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ANALYSIS OF THE HEAT TRANSFER PERFORMANCE OF NANOFLUIDS IN MICRO-CYLINDER GROUPS

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The objective of this study is to investigate, through numerical simulations, the flow and heat transfer characteristics of Al_2O_3, Cu, TiO_2, and SiC water-based nanofluids flowing over micro-cylinder groups arranged in an inline configuration. The simulations were carried out under laminar flow conditions, and the analysis considered seven different low values of the Reynolds number, with a constant volume fraction of 2 %. The aim of this investigation was to determine how nanofluids, i.e., suspensions of nanoparticles in water as the base fluid, can affect the pressure drop and heat transfer performance in micro-cylinder groups. To accomplish this, the finite volume method was employed to evaluate the impact of the nanofluids on pressure drop and heat transfer characteristics in the micro-cylinder groups. The study results demonstrate that, for all the nanofluids studied, the pressure drop and friction factor of the micro-cylinder groups increased with increasing Reynolds number. This behavior can be attributed to the interaction between the nanoparticles and the wall, which results in an increase in friction. Furthermore, the Nusselt number was found to increase with increasing Reynolds number. The SiC/Water nanofluid exhibited the highest Nusselt numbers among the four nanofluids tested, indicating that it provides better heat transfer performance than the other nanofluids. These results are consistent with experimental findings, indicating that the numerical simulations were accurate and reliable.

Keywords: *Nanoparticles; Micro-cylinder-group; Heat transfer enhancement; Convection; Laminar regime*
PACS: 02.70.−c, 02.60.Cb, 05.70.−a, 44.15.+a, 44.27.+g, 47.10.A−, 47.11.Df, 47.15.−x, 47.15.Rq, 47.27.Te

INTRODUCTION

The electronics industry is a constantly growing industry worldwide. With the increasing demand for energy-efficient technologies, research in this field has focused on minimizing the heat generated by electronic chips and maximizing their efficiency. Several innovative technologies have been developed to enhance heat transfer, including microchannel cooling technology and nano-technology. Microchannel cooling technology was first introduced by Tuckerman and Pease [1] in an attempt to transfer maximum heat in minimum volume. The technology uses micro-sized channels to circulate cooling fluids close to the heat source, which results in an effective cooling system. In addition to microchannel cooling technology, researchers have explored the use of micro-finned surfaces to improve heat transfer efficiency. Mizunuma et al. [2] conducted experimental and numerical studies to investigate the forced convective heat transfer from a micro-finned surface. They found that micro-finned surfaces can be effective in improving heat transfer performance in microchannels. Overall, the development of innovative technologies such as microchannel cooling and micro-finned surfaces has opened up new possibilities for enhancing heat transfer and improving the energy efficiency of electronic devices. Kosar et al. [3] conducted an experimental investigation on the pressure drops and friction factors associated with the forced flow of de-ionized water over staggered and in-line circular/diamond-shaped micro pin-fin bundles. The study aimed to determine the pressure drops and friction factors in micro pin-fin heat exchangers. In a similar vein, Galvis et al. [4] have studied several models of pin-fin heat exchangers. The results show that the micro pin-fin heat exchanger's thermal performance always exceeded that of the smooth channel and that pin-fin heat exchangers can be highly effective in enhancing heat transfer in electronic cooling systems. Moreover, Ohadi et al. [5] have investigated thermal managements techniques for cooling high-flux electronics. The techniques included immersion cooling, jet impingement, spray cooling, and ultra-thin film evaporation (UTF), which are used primarily for hot spot cooling of the chip. The study aimed to develop effective cooling techniques that can prevent overheating and improve the overall performance of electronic devices. Liu and Guan et al. [6,7] conducted a numerical analysis of the relationship between vortex and temperature distributions in in-line and staggered arranged micro-cylinder groups. They suggested that the end wall effect and the vortex distribution have a significant impact on the thermal performance of micro-cylinder groups. This study aims to improve the understanding of the heat transfer mechanisms in micro-cylinder groups to optimize their thermal performance. In addition, nano-technology has become an important area in the field of heat transfer. Nanofluids are fluids containing nano-scale particles added to a base fluid such as water, ethylene glycol, or oil. They have various applications in microelectronics, fuel cells, heat exchangers, micro-electro-mechanical systems, and pharmaceutical devices. Choi [8] conducted a theoretical examination of the thermal conductivity of a fluid with Cu nanoparticles, which is later referred to as a nanofluid. The study aimed to enhance the understanding of the thermal conductivity of nanofluids, which is crucial for designing efficient heat transfer systems. Furthermore, Abu-Nada et al. [9] carried out a numerical

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study on the natural convection of different nanofluids in horizontal concentric annuli. They found that the addition of nanoparticles to the base fluid leads to higher thermal conductivity and better heat transfer, especially at high Rayleigh numbers. Mohammed et al. [10] performed a numerical study on the flow and heat transfer of an alumina-water nanofluid in a microchannel heat sink. Their results showed that increasing the volume fraction of nanoparticles led to an increase in both heat transfer coefficient and wall shear stress, while the thermal resistance decreased. In another study, Akbani et al. [11] compared single-phase and two-phase models of a nanofluid for turbulent forced convection. They concluded that the single-phase model was more suitable due to its less expensive numerical integration and its simplicity of implementation. Moraveji et al. [12] developed a numerical model of the flow of nanofluids in a mini-channel heat exchanger with TiO_2 and SiC nanoparticles, considering various concentrations. Their study found that heat transfer extended with increasing volume fraction and Reynolds number.

Adriana [13] conducted a numerical analysis of the flow and heat transfer characteristics of water- Al_2O_3 nanofluid in a horizontal tube. They found that the heat transfer coefficient increased by 2.33% to 26.45% compared to pure water and that uncertainties in the properties of the nanofluid have a significant effect on the results. Said et al. [14] investigated the thermal performance of TiO_2-water nanofluid for different mass flow rates and volume fractions. They concluded that an increase in energy efficiency of up to 76.6% was observed for a volume fraction of 0.1% and a flow rate of 0.5 kg/min. In a study by Bouhazza et al. [15], the heat transfer of nanofluids containing Cu and TiO_2 nanoparticles was simulated at various volume fractions. The results revealed that increasing the volume fraction led to enhanced heat transfer and that the Cu-water nanofluid exhibited the best heat conductivity. Dabiri [16] conducted experiments and found that using SiC nanofluid in a circular tube led to an increase of up to 8.88% in the Nusselt number. Bowers [17] experimentally investigated the flow and heat transfer of silica and alumina nanofluids in micro-channels and found that at low volume fractions of both nanofluids, there was an improvement in heat transfer which increased with rising Reynolds number and hydraulic diameter. Goodarzi [18] employed the finite volume method to investigate the natural convection of nanofluids containing Cu, MWCNT, and Al_2O_3 nanoparticles in a two-dimensional closed cavity. The study revealed that the presence of nanofluids led to heat transfer in the cavity with distinct regions of low and high temperatures. On the other hand, Zhang et al. [19] utilized both nanofluid and micro-channel technologies to experimentally investigate the heat transfer of SiC-water nanofluid in micro-cylinder-groups under laminar flow with varying volume fractions and two different arrangements. The results indicated a decrease in the Nusselt number with increasing volume fraction and a heat transfer enhancement factor above 1 for volume fractions of 0.02 and 0.05. Kamini et al. [20] conducted an experimental study on the convective heat transfer of SiC-water nanofluid in a shell and tube heat exchanger. The results showed that the presence of SiC nanoparticles increased heat transfer by 19.8%. Zheng et al. [21] also carried out an experimental investigation on the flow and heat transfer of nanofluids containing Al_2O_3, SiC, Cu, and Fe_3O_4 in water. They found that the Fe_3O_4-water nanofluid had the greatest thermal enhancement, and empirical relations were developed to predict the thermal behavior of nanofluids. Ahmad [22] performed a simulation and experimental analysis on the effect of twisted tape and nanofluids on heat transfer in a circular tube at high Reynolds numbers. Two types of nanofluids (SiC/Water and Al_2O_3/Water) at various volume fractions were used, and the results showed that the heat transfer efficiency was improved by up to 10% with the use of SiC/Water nanofluid. Presently, there has been significant scholarly interest in exploring the flow and heat transfer characteristics of nanofluids in microchannels. Researchers from various fields have conducted investigations to understand how nanofluids behave in different types of microchannels. However, there remains a noticeable gap in the literature regarding the heat transfer behavior of nanofluids in micro-channels that consist of micro-cylinder groups. This specific configuration has received limited attention in research studies thus far. Moreover, the existing studies that have examined the heat transfer phenomena in micro-cylinder groups using nanofluids have primarily relied on experimental approaches [19] rather than numerical simulations or modeling. Furthermore, there is a dearth of conclusive evidence regarding the accuracy and reliability of numerical models in replicating the flow and heat transfer characteristics of nanofluids in micro-cylinder groups. The capability of numerical models to accurately predict the behavior of nanofluids in this particular micro-channel configuration has not been firmly established. As a result, further research and investigation are needed to evaluate and enhance the performance of numerical models in capturing the intricate flow and heat transfer phenomena exhibited by nanofluids in micro-cylinder groups.

In the current study, the four different water-based nanofluids containing SiC, Cu, Al_2O_3, and TiO_2 nanoparticles were simulated numerically to investigate their flow and heat transfer characteristics in the micro-cylinder groups arranged in an inline configuration. The simulations were conducted under laminar flow conditions, with low Reynolds numbers. The volume fraction of the nanoparticles was set to 0.02. This work also examines the agreement between the experimental and numerical results and the ability of these simulations to reproduce the physical phenomena acting in this geometry in the presence of nanofluids. Conducting this research will also help to provide prime predictions on the potential applications of these different nanofluids in such heat transfer systems. The effects of the nanoparticles on the flow and heat transfer characteristics, such as velocity profiles, temperature distributions, and heat transfer coefficients, were analyzed and compared to those of pure water.

PHYSICAL MODEL AND MATHEMATICAL FORMULATION

The physical domain of the micro-cylinder groups is shown in Figure (1). It consists of thirty circular cylinders arranged in line, placed in a micro-channel filled with four different water-based nanofluids in a laminar flow regime. The dimensions of the micro-cylinder-groups, including the diameter of the micro-cylinders (d), the length and width of the micro-channel (L and W, respectively), and the height of the micro-cylinders (M), are presented in Table 1. To analyze the forced convection of the nanofluids, the continuity, momentum, and energy equations were solved using both the single-phase approach and the two-phase mixture approaches.

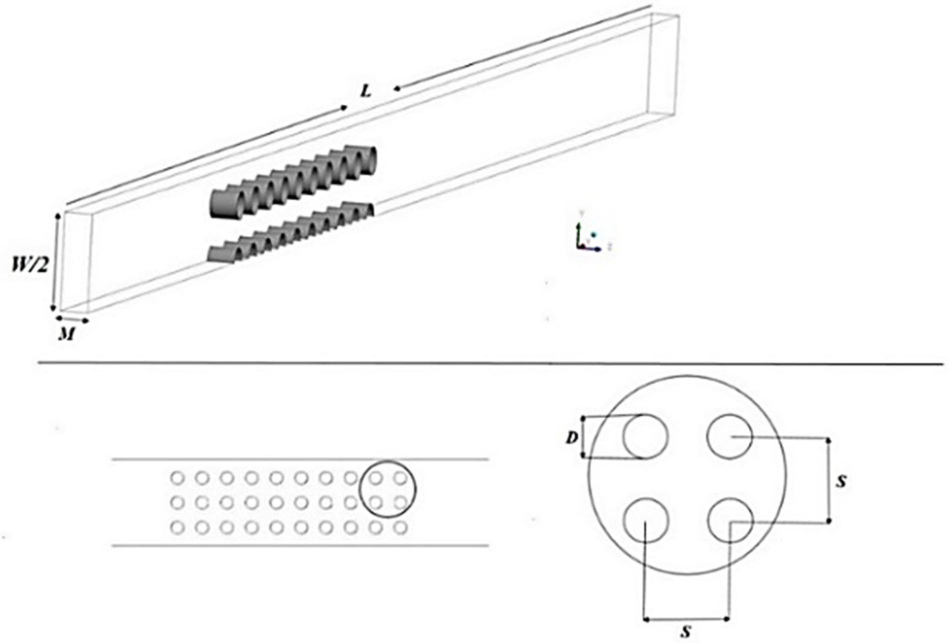

Figure 1. The physical domain of the micro-cylinder-group

Table 1. Detailed dimensions of the micro-cylinder-groups

d(mm)	*S/d*	*N*	*M(mm)*	*L(mm)*
0.5	2	10	0.5	40

Single Phase Approach

The single-phase approach is a modeling approach that treats nanofluids as a single homogeneous liquid with effective thermophysical properties. In this approach, the continuity, momentum, and energy equations are solved for the nanofluid as a single-phase fluid. The effective properties of the nanofluid are obtained by using the volume fraction of nanoparticles and the properties of the base fluid. The equations are:

Continuity:

$$\nabla.(\rho\vec{V}) = 0 \tag{1}$$

Momentum:

$$\nabla.(\rho\vec{V}\vec{V}) = -\nabla.P + \nabla.(\mu\nabla.\vec{V}) + \rho g \tag{2}$$

Energy equation:

$$\nabla.(\rho\vec{V}H) = -\nabla.\mathrm{q} - \tau : \nabla.\vec{\mathrm{V}} \tag{3}$$

Reynolds number

$$\mathrm{Re} = \frac{\rho_{nf} U_{\max} d}{\mu_{nf}} \tag{4}$$

In order to solve the above equations, accurate effective thermo-physical properties must be involved. The literature contains various models allowing us to theoretically calculate the nanofluid's hydrothermal properties. The expressions used to define these properties used in this work are: for the homogeneous single-phase model with constant properties, density and heat capacity of nanofluid, are estimated by using classical models [23,24,25] as follows:

Density:

$$\rho_{nf} = (1-\varphi)(\rho Cp)_f + \varphi(\rho Cp)_p \tag{5}$$

Specific heat:

$$(\rho Cp)_{nf} = (1-\varphi)(\rho Cp)_f + \varphi(\rho Cp)_p \tag{6}$$

Thermal expansion coefficient:

$$(\rho\beta)_{nf} = (1-\varphi)(\rho\beta)_f + \varphi(\rho\beta)_p \tag{7}$$

Dynamic viscosity (Brinkman [26]):

$$\mu_{nf} = \frac{\mu_f}{(1-\varphi)^{2.5}} \tag{8}$$

On the other hand, nanofluid thermal conductivity is determined by the correlation reported by Maxwell [27]

Thermal conductivity (Maxwell [27]):

$$\frac{k_{nf}}{k_f} = \frac{(1-\varphi)(k_p+2k_f)+3\varphi k_p}{(1-\varphi)(k_p+2k_f)+3\varphi k_f} \tag{9}$$

Table 2. Thermo-physical properties of water and nanoparticles **[28], [29], [30], [31]**

Thermo-physical properties	*Density (Kg/m^3)*	*Specific heat*	*Thermal conductivity*
Water	997	4179	0.673
Al2O3	3970	765	40
Cu	8933	385	401
TiO2	4250	686.2	8.4
SiC	3160	723	490

Mixture Two-Phase Approach

The mixture model considers the nanofluid as a two-phase fluid where water is considered as the continuous liquid first phase while the nanoparticles as the dispersed solid secondary phase. The continuity, momentum, and energy equations are solved for the mixture at the same time an additional equation: the mass conservation equation or volume fraction equation is solved only for the second phase.

Continuity equation for the mixture:

$$\nabla.(\rho_m \vec{V}_m) = 0 \tag{10}$$

Momentum equation of the mixture:

$$\nabla.\left(\rho_m \vec{V}_m \vec{V}_m\right) = -\nabla.P_m + \nabla.\left(\mu_m \nabla.\vec{V}_m + \sum_{k=1}^{n} \varphi_k \rho \overline{v_k v_k}\right) + \rho_m g + \nabla.\left(\sum_{k=1}^{n} \varphi_k \rho_k V_{dr,k} \vec{V}_{dr,k}\right) \tag{11}$$

Energy equation of the mixture:

$$\nabla.(\sum_{k=1}^{n} \varphi_k \rho_k \vec{V}_k H_k) = -\nabla.q_m - \tau : \nabla \vec{V}_m \tag{12}$$

Volume fraction equation of the secondary phase:

$$\nabla.\left(\varphi_p \rho_p \vec{V}_m\right) = -\nabla.\left(\varphi_p \rho_p \vec{V}_{dr,p}\right) \tag{13}$$

The mixture velocity, density and viscosity are:

$$\vec{V}_m = \frac{\sum_{k=1}^{n} \varphi_k \rho_k \vec{V}_k}{\rho_m} \tag{14}$$

$$\rho_m = \sum_{k=1}^{n} \varphi_k \rho_k \tag{15}$$

$$\mu_m = \sum_{k=1}^{n} \varphi_k \mu_k \tag{16}$$

The kth phase's drift velocity is:

$$\vec{V}_{dr,k} = \vec{V}_k - \vec{V}_m \tag{17}$$

Where φ_k is the volume fraction of the phase k.

The formulation of friction factor is given by:

$$f = \frac{2H\Delta p}{L\rho U^2_{\max}} \tag{18}$$

Nusselt number:

$$Nu = \frac{hD}{\mu_{nf}} \tag{19}$$

Convective heat transfer coefficient:

$$h = \frac{Q}{\Delta T} \tag{20}$$

Thermal enhancement factor:

$$TEF = \frac{Nu_{nf} / Nu_f}{\left(f_{nf} / f_f\right)^{1/3}} \tag{21}$$

Boundary conditions

The physical problem's boundary conditions consist of various components, such as adiabatic walls, heating walls, a velocity inlet, a fully developed outlet, and a symmetry plane as presented in Figure (2). These components are crucial for the analysis of the flow and heat transfer of the nanofluids within the micro-cylinder groups.

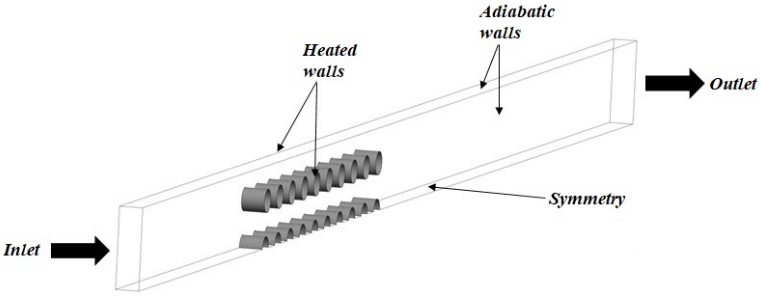

Figure 2. Boundary conditions

Heated walls: $u, v, w_{wall-h} = 0, \frac{\partial T}{\partial \vec{n}}_{wall-h} = q$.

Adiabatic walls: $u, v, w_{wall-ad} = 0, \frac{\partial T}{\partial \vec{n}}_{wall-ad} = 0$.

Inlet: $u = u_{in,}, v, w = 0, T_{in} = 293.15K$.

Outlet: $\frac{\partial u}{\partial x}_{out} = 0, \frac{\partial v}{\partial y}_{out} = 0, \frac{\partial w}{\partial z}_{out} = 0, \frac{\partial T}{\partial \vec{n}}_{out} = 0$.

Symmetry: $\frac{\partial u}{\partial x}_{sym} = 0, \frac{\partial v}{\partial y}_{sym} = 0, \frac{\partial w}{\partial z}_{sym} = 0, \frac{\partial T}{\partial \vec{n}}_{sym} = 0$.

The resolution of the equations cited above allowed the analysis of the variations in the pressure drops, the Nusselt numbers as well as the temperature distributions, and their influence on the thermal performance of the nanofluids.

MESH AND VALIDATION

The simulation considers the flow to be three-dimensional, and a 3D hexahedral mesh is generated based on half of the physical model, taking into account the structural symmetry of the micro-cylinder groups. Preliminary calculations are carried out to evaluate the mesh sensitivity, and three meshes (800000, 1700000, and 2300000) are employed. Table 3 summarizes the sensitivity measures, which are the obtained values of the average Nusselt numbers and the pressure drop. The deviation of the pressure drops and Nusselt number among the three different grids is less than 0.6% and 2.5%, respectively. Consequently, the mesh containing 1700000 elements is deemed satisfactory for the simulation of flow and heat transfer characteristics.

Table 3. Comparison of average Nusselt number and pressure drop among different grids tested for **Re = 236**

Grid	Nusselt number	Err %	Pressure drop	Err %
Grid 1 (800000)	9,7574037		1221,7252	
Grid 2 (1700000)	10,00619	2,486323965	1215,6107	0,500480796
Grid 3 (2300000)	10,04324	0,368904855	1215,2634	0,028578167

In order to validate the numerical predictions with the experimental results **[19],** both single phase approach and mixture two phase approach were employed.

Figures (3) and (4) provide a comparison between the experimental and numerical results obtained through both approaches for the pressure drop and Nusselt number. As indicated in Figure (3), the three graphs have consistent trends. However, at low Reynolds numbers, the mixture two-phase model yielded results that were closer to the experimental findings. In contrast, at higher Reynolds numbers, the single-phase model was more accurate. Figure (4) shows that the mixture approach overestimated the Nusselt number, while the single-phase approach produced results that were close to the experimental findings. These comparisons provide validation for the numerical model proposed in this study and demonstrate its accuracy.

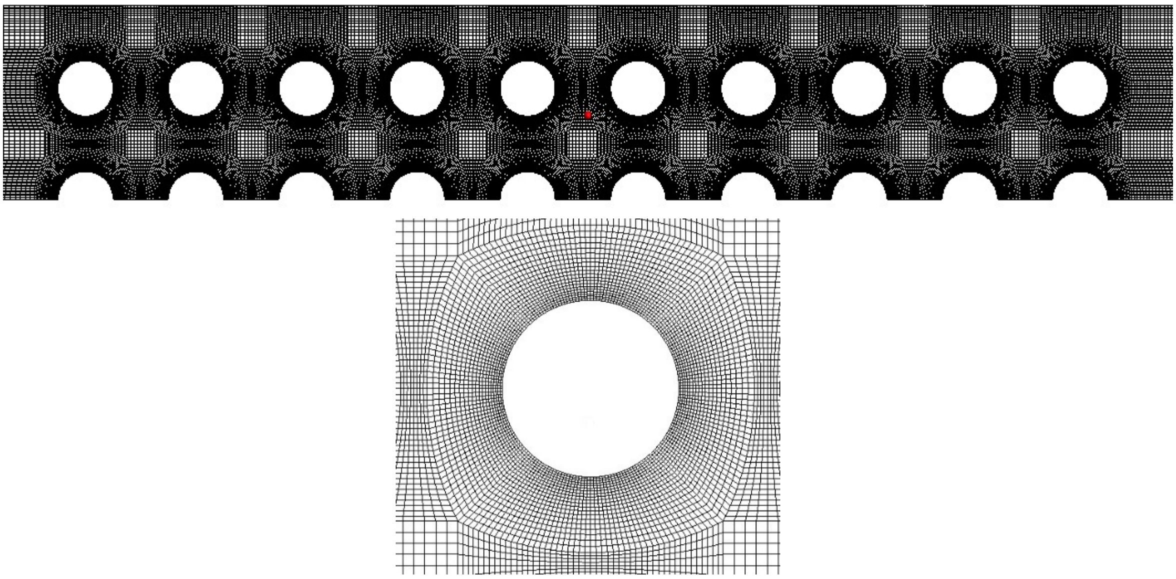

Figure 3. View of the grid distribution of the physical domain

NUMERICAL METHODS

To solve the governing equations that describe the flow and heat transfer characteristics in the micro-cylinder groups, the finite volume method was used. This method involves dividing the computational domain into a grid of discrete cells and evaluating the variables at specific locations within each cell. The differential equations were then converted to algebraic equations that can be solved numerically. By resolving these equations, it was possible to analyze the influence of the nanoparticles on the pressure drop, heat transfer, and efficiency of the system. The resolution of the equations was carried out using the second-order upwind scheme, which is a numerical scheme commonly used for the discretization of the energy and momentum equations. The coupling between the pressure and velocity fields was achieved using the SIMPLE algorithm, which is a well-established approach for solving the Navier-Stokes equations in computational fluid dynamics. To ensure the accuracy and reliability of the numerical simulations, a convergence criterion of 10^{-6} was used for all computations. This criterion ensures that the solution has converged to a stable and consistent solution. With these numerical tools and techniques, it was possible to gain insights into the flow and heat transfer characteristics of the micro-cylinder groups and understand how the nanoparticles affect these characteristics.

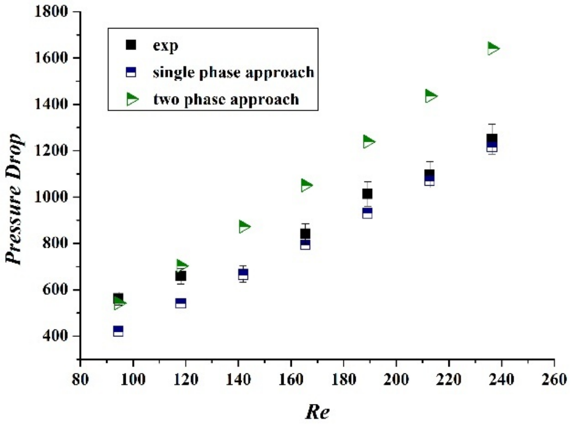

Figure 4. Comparison of pressure drop variation

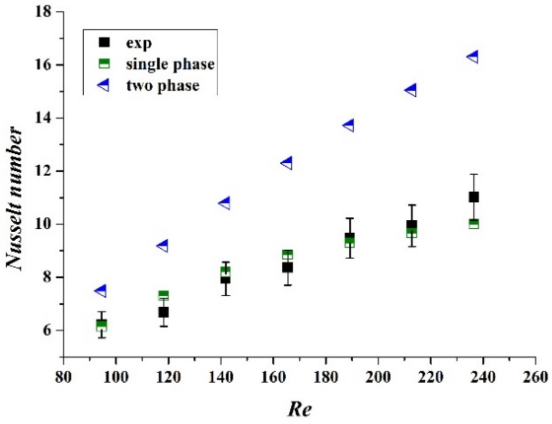

Figure 5. Comparison of Nusselt number variation

RESULTS AND DISCUSSION

In this study, the thermal performance of four different water-based nanofluids in micro-cylinder groups was numerically analyzed to assess the enhancement of heat transfer. The simulations were performed in a laminar regime with Reynolds numbers below 300 and a volume concentration of 2%. Figure 6 depicts the variation of pressure drop for each nanofluid. It can be observed that the pressure drop increases with increasing Reynolds number, and this is primarily attributed to the increase in velocity. In this micro-flow, the boundary layer between the micro-cylinders is thin, and the presence of solid particles disturbs this layer, exacerbating the pressure drop. The presence of nanoparticles in the nanofluids has a significant effect on the pressure drop, and this effect increases with increasing Reynolds number.

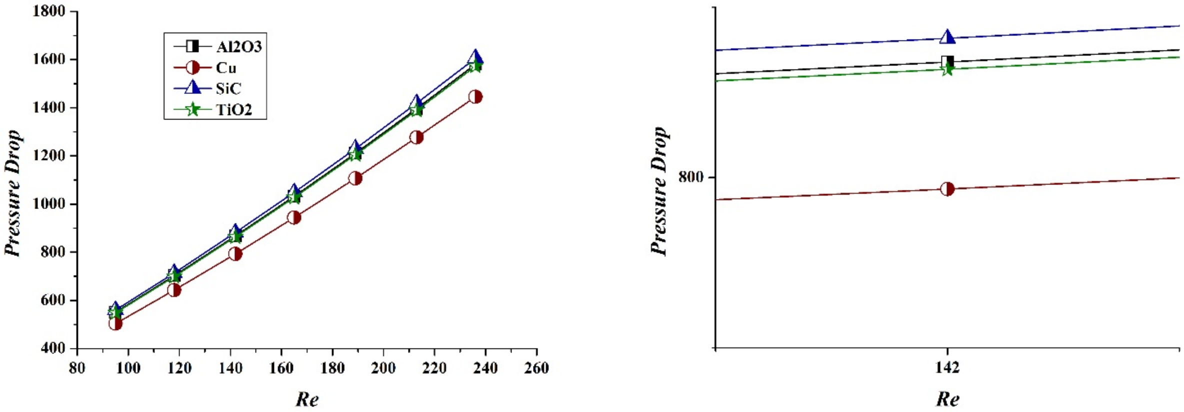

Figure 6. variation of pressure drops

In Figure 7, the velocity fields of SiC/water nanofluid at a specific location (z=0.25 mm) along the x-direction are depicted for two different Reynolds numbers, namely a low and a high value. Upon analysis, it becomes apparent that there are two distinct regions of intensified velocity located in the upper section of the geometry, positioned between the two columns of micro-cylinders. With an increase in the Reynolds number, these high-speed regions not only expand in size but also exhibit an augmentation in the maximum velocity magnitude within those areas. This observation suggests that the flow behavior and characteristics are strongly influenced by the Reynolds number. The occurrence of these high-speed narrow regions can be attributed to multiple factors. Firstly, viscous forces play a significant role in shaping the flow patterns. The presence of the micro-cylinders causes the fluid to experience changes in momentum, resulting in localized regions with elevated velocities. These regions are confined and exhibit a narrow shape due to the influence of the micro-cylinder geometry. Secondly, the superposition of velocity fields contributes to the formation of these high-speed regions. As the fluid flows past the micro-cylinders, the velocity fields from different regions combine, leading to regions of accelerated flow. It is important to note that the expansion and intensification of these high-speed regions are directly associated with the Reynolds number. As the Reynolds number increases, the impact of viscous forces and the superposition of velocity fields become more pronounced, resulting in larger and more energetic high-speed regions. In summary, the appearance of the two high-speed narrow regions in the upper part of the geometry, positioned between the micro-cylinders, can be attributed to the interplay between viscous forces and the superposition of velocity fields. These regions expand and exhibit higher velocities with increasing Reynolds numbers, indicating the significant influence of fluid dynamics on the flow behavior within micro-channel configurations.

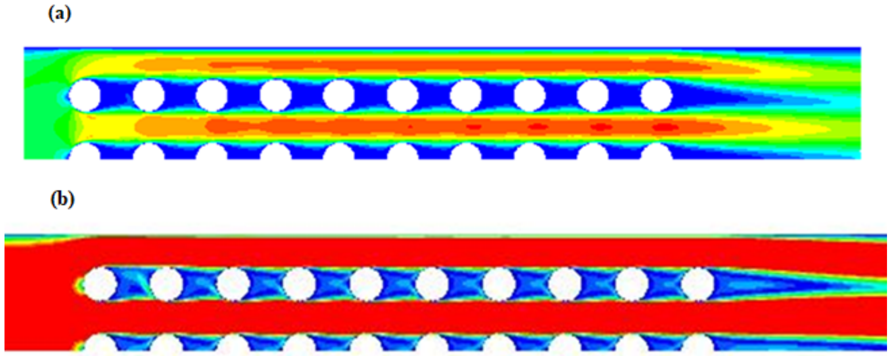

Figure 7. Velocity fields (a) Re= 94, (b) Re=212

Furthermore, Figure 8 displays the variation of Nusselt number for the nanofluids studied, with a heat flux of 15 W/cm2 and under laminar flow conditions. All the graphs show a consistent trend in which the Nusselt number increases with the rise of Reynolds number. This increase in Nusselt number is an indication of enhanced heat transfer, which is produced by the disturbance or separation of the boundary layer caused by the increasing velocity. The presence of nanoparticles in the nanofluids has a significant effect on the improvement and increase of thermal conductivity, which in turn enhances the heat transfer.

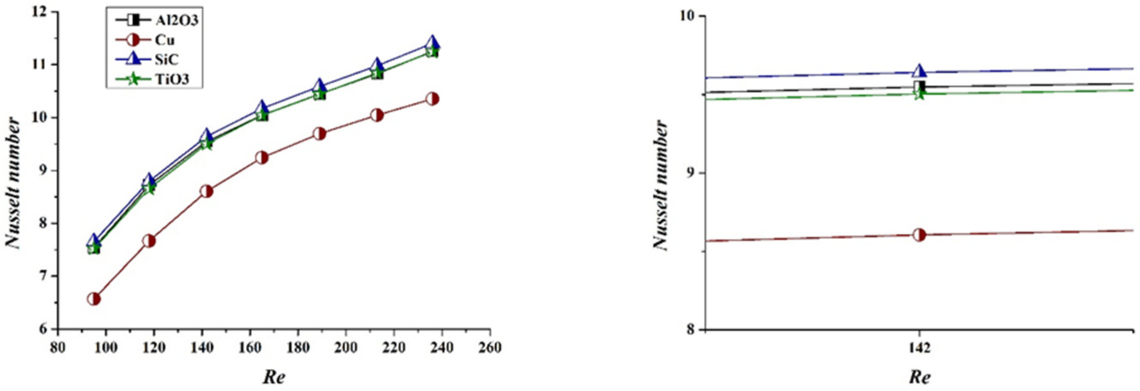

Figure 8. Variation of Nusselt Number

Figure 9 shows the temperature distributions of SiC/water nanofluid for two different Reynolds numbers: a low Reynolds number of 94 and a high Reynolds number of 212. The analysis reveals that there is a prominent low-temperature region upstream of the micro-cylinders. This behavior is due to an increased heat transfer resulting from the separation of the boundary layer in this region. Conversely, in the downstream region of each micro-cylinder, there is a decrease in the heat transfer coefficient, leading to a high-temperature region. These regions become larger with an increase in the Reynolds number, thereby significantly impacting the overall temperature distribution of the system.

It's worth noting that the temperature downstream of the micro-cylinder is higher than the temperature upstream, which is in agreement with the theory of boundary layer flow. The separation of the boundary layer creates a wake vortex downstream of the micro-cylinder, which leads to a decrease in flow velocity and, consequently, an increase in temperature. The present analysis of temperature distributions for different Reynolds numbers provides valuable insights into the flow dynamics and heat transfer in this complex system.

The thermal enhancement factor is a key parameter that measures the relative effectiveness of nanofluids compared to the base fluid. It is defined as the ratio of the heat transfer coefficient and friction factor of the nanofluid to those of the base fluid. When this factor is above 1, the nanofluid is considered to be effective, which means that the growth of heat transfer is greater than the loss of pressure drops. This factor is an essential tool used in this study to evaluate the thermal efficiency of nanofluids inside micro-cylinder groups. It provides insights into the performance of nanofluids in terms of heat transfer and fluid flow. Furthermore, it offers a useful means of comparing the thermal performance of different nanofluids and identifying the most effective nanofluid for a specific application.

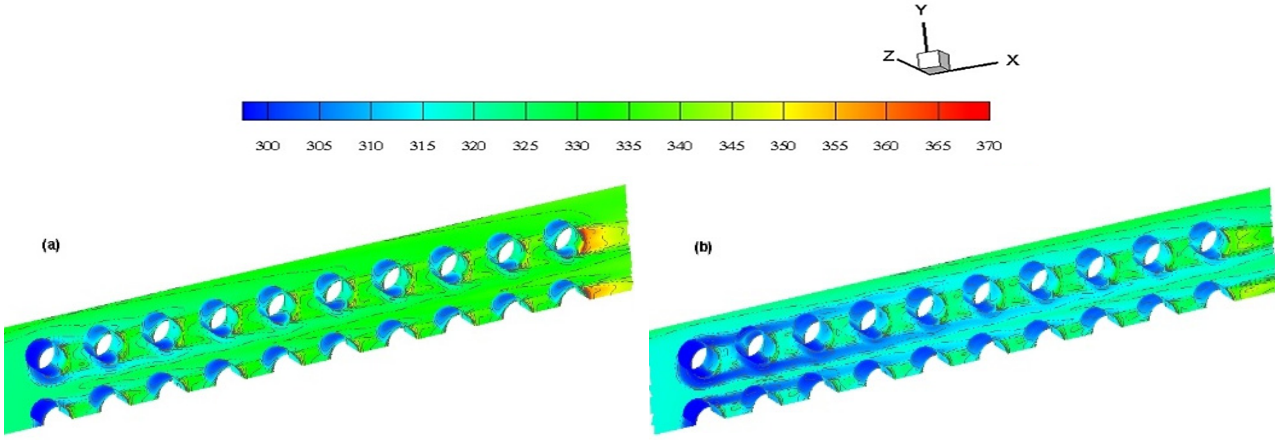

Figure 9. Temperature distributions at **(a)** Re=94 and **(b)** Re=212

Figure 10 depicts the variation of thermal enhancement factor with the Reynolds number for various nanofluids containing metallic oxide nanoparticles. The graph reveals a positive correlation between the Reynolds number and the thermal enhancement factor, suggesting an increase in heat transfer performance with an increase in Reynolds number. However, the nanofluids containing metallic oxide nanoparticles exhibit better performance under specific conditions, including geometry, volume fraction, and Reynolds number. In these conditions, the presence of metallic oxide nanoparticles can improve heat transfer, resulting in a thermal enhancement factor greater than 1 for SiC nanoparticles. Nevertheless, in general, the introduction of metallic oxide nanoparticles does not have a positive impact on heat transfer, as indicated by thermal enhancement factors below 1. These findings indicate the need for further investigations to explore the influence of various parameters on the heat transfer performance of nanofluids. The parameters to be considered in such studies include particle size, shape, and concentration, among others. An in-depth understanding of the effect of these parameters on the performance of nanofluids could lead to the development of optimized nanofluid formulations for various engineering applications.

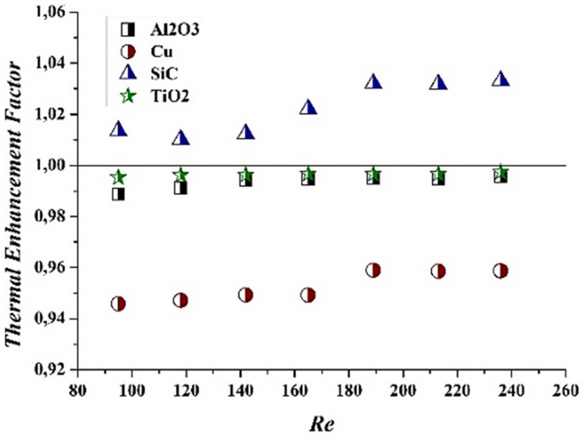

Figure 10. variation of the Thermal Enhancement Factor

CONCLUSIONS

The objective of this research was to examine the heat transfer and flow properties of four types of nanofluids in micro-cylinder groups operating under laminar conditions and a volume fraction of 0.02.

In order to validate the new numerical findings, a comparison was made between the results obtained in this study and the experimental data from a previous work conducted by Zhang et al. [19]. Remarkably, the two sets of results exhibited strong agreement, further corroborating the validity and accuracy of the numerical findings in this study.

- The obtained results clearly indicate that an elevation in Reynolds number corresponds to amplified values of both pressures drop and Nusselt number. This observation can be attributed to the escalating disturbance of the boundary layer as the Reynolds number increases.
- Under the specific conditions considered, the SiC/water nanofluid demonstrated the highest Nusselt number among the Cu, Al2O3, and TiO2 nanofluids. The SiC/water nanofluid exhibited superior heat transfer performance compared to the other nanofluids in terms of convective heat transfer efficiency.
- The increased viscosity of nanofluids compared to the base fluid can limit their effectiveness in certain applications. However, an analysis of the thermal enhancement variation reveals that only SiC nanofluids, at the specific concentration studied, exhibit significant and effective performance with thermal enhancement factors exceeding 1.

Further study into this issue is still required in order to check the enhancement of the heat transfer processes in such geometries. A more detailed research effort that will consider different factors, such as volume fraction and micro-cylinder arrangements, to expand our understanding of the flow and heat transfer properties of nanofluids.

List of abbreviations

Re	Reynolds number
d	Micro-cylinders diameter (mm)
S	Space between micro-cylinders (mm)
N	Micro-cylinders column number
M	Microchannel height (mm)
L	Microchannel length (mm)
V	Velocity (m s^{-1})
P	Pressure (pa)
g	Gravity (m s^{-2})
Q, q	Heat flux (W m^{-2})
H	Entropy (J k^{-1})
U	X velocity (m s^{-1})
Cp	Specific heat (j kg^{-1} k^{-1})
k	Thermal conductivity (W m^{-1} k^{-1})
Nu	Nusselt number
f	Friction factor
h	Convective heat transfer coefficient
T	Temperature (k)
TEF	Thermal enhancement factor

Greek letters

ρ	Density (kg m-3)
μ	Dynamic viscosity (N s m-2)
τ	Stress tensor (N m-2)
φ	Volume fraction
β	Thermal expansion factor (k)

Subscripts

Nf	Nanofluid
Max	maximum
F	fluid
P	particle
M	mixture
N	Nth phase
K	Kth phase
dr	Drift
Wall-h	Heated wall
Wall-ad	Adiabatic wall
In	Inlet
out	Outlet
sym	symmetry

Declarations

Availability of data and materials. The data acquired and/or evaluated during the present research are accessible upon valid request from the corresponding author.

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Authors' contributions.
Lina Wafaa Belhadj Senini: conceived of the presented idea, developed the theory and performed the computations and contributed to the final version of the manuscript. **Mustapha Boussoufi**: performed the analytic calculations and the numerical simulations. **Amina Sabeur**: developed the theoretical formalism, discussed the results, and contributed to the final manuscript

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АНАЛІЗ ХАРАКТЕРИСТИК ТЕПЛООБМІНУ НАНОРІДИН В МІКРОЦИЛІНДРИЧНИХ ГРУПАХ

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Мета цього дослідження полягає в дослідженні за допомогою чисельного моделювання характеристик потоку та теплопередачі нанофлюїдів на водній основі Al_2O_3, Cu, TiO_2 та SiC, що протікають через групи мікроциліндрів, розташовані в рядній конфігурації. Моделювання проводилося в умовах ламінарного потоку, і аналіз враховував сім різних низьких значень числа Рейнольдса з постійною об'ємною часткою 2%. Метою цього дослідження було визначити, як нанофлюїди, тобто суспензії наночастинок у воді як базовій рідині, можуть впливати на перепад тиску та тепловіддачу в групах мікроциліндрів. Щоб досягти цього, був застосований метод кінцевого об'єму для оцінки впливу нанофлюїдів на перепад тиску та характеристики теплообміну в групах мікроциліндрів. Результати дослідження демонструють, що для всіх досліджуваних нанофлюїдів перепад тиску та коефіцієнт тертя груп мікроциліндрів зростали зі збільшенням числа Рейнольдса. Таку поведінку можна пояснити взаємодією між наночастинками та стінкою, що призводить до збільшення тертя. Крім того, було виявлено, що число Нуссельта зростає зі збільшенням числа Рейнольдса. Нанорідина SiC/вода продемонструвала найвищі числа Нуссельта серед чотирьох протестованих нанорідини, що вказує на те, що вона забезпечує кращі показники теплопередачі, ніж інші нанорідини. Ці результати узгоджуються з експериментальними висновками, вказуючи на те, що чисельне моделювання було точним і надійним.

Ключові слова: *наночастинки; мікроциліндрична група; посилення тепловіддачі; конвекція; ламінарний режим*