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# A Review on Advances in Nan of luid Heat Transfer in Porous Media

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***Abstract***
*In the pursuit of improving energy system efficiency, heat transfer researchers are consistently exploring new techniques to enhance thermal performance. One prominent approach is the addition of solid nanoparticles to traditional fluids like water, creating what is known as a nanofluid. Another proven method involves incorporating porous media into heat exchangers, where the increased surface area facilitates greater heat transfer within flow passages. This review presents an in-depth examination of the combined use of nanofluids and porous structures for heat transfer enhancement across various system configurations, flow regimes, and boundary conditions.*
***Keywords:*** *Porous media, Nanofluids, Heat transfer*

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## I. Introduction

Heat transfer plays a vital role in numerous industrial applications, including energy generation, thermal storage, and chemical processing. With the rapid advancement of modern technology, the demand for more efficient heat transfer systems has significantly increased. Various techniques have been developed to enhance heat transfer, such as using extended or rough surfaces, wavy walls, porous media, large particle suspensions, nanofluids, phase change materials, advanced sealing systems, vortex generators, surface protrusions, and materials with extremely high thermal conductivity [1].

Among these methods, porous media—especially when combined with other enhancers like nanofluids, wavy surfaces, or composite materials—stand out as a particularly effective solution for improving heat transfer rates in both

thermal and chemical systems. Porous structures offer several advantages, including uniform temperature distribution, enhanced heat transfer efficiency, better heat flux absorption, accelerated reaction rates, reduced system weight, and sound insulation [2]. Because of these benefits, porous media have gained considerable interest in scientific research and are now widely used in applications such as fluid filtration, rocket engine combustion chambers, exhaust nozzles, porous-wall reactors, battery electrodes, and various other thermo-electrochemical systems.

Porous materials are especially valuable in thermofluidic systems due to their ability to lower operating temperatures, which in turn boosts the Nusselt number—a key parameter that measures the efficiency of convective heat transfer. Studies have shown that the presence of porous media can increase the Nusselt number by up to 50% compared to conventional laminar flow systems without them [3, 4]. This is largely because porous materials often have higher thermal conductivity than the fluids passing through them, resulting in a greater convective heat transfer coefficient.

To analyze transport phenomena within porous media, three fundamental laws are commonly applied. These laws, and their core principles, are outlined in Table 1. Despite the significant advancements already made in this field, there is still ample opportunity for developing innovative approaches to further boost the thermal performance of heat transfer systems.

**Table 1**
Different flow transport models used for numerical modeling of porous media [2,5].

| Flow transport model | Considerations |
|---|---|
| Brinkman-Forcheimer's equation | Consider Darcy resistance; Consider B.Cs.; consider form drag; consider convections[9]. |
| Darcy's Law | Simple, consider Darcy resistance, neglect boundary conditions, neglect form drag, neglect convections[8]. |
| Brinkman's equation | Consider Darcy resistance, consider boundary conditions, neglect form drag, neglect convections[6,7]. |

The following section provides a review of various research studies focused on the use of porous media, both individually and in combination with other heat transfer enhancement techniques.

## II. Literature survey

2.1.Porous media

The integration of porous materials in various geometric configurations has shown significant potential in improving heat transfer performance. Research indicates that multilayer porous structures are more effective than single-layer arrangements [10]. Additionally, heterogeneous porous media with optimized pore sizes can boost heat transfer rates by approximately 8.5%[11]. or example, Abu-Hijleh [12], observed a remarkable 170% enhancement in heat transfer and a 16% increase in the average Nusselt number when a porous floor was incorporated into a reattaching flow over a backward-facing step. Similarly, Zhao et al. [13], investigated heat transfer behavior during sudden flow expansion with a porous medium placed downstream. Their findings showed an approximate 40% increase in the Nusselt number at a Reynolds number of 300. They also noted a 16% increase in the Nusselt number and an improvement in the performance number up to 0.94,though this came with a slightly higher pressure drop. Porous materials can also be formed using solid particles. Foudhil et al.[14], studied heat transfer in a vertical porous channel filled with spherical beads using the two-temperature model and the Darcy–Brinkman–Forchheimer equation. Their results indicated that for large, highly conductive beads, the influence of particle thermal conductivity on air heat transfer was minimal. Heat transfer was observed to decrease with a higher form factor, whileit increased withrising Biot number, Reynolds number, and the thermal conductivity of the solid beads.

Fu et al. [15], applied the Boltzmann–Cellular Automata (LB–CA) probabilistic model to examine the role of porous media in engine particulate filters. They found that permeability was higher in ordered structures compared to disordered ones. Filtration efficiency improved with both small and large particles, but medium-sized particles had a negative impact due to unpredictable behavior resulting from inertia and Brownian motion. The Nusselt number was also seen to increase with higher porosity and Reynolds number. Moreover, particle size and fineness in the porous medium affect heat transfer performance. Pastore et al[16]. compared forced convection through media with different grain sizes and found that coarse particles, due to their high permeability, led to greater heat loss and reduced heat transfer efficiency. In contrast, finer particles provided a more uniform path for heat flow, resulting in better heat transfer efficiency through improved fluid interaction.

Investigating temperature-dependent thermal conductivity is crucial for the effective application of porous materials in high-temperature industrial heat transfer systems[17]. However, the complex nature of real-world scenarios makes it difficult to derive analytical solutions for the Nusselt number. As a result, researchers focus on finding the most accurate models for predicting heat and fluid flow behavior through porous media when thermal conductivity varies with temperature[18]. Nield and Kuznetsov[19], due to the problem's complexity, were only able to derive a closed-form solution for temperature-dependent thermal conductivity in the context of radiative heat transfer within porous materials. Similarly, Dehghan et al. [20], attempted to estimate Nusselt numbers at elevated temperatures, acknowledging the associated uncertainties. Their study involved convective heat transfer in a tubular channel packed with porous material, using the Darcy–Brinkman–Forchheimer model. They examined flow regimes ranging from clear fluid to slug flow using a linear temperature-based model. Their results showed a linear increase in both Nusselt number and heat transfer with increasing thermal conductivity. The influence of temperature-dependent conductivity was particularly significant in enhancing the Nusselt number. Despite these benefits, the use of porous media often leads to a substantial pressure drop. To mitigate this issue, partially filled porous structures are generally preferred over fully filled ones. The performance improvement in partially filled systems is primarily attributed to three mechanisms: redistribution of flow, changes in effective thermal conductivity, and alteration of the medium's radiative properties. The dynamics of energy and momentum transfer in partially filled channels differ significantly from those in completely filled systems, particularly near the porous interface. In partially filled channels, fluid particles are closer to the walls, enhancing the heat transfer coefficient. In contrast, in fully packed channels, the fluid cannot efficiently flow through the region between the wall and the porous core, limiting heat transfer. Optimal heat transfer coefficients are achieved at a specific porous core diameter ratio, which varies based on the Darcy number[21]. For example, Satyamurty and Bhargavi[22] found that a porous volume fraction of 0.8 provided the maximum heat transfer enhancement in an asymmetric, partially filled channel at a Darcy number of 0.001.

The positioning of porous material also influences forced convection heat transfer. Maerefat et al[23], numerically analyzed two configurations within a circular pipe: one with a cylindrical porous core and the other with annular porous media lining the pipe's inner wall. Their results showed an increase in Nusselt number for the core-inserted configuration (with porous thickness of 0.6) and only a minor pressure drop. In contrast, the wall-lined configuration showed a decrease in Nusselt number under identical conditions.Cekmer et al[24], examined a parallel-plate channel with a centrally positioned porous region. Their results indicated that while the system's performance was affected by the Darcy number, it remained largely independent of thermal conductivity ratio when it exceeded a value of 2. Similarly, Ucar et al.[25], studied a similar setup, but with the porous material placed along one wall of the channel. In that case, the Nusselt number peaked when the thermal conductivity ratio was 1. Additionally, when the wall temperature equaled the mean temperature of both walls, the Nusseltnumber tended toward infinity under specific combinations of thermal conductivity and Darcy number. All the studies mentioned above generally assume a small temperature difference between the fluid and solid phases and therefore apply the local thermal equilibrium (LTE) model to simplify the analysis.

When a noticeable temperature difference exists between the solid and fluid phases in porous media, an additional boundary condition is required at the interface, and the Local Thermal Non-Equilibrium (LTNE) model is employed instead of the Local Thermal Equilibrium (LTE) approach[26]. Zhang etal[27], conducted a comprehensive comparison of several mathematical models—including the LTNE model, radiation heat transfer model, momentum source term model, and others—to study thermal transport and fluid flow through porous media in thermochemical reactors. They concluded that the LTNE model provides the most accurate predictions at moderate flow velocities and high temperatures. Notably, the temperature difference between LTE and LTNE models can increase significantly—up to tenfold—as velocity rises from 0.005 to 0.5 m/s. At high temperatures, radiative heat transfer becomes a critical factor and must be included in the analysis.

In the LTNE framework, three modeling approaches are typically used:

- **Model A** distributes the incoming heat flux between the solid and fluid phases based on their individual thermal conductivities and temperature gradients.
- **Model B** assumes equal heat distribution between both phases, regardless of differences in conductivity or gradient[28,29].
- **Model C** employs volume averaging theory to determine heat flux at the porous–fluid boundary and introduces an additional term accounting for excess interfacial heat exchange[30].

Mahmoudi and Maerefat[31] found that an optimal porous layer thickness of around 0.8 yields the best balance between heat transfer and pressure drop. However, they also noted that the LTE assumption breaks down when the porous layer exceeds a thickness of 0.6. Under such conditions, Models A and B offer more reliable solutions for forced convection in channels with centrally placed porous media.

In a related study, Mahmoudi et al[32], showed that when the porous layer thickness is less than 0.9, neither the Darcy number nor the choice of interface model significantly impacts heat transfer efficiency. Further research by Mahmoudi and Karimi[33] compared Models A and B in the context of forced convection with inertia effects. Although the trend in Nusselt number relative to porous layer thickness remained consistent across both models, the actual values differed. They also observed that, for Darcy numbers below 1000, the Nusselt number was unaffected by inertia. Torabi et al[34,35], analyzed entropy generation and heat transfer in an asymmetric channel, where heat was applied through the lower wall while the upper wall remained adiabatic. Porous material was placed near the heated wall, and Model A was used. Their findings indicated a distinct split in total entropy generation under these conditions.

Li et al. [26], investigated heat transfer through porous-filled channels using the Brinkman–Darcy model under LTNE assumptions. They found that Nusselt number variation with the hollow ratio followed three distinct patterns based on the thermal conductivity ratio and Biot number. The maximum Nusselt number occurred at the lowest hollow ratio, with an overall trend showing increasing Nusselt values as the hollow ratio decreased. At low Darcy numbers, both Nusselt number and pressure drop were found to be unaffected by the stress jump condition at the interface. However, at higher Darcy numbers, pressure drop became significant, and differences between LTE and LTNE model predictions at the interface were clearly observed.

2.2.Porous media and nanofluids

The addition of nanofluids and nanoparticles into porous media is well recognized for significantly improving heat transfer performance in such systems[36]. Research by Nohooji et al. [37], revealed that the effectiveness of nanoparticles within porous structures largely depends on their concentration. In their study, they assessed six different concentrations of water/$Al_2O_3$ nanofluids and found that when the $Al_2O_3$ nanoparticle concentration exceeds 2%, it leads to a reduction in the Nusselt number along with a noticeable increase in pressure drop. Interestingly, they concluded that the presence of porous media has a greater impact on heat transfer enhancement than the nanofluid itself. Pourfarzad et al. [38], also explored the behavior of forced convection and pressure drop in a copper heat sink embedded with porous material and filled with alumina-water nanofluids. The copper matrix was designed with two pore sizes—15 and 30 pores per inch—and the nanofluid was tested in three volume fractions: 0.1%, 0.3%, and 0.5%. Their results showed that both a higher nanofluid concentration and increased pore density improved the heat transfer rate. However, higher pore densities also resulted in a greater pressure drop. Additionally, Nusselt number and heat transfer coefficients were found to rise with increasing Reynolds number. In terms of heat transfer improvement, Kumar and K.M. Pandey reported that the heat transfer coefficient increased by 1–22% for systems with higher porosity and by 2.3–26.4% for systems with lower porosity, depending on the nanofluid concentration. These findings indicate that using nanofluids with higher volume fractions in porous media with lower pore density can enhance the overall thermal efficiency. Several studies have also focused on entropy generation in nanoparticle-laden porous flows. It has been observed that as the nanoparticle concentration increases, the Bejan number tends to rise as well, indicating an increasing proportion of heat transfer entropy relative to total entropy generation in the system. [39,40]

2.3.Porous media and composite materials

Porous media are commonly found in forms such as foams, tubular structures, and fibrous insulation materials. The pores and grains within these materials are often oriented in different directions, giving them anisotropic properties. In isotropic porous media, permeability remains uniform in all directions, while in anisotropic media, it varies with direction and is represented as a tensor, which complicates the momentum equations used to model fluid flow. Karmakar et al. [41], investigated how factors like anisotropic permeabilityratio, anisotropic orientation angle, and inertial effects influence heat transfer and fluid dynamics in a channel filled with porous material and bordered by impermeable walls. Their results showed that, in anisotropic porous media with Darcy numbers ranging from $10^{-2}$ to $10^{2}$, inertia has a significant impact on the Nusselt number. They reported that anisotropic porous materials can improve heat transfer by up to 20% compared to isotropic ones. In another study, Jiang et al. [42], examined heat flow through a graded porous medium partially saturated with hydrocarbon fuel under saturated pressure conditions. They found that graded porous structures can enhance heat transfer by 40% near the boundaries and by 10% in the central regions. This improvement is primarily due to a reduction in flow area, which increases fluid velocity, intensifies turbulence, and thereby boosts heat transfer efficiency.

## III. Conclusion

This review paper begins with a brief overview of the fundamental equations used to analyze heat flow through channels, followed by a detailed explanation of the applicability and limitations of the Local Thermal Equilibrium (LTE) and Local Thermal Non-Equilibrium (LTNE) models. It then explores the impact of fully and partially filled porous media on thermal performance, along with the influence of wavy wall geometries and the incorporation of nanofluids within porous structures. The effects on Nusselt number, entropy generation, and overall heat transfer efficiency are thoroughly discussed. The key findings and major conclusions derived from this study are summarized below.

- Heat flow through porous media is commonly analyzed using Darcy's Law, Brinkman's equation, and the Brinkman–Forchheimer equation, either in their original or modified forms.
- In laminar flow conditions, introducing porous media can enhance the Nusselt number by up to 50% and improve the performance coefficient to around 0.94, primarily due to the high thermal conductivity of porous materials.
- Particle size and fineness in porous media significantly affect thermal performance. Finer and smaller particles increase the Nusselt number and heat transfer efficiency but also lead to a higher pressure drop, necessitating an optimized balance.
- Higher thermal conductivity of porous materials contributes to better heat transfer in high-temperature applications, resulting in a noticeable rise in the Nusselt number.

- To address the pressure, drop associated with porous media, partially filled porous channels are often used. A porous fraction of 0.8 yields the best heat transfer results.
- Nanofluids and nanoparticles within porous media further boost heat transfer and Nusselt number, though their effectiveness depends on concentration. Excess concentrations can negatively impact performance due to pressure losses.
- Combining porous media with wavy wall geometries and nanofluids/nanoparticles can lead to a 100% improvement in heat transfer rate.
- In partially filled porous channels, entropy generation decreases, with viscous entropy being dominant near the wavy walls and thermal entropy highest along the centreline of the channel.
- Graded and anisotropic porous structures also enhance heat transfer, with graded media showing a 40% increase in heat transfer at boundaries and a 10% increase in the central region due to improved flow dynamics.

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