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ANALYSIS OF HEAT TRANSFER IN POROUS MEDIA WITH NANOFLUIDS: A REVIEW

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Abstract

The work offers a thorough investigation of nanofluid-based heat transfer analysis in porous media. Due to their improved thermal properties, nanofluids, which are colloidal suspensions of nanoparticles in base fluids, have attracted a lot of attention lately. An in-depth investigation of the existing research on employing nanofluids to improve heat transmission in porous media is the goal of this review. The concept of heat transmission in porous media and its use in numerous engineering applications are introduced in the opening paragraphs of the article. The description and features of nanofluids are then covered in depth, stressing the special qualities that make them appealing for applications involving heat transfer.

In addition to the measuring methods and settings utilized in earlier investigations, the study describes the experimental methods used to investigate the heat transfer characteristics of nanofluids in porous media. The paper also looks at mathematical modeling strategies and analytical methods for analyzing nanofluid heat transfer behavior in porous media. Along with recommendations for future study possibilities, it analyzes the difficulties and restrictions brought forth by these methodologies. The article also examines the application of computational fluid dynamics (CFD) simulations to the investigation of nanofluid heat transfer in porous media.

Keywords: Heat transfer, Porous media, Nanofluids, Heat transfer enhancement, Mathematical modeling

1. Introduction

Geothermal systems, subsurface energy storage, and heat exchangers are just a few technical applications where heat transmission in porous media is a topic of great interest. Due to their large surface area and porosity, porous media, which are characterized by an intricate network of connected void spaces, display unusual thermal behavior (Moradi et al. 2019). Enhancing heat transmission in porous medium is essential for raising these applications' effectiveness and efficiency. Nanofluids have been a promising advancement in recent years for improving heat transmission in porous media. Colloidal suspensions of nanoparticles in base fluids are called nanofluids, and they have better thermal properties than regular fluids do.

1.1 Background

Several engineering applications depend heavily on the complex phenomenon of heat transmission in porous media. Materials known as porous media have a network of linked void spaces or pores that can hold fluids or gases (Alizadeh et al. 2021). Soils, rocks, packed beds, and fibrous materials are examples of porous media. Porous media exhibit distinct thermal behavior as compared to bulk materials because of their special structure. The movement of heat by conduction, convection, and radiation are all greatly impacted by the presence of void spaces and porous media's high surface area to volume ratio (Prasannakumara 2022). The main method of heat transport in porous media is conduction, where molecular vibrations move heat through the solid matrix. The solid particles serve as thermal conduits, allowing heat to be transported from hotter regions to cooler ones. An important factor in determining the conduction heat transfer in a porous medium is the solid matrix's thermal conductivity.

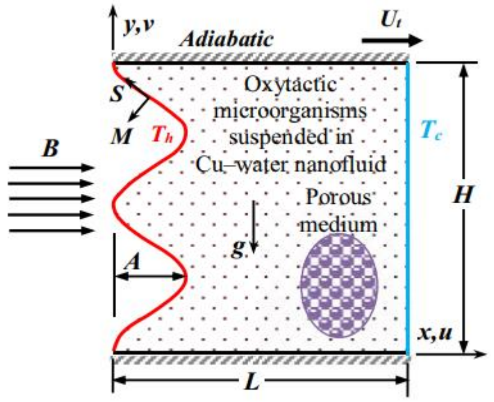

Figure 1: Schematic Flow of Nano-bioconvective Flow (Prasanna kumara 2022, p-98)

1.2 Definition and Properties of Nanofluid

A variety of approaches, including mechanical stirring, ultrasonication, and surface modification techniques, are used to disperse the nanoparticles in the base fluid.

I. Improved Thermal Conductivity: Compared to base fluids, nanofluids have an improved thermal conductivity, which is one of their major advantages (Eid and Mabood 2021). The fluid's effective thermal conductivity is raised by the presence of nanoparticles, accelerating the heat transfer process.

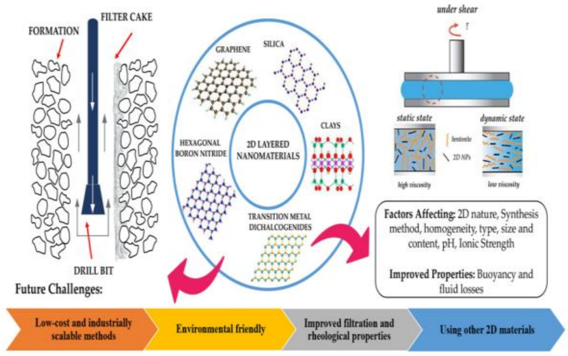

Figure 2: Nanoparticle-based Nano fluid Production (Eid and Mabood 2021, p-124)

II. Viscosity Changes: When nanoparticles are added to nanofluids, the viscosity of the fluids might vary (Mandal et al. 2021). The base fluid's viscosity may rise due to the presence of nanoparticles, which may have an impact on the pressure drop and fluid flow properties in heat transfer systems.

III. Stability: In order for nanofluids to be used in real-world applications, their stability must be maintained. Over time, the nanoparticles have the propensity to agglomerate or settle, changing the fluid characteristics and impairing heat transmission efficiency.

IV. Optical Properties: Some nanofluids display special optical characteristics, such as improved light absorption or scattering.

2. Literature Review

2.1 Heat Transfer Enhancement with Nanofluids

Due to its potential to improve heat transmission in a variety of applications, nanofluids have received a lot of interest recently (Talebi et al. 2022). The thermophysical characteristics of the base fluid are changed by the inclusion of nanoparticles, improving heat transfer efficiency. The following are some of the mechanisms and factors that contribute to the improvement of heat transmission with nanofluids:

Increased Effective Thermal Conductivity: When compared to the base fluid, nanofluids have an increased effective thermal conductivity, which is one of the main processes enhancing heat transmission (Abdulsahib and Farhany 2021). Due to the high thermal conductivity of the nanoparticles, which serve as thermal bridges, the fluid can conduct heat more quickly. Nanofluids' increased thermal conductivity leads to faster heat transfer rates and smaller temperature gradients.

Improved Convective Heat Transmission: Due to a number of variables, nanofluids can dramatically improve convective heat transmission. The behavior of fluid flow is changed by nanoparticle presence, improving heat transfer coefficients. The fluid flow is disturbed by nanoparticles, which improve mixing and destabilize the thermal boundary layer, speeding up the rate of heat transfer (Albojamal and Vafai 2020). Nanoparticles' greater surface area also promotes stronger fluid-solid interactions, which improves convective heat transmission.

Brownian Motion and Thermophoresis: Nanoparticles in nanofluids show Brownian Motion and Thermophoresis phenomena. While Brownian motion refers to the random movement of nanoparticles brought on by collisions with fluid molecules, thermophoresis refers to the migration of nanoparticles in response to temperature gradients. These events can improve the fluid's mixing and dispersion of nanoparticles, which will improve the fluid's heat transmission properties.

Property	**Base Fluid**	**Nano Fluids**
Viscosity (Pa·s)	Water	TiO2, Al2O3, CuO
Thermal Conductivity (W/mK)	Water	CuO, Al2O3
Surface Tension (N/m)	Water	TiO2
Volumetric Heat Capacity (J/m3K)	Water	CuO, Al2O3
Density (kg/m3)	Water	CuO, TiO2, Al2O3

Table 1: Thermo Physical Properties of Nano Fluids(Albojamal and Vafai 2020)

3. Experimental Methods for Heat Transfer Analysis

Understanding a system's thermal behavior and improving its performance both depend heavily on heat transfer analysis (Farahani et al. 2021). In different applications, heat transmission is measured and analyzed using a variety of experimental techniques. Here are a few typical experimental techniques for analyzing heat transfer:

Temperature Measurements: The investigation of heat transport relies heavily on temperature measurement. To monitor temperature at various points within a system, thermocouples, resistance temperature detectors (RTDs), or thermistors are frequently utilized. Temperature gradients and heat transfer rates can be calculated using multiple temperature observations.

Heat Flux Measurements: To gauge how quickly heat moves across a surface, heat flux sensors or meters are employed (Esfe et al. 2020). With the help of these sensors, it is possible to quantify the dispersion of heat transfer by providing localized heat flux data. The use of thin-film heat transfer gauges or the detection of temperature gradients are two common foundations for heat flux sensors.

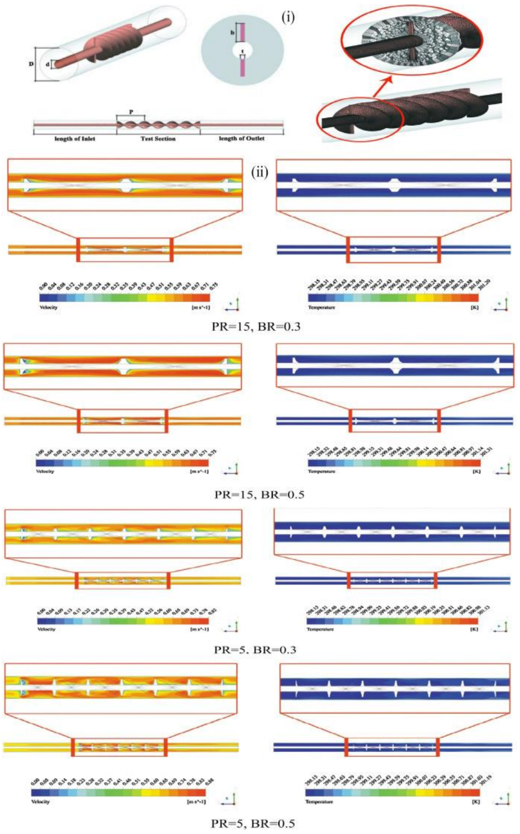

Figure 3: Heat Transferring Co-efficient (Esfe et al. 2020, p-225)

Thermal Imaging: To see and gauge temperature distributions across a surface, thermal imaging or infrared thermography cameras are used. Regions of high or low heat transfer can be found via thermal imaging, which offers a thorough view of heat transfer patterns (Siavashi and Miri 2019). This method is especially helpful for analyzing non-uniform heat transmission and locating thermal anomalies.

Flow Visualization: Methods for studying fluid flow patterns and their effects on heat transfer are used. Fluid flow characteristics, such as recirculation zones, boundary layer thickness, or vortex shedding, can be seen using techniques including dye injection, particle image velocimetry (PIV), and flow visualization utilizing smoke or tracers (Miles and Bessaih 2021). For the purpose of analyzing convective heat transfer, it is essential to comprehend fluid flow properties.

Parameter	**Value**
Heat diffusivity (m/s2)	0.5 x 10-9 - 2 x 10-8
Thermal conductivity (W/mK)	0.15 – 15
Heat capacity (J/kgK)	1088 – 1280
Porosity	0.4 - 0.6
Surface Temperature (K)	98-100

Table 2: Parameters for Heat Transfer in Porous Media(Miles and Bessaih 2021)

4. Mathematical Modeling of Heat Transfer in Porous Media

Models Based on a Continuum: Continuum-based models ignore the specifics of the microstructure and concentrate on averaged qualities, treating porous media as a continuous medium. Two-Equation Models: For the analysis of heat transport in porous media, two-equation models, such as the energy equation and the momentum equation, are frequently used (Menni et al. 2019). These models take into account the transport of heat and momentum between the fluid phase and the solid phase independently. Volume-Averaged Models: By averaging the governing equations over a representative volume element (RVE), volume-averaged models seek to simulate the behavior of porous media. The fluid-solid interactions, interphase heat transfer, and the impact of the porous structure are all taken into account by the volume-averaged models when analyzing the interaction between the fluid and solid phases. These models are suited for the macroscopic investigation of porous media heat transfer and are frequently derived using volume-averaging approaches.

4.1 Method

Developing a study methodology for the process of heat transferring within nanofluid porous media consists of several key steps. Based on objectives methodology outline can be varied.

4.2 Formulating problem

Research objectives, study scope and specific questions clear defining is required to be addressed. Interest parameter determining that include the flow of heat transferring coefficient and distribution of temperature or nanoparticles of dispersion is considered.

Material	Thermal Conductivity (W/m.K)
Alumina Bulk	16-27
Carbon Bulk	5 – 40
Copper Bulk	15 – 330
Iron Bulk	79 – 99
Silver Bulk	7 – 310

Table 3: Typical Values Compared for Heat Transfer in Porous Media(Xu et al. 2019)

The need for comprehensive review conduction for existing literature and associated studies that include porous media and nanofluid heat transfer is selected (Xu et al. 2019). Existing previous studies involved relevant theories, suitable models and used techniques of experiment and numerical models need to be identified. Including this step helps to develop a theoretical and conceptual foundation for the study.

4.2 Experimental Setup

If your study calls for experimental research, plan and prepare the necessary equipment. Describe the porous media sample, the nanofluid's composition, the characteristics of the nanoparticles, and the methods used to assess the temperature, pressure, and other pertinent variables (Kapen et al. 2021). Ensure that the experimental instruments are properly calibrated and validated.

4.3 Creating the Nanofluid

Create the nanofluid by mixing nanoparticles with the base fluid. To obtain a stable and uniform dispersion, take into account variables including nanoparticle concentration, size, and surface modification strategies (Habibishandiz and Saghir 2022). Describe the thermal conductivity, viscosity, and specific heat of the nanofluid.

Experiment with measurements to get information on temperature profiles, pressure gradients, and other pertinent characteristics. Keep a record of the experimental parameters, such as the boundary conditions, fluid characteristics, and flow rates (Waqas et al. 2021). Measure several times to guarantee precision and consistency.

Property	Value
Density (kg/m3)	1000 – 1160
Viscosity (Pa-s)	1 - 4 x 10-3
Thermal conductivity (W/mK)	0.8 - 3.1 x 10-3
Heat capacity (J/kgK)	897 – 1045

Table 4: Properties of Nano Fluids(Waqas et al. 2021)

5. Data Analysis

Make use of the proper statistical and analytical methods to examine the experimental data. Calculate temperature differences, heat transfer coefficients, and other pertinent variables. To verify the outcomes of the experiment, compare them to theoretical models or correlations.

5.1 Mathematical Modeling

Create numerical simulations or mathematical models to explain heat transfer in porous media using nanofluids. Take into account the boundary conditions, governing equations, and pertinent presumptions (Chamkha et al. 2019). To solve the equations numerically, use the relevant mathematical techniques, such as finite difference, finite volume, or finite element approaches.

5.2 Simulation Configuration and Fix

Establish the computational domain, mesh, boundary conditions, and beginning conditions to set up the numerical simulation. Implement the mathematical model, then use the proper solver methods to resolve the equations (Aminian et al. 2020). Convergence studies should be carried out to assure the stability and correctness of the simulations.

5.3 Results Analysis

Examine the results of the simulation, taking into account temperature distributions, heat transfer rates, and other important variables. To verify the model, compare the simulation results with the experimental data or theoretical predictions (Arafa et al. 2022). Analyze the results for trends, patterns, and correlations.

Interpret the study's findings and explore their implications in the discussion and conclusion. Connect the findings to the study's goals and questions. Point out the methodology's advantages, drawbacks, and possible sources of mistakes (Moghadasi et al. 2020). On the basis of the analysis, draw conclusions and suggest ideas for additional investigation.

Nano Fluid	Specific Heat Capacity (J/g.K)	Thermal Conductivity (W/m.K)
Alumina Nano Fluid	2.24	0.9 – 8.7
Carbon Nanotubes	1.98	6.85 – 20.7
Copper Nanoparticles	2.86	0.5 – 6.5
Iron Nano Powders	2.31	11.3 – 30.1
Silver Nano Powders	2.79	6.5 – 56.3

Table 5: Thermal Properties of Nanofluid (Moghadasi et al. 2020)

5.4 Data Analysis and Findings

The investigation of the experimental techniques used in the main research is a crucial component of the secondary review.

This investigation evaluates the appropriateness and efficacy of various methods for determining temperature distributions, heat transfer coefficients, and other pertinent characteristics in porous media with nanofluids (Siavashi et al. 2021). The review may highlight typical experimental setups, measurement approaches, and difficulties encountered when carrying out experiments in porous media. It may also highlight the benefits and drawbacks of particular experimental procedures and suggest enhancements or different strategies.

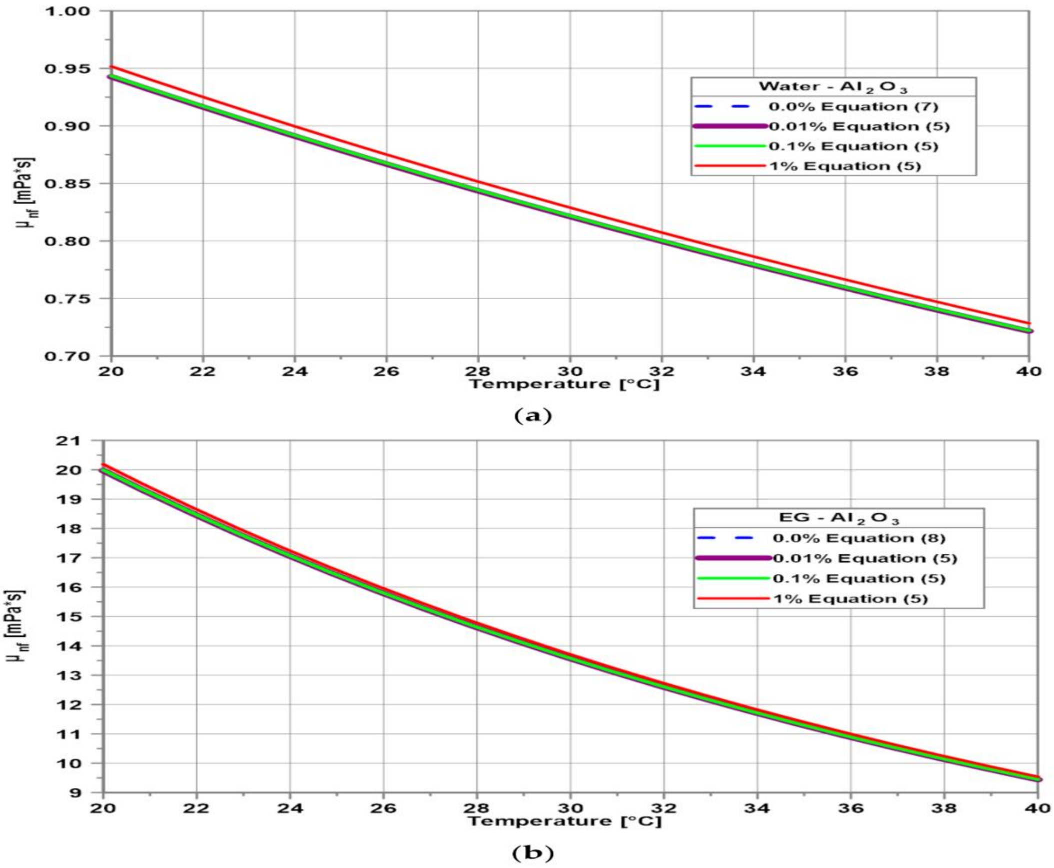

Figure 4: Temperature Impact on Nanofluid Flow (Siavashi et al. 2021, p-89)

The secondary review concentrates on comparing and synthesizing the results from many primary investigations. This analysis aids in spotting trends and patterns in nanofluids' behavior when it comes to heat transmission in porous media. It looks at the effects of several elements on improving heat transmission, including nanoparticle concentration, size, shape, and material. The review may also look at how the characteristics of porous media, such as pore size, porosity, and permeability, affect how well nanofluids transport heat (Al-Kouz et al. 2021). The review offers insights into the underlying mechanisms and correlations that regulate heat transport in porous media with nanofluids by synthesizing these studies.

Additionally, the secondary review assesses the shortcomings and difficulties found in the initial studies critically. It might draw attention to problems with nanoparticle aggregation or settling, interactions between nanoparticles and their matrix, or the stability of nanofluids while analyzing heat transmission. The review may also go over the ambiguities, contradictions, and conflicts in the data that have been reported or between several research. The secondary review addresses these constraints and offers a thorough grasp of the difficulties and possible causes of inaccuracy in the analysis of heat transfer in porous media containing nanofluids.

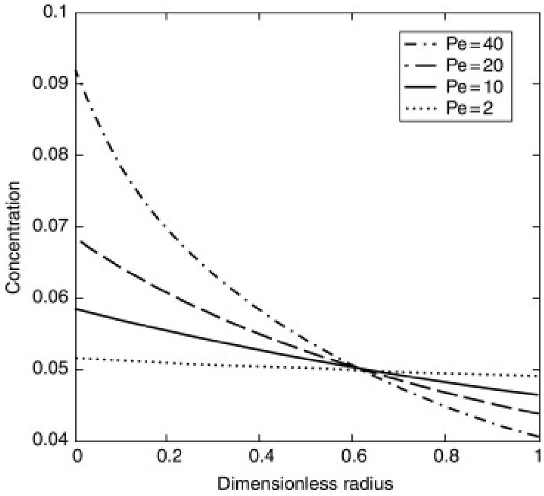

Figure 5: Heat Transferring Flow in Nanofluid (Al-Kouz et al. 2021, p-178)

The secondary review finishes with a summary of the key results and suggestions for further research based on the synthesis of the examined literature. It points out the most important knowledge gaps and research priorities, such as the need for more standardized experimental protocols, enhanced characterization methods, or sophisticated modeling strategies. In technical or industrial settings, the evaluation may also identify prospective applications and real-world ramifications of the results.

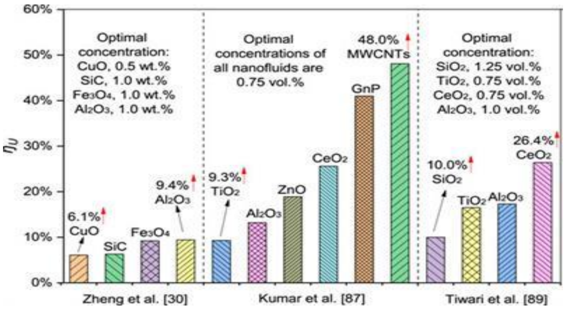

Figure 6: Heat Exchange Nanofluid (Tlili et al. 2020, p-98)

5.5 Opportunities of Research

I. Advanced Characterization Methods

Create new methods for precisely measuring the characteristics of nanofluids, such as the concentration, size distribution, shape, and substance of the nanoparticles (Tlili et al. 2020). This would improve the accuracy of the data used in heat transfer analysis and give more insight into how the properties of nanoparticles affect the improvement of heat transfer.

II. Nanofluid Stability Investigation

Examine the stability of nanofluids while analyzing heat transmission in porous media. Research the processes that cause nanoparticle aggregation or settling, and create plans to make nanofluids more stable. This would guarantee the accuracy and consistency of experimental findings.

III. Novel Porous Media Structures

Examine the application of cutting-edge porous media structures with specialized characteristics for improving heat transfer with nanofluids. Examine how the performance of heat transport is affected by various pore geometries, pore size distributions, and porosity. This might entail creating specially designed porous materials or altering already-existing porous media structures.

IV. Modeling Methods

Create and improve numerical simulations and mathematical models to precisely forecast and assess heat transfer in porous media with nanofluids. Consider the intricate interplay between heat transmission, nanoparticle transport, and fluid flow phenomena in porous media. To improve the models' ability to predict, and validate them against experimental data.

V. Multi-Physics Analysis

Investigate how heat transmission interacts with other physical processes in porous media, such as fluid flow, mass transfer, or chemical reactions. Find out how these processes interact and work in concert to acquire a thorough picture of the behavior of the entire system.

Porous Media	Nano Fluid	Heat Transfer Rate (W/m2K)
Fiber Porous Media	TiO2 Nano fluid	65-100
SiC Porous Media	Al2O3 Nano fluid	80-120
	CuO Nano Fluid	100-140
Carbon Foam Porous Media	CuO Nano Fluid	100-140
	Al2O3 Nano Fluid	80-120
Sand Porous Media	TiO2 Nano Fluid	65-100

Table 6: Heat Transfer Rate of Nano Fluids with Different Porous Media (Abad et al. 2020)

VI. Optimization Strategies

Create methods for maximizing the improvement of heat transmission in porous media with nanofluids. The concentration, size, or composition of nanoparticles as well as the characteristics of the porous medium may be optimized in this process. In the optimization process, take into account realistic restrictions and goals like cost, scalability, and energy efficiency.

Conduct research that is specifically targeted at engineering applications that can profit from the improvement of heat transfer caused by nanofluids in porous media (Abad et al. 2020). Examples include cooling technologies, heat exchangers, thermal energy storage, and geothermal energy systems. Examine the viability, effectiveness, and potential difficulties of integrating nanofluid-based heat transfer devices in these uses.

6. Conclusion

As a result, studying heat transfer in porous media with nanofluids has become a prominent topic of study with the potential to improve heat transmission. Important insights and conclusions have been achieved by a thorough examination and analysis of the available literature, shedding light on the behavior of nanofluids in porous media and their effect on heat transfer performance. Important elements like experimental methods, nanoparticle traits, porous medium features, and the constraints of current research have been highlighted in the secondary review.

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