach has become not only important but essential for obtaining the accurate results in the analysis. The analysis incorporating the local thermal non-equilibrium model of the heat transfer in the porous medium has received less attentions of researchers than which it deserves. The literature pertaining to the thermal non-equilibrium analysis are insufficient compared with the work on thermal equilibrium approach. The following section provides the details about the work carried out considering the thermal non-equilibrium approach.

Hao and Tao (Hao and Tao, 2003) investigated the thermal non-equilibrium characteristics of melting of a packed bed under horizontal forced and mixed convections. The typical melting processes characterized by varying the mainstream velocity, supplied temperatures and initial mass of packed bed. The effects of water velocity and water temperature on melting and heat transfer in the melting process analysis and the effect of packing patterns on Nusselt number correlations were demonstrated. Using the definition of a terminal velocity, a Reynolds number ratio was developed as the criterion defining the floating, non-floating or transitional packing pattern.

Rees et al. (Rees et al., 2003) examined the steady forced convective boundary layer flow past circular cylinder embedded in a saturated porous medium. The heat transfer coefficients for the fluid and solid phases were computed numerically. The partial differential equations were solved by the matched asymptotic approach. Detailed numerical results were presented in their study. At the low inter-phase heat transfer coefficient H , the thermal field corresponding to the solid phase was found to occupy a much greater region than the thermal field of the fluid phase.

Jiang and Ren (Jiang and Ren, 2001) investigated the effects of viscous dissipation, the boundary condition assumptions thermal dispersion, particle diameters and variable properties of oil on convection heat transfer using thermal non-equilibrium assumption. They found that the viscous dissipation reduced the convection heat transfer on the wall in the porous media. The variations of the thermal physical properties of oil had a profound influence on the convection heat transfer coefficient that increased with heat flux.

Nnanna et al. (Nnanna et al., 2004) presented their experimental investigation about local thermal non-equilibrium behaviour in PCM-saturated porous media. The coefficients

that affected the heat transfer during the phase change such as the effective latent heat, the contribution of the interstitial heat transfer coefficient, effect of contact/constriction resistance were estimated in the studies. The experimentally measured data was compared with the theoretical predictions reported in the literature.

A two energy equation model was developed by the Nakayama et al. (Nakayama et al., 2001) to analyze the conduction and convection phenomena in porous medium. They showed that for one dimensional steady problem, the two energy equations can be combined together to form a fourth order O.D.E with respect to the intrinsically averaged fluid temperature, that are solved with appropriate boundary conditions to find the exact solution. Malashetty and Basavaraja (Malashetty and Basavaraja, 2004) studied the thermal non equilibrium modeling analytically in horizontal fluid saturated sparsely packed porous layer. The various parameters showed in their results, that fluid flow transition had taken place from the Brinkman to the Darcy regime. It was also found that the results of the Darcy model for the non-equilibrium case can be recovered in the limit as the Darcy number, Da , approaches 0.

Saito and Lemos (Saito and Lemos, 2005) presented their study on the computational procedure to determine the coefficient of convective heat exchange between the porous substrate and the working fluid. The results were computed by considering the repetitive velocity and temperature fields. A detailed computational procedure was presented to determine the convective coefficient of heat exchange between the porous substrate and the working fluid.

Banu and Rees (Banu and Rees, 2002) formulated the thermal non-equilibrium model for solid and fluid phase temperatures in fluid-saturated, porous medium. They studied the effect of the onset criterion for the convection in a horizontal layer by adoption

of such a model.

Marafie and Vafai (Marafie and Vafai, 2001) investigated the forced convective flow filled with porous medium. Energy equations for solid and fluid phase were solved using the thermal non-equilibrium model. It was found that the Darcy number and inertial parameter have lesser influence in establishing the validity of the local thermal non-equilibrium assumption.

The entropy generation in a saturated porous cavity for laminar natural convection was investigated by Baytas (Baytas, 2007). The study considered the non-Darcy flow model and a thermal non-equilibrium approach. Two-dimensional steady convection in a cavity bounded by isothermal walls at a constant temperature was studied numerically and it was assumed that the heat generation is only in the solid phase. The emphasis was given on the entropy generation distribution for the solid fluid scaled heat transfer coefficient and the porosity-scaled conductivity ratio. The non-Darcy and thermal non-equilibrium approach was adopted by using the second law of thermodynamics.

Barletta et al. (Barletta et al., 2008) presented the study on mixed convection seepage flow on the fully developed parallel flow in an annular region filled with a porous medium surrounding an electric cable. The effects of buoyancy and MHD force along with the heat generation due to Joule heating and viscous dissipation were considered. The problem was solved both analytically and numerically. It was found that there existed significantly strong magnetic force which tends to inhibit the flow even for a high hydrodynamic pressure gradient.

Singh and Roy (Singh and Roy, 2007) reported the study on the development of unsteady mixed convection flow of an incompressible laminar viscous fluid over a vertical cone. The smooth transition from the initial steady state to the final steady state

was observed. Velocity, temperature, and concentration profiles and their gradients at the surface for various values of the governing parameters were reported. In another study Singh and Roy (Singh and Roy, 2008) later reported the investigation on fluid flow and heat transfer characteristics for mixed convection along a rotating vertical slender cylinder. They found that the velocity profiles in x - and θ -directions and the temperature profile were substantially influenced by rotational, buoyancy and suction/injection parameters. The results were presented in terms of skin friction coefficients in x - and θ -directions and Nusselt number.

Mixed convection of laminar pulsative flow and heat transfer past a backward-facing step in a channel was analyzed by Khanafer et al. (Khanafer et al., 2008). It was found that the Reynolds and Richardson numbers and dimensionless oscillation frequency had significant effect on the structure of fluid flow, heat transfer fields and skin friction coefficient. Chiu and Yan (Chiu and Yan, 2008) conducted a numerical study to investigate the radiation effect on the characteristics of the mixed convection fluid flow and heat transfer in inclined ducts. The effects of the thermal buoyancy and the radiative heat transfer on the distribution of the bulk fluid temperature. The friction factor and the Nusselt number were discussed in detail. It was found that significant radiation effects on the heat transfer tend to reduce the thermal buoyancy effects.

Zanchini (Zanchini, 2008) studied the mixed convection with a temperature-dependent viscosity in a vertical annular duct with uniform wall temperatures analytically. It was concluded that the combined effects of buoyancy forces and of a variable fluid viscosity on the cross-section-averaged Fanning friction factor were important and that negative values of this quantity were occurred.

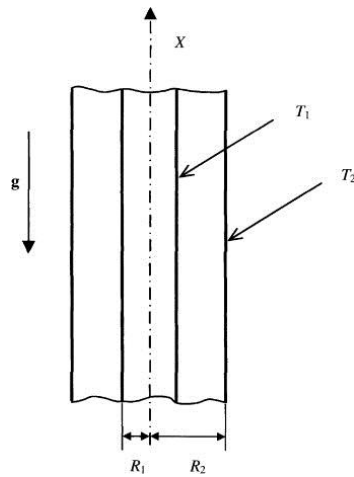


Figure 2.6.1: Schematic of the annular duct (Zanchini, 2008)

Dhiman et al. (Dhiman et al., 2008) presented the study of the effects of cross-buoyancy and of Prandtl number on the heat transfer characteristics of an isothermal square cylinder confined in a channel. The drag coefficient was found to be less sensitive to the Richardson number than the lift coefficient. The overall drag and lift coefficients, local and average Nusselt numbers and the representative streamline and isotherm plots were presented to elucidate the role of Reynold, Prandtl and Richardson numbers.

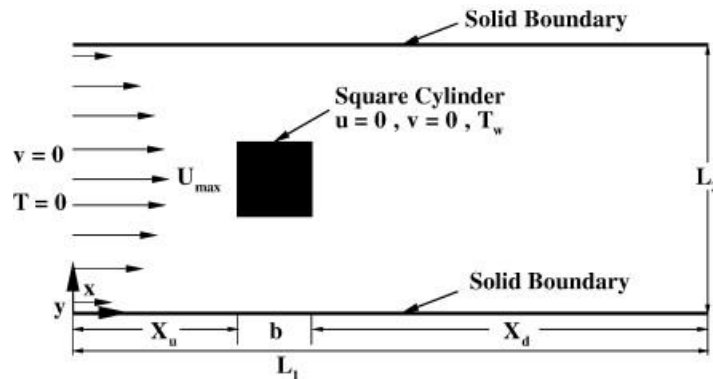


Figure 2.6.2: Schematic of the flow around a square cylinder (Dhiman et al., 2008)

Voicu et al. (Voicu et al., 2007) examined the steady state, simultaneously developing, and laminar mixed convection in a vertical double pipe heat exchanger. The flow was assumed as upward parallel flow. The viscosity and the density of the fluids were made to depend on the temperature while all other thermo-physical properties were

assumed to be constant. The results were presented in the form of temperature and velocity profiles at different cross sections. Results were calculated for fixed inlet temperatures, a Richardson number equal to 1 for the annular space and three different values in the cylinder (4.85, 1 and 0.34).

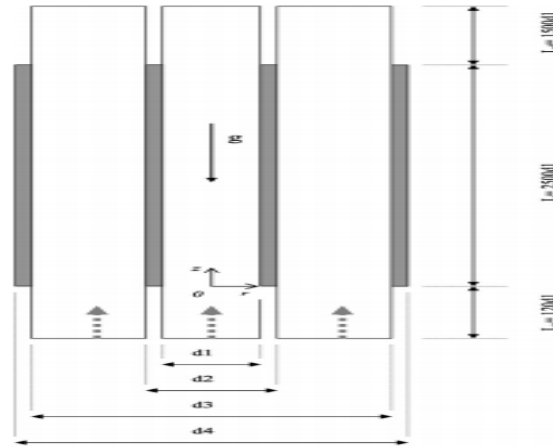


Figure 2.6.3: Vertical double pipe heat exchanger (Voicu et al., 2007)

2.7 Critical literature review

In recent years the importance of the heat transfer analyses in square and cylindrical geometries have gained—considerable attention due to its relevance in the various industrial, engineering and biological applications such as electronic cooling system, human thermal comfort, flow through arteries and veins and solar energy collection/storage techniques. As evidenced from the open literature, a lot of research carried out with greater emphasis on the specific geometries to determine the solutions to the problems sought in this field. Several researchers carried out remarkable investigation in similar geometries (Prasad and Kulacki, 1984), (Beckermann et al., 1986; Manole and Lage, 1992; Moya et al., 1987; Rajamani et al., 1995; Sathiyamoorthy et al., 2007). The parametrical study was carried out so far is considered as comprehensive work in this

aspect. However, the applications pertaining to various aspects such as conjugate heat transfer, conjugate heat and mass transfer, segmental heating, mixed convection analysis with segmental heating are not adequately addressed. Thus following problems need thorough investigation to understand the various aspects of heat transfer

- Investigation of heat transfer characteristics in a square porous annulus.
- Investigation of conjugate heat transfer behaviour in a cylindrical annulus.
- Conjugate heat and mass transfer in a vertical annulus.
- Discrete heating and mixed convection in a vertical annulus.

Thus an attempt is made in the current study to explore these new areas.