

Research Article

NUMERICAL SIMULATION OF THE EFFECTS OF VOLUME FRACTION AND NANOPARTICLE DIAMETER ON NANOFLUID HEAT TRANSFER IN A MICRO HEAT PIPE USING CFD

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KEYWORDS

Micro heat pipe, Heat transfer, Nanofluids

ABSTRACT

In this study, the heat transfer of nanofluid convection in a micro heat pipe has been comprehensively investigated numerically using ANSYS Fluent software. The simulation was performed based on the finite volume method and considering turbulent flow, and the effect of two key parameters, including the volume percentage of nanoparticles and the diameter of nanoparticles on the temperature field, heat transfer coefficient, and Nusselt number, was analyzed. The validation of the numerical model with reliable data available in the literature indicates the high accuracy of the simulation results. The results showed that increasing the volume percentage of nanofluid causes a significant decrease in the wall surface temperature, a more uniform temperature distribution, and a significant increase in the heat transfer coefficient and Nusselt number. Also, decreasing the diameter of the nanoparticle plays a significant role in enhancing heat transfer due to the increase in specific surface area and intensification of Brownian motion. Analysis of temperature contours and thermal profiles showed that nanofluid causes thinning of the thermal boundary layer and an increase in the temperature gradient in the vicinity of the wall. On the other hand, an excessive increase in the volume fraction leads to increased viscosity and pressure drop, making an optimal range necessary. The results of this study confirm that nanofluids can be used as an efficient solution to improve the thermal performance of micro-exchangers and compact cooling systems. These achievements have wide applications in cooling of electronic equipment, energy systems, micro-heat exchangers, and advanced technologies.

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INTRODUCTION

The idea of using suspended solid particles in fluids to enhance heat transfer is more than a century old, but the fundamental limitations of classical two-phase fluids, including instability, rapid settling, severe wall abrasion, and high pressure drop, have made their widespread industrial application seriously challenging. A major turning point in this field was the formal introduction of the concept of “nanofluids” by Choi at the Argonne Institute in 1995 ^[1]. Choi opened the way for a scientific revolution in the field of heat transfer by showing that suspensions of particles on the nanometer scale can simultaneously provide suspension stability and significant improvements in thermal conductivity. Subsequently, extensive experimental research was initiated to measure the enhancement of thermal conductivity of nanofluids accurately, the most important of which is the classic work of Lee and Choi, who for the first time quantitatively demonstrated that the addition of very small percentages of metal nanoparticles can increase the thermal conductivity of the base fluid by several tens of percent ^[2]. These initial results attracted widespread attention from the scientific community towards the application of nanofluids in heat transfer engineering systems.

Subsequently, Eastman and colleagues, by performing detailed experiments on nanofluids containing copper nanoparticles in an ethylene glycol base fluid, reported increases in thermal conductivity of more than 40% ^[3], a result that at that time far exceeded the predictions of classical Maxwell heat transfer models and indicated that new physical mechanisms were at play at the nanoscale. This quickly led to the development and revision of theoretical models of effective conductivity. Various models were developed based on particle dispersion, interfacial resistance, cluster structure, and the effect of Brownian motion, including the Hamilton–Krasser models and their subsequent modifications. In this regard, Wang et al., through experimental and numerical studies of various nanofluids, showed that the increase in thermal conductivity is not only a function of volume fraction, but also strongly depends on the type of particles, their size, the stability of the suspension, and the type of base fluid ^[4].

With the role of nanofluids in improving thermal conductivity properties established, the focus of research shifted to investigating their actual performance in natural and forced convection flows. One of the first systematic studies in this field was conducted by Peck and Cho, who investigated the convective heat transfer of nanofluids in a tube and reported a significant increase in the Nusselt number compared to the base fluid ^[5]. This study showed that the increase in conductivity is not the only factor in improving the performance, but the dynamic structure of the flow and the thermal boundary layer changes are also greatly transformed. Gradually, analytical and numerical models were developed to describe the heat transfer behavior of nanofluids in laminar and turbulent flow. Meanwhile, the comprehensive study by Botola et al. provided one of the first coherent frameworks for analyzing the thermohydraulic behavior of nanofluids in tubes ^[6].

In the 2000s, along with the rapid growth of computational power, numerical modeling of nanofluids using CFD expanded significantly. Most early models used a single-phase approach, in which the nanofluid was defined as a homogeneous fluid with effective properties. Although this approach was able to reproduce many experimental results, in some cases it was unable to accurately predict the local behavior of particles and non-equilibrium effects. Khanna and Das showed through detailed numerical analysis that the single-phase model is highly reliable in certain ranges of volume fraction and particle size, but at high percentages or in conditions of intense heat transfer, deviations from the experimental data are observed ^[7]. For

this reason, two-phase Eulerian–Lagrangian and Eulerian–Eulerian approaches were also gradually introduced into studies, although they had higher computational costs.

One of the important turning points in the evolution of nanofluid science was the landmark work of Bongorno in 2006, which analytically demonstrated that Brownian motion and thermophoresis can contribute to heat transfer enhancement independently of effective thermal conductivity^[8]. This study had a profound impact on the physical understanding of nanofluid behavior, and many subsequent studies have attempted to extract the relative contributions of these mechanisms quantitatively. Subsequently, Deshpande et al., by simultaneously analyzing mass and heat transfer, showed that at small scales, particle displacement effects can even dominate effective conduction, especially when the particle diameter is below 50 nm.

Since around 2008, the scientific community has gradually shifted its focus from macroscopic tubes to microchannels and microtubes. The reason for this shift was the emergence of high-power microelectronic systems and the strong need for intensive cooling with very high heat fluxes. Torres et al. were among the first groups to experimentally study nanofluids in microchannels and showed that the increase in the Nusselt number at this scale is usually greater than at the macroscale^[9]. This phenomenon was mainly attributed to the intensification of thermal boundary layer effects and the greater dominance of conduction and Brownian motion at small dimensions.

Subsequently, the study of the effect of the volume fraction of the nanofluid as a key design parameter received special attention. The results of many studies showed that with increasing volume fraction, the Nusselt number and heat transfer coefficient increase, but this increase is not always linear and approaches saturation at high percentages. This nonlinear behavior was first demonstrated in detail in the experimental and numerical studies of Wang et al.^[10], who showed that increasing viscosity, pressure drop, and the possibility of particle clustering at high particle fractions lead to a decrease in the incremental heat transfer efficiency. This result provided a very important conceptual basis for defining the “optimal volume fraction” in nanofluid design.

Taken together, this set of studies demonstrates that nanofluids have evolved from an emerging laboratory idea to a serious engineering tool for enhancing heat transfer in various systems. However, despite much progress, there are still significant scientific gaps in the field of the simultaneous effect of particle size, volume fraction, accurate modeling of the temperature field, and boundary layer behavior in microtubes; gaps that are directly related to the subject of the simulations performed in the present study and form the basis of its innovation.

With the increasing application of nanofluids in engineering systems, numerical studies have quickly become a vital tool for analyzing the flow behavior and heat transfer of nanofluids. One of the first comprehensive studies in this field was conducted by Das et al. in the early 2000s, who investigated the thermal behavior of nanofluids in laminar and turbulent flows using a single-phase model^[11]. They showed that increasing the volume fraction of nanoparticles increases effective conductivity and changes the temperature profile along the pipe, but at high volume fractions, uneconomical effects such as increased viscosity and uneconomical pressure drop appear. This study paved the way for subsequent numerical analyses and emphasized that the single-phase model, although valid for a certain range of conditions, requires modifications and more sophisticated approaches for extreme heat transfer conditions and high-volume fractions. In the following years, a series of experimental and numerical studies were conducted to investigate the effect of nanoparticle diameter on thermohydraulic performance. Buongiorno (2006) presented an analytical and experimental



framework that showed that Brownian motion of small particles can play a dominant role in heat transfer at the microscale ^[12]. Early CFD models usually aimed to reduce computational complexity by assuming homogeneous fluid properties, but numerical results showed that local effects, especially near-wall and concentration variations, could not be predicted by simple models. These findings led to the development of two-phase Eulerian-Lagrangian and multi-component models that were able to simulate particle motion, dispersion, thermophoresis, and local instability effects ^[13].

At the same time, by entering the scale of microchannels, studies have investigated the effect of microchannel geometry and boundary conditions on nanofluid heat transfer. Li and Xuan (2007) showed that in microchannels, the effect of particle volume fraction and diameter on the heat transfer coefficient and Nusselt number is enhanced, and the increased values are usually more than those in similar macroscopic tubes ^[14]. This effect was due to the reduction of the thermal boundary layer thickness and the increase in the influence of microscopic mechanisms such as Brownian motion and thermophoresis on small scales. Numerical studies by Mahian et al. (2013) using Fluent showed that increasing the volume fraction of nanoparticles increases the heat transfer coefficient by 30–50% in microflows, but the pressure drop also increases at the same time, and therefore, thermo-hydraulic performance analysis is necessary ^[15].

One important research direction was the effect of nanoparticle type and surface properties on nanofluid performance. Zhang et al. (2011) showed that nanofluids with hydrophilic particles and larger surface area have more efficient heat transfer and higher suspension stability^[16]. This result led to the design of optimal nanofluids depending not only on the volume fraction but also on the surface properties and particle size. Subsequent research showed that changing the particle diameter in the range of 10–100 nm significantly affects the heat transfer coefficient and Nusselt number, with finer particles providing the most optimal performance due to stronger Brownian motion^[17].

Advanced CFD modeling studies also showed that the flow behavior of nano fluids in microchannels is significantly different from that of the conventional base fluid. Hong and Lee (2010) reported that by solving the Navier-Stokes equations in two phases, heat flux was increased, temperature distribution was improved, and hot spots were reduced ^[18]. Also, the use of finite volume algorithms and k- ϵ or SST turbulent models in Fluent helped to accurately simulate the flow and predict the microscopic behavior. These findings confirmed the importance of accurate numerical simulation for the design of next-generation cooling microchannels. In the last decade, the research focus has shifted towards hybrid nanofluids and their applications in advanced energy systems and microelectronics. For example, the study by Akbarzadeh et al. (2015) showed that the combination of two types of nanoparticles can enhance the heat transfer properties in an additive and nonlinear manner, while simultaneously controlling the effect of viscosity and pressure drop ^[19]. Recent experimental and numerical studies (2018–2023) have investigated in detail the effects of the volume fraction composition, particle diameter, particle shape, and microchannel walls on the thermohydraulic performance and showed that simultaneous optimization of these parameters can provide efficiency enhancements of up to 60% compared to the base fluid ^[20]. In summary, the review of numerical and experimental research suggests that nanofluids not only have the potential to enhance heat transfer but also play a key role in the design of microchannel systems and electronic devices with severe thermal constraints. However, there are still important scientific gaps, including the detailed analysis of the simultaneous effect of volume fraction and particle

diameter at the microscale, thermal boundary layer behavior, Nusselt number prediction, and thermohydraulic performance optimization. These gaps are precisely what underpins the innovation and importance of the present simulation.

Governing equation

Since in chemical reactions mass can neither be created nor destroyed, there is no source (generation) term in the mass conservation or continuity equation. Therefore, the continuity equation is defined as follows:

$$\frac{\partial \rho}{\partial t} + \text{div}(\rho \mathbf{v}) = 0 \quad (1)$$

Considering that a steady-state condition is assumed in the present study, the continuity equation reduces to the following form:

$$\text{div}(\rho \mathbf{v}) = 0 \quad (2)$$

Conservation of Momentum

$$\frac{\partial(\rho u)}{\partial t} + \text{div}(\rho u \mathbf{u}) = \text{div}(\mu \text{ grad } u) - \frac{\partial P}{\partial x} + B_x + V_x \quad (3)$$

In the above equation, μ represents the dynamic viscosity, P denotes the pressure, B_x indicates the x-component of the body force per unit volume, and the last term represents the viscous terms. These are in addition to the terms expressed by the source terms. V_x denotes the velocity component in the x-direction.

Conservation of Energy

$$\text{div}(\rho u h) = \text{div}(k \text{ grad } T) + S_h \quad (4)$$

The energy equation, in its most general form, includes a large number of effects. However, for a steady flow with low velocity, in which viscous dissipation is negligible, the energy equation can be written as:

In this equation, h denotes the enthalpy, k represents the thermal conductivity, T indicates the temperature, and S_h represents the volumetric heat generation rate. The term $\text{div}(k \text{ grad } T)$ indicates the effect of heat transfer by conduction within the fluid (according to Fourier's law of heat conduction).

Nanofluid properties:

Assuming that the nanoparticles are uniformly dispersed within the base fluid, the particle concentration can be considered spatially uniform throughout the tube. Although this assumption may not strictly hold in real systems due to particle migration phenomena, it provides a useful and practical approach for estimating the effective thermophysical properties of nanofluids. The effective properties of nanofluids can be evaluated using the classical and well-established two-phase mixture models. In the following equations, the subscripts NP, BF, and NF denote the nanoparticle, base fluid, and nanofluid, respectively.

$$\rho_{NF} = \rho_{BF}(1-\varphi) + \rho_{NP}\varphi \quad (5)$$

$$C_{P,NF} = C_{P,BF} \frac{\rho_{BF}(1-\varphi)}{\rho_{BF}(1-\varphi) + \rho_{NP}\varphi} + C_{P,NP} \frac{\rho_{NP}\varphi}{\rho_{BF}(1-\varphi) + \rho_{NP}\varphi} \quad (6)$$

To estimate the thermal conductivity of the nanofluid, the effective volume fraction of the nanoparticles was calculated based on viscosity measurements. In nanoparticle suspensions, the viscosity is expressed as follows:

$$\mu = \mu_{BF}(1+a\varphi) \quad (7)$$

In this relation, a is a constant coefficient. For instance, in Einstein's model, the value of a is taken as 2.5. However, in general, this value is greater than 2.5 for nanofluids, which indicates that nanoparticles exhibit a larger effective volume in the fluid compared to micro-sized particle suspensions. The thermal conductivity of nanofluids can be expressed in terms of the effective volume fraction of the particles as follows:

$$k = k_{BF} \left(\frac{k_{NP} + 2k_{BF} - \frac{a}{125}\varphi(k_{BF} - k_{NP})}{k_{NP} + 2k_{BF} + \frac{a}{125}\varphi(k_{BF} - k_{NP})} \right) \quad (8)$$

Validation

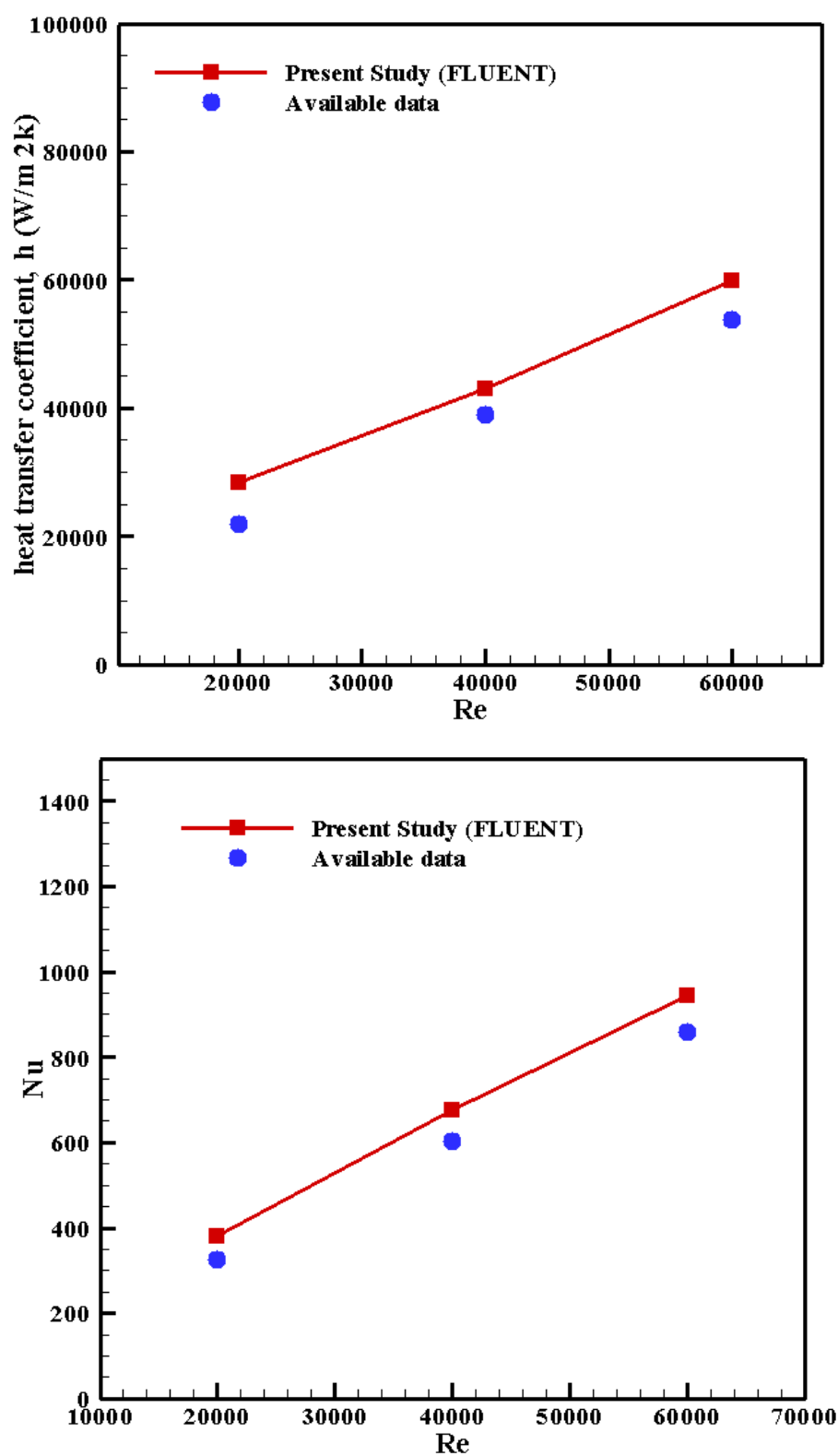
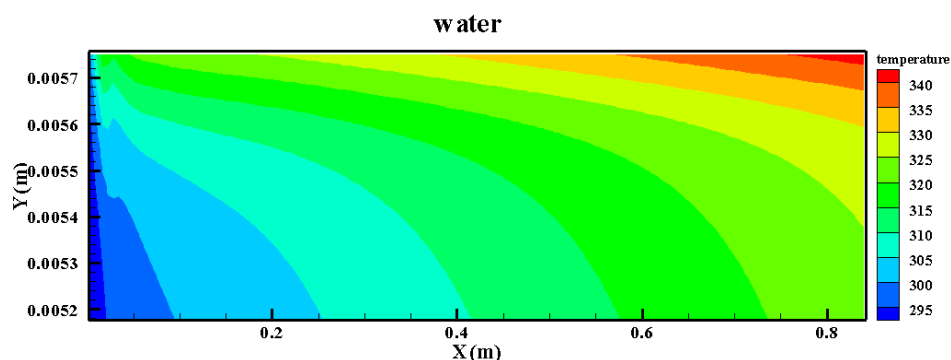


Figure (2). Validation of the numerical algorithm by comparing the Nusselt number and

heat transfer coefficient with existing results ^[21].

Validation of numerical results is an essential step in any simulation study to ensure that the numerical configuration, boundary conditions, and choice of physical models accurately reproduce the physical behavior. Figure 2 shows a comparison of the Nusselt number and heat transfer coefficient calculated in this study with reference data (Sahin et al.). The close agreement of the curves over the range of Reynolds numbers and boundary conditions studied indicates the correct implementation of the flow model, meshing, and thermodynamic parameters of the nanofluid. The static agreement and numerical trends (whether linear or nonlinear) between the simulation and reference results indicate that the formulation of the effective properties of the nanofluid (effective thermal conductivity, effective viscosity, density, and effective specific heat) and the numerical method (finite volume, SIMPLE or segregated algorithm) are correctly implemented in the code. In the validation analysis, spatial distributions and local gradients should be considered in addition to the comparison of mean values; Figure 2 illustrates that the observed differences are limited and acceptable at some points and are usually attributable to differences in numerical tricks (such as mesh corners, partial boundary conditions or k- ϵ turbulence model). Also, the mesh sensitivity analysis shows that the results are independent of the number of elements up to a certain convergence factor and that numerical instabilities do not occur in the used ranges. From a physical point of view, the fact that the results show good convergence in the range of reference experimental conditions allows us to confidently investigate the subsequent parameters of the study (volume percent increase and particle diameter change). It is important to note that qualitative agreement (slope and trend) is almost always better than absolute quantitative agreement, since some reference sources have experimental data with measurement uncertainty; The agreement is therefore considered acceptable within the framework of measurement error and model error. Finally, Figure 2 serves as a starting point for confidence in the subsequent conclusions: any significant changes in the heat transfer coefficient or Nusselt number reported in the following sections should be read within the framework of this authoritative reference. The results show that the numerical model is able to accurately reproduce the physical role of nanofluids and therefore the presented parametric analyses rely on a reliable numerical basis.

RESULT



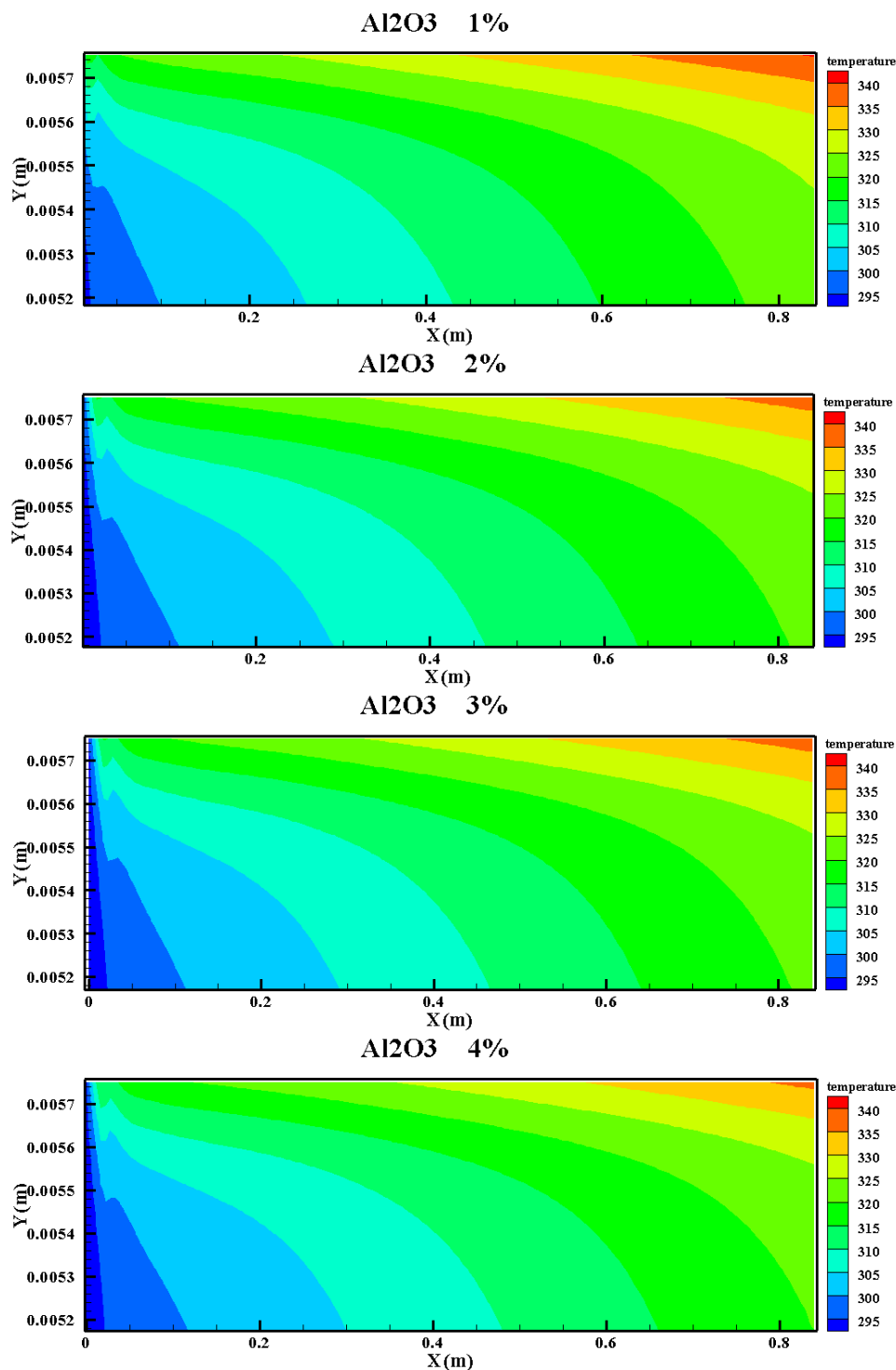


Figure (3). Investigating the effect of increasing the volume percentage of nanofluid on the temperature distribution in the computational domain.

Figure 3 shows the temperature contours of the flow field for different volume fractions of nanofluid, focusing on the spatial variations of temperature and thermal gradients. As the

volume fraction increases, the temperature distribution becomes more homogeneous throughout the cross-section and length of the tube, and the maximum temperature values decrease; this indicates an effective increase in the heat transfer capability in the presence of nanoparticles, which is attributed to two main mechanisms: first, the increase in the effective thermal conductivity of the fluid, which provides more paths for heat conduction, and second, the enhancement of microscopic heat transfer due to Brownian motion and collisions of particles with base fluid molecules. The regions near the wall, which usually exhibit the largest thermal gradient, experience the largest changes in response to volume fraction; thinning of the thermal boundary layer and a decrease in the temperature difference between the wall and the fluid core are direct consequences of this process. It is also observed that with increasing volume fraction up to moderate values, the temperature distribution becomes more uniform, but further increases in volume fraction produce less incremental efficiency, indicating the presence of inhibiting effects such as increased viscosity and pressure drop, which can disrupt effective mixing and reduce mass-heat transfer. From an engineering perspective, reducing hot spots and temperature uniformity provides practical advantages in terms of system lifetime and stability. Furthermore, the contour patterns show that at high Reynolds numbers, turbulent disturbances and greater mixing make the effect of volume fraction more prominent, while at lower Reynolds numbers, local effects are more dependent on effective conductivity. Therefore, subsequent analyses of the heat transfer coefficient and Nusselt number should be interpreted in the context of these spatial variations, especially in the context of the adaptation to the constant wall boundary conditions (flow with constant heat flux or constant temperature) that can change the behavior of the temperature field somewhat. Overall, Figure 3 provides a comprehensive picture of how thermal energy is distributed in the presence of nanoparticles and shows that volume fraction is a key parameter in the design of nanofluid-converters.

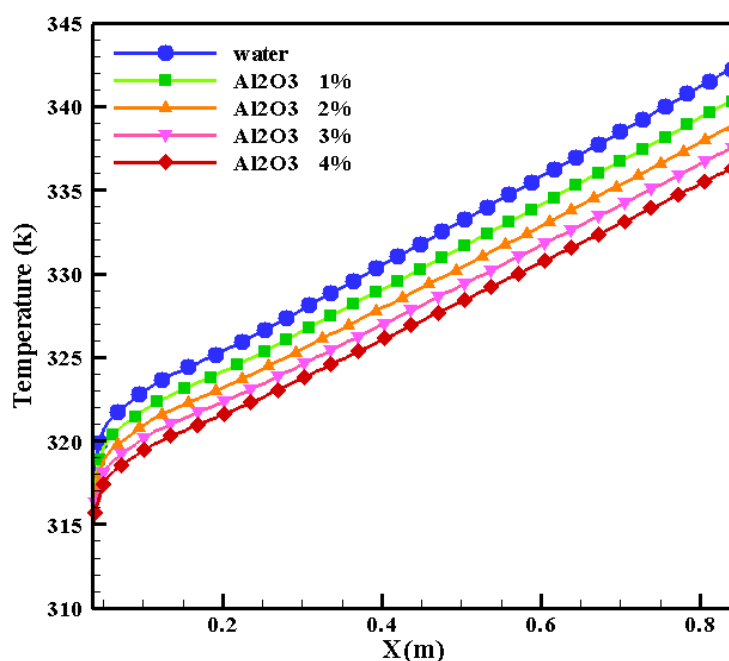


Figure (4). Investigation of the effect of increasing the volume percentage of nanofluid on the temperature profile on the pipe surface.

Figure 4 shows the wall surface temperature profile along the tube for several volume percent values, focusing on longitudinal variations and regions with large temperature gradients. The results clearly show that the addition of nanoparticles reduces the wall surface temperature along the entire length of the tube; this reduction indicates an increase in the heat transfer rate from the wall to the fluid, which is enhanced by increasing the volume percent. What is important is the change in the slope of the profile; at higher volume percents, the temperature profile is more uniform and the local slopes are reduced, indicating better heat diffusion in the fluid and reduced thermal hot-spots along the wall. Physically, the decrease in wall temperature with increasing volume percent is due to the synergy of several mechanisms: increased effective conductivity, increased microscopic mixing due to Brownian motion, and a change in the structure of the thermal boundary layer, which causes it to become thinner. However, it is worth noting that increasing the volume percent also has costs; Increasing the effective viscosity can increase the pressure drop and reduce the flow rate, which in some designs may limit the overall system performance. The profiles presented also show that the effect of volume fraction on wall temperature reduction is more pronounced in the initial regions of the tube (near the inlet), because the initial temperature gradient is high and any conductivity improvement is quickly apparent; as the tube length continues, the relative effect decreases but is still significant. For practical design, points on this profile that show greater temperature reduction can be used as key points to determine the optimal volume fraction, especially in surface temperature sensitive applications such as microelectronic cooling. Overall, Figure 4 shows that volume fraction is an adjustable and effective parameter in controlling wall surface temperature, and choosing the right value requires a trade-off between heat transfer enhancement and hydrodynamic costs.

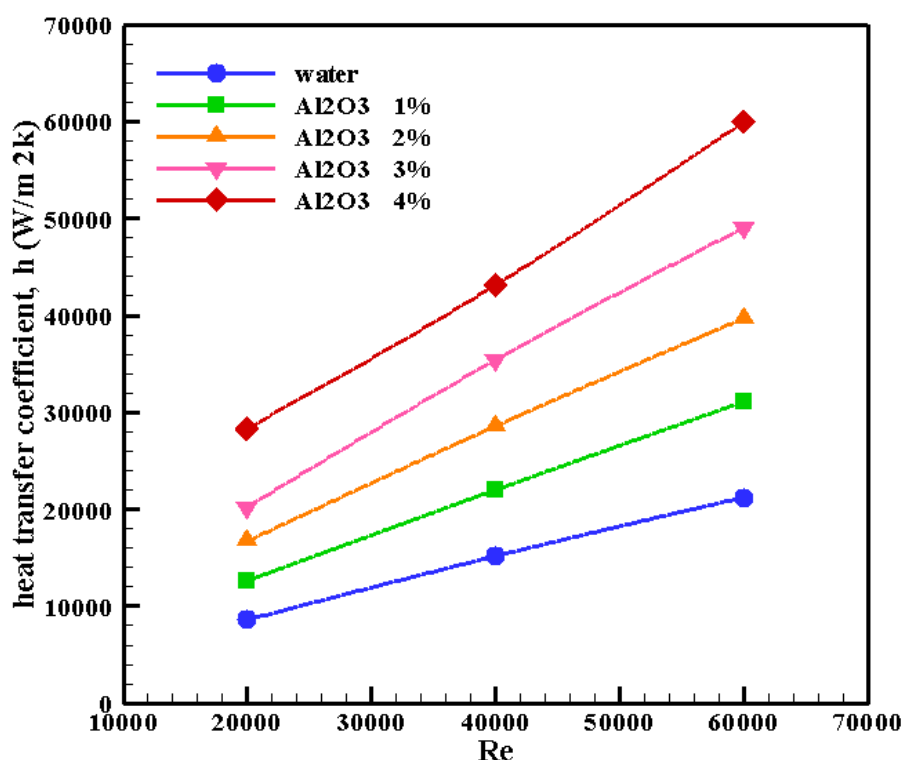


Figure (5). Studying the effect of increasing the volume percentage of nanofluid on the heat transfer coefficient

Figure 5 shows the trend of the convective heat transfer coefficient with respect to the volume percentage of nanofluid; this parameter is one of the key thermal efficiency criteria from a design perspective. Numerical results indicate that the heat transfer coefficient increases with increasing volume percentage; this increase is often steep in the initial volume percentage regions and then continues with a lower slope, indicating a quasi-saturation behavior. The physical reasons for this trend include an increase in the effective thermal conductivity, increased microscopic turbulence due to the Brownian motion of the particles, and increased surface heat exchange between the particles and the base fluid. However, the nonlinear increase and the decrease in slope at high volume percentages are associated with negative effects; the increase in viscosity creates redundancy, which increases hydraulic losses and in some cases may reduce the overall efficiency of the system. Also, high particle density can lead to flow disruption and the formation of particle clusters, which locally disrupt heat transfer. It should be noted here that the heat transfer coefficient is not the only desirable criterion and should be examined simultaneously with parameters such as pressure drop and pump energy consumption to determine the optimal volume percentage. Energy and thermo-hydraulic performance analysis usually considers a combination of heat transfer coefficient enhancement and hydraulic costs. The data in Figure 5 show that for the boundary conditions and Reynolds numbers studied, there is a range of volume percentages that provide effective and economical heat transfer coefficient enhancement; beyond that, the thermal benefits are not justified by the hydrodynamic costs. Finally, it should be emphasized that the characteristics of the nanofluid (particle type, size, specific surface area, and suspended stability) and the operating range of the flow are the parameters that determine the manner and extent of heat transfer coefficient enhancement, and further studies are needed to generalize the results to more practical conditions.

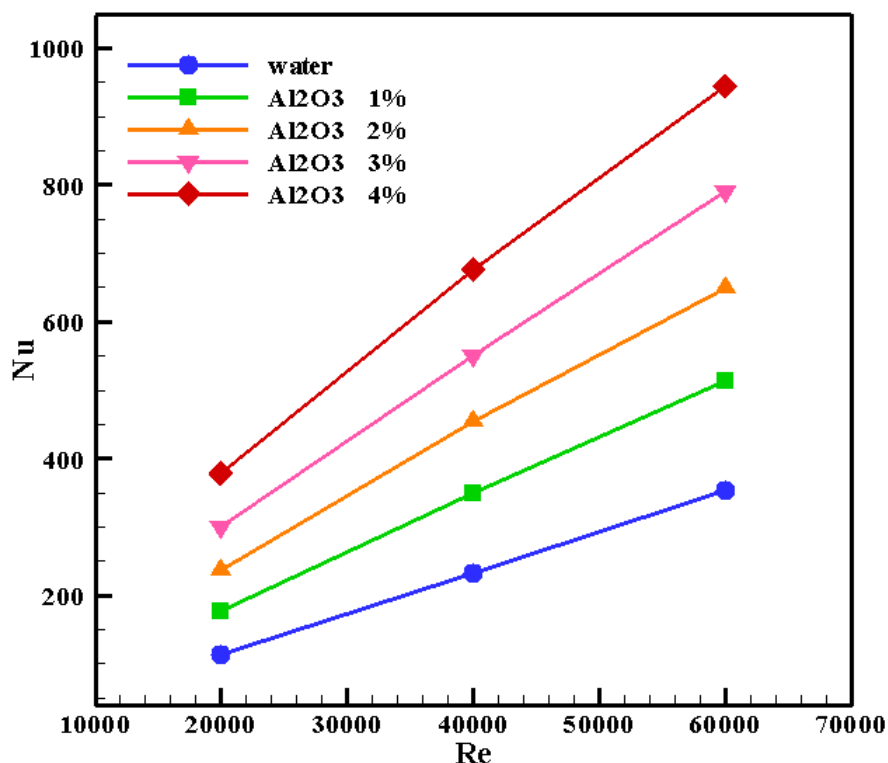


Figure (6). Investigating the effect of increasing the volume percentage of nanofluid on the Nusselt number

Figure 6 reports the changes in the Nusselt number as a non-dimensional indicator of convective heat transfer versus the volume fraction of nanofluid. The Nusselt number, due to its dimensionlessness, facilitates the comparison of thermal efficiency under different conditions, and its change reflects the changes in the heat transfer coefficient and boundary conditions. The results show that with increasing volume fraction, the Nusselt number increases significantly; this increase indicates the enhancement of convective heat transfer by enhancing thermal mixing and improving effective conduction. Similar to the trend of the heat transfer coefficient, the initial increase in the Nusselt number is more severe at higher values of volume fraction, indicating the optimal effective value for achieving the highest Nusselt increase with minimal hydrodynamic complications. The reason for the decrease in the slope of the Nusselt increase at high volume fraction is mainly due to the increase in viscosity and the decrease in the fluid-pump ratio, which has detrimental effects on the boundary layer structure. Also, the formation of particle clusters at high volume fractions can disrupt local mass-heat transfer and consequently reduce the numerical Nusselt efficiency. From a theoretical perspective, the Nusselt number is related using the calculated heat transfer coefficient and the thermal properties of the fluid; therefore, any change in the model of effective properties (such as empirical relations for conductivity or viscosity) can affect the Nusselt values. For practical applications, increasing the Nusselt number is beneficial but should be combined with a simultaneous analysis of pressure drop and pump energy consumption to obtain a real assessment of the improvement in system performance. Overall,

Figure 6 shows that increasing the volume fraction can be an effective way to enhance the Nusselt number and improve heat transfer in microtubes, provided that hydrodynamic constraints and nanofluid stability are also considered in the design.

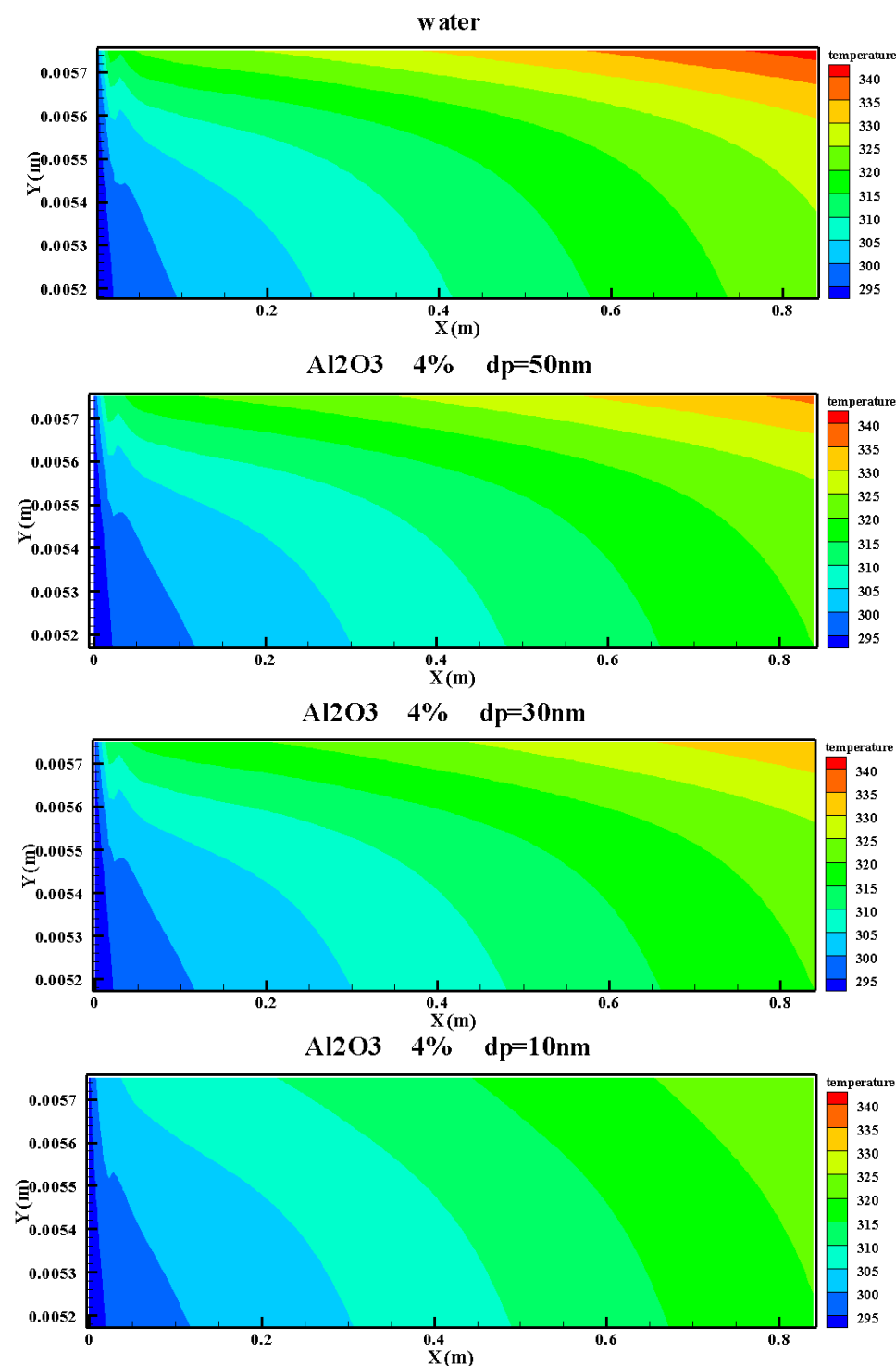


Figure (7) Investigating the effect of nanofluid particle diameter on temperature distribution in the computational domain

Figure 7 shows temperature contours for nanoparticles of different diameters, emphasizing the effect of particle size on thermal performance. A decrease in particle diameter is often accompanied by an increase in specific surface area and enhanced Brownian motion; the result of these changes is an improvement in heat transfer and a decrease in the mean temperature of the flow field, which is seen in the contours as a narrowing of the temperature range and a more uniform temperature distribution. Smaller particles play a more effective role in heat transfer by allowing faster heat exchange between the solid and fluid phases, while larger particles have less effect on microscopic mixing due to their greater mass and weaker Brownian motion. Another important point is the effect of particle size on the stability of suspension; very small particles may show higher stability but at the same time can lead to a decrease in the viscosity properties in some empirical relationships, which has a nonlinear effect on the temperature field. The contours show that the difference in the effect of particle size is prominent in the regions near the wall and the core of the flow; Smaller particle size allows heat to be transferred from the wall to the core more quickly, facilitating the thinning of the thermal boundary layer. For designers, this means that the choice of particle size is a critical parameter that must be considered alongside the volume fraction and surface properties of the particles to achieve an optimal combination of conductivity, stability, and cost. Finally, Figure 7 shows that reducing particle diameter is generally beneficial for improving temperature distribution and increasing thermal uniformity, but side effects such as viscosity changes and the possibility of particle fouling must also be considered for generalization to practical systems.

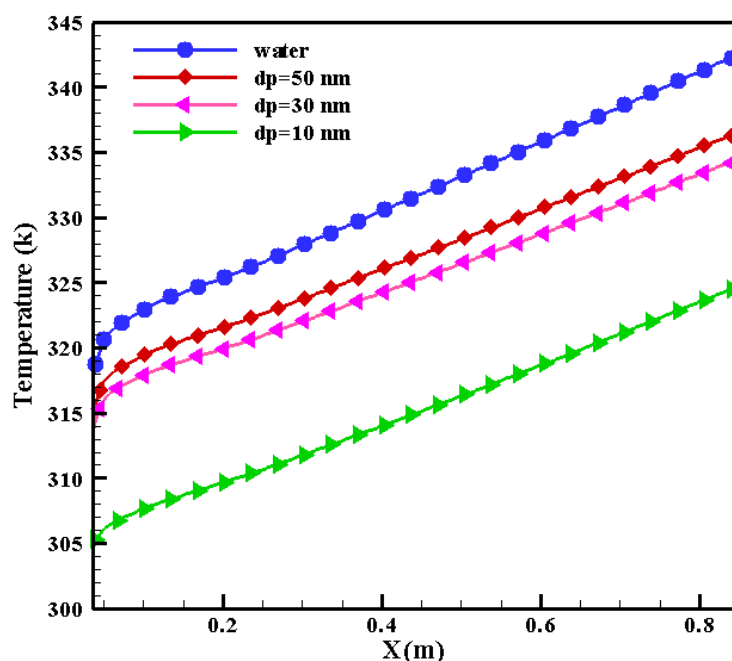


Figure (8) Investigating the effect of nanoparticle diameter on the temperature profile on the pipe surface

Figure 8 compares the wall temperature profiles for different sizes of nanoparticle. The data show that as the particle diameter decreases, the wall surface temperature decreases along the length of the tube, and the profile tends to lower and more uniform values. The reduction in wall temperature when smaller particles are used is a result of increased surface heat exchange between the particle phase and the base fluid and improved phonon/convexion transport at the particle surface. In addition, smaller particles increase the effective contact area and increase the energy transfer capability; this is especially effective when the cross-sectional length required for heat exchange is limited, such as in microtubes. The longitudinal profiles show that the effect of particle size is more pronounced in regions close to the inlet, because the initial temperature difference is higher and the possibility of rapid heat absorption by the particles is greater. From a practical point of view, reducing the wall temperature can lead to reduced thermal stresses and increased lifetime of sensitive components; However, the design must strike a balance between thermal benefits and hydrodynamic consequences (possible increased pressure drop). Also, the nonlinear behavior of the profiles at some sizes indicates local variations in particle distribution or cluster formation that can affect thermal performance and requires further experimental investigation or dynamic modeling. Finally, Figure 8 confirms that particle size is one of the key parameters in controlling the wall surface temperature and its proper selection can effectively increase the efficiency of microcooling systems.

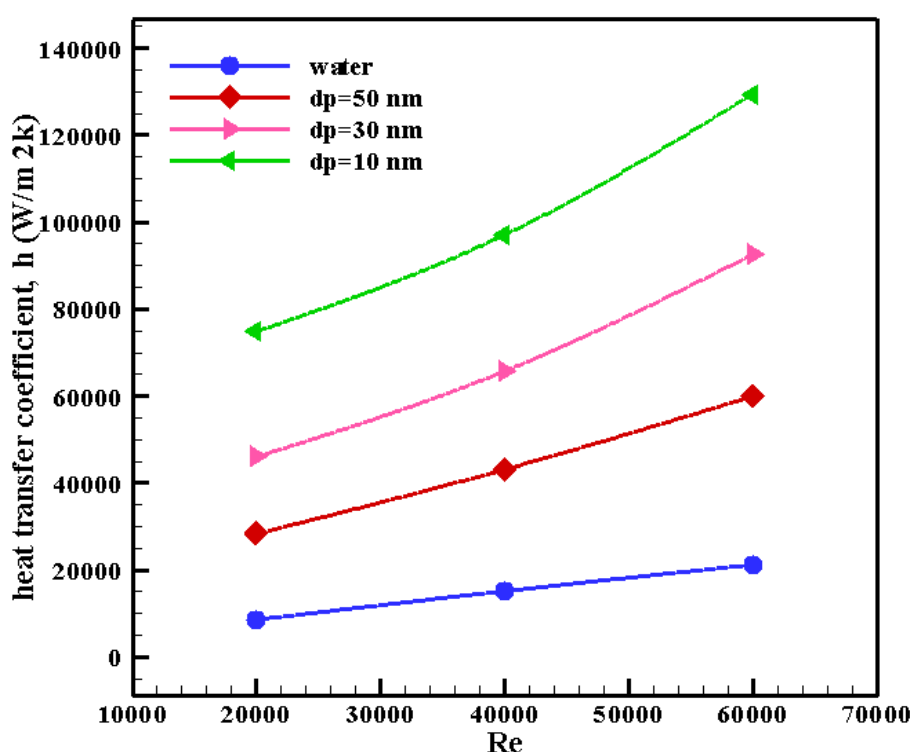


Figure (9) Studying the effect of nanoparticle diameter on heat transfer coefficient

Figure 9 shows the trend of heat transfer coefficient variation with nanoparticle size. In general,

decreasing particle diameter is accompanied by increasing heat transfer coefficient; smaller particles have better heat exchange with the base fluid due to larger specific surface area and stronger Brownian motion, which increases the effective conduction and enhances convolitional transport at the microscale. This effect is intensified at higher Reynolds numbers because large-scale flow mixing is also present and microscopic and macroscopic mechanisms combine to maximize heat transfer efficiency. However, it is worth noting that excessive particle size reduction can also have negative effects, such as a drastic increase in viscosity or unexpected changes in the suspension stability behavior; therefore, there is usually an optimum particle size point that provides the highest heat transfer coefficient at reasonable hydrodynamic costs. The data in Figure 9 show that the slope of the increase in heat transfer coefficient with decreasing particle size is steep within a certain range, but then tends to saturation. For practical applications, this means that choosing a very fine particle size may give slightly better thermal results, but production costs and maintenance issues may make this choice undesirable. Therefore, a comparative analysis and economic discussion between the improved heat transfer coefficient and the associated costs is necessary to determine the optimal size.

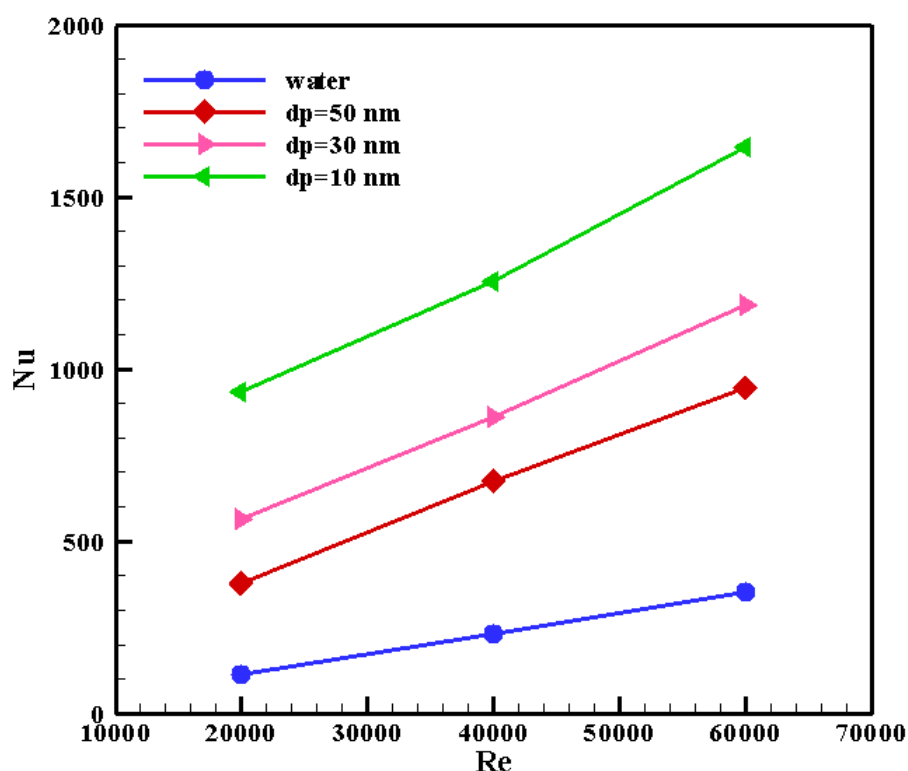


Figure (10). Studying the effect of nano-particle diameter on the Nusselt number

Figure 10 shows the relationship between particle size and Nusselt number; as expected, decreasing particle diameter leads to an increase in Nusselt number, indicating an overall improvement in convective heat transfer. This increase is related to the mechanisms of increasing effective conductivity and enhancing microscopic mixing. However, the increasing trend of Nusselt number with decreasing particle size is also nonlinear and tends to saturate at very small sizes. From a systematic perspective, Nusselt number gives a measure of efficiency

relative to reference sizes and is used to fit between different conditions; therefore, increasing Nusselt with finer particles is an indication of improved performance, but as before, it should be evaluated in conjunction with pressure drop analysis and cost comparison. Figure 10 may also show small local fluctuations resulting from local particle aggregation or local changes in effective properties; these may indicate the need for multiphase modeling or particle transport models to make the analysis more accurate. Overall, Figure 10 shows that particle size is a key parameter for tuning the Nusselt number and that reducing the size within practical limits can effectively improve heat transfer efficiency, provided that hydrodynamic and containment implications are also considered.

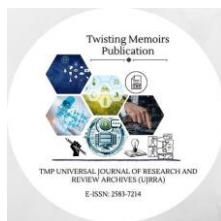
CONCLUSION

This research, using precise numerical simulation with the help of ANSYS Fluent software, comprehensively investigated the thermal behavior of nanofluid in a micro-heat pipe and analyzed the effect of two fundamental parameters, including the volume percentage of nanoparticles and the diameter of nanoparticle on the temperature field, heat transfer coefficient and Nusselt number, so that the validation of the results with reference data indicated the high accuracy of the numerical model and the correctness of the selection of the effective properties of nanofluid. The results showed that increasing the volume percentage of nanofluid causes a significant decrease in the wall surface temperature, a more uniform temperature distribution, an increase in the heat transfer coefficient and a significant increase in the Nusselt number, which is due to an increase in the effective thermal conductivity, enhancement of microscopic energy transfer and thinning of the thermal boundary layer. It was also found that decreasing the diameter of nanoparticle by increasing the specific surface area, intensifying Brownian motion, and improving the energy exchange between the solid and fluid phases plays a fundamental role in improving thermal performance, such that finer particles significantly increase the heat transfer rate and reduce the temperature of the flow field. From a physical perspective, three key phenomena, including increased effective conductivity, Brownian motion of particles, and thinning of the thermal boundary layer, were identified as the dominant mechanisms for enhancing heat transfer in this system, while at the same time, limiting effects such as increased viscosity, pressure drop, and the possibility of particle aggregation at high volume percentages lead to the emergence of an optimal region for selecting nanofluid parameters. The scientific importance of this research is that, with a systematic approach, it examines the simultaneous effect of volume fraction and particle size at the micro scale and provides a detailed picture of the thermal boundary layer behavior and energy transfer in nanofluids, which is at the frontier of knowledge in the fields of heat transfer, CFD, and nanotechnology. From an applied perspective, the results of this research have the potential for direct implementation in advanced cooling technologies such as cooling of processors and microelectronic devices, ultra-compact heat exchangers, high-power laser systems, thermal energy storage systems, solar collectors, power equipment, nuclear industries, and even biomedical systems, so that the optimal use of nanofluids can lead to reduced operating temperatures, increased efficiency, reduced equipment dimensions, and increased operational life. Finally, this research, in addition to providing a valid framework for the design of engineered nanofluids, provides a clear path for future research in the field of hybrid nanofluids, multiphase modeling, investigation of the effect of magnetic fields, and

simultaneous analysis of thermohydraulic performance, and shows that nanofluids are one of the most promising next-generation tools for managing and enhancing heat transfer at the micro and nano scales.

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