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Heat Transfer and Flow Behavior in Porous Media: A Review

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ABSTRACT

Heat transfer through porous media has gained considerable interest in recent years due to its ability to enhance the thermal performance in various engineering applications. There are two key advantages of using porous materials. First, the effective heat dissipation surface area is larger than that of traditional solid fins, which intensifies convective heat transfer. Second, the irregular motion of fluid around the internal porous structure improves mixing, promoting greater thermal uniformity by breaking the boundary layer and generating vortices, while in contrast, there is a drop in the pressure of the working fluid. This review provides a structured overview of the developments in heat transfer within porous media, focusing on two categories of working fluids: conventional fluids and nanofluids. Each category is further classified according to the flow regime involved: natural, forced and mixed convection. For conventional fluids, porous structures demonstrate considerable improvements in Nusselt number and thermal efficiency in compact heat exchangers and flow channels. For nanofluids, enhanced thermal conductivity and the possibility of coupling with magnetic fields (MHD) show promising results, especially under forced and mixed convection conditions. The findings from this review reveal that while both conventional and nanofluid systems benefit from the use of porous media, nanofluids exhibit superior heat transfer capabilities when properly optimized. Additionally, the effectiveness of porous media strongly depends on geometric properties, porosity, flow regime, and thermal boundary conditions. This paper offers a comparative understanding of these systems and identifies potential directions for future research in advanced thermal system design.

1. Introduction

It is widely accepted within the scientific and engineering communities that heat transfer is one of the most fundamental, practical, and interdisciplinary engineering problems. This significantly affects practically every element of our existence, particularly in the industrial, environmental, and

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economic perspectives. Certainly, there is some major progress to be achieved in this field of investigation [1, 2]. Heat transfer is primarily utilised in contemporary society, from the production of smallest electronic chips or optoelectronic chips [3, 4], air-conditioning and cooling systems, and generation of renewable energy sources such as solar energy and nuclear power to the creation of largest man-made structures also used in aerospace and space industry [5, 6].

Active, passive, and compound techniques are the three classifications into which many strategies that are used to promote heat transmission fall [7]. The active technique involves increasing the quantity of heat transfer by adding a second power source to the system. Surface vibration, electro hydrodynamics, and magnetohydrodyn-amics are a few examples. Conversely, passive technologies have the advantage of not requiring external power, which makes them applicable to a greater variety of technical applications. A compound method is the result of combining two earlier technologies. For instance, it describes the simultaneous use of an active method, such as fluid vibration, and a passive approach, such as rough surfaces, which results in increased pressure losses [8].

In addition to being less expensive than active methods, passive methods are also often thought to be more dependable since they don't require moving elements. They are also simple to set up, which increases their adaptability to a variety of applications [9]. Conversely, active approaches benefit from outside power, which makes them more successful than passive ones. This makes them appropriate for devices with very difficult characteristics [10].

The rate of heat transmission in the passive approach may be increased using a variety of techniques. Porous medium can be used to improve the surface area of heat exchange. An appealing and successful method for enhancing heat transmission in industrial systems is the use of porous metal materials, such as aluminum foams (see Figure 1), in heat exchangers and channels. The materials used to make the porous medium can be alloys, metals, or plastics. Common metals include iron, aluminum, and copper, and they can also be natural, such as porous stones. There are properties of the mineral porous medium used to improve heat transfer, including: 1- Cell shape. 2- Number of cells per inch. 3- Porosity of the material. A solid matrix with holes (voids) that are usually filled with fluid is called porous media. Depending on the structure, pores can be open-cell, closed-cell, or semi-open, where the degree of interconnectivity governs fluid transport. This means that the fluid may pass through the voids, as the pores are interconnected and fully filled with the fluid. Porous media increase the contact surface area between the liquid and the solid surface. Consequently, it appears that the efficiency of conventional thermal systems may be significantly increased by employing porous media [11, 12].

Porous media can be homogeneous or heterogeneous, post-dispersed or non-dispersed, multi-structured or the product of many structures. The primary attribute of a porous media is porosity and PPI (porous per inch= cell intensity per inch). The porosity is a measurement of the material's empty spaces and a proportion of the volume of the empty spaces over the entire volume between 0 and 1. The porosity of the majority of naturally occurring porous materials, excluding hair, is 0.6. However, the porosity of produced materials, such metal foams, can reach 0.99 [13].

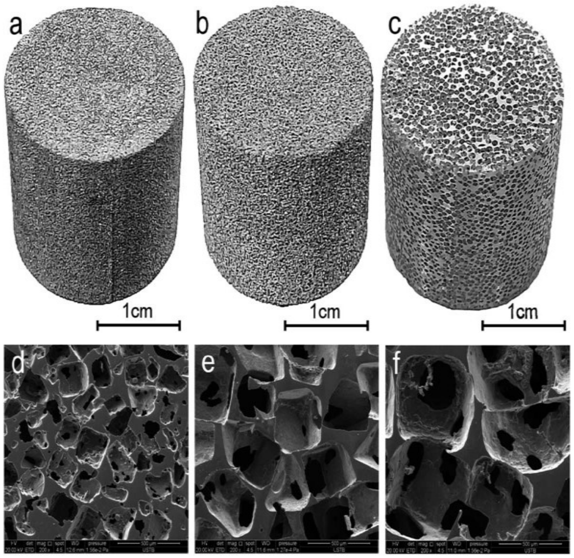

Figure 1. Aluminium porous foams with various pore sizes and their connected structures were manufactured at a pressure of 353 kPa: (a) and (d) 200 μm, (b) and (e) 400 μm, (c) and (f) 600 μm [14].

In light of the critical role that porous media assumes in enhancing heat transfer across various engineering applications, this review aims to provide a comprehensive overview of the current condition of research on heat transfer in techniques incorporating porous structures. The study is classified into two main parts: the first part focuses on conventional fluids (such as air and water ..... etc.), while the second part explores the use of nanofluids, which offer superior thermal conductivity and potential for advanced thermal management. Each part is further classified according to the type of fluid flow involved namely, natural (free) convection, forced convection, and mixed convection. By systematically comparing the findings across these categories, the review seeks to identify key parameters, dominant mechanisms, and emerging trends that can guide future developments in thermal system design and optimization. This structured approach is intended to serve both as a foundation for newcomers to the field and as a reference for experienced researchers and engineers working on advanced heat transfer technologies.

2. Heat Transfer with Conventional Fluids in Porous Media

2.1 Forced and Mixed Convection with Conventional Fluids

The investigations of forced convection flow and thermal characteristics in cavities and enclosures filled with porous media have received significant attention from many researchers due to their vital role in a wide range of engineering and industrial applications. The benefit of the metal medium in forced convection systems enhances thermal performance by increasing the effective surface area for heat transfer and promoting mixing at the microscopic level. These media are widely utilized in the design of compact heat exchanger, where they enable high heat flux removal within limited space. In electronic cooling, metallic foams act as effective passive cooling elements, aiding in dissipating heat from high-power microchips and processors [10, 15-18].

Additionally, Porous structures (such as metal foams) are widely used to improve heat transfer in conventional technologies by increasing the surface area and improving fluid mixing, which increases the effective thermal conductivity, resulting in a significant improvement in convective heat transfer. In solar thermal collectors, porous inserts are used to improve the absorption and conduction of thermal energy. The coupling of porous media with forced convection also plays a critical role in energy systems, such as fuel cells and battery thermal management, where controlled flow and uniform temperature distribution are essential for system stability and perfomance. With advancements in material engineering, modern porous structures can be optimized in terms of porosity, permeability, and thermal conductivity, allowing for tailored designs that meet specific thermal and hydraulic requirements in various engineering systems [19-21]. Taha and Farhan [22] conducted an experimental work to assess the thermo-hydraulic efficiency of a single duct single-glazed SAH with herringbone metal foam fins attached beneath the absorber plate. Three corrugation angle values (30, 60, 90°) for the herringbone fins were examined. They found that an unfinned SAH at an air flow rate of 0.05 m3/s achieved a maximum thermal efficiency of 29.4%, while a finned SAH with a corrugation angle of 30° achieved 87.7% at an air flow rate of 0.04 m3/s. Hasan and Farhan [23] performed an experimental investigation in Baghdad, Iraq, to evaluate the performance of a photovoltaic (PV) panel with staggered metal foam fins. They examined three special preparations of staggered aluminum foam fins that have been affixed to the PV panel's backside. The most electric performance improvement over the reference PV panel was found to be 4.7% for staggered metal foam fins (case III). Farhan et al. [24] conducted an experimental study on solar air with absorber plates featuring various fin configurations. They used two kinds of fins: metal foam and solid. Staggered, corrugated, and longitudinal fin configurations were examined under the weather conditions encountered. They found that the metal foam of corrugated fins presents more turbulent air flow than the other configurations. In order to improve heat transfer, Aljubury et al. [25] conducted an experimental investigation on metal foam twisted tape, which, under the same circumstances, offers a better thermal enhancement factor than conventional twisted tape. It is discovered that the suggested metal foam twisted tape's maximum effectiveness in the range of Re utilized is roughly 18% greater than that produced by the conventional twisted tape.

Baragh et al. [26] presented an experimental study of a single-phase air flow in a channel having a circular cross-section with various configurations of porous media (see Figure 2). Differences in hydrodynamic parameters, the enhancement of heat transfer by porous media in the channel, and the pressure losses resulting from the presence of porous media are investigated. Outcomes showed that the existence of porous media leads to the thermal flux applied to the walls of the channel being transmitted into the air flow due to the raised conductivity of the metallic foam. Furthermore, the average temperature of the air flow rises, which leads to a reduction in the temperature distinction between the channel surfaces and the average temperature of the air flow. They found that the completely filled tube of the metallic foam has the highest heat transfer improvement (in the laminar and turbulent flows). The results showed that the tube with porous annular regions gave the best heat transfer and a lower pressure drop.

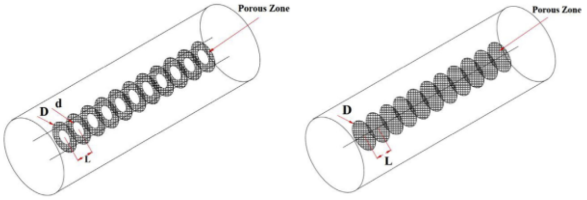

Figure 2. Diagram illustrating the test's porous media models [26].

Nimvari et al. [27] introduced a numerical investigation of heat transfer and flow via a partially porous medium in a channel with laminar and turbulent regimes. They used two typical configurations of a porous medium with Various layer thicknesses in the channel: boundary configuration and central configuration, as shown in Figure 3. They found that at a particular thickness exists, the mean Nusselt number is highest for the central configuration and lowest for the boundary configuration, due to the channeling influence. Porous thickness changes concerning Darcy number are significantly smaller in the turbulent regime than in the laminar regime, according to a comparison of the obtained results with similar laminar flow values.

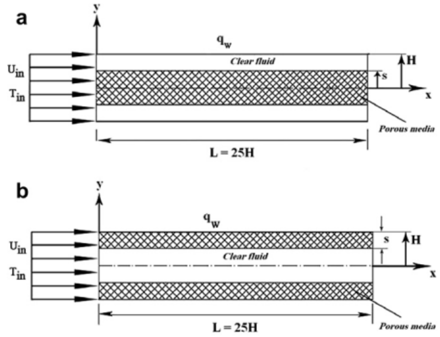

Figure 3. (a) centrally arranged channels and (b) boundary-configured channels [27].

Metal foams were classified as a porous medium having sinuous, irregularly shaped flow channels and generally high porosity [28]. Various thermal and fluid flow characteristic ideals of magnetic field with porous medium in the publications have been summarised by Mahjoob and Vafai [29]. Altogether, the outcomes indicated that despite the extensive pressure losses, metal foams (porous medium) can seriously improve the rate of heat transfer.

Analytical investigations into the forced convection heat transfer of double pipe heat exchangers refilled with high porous metals were conducted by Lu et al. [30] and Zhao et al. [31]. They studied the prediction of the optimum porosity of metal foam filled in a counterflow two-tube heat exchanger. Furthermore, they noted that using metal foam in a heat exchanger performed significantly better at heat transmission than the conventional fin tube heat exchanger [32].

Yang et al. [33] used the non-thermal equilibrium and local thermal studies for the two cases of partial porous media filling to examine the local thermal equilibrium deduction. Their theoretical study found that the heat transfer performance of the tube with a porous medium core is superior to that of the tube with a porous medium layer covering the wall in a relatively modest range of pumping power. However, the latter performs better than the former over a wide range of pumping power. Thus, for assigned operating states, a careful investigation is needed to determine which arrangement is more useful in view of thermal enhancement.

Kuznetsov [34] introduced analytical research to study the influence of the thermal dispersion on the fully developed forced convection in the parallel-walls channel via a partially filled porous medium channel. The channel walls are maintained under uniform heat flux. The porous media saturated with a fluid of uniform porosity occupy the channel's periphery, and a homogeneous fluid occupies the middle region. He hypothesized that the Brinkman-Forchheimer-extended Darcy equation describes the momentum flow in the porous zone. The goal of the study is to identify the situations in which taking thermal dispersion into consideration can have a major impact on the solution.

Shokouhmand et al. [35] examined the influence of the porous insert assignment on thermal enhancement in the parallel-walls channel partly filled with a saturated porous media. They simulated forced convective and fully developed laminar regime by using the Lattice Boltzmann Method (LBM). A uniform wall temperature was applied to the channel walls. They studied the thermal performance and fluid flow field for two arrangements: the porous layer was bound to the channel surfaces, and second, an identical quantity of porous layer was placed in the channel core. It is found that the thermal performance is significantly affected by the location of the porous insert. Jen and Yan [36] designed a 3D computational sample to study the flow characteristics and heat transfer mechanisms in a channel partly filled with porous media. They employed a single-domain CFD formulation for the porous media and fluid layer instead of numerous domains, which necessitates the definition of the interface conditions. One pair of strong counter-rotating secondary flow vortices can be observed in the channel cross-section in the entrance flow region due to the pore blowing effect of the porous media. It is observed that with the increase of the ratio of porosity, the flow was accelerated in the layer of fluid, and the frictional losses and heat transfer are raised.

Zhu et al. [37] conducted a numerical simulation of a 2D cooling channel using porous media to explain the augmentation in total heat transfer of hydrocarbon fuels. Researchers suggest that inserting a layer of porous material acts like a coupling link that boosts heat flow, yet paradoxically, raises overall thermal resistance (see Figure 4). Simulations show the porous insert breaks up thermal layers in the cooling duct, producing a more uniform temperature field than that seen in a plain flat channel. In addition, it is shown that as the porous media porosity decreased, the overall heat transfer rate of the fuel increased. They concluded that by positioning porous media at various locations, the ideal placement position is determined in order to study the heat transfer coupling rule of porous media.

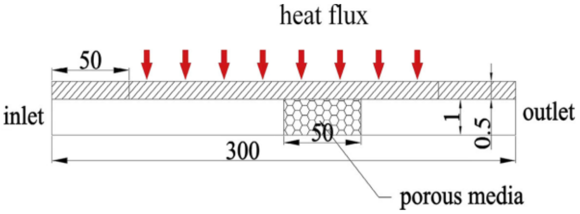

Figure 4. Graphical geometry of the investigation [37]

Wen et al. [38] presented an experimental investigation to study the features of sub-cooled flow boiling pressure losses and enhanced heat transfer of a hydrocarbon refrigerant (R600a) through copper porous circular tube inserts. The impacts of Reynolds number and the geometry of inserts on the thermal and flow features were reported. It is found that as the heat flux and mass velocity rise, the coefficients of heat transfer for the study tubes increase. Moreover, porous inserts caused a considerably higher pressure drop, which became even higher when the average pore diameters of the inserts were reduced.

Yang et al. [39] presented a numerical analysis on forced convection thermal performance in porous medium, with a special focus on the effect of permeability. Original rock samples with identical porosity but with different permeabilities are utilised to establish digital rock samples with a laminar water flow regime. Results showed that the rock Darcy number (Da), in terms of permeability, plays a critical role based on the numerical simulation, and a higher Nusselt number (Nu) was obtained when compared to the lower Da case. The corresponding correlations for predicting forced convective heat transfer characteristics in rock media are offered.

Dai et al. [40] presented a numerical study of the porous medium influenced by a water impinging jet in which the heated surface is covered with a different shape or a double-layer porous medium. The effects of different porosity distributions, thickness ratios, and porous morphologies on heat dissipation are examined computationally for both the top and bottom layers with different porosities in a gradient variation configuration. Outcomes indicated that the surface is more sensitive to changes in jet velocity when it is covered by a rectangular porous medium, while the surface covered by a triangular porous medium resulted in a better heat transfer coefficient at the stagnation point and a lower surface temperature.

Tu et al. [41] developed a practical research analysis to examine the pressure losses and thermal performance of metal foam (porous media) layers in a single phase for Reynolds numbers from 3654 to 14617. The influence of particle shape and particle size on the friction factor, heat transfer rate and thermal-hydraulic performance is investigated. It is found that the shape and size of particles have a significant effect on the thermal and water flow field. Moreover, the results indicated that spherical particles exhibit a higher heat transfer rate compared to dendritic particles. Additionally, the dendritic particle has the best heat transfer performance, for it has the highest heat transfer rate, and its flow resistance is also the lowest. Thus, they discovered that the hydrothermal performance values must be accounted for in the heat exchanger design.

Tavakoli et al. [42] conducted an experimental analysis to examine the impacts of various porous material arrangements and the air flow rates on the thermal enhancement in various arrangements. They used porous medium with various porosity ratios varying from 96.5 to 98.9% and Reynolds numbers of 5000 - 40,000, to analyze the heat transmission improvement and pressure losses. The findings demonstrate that the tube without a porous medium works more efficiently than designs with a porous medium in the Reynolds numbers regime. They showed that the porous medium configuration has a significant effect on the overall Nusselt number and Pressure drop. Furthermore, pressure drop can increase to about 900 times the dynamic pressure when the entire enclosure is porous; however, the loss is significantly reduced with alternative configure-ations. The researches of mixed convection heat transport in fluid-saturated porous medium has been the interest subject in several investigations because thermally driven flows in porous media have found general applications in a variety of thermal sectors [43]. Several other analyses displayed the importance of mutual mixed convection heat transfer in the porous medium [44, 45].

Bhakta et al. [46] conducted a numerical study of a mixed convection air flow through a square cavity that held an oscillating porous circular cylinder with different diameters that was thermally conductive and positioned in the center, as shown in Figure 5. The investigation is performed within a mixed convection province with Reynolds number of (Re = 100), Grashof number of ($10^3 \le Gr \le 10^5$), and Richardson number of ($0.1 \le Ri \le 10$). They concluded that the average heat transfer rate indicated the highest enhancement of 21.50 % at the largest cylinder diameter.

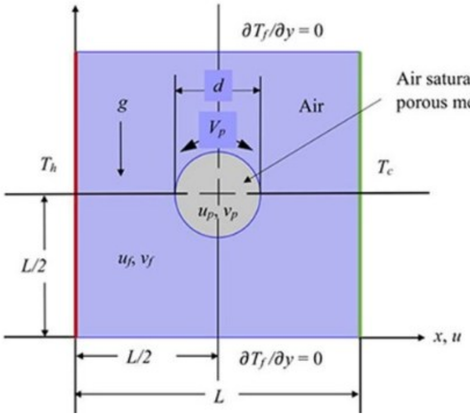

Figure 5. Physical Model of the study [46].

A computational investigation was performed by Abu-Hamdeh et al. [47] to analyze the influences of various parameters on free-force convection in a porous structure filled lid-driven enclosure with one side opening in the heat generation presence (see Figure 6). They found that the flow field and heat transfer inside the chamber were so difficult due to the moving lid, heater and open side wall. Heat transfer improved with the increase of heater length, Grashof numbers and was reduced with Darcy numbers.

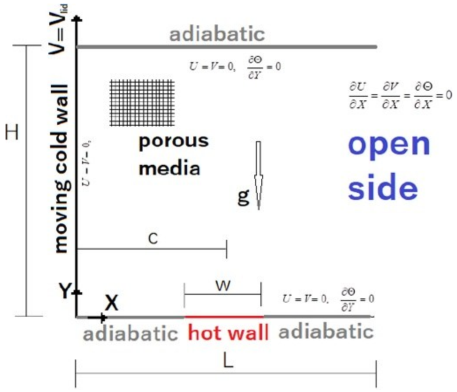

Figure 6. Geometry model of the study [47]

2.2 Natural Convection with Conventional Fluids

Natural convection heat switch in porous enclosures saturated with different conventional fluids is one difficulty that is now attracting a lot of attention from researchers. In porous media, natural convection can appear whilst temperature or composition variations cause the saturated fluid's density to differ. There are several makes use of for this phenomenon in porous enclosures, together with gas cells, food storage, nuclear reactors, solar collectors, compact heat exchangers, electronic tool cooling, building insulation, geothermal heat utilization, blood flow modelling, and fuel cells [48-50].

Al-damook and Azzawi [51] presented a numerical study of natural convection heat transfer and flow characteristics through an annular elliptical pipe entirely filled with a saturated porous metal. The inner wall of the annular pipe was maintained at a uniform cold temperature, while the outer wall was subjected to a varying hot temperature. The main findings indicated that as the temperature of the hot surface rises and the contraction ratio falls, the overall and local coefficients of skin friction were raised, while the Nusselt number and heat transfer rate were improved. In addition, results showed that the viscous resistance and porosity of porous media had a major influence on the thermal-hydraulic performance enhancement. Chandra et al. [52] conducted a numerical simulation to study the natural convection of thermal and flow characteristics occurring porous square with insulated side surfaces. They studied two cases: (I) identical constant heat flux on the bottom and top surfaces, and (II) the top surface's constant heat flux was negative in relation to the bottom surface's heat flux (see Figure 7). They showed that the streamline and isotherm structure for Case (I) is multicellular and depends on the periodicity parameter value and media permeability, while the other case is unicellular.

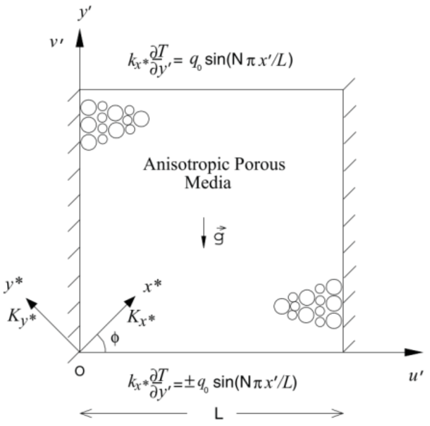

Figure 7. Physical geometry of the study of Chandra et al. [52].

Cheong et al. [53] conducted a numerical investigation to examine two-dimensional free convective heat transfer and flow in a sinusoidally heated wavy porous medium with internal heat generation or absorption. The right wall of the cavity wavy is kept at a steady temperature while the vertical left side sinusoidal wall receives heating (see Figure 8). The research assumed that the top and bottom walls are adiabatic. For fluid flow through the metal foam cavity, the Darcy model was used. They found that the waviness of the right wall influenced the temperature distribution and flow field cavity. Additionally, the porous medium's wavy shape improved heat conduction into the system. Mirzaei et al. [54] conducted a CFD analysis of the free convection and entropy generation through a trapezoidal porous cavity with a square hollow, regarding the influences of thermal radiation and dissipation (see Figure 9). They analyzed the impacts of Rayleigh number, Darcy number, radiation parameter and Forchheimer resistance on the thermal field, entropy generation, and the flow patterns. The results indicated that an increase in the Rayleigh number heightens the buoyancy influences, which led to more increase in entropy generation and changed temperature distribution. Furthermore, entropy generation and heat transfer were reduced when the permeability decreased due to an increase in the inverse Darcy number.

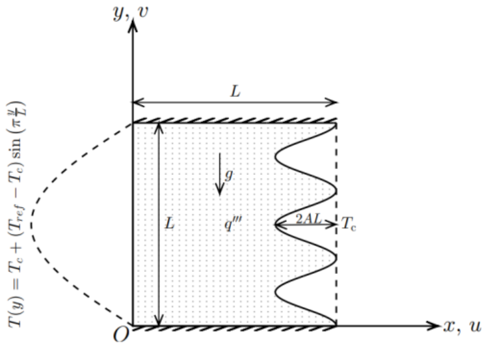

Figure 8. Schematic of the physical study of Cheong et al. [53].

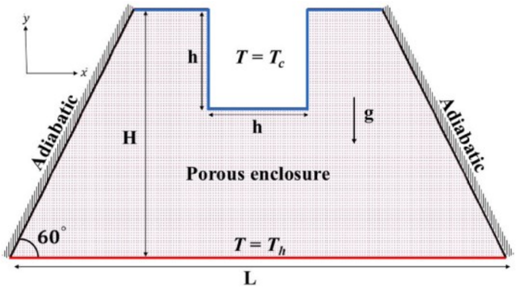

Figure 9. Trapezoidal porous schematic enclosure geometry with a square cavity of Mirzaei et al. [54].

Hussain et al. [55] explored the generation of entropy for the free convection in a porous medium, partly heated square cavity, evaluating the influences of cavity inclination, viscous dissipation, and magnetic field. It is found that the overall heat transfer enhancement reduces and the average entropy generation rises as the cavity inclination increases.

Alabdaly et al. [56] conducted a numerical study of free convection and entropy losses through a porous Cassini oval annular cavity pipe (see Figure 10), which was essential for various thermal engineering techniques. They studied the influence of aspect ratio ($0.08 \leq AR \leq 0.2$), annular inclination ($0° \leq \theta \leq 90°$), porosity ($0.15 \leq \varepsilon \leq 0.95$), and the density of porous ($10 \leq PPI \leq 30$) on the thermal enhancement, flow characteristics and entropy generation. In comparison to the baseline, the optimum design ($AR = 0.2$, $PPI = 30$, $\varepsilon = 0.15$, and $\theta = 0°$) maximizes the thermal efficiency in terms of thermal and the losses of friction by about 23.78 times.

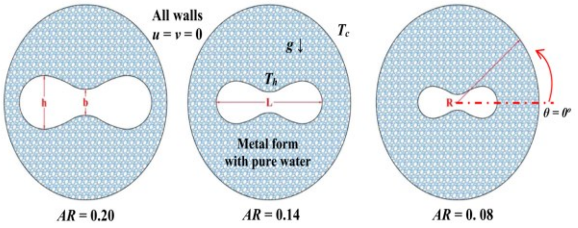

Figure 10. The physical domain of the study of Alabdaly et al. [56].

Khalil et al. [57] conducted a CFD investigation of free convection within a W-shaped cavity completely filled with a porous medium. They considered several effective physical parameters, such as the applied temperature deviation of (ΔT = 10 - 40 K), the number of wave amplitudes of ($1 \leq n \leq 3$), pore size of ($10 \leq PPI \leq 30$), and the aspect ratio of (AR = 0 - 0.8) on the thermal enhancement, flow characteristics and entropy generation. The outcomes indicated that the best way to construct natural convection in a fully saturated metal structural W-shaped cavity at PPI = 10, n = 3, and W = 0.8 led to improvements of about 2.875 times in heat transfer and friction losses. Azzawi and Al-damook [58] performed a Response Surface Methodology (RSM) and CFD study of free convection in an isosceles triangular cross-section cavity heated from the bottom, cooled along the sidewalls, filled with metal foams (see Figure 11). They studied the effects of different Rayleigh numbers (Ra), from 10^2 to 5×10^3, for different angles of inclination (θ), lengths of heaters (Lh), and locations of heaters (Ph). It is found that the aspect ratio (AR), porosity (ε), and Rayleigh numbers have a significant influence on thermal-hydrolic efficiency.

Al-damook and Azzawi [59] examined free convection in a horizontal annular concentric tube for six different arrangements (Square, Circular, Triangular, Diamond, Rectangular and Elliptic) using distilled water. They discovered that the rate of heat transmission of elliptical and circular tubes was around 40% and 37%, respectively, more than that of other shapes. Lam and Prakash [60] studied the free convection through a porous square cavity with interior heat sources. They examined the influence of Darcy number, Rayleigh number, and porosity on thermal dissipation and flow flied. It was demonstrated that the Rayleigh number, porosity, and Darcy number are all directly correlated with the rate of heat transfer on the bottom and top walls.

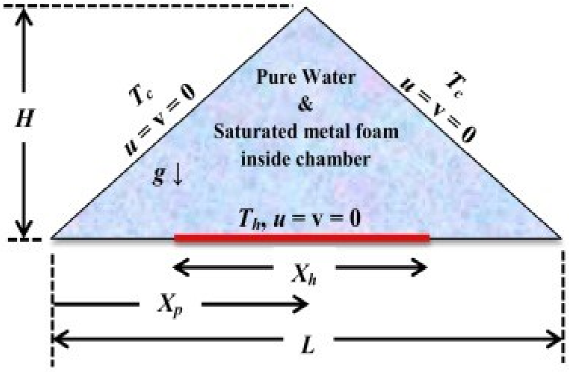

Figure 11. The physical geometry of the triangular cross-section cavity of Azzawi and Al-damook [58].

3. Heat Transfer with Nanofluids in Porous Media

Conductive nanoparticles can be added to the base fluid to enhance heat transmission further. After that, the working fluid is regarded as a nanofluid. The additional nanoparticles may be metallic, consisting of metals like copper and aluminium, or they may be composed of non-metallic elements like carbon or metal oxides. Fluids that include two or more different kinds of nanoparticles are referred to as hybrid nanofluids. Increasing the fluid's thermal conductivity is the primary goal of scattering nanoparticles in it. However, there is a disadvantage to incorporating nanoparticles into a fluid that is to be avoided. Above a certain point, increasing the volume percentage of the nanoparticles raises the fluid's viscosity, which might impede heat transmission [61].

3.1 Forced and Mixed Convection with Nanofluids

A practical method for advancing heat transfer in industrial systems has been provided by forced and mixed convection with nanofluids and porous media. Heat transmission can also be improved by using porous materials with high thermal conductivity. In addition to improving heat transmission, porous material can increase the pressure drop. Joibary and Siavashi [62] presented a numerical investigation to improve the thermal performance of a counterflow double-pipe heat exchanger by utilizing porous layers and nanofluids (see Figure 12). They studied the influences of full filling one or both tubes and the Reynolds number of Re = 100 - 2000 on the pumping power, heat transfer rate and the hydrothermal performance. They observed that the metal foams have a significant effect on the heat transfer rate and the performance evaluation criterion (PEC). Furthermore, PEC analysis showed that each channel has ideal Re values for flow, and the highest efficacy is obtained when using both channels.

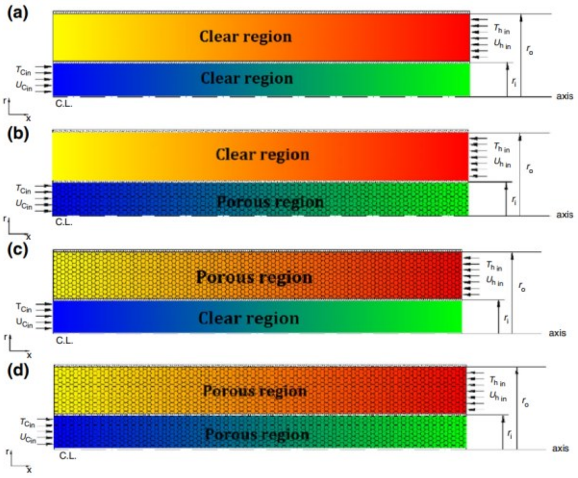

Figure 12. Schematic geometry of the study of Joibary and Siavashi [62].

Chen and Ding [63] performed a numerical analysis of the forced Convection thermal and flow characteristics through a micro-channel heat sink using water−γAl_2O_3 nanofluid with various nanoparticle concentrations. Because the microstructures are so minute, the micro-channel heat sink is modelled as a fluid-saturated porous medium to help solve problems (see Figure 13). The influences of the inertial force parameter on the micro-channel heat sink efficiency and the thermal characteristics were studied. Their results showed that the inertial force did not modify the temperature distribution surface channel, but it did impact the total thermal resistance and the fluid temperature distribution in a big way. Torabi et al. [64] presented a forced convection numerical study of water-Al_2O_3 nanofluid via an isotropic porous medium with two configurations of square obstacles: in-line and staggered (see Figure 14). They found that the Nusselt number showed a declining trend, whereas the heat flux rose as the nanofluid volume percentage increased. The findings also indicated that the dimensionless overall entropy production rate reduced as the nanoparticle concentration increased, irrespective of the square pillar configuration.

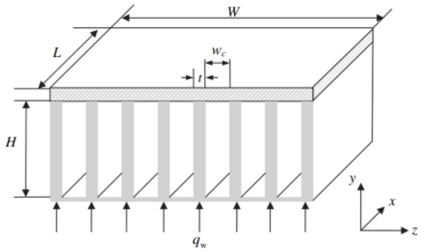

Figure 13. Schematic diagram of the physical model of Chen and Ding [63].

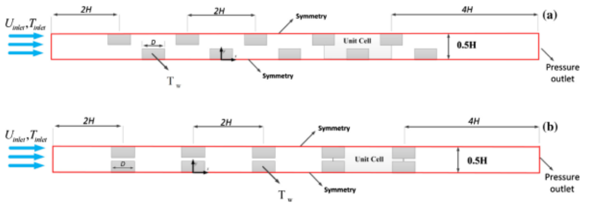

Figure 14. (a) staggered configuration, (b) in-line configuration [64].

The combination of forced convection of flows and magnetic field interactions within nanofluid-containing porous media has garnered significant attention. This increased interest arises from its inherent roles within contemporary thermal systems like heat exchangers, solar collectors, and electronic cooling systems [65, 66]. A nanofluid under a magnetic field induces a Lorentz force within the electrically conducting nanofluid. The force resists motion within the fluid medium. Thus, this leads to a reduction of fluid velocity and suppresses flow turbulence. Meanwhile, enhanced thermal conductivity of the nanofluid can enhance heat transfer performance [67-72].

Selimefendigil and Öztop [73] performed a forced convection of a CNT-water nanofluid in a layered U-shaped vented cavity involving a porous zone under the wall corrugation influence. Researchers studied several effects, including the Reynolds number of ($Re = 100 - 1000$), the Hartmann number of ($Ha = 0 - 50$) and the height of the porous layer on the thermal and flow features. They found that the magnetic field force, the Reynolds number and the porous medium permeability had a significant effect on the rate of heat transfer and flow field.

Servati et al. [74] used the lattice Boltzmann model to investigate the impacts of applied magnetic field on forced convection discharge of water–Al_2O_3 nanofluids in a partly filled channel with porous medium (see figure 15). They studied the effects of nanoparticle concentration, Hartman numbers on the flow and thermal characteristics. They found that the overall Nusselt number as well as the outlet velocity were increased as the nanoparticles volume fraction increased. In addition, it was found that the magnetic field represented by the Hartmann number has a weaker influence on enhancing heat transfer than the concentration of nanofluid particles.

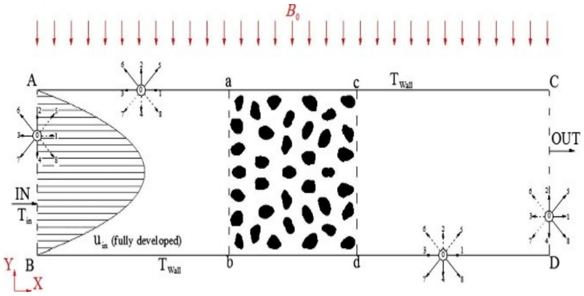

Figure 15. Geometry of the study of Servati et al. [74]

Ghazvini and Shokouhmand [75] investigated numerically and analytically forced convective heat transfer and fluid flow of water-CuO nanofluid with nanoparticle volume fraction of (0-4) % via a micro-channel heat sink subjected to uniform heat flux boundary conditions. They used two analytical techniques: the porous media and the fin model techniques. The outcomes showed that the fin technique displayed a higher significance for the temperature of the nanofluid and solid than the porous medium technique.

Moghadasi et al. [76] conducted a three-dimensional numerical simulation using ANSYS-FLUENT of laminar flow and heat transfer of CuO-Al_2O_3-water nanofluid through a U-bend tube within the metal foam (porous media). They investigated two configurations of the porous media: a porous layer positioned at the wall and another at the centre of the U-bend, and compared the results with a baseline case without porous media (see Figure 16). Results found that the overall Nusselt number and pressure losses for all nanoparticles concetrations showed an increasing pattern as the volume fraction increased, whereas PEC depicted a decreasing trend. Moreover, an increase in the permeability of porous media led to an increase in the heat transfer rate. In another research, Nazari et al. [77] examined experimentally the impacts of the metal foams and Al_2O_3-water nanofluids of the extended wall on the thermal efficiency in a circular pipe filled with porous medium. The outcomes of the forced convection indicated that the heat transfer rate was directly connected with the volume fraction of nanoparticles.

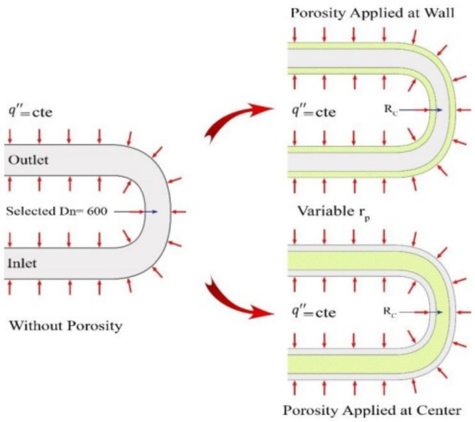

Figure 16. Schematic geometry of the study of Moghadasi et al. [76]

Xu and Zhao [78] conducted an experimental investigation on the boiling thermal efficiency of Al_2O_3-water nanofluid in the gradient metal foam. Results found that alumina nanoparticles can affect the boiling heat transfer efficiency. The outcomes indicated that the presence of nanoparticles leads to an increase in the viscosity of the liquid during boiling, while increasing its effective thermal conductivity. Siavashi et al. [79] studied the effects of the porous media ribs and nanofluid on the rate of heat transfer in an annulus heated on both surfaces. The results demonstrated that for all porous rib heights and porous medium permeabilities, the pressure drop increase is significant, and the heat transmission is improved as the porous ribs are positioned on the exterior wall.

Hajipour and Dehkordi [80] studied the free-forced convection of Al_2O_3-water nanofluids in a vertical square enclosure partly filled with open porous media under the uniform surface heat flux, utilizing the numerical and experimental methods. The received results indicated that heat transmission may be enhanced by nanofluid flow when porous metal foams are present. In another research, the mixed convective thermal and flow features were numerically examined by Mahdi et al. [81, 82] using four models in a rectangular horizontal cavity filled with nanofluid and a variety of open-cell porous media (metal foams) around circular heat source shapes with uniform temperature (see Figure 17). The impacts of aluminum foams' angle, properties of nanofluid and the number of Richardson on thermal and flow characteristics were studied. The findings indicated that employing a rectangular model combined with using the metal foams and nanofluid led to a more increased average Nusselt number. Furthermore, the overall Nusselt number rises with the volume fraction of nanoparticles, as well as with the mixed convection parameter.

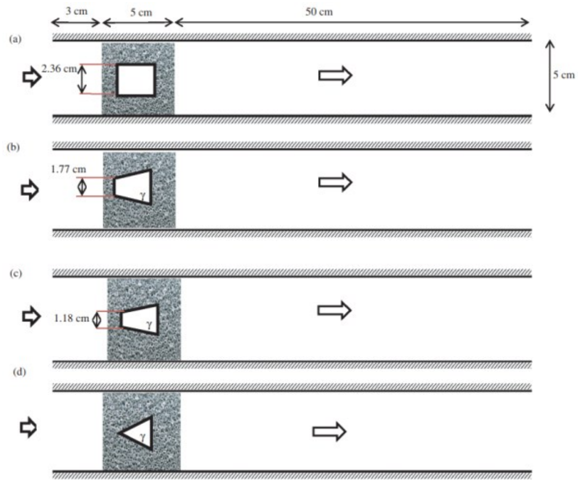

Figure 17. Test section models of the study of Mahdi et al. [81].

Amrei and Dehkordi [83] examined mixed convection in vertical and regular porous channels for both nanofluids and regular fluids. They used the CFD method to solve the problem in the momentum and heat transfer entrance regions while accounting for the impact of viscous heating and inertial force. They studied how the Grashof number value affected the temperature and velocity distributions in the entry and developed areas. Also, they compared the temperature and velocity distributions of ordinary fluids and nanofluids in porous and regular channels.

Raizah et al. [84] conducted a mixed convection heat transfer within a corrugated vertical cavity containing hybrid nanofluids and porous media with magnetic field effects. The corrugated vertical surfaces of a cavity have a cold temperature, and the other surfaces are adiabatic. The heated wall is set in the bottom wall, and the left-top surfaces have lid velocities (see Figure 18). They found that increasing the heat absorption/generation coefficient enhanced the solid-phase isotherms.. Further, the heat transmission between the fluid and solid phases is improved by expanding the porosity parameter.

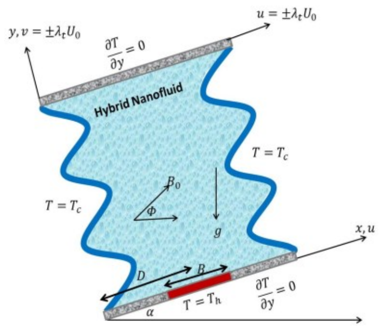

Figure 18. Geometry of an inclined corrugated vertical cavity of the study of Raizah et al. [84].

3.2 Natural Convection with Nanofluids

Abed and Al-damook [85] performed a 2D numerical study of free convective heat transfer in a square cavity filled with a saturated porous medium and Al_2O_3-water nanofluid. The cavity included three heated circular tubes (see Figure 19) with Rayleigh numbers of (10^2 - 3×10^4). The effects of the nanoparticle concentration, aspect ratio, and metal foam porosity on the thermal and flow features were investigated. They concluded that the optimal average Nusselt number was obtained at the lowest values of possible porosity and nanofluid concentration.

Previous studies have examined the effects of magnetic fields on the free convection in nanofluid-saturated porous media. A clear distinction must be made between metal foams and non-Darcy porous structures, as the mechanisms of heat transfer and the challenges they present differ significantly between them, such as nanoparticle deposition. This has been applied to solar dryers, adsorption reactors, electronics cooling systems that store thermal energy, and spacecraft heat management. These applications benefit from enhanced heat flow of nanofluids and tunable flow resistance produced by porous materials and external magnetic fields [86-88].

RamReddy et al. [89] examined how viscous dissipation affected natural convection in a non-Darcy porous medium that included nanofluid. They employed a vertically implanted plate for the metal foam part. Results indicated that the field of magnetism improved the mass and heat transfer. Chamkha et al. [90] conducted an investigation into the effects of viscous heating and a magnetic field on non-Darcy porous media. They found that increasing the magnetic field led to a decrease in velocity, in addition to an increase in temperature and size distributions of nanoparticles in the boundary layer. In another research, a free convection of thermally stratified nanofluid flow in a non-Darcy porous structure was investigated numerically by RamReddy et al. [91]. The magnetic field was included for the mass and heat transfer improvement. They found that adding a magnetic field with a porous medium had a significant effect on the velocity and temperature distributions.

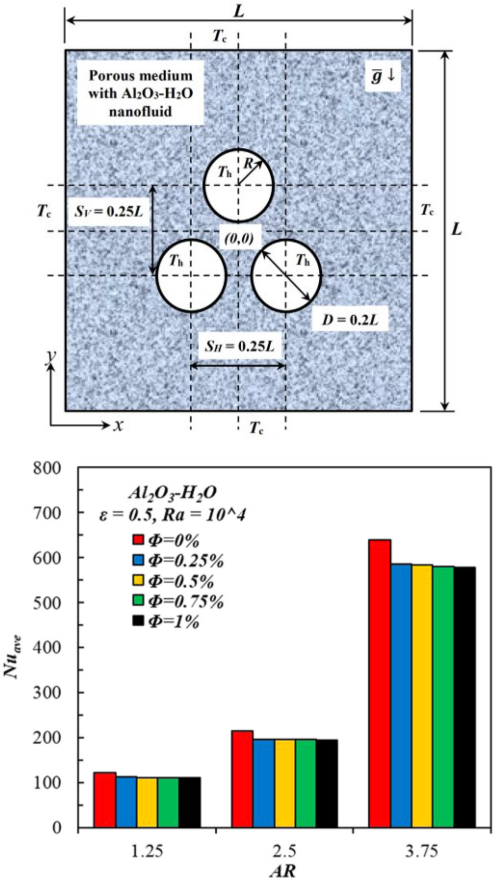

Figure 19. Physical domain and the variation of average Nusselt numbers of the study of Abed and Al-damook [85].

Redouane et al. [92] conducted a CFD analysis of the thermal evaluation of free convection inside a metal foam triangular with rotate cylindrical chamber filled with oxide/water silver-magnesium hybrid nanofluids [Ag-MgO/H_2O] supplied by a constant magnetic field (see Figure 20). They studied the effects of Rayleigh, Darcy, and Hartmann numbers, porosity and the nanoparticles concentration on the thermal and flow features. They concluded that the use of a porous medium with nanofluids had a significant effect on the isotherms and streamlines, resulting in an increase in heat transfer.

Table 1 summarizes several investigations dealing with the free, forced, and mixed convection of nanofluids and conventional fluids using porous media.

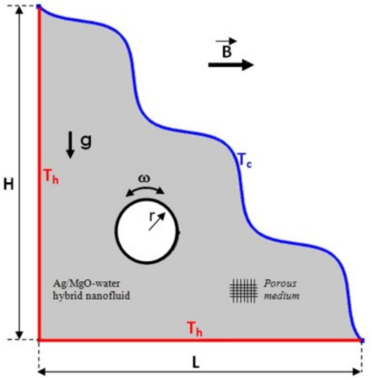

Figure 20. Physical geometry of the analysis of Redouane et al. [92].

4. Mathematical Models Employed to Investigate the Heat Transfer and Fluid Flow in Porous Media

Mathematical models can be developed based on the fundamental principles of conservation equations of mass, momentum, and energy to investigate the heat transfer and fluid flow in the porous medium. These models may extend from basic analytical approaches to sophisticated numerical analyses. The continuity equation ensures mass conservation, expressed as $\nabla\ u = 0$. The Brinkman equation is a generally employed mathematical model for the fluid flow in the porous medium, which is a modified version of the Navier–Stokes equations that includes a different drag term due to the presence of the solid matrix. One way to express the Brinkman equation is as follows [19]:

$$\rho\frac{\partial u}{\partial t} = \rho u \cdot \nabla u = -\nabla P + \mu\nabla^2 u - \frac{\mu}{K}u \qquad (1)$$

where ρ is the density of fluid, u is the fluid velocity, μ is the fluid dynamic viscosity, P is the flow pressure, and K is the porous medium permeability. The energy transport is generally modeled using the Local Thermal Equilibrium (LTE) assumption, as follows [19]:

$$\rho c\frac{\partial T}{\partial t} + u \cdot \nabla \mathrm{T} = \nabla \cdot (K \cdot \nabla T) + S \qquad (2)$$

where T is the fluid and solid phases' average temperature, c is the porous medium specific heat capacity, and S is a heat source.

Table 1. A summary of many investigations on different working fluids flowing within porous media, utilising various methodologies.

Author	Geometry	Working fluids	Methodology	Result	Variables
Rahman et al. [93]	Square enclosure filled with a porous medium	Fe_3O_4-water nanofluid	Natural convective - Lattice–Boltzmann	An increase in Ra and φ led to improve in Nu	$10^3 < Ra < 10^5$ $0.4 < \varepsilon < 0.9$ $0 < \varphi < 0.003$
Izadi et al. [94]	Inverse T-shaped chamber	Fe_3O_4-water nanofluid	Natural convection Forchheimer model	The parameter of magnetic field viscosity led to significant heat transfer improvement.	$0.7 \leq$ porosity ratio ≤ 1.4 $Ra = 10^5$
Hussain and Rahomey [95]	Square cavity with various geometries of a central circular cylinder	Ag-H_2O nanofluid	Natural convection, Brinkman–Darcy mode	An increase in the thickness of the porous layer from 20% to 80% led to a reduction in free convection efficiency (up to 50%)	$10^3 < Ra < 10^6$ 0% < porous layer thickness < 100%
Al-Srayyih et al. [96]	Using porous layers and the left wall of the square chamber is heated linearly	Cu-H_2O nanofluid	Natural convection, Darcy–Brinkmann model	Raising the Rayleigh numbers led to an increase in the streamlines' intensity	$10^3 < Ra < 10^7$ $\varphi = 0.1$
Kadhim et al. [97]	Lied cavity with opposing wavy walls and a partially porous medium layer.	Al_2O_3-Cu - water nanofluid	Natural convection, The Galerkin finite element method	Adding nanoparticles led to an enhancement of the heat transfer compared with the pure fluid.	$10^4 \leq Ra \leq 10^7$ $0 \leq \varphi \leq 0.2$ $0.2 \leq$ porous layer width ≤ 0.8
Ferdows and Alzahrani [98]	Moving a flat porous surface with external magnetic conditions	Cu, Al_2O_3 and TiO_2-water nanofluid	Forced convection	Cu nanoparticles have the least temperature distribution and the largest velocity profile.	Coefficient of Skin friction; Local Nusselt number
Tlili et al. [99]	horizontal flat surface with convection boundary condition	Cu, Al_2O_3 and TiO_2-water nanofluid	Forced convection	Increased porosity correlates with enhanced heat transfer intensity.	$0 \leq \varphi \leq 0.2$ $0.05 < \varepsilon < 0.95$
Eleiwi [100]	Horizontal cylinder cross flow	Air	Forced convection	Heat transfer (Nu) increases with Peclet number (Pe)	(Pe = 1–10)
Pastore et al. [101]	Thermal column with thermally insulated porous medium	Water	Forced convection	The porous medium Heterogeneity influences heat transportation dynamics	Peclet number and porous thermal conductivity
Jiang et al. [102]	channel with no-sintered porous media	Air	Forced convection	The porous medium greatly raised the pressure losses in the channel compared to a clear channel	Reynolds number and properties of porous medium
Amoli et al. [103]	Flat tube partially filled with a metal structure	Water	Forced convection	The smaller porous material thickness led to reduce the heat transfer rate	$\varepsilon = 0.75$ and the thickness of porous medium
Khudhair and Khudhur [104]	Eight inline cylinders are submerged in a packed substrate of porous material	Air	Forced convection	The heightened porosity close to the cylinder's surface led to an enhancement of the heat transfer.	Re = 1100 - 2250

5. Conclusion

Based on the comprehensive review of heat transfer in porous media using both conventional and nanofluids under different convection regimes, the following conclusions can be drawn:

- The integration of porous structures significantly enhances convective heat transfer due to the enlarged surface area and induced microscale fluid mixing.
- Porosity plays a crucial role in determining flow resistance and thermal exchange. Moderate porosity values tend to optimize the balance between permeability and thermal conduction.
- The incorporation of nanofluids into porous media results in markedly higher heat transfer performance, primarily attributed to the augmented thermal conductivity of the suspended nanoparticles.
- The type and concentration of nanoparticles substantially influence the thermal response. Hybrid nanofluids (e.g., $Cu–Al_2O_3$/water) offer superior performance compared to single-component nanofluids.
- The application of a magnetic field introduces Lorentz forces that suppress flow velocity but, in some cases, stabilize the thermal boundary layer and improve temperature uniformity.
- Entropy generation analysis revealed that porous media can reduce total irreversibility in thermally optimized configurations, making them beneficial for energy-efficient systems.
- Mixed convection in porous domains shows complex behavior; however, the proper tuning of Grashof, Reynolds, and Hartmann numbers can maximize thermal performance.
- The selection of boundary conditions and geometrical design (e.g., wavy walls, eccentric porous blocks) has a measurable impact on local and average Nusselt numbers.

In summary, porous media remain a promising passive enhancement technique in thermal system design, especially when synergized with nanofluids and magnetic control mechanisms. Future studies are encouraged to explore optimized configurations through multiphysics modeling and experimental validation.

5.1 Future Directions

Despite significant advances in understanding heat transfer and flow in porous media using conventional and nanofluids, several research gaps remain that offer opportunities for future studies. These include the lack of experimental data for complex geometries, the need to determine optimal porosity and pores-per-inch (PPI) for balancing heat transfer enhancement and pressure drop, understanding the stability and long-term effects of hybrid nanofluids, investigating the influence of magnetic fields, analyzing non-Darcy flow effects in irregular media and high Reynolds number regimes, minimizing entropy generation while maximizing heat transfer, incorporating transient and multi-physics phenomena such as phase change and chemical reactions, and addressing challenges in scaling up laboratory findings to practical industrial applications.

To address the existing research gaps and enhance the understanding and practical application of heat transfer in porous media, the following future research directions are proposed:

- Experimental validation of complex and hybrid porous structures.
- Optimization studies for porosity, PPI, and nanoparticle parameters.
- Investigation of multi-physics effects including magnetic, chemical, and transient phenomena.
- Development of predictive models combining non-Darcy flow, entropy generation, and multiphase behavior.
- Scale-up studies for industrial applications with performance and energy efficiency analysis.

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Conflicts of Interest

The author declares that he has no conflict of interest.

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