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ADVANCES OF HEAT TRANSFER IN POROUS MEDIA—A REVIEW

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This study proposes to enhance the porous media heat and mass transfer inside thermal devices like heat exchangers, flat-plate solar air collectors, and other electronic equipment. These devices play an important role in industry today. The present study aims to conduct a comprehensive literature review on the porous media laminar and turbulent heat transfer, in the presence of turbulators with different geometries, placed in various manners, inside geometries of irregular shape. This represents a very important issue in the area of heat exchangers where the flow must be characterized; there is also a need to identify the velocity distribution, as well as the existence and the extension of possible recirculations.

KEY WORDS: *porous media, heat transfer, channel, heat exchanger, obstacle, turbulence*

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).

2. COMPLEX GEOMETRIES WITH POROUS OBSTACLES

Through our bibliographic research, we found that a wide range of studies on this subject exist; these may be experimental, analytical, and numerical. Huang and Vafai (1994) presented a numerical investigation for forced convection in a constant-temperature parallel plate channel with porous obstacles alternately emplaced on the bottom plate. The Brinkman-Forchheimer-extended Darcy model, which accounts for the effects of impermeable boundary and inertia, was used to characterize the flow field inside the porous region. Yucel and Guven (2009) performed a numerical study to analyze the steady laminar forced convection in a channel in which discrete heat sources covered with porous material are placed on the bottom wall. The flow in the porous medium was modeled using the Darcy–Brinkman–Forchheimer model. 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. Alhussan et al. (2012) reported a study of the influence of a porous obstacle on deflagration-to-detonation transition in a pulse combustion chamber of small length. Dependences of the detonation-wave velocity on the distance were obtained for two samples of a porous material, i.e., steel spheres and a ceramic porous body. 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. Moghaddam et al. (2013) proposed an analytical method for rapid determination of dissolution rate in a convection-diffusion mechanism. Zapryagaev et al. (2015) reported the results of studying impingement of a supersonic under expanded air jet onto a finite thickness porous metal obstacle whose frontal plane is normal to the jet axis and whose side surface is impermeable for the gas flow. 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. 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). 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 by Mahdy et al. (2017). The model used for the nanofluid refers to a solid–liquid mixture with a continuous phase which was a nanometer-sized nanoparticle such as copper dispersed in conventional base fluid.

3. COMPLEX GEOMETRIES WITH POROUS BAFFLES

Yang and Hwang (2003), Ko and Anand (2003), Yilmaz (2003), Tsay et al. (2003), and Guerroudj and Kahalerras (2010) explored the influences of different aspect ratio channels and different porosity baffle geometries. 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. 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 firewood. Ko and Anand (2003) carried out an experimental investigation to measure module average heat transfer coefficients in uniformly heated rectangular channel with wall-mounted porous baffles. Baffles were mounted alternatively on top and bottom of the walls. Yang and Hwang (2003) presented the numerical predictions on the turbulent fluid flow and heat transfer characteristics for rectangular channel with porous baffles which are arranged on the bottom and top channel walls in a periodically staggered way.

Miranda and Anand (2004) conducted a detailed numerical study of fluid flow and heat transfer in a 2D parallel plate channel with 16 staggered porous baffles. The pressure and velocity fields were linked by the SIMPLEC algorithm. The extended Darcy–Forchheimer model was used to describe resistance to flow through the porous baffles. Santos and de Lemos (2006) presented simulations for laminar flow in a channel containing baffles made with solid (impermeable) and porous materials. The numerical results for the friction factor f and for the Nusselt number Nu are compared with available data, indicating that results herein differ by less than 5% in relation to published results.

Targui and Kahalerras (2013) carried out a numerical investigation to analyze the effect of porous baffles and flow pulsation on a double-pipe heat exchanger performance. 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. Xu (2017a) theoretically investigated the flow and heat transfer in microchannel with micro-/nano-porous medium, and the analytical solutions for velocity and temperature were obtained by considering the local thermal non-equilibrium (LTNE) effect and the slip boundary. 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. Xu (2017b) analytically investigated the flow and heat transfer in a micro-annulus with the porous material using local thermal equilibrium and LTNE models with effects of flow/thermal slips and asymmetric heat fluxes. Analytical solutions for velocity and temperatures were obtained. Shamsabadi et al. (2018) performed a numerical simulation to investigate thermal and viscous irreversibilities for Al_2O_3-water nanofluid inside a duct equipped with porous baffles.

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. 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. Xu et al. (2018b) numerically investigated the fully developed forced convective heat transfer in tubes sintered with partially filled GMFs. 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.

4. COMPLEX GEOMETRIES WITH POROUS FINS

Reconfiguring porous fin geometry is another important issue in heat transfer problems, especially in heat exchangers. This is among the most important ways used in the design of channel heat exchangers. For this topic, the several studies proposed several new situations of porous fins, for example, Varol et al. (2000), Vaszi et al. (2003), Reddy and Satyanarayana (2008), Kahalerras and Targui (2008), Hamdan and Al-Nimr (2010), Darvishi et al. (2013), Saedodin and Shahbabaei (2013), Feng et al. (2013), Darvishi et al. (2014), Moradi et al. (2014), Asadian et al. (2016), Patel and Meher (2016), Yang et al. (2016), Juan and Hai-Tao (2017), Kim (2017), and Mesgarpour et al. (2018). In those studies, different geometry parameters and various operating conditions were examined. Varol et al. (2000) considered the steady incompressible, viscous, two-dimensional flow of a solution in a channel. The bottom wall was porous and the fins were attached to the top wall. Vaszi et al. (2003) reported a two-dimensional boundary-layer investigation of the steady-state free convection from a vertical plate and cylindrical fin, which is embedded in a saturated porous medium. Reddy and Satyanarayana (2008) proposed a numerical model to evaluate the heat transfer characteristics of a solar parabolic trough receiver by introducing porous inserts.

Kahalerras and Targui (2008) reported a numerical modeling of fluid flow and heat transfer in a double-pipe heat exchanger with porous fins inserted in the annular gap. The effects of several geometrical, physical, and thermal parameters such as fins spacing and height, Darcy number and the thermal conductivity ratio on the structure of the hydrodynamic and thermal fields were analyzed. Hamdan and Al-Nimr (2010) numerically investigated in this study a steady, fully developed laminar forced convection heat augmentation via porous fins in isothermal parallel-plate duct. Darvishi et al. (2013) conducted a numerical study of the convection heat transfer in porous media by the homotopy analysis method (HAM). The geometry considered is that of a rectangular profile fin. Saedodin and Shahbabaei (2013) introduced a simple method to analysis the performance of a porous fin. Feng et al. (2013) presented a porous medium model for forced air convection in pin/plate-fin heat sinks subjected to non-uniform heating of a hot gas impinging jet.

Darvishi et al. (2014) performed the unsteady thermal analysis on three types of fin cases: the infinite fin, finite length fin with insulated tip, and finite length fin with known convective coefficient at the tip. Moradi et al. (2014) conducted the thermal analysis of simultaneous natural convection and radiation in moving porous fin. HAM was applied to solve energy equation considering two types of boundary conditions. Umavathi et al. (2015) investigated the effect of thermal conductivity and viscosity on linear and nonlinear stability in a horizontal porous medium saturated by a nanofluid. Reich et al. (2015) proposed a dual-cavity solar thermochemical reactor concept to capture carbon dioxide via the calcium oxide based calcination–carbonation cycle. Sarkar et al. (2015) reported with 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. Asadian et al. (2016) studied the heat transfer in a rectangular porous fin (Si_3N_4) with temperature-dependent internal heat generation and the Darcy model was used for passage velocity.

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%. Patel and Meher (2016) analyzed the heat transfer in rectangular solid and porous fin with the temperature-dependent internal heat generation, by using Adomian decomposition sumudu transform method (ADSTM) and used the concept of T-stable mapping and the fixed-point theorem to prove the stability of ADSTM. Rokhforouz et al. (2016) mathematically investigated the effect of highly conductive copper oxide nanoparticles on the effective thermal conductivity (ETC) of rock samples.

Yang et al. (2016) proposed the multiparameter constrained optimization procedure integrating the design of experiments (DOE), genetic algorithm (GA), and computational fluid dynamics (CFD) to design three-dimensional porous pin fins in a rectangular channel. 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. Murthy et al. (2016) investigated in this study contribution 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. 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. 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. Juan and Hai-Tao (2017) proposed a full-size numerical model in order to investigate the thermodynamic characteristics of a full-size plate-fin heat exchanger (PFHE), by applying the porous media approach. The porous parameters as porous coefficients and porosity can be obtained by the local simulation results, and the model was verified by the experimental data. Kim (2017) purposed a study to estimate the pressure drop and thermal performance of three-dimensional heat exchanger units by the porous approximation, considering inertia effects. Ellahi et al. (2017a) carried out an analysis to study the peristaltic flow of nanofluid in a vertical asymmetric channel. The mathematical model consisted of continuity and momentum equations, while a new model was proposed for the nanoparticle concentration. Ellahi et al. (2017b) proposed a new model to examine the effects of nano-Ferro liquid under the influence of low oscillating over stretchable rotating disk.

Mesgarpour et al. (2018) investigated the effect of connection type of sintered porous fins on heat transfer and pressure drop in the fluid flow. A connection model of four- and six-contact sintered balls of constant dimensions was evaluated by means of CFD simulation in this research. 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. Kumar and Kumar (2018) conducted an analysis to consider the fascinating and novel characteristics of MHD convective nanofluid over a stretching sheet through a porous medium. 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. Ellahi et al. (2018a) investigated the combined effects of MHD heat transfer flow under the influence of slip over a moving flat plate. Ijaz et al. (2018) presented a comprehensive study on the liquid and solid particles interaction propagating through a finite symmetric wavy channel. A non-Newtonian power-law model was used to determine the flow behavior with heat and mass transfer.

5. COMPLEX GEOMETRIES WITH POROUS RIBS

Among the important studies are the following. Li et al. (2016) conducted crude oil displacement experiments of cores using chemical agents with good thermal stability. A fitted equation between the chemical agent concentration efficiency and the temperature was obtained. Esfahani et al. (2017) investigated an entropy generation analysis for the Cu–water nanofluid flow through a wavy channel over heat exchanger plate. Entropy generation was expressed as a function of velocity and temperature. Nasiri and Jafari (2017) prepared a nanocomposite gel polymer by xanthan (as polymer), chromium acetate (III) (as cross-linker), montmorillonite nanoclay (as additive), and formation water (as solvent). Khan et al. (2002) described an experimental investigation of heat transfer with turbulent flow in a rectangular channel with inclined solid and perforated baffles combined with rib turbulators. Yang and Hwang (2004) numerically studied the mechanisms of heat transfer augmentation in rectangular ducts with solid and slit ribs on one wall. The parameters studied include the entrance flow Reynolds number and rib void fraction, whereas the rib height-to-duct hydraulic diameter was fixed and the working medium was air.

Zhang et al. (2015) performed the numerical investigation of flow pattern and heat transfer performance of parallel channel with 10 staggered porous/solid ribs with the two-domain approach and adoption of the preconditioned density-based algorithm. Hassan et al. (2017) purposed a study to theoretically examine nanoparticle shapes behavior on mass and heat flow of ferrofluid over a rotating disk with the presence of low oscillating magnetic field. 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. 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. Shirvan et al. (2017b) proposed the response surface methodology (RSM) 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. 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 RSM. Zeeshan et al. (2018) explored the energy activation in MHD radiative Couette–Poiseuille flow nanofluid in horizontal channel with convective boundary conditions.

6. COMPLEX GEOMETRIES WITH POROUS BLOCKS

This type of turbulator has been the subject of many numerical and experimental studies, as shown here. Shuja and Yilbas (2010) studied the flow over two heat-generating porous blocks situated in a cavity, and examined the effects of porous blocks geometric orientations in the cavity (configurations). Kirsanov et al. (2013) presented a technique of designing a heat exchanger with porous inserts that is the development of the classical method for thermal design of recuperative finned heat exchangers. Gortyshov et al. (1991) presented the results of an experimental investigation of heat transfer, hydraulic resistance, and critical heat fluxes for the flow of coolant in a channel with a square cross section and porcelain inserts consisting of highly porous permeable cellular materials. Experimental data for sprayers with porous elements of different permeability showed that the flow-rate characteristic for the liquid declines practically linearly with decrease in permeability of the material (Biryukov and Romakhin, 2008). Fu et al. (1996) numerically investigated a study of a porous block mounted on a heated wall in a laminar flow channel to enhance convection heat transfer rate. Fu and Huang (1997) numerically investigated a study of appropriate sizes of both porous and solid blocks mounted on a heated region impinged by a laminar slot jet. Chikh et al. (1998) presented a numerical study of forced convection enhancement in a channel intermittently heated. The use of porous blocks mounted on the heated parts of the channel to improve thermal performance was investigated. In order to account for the inertia, drag, and boundary effects, the Brinkman–Forchheimer–extended Darcy model was adopted for the flow inside the porous regions.

Tzeng et al. (2007) experimentally explored the friction and forced convective heat transfer in a sintered porous channel with obstacle blocks. The local Nusselt number distributions at various positions were obtained for various particles Reynolds numbers. Shuja and Yilbas (2007) numerically investigated the mixed convection in a channel containing a rectangular heated porous block. The influence of aspect ratio of the rectangular porous block on the flow field and heat transfer rates was examined. Shuja et al. (2008) examined the entropy generation in the flow field subjected to a porous block situated in a vertical channel. The effects of channel inlet port height (vertical height between channel inlet port and the block center), porosity, and block aspect ratio on the entropy generation rate due to fluid friction and heat transfer in the fluid were examined.

Guerroudj and Kahalerras (2010) reported a numerical simulation of laminar mixed convective in a two-dimensional parallel-plate channel provided with porous blocks of various shapes. Li et al. (2010) conducted a detailed numerical study of the fluid flow and heat transfer in the channel with staggered porous blocks. The effects of various parameters such as the Darcy number, Reynolds number, porous block height and width on the velocity field, and the local heat transfer were systematically investigated. Guerroudj and Kahalerras (2012) numerically studied the mixed convection in an inclined channel provided with porous heated blocks on its lower plate using the control volume method. Rees and Nield (2016) sought to determine in as comprehensive a fashion as possible what the effect is of the presence of a centrally placed square solid block on the onset and development of Darcy–Bénard convection in a square porous cavity.

Lee et al. (2015) employed multi-stacked porous baffle obstructions to enhance the flow relaxations of water-soluble buoyant gases inside an odor-removing basin system. They performed qualitative flow visualization by using tracing particles in working fluid to evaluate the effects of porous baffles. Yang et al. (2016) proposed the multiparameter constrained optimization procedure integrating the design of experiments (DOE), genetic algorithm (GA), and computational fluid dynamics (CFD) to design three-dimensional porous pin fins in a rectangular channel. Li et al. (2016) studied the effects of design parameters on the thermal performance and flow resistance under the forced convection of a rectangular mini-channel with short elliptical pin fins. Panchal et al. (2018) reported that the fins increase 25% distillate output compared with a lone double-basin solar still with evacuated tubes. Logesh et al. (2018) conducted a numerical simulation of heat transfer enhancement possibilities and flow parameters improvement using porous fins in a concentric tube heat exchanger. Girish et al. (2018) presented a numerical investigation of developing natural convection in vertical double-passage porous annuli by imposing two sets of thermal conditions. The effect of geometrical parameters such as radius ratio, baffle position, and physical parameters, namely Grashof and Darcy numbers on flow pattern, thermal distribution, and rate of heat transfer was analyzed in detail.

7. COMPLEX GEOMETRIES WITH POROUS INSERTS

Among important contributions, Wang et al. (2000) presented a new method for enhancement of film-wise condensation heat transfer on a vertical tube. The method is that a tube is fluted on its outer surface and coated with metallic powder on the crest, which is called a fluted tube with coatings. Vaszi et al. (2003) reported a two-dimensional boundary-layer investigation of the steady-state free convection from a vertical plate and cylindrical fin, which is embedded in a saturated porous medium. Sergeev et al. (1974) obtained an analytical description for the distribution of the mean axial or radial velocity at the wall along the length of the channel. The movement of a stream in a channel with permeable walls was examined on the basis of the energy equation. Torii et al. (1999) performed a theoretical and experimental study to investigate unsteady, two-dimensional, incompressible fluid flow over both sides of a slot-perforated flat surface, which is placed in a two-dimensional channel.

Fateev et al. (2002) developed and manufactured an experimental model of a two-channel metal-hydride thermal converter that realizes the process of heat conversion in the regime of a super-adiabatic wave of cold. Yucel and Guven (2007) presented a numerical investigation of the two-dimensional, laminar forced-convection cooling of heat-generating obstacles mounted on adiabatic walls in a parallel-plate channel. Wang (2008) studied the fully developed laminar forced convection inside a semi-circular channel filled with a Brinkman–Darcy porous medium. Habibi et al. (2011) presented the effect of introducing a porous medium on the flow regime and heat transfer of a two-dimensional channel through which the flow is reciprocating. Rad et al. (2015) carried out a numerical simulation to investigate the thermal enhancement in a shell-and-tube heat exchanger using a porous medium inside its shell and tubes, separately.

Celik et al. (2017) computationally determined the local and average interfacial convective heat transfer coefficient of a periodic porous medium under mixed convection heat transfer by using the volume-averaging method. Jamarani et al. (2017) investigated the thermal performance improvement of a double-tube heat exchanger by inserting porous substrates in inner and outer tubes in this paper. Two different configurations were considered in order to study the effect of porous inserts on the heat transfer and pressure drop. Astanina et al. (2017) numerically studied the laminar natural convection in a square cavity having two centered adherent porous blocks filled with an alumina/water nanofluid under the effect of horizontal temperature gradient. Akbarzadeh et al. (2018) investigated the combined effects of using nanofluid, a porous insert and corrugated walls on heat transfer, pressure drop, and entropy generation inside a heat exchanger duct. Siavashi et al. (2017) numerically studied the effect of porous rib arrays on the heat transfer and entropy generation of laminar nanofluid flow inside annuli, using a two-phase mixture model for nanofluid flow simulation. Toghraie et al. (2018) numerically investigated the flow and heat transfer of water/CuO nanofluid in the microchannel with L-shaped porous ribs. The validation of obtained numerical results with the results of valid references showed the accuracy of this solving procedure. Other studies for turbulent and laminar flows over simple obstacles can be found in the referenced papers (Patankar et al., 1977; Berner et al., 1984; Webb and Ramadhyani, 1985; Kelkar and Patankar, 1987; Habib et al., 1988, 1994; Hong and Hsieh, 1991; Cheng and Huang, 1991; Lopez et al., 1996; Yuan et al., 1998; Li and Kottke, 1998; Demartini et al., 2004; Bazdid-Tehrani and Naderi-Abadi, 2004; Mousavi and Hooman, 2006; Mohammadi Pirouz et al. 2011; and Mokhtari et al., 2017); see Table 1.

TABLE 1: Some numerical and experimental studies conducted on the heat transfer enhancement by forced convection over conventional obstacles in air channels

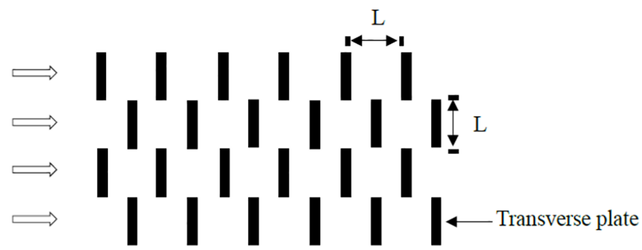
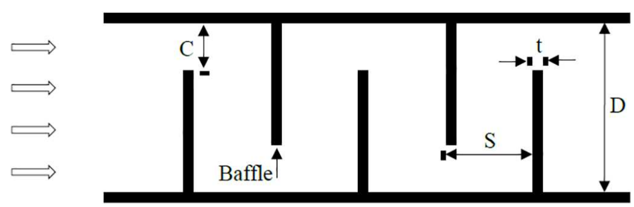
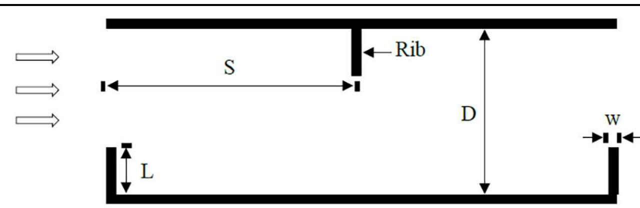
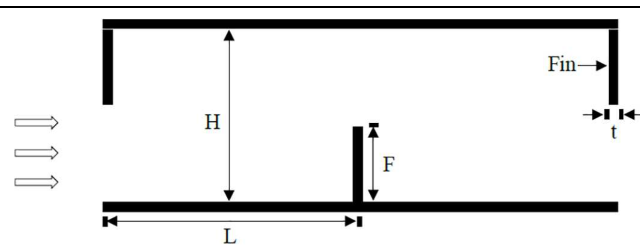
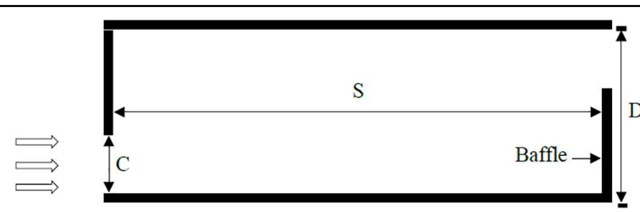
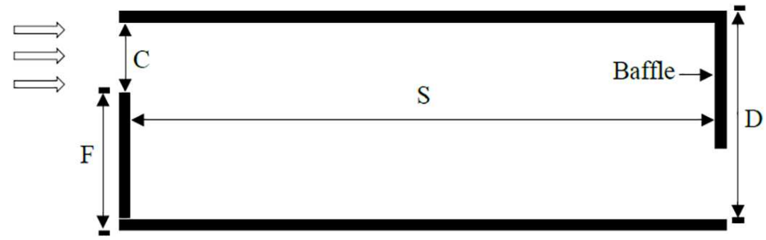
Researcher	Computational domain and geometrical parameters
Patankar et al. (1977)	
Berner et al. (1984)	
Webb and Ramadhyani (1985)	
Kelkar and Patankar (1987)	
Habib et al. (1988)	

TABLE 1: *(continued)*

<table>
<tr><th>Researcher</th><th>Computational domain and geometrical parameters</th></tr>
<tr><td>Habib et al. (1994)</td><td>
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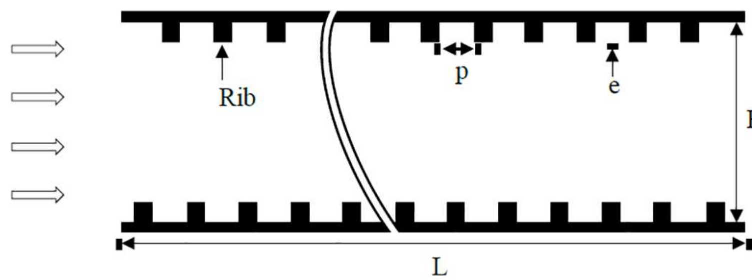
<tr><td>Hong and Hsieh (1991)</td><td>
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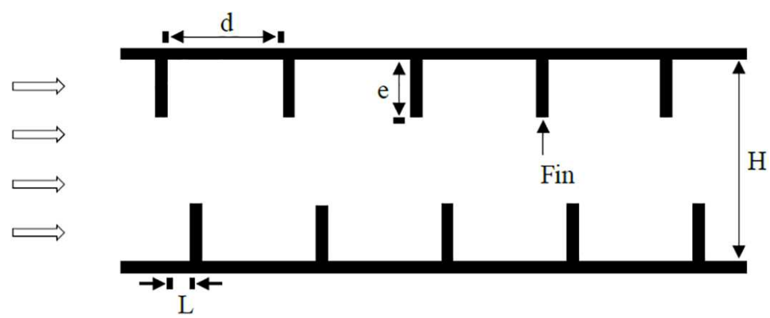
<tr><td>Cheng and Huang (1991)</td><td>
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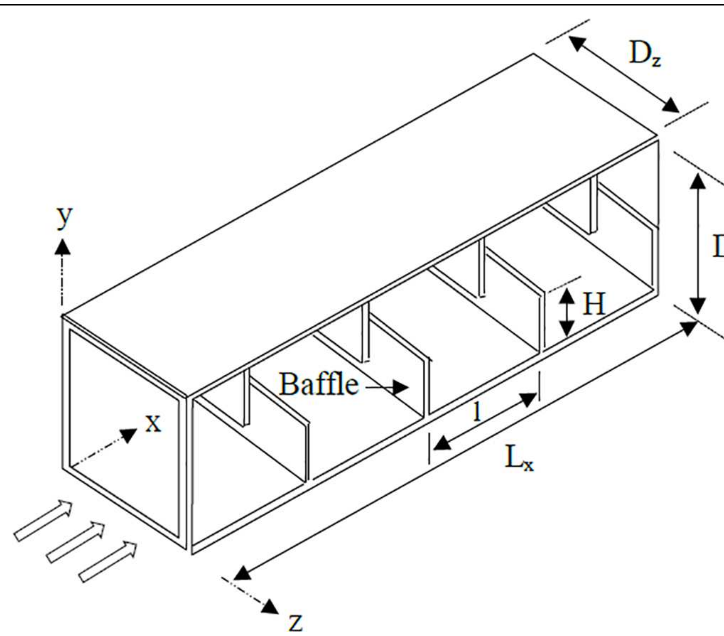
<tr><td>Lopez et al. (1996)</td><td>
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TABLE 1: *(continued)*

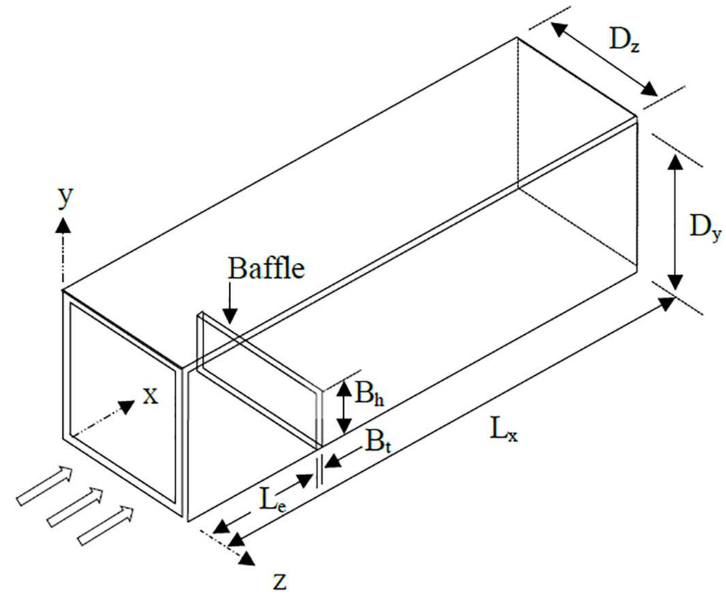
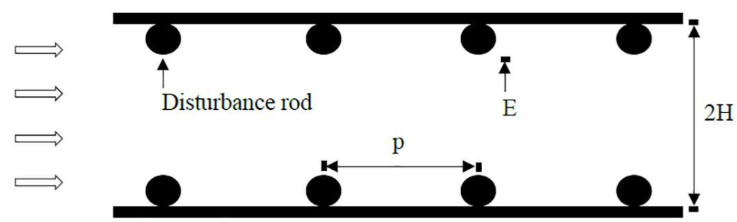
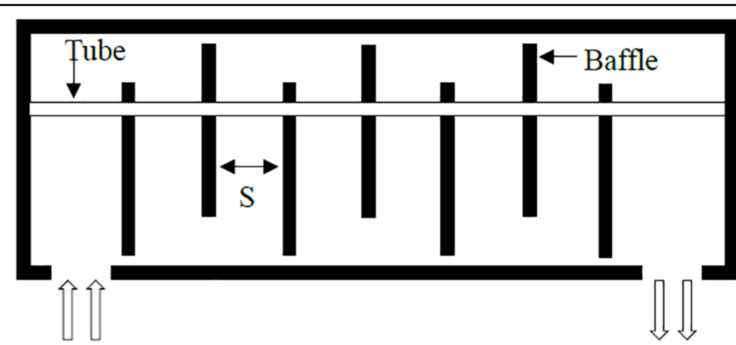
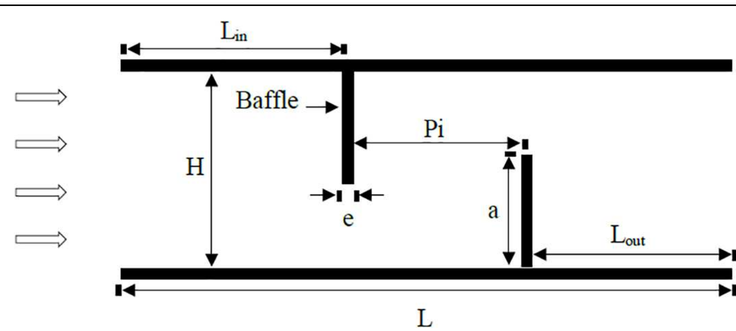
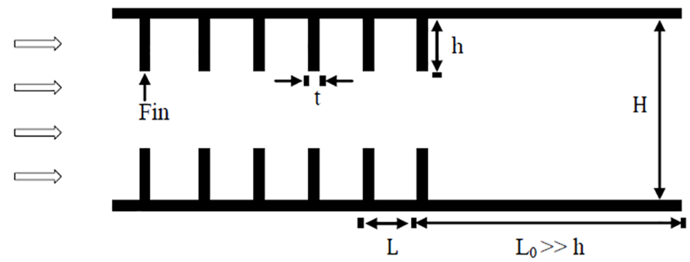
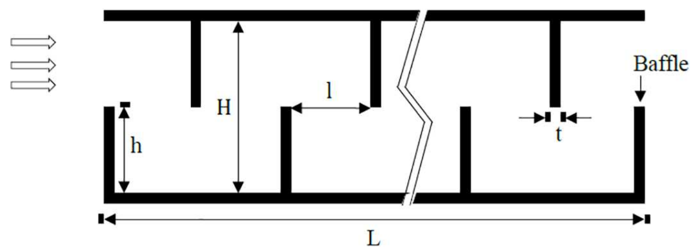
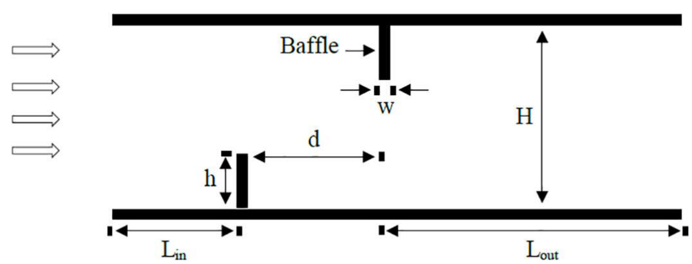
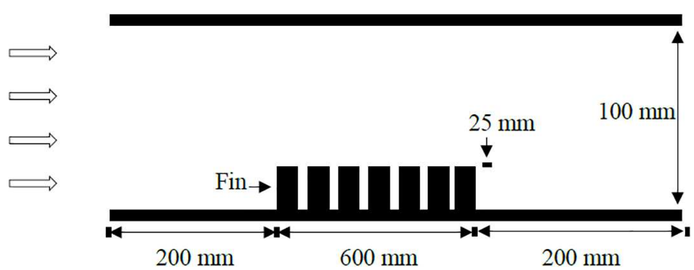
Researcher	Computational domain and geometrical parameters
Guo and Anand (1997)	
Yuan et al. (1998)	
Li and Kottke (1998)	
Demartini et al. (2004)	

TABLE 1: *(continued)*

Researcher	Computational domain and geometrical parameters
Bazdid-Tehrani and Naderi-Abadi (2004)	
Mousavi and Hooman (2006)	
Mohammadi Pirouz et al. (2011)	
Mokhtari et al. (2017)	

8. MODELS AND APPLICATIONS

Porous media heat transfer problems have several engineering applications such as geothermal energy recovery, crude oil extraction, ground water pollution, thermal energy storage, and flow through filtering media. Cheng and Minkowycz (1977) presented similarity solutions for free convective heat transfer from a vertical plate in a fluid-saturated porous medium. Gorla and co-workers (Gorla and Zinolabedini, 1987; Gorla and Tornabene, 1988) solved the non-similar problem of free convective heat transfer from a vertical plate embedded in a saturated porous medium with an arbitrarily varying surface temperature or heat flux. The problem of combined convection from vertical plates in porous media was studied by Minkowycz et al. (1985) and Ranganathan and Viskanta (1984). All these studies were concerned with Newtonian fluid flows.

Mohammadi et al. (2009) used the commercial CFD code FLUENT to investigate the effect of baffle orientation and of viscosity of the working fluid on the heat transfer and pressure drop in a shell-and-tube heat exchanger in the domain of turbulent flow. Lotus-type porous metal with many straight pores is attractive as a heat sink because larger heat transfer capacity is obtained due to the small diameter of the pores (Chiba et al., 2010). Ramana et al. (2010) investigated the effect of tube-to-tube copper porous interconnectors on the thermohydraulic performance of an in-line and staggered confined tube bank. As a sequel to the study in determining the permeability of the porous media composed of obstacles of different sizes, exhaustive numerical calculations were conducted by Renxing et al. (2012) using the same two-dimensional numerical models of square rods as in the previous study. Wen-Yong et al. (2013) found the parameters influencing the shape of the varying sectional cylindrical cavity and presented the optimized algorithm based on the genetic algorithms.

9. CONCLUDING REMARKS

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. Cheng and Minkowycz (1977) have used the Darcy law in their study on free convection about a vertical impermeable flat plate in porous media. The problem of a vertical cylinder embedded in porous media has been investigated by Minkowycz and Cheng (1976) using the local non-similarity method and by Kumari et al. (1985) using the finite difference and improved perturbation methods. Some studies which considered coupled heat and mass transfer include the works of Gebhart and Pera (1971) on vertical plates, Pera and Gebhart (1972) and Chen and Yuh (1980) on inclined plates. Also, Lai (1991) has investigated coupled heat and mass transfer by mixed convection from an isothermal vertical plate in a porous medium and Yih (1997) has studied the effect of transpiration on the problem of Lai (1991). Future work will involve more complex geometries and using nanofluids to assess the optimum conditions for heat transfer enhancements.

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