ATATÜRK ÜNİVERSİTESİ YAYINLARI
ATATURK UNIVERSITY PUBLICATIONS

Research Article *Araştırma Makalesi* DOI: 10.5281/zenodo.14670760

Research on Heat Transfer of Nanofluid in Porous Media: A Mini Review

Gözenekli Ortamda Nanoakışkanın Isı Transferinin Araştırılması: Mini Derleme

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ABSTRACT

In this article, the recent developments in the literature on the application of heat transfer of nanofluids used in porous materials are examined. By analysing the articles published between 1998-2024, it is aimed to facilitate the researchers working in this field in their studies in this field. In this context, different analytical methods are used to describe flow and heat transfer in different porous media. In addition, various methods used in the modelling of nanofluids are described in detail. Here, analytical methods and forced convection heat transfer in porous media are discussed. In various studies in the literature, it is stated that a change in the height of the solid and porous media causes a change in the flow regime inside the pore cell. However, the effect of Darcy number (permeability value) as a dimensionless number in heat transfer varies. In this context, the statistical results obtained from the investigations examined in relation to the representation of various parameters such as the type of nanofluid and the geometry of the flow region are compared and it is thought to give an idea for future studies.

Keywords: Nanofluid, porous media, forced heat transfer, migration of nanoparticles, volume fraction.

ÖZ

Bu makalede gözenekli malzemelerde kullanılan nanoakışkanların ısı transferi uygulanmasındaki literatürde yer alan son gelişmeleri incelenmiştir. 1998-2024 yılları arasında yayınlanan makaleler incelenerek bu alanda çalışan araştırmacılara bu alana yönelik çalışmalarında kolaylık sağlaması hedeflenmiştir. Bu kapsamda farklı gözenekli ortamlarda akışı ve ısı transferini tanımlamak için farklı analitik yöntemler kullanılmaktadır. Bununla beraber nanoakışkanların modellenmesinde kullanılan çeşitli metodlar ayrıntılı olarak anlatılmıştır. Burada gözenekli ortamda analitik yöntemler ve zorlanmış taşınımla ısı transferi konusu ele alınmıştır. Literatürdeki çeşitli çalışmalarda, katı ve gözenekli ortamın yüksekliğindeki bir değişiklik, gözenek hücresi içindeki akış rejiminde bir değişikliğe sebep olduğu ifade edilmektedir. Bununla beraber ısı transferinde boyutsuz bir sayı olarak Darcy sayısının (geçirgenlik değeri) etkisi değişiklik göstermektedir. Bu bağlamda nanoakışkanın türü ve akış bölgesinin geometrisi gibi çeşitli parametrelerin gösterimi ile ilgili olarak incelenen araştırmalardan elde edilen istatistiksel sonuçlar karşılaştırılarak ileriye dönük çalışmalara fikir vermesi düşünülmüştür.

Anahtar Kelimeler: Nanoakışkan, gözenekli ortam, zorlanmış ısı transferi, nanopartiküllerin göçü, hacim kesri.

Received/Geliş Tarihi: 04.09.2024
Accepted/Kabul Tarihi: 24.12.2024
Publication Date/Yayın Tarihi: 17.01.2025

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Cite this article: Mustafaoğlu M., Yeşilyurt M.K., Topçu M.T., Öner İ.V., Bilen K., (2024), Research on Heat Transfer of Nanofluid in Porous Media: A Mini Review. *Journal of Energy Trends*, 1(2) 79-94

Introduction

Nanofluids are the type of fluid used in heat transfer processes in many fields and where different particles are preferred. Here, various particles of different nanosize (Al_2O_3, CuO, SiC, etc.) are used. The thermal conductivity of nano fluids varies according to the amount of concentration.

This situation has been evaluated by many researchers in the literature through various media and particles. In the researches, the heat conducting capacities and concentration values of different nano particles in the solution they formed with water were compared. This study investigated the experimental data of studies conducted by many researchers in recent years. In addition, the thermal conductivity enhancement coefficient was gathered from data found in the literature. The thermal conductivity improvement ratio is defined as the ratio of the thermal conductivity of the nanofluid to the thermal conductivity of the base fluid. According to the researchers' findings, eight parameters are effective in improving the thermal conductivity of nanofluids, and the laboratory results include the following: volume percent or particle concentration (Choi, 2002) particle material type (Keblinski et al. 2005) particle size (Putra et al. 2003) particle shape (Eastman et al. 2001) base fluid material type (Das et al. 2003) temperature (Pak & Cho, 1998), additives (Yu et al. 2008), acid strength (Wang et al. 1999). Each of these parameters is examined individually for data behavior, size, and stabilization through multiple tests. Heat exchangers, thermal storage, geothermal systems, and drying methods are just a few of the industrial and engineering domains where the study of heat transfer qualities in porous media is of great interest. One passive way to enhance heat transfer in a mechanical system is to incorporate a porous substance into it. In actuality, the inclusion of a porous material modifies the flow pattern and raises the system's overall thermal conductivity (Whitaker, 1986; Murshed et al. 2008; Meng & Yang, 2019; Boccardo, 2020; Ling et al. 2021; Gundogdu, 2023; Mustafaoğlu, 2023; Zhang et al. 2024). Nanofluids and porous materials are of great importance in enhancing heat transfer, and considerable research has been conducted to study the thermal properties of nanofluid flow in porous media. This paper provides a comprehensive summary of the latest research on this topic. The authors have surveyed their work from 1998 to 2024, given the large number of papers published since the last review article and their analytical complexity. The work is organized by fluid flow, heat transfer models, and applications of nanofluids in porous media.

Materials and Methods

The most important parameter in nanofluid models is the calculation of the volume occupied by the nanoparticles in the whole mixture and the thermal conductivity value. The efficiency of the mixture can be evaluated by calculating the particle volume percentage. The effect of particle volume percentage is clear. Figure 1 shows the effect of volume percentage or particle concentration on increasing the thermal conductivity of the nanofluid. The figure shows the experimental work of a group of researchers for Al_2O_3 in water. The particle size and temperature of the nanofluid varied between the groups in Figure 1, however, the results were consistently close. Thermal conductivity increases as the particle volume ratio increases. There are usually 4-5% oxide particles in the nanofluid. The amount of nano particles in the fluid is considered the most optimum value in terms of viscosity and heat transfer (Figure 1)

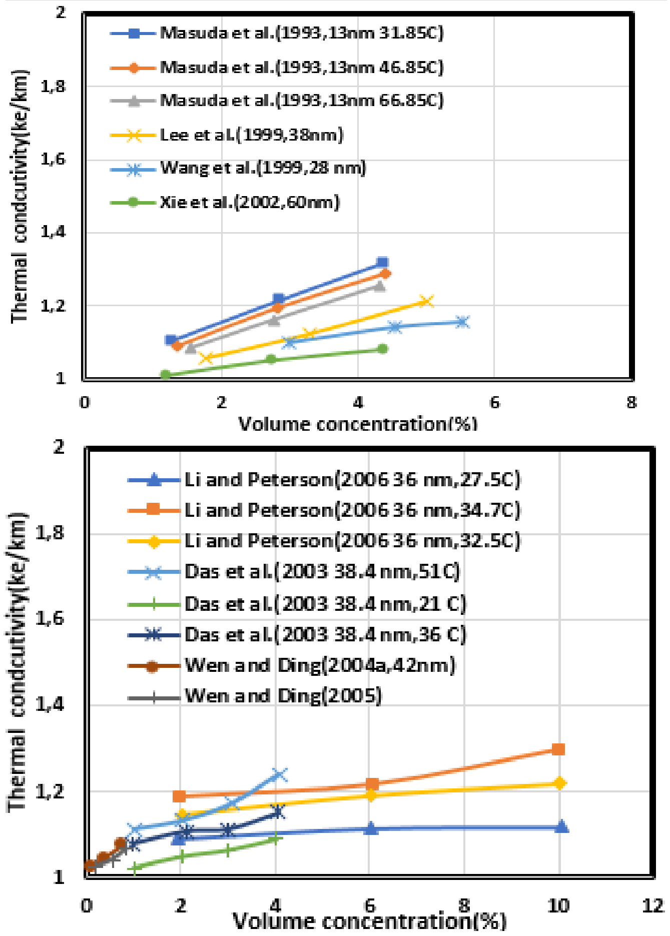

Figure 1.
Increasing the thermal conductivity of Al_2O_3 in water (Yu et al. 2008)

Particle volume percentage's effect on thermal conductivity is distinctly shown in Figure 1. The results of two groups using the same nominal particle sizes are presented for comparison. Figure 2 shows that the results are almost identical for the two groups using the same parameters. The increase in Figure 2 is relatively small due to the relatively small diameter of the particle. Figure 3 shows the results of other tests to increase the thermal conductivity of CuO in water. Figure 3 shows the particle size and fluid temperature ranges relative to Figure 1. Figure 4 shows a separate concentration parameter, using the particle size and fluid temperature. The overall behavior is identical to

Figures 1 to 4, and the values in Figures 3 and 4 were validated with two sets of experiments.

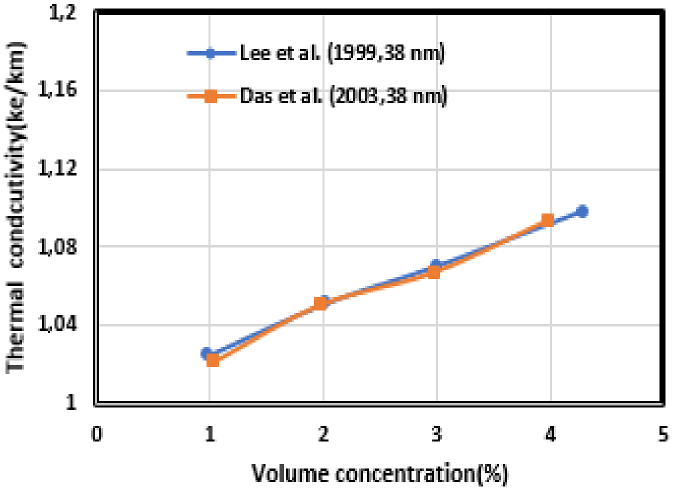

Figure 2.
Effect of particle concentration for Al_2O_3 in water (Yu et al. 2008)

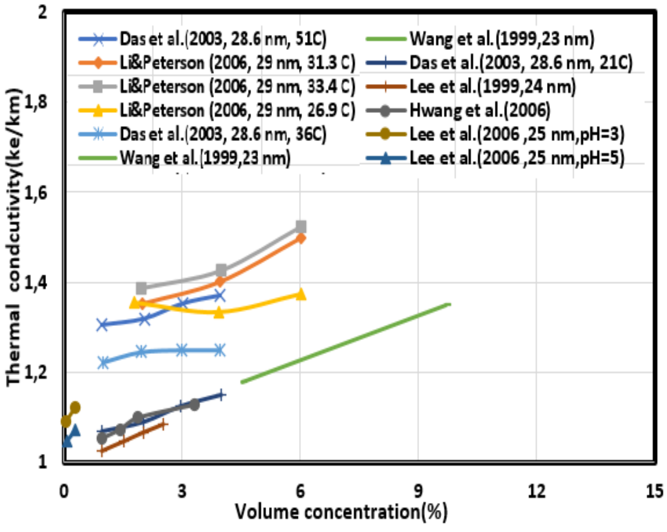

Figure 3.
Increasing the thermal conductivity of CuO in water (Yu et al. 2008)

Figure 4 clearly demonstrates the effect of the volume fraction of copper oxide nanofluid in ethylene glycol, which exhibits the same behavior as Figures 1 to 4. Additionally, the values obtained from the data of the two groups in Figure 5 are in excellent agreement. Figures 1 to 4 clearly demonstrate that the thermal conductivity increases with an increasing volume fraction. The influence of particle type on increasing silicon carbide oxide particle thermal conductivity in water is obviously shown in Figure 5. The remaining parameters, which are nearly constant in Figure 5, clearly demonstrate the impact of material properties. As shown, particle type has no significant effect on thermal conductivity in the low volume fraction.

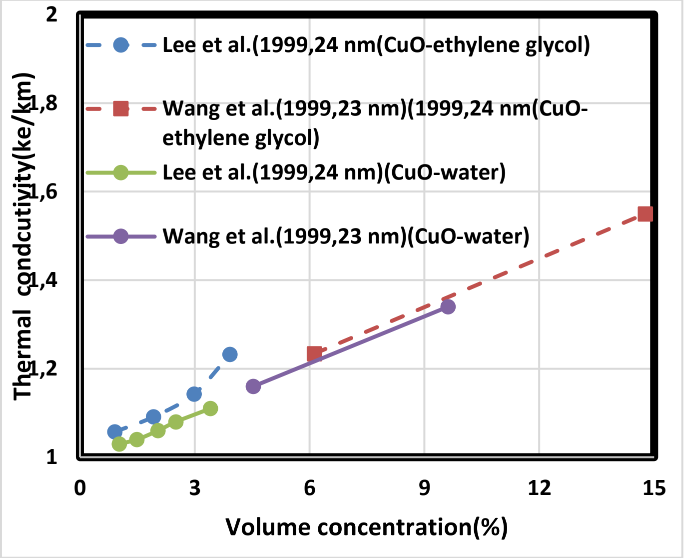

Figure 4.
Effect of particle concentration for thermal conductivity of CuO in water and CuO in ethylene glycol (Yu et al. 2008)

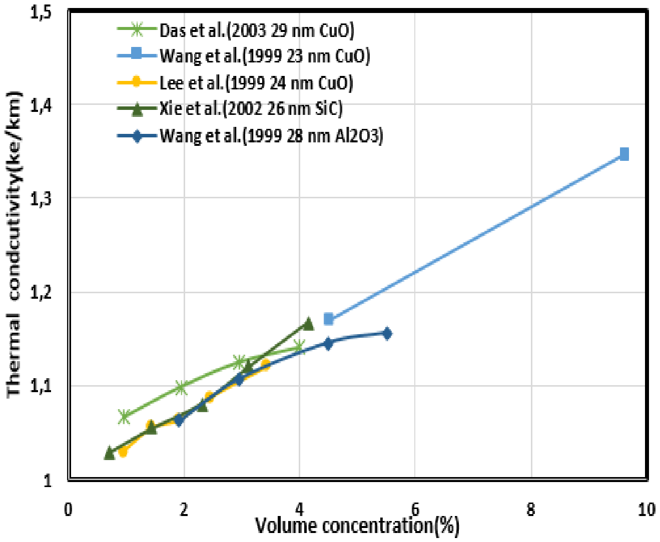

Figure 5.
Effect of particle type for particles in water (Yu et al. 2008)

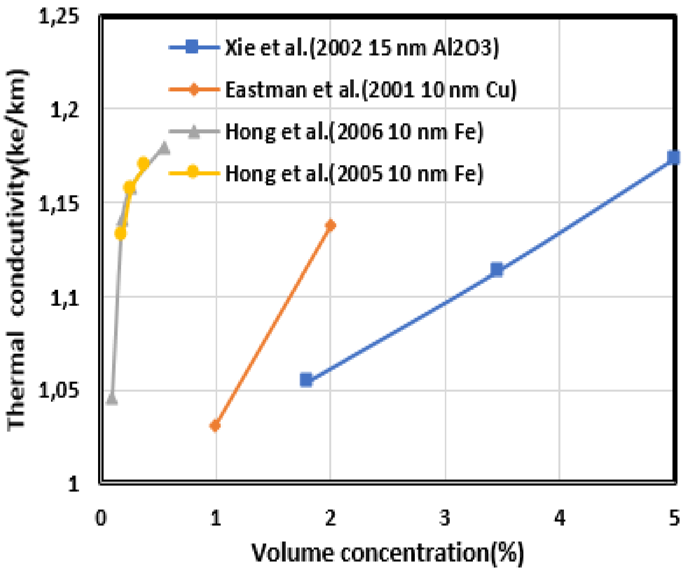

Figure 6.
Effect of particle type for particles in ethylene glycol (Yu et al. 2008)

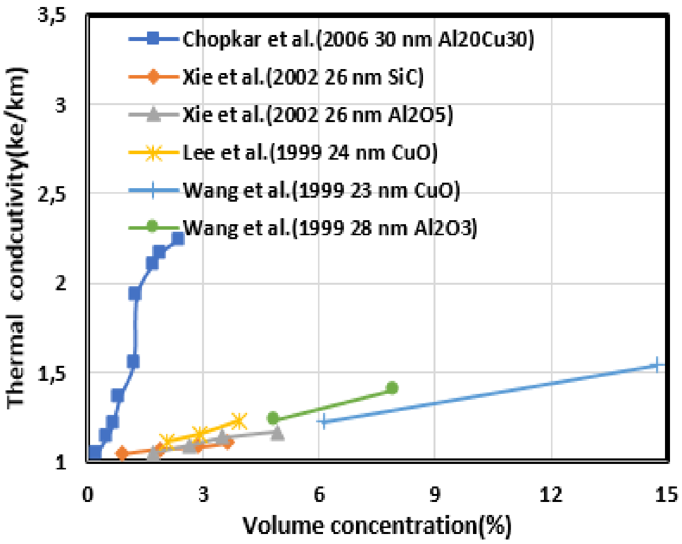

Figure 7.
Effect of particle type for particles in ethylene glycol (Yu et al. 2008)

The results of increasing the thermal conductivity are shown in Figure 6, which includes iron and copper oxide metal particles for comparison. As can be seen, the metal particles provided the same increase as the oxide particles at a much lower volume fraction. Figure 6 shows that the thermal conductivity coefficient of metal is higher than that of oxide particles. Therefore, the particle concentration for the highest level is included in the execution of the experiments. This can also be seen in Figure 7. The results of oxide particles, silicon carbides and metal particles at the same time. The size of the particles in Figure 7 is larger than the particles in Figure 6. However, the most significant effect seen is a large increase in the thermal conductivity of the metal particle nanofluid when the volume percentage of metal particles increases to 2.5% compared to 0.7% in Figure 7.

At 2.5% volume percent of metal particles, the thermal conductivity of the nanofluid shown in Figure 7 is up to 115% higher than that of ethylene glycol. This result is significantly higher than the results for non-metallic particles in Figure 7 and points to the research and production areas of nanofluids. However, as mentioned before, the main disadvantage of nanofluids with metal particles is the oxidation process during production and use. The influence of the size of the spherical particles on the increase of thermal conductivity will be discussed later. Here the size parameter is the nominal diameter. The results for aluminum nanofluid with particle diameters from 28 to 60 nm are shown in Figure 8. For 38 nm particles, there is a similarity between the data from the two groups. The results indicate an improvement in heat conductivity for larger particles (60 nm, for example). According to these results, smaller particles are expected to show the least increase. However, the results for 28 nm particles are in between the two larger particles. The results in Figure 8 show similar results to those obtained for ethylene glycol. The case in Figures 8, apart from the results of Wang et al. (1999) results in larger diameter particles producing a greater increase in thermal conductivity. This result contradicts some theories that assume a uniform distribution of small particles even with the best manufacturing method.

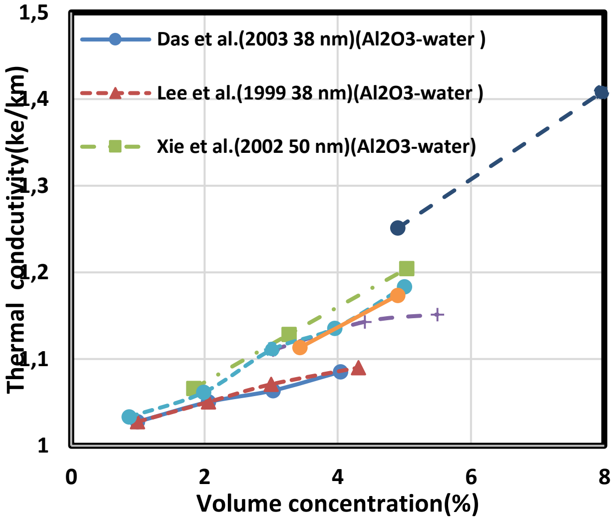

Figure 8.
Effect of particle size for Al_2O_3 in water and particle size for Al_2O_3 in ethylene glycol (Yu et al. 2008)

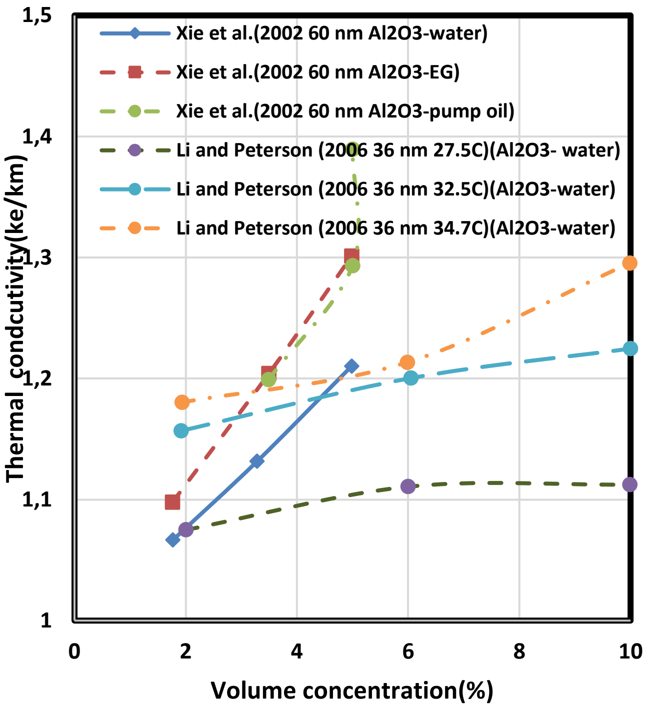

Figure 9.

Effect of particle size for CuO in water,SiC in water and particle shape for SiC in ethylene glycol (Yu et al. 2008)

The third comparison of the effect of particle size on the increase in thermal conductivity is shown in Figure 9 for CuO in water. The results of Figures 9 show that the increase in thermal conductivity does indeed increase with the diameter of the spherical nanometer particles. Figure 9 compares the effect of particle shape (spherical and cylindrical). Cylindrical particles show an increase in thermal conductivity; this result appears to be due to the network of elongated particles conducting heat from the fluid. All of the results in Figures 9 through 10 show that elongated particles are better than spherical particles at increasing thermal conductivity. This result points to other areas for nanofluid research and production, although spherical particles are generally available at more reasonable prices.

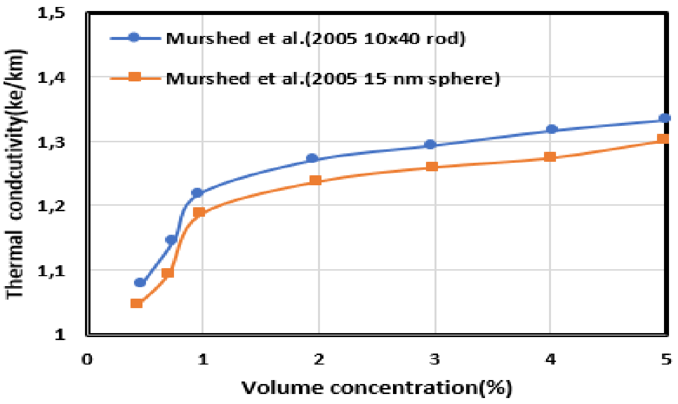

Figure 10.

Effect of particle shape for TiO_2 in water

The effect of the base fluid (such as water, ethylene glycol, and pump oil) on increasing the thermal conductivity of the nanofluids is shown in Figure 11. The results show that the thermal conductivity increases in fluids that are poor in heat transfer. Water is the best heat transfer fluid with the maximum thermal conductivity when compared to other fluids, and the results in Figure 11 demonstrate the least rise in water.

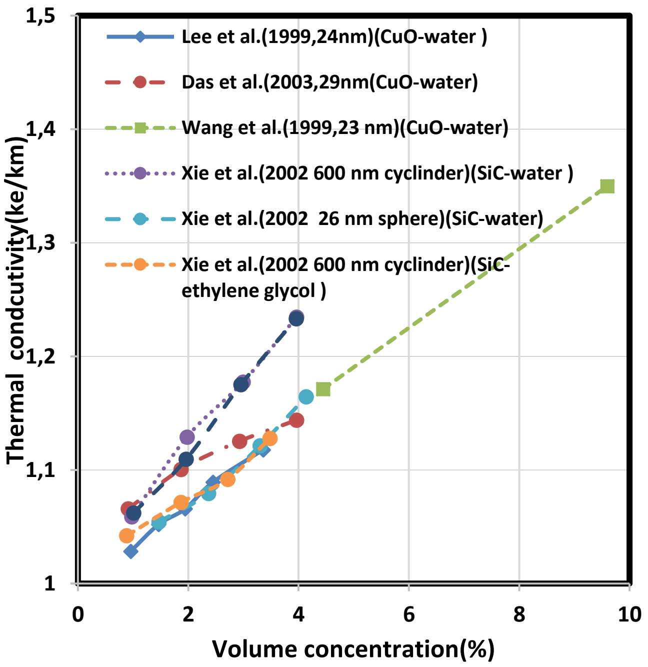

Figure 11.

Effect of base fluid type and for Al_2O_3 in water (Yu et al. 2008)

The thermal conductivity is usually more sensitive to temperature than the bulk liquid. Wang et al. (2003) presented nanofluid data for Al_2O_3 in water and CuO in water over a small temperature range. The authors proposed that the motion of the nanoparticles is responsible for the considerable temperature dependency of the thermal conductivity of the nanofluid. Figures 11 through 12 display the Al_2O_3 in water results for each of the three groups. While the fluid temperatures and particle sizes vary throughout the figures, the temperature and particle size remain consistent across all figures. Only the results of Masuda et al. (1993) deviate from the general behavior. The increase in thermal conductivity of CuO in water is shown in Figures 13 two groups of researchers. The data show that the thermal conductivity increases with increasing temperature. Similar results were obtained from the two laboratory values for multi-walled carbon nanotubes in water, as shown in Figures 14. Although the behavior of some data is not consistent with the general temperature behavior, it should be noted that this does not mean that the self-test is completely inaccurate. The inconsistent temperature behavior was reported by Masuda et al. (1993) for SiO_2. However, the results for TiO2 in water were not the same with respect to temperature. Anyway, considering all the results, we see that the general proof of the general temperature behavior has been made. This behavior is essential for heat transfer applications in the transportation industry, where fluids operate at high temperatures.

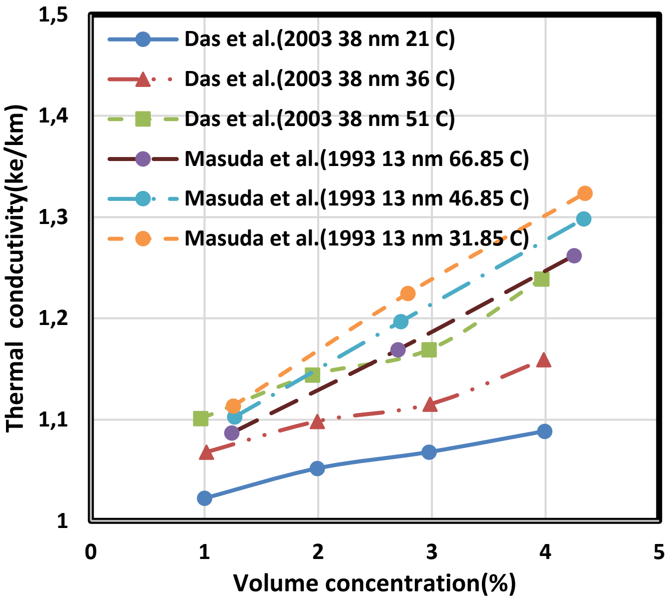

Figure 12.
Effect of temperature for Al_2O_3 in water (Yu et al. 2008)

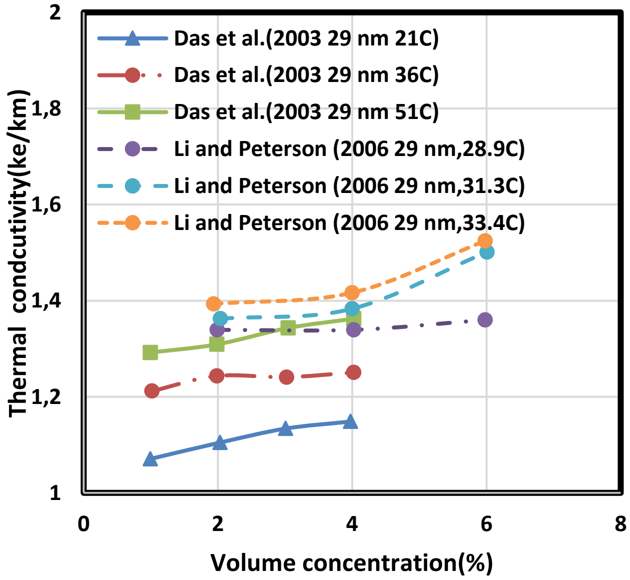

Figure 13.
Effect of temperature on CuO water (Yu et al. 2008)

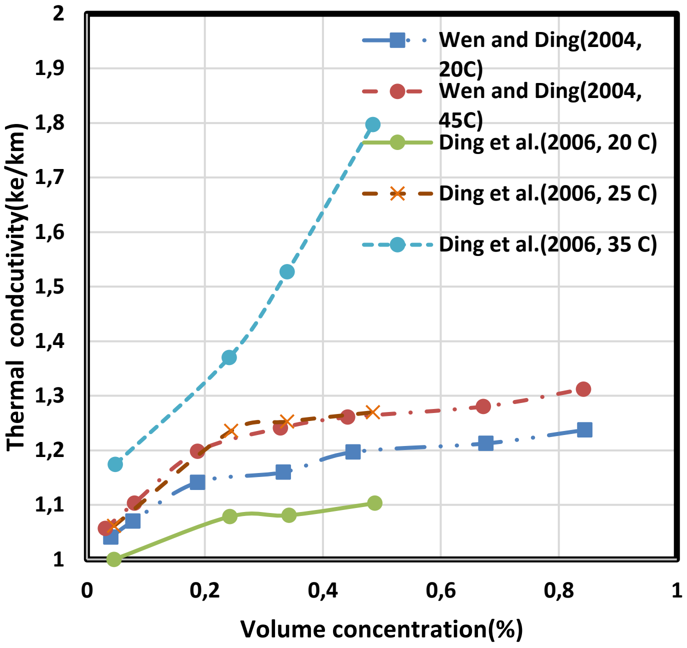

Figure 14.
Effect of temperature for multi-walled carbon nanotubes in water (Yu et al. 2008)

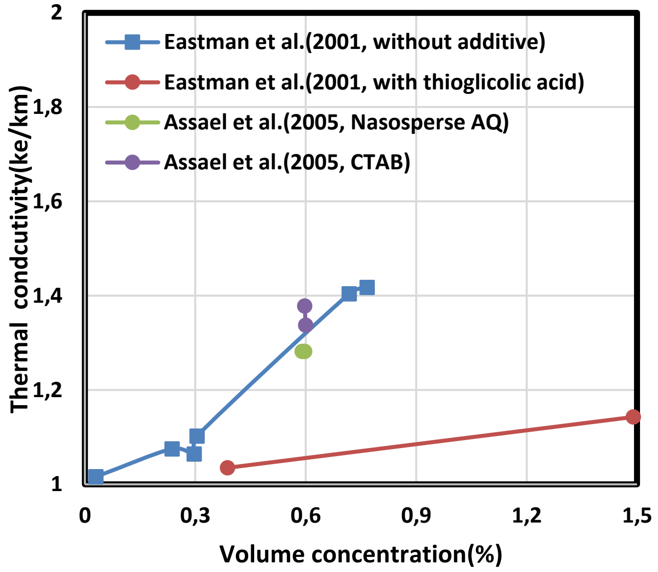

Figure 15.
Addition effect of copper in ethylene glycol and multi-walled carbon nanotubes in water (Yu et al. 2008)

Researchers use additives to keep nanoparticles in solution and prevent them from agglomerating. A review of previous studies shows that there has been a wide range of results depending on the type of additive, concentration and other factors. However, most studies involving additives show an increase in thermal conductivity. Data from two sets of studies for nanofluids with different additives are shown in Figures 15, in both cases the improvement in thermal conductivity increases with the use of additives. In addition, very few studies have been published on the effect of the acid strength of the fluid on improving the thermal conductivity of nanofluids, and the results of the two groups are presented separately below. The results of Figure 16 show the same behavior for different particles in water.

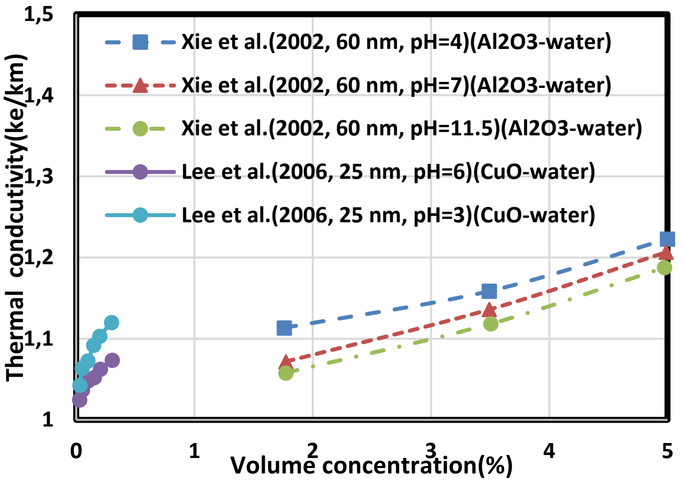

Figure 16.

Effect of acid strength for Al_2O_3 in water and CuO in water (Yu et al. 2008)

Convection Heat Transfer of Nanofluids in Porous Media

As for experimental research, Eastman (1999) conducted an experiment for copper oxide in water. He tested the turbulent flow regime in a nanofluid tube with a volume fraction of 0.9%. The test result shows a 15% increase in heat transfer for nanofluids compared to the base fluid. Wen and Ding (2004) conducted several experiments with aluminum oxide-water nanofluid flowing in a slow-flowing copper tube. In this context, the penetration of nanoparticles into the base fluid shows an increase in the displacement heat transfer coefficient. As the concentration of nanoparticles increases, the heat transfer coefficient also increases. Heris et al. (2006) conducted their experiments with alumina nanofluid in copper water in water in a tube with slow flow and constant wall temperature. In another experiment conducted by Heris et al. (2007) the heat transfer of alumina in water with volume fraction from 0.2% to 2.5% and Reynolds number from 2050 to 7000 was tested in a constant temperature tube. It shows that the Nusselt number increases with increasing volume fraction and Reynolds number. Lai et al. (2006) investigated alumina nanofluid in water in a stainless steel tube (the tube was made in mm) with a constant heat flow of Reynolds number less than 270. The results showed that for a volume fraction of 1%, the heat transfer increased by 8%. Jung et al. (2006) investigated alumina nanofluid in water in a rectangular microchannel with laminar flow and presented a new relationship for the heat transfer of nanofluids in microchannels. Rea et al. (2008) investigated the displacement heat transfer in fully developed turbulent flow with alumina in water and zirconia in water and found good agreement with the presented single-phase relations. Xuan and Li (2003) performed an experiment with copper nanofluid in water flowing in a tube in a turbulent regime with a Reynolds number between 10,000 and 25,000 and a volume fraction of 0.3 to 2% and reported a significant increase in heat transfer. In another study, Li and Xuan (2004) reported a 39% increase in Nusselt number for 2% by volume of copper nanoparticles in water. Zhou (2004) studied copper-acetone heat transfer for 80 to 100 nm particles and 0 to 4 gL^{-1} concentration. Li et al. (2005) studied copper-water heat transfer for 26 nm nanoparticles at 0.5 to 2% by volume and reported the heat transfer ratio of nanofluid to base fluid to be 1.6 to 1.39. Faulkner et al. (2004) investigated the heat transfer of carbon nanotubes in water and microchannels with a hydraulic diameter of 335 micrometers and volume fractions of 1.1, 2.2, and 4.4%. The results showed that increasing the volume fraction increased the heat transfer coefficient. Yang et al. (2005) also performed an experiment with graphite nanoparticles fully dispersed in water. The test was performed inside the tube and showed a 22% increase in heat transfer. Ding et al. (2006) have found a 350% increase for multi-walled carbon nanotubes at Reynolds 800. Duangthongsuk and Wongwises (2008) reported an increase in heat transfer for 0.2% titanium oxide and noted that the heat transfer coefficient is highly dependent on the measurement and calibration system. Jang and Choi (2004) reported an 8% increase in heat transfer for 0.3% alumina in water. Duangthongsuk and Wongwises (2009) estimated an 11.6% increase in displacement heat transfer for 2% titanium oxide volume fraction in water and concentric tube heat exchangers.

Theoretical Investigations of Nanoflows in Porous Media

Nanofluids in porous media can be analyzed theoretically by creating different models in the computer environment. In this context, nanofluidscan be modeled in two ways as single-phase and two-phase. In the single-phase method, nanofluids are assumed to be continuous and continuity equations are solved accordingly. In this method, the particles are assumed to be uniformly distributed throughout the fluid and the fluid does not disturb the uniform distribution of the nanoparticles. In this method, continuity equations, momentum, and energy are solved for the base fluid to model the heat transfer of the nanofluids, but the viscosity and conductive heat transfer coefficient of the nanofluids replace the physical properties of the base fluid. One of the advantages of the single-phase method is that it is much simpler and more computationally efficient than the two-phase method. The two-phase method solves three continuity, momentum and energy equations for the base fluid and one continuity equation for the nanoparticles and gives a much more accurate answer. Here Eastman et al. (2001) first used the single-phase method for modeling nanofluid heat transfer. In another study, Xuan and Roetzel (2000) found that the enhancement of heat transfer in nanofluids is influenced by two factors: high conductivity coefficient and thermal dispersion of nanoparticles. Khanafer et al. (2003) studied the performance of nanofluid in heat transfer compared to the base fluid in vacuum. In this research, the conductivity coefficient is a combination of conductivity coefficients, displacement and scattering effects. Buongiorno (2006) discussed seven motion mechanisms for nanofluids in his study and revealed two mechanisms as the dominant mechanisms for improving heat transfer through their investigations and dimensional analysis:

Brownian motion (random motion of nanoparticles caused by the continuous collision of nanoparticles with each other and with the base fluid molecules) and the effects of thermophoresis (motion of particles due to temperature gradient). The addition of these two mechanisms to the classical energy equation and the volume fraction equation is called the Bongiorno model. The Bongiorno model has become the basis for modeling nanofluid heat transfer by many researchers. Behzadmehr et al. (2007) modeled the heat transfer of copper-iron nanofluid for turbulent flow in a constant flow tube using a two-phase method. They obtained a 51% increase in heat transfer for a volume fraction of 1%. Maïga et al. (2004) used the single-phase approach to study the thermal and hydrodynamic characteristics of nanofluids moving in a tube under laminar and turbulent flow conditions. The results showed an increase in heat transfer when nanoparticles were injected into the base fluid. The researchers also found that alumina in ethylene glycol had better heat transfer than aluminum oxide in water. A study carried out by Roy et al. (2004) was comparable to the aforementioned research and yielded results that were analogous to those reported by Maïga et al. (2004). Sheikholeslami and Rokni (2017) employed two single-phase and two-phase methods to model nanofluids and investigated the movement of particles' effects on heat transfer. Their findings indicated that the Peclet number increases markedly with increasing nanoparticle size, and the influence of Brownian motion is particularly pronounced when the Peclet number is less than 10. Furthermore, they proposed an optimal nanoparticle size at which the enhancement in heat transfer is not accompanied by an equivalent increase in pressure drop. Kim et al. (2007) investigated the thermal transfer and stability of a double nanofluid comprising silver and copper nanoparticles. The findings indicated that the silver nanofluid exhibited a more pronounced enhancement in heat transfer compared to the copper nanofluid. In examining the physical properties of nanofluids, Mansour et al. (2007) employed the modified Hamilton-Cruiser and Maxwell model for thermal and hydraulic coefficients in completely formed turbulent and laminar flow in a tube with continuous heat flux. Prakash and Giannelis (2007) conducted a study on copper nanofluid in ethylene glycol and reported that cylindrical nanoparticles exhibited superior heat transfer properties compared to their spherical counterparts. Heyhat and Kowsary (2010) conducted a numerical investigation into the effects of nanoparticle migration in a pipe with slow flow and constant heat flux, with a particular focus on the influence of Brownian motion and thermophoresis. In this research, the Bongiorno model was employed to model nanofluids and the migration effects of nanofluids. The findings indicate that the impact of nanoparticle migration on heat transfer is significant, with a notable enhancement in heat transfer observed compared to the single-phase method. The potential applications of microchannels include the cooling of electronic devices. Based on the properties of nanofluids, their use in liquid-based cooling systems has been proposed by researchers. Moreover, numerous researchers have recently employed the porous media approach and associated relationships to model the flow of nanofluids in microchannels. The modeling of the motion of nanofluids in microchannels is therefore of great importance in order to gain a deeper understanding of the concepts of nanofluid motion in porous media. This is evidenced by several researchers (Kim et al. 2001; Kim & Kuznetsov, 2003; Abbassi & Aghanajafi, 2006; Tsai & Chein, 2007; Ghazvini et al. 2009; Ghazvini & Shokouhmand, 2009).

Nanofluids are of significant value in numerous domains, with particular preference for use in the field of heat transfer across a range of scenarios. In this context, it is employed in the treatment of damaged tumors with temperatures above 43°C, with living tissues serving as an illustrative example of a fluid and porous environment. It is therefore imperative to gain a deeper understanding of the concepts of heat transfer and the movement of nanofluids in porous media.

In the field of research, publications by (Salloum et al. 2008; Salloum et al. 2009) have been made available. Kuznetsov and Nield (2010b) investigated the initial conditions of double penetration of nanofluid transfer and free heat transfer in the flow between two plates, utilizing the Bongiorno equations. The Darcy equation was employed to model the flow of nanofluids, with consideration given to the temperature equilibrium condition. The dimensionless equations were further analyzed to extract a set of dimensionless parameters, which were found to be identical to the dimensionless coefficients presented by Buongiorno (2006). However, in these coefficients, the parameters associated with the porous medium were discernible. In a pioneering contribution, Kuznetsov and Nield (2011) articulated the three-temperature equation methodology for thermal instability in the context of the base fluid, nanoparticles and the solid phase of the porous medium. Research has been conducted into the temperature instability and free heat transfer of nanofluids in porous media. In this context, Kuznetsov and Nield (2010a) Kuznetsov and Nield (2010c) have published several research articles on this challenging topic. They undertook an investigation into the factors that contribute to the stability of nanofluids in porous media. In their seminal work, Nield and Kuznetsov (2009) first addressed the topic of heat transfer of nanofluids in porous media. The authors emphasized two key reasons for this investigation: firstly, to ascertain the stability of nanofluids in porous media and in contact with solids, and secondly, to ensure the accuracy of the governing equations.

1. Nanoparticles are defined as extremely small particles that remain suspended in nanofluids alongside the base fluid in porous media.
2. Nanoparticles dispersed in the base fluid together with surfactants demonstrate sufficient resistance to aggregation and precipitation in porous media. Furthermore, the low volume fraction of the nanofluid mitigates concerns about the deposition of nanoparticles.

In recent years, numerous researchers have employed the use of EI in order to model the phenomenon of heat transfer. However, in comparison to the utilization of two-phase methods (including Brownian terms and thermophoresis) from the single-phase model to the current reports, the employment of two-phase methods in the context of nanofluids in porous media (Tham & Nazar, 2012; Rosca et al. 2012; Mahdi et al. 2015; Sheikholeslami & Ganji, 2016) and two-phase (Sun & Pop, 2011; Rashad et al. 2013; Kasaeian, 2017; Xu et al. 2019) is more prevalent. The paper presented by Nield and Kuznetsov (2014) offers a logical and more realistic approach to the physics of the problem, particularly in the context of forced displacement heat transfer of nanofluids in porous media.

1. An enhanced flow that is slow and incompressible
2. No chemical reaction
3. Absence of external force
4. Dilute solution (φ <<1)
5. No radiation heat transfer

A porous medium is a network or solid matrix with interconnected holes; under normal conditions the matrix is assumed to be solid or rigid or undergo very small deformations. The connection and interconnectedness of the holes allows the fluid to flow.

Porous Media Analysis Methods

The microscopic method is employed in order to gain insight into the distribution of holes according to shape and size, as well as the flow quantities, in porous media such as sandstone, limestone, sand, wood, bread, human skin, and so forth. In porous media such as sandstone, limestone, sand, wood, bread, human skin, and so forth, the distribution of holes according to shape and size is irregular, and the flow quantities are analogous to velocity, pressure, and so on. At the scale of the cavity, the irregularity is evident, and the investigation of the behavior of the flow and temperature fields at this scale is inherently complex.

The macroscopic method is as follows: In this method, the desired quantities of the flow field and temperature field are measured over an area containing a large number of holes. These quantities are then averaged over the volume, resulting in regular variations with time and space. These variations require theoretical analysis.

1. Statistical method: This methodology entails the aggregation of macroscopically identical holes and the subsequent averaging of resultant data. The principal challenge associated with this approach is that the statistical data pertaining to hole groups is typically derived from a single model, which is only feasible if statistical homogeneity is assumed.
2. Spatial method: In this method, macroscopic variables are defined as an appropriate mean value over a standard volume. This method is frequently employed in homogeneous porous media where the standard volume is periodically repeated. The fundamental principle of this method is the integration of variables into the standard volume.

The Darcy-Brinkman-Forchheimer equation is utilized to solve the flow in the developed mode:

$$\frac{\mu_{nf}}{\varepsilon}\nabla^2 u-\frac{\mu_{nf}}{K}u-\rho_{nf}F\frac{\varepsilon}{\sqrt{K}}u^2\frac{dp}{dx}=0 \qquad (1)$$

porosity rate ($\varepsilon=\frac{V_{nf}}{V_{tot}}$) , where V_{nf} is the nanofluid volume and V_{tot} is the total volume. Eq. 1 F is the Forchimer coefficient and K is the permeability coefficient of the porous medium. µnf and ρnf viscosity and density of the nanofluid, respectively. The Bongiorno model for energy and volume fraction equations is used as follows. When the base fluid, nanoparticles and solid body are in temperature and thermal equilibrium, the temperature distributions will be the same and an energy equation will be solved for them.

$$(\rho c)_m \frac{\partial T}{\partial t} + (\rho c)_m u.\nabla T = k_m \nabla^2 T + \varepsilon(\rho c)_p \left(D_B \nabla\varphi + \frac{D_T}{T_c}\nabla T.\nabla T\right) \qquad (2)$$

$$\frac{1}{\sigma}\frac{\partial\varphi}{\partial t} + \frac{1}{\varepsilon}u.\nabla\varphi = D_B\nabla^2\varphi + \frac{D_T}{T_c}\nabla^2 T \qquad (3)$$

Eq 2-4 here ρ represents the density, c represents the specific heat capacity, u represents the speed, and φ represents the solution ratio. In this study, the Darcy-Brinkman-Forchheimer equation developed to study nanofluid flow in porous media is used. The central difference method was used to discretize the equation developed by Darcy-Brinkman-Forchheimer. The discrete form of the Darcy-Brinkman-Forchheimer equation in its extended form is as follows:

$$\frac{u^*(j+1)-2u^*(j)+(j-1)}{\Delta y^2} - \frac{u^*(j)}{Da} - \frac{\Delta}{\sqrt{Da}}(u^*(j))^2 - \frac{1}{Da}\frac{dP^*}{dx^*} = 0 \qquad (4)$$

Here Da represents the Darcy factor and dP represents the pressure value. The Forchimer term in the Darcy-Brinkman-Forchimer equation is the nonlinear term of the above equation and the Newton method is used to solve this equation. In Newton's method, the derivative of the equation is calculated with respect to the velocity of the nodes at the initial velocity and the product of this matrix, which is a tridiagonal matrix, in the velocity matrix is equal to The velocity at the initial velocity of the Darcy-Brinkman-Furchimer equation, i.e. the velocity at the next step, is obtained from the product of the inverse matrix in the matrix of values and the steps continue until the final velocity is calculated (Epperson, 2021). Brownian motion and thermophoresis are located on the right hand side of equation (2-2).

In the work of Nield et al. (2003), the viscosity loss was expressed by the Brinkman number defined as μU2 / kΔTK, where k, ΔT and K are the order of the thermal conductivity coefficient, temperature difference and permeability of the porous medium. By comparing the order of magnitude, the other terms, including the viscosity loss, can be neglected, i.e., the temperature difference of the porous medium increases as the wall and nanofluid increase, while the viscosity loss This assumption is acceptable for heat transfer problems where heat flux or wall temperature is the dominant source of energy transfer. A uniform mesh is used for the computational domain and the construction of the mesh is done by an algebraic method. Figure 17 shows the grid of size 300x300 is considered for the computational domain and the equations are solved on this grid. The numerical solution flowchart is as follows:

The boundary conditions (for constant wall flux) are as follows(Eq 5-13):

$$y^*=0 \qquad \frac{\partial T^*}{\partial y^*}=-1,\ \ \varphi^*=0,\ u^*=0 \qquad (5)$$

$$y^*=2 \qquad \frac{\partial T^*}{\partial y^*}=1,\ \ \varphi^*=0, u^*=0 \qquad (6)$$

$$x^*=0 \qquad T^*=0,\ \ \varphi^*=1 \qquad (7)$$

For the outflow boundary condition, we consider the longitudinal slope to be zero, which is a very small value due to the length of the channel:

$$x^*=20 \qquad \frac{\partial T^*}{\partial x^*}=0\ ,\ \frac{\partial\varphi^*}{\partial x^*}=0 \qquad (8)$$

The basic conditions are as follows:

$$T^*(t^*=0)=0,\ \varphi^*(t^*=0)=1 \qquad (9)$$

For the boundary condition of constant temperature, a dimensionless temperature equal to one is placed on the walls.

For porous media in thermal instability, the boundary conditions of constant temperature and constant boundary flux are considered. The constant flux boundary condition and the flux contribution of each phase (fluid, nanoparticle and solid body) are introduced and discussed in the following chapters as part of the innovations and achievements in this thesis. The boundary conditions for the thermal instability case with constant wall temperature are as follows:

$$y^*=0 \ \ \textit{and} \ \ 2 \quad T_f{}^* = 1, T_p{}^* = 1,\ \ T_s{}^* = 1\varphi^*=0\ \ , u^*= \ 0 \qquad (10)$$

$$x^*=0 \quad T_f{}^* = 1, T_p{}^* = 1, T_s{}^* = 1\ ,\ \varphi^*=1 \qquad (11)$$

$$x^*=20 \ \frac{\partial T_f{}^*}{\partial x^*}=0\ ,\ \frac{\partial T_p{}^*}{\partial x^*}=0,\ \frac{\partial T_s{}^*}{\partial x^*}=0,\ \frac{\partial\varphi^*}{\partial x^*}=0 \qquad (12)$$

The basic conditions are as follows:

$$T_f{}^*(t^*=0)=T_p{}^*(t^*=0)=T_s{}^*(t^*=0)=0$$

$$\varphi^*(t^*=0)=1 \qquad (13)$$

It should be noted that the energy balance relation is included in each iteration of the numerical solution and hence the temperature gradient relation equal to zero can also be applied for constant flux.

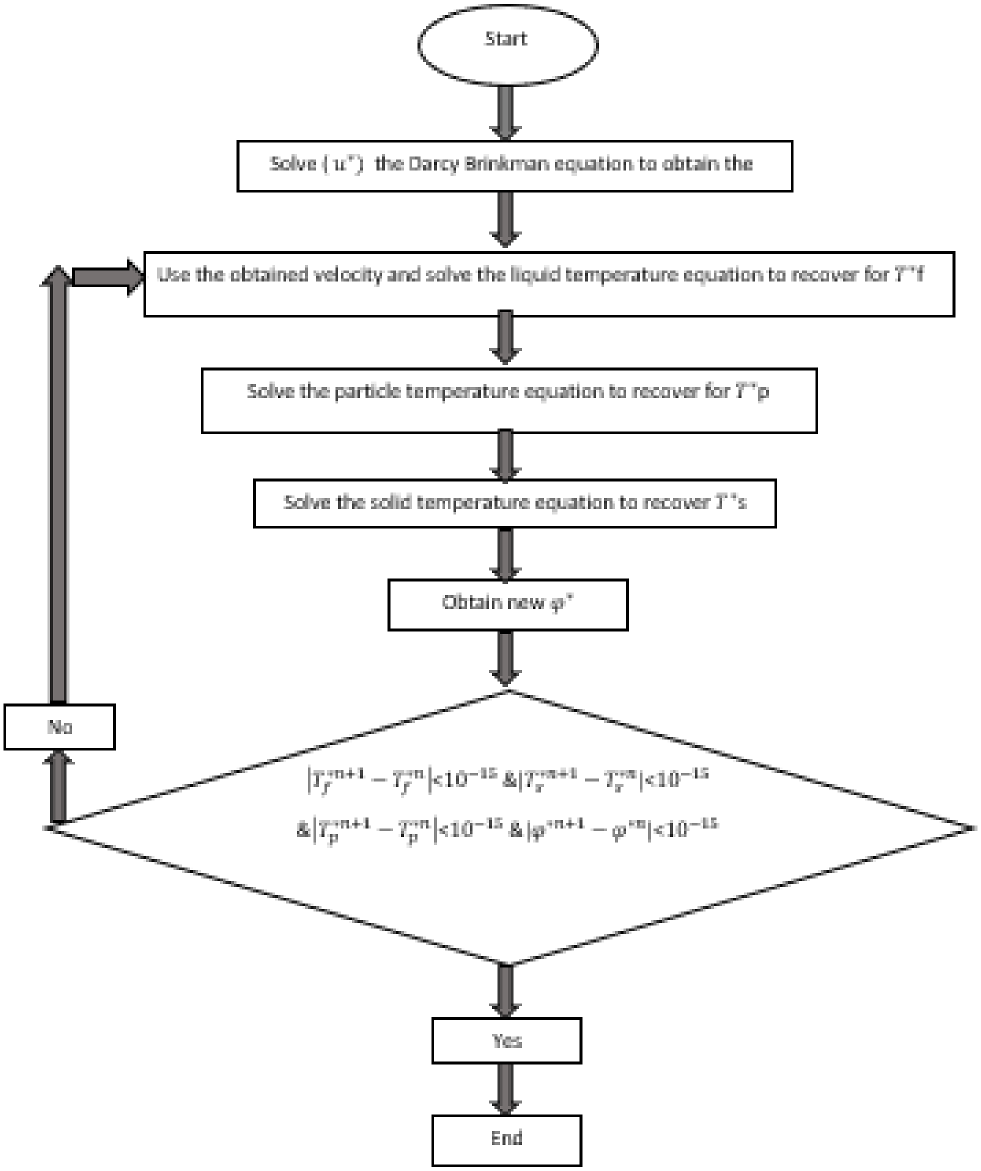

Figure 17.
Solution algorithm

Results and Discussion

In all analytical methods and most numerical methods, a constant porosity ratio and a homogeneous porous material are used to model fluid flow in a channel containing porous material. In other words, the porosity ratio is assumed to be constant in the equations. However, in experimental work it is difficult to create a homogeneous porous medium and it is difficult to keep the local porosity constant. Therefore, the fluid flow and heat transfer in the constructed (experimental) model are different from the equations and solved models. It is difficult to compare numerical models with experimental studies according to the situations briefly mentioned. Therefore, the validation was done with the help of classical equations with exact solutions.

The flow developed by Darcy Brinkman Forchheimer: Checking the accuracy of the numerical program written to solve the flow equation developed by Darcy Brinkman Forchheimer is as follows: Comparison with the analytical solution of the flow equation developed by Darcy Brinkman: The Darcy-Brinkman-Forchheimer equation in the limit state, i.e. at 0, is identical to the Darcy-Brinkman equation and its analytical solution, the second order ordinary differential equation.

Comparison with the analytical solution of the developed Darcy Brinkman Forchheimer flow equation: The channel up to the wall of the porous medium is considered.

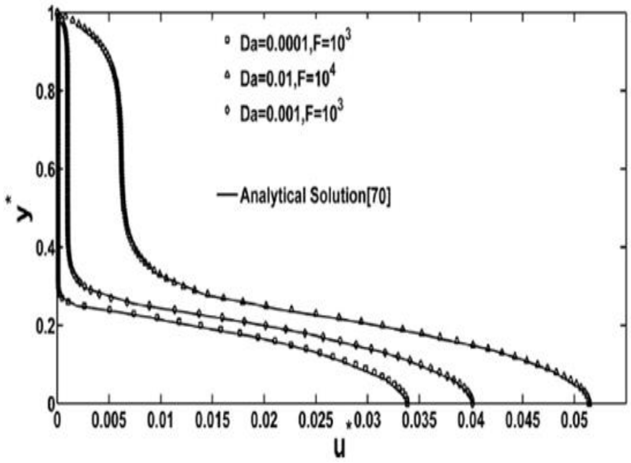

Figure 18.
Comparison of the numerical solution with Kuznetsov's analytical solution (Nield et al. 2003)

Figure 18 shows a very good agreement between the numerical and analytical results. The hot source temperature and the surrounding fluid temperature differences results in a change in the fluid density, which is a consequence of the influence of temperature-related buoyancy forces. Consequently, in accordance with the temperature differential, the fluid commences to flow over the solid surface. In such instances, naturally occurring heat transfer that takes place without any external stimulus is known as free or natural convective heat transfer. Given the importance of heat transfer, it is essential to take into account all factors and options in order to maximize the rate of heat transfer. The phenomenon of natural heat transfer is dependent on the random movements of molecules and the mass movement of the fluid. Consequently, it is advantageous to utilize compounds that exhibit a high thermal conductivity ratio in comparison to the fluid. In this context, the employment of fine particles with high thermal conductivity is a viable option. Subsequent studies have demonstrated that the reduction in particle size and dimensions has a significant impact on the heat transfer rate (Takabi & Shokouhmand, 2015; Babar & Ali, 2019; Said, 2022)s. In a semi-annular chamber with inclined pores, Motlagh et al. (2019) studied the free transport of a two-phase nanofluid. They applied the Darcy and Bongiorno models utilized Fe3O4 water as a magnetic nanofluid. They came to the conclusion that as the volume proportion of nanoparticles grows, so does the Nusselt number. Table 1 and Table 2 provides an overview of the features and findings of research articles on free convection heat transfer.

Conclusion

In this article, studies published between 1998 and 2024 on nanofluid heat transfer in porous media are reviewed. For this purpose, a general numerical evaluation of the published papers has been made. The results obtained from the Bongiorno model are also compared with the single-phase modeling of nanofluids and the results show that the migration of nanoparticles plays an important role in enhancing the heat transfer compared to the single-phase model. According to the findings, adding nanoparticles to the base fluid enhances temperature transfer. Nevertheless, the viscosity effect reduces thermal conductivity and obstructs heat transfer as nanoparticle volume concentration rises. Heat transfer increases with an increase in Darcy number and porosity coefficient and decreases with an increase in nanoscale conductivity when compared to a porous matrix. In this context, nanofluid heat transfer in porous media can be summarized as follows.

1. The relationship between porous matrix and nanoscale conductivity: As nanoscale conductivity increases, heat transfer within the porous matrix generally decreases. This is related to the fact that nanoscale structures, which conduct heat more efficiently due to better conductivity, reduce heat transfer by increasing thermal resistance.
2. Effect of Darcy number and porosity coefficient: When the Darcy number and porosity coefficient increase, heat transfer generally increases. The Darcy number is a measure of fluid motion in a porous medium through which a fluid passes, and when this magnitude increases, there is usually more flow and more efficient heat transfer. The porosity coefficient is a measure of the pore structure of a porous medium. Increasing the porosity coefficient usually results in more surface area and therefore more heat transfer.
3. The solid and porous medium height can be changed causes the flow regime in the room to change and has the effect of increasing or decreasing heat transfer.
4. Heat transfer is increased when the Rayleigh number rises.

These results explain the effects of factors such as nanoscale conductivity, Darcy number and porosity coefficient on heat transfer and show that heat transfer in general is determined by the interaction of these factors in a complex way. The main disadvantage of utilizing nanofluids in porous media is the increased pressure drop, which can be attributed to a number of factors. The movement of nanofluids through a porous medium can result in a greater pressure drop. In narrow passages between porous structures, nanofluids may encounter greater resistance, necessitating a higher pressure differential for flow. This can result in increased energy losses within the system, which may subsequently lead to elevated processing costs. Secondly, concerns may be raised regarding the durability of nanofluids, especially when it comes to long-term uses. The tendency of nanosized particles to agglomerate or form precipitates can have a detrimental impact on the homogeneity and performance of the fluid. Such stability issues may restrict the utilization of nanofluids or necessitate the implementation of appropriate stabilization techniques. These shortcomings may restrict the utilization of nanofluids in porous media or impact their applicability. Nevertheless, the implementation of appropriately designed systems and effective stabilization techniques can facilitate the resolution of these issues.

Table 1.
Experimental results of the investigation of nanofluid displacement heat transfer

Author	Base Fluid	Nano Particle	Size of Nanoparticles (nm)	Volume Ratio in Percentage	Geometry	Flow Regime and reynols number	Outcomes
Pak and Cho (1998)	Water	Al_2O_3 and TiO_2	13 27	3-1 3-1	Pipe	Turbulence 105-104	ϕ=0,1 Nusselt increases as Re increases
Wen and Ding (2004)	Water	Al_2O_3	56-25	1,6-0,6	Pipe	Laminar 2500-500	ϕ=0,1 heat transfer coefficient increased by 41%.
Heris et al. (2006)	Water	Al_2O_3CuO	20 60-50	3-2	Pipe	Laminar 2010-650	Heat transfer coefficient increased with increasing ϕ
Lai et al. (2006)	Water	Al_2O_3	20	1-0	Pipe	Laminar 270	The Nusselt number increased by 8% for every 1% ϕ.
Jung et al. (2006)	Water	Al_2O_3	10	1,8-0,5	Micro channel	Laminar 300-5	The Nusselt number increased by 32% for ϕ 1.8%.
Rea et al. (2008)	Water	ZrO2	46 60	3,6-0,9 0,9-0,2	Pipe	Turbulence 63000-9000	Slightly increased heat transfer
Zhou (2004)	Acetone	Cu	100-80	4	Pipe	-	Increase in heat transfer coefficient with increase in Cu
Li et al. (2005)	Water	Cu	26	2-0,5	Pipe	Turbulence Laminar	The Nusselt number ratio of the nanofluid to the base fluid varies between 1.6-1.39.
Faulkner et al. (2004)	Water	CNT	100	4,4-1,1	-	Laminar	Increasing the heat transfer coefficient by increasing the concentration of nanofluids.
Yang et al. (2005)	Oil	MWCNT	100	1-0,1	Pipe	Laminar	35% increase in heat transfer

Table 2.
Overview of some other studies

Author	Theoretical review	Modeling method	Outcomes
Xuan and Roetzel (2000)	Heat transfer coefficient in copper with oil and water	Single phase	Increasing the heat transfer coefficient by reducing the particle size.
Buongiorno (2006)	Displacement of nanofluids	Two-phase model with non-uniform phase for the particle	Brownian effects and thermophoresis are the dominant effects.
Behzadmehr et al. (2007)	Forced convection heat transfer in turbulent regime	Dual phase	Increasing the displacement heat transfer coefficient with increasing ϕ and Re
Maïga et al. (2004)	Forced heat transfer in a tube containing aluminum and ethylene glycol in water	Single phase	60% increase in heat transfer
Mansour et al. (2007)	Thermal and hydraulic behavior in laminar and turbulent flow in a pipe with constant flux	Single phase	Heat transfer coefficient increase in both regimes

Peer-review: *Externally peer-reviewed*

Author contributions:

M.Mustafaoğlu : Writing, Literature search, analysis

MK.Yeşilyurt : Supervision, literature search, writing manuscript, methodology

MT. Topcu : Investigation, analysis Supervision, conceptualization

İV.Öner : Investigation, analysis

K.Bilen : Supervision

Financial disclosure: *This study was funded by Atatürk University Coordination Unit of Scientific Research Projects under grant no FBA-2023-12999.*

Conflict of Interest*: The author has no conflicts of interest to declare.*

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