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RESEARCH ARTICLE

REVIEW OF HEAT TRANSFER ENHANCEMENT IN A HEAT EXCHANGER WITH PARTIALLY FILLED POROUS MEDIA

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ABSTRACT

In thermal devices like heat exchangers, improvement of convection heat transfer becomes an important factor in the development of modern industrial world. Inserting porous medium in a fluidic region is one of the effective methods among the passive heat transfer augmentation technics. Further it is preferred not to fully fill the system with the porous medium. This is to avoid the significant pressure drops occurring in the fully filled systems. This paper presents a brief discussion on the application of partially filled porous medium in a channel and circular pipe for forced convection. And also it is extended to some special cases like flow through rotating pipes, oscillating and MHD flows. The overall review of analytical, numerical and experimental work gives an idea about the position, thickness, porosity and area to be filled to achieve maximum heat transfer with minimum pressure drop.

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INTRODUCTION

A Porous medium is a composite medium containing interconnected voids or solid particles embedded into fluid containing medium. The transport of heat inside porous media has attracted the advertence of scientists and engineers due to its many engineering applications. Such applications can be found in, heat exchangers, food industry, Petroleum Engineering, Agricultural Engineering, Biomedical Engineering, Geothermal Engineering, grain drying equipment, heat sink units etc. Authoritative books by Bear (1972) (1), Nield and Bejan (1992) (2) and Ingham and Pop (1998) (3), Kambiz Vafai (2000) (4), George F. Pinder, William G. Gray (2008) (5), FarukCivan (2011) (6) etc. had documented extremely important information about the heat transfer phenomena in porous medium. Heat transfer magnification associated with filing the fluidic volume by the porous medium take place by (7) Enhancing effective thermal conductivity of the fluid under static and dynamic conditions. Increasing the order of the fluid molecules, and also due to Redistribution of the flow. Furthermore the advantage of the porous media as the heat exchanger is its wide contact area to the working fluid. In most of the applications, it is preferred not to fully fill, this is to avoid the significant pressure drops occurring in the fully filled systems. Therefore, partial filling is a prepossessing way of enhancing heat transfer, while maintaining the pumping losses at a reasonable level.

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Heat transfer enhancement using partially filled porousmedia

Partially filled porous media in a channel flow

Poulikakos and Kazmierczak (8) studied theoretically Both the parallel plate and circular tube channel configurations partially filled with a porous medium for fully developed forced convection. Again, for each configuration, both the case of constant wall temperature and constant heat flux are considered.. Brinkman flow equations were used to model the flow inside porous region. It documented the effect of Darcy number, thickness of porous region, ratio of effective thermal conductivities of porous medium and fluid on the flow field and on heat transfer inside the channel. This investigation shows that the Nusselt number variation on the thickness of porous medium was not categorical. A critical thickness exists at which the value of Nu reaches a minimum. Heat transfer performance of different partially filled porous systems. Have been studied by a number of authors. Poulikakos and Kazmierczak (9) investigated fully developed forced heat convection in a channel partially filled with a porous medium. In this study, the porous material was placed at the channel wall. They found that there is an extreme porous thickness at which Nusselt number is minimum. Successive study showed that the thermal performance of a conventional concentric tube heat exchanger could be improved by inserting high thermal conductivity porous substrates. Vafai and Kim (10) found that enhancement of heat transfer using porous material depends on the ratio of the effective thermal conductivity of the porous medium to that of the fluid. Darcy number, porous medium thickness, ratio of the effective thermal conductivity of the porous medium to that of the fluid and the configuration of the porous insert have been all found Hadim (11) performed a comprehensive numerical study of forced convection in a porous channel with Heat sources mounted on the bottom wall. The heat transfer enhancement and pressure drop in a partially filled porous channel are calculated and compared with a fully filled porous channel case.., The momentum equation for the porous region consists of the Brinkman-Forchheimer-Darcy model had been used, The continuity, momentum and energy equations are first transformed into dimensionless governing equations using vorticity –stream function formulation. Subsequently, these were transformed into algebraic, finite-difference equations using the control volume formulation outlined by Gosman *et al*. (12). These algebraic equations were solved using Gauss-Siedel point iterative scheme. In the partially porous channel, it is found that when the width of the heat source and the spacing between the porous layers are of the same magnitude as the channel height, the heat transfer enhancement is almost the same as in the fully porous channel while the pressure drop is significantly lower. These results suggest that the partially porous channel configuration is a potentially attractive heat transfer augmentation technique for electronic equipment cooling.

Mixed convection was studied by Chang and Chang (13) in a vertical channel partially filled with highly permeable porous media the diffusion and convection are handled by a hybrid scheme. The non-Darcy model, which includes inertia effect, boundary friction effect and convection, is used in the momentum equations for the porous medium layer. The velocity and temperature distributions, local Nusselt number (Nux), local friction coefficient (Cf), pressure drop and entrance length in a vertical parallel-plate channel partially filled with porous medium are obtained under various parameters, such as different thickness of porous medium (Rs), Darcy number (Da), Grashof number (Gr). The numerical results of this investigation show that (a) the local Nusselt number increases as Rs decreases and Da and Gr increase; (b) the local friction coefficient increases as Da and Gr increase; and (c) the pressure drop in the parallel-plate channel increases as Rs increases and Da decreases. There is a minimum non-zero local friction coefficient where the thickness of the porous medium is about 0.2. Hydrodynamic entrance length is shorter as the value of Rs is increased, and is longer as the values of Da and Gr are increased. Thermal entrance becomes longer as the values of Rs and Da increase and shorter as the values of Gr increase. Kuznetsov (14) studied the similar problem of the fully developed forced convection in a parallel-plate channel with a porous medium in the center by means of mathematical analysis, and the analytical solutions for the critical parameters of heat transfer were obtained. Al-Nimr and Hadded (1999) (15) examined the effects of free convection fully developed flow through open-ended vertical channels that are filled partially by porous medium Al-Nimr and co-workers (16) investigated numerically the transient forced convection of laminar flow in the developing region of parallel-plate ducts filled partially with porous inserts, and studied the effects of several operating parameters including porous layer thickness, Darcy number, thermal conductivity ratio, and microscopic inertial coefficient on the flow hydrodynamics and thermal characteristics. (17) Al-Nimr and Khadrawi investigated transient free convection flow in channels partially filled by porous substrates in various configurations. Convective heat transfer in porous media features a wide range of engineering applications, including those in oil recovery, geothermal engineering, chemical reactors, hydrogeology, heat pipes, solid matrix heat exchangers and thermal insulation. (18–20). In most of these applications, it is preferred not to fully fill the system with the porous medium. For maintaining the pumping expense at a reasonable level, B.I. Pavel, A.A. Mohammad, (21) showed that Nusselt number increases through partial filling, while the pressure drop is less than that of a conduit fully filled with a porous medium. Importantly, the configuration of the porous insert in the pipe can have a substantial effect on the rate of heat transfer.

Tien-Chien Jen *, T.Z. Yan (22) developed a three-dimensional computational model to analyze fluid flow in a channel partially filled with porous medium. In order to understand the developing fluid flow and heat transfer mechanisms inside the channel partially filled with porous medium, the conventional Navier–Stokes equations for gas channel, and volume-averaged Navier–Stokes equations for porous medium layer are adopted individually in this study. Conservation of mass, momentum and energy equations are solved numerically in a coupled gas and porous media domain along a channel using the vorticity–velocity method with power law scheme. Detailed development of axial velocity, secondary flow and temperature field at various axial positions in the entrance region are presented. The friction factor and Nusselt number are presented as a function of axial position, and the effects of the size of porous media inside the channel partially filledwith porous medium are also analyzed in the present study.

Kuznetsov (23) numerically studied the heat transfer of turbulent flow in a composite porous/fluid duct with porous media attached to the duct wall by using a two-layer k–e model to account for interface roughness. The results showed that the roughness of the porous/fluid interface significantly impacts turbulent flow in the clear fluid region as well as overall heat transfer in the duct, and an unexpected feature that there is a minimum of dependence of the Nu number on the position of the interface was found and explained. Experimental works in this area were also performed. Hetsroni *et al*. (24) experimentally investigated the heat transfer and pressure drop in a rectangular channel with low porosity sintered porous inserts. The results showed that the heat sink has good performance of heat transfer, when it also leads to a drastic increase in the pumping power.

Carlos *et al*. (25) In their work solved effective-medium equations for modeling momentum and heat transfer in a parallel-plate channel partially filled with a porous insert., it was found that the thermal performance is improved by either increasing the size of the porous insert or by favoring mixing inside the channel. A drawback of this approach is the high computational demand associated to modeling transport in the vicinity of the porous medium and the fluid Umesh Gupta *et al*. (26) studied The laminar fully developed free-convection flow in a channel bounded by two vertical plates, partially filled with porous matrix and partially with a clear fluid, has been discussed when both the plates are moving in opposite direction. The momentum transfer in porous medium has been described by the Brinkman-extended Darcy model. The effect of Darcy number on flow velocity has been discussed in fluid region, interface region and porous medium with the help of graphs. Analytic method has been adopted to obtain the expressions of velocity and temperature. The skin-friction component has also been determined and presented with the help of tables. Enhancement of forced convective heat transfer is analytically investigated by Yasser Mahmoudi *et al*.(27) in a channel partially filled with a porous medium under local thermal non-equilibrium (LTNE) condition. The flow inside the porous material is modeled by the Darcy–Brinkman–Forchheimer equation. The thermal boundary conditions at the interface between the porous medium and the clear region are described by two different models

Partially filled porous media in a circular pipe

Vafai and Thiyagaraja (28) investigated the velocity and temperature fields at the interface region. They used the Brinkman–Forchheimer extended Darcy equation and considered three fundamental types of interface. These included the interfaces between two porous regions, a porous medium and a fluid layer and a porous medium and an impermeable medium. An exact solution for the fluid mechanics of the interface region between a porous medium and a fluid layer was put forward by Vafai and Kim(29). This solution accounts for both boundary and inertial effects. When a heat flux is applied to the outer surface of a porous medium, the applied heat is transferred to the solid and fluid parts. The constant heat flux boundary condition could be viewed in two different ways (30). The first is to assume that the heat division between the two phases is based on their effective conductivities and the corresponding temperature gradients. In the second approach, each of the two phases at the interface receives an equal amount of heat flux. Hwang *et al*. (31) used the first approach and found good agreement between their numerical and experimental results. Another example can be a partially filled pipe with large heat transfer between the fluid and solid phases at the interface. In this case, temperatures of the two phases are equal at the interface and therefore model A is applicable. However, when the heat transfer between the fluid and solid phases at the interface is not strong enough the fluid and solid temperatures at the interface are not equal and model B is preferred. Furthermore, previous works have shown that depending on the thickness of the porous material and other pertinent parameters the fluid velocity in the clear region and at the interface changes.

Alkam and Al-Nimr studied the problem of transient developing forced convective flow in concentric pipes (32) and in circular channels (33) partially filled with porous inserts. They showed the role played by the thickness of the porous medium, the Darcy and Forchheimer numbers, upon the hydrodynamic and thermal system performances. These researchers reported that heat transfer can be enhanced up to 8 times and that the Nusselt number may improve up to 1200% by the inclusion of a porous substrate. Alkam and Al-Nimr (34) presented a numerical simulation for the transient forced convection in the developing region of a pipe partially filled with a porous material. The porous matrix is adhered to the inner wall of a pipe which is subjected to a step change in the temperature. They found that the time needed to reach steady state condition increases as the porous thickness increases up to a definite limit and then decreases with further increase in the layer thickness. Alkam and Al-Nimr (34) also studied the improvement of conventional concentric tube heat exchanger performance by using porous substrates. The numerical results indicated that the placement of the porous layer may enhance the heat exchanger effectiveness considerably for both parallel flow and counter flow arrangements, especially high heat capacity ratios.

Alkam and Al-Nimr (35) introduced another method by Inserting porous substrates at both sides of the inner tube wall, the thermal performance of a conventional concentric tube heat exchanger can be improved. The improvement was investigated numerically and the results showed that inserting the porous substrate may enhance the effectiveness of the heat exchanger considerably, exchanger at the same time. Ref (36,37). For instance, it has been shown that in a fully filled channel when the thermal conductivities of the fluid and solid phases are similar, the two phases are close to the local thermal equilibrium Ref. (38). New boundary layer type analytical solutions were obtained for these fundamentally important partly porous configurations (39). However, for different thermal conductivities of the fluid and solid phases, model B matches the experimental data (66).

Mohamad (40) numerically investigated the problem of heat transfer enhancement for a laminar flow in a pipe fully or partially filled with porous medium inserted at the core of the conduit. It was shown that with the porous material partially filling in the core of a conduit, the rate of heat transfer from the wall can be increased with a reasonable pressure drop, and the thermally developing length can be reduced by 50% or more. This partially filling method works better than the fully filled one. Mohamad (41) studied convection heat transfer of laminar flow in a tube partially or totally filled with porous medium numerically. The porous substrate was inserted at the core. It was shown that in the case of partially filling, heat transfer rate increased while the pressure drop decreased in comparison with fully filled tube. Mohamad (42) further investigated the enhanced heat transfer effect of metallic porous materials that are inserted into the core of a pipe with a constant and uniform heat flux experimentally and Numerically. The results obtained showed that compared with the clear flow case where no porous materials was used, higher heat transfer rates can be achieved using porous inserts whose Diameters approach the diameter of the pipe and it is very important to get the accurate physical parameters of a porous material from the experiment for a successful numerical simulation. The same problem was studied by Huang *et al.* (43) and Pavel and Mohamad (44) numerically and experimentally including laminar and turbulent regimes. Chen and Sutton (45) demonstrated that the heat transfer by radiation can be augmented about 105% by using ceramic porous inserts in circular ducts. For turbulent flow. Morosuk (46) considered entropy generation rate in conduit filled with porous numerically and analytically. The porous medium was inserted at the centerline. The entropy generation rates were reported for different porous thicknesses and permeability's. Liu *et al.* (47) developed the new concept of enhanced heat transfer in the core flow along a tube. He believes that the core flow of tubes is worthy to be well used for heat transfer augmentation. The most direct way is to make temperature as uniform as possible in the core flow of the tube in order to form a thin thermal boundary layer near the wall with great temperature gradient, thus resulting in a significant heat transfer enhancement effect. Yang and Hwang (48) numerically investigated the turbulent fluid flow behavior and heat transfer enhancements in a pipe fully or partially filled with porous medium inserted at the core of the conduit. The impact of Re number, Da number and porous radius ratio on heat transfer performance was analyzed in detail. Huang *et al.* (49) carried out experiments inserting a porous medium with high porosity (0.951e0.975) in the core of a tube. They studied the flow resistance and heat transfer characteristics experimentally and numerically. In these and other applications, one of the main problems is to characterize the rapid variations of transport properties taking place in the vicinity of the fluid porous dividing surface. Commonly, the boundary conditions applying at the fluid porous interface are postulated from the macro scale (normally imposing continuity conditions), which can lead to physical inconsistencies with the phenomenon taking place at the micro scale

Yang and Hwnag (50) recently investigated the heat transfer enhancement in a tube with a porous core for a broad range of the Reynolds number values (5000e15,000). Moreover, these authors reported that the optimum porous-radius ratio is around 0.8. Z.F. Huang *et al.* (51) According to the concept of heat transfer enhancement in the core flow, porous media with a slightly smaller diameter to a tube are developed and inserted in the core of the tube under the constant and uniform heat flux condition. The flow resistance and heat transfer characteristics of the air flow for laminar to fully turbulent ranges of Reynolds numbers are investigated experimentally and numerically. Both numerical and experimental results show that the convective heat transfer is considerably enhanced by the porous inserts of an approximate diameter with the tube and the corresponding flow resistance increases in a reasonable extent especially in laminar flow. It shows that the core flow enhancement is an efficacious method for enhancing heat transfer. Yang *et al.* (52) studied Forced convection in a tube with its core partially filled with a porous medium both analytically and numerically to find its high heat transfer performance. Assuming a fully developed flow subject to a constant heat flux, both friction factor and Nusselt number are presented explicitly as functions of the Reynolds number, Darcy number and porous core diameter ratio. It shows that, there exists the optimal porous core diameter ratio as a function of the Darcy number, which yields the maximum heat transfer coefficient Teamah *et al.* (53) carried out a numerical investigation of laminar forced convection in a horizontal pipe partially filled with porous material considering three different cases. In the first case, cylindrical shape porous material was placed at the centerline of the pipe. In the second case the porous material had an annular shape while in the third one it had a cylindrical shape placed at z = 0.05L from the pipe inlet. The effects of porou material radius as well as Darcy number on local Nusselt number and pressure loss were covered. It was concluded that case 1 possesses the highest heat transfer rate with the largest pressure loss. (54). Most works on convective heat transfer in porous media have assumed laminar fluid flow. None the less, other flow regimes have been also studied numerically in the partially filled pipes (55,56). Assuming turbulent flows, it has been shown that to enhance heat transfer the optimum ratio of the porous medium thickness to pipe diameter is 0.8 Boundary conditions and the physics of porous-fluid interface have been already subjected to detailed studies Ref (57). In an analytical work, Most recently, Mahmoudi and Karimi (58) studied numerically the heat transfer enhancement in a pipe partially filled with a porous medium under LTNE condition. They used two interface models A and B and considered the inertia term (F). These authors found that for a given interface model and for Darcy numbers less than 103, the Nusselt number is independent of the inertia. Nonetheless, for Darcy numbers higher than 103 as F increases, the Nusselt number also increases (58). Validity of LTE has been also analytically examined for a thermally fully developed flow in a partially filled tube under constant wall heat flux Ref (59). It was shown that the local thermal equilibrium assumption might fail for the case of constant heat flux wall (59).The validity of LTE in a partially filled pipe under two different configurations has been also studied analytically (60). Local thermal equilibrium condition found to be invalid when the porous material is attached to the pipe wall. However, it was found out that LTE holds when the porous material is inserted at the core of the pipe (60).

Most recently, Vafai and Yang (61) highlighted the heat flux bifurcations at the porous-fluid interface as a fundamental problem with potentials of opening new research areas. In a separate work (62), Yang and Vafai investigated heat flux bifurcation inside a porous medium in a channel partially filled with a porous material and determined the validity range of LTE. The effects of thermal dispersion and inertia on the validity of LTE were further considered in their study.(63)In the present work, entropy generation and convective heat transfer through a pipe partially filled with a porous material is studied numerically for two different cases. In the first one, the cylindrical porous material is placed at the core, while in the second case it is attached to the inner wall, which has subjected to constant heat flux. The results indicated that the position of the porous medium has considerable effect on the performance of the composite pipe

Rotating pipes

Dileep Singh Chauhana* & Rashmiagrawala (64), studied magneto hydrodynamic fully developed flow in a parallel-plate channel partially filled with a porous medium In a rotating system in the presence of an inclined magnetic field.. The effects of appropriate parameters such as the), rotation parameter (R), permeability parameter (k), Hall current parameter (m), viscosities ratio (φ), and the angle of inclination ′θ′ of applied magnetic field on the velocity profiles and induced magnetic field are expressed graphically and discussed.

Bhupendra Kumar Sharma1*, Pawan Kumar (65) investigated the unsteady flow of viscous incompressible fluid through porous medium induced by periodically heated half-filled concentric cylindrical annulus placed horizontally. The boundaries of the annulus are rotating frequently with different angular velocities in the same or opposite directions about their common axis. The analytical solutions have been obtained by expanding the variables in a power series of the annulus aspect ratio. The expressions for stream lines, temperature distribution and rate of heat transfer are obtained and the effects of various parameters upon them have been examined.

MHD Flows

M. K. Sharma, Kuldip Singh, Ashok Kumar (66) Steadied incompressible axisymmetric flow in a circular cylinder partially filled with concentric cylinder of non-Darcy porous medium in the influence of a transverse static magnetic field. The Joule heating effect produced by the magnetic field is also included to analyze effect of magnetic field and fluid flow field on heat convection process. The governing equations were solved using Quasi-numerical method–the Differential Transform. The velocity and temperature profiles for the fluid saturated porous region and clear fluid annulus region are derived and computed with the use of Matlab, Nusselt number at the wall of the outer cylinder and at the surface of the concentric inner porous cylinder are computed and discussed. Dileep Singh Chauhan, Rashmi Agrawal (67) MHD Couette flow in a channel with non-conducting walls, partially filled with a porous medium, is investigated in the presence of an inclined magnetic field in a rotating system. It is observed that the MHD flow behaviour in the channel has been influenced significantly by the Coriolis force, the hydro magnetic force with an inclusion of Hall current and the permeability of the porous medium. Effects of the parameters of these forces on the velocity distributions, induced magnetic field distributions and the skin friction have been depicted graphically and discussed.

Pulsating flows

Zhixiongguo, se young kim and hyungjin sung (68) have investigated numerically of pulsating flow and heat transfer characteristics in a circular pipe partially filled with a porous medium. The impacts of the Darcy number Da, the thickness of porous layer S, the ratio of effective thermal conductivity of porous material to fluid, Rk, as well as the pulsating frequency, β, and the amplitude, A, are investigated. The enhanced longitudinal heat conduction due to pulsating flow and the enhanced convective heat transfer from high conducting porous material are examined. KavehHabibi, Ali Mosahebi, Hossein Shokouhmand (69) have studied 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. energy equation is solved numerically using alternating direction implicit (ADI) method. Finally a case study is investigated for a high-porous and high-conductive medium (Aluminum alloy T-6201) and the enhancing effect and optimization criteria are discussed. D. Dhah (70) investigated numerically study is reported here to investigate a laminar incompressible oscillating flow and heat transfer into a finite length pipe of circular crss section partially filled with an annular lining of porous medium. The porous substrate is attached to the wall, which is heated with uniform temperature. Brinkman-Lapwood-Forchheimer extended Darcy model with variable porosity was used. The control volume-based finite element method (CVFEM) was used for solving the governing differential equations system A comprehensive analysis of the influence of the Darcy number, the Womersly number, the thermal conductivity ratio, the heat capacity ratio, the porous layer thickness, and the Eckert number is presented and discussed. Dileep S. Chauhan* and Vikas Kumar (71) A non-Newtonian second grade fluid flow is considered in a parallel plate horizontal channel partially filled by a porous medium. A porous layer of finite thickness is perfectly attached to upper stationary impermeable plate and the lower impermeable plate moves suddenly with a constant speed or it starts oscillating in its own plane with constant amplitude and frequency. Laplace transform method is applied to determine the solution of the unsteady flow problem for both cases.

Nanofluids

Mastaneh Hajipour *et al*. (72) have investigated, mixed-convective heat transfer of nano fluids in a vertical channel partially filled with highly porous medium. In the porous region, the Brinkman–Forchheimer extended Darcy model was used to describe the fluid flow pattern. The analytical solution was obtained using a two-parameter perturbation method, a numerical analysis was conducted using finite-difference method to compare the obtained results. The predicted results clearly indicate that the presence of nanoparticles in the base fluid augment the heat-transfer process appreciably.

Conclusion

When the fluid flows through porous media the heat transfer is enhanced due to some of the reasons like flow redistribution, thermal conductivity modification, thermal dispersion .etc. This review paper discuss the considerable analytical, numerical and experimental work which has been done on the performance of porous insert techniques in the stand point of heat transfer rate especially for channel and pipe flows partially filled with a porous medium. It has been noticed that, Darcy number, thickness of porous region, ratio of effective thermal conductivities of porous medium and fluid on the flow field have significant effect on the heat transfer enhancement. Furthermore a critical thickness exists at which the value of Nu reaches a minimum. However, under the same configuration and for the high values of thermal conductivity the obtained Nusselt number is always higher than its equivalent in the clear pipe.

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