NANOFLUID TRANSPORT IN POROUS MEDIA: A REVIEW

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Convection heat transfer mode is the principal topic in thermal transfer. So, it is the matter of many numerical and experimental studies. In recent years, much attention was given to the use of free/forced/mixed convection heat transfer with nanofluids in geothermal engineering, storage of radioactive nuclear waste, solar collectors, transpiration cooling, performance of cold storage, separation processes in chemical industries, thermal insulation of buildings, filtration, space technology, transport processes in aquifers, nuclear reactor cooling system, groundwater pollution, underground nuclear wastes disposal, geothermal extraction, and fiber insulation, etc, and many researches were reported in this topic. This paper presents a detailed review of the numerical and experimental studies carried out by various researchers in order to obtain enhanced heat transfer in free, forced, and mixed convection by using nanofluids in porous media. Critical information of all studies in three categories (analytical, experimental. and numerical) has been collected.

KEY WORDS: *nanofluids, porous media, natural convection, forced convection, mixed convection*

1. INTRODUCTION

Fluid flow and heat transfer in porous media received considerable interest during the last several decades. This is primarily because of the numerous applications of flow through porous medium, such as storage of radioactive nuclear waste, transpiration cooling, separation processes in chemical industries, filtration, transport processes in aquifers, groundwater pollution, geothermal extraction, and fiber insulation. Theories and experiments of thermal convection in porous media and state-of-the-art reviews with special emphasis on practical applications are presented in the recent books by Nield and Bejan (2006), Pop and Ingham (2001), Ingham and Pop (2002), Bejan et al. (2004), and Vafai (2005).

In the past decades, many scientists and engineers attempted to increase the efficiency and the rate of heat transfer, and various methods have been employed to meet this need. One of these methods for enhancing the heat transfer rate is to increase conducting properties of the fluid. This improvement can be obtained by using nanofluids, i.e., a combination of a base fluid (usually water, oil, or ethylene glycol) and high thermal conductive metallic nanoparticles such as Cu, Al_2O_3, SiO_2, and so on (Siavashi and Rostami, 2017).

Nanofluid is made by adding nanoparticles and a surfactant into a base fluid can greatly enhance thermal conductivity and convective heat transfer. The diameters of nanoparticles are usually less than 100 nm, which improves their suspension properties. Nanofluid technology has emerged as a new enhanced heat transfer technique in recent years (Nasrin et al., 2013). Nanofluids strengthen solar energy applications such as heat exchanger design and medical applications including cancer therapy and safer surgery by heat treatment. Nanofluid technology can also help to develop better oils and lubricants for practical applications (Ellahi, 2018).

In the recent years, simultaneous use of nanofluids and porous materials in enhanced heat transfer problems has also found a great deal of attention (Siavashi and Rostami, 2017). In many studies the natural/forced/mixed convection heat transfer of a nanofluid in porous media has been analyzed.

2. NATURAL CONVECTION HEAT TRANSFER

The convective heat transfer in enclosures is important, as it does not need an external power source for inducing convective heat transfer, so that in this type of convective heat transfer, there is no need of any electrical supplies and electronic regulation. The natural convection process also excludes the risks of mechanical malfunction existing for systems owing to forced convection flow. The absence of external power supplies systems reduces the cost, sound, and the magnetic noise in natural convection process. These are only some of the advantages of the natural convection flows, which continuously increase the interest of industrial sections and researchers to resort to this heat transfer phenomenon. In addition, the natural convection phenomena are especially important for equipment located in limited volumes (or enclosures), which frequently are encountered in many industrial applications and situation (Ghalambaz et al., 2015).

Rajarathinam and Nithyadevi (2018) studied the numerical investigation of the laminar natural convection flow of a Cu–water nanofluid in an inclined porous square cavity. The cavity was bounded by isothermal vertical walls and adiabatic horizontal walls. It was found that the inclination angle plays a significant role on the flow patterns when the values of the Darcy number and nanoparticle size are relatively high.

Chamkha and Ismael (2013) numerically investigated the problem of steady conjugate natural convection–conduction heat transfer in a square porous cavity heated diagonally and filled with nanofluids using Over Successive Relaxation (OSR) finite-difference method. Three types of nanoparticles were examined under a wide range of nanoparticles volume fraction, triangular wall thickness, triangular wall to base-fluid conductivity ratio, and Rayleigh number.

The second law analysis for free convection heat transfer along a cone embedded in a nanofluid saturated non-Darcy porous medium with the effects of viscous dissipation and Newtonian heating was studied [Mahdy et al. (2017)] in this work. The effects of the governing parameters, such as non-Darcy, viscous dissipation, and solid volume fraction parameter on the velocity, temperature, profiles, entropy generation, and Bejan number were presented in graphs.

Astanina et al. (2018) analyzed the natural convective fluid flow and heat transfer in a square cavity with a local heat-generated and heat-conducting element under the effects of temperature-dependent viscosity and porous layer in dimensionless stream function, vorticity, and temperature using the finite-difference method. Distributions of streamlines and isotherms as well as the average Nusselt number, fluid flow rate, and the average temperature inside the heater in a wide range of governing parameters were obtained.

Sheremet et al. (2015a) investigated the effect of variable thermal boundary condition on free convection of nanofluid in a square porous cavity using the Tiwari and Das nanofluid model. The authors showed that an augmentation in the volume fraction of nanofluid in the aluminum porous zone leads to a diminution in the average Nusselt number, while the opposite fact is observed in the porous zone with glass balls.

Reddy et al. (2016) performed a study on free convective heat and mass transfer characteristics of heat-generating magneto-nanofluid flow through a vertical moving porous plate in a conducting field. The water-based nanofluid with the composition of copper was considered in this analysis. The novelty of this study was the consideration of simultaneous occurrence of porous medium, radiation, heat source, and Soret effect.

Belhaj and Ben-Beya (2018) numerically investigated the unsteady natural convection flow in the presence of a uniform magnetic field. The cavity was filled with carbon nanotube carbon nano-tube (CNT)-water nanofluid and heated from below with a sinusoidal temperature distribution. The effects of Hartmann number, Rayleigh number, and unsteadiness on fluid flow and heat transfer were predicted and analyzed at different combinations of the parameters.

Bhadauria and Agarwal (2011) investigated the thermal instability in a horizontal porous layer saturated by a nanofluid, and rotating about the z axis with uniform angular velocity ω. The porous layer was heated from below and cooled from above. The distribution of nanoparticles was considered to be bottom heavy, i.e., the density of nanoparticles decreases as we go up in the porous layer.

Chamkha et al. (2011) presented a boundary-layer analysis for the natural convection past a sphere embedded in a porous medium saturated with a nanofluid. Numerical results for friction factor, surface heat transfer rate, and mass transfer rate were presented for parametric variations of the buoyancy ratio parameter N_r, Brownian motion parameter N_b, thermophoresis parameter N_t, and Lewis number Le. The dependency of the friction factor, surface heat transfer rate, and mass transfer rate on these parameters was discussed.

Chamkha et al. (2014b) investigated the influence of viscous dissipation and magnetic field on natural convection from a vertical plate in a non-Darcy porous medium saturated with a nanofluid. In addition, a convective boundary condition was incorporated in the nanofluid model. A non-similarity transformation was used to reduce the mass, momentum, thermal energy, and the nanoparticle concentration equations into a set of nonlinear partial differential equations.

Chamkha et al. (2014a) numerically analyzed the natural convection in differentially heated and partially porous cavity filled with a nanofluid based on the double-domain formulation. The main feature of this study was to determine if the conventional studied parameters in partially porous cavity like the permeability and the thickness of porous layer, Rayleigh number, and the cavity aspect ratio were determined by the volume fraction of the nanoparticles or not.

Ghasemi and Siavashi (2017a) examined nanofluid natural convection inside a porous enclosure with different linear temperature distribution on its side walls using Lattice Boltzmann method (LBM). The investigators found an optimal Rayleigh number to maximize heat transfer for each Darcy number.

Ghasemi and Siavashi (2017b) analyzed magnetohydrodynamic (MHD) nanofluid free convection in a porous enclosure with different porous-fluid thermal conductivity ratios (K^*). The obtained results showed that depending on K^*, Ra, and Ha values, use of nanofluid with porous media can be either beneficial or detrimental for heat transfer enhancement.

Gorla and Chamkha (2011) presented a boundary-layer analysis for the natural convection past a nonisothermal vertical plate in a porous medium saturated with a nanofluid. The effects of Brownian motion and thermophoresis were included for the nanofluid. Numerical solutions of the boundary-layer equations were obtained and discussion was provided for several values of the nanofluid parameters governing the problem.

Kolsi et al. (2016) performed numerical simulations on a cubical cavity filled with nanofluid. The effect of adiabatic blocks on natural convection and entropy generation was studied. The variables considered were Ra, volumetric fraction of aluminum oxide particles, and block size. The results for fluid flow with a single-phase model were elucidated with iso-surfaces of temperature, Nusselt number, and Bejan number.

Toosi and Siavashi (2017) conducted a numerical analysis on nanofluid natural convection in a square cavity partially filled with a porous medium layer on its walls. The authors indicated that an optimal porous thickness and nanofluid concentration exist depending on Rayleigh and Darcy numbers.

Moghaddam et al. (2013) proposed an analytical method for rapid determination of dissolution rate in a convection–diffusion mechanism. Experimental tests were conducted in porous media to evaluate this new diffusion coefficient. It was shown that this coefficient can be approximated by a relationship for the Rayleigh number of the system. This relation was entered into the diffusion equation and used as a new diffusion coefficient. They suggested that the analytical method presented herein could be used as a simple and rapid tool to screen the technical or economic feasibility of a proposed CO_2 injection scenario in actual fields.

Aziz et al. (2012) numerically reported the free convection boundary-layer flow past a horizontal flat plate in nanofluid containing gyrotactic microorganisms, and they found that the bioconvection parameters have strongly influenced the mass, heat, and motile microorganism transport rate.

Mansour et al. (2013) numerically investigated the natural convection fluid flow and heat transfer characteristics inside H-shaped enclosures filled with nanofluid using the finite-difference method. The governing parameters considered were the Rayleigh number, the aspect ratio of the H-shaped enclosure, the different lengths of the heat source, the different locations of the heat source, the volume fraction of the nanoparticles, and the different types of nanoparticles (Cu, Ag, Al_2O_3, and TiO_2).

Rahman et al. (2016) performed a finite element solution in this work to solve unsteady governing equations of natural convection in a CNT-water filled cavity with inclined heater. The temperature of ceiling and left vertical walls was lower than that of the heater while the other walls were adiabatic. The main governing parameters were nanofluid volume fraction and Rayleigh number (Ra).

RamReddy and Rao (2017) presented a numerical analysis to explore the effects of thermal and solutal stratification on the natural convective flow of a nanofluid over vertical frustum of a cone embedded in a non-Darcy porous medium. The components of flow attributes were investigated by plotting graphs and explored in detail for various values of thermal stratification, solutal stratification, non-Darcy parameter, and Lewis number.

Agarwal et al. (2011) aimed at studying the thermal instability in a rotating anisotropic porous layer saturated by a nanofluid. The model used for nanofluid combines the effect of Brownian motion along with thermophoresis, while for a porous medium the Darcy model was used. Using linear stability analysis the expression for the critical Rayleigh number was obtained in terms of various nondimensional parameters. Bottom-heavy and top-heavy arrangements of nanoparticles were shown to prefer oscillatory and stationary modes of convection, respectively. Several results were obtained as limiting cases of the present study.

Sheremet et al. (2015b) studied the natural convection in a square porous cavity with isothermal vertical walls and adiabatic horizontal ones filled with a water-based nanofluid. Particular efforts were focused on the effects of the Rayleigh number, solid volume fraction parameter of nanoparticles, porosity of the porous medium and solid matrix of the porous medium on flow field, temperature distribution, and Nusselt number.

Sheremet et al. (2016) numerically studied the natural convective heat transfer and fluid flow in an open porous cavity filled with a nanofluid using the Tiwari and Das nanofluid model. The transport equations for mass, momentum, and energy formulated in dimensionless stream function and temperature were solved numerically using a second-order accurate finite-difference method. Particular efforts were focused on the effects of the governing parameters on the heat and fluid flow.

Shirvan et al. (2017a) investigated a numerical study on natural convection along with surface radiation heat transfer in an inclined porous solar cavity receiver by means of response surface methodology (RSM). It was found that the sensitivity of mean Nusselt number increases by increasing Rayleigh number, Darcy number, and inclination angle θ whereas the sensitivity of mean Nusselt number of natural convection heat transfer to porous substrate thickness δ declines.

Sivasankaran and Pan (2014) conducted a numerical study to investigate the effects of amplitude and phase deviation of sinusoidal temperature distribution on the convective flow and heat transfer of nanofluids in a square cavity. The horizontal walls of the cavity were adiabatic. The results showed that the heat transfer rate is increased when increasing the amplitude ratio and volume fraction of nanoparticles. The heat transfer behaves nonlinearly with the Rayleigh number and the phase deviation, attaining the maximum at $3\pi/4$.

Tahmasebi et al. (2018) addressed the natural convection heat transfer in a cavity filled with three layers of solid, porous medium, and free fluid. The porous medium and free fluid layers were filled with a nanofluid. The porous layer was modeled using the local thermal nonequilibrium (LTNE) model, considering the temperature difference between the solid porous matrix and the nanofluid phases. The nanofluid was modeled using the Buongiorno's model incorporating the thermophoresis and Brownian motion effects. The effects of various non-dimensional parameters were discussed.

Uddin et al. (2012) numerically studied the steady laminar incompressible free convective flow of a nanofluid over a permeable upward-facing horizontal plate located in porous medium taking into account the thermal convective boundary condition. Using similarity transformations the continuity, the momentum, the energy, and the nanoparticle volume fraction equations were transformed into a set of coupled similarity equations, before being solved numerically, by an implicit finite-difference numerical method.

Wang et al. (2014) reported a numerical study of natural convective heat transfer of copper-water nanofluid in a square enclosure where the temperature of the left vertical sidewall was sinusoidally oscillated with a constant average temperature, the right sidewall was cooled at a relatively low temperature, and the other walls were kept adiabatic. The influence of pertinent parameters such as Rayleigh number, solid volume fraction of copper nanoparticles, and dimensionless time period on the heat transfer characteristics was studied. The results showed that the heat transfer rate increases using copper nanoparticles.

Wu et al. (2015a) numerically studied the steady non-Darcy natural convection in a porous cavity with sinusoidal thermal boundary condition by adopting the LTNE model. The top and bottom walls of the enclosure were adiabatic, whereas the left vertical wall was partially heated and cooled by a sinusoidal temperature profile and the right vertical wall was cooled by the uniform thermal boundary condition. The results showed that, compared with the uniform boundary conditions, the sinusoidal boundary conditions can enhance the heat transfer rate of a porous cavity.

Wu et al. (2015b) numerically investigated a two-dimensional steady-state fluid flow and heat transfer problem inside an enclosure filled with a heat-generating porous medium by linearly thermal boundary condition. The study used the generalized non-Darcy model to describe the flow field. Furthermore, the thermal non-equilibrium model was used to describe the local solid and fluid temperature profiles.

Chamkha and Rashad (2012) studied steady, laminar, natural convection boundary-layer flow over a permeable vertical cone embedded in a porous medium saturated with a nanofluid in the presence of uniform lateral mass flux. The presence of nanoparticles has significant effects of heat transfer.

Mansour and Ahmed (2015) discussed the natural convection heat transfer in an inclined triangular enclosure filled with Cu-water nanofluid-saturated porous medium in the presence of heat generation effect. Two symmetric heat sources were located at the bottom and left walls of the enclosure while the remaining parts were thermally insulated. The inclined wall of the enclosure was considered to be cold. It was found that a good enhancement in the average Nusselt number can be obtained by an increase in the nanoparticle volume fraction. Also, an increase in the heat generation parameter led to a decrease in the average Nusselt number.

Ghalambaz et al. (2016) studied the influence of the viscous dissipation and radiation effects on the natural convection heat transfer in a square cavity filled with porous media saturated with a nanofluid. The influences of viscous dissipation and radiation effects on the concentration distribution of nanoparticles were discussed. The average and local Nusselt numbers were reported for various values of viscous dissipation (Eckert number) and radiation effects.

Xu and Xing (2017) numerically investigated the flow and thermal performance of the natural convection of a nanofluid flowing in a porous medium cavity with the proposed LB model. The highly conductive porous foam and the nanofluid can obviously promote the thermal performance of natural convection, and the combination of the two has great potential for high heat flux applications.

3. FORCED CONVECTION HEAT TRANSFER

The knowledge of forced convection heat transfer inside geometries of irregular shape (for example, channel, pipe bend, channel with cavity) for porous media has many significant engineering applications; for example, geothermal engineering, solar collectors, performance of cold storage, and thermal insulation of buildings (Nasrin et al., 2013).

Simultaneous heat and mass transfer from different geometries embedded in porous media has many engineering and geophysical applications such as geothermal reservoirs, drying of porous solids, thermal insulation, enhanced oil recovery, packed-bed catalytic reactors, cooling of nuclear reactors, and underground energy transport (Chamkha and Khaled, 2000). In many studies the forced convection of a nanofluid in porous media has been investigated.

Xu (2017a) theoretically investigated the flow and heat transfer in microchannel with micro-/nanoporous medium, and the analytical solutions for velocity and temperature were obtained by considering the LTNE effect and the slip boundary. Thermal transport in multi-layered porous-medium microchannel heat exchangers was analyzed. The local temperature distribution of the two fluids was obtained for parallel-flow/counter-flow arrangements.

Shirvan et al. (2016) carried out a 2D numerical simulation and sensitivity analysis on turbulent heat transfer and heat exchanger effectiveness enhancement in a double-pipe heat exchanger filled with porous media. It was found that the mean Nusselt number increases by increasing the values of Reynolds number and dwindling of the Darcy number and porous substrate thickness.

Xu et al. (2018a) analytically modeled the forced convective flow in a microchannel partially filled with a porous medium with the velocity slips at the solid walls and the porous–fluid interfaces. The inertial effect in the porous medium was taken into account. A flow heterogeneity coefficient based on the flow characteristics of the porous medium was proposed, which was used for evaluating the flow characteristics of a partially filled porous channel.

Armaghani et al. (2014) investigated the effects of Nield number on particle migration and heat transfer of nanofluid in local thermal nonequlibrium porous channel. The thermal nonequilibrium model was assumed between the fluid, particles, and solid phases. It was also assumed that the nanoparticles are distributed non-uniformly inside the channel and therefore the volume fraction distribution equation is coupled with the other governing equations. In this condition, a new heat flux model was introduced for calculation of the absorbed heat flux by the solid, particle, and fluid phases. The effects of Nield number on the heat transfer were completely studied.

Kuznetsov (1998) presented an analytical investigation of fully developed forced convection in a parallel-plate channel partly filled with a homogeneous porous material. The flow in the porous material was described by a non-linear Brinkman–Forchheimer-extended Darcy equation. Utilizing the boundary-layer approach, analytical solutions for the flow velocity, the temperature distribution, as well as for the Nusselt number were obtained. Dependence of the Nusselt number on several parameters of the problem was extensively investigated.

Kuznetsov et al. (2003) applied a modified Graetz methodology to investigate the thermal development of forced convection in a circular duct filled by a saturated porous medium, with walls held at constant temperature, and with the effects of longitudinal conduction and viscous dissipation included. The Brinkman model was employed. The analysis led to expressions for the local Nusselt number, as a function of the dimensionless longitudinal coordinate and other parameters (Darcy number, Péclet number, and Brinkman number).

Xu et al. (2017) presented analytical solutions for the fully developed forced convection in a porous annulus with asymmetrical heat fluxes using five flow/thermal models. The classic Darcy and Brinkman models were employed for the fluid flow, while the local thermal equilibrium (LTE) and the LTNE models were employed to describe the heat transfer process in porous media. Exact solutions with Darcy-LTNE, Darcy-LTE, Brinkman-LTNE, Brinkman-LTE, and the fin models were obtained.

Mashaei et al. (2016) numerically carried out a study on the flow and heat transfer characteristics of nanofluid forced convection in an annular porous medium, as the main part of a cylindrical heat pipe, to investigate the effect of nanoparticles on hydrothermal performance of a cylindrical heat pipe. The Al_2O_3–water mixture was considered as working fluid and a single-phase approach with variable properties adopted to formulate it.

Akbarzadeh et al. (2018) investigated the effects of simultaneous implementation of corrugated walls and nanoparticles upon the performance of solar heaters. In this paper, the first and second laws of thermodynamics analyses were performed on nanofluid turbulent flows in a solar heater with the wavy absorber plate. The effects of wavy profiles and nanoparticle concentration on different parameters including heat transfer, pressure drop, performance evaluation criterion (PEC), and thermal and frictional irreversibilities were investigated.

Nasrin et al. (2013) aimed to numerically investigate forced convection heat transfer phenomena in a two-dimensional horizontal channel having an open cavity with porous medium. A non-uniform heat flux was considered to be located on the bottom surface of the cavity. Three different heating modes were considered at this wall. The rest of the surfaces were taken to be perfectly adiabatic. The physical domain was filled with water-based nanofluid containing TiO_2 nanoparticles. The fluid enters from the left and exits from the right with initial velocity Ui and temperature Ti. Governing equations were discretized using the penalty finite-element method.

Nield and Kuznetsov (2014) presented an analytical study of fully developed forced convection, using the Buongiorno model, in a parallel-plane channel with uniform heat flux on the boundaries. A model incorporating the effects of Brownian motion and thermophoresis was adopted. (Previous analytical studies using this model were concerned with natural convection.) It was found that the combined effect of these two agencies is to reduce the Nusselt number.

Sheikholeslami and Bhatti (2017) studied the nanofluid forced convective heat transfer in a porous semi-annulus in the presence of uniform magnetic field. Various shapes of nanoparticles were considered. Brownian motion impact on viscosity of nanofluid was taken into account. Governing equations were presented in vorticity stream function formulation. Control volume based finite-element method (CVFEM) was utilized to obtain the results. At first, the best shape of nanoparticles was selected and then influences of nanofluid volume fraction, Darcy, Reynolds, and Hartmann numbers were presented

Torabi et al. (2017) utilized a first and second law of thermodynamics-based method to examine porous media using a pore scale modeling approach. Both longitudinal elliptical and transverse elliptical cross-sectional configurations were represented as the solid matrices. The results indicated that the longitudinal elliptical cross-sectional configuration with porosity equal to 0.53 provides superior performance when applying the performance evaluation criterion utilized.

Xu et al. (2018b) numerically investigated the fully developed forced convective heat transfer in tubes sintered with partially filled gradient metal foams (GMF). The inner surface of the tubes was subjected to constant heat flux. In the GMF region, the Brinkman extended Darcy flow model and the LTNE model were used to predict fluid and thermal transport. The results show that the heat transfer performance and flow resistance of GMFs were heavily dependent on porosity, pore density, and GMF thickness gradients.

Lavanya and Babu (2016) discussed in detail the influence of variable suction, Newtonian heating and heat source or sink heat and mass transfer over a permeable shrinking sheet embedded in a porous medium filled with a nanofluid. The influence of the physical parameters on skin-friction coefficient, local Nusselt number, and local Sherwood number were shown in a tabulated form.

Xu (2017b) analytically investigated the flow and heat transfer in a micro-annulus with the porous material using LTE and LTNE models with effects of flow/thermal slips and asymmetric heat fluxes. Analytical solutions for velocity and temperatures were obtained. Effects of key factors on convective heat transfer were examined. This analytical solution predicted the thermal performance of porous medium micro-annulus in wide ranges of radius ratio, Knudsen number, and HF ratio.

4. MIXED CONVECTION HEAT TRANSFER

The thermal radiation effect on mixed convection heat transfer in porous media is very important in high-temperature processes and space technology and has many important applications such as space technology, and processes involving high temperatures such as geothermal engineering, the sensible heat storage bed, the nuclear reactor cooling system, and underground nuclear wastes disposal (Chamkha et al., 2012).

Chamkha et al. (2014a) presented a boundary-layer analysis for the mixed convection past a vertical wedge in a porous medium saturated with a power law type non-Newtonian nanofluid. The approach used was useful in optimizing the porous media heat transfer problems in geothermal energy recovery, crude oil extraction, groundwater pollution, thermal energy storage, and flow through filtering media.

Alizadeh et al. (2018) presented an analysis of heat transferring stagnation-point nanofluid flow over a cylinder embedded in porous media in the presence of gravitational and magnetic effects. In the analysis, 3D equations of transport of momentum together with one-equation model of transport of heat in porous media were employed and a temperature-independent model of nanofluid was considered. Through assuming certain self-similar solutions, these equations were reduced to simpler versions solvable with a finite-difference technique. Hydrodynamic, thermal, and entropy generation fields were analyzed in detail.

Ellahi et al. (2018b) investigated the influence of inclined magnetic field on plane Poiseuille kerosene-based nanoliquid flow through parallel walls of a channel under the impact of variable thermal conductivity with constant pressure gradient. Consequences of emerging flow parameters like Grashof number Gr, heat source/sink parameter Ω, Eckert number Ec, thermal radiation Rd, inclined magnetic parameter M, variable thermal conductivity ε, and suction/injection parameter S on flow profiles, temperature profiles, skin-friction coefficient, and Nusselt number were discussed graphically and tabular form.

Aman et al. (2016) studied the impacts of gold nanoparticles on MHD Poiseuille flow of nanofluid in a porous medium. The mixed convection was induced due to external pressure gradient and buoyancy force. Additional effects of thermal radiation, chemical reaction, and thermal diffusion were also considered. The impact of different parameters was observed on velocity, temperature, and concentration profiles. Thermal conductivities were found relying on volume fraction of nanoparticles.

Chamkha et al. (2012) studied the problem of steady, laminar, mixed convection boundary-layer flow over an isothermal vertical wedge embedded in a porous medium saturated with a nanofluid, in the presence of thermal radiation. The model used for the nanofluid incorporates the effects of Brownian motion and thermophoresis with the Rosseland diffusion approximation. A parametric study of the physical parameters was made, and a representative set of numerical results for the velocity, temperature, and volume fraction, the local Nusselt and Sherwood numbers were presented graphically.

Chamkha et al. (2013) presented numerical solutions of steady mixed convection flow of a nanofluid over a vertical cone embedded in a saturated porous medium in the presence of thermal radiation with Rosseland diffusion approximation. The model used for the nanofluid incorporated the effects of Brownian motion and thermophoresis. The entire regime of mixed convection was included, as the combined convection parameter varies from 0 (pure free convection) to 1 (pure forced convection). The resulting governing equations were non-dimensionalized and transformed into a non-similar form and then solved by the Keller box method.

Maghsoudi and Siavashi (2018) examined the mixed convection heat transfer of Cu-water nanofluid inside a two-sided lid-driven cavity saturated with heterogeneous porous media. The heterogeneity of the porous medium was optimized to reach the maximum heat transfer rate. The two-phase mixture model and Darcy–Brinkman–Forchheimer relation were employed for simulation of nanofluid and fluid flow through porous region, respectively. The maximization of Nusselt number with pattern search algorithm was conducted for various Rayleigh ($Ra = 10^3$, 10^4, 10^5, and 10^6) and Richardson (0.01, 0.1, 1, 10, and 100) numbers.

Matin and Ghanbari (2014) conducted an analysis to combined convection heat transfer of nanofluids through a vertical channel filled with a homogeneous and isotropic porous medium. The effects of the influential dimensionless parameters such as Brownian and thermophoresis parameters, mixed convection parameter (Gr/Re), Brinkman, Darcy and Lewis numbers on dimensionless velocity and temperature distributions and pressure drop were studied.

Nazar et al. (2011) studied the problem of steady laminar mixed convection boundary layer flow over an isothermal horizontal circular embedded in a porous medium filled with a nanofluid. They looked into the effects of the mixed convection parameter λ, the type of nanoparticles (Cu, Al_2O_3, TiO_2), and the nanoparticle volume fraction ϕon the flow and heat transfer characteristics.

Nithyadevi and Begum (2017) numerically analyzed the two-dimensional combined free-forced convection of Cu-water nanofluid in a square enclosure filled with fluid-saturated porous medium subjected to uniform magnetic field. Study was performed over various ranges of governing parameters like Richardson number, Darcy number, Hartmann number, and solid volume fraction. The results were presented in the form of hydrodynamic and temperature fields, average Nusselt number, and velocity graphs and they were discussed to expound the effects of the physical parameters in the solution.

Rohni et al. (2013) considered the steady mixed convection boundary-layer flow and heat transfer on a vertical cylinder in a porous material filled with a nanofluid. Solutions of the resulting ordinary differential equations for the flow and heat transfer characteristics were evaluated numerically for various values of the governing parameters, namely the nanoparticle volume fraction ϕ, the mixed convection or buoyancy parameter λ, and the curvature parameter γ. The results were presented for the specific case of copper nanoparticles.

Sheremet et al. (2015c) numerically studied the double-diffusive mixed convection in a porous cavity with one isothermal vertical wall filled with a nanofluid. Particular efforts were focused on the effects of the Rayleigh, Reynolds and usual Lewis numbers, Brownian motion, and thermophoresis parameters on flow field, temperature, contaminant, and nanoparticles volume fraction distributions, and average Nusselt and Sherwood numbers.

Srinivasacharya and Kumar (2015) studied the mixed convection in a nanofluid along an inclined wavy surface embedded in a porous medium. The complex wavy surface was transformed to a smooth surface by employing a coordinate transformation. The effects of Brownian motion parameter, thermophoresis parameter, amplitude of the wavy surface, angle of inclination of the wavy surface for aiding and opposing flows on the non-dimensional velocity, temperature, nanoparticle volume fraction, heat and nanoparticle mass transfer rates were studied and presented graphically.

Sudhagar et al. (2017) investigated the boundary-layer analysis on the steady, laminar, mixed convection flow over a vertical cone implanted in a porous medium filled with a nanofluid. A parametric study was performed for different physical parameters, such as magnetic (M), cone angle (m), mixed convection (v), Brownian motion (Nt), and thermophoresis (Nb), on the velocity, temperature, and nanoparticle concentration profiles. The dependency of the rate of heat and mass transfer on the governing parameters was discussed.

Gorla et al. (2011a) studied the steady boundary-layer flow of a nanofluid on a stretching circular cylinder in a stagnant free stream. Furthermore, Gorla et al. (2011b) analyzed the problems of mixed convection past a vertical wedge embedded in a porous medium saturated by a nanofluid and the heat transfer in the boundary layer on a stretching circular cylinder in a nanofluid, respectively.

Zahmatkesh and Naghedifar (2017) simulated and discussed the oscillatory mixed convection in the jet impingement cooling of a partially heated horizontal surface immersed in a nanofluid-saturated porous medium. This situation appeared when the jet flow and the flow due to buoyancy have opposing effects and was in conflict for domination. The aim of this contribution was to explore how governing parameters may alter these oscillations and the resulting heat exchange.

Other works can be found in the literature (i.e., Kumar and Kumar, 2018; Rashidi et al., 2018; Zeeshan et al., 2018; Nasiri and Jafari, 2017; Hassan et al., 2017; Tarmian et al., 2012; Tham et al., 2012; Ijaz et al., 2018; Ellahi et al., 2018a; Reddy and Chamkha, 2016) that studied the heat transfer and nanofluid flows using numerical and experimental techniques. Konstantakou et al. (2010) employed grand canonical Monte Carlo (GCMC) simulations for the estimation of the density of CO_2 in energetically smooth carbon slit-shaped and cylindrical pore models for predefined temperatures and ranges of relative pressures. The results (adsorption isotherms, local fluid density, and gas molecule orientation profiles) provided valuable information concerning the densification process in the nanopores and the configuration of the gas molecules packing in the individual pores at various pressure levels.

Taghiyari et al. (2013) studied the effects of a 400 ppm aqueous dispersion of silver and copper nanoparticles on the gas and liquid permeability of heat-treated beech, poplar, and fire wood. Gas permeability values were measured under seven different vacuum pressures in a single run and the correlation of each was analyzed with two liquid permeabilities as first-drop and 50-mm-lowering times; both liquid permeabilities were measured using an RILEM test tube.

Dinarvand et al. (2014) numerically investigated the MHD flow and heat transfer of a nanofluid over a non-linearly stretching permeable sheet in porous medium. The stretching velocity of sheet was assumed to have a power-law variation with the horizontal distance along the plate. It was found that the values of the skin friction coefficient and the Nusselt number increase with non-linear velocity parameter. Also, the Nusselt number was found to increase as temperature power-law exponent increases.

Chand and Rana (2014) investigated the thermal instability in a horizontal layer of nanofluid in a porous medium. Boundary conditions for nanoparticles volume fraction were taken to be zero flux. It was found that in case of stationary convection Brinkman–Darcy number, the Lewis number and modified diffusivity ratio have a stabilizing effect while the porosity has a destabilizing effect on the fluid layer.

Umavathi et al. (2015) investigated the effect of thermal conductivity and viscosity on linear and non-linear stability in a horizontal porous medium saturated by a nanofluid. It was found that for stationary convection Lewis number, the modified diffusivity ratio, viscosity ratio, and conductivity ratio have a stabilizing effect while nanoparticle concentration Rayleigh number and porosity destabilize the system.

Reich et al. (2015) proposed dual-cavity solar thermochemical reactor concept to capture carbon dioxide via the calcium oxide based calcination–carbonation cycle. The reactor design was refined using a numerical heat and fluid flow model for the calcination step. The cavity diameter and length-to-diameter ratio were varied to study their effects on pressure drop, temperature distribution, and heat transfer in the reactor.

Sarkar et al. (2015) reported a theoretical investigation of the peristaltic flow of nanofluids in a vertical asymmetric channel filled with a saturated porous medium in the presence of a transverse magnetic field and thermal radiation. The fluid velocity profiles were parabolic with maximum magnitude occurring slightly at the right half of the channel centerline and minimum at the channel walls.

Alrubaye et al. (2016) considered the soil stabilization of a soft clay soil (Kaolin S300) stabilized with various percentages of lime and 4% silica fume (SF). The percentage of lime varied at 3%, 5%, 7%, and 9%, while the percentage of SF was fixed at 4%. The focus of the study was on determining the physical properties of the soils tested and the consolidation of kaolin mixed with 4% SF and different percentages of lime. The optimum percentages for enhancing the shear strength and the angle of friction were 7% and 4% for lime and SF, respectively.

Rokhforouz et al. (2016) mathematically investigated the effect of highly conductive copper oxide nanoparticles on the effective thermal conductivity (ETC) of rock samples. The results obtained from the mathematical modeling of the rock samples showed that the conductive heat transfer through porous media was affected by copper oxide nanofluid, porosity, and nanoparticle concentration.

Chand and Rana (2016) analytically studied the thermal convection in a horizontal layer of rotating nanofluid with vertical AC electric field in a porous medium. The effects of the rotation, AC electric Rayleigh number, Lewis number, concentration Rayleigh number, modified diffusivity ratio, and porosity on the stability of the system were investigated for the stationary convection.

RamReddy et al. (2016) investigated in this study contribution of the significance of the Soret effect on the boundary-layer stagnation-point flow past a stretching/shrinking sheet in a nanofluid-saturated non-Darcy porous medium. The flow; temperature; concentration and nanoparticle concentration fields; skin friction coefficient; and heat, mass, and nanoparticle mass transfer rates were affected by the complex interactions among the various physical parameters involved in the analysis.

Yuan et al. (2016) illustrated the research on numerical simulation method, theory, and application, which consists of two factors such as black oil (oil, gas, water) polymer flooding and black oil (oil, gas, water) ternary composite drive. A type of software applicable in major industries was completed and is applied in numerical analysis and simulations of oil extraction in national major oilfields such as Daqing Oil field, Shengli Oil field, and Dagang Oil field, which brings huge economic and social benefits.

Du et al. (2016) measured the pressure distribution in heterogeneous porous media packed with two- and three-layer quartz sand of different particle sizes by setting pressure transducers on different layers. Computed tomography (CT) was also carried out to visualize the dynamic propagation behavior of CO_2 foam flow in heterogeneous porous media.

Li et al. (2016) conducted crude oil displacement experiments of cores using chemical agents with good thermal stability. Under the condition of constant temperature, the flow of a chemical agent with better thermal stability can result in higher amounts of oil recovery. An optimum temperature existed that will produce the highest level of crude oil recovery with chemical agent displacement flow.

Ellahi et al. (2017a) carried out an analysis to study the peristaltic flow of nanofluid in a vertical asymmetric channel. The significant effects of a thermal conductivity model of Brownian motion for nanofluids comprising the effects of particle size, particle volume fraction, and temperature dependence were included. The obtained expressions for pressure gradient, temperature, and velocity profile were described through graphs for various pertinent parameters.

Ellahi et al. (2017b) proposed a new model to investigate the effects of nano-Ferro liquid under the influence of low oscillating over stretchable rotating disk. The physical parameters such as shear stress at wall, heat transfer rate through wall, boundary-layer thickness, and volume flow rate in axial direction were also presented in tabular form. Finally, a comparison with the existing literature was made as a limiting case of the reported problem and found in good agreement.

Esfahani et al. (2017) investigated an entropy generation analysis for the Cu-water nanofluid flow through a wavy channel over heat exchanger plate The obtained results indicated that the thermal entropy generation is the main term in most part of the channel, including near the wavy walls. Moreover, the rise in viscous entropy generation with Reynolds number increased with increasing dimensionless amplitude.

Liu et al. (2017) measured the porosity, permeability, electrical resistivity, and NMR T2 spectrum of the tight sandstone samples from Yanchang Formation Ordos Basin China. The experimental results indicated weak correlation between porosity and other bulk properties. A series of scanning electron microscopes (SEM) images tiles (MAPS technique) with a resolution of 100 nm in a large field of view (FOV) were first recorded on one end surface of the sample and then stitched together to reveal fine pore structure, pore type, and pore size distribution.

Rashidi et al. (2017) developed a two-way coupling of discrete phase model in order to track the discrete nature of aluminum oxide particles in an obstructed duct with two side-by-side obstacles. The effects of space ratios between two obstacles and particle diameters on different parameters containing concentration and deposition of particles and Nusselt number were studied for the constant values of Reynolds number ($Re = 100$) and volume fractions of nanoparticles ($\phi = 0.01$).

Shirvan et al. (2017b) proposed the Response Surface Methodology and two-phase mixture model to investigate the sensitivity analysis of heat transfer and heat exchanger effectiveness in a double-pipe heat exchanger filled with Al_2O_3 nanofluid. The effective parameters of the Reynolds number, nanoparticles volume fraction, and the entrance status of nanofluid (S) (inner pipe, outer pipe, and both of them) were considered to serve the purpose.

Shirvan et al. (2017c) investigated a numerical study on natural convection along with surface radiation heat transfer in an inclined porous solar cavity receiver by means of response surface methodology (RSM). Effects of physical parameters such as Rayleigh number, Darcy number, inclination angles, dimensionless porous substrate thickness, wall surface emissivity, and surface radiation heat transfer rate were examined.

Das et al. (2018) reported an analysis of entropy generation due to the peristaltic flow of magnetohydrodynamic (MHD) copper-water nanofluid in a tube filled with a porous medium under long wavelength and low-Reynolds number assumptions. The results revealed that the axial velocity and temperature of nanofluid are decreasing functions of a magnetic parameter. The entropy generation number attains high values in the region close to the wall of the tube, while it has low values near the center region of the tube.

Bhatti et al. (2018) reported a simultaneous impact of mass and bio-heat transfer on the peristaltic propulsion of two-phase (particle-fluid) flow through a Darcy–Brinkman–Forchheimer porous medium. A Sisko fluid model was considered in the presence of extrinsic magnetic field through a compliant porous channel. An efficient Homotopy perturbation technique was applied to solve the non-linear differential equations under an appropriate approximation of long wavelength of a peristaltic wave and small Reynolds number.

5. CONCLUSION

Several engineering applications require high heat transfer performance. Over the last several decades, scientists and engineers have tried to develop fluids, which provide better performances for a variety of thermal applications. Applying nanotechnology to heat transfer, the new concept of "nanofluid," has been proposed to meet the new heat transfer challenges. This new kind of fluid is manufactured by dispersing an amount of solid nanoparticles in traditional heat transfer fluids. The improvement in their performance has been and is still of major concern to theorists and practitioners. Therefore, it is an ambitious attempt to work on such a topic.

Porous media heat transfer problems have several engineering applications such as geothermal energy recovery, crude oil extraction, groundwater pollution, thermal energy storage, and flow through filtering media.

Nanofluids in porous media constitute an emerging topic. Porous foam and microchannel heat sinks used for electronic cooling are optimized utilizing the porous medium. The utilization of nanofluids for cooling of microchannel heat sinks requires understanding of fundamentals of nanofluid convection in porous media. In many studies the thermal convection of a nanofluid in porous media has been examined.

This paper presented a detailed review of the numerical and experimental studies carried out by various researchers in order to obtain enhanced heat transfer in free, forced, and mixed convection by using nanofluids in porous media. Critical information of all studies in three categories (analytical, experimental, and numerical) has been collected.

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