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Numerical investigation of heat transfer performance in laminar flow of nanofluids in the wavy micro-channel

Dalgalı mikrokanalda nanoakışkanların laminer akışta ısı transfer performansının sayısal olarak incelenmesi

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Numerical Investigation of Heat Transfer Performance in Laminar Flow of Nanofluids in the Wavy Micro-Channel

Highlights

- *Nanofluids' heat transfer performance has been investigated in a wavy microchannel.*
- *Theoretical and computational fluid dynamics solutions have been compared.*
- *The heat transfer performance increased by percentage volumetric nanoparticle ratio.*

Graphical Abstract

Thermal conductivity efficiency and convective heat transfer coefficient based on nanoparticle percent volumetric ratio.

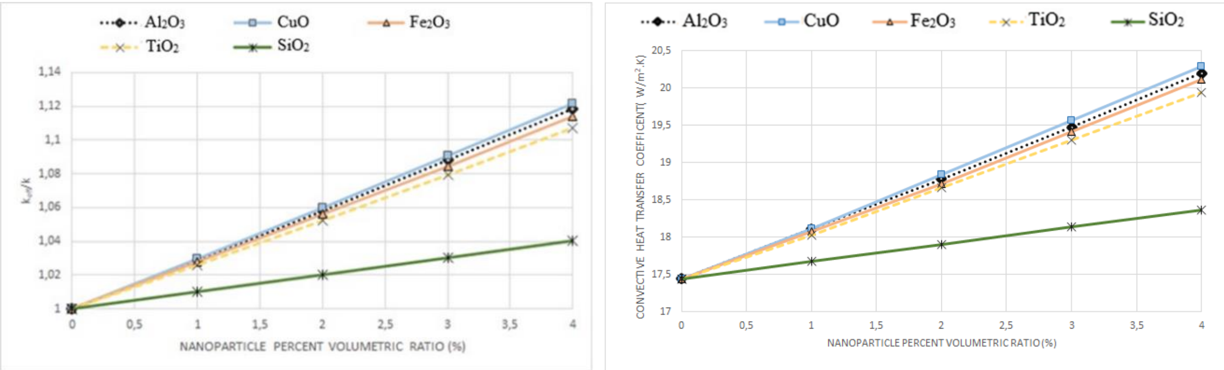

Figure. Thermal conductivity efficiency and convective heat transfer coefficient based on nanoparticle percent volumetric ratio

Aim

The study aims to increase the heat transfer performance of nanofluids in a wavy microchannel.

Design & Methodology

In our study, the heat transfer performance of nanofluids has been compared with both computational fluid dynamics (CFD) and theoretical calculations.

Originality

The thermal performance of five different nanoparticles in a wavy microchannel has been investigated. Thus, We understood which nanoparticle is more thermally efficient at the same Reynolds numbers.

Findings

In theoretical calculations, the highest increase in heat transfer amount has been observed at 0.04% SiO_2 volumetric rate in 100 Reynolds number and this increase is 16.26%. In computational fluid dynamics, two different nanofluids have the highest heat transfer amount. These nanofluids are 17.33% increase for 0.04% Al_2O_3 and 17.32% for 0.04% SiO_2 at 100 Reynolds value.

Conclusion

It observed that the heat transfer performance increased thanks to the increasing Reynolds number and the increasing percentage volumetric nanoparticle ratio.

Declaration of Ethical Standards

The author(s) of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

Dalgalı Mikrokanalda Nanoakışkanların Laminer Akışta Isı Transfer Performansının Sayısal Olarak İncelenmesi

Araştırma Makalesi / Research Article

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ÖZ

Çalışmada, teorik analiz ve hesaplamalı akışkanlar dinamiği kullanılarak dalgalı mikrokanalda nanoakışkanların ısı transfer performansı araştırılmıştır. Al_2O_3, CuO, Fe_2O_3, TiO_2 ve SiO_2 nanopartikül olarak hesaplamalarda kullanılmıştır. Nanopartiküllerin nanoakışkan içerisindeki hacimsel oranı sırasıyla 1%, 2%, 3% ve 4% şeklindedir. Nanoakışkanların 100, 250, 500 ve 1000 Reynolds sayısında çıkış sıcaklıkları, Nusselt sayısı, termal iletkenlik verimliliği ve termal taşınım katsayıları incelenmiştir. Artan Reynolds sayısı ve artan hacimsel nanoparçacık oranı sayesinde ısı transfer performansının arttığı gözlemlenmiştir.

Anahtar Kelimeler: Dalgalı mikrokanal, nanoakışkan, ısı transferi.

Numerical Investigation of Heat Transfer Performance in Laminar Flow of Nanofluids in the Wavy Micro-Channel

ABSTRACT

Our study has been investigated nanofluids' heat transfer performance in a wavy microchannel using theoretical and computational fluid dynamics. Al_2O_3, CuO, Fe_2O_3, TiO_2 and SiO_2 have been used in the calculations as nanoparticles. Volumetric nanoparticle ratios in the nanofluid are 1%, 2%, 3% and 4%. Outlet temperatures, Nusselt number, thermal conductivity efficency and convective heat transfer coefficients of nanofluids at 100, 250, 500 and 1000 Reynolds numbers have been investigated. It observed that the heat transfer performance increased thanks to the increasing Reynolds number and the increasing percentage volumetric nanoparticle ratio.

Keywords: Wavy micro-channel, nanofluid, heat transfer.

1. INTRODUCTION

With the development of microelectronic technology, the use of chips in power electronics devices and the current-voltage capacity are increasing, and therefore high heat fluxes such as 100 W/cm^2 occur. Since conventional cooling systems will be insufficient for such devices, it is aimed to develop new cooling methods with high heat dissipation capacities [1]. When conventional cooling systems and microchannel systems are compared, it has been stated that microchannel heat sinks can be used for high power density microelectronic devices due to their benefits such as less coolant necessity, compact structure and high heat removal capacity [2-4].

The first study on the micro-channel has designed by Tuckerman and Pease [2] to cool very large-scale integration applications. They have developed a water-cooled integrated heat sink for silicon integrated circuits. In conclusion, the cooler they designed greatly improved the applicability of ultra-high-speed, very large-scale integration circuits at high power densities. In this way, they have developed this device that plays a significant role in heat transfer.

In Table 1, the classification of channel types according to their hydraulic diameters has been specified. Although the criteria developed for gas flow, it is suitable for both liquid and two-phasis fluids. The Channels in the range of 10-200 µm are defined as micro-channels in Table 1 [5].

Table 1. Classification of channel types according to hydraulic diameter (D_h) size [5]

Channel Type	**Hydraulic Diameter (D_h)**
Micro-channels	200 µm≥ D_h>10 µm

Vinoth and Kumar [6] have chosen semicircular trapezoidal square as geometry in their study on micro-channels. Compared with different geometric structures, they found the highest heat transfer in the micro-channel with trapezoidal geometry. In the trapezoidal microchannel, an increase in the Nusselt number is 8.54% and 26.4%, and the amount of heat transfer is

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3.13% and 5.87%, respectively, compared to the square and semicircular micro-channel. The flow regime is laminar. Water is the base fluid, and the nanoparticle is Al_2O_3. Nanoparticle concentration has been selected as 0-0.25% and the maximum increase in heat transfer is 4.6%.

Tran et al. [7], have studied laminar flow in the trapezoidal micro-channel. The base fluid is water, and nanoparticle materials have been selected Al_2O_3 and TiO_2. Nanoparticle diameters are 5 nm for both materials. Nanoparticle concentration is 0.1-1%, and the increase in maximum heat transfer has been 36.6%.

Kalteh et al. [8] have studied laminar flow in a rectangular microchannel. The flow regime is laminar, and Reynolds number 200-1000 has been chosen. Water is the base fluid and Al_2O_3 with a diameter of 40 nm has been used as the nanoparticle. The nanoparticle concentration has been chosen as 0.1-0.2%, and the maximum increase in heat transfer has been observed as 130%. They have stated that the two-phase method gives more accurate results instead of homogeneous calculations. At the same time, the two-phase method results have shown that the temperature and velocity differences between phases are very small and negligible. It has been observed that the Nusselt number increased with increasing Reynolds number and volume concentration.

Azizi et al. [9] have chosen a cylindrical micro-channel as geometry in their study. The flow regime is laminar. Water is the base fluid, and the nanoparticle is CuO. Nanoparticle size is 25 nm, and it has been chosen as 0.05-0.3% by weight. An increase of 23% has been observed in heat transfer.

Duangthongsuk and Wongwises [10] have preferred micro-channel with zig-zag geometry in their study. Flow regime has been chosen turbulence, and Reynolds number is 2500-8000. De-ionized water is the base fluid, and 15 nm SiO_2 has been used as the nanoparticle. The nanoparticle concentration is 0.3-0.8%, and the increase in the heat transfer amount is 15%. They have observed that as the flow rate has increased, the pressure drop in the flow has increased. However, as the particle concentration increased, a slight increase in pressure drop has observed.

Yu et al. [11] have studied the rectangular micro-channel as geometry in their work. The flow regime is laminar. Water is the base fluid, and the nanoparticle is TiO_2. The nanoparticle has been chosen as 0.005-0.01% by weight and the maximum increase in heat transfer is 91.9%.

Thansekhar and Anbumeenakshi [12] have selected a rectangular micro-channel in their study. Flow is laminar, water as the base fluid and CuO, SiO_2 nanoparticles with 43 nm diameter have been used. Nanoparticle concentration is 0.1-0.25%, and the maximum increase in heat transfer has been found to be 32.8%. Better heat transfer increase has been detected in nanofluids with higher volume concentrations.

Table 2. The density, specific heat and thermal conductivity coefficient values of the nanofluids used in the calculations [13-15]

MATERIALS	Density (kg/m^3)	Specific Heat (J/kg.K)	Thermal Conductivity (W/m.K)
Water (293.15K)	998.2	4182	0.6
Al_2O_3	3960	850	35
CuO	6400	531	76.5
Fe_2O_3	5250	650	20
TiO_2	4050	697	11.8
SiO_2	2220	745	1.5

In our study, the density, specific heat and thermal conductivity values specified in Table 2 have been used in the calculations. Al_2O_3, CuO, Fe_2O_3, TiO_2 and SiO_2 have been used in the calculations in volumetric ratios specified as nanoparticles. Volumetric nanoparticle ratios in the nanofluid are 1%, 2%, 3% and 4%. Since the surface area to volume ratio of nanoparticles is high, it has been stated that the surface energies are also high. The energy caused by the surface tensions will cause agglomeration and make it challenging to mix homogeneously with the base fluid. For this reason, the nanoparticle values in the nanofluid have been chosen between 0-4%. A constant heat flux of 100000 W/m^2 has been applied throughout the micro-channel. The outlet temperatures, thermal conductivity efficiency and convective heat transfer coefficients of nanofluids at 100, 250, 500 and 1000 Reynolds numbers have been compared. The thermal performance of five different nanoparticles in a wavy microchannel has been investigated. Thus, we understood which nanoparticle is more thermally efficient at the same Reynolds numbers.

2. MATERIALS AND METHODS

2.1. Geometry of the Wavy Micro-channel

The technical drawing of the wavy microchannel is shown in Figure 1. The total length of the channel is 9.8 mm and the diameter of the channel is 150 μm. The inner radius of the wavy channel is 0.63 mm and the outer radius is 0.78 mm. A constant heat flux of 100000 W/m^2 has been applied along the channel.

2.2. Theoretical Analysis

In Maxwell's study, the effective thermal conductivity of a homogeneous suspension is expressed in Equation 1 [16].

$$k_{Maxwell} = \frac{k_p + 2k_l + 2(k_p - k_l)\varphi}{k_p + 2k_l - 2(k_p - k_l)\varphi} k_l \qquad (1)$$

k_p is the thermal conductivity of the particles, k_l is the thermal conductivity of the liquid, and φ is the volumetric fraction of the particles in the base fluid [17].

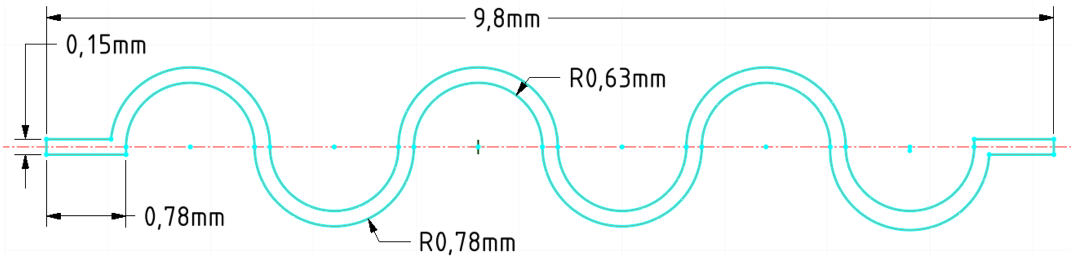

Figure 1. Technical drawing of the wavy micro-channel used in calculations

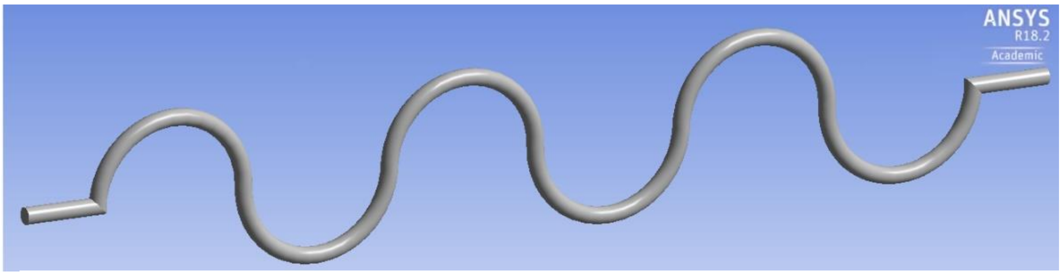

Figure 2. Three-dimensional view of the wavy micro-channel

Yu and Choi recommend Equation 2 by modifying Maxwell's formulation in Equation 1 [18].

$$k_e = \frac{k_{pe} + 2k_l + 2(k_{pe} - k_l)(1+\beta)^3\varphi}{k_{pe} + 2k_l - (k_{pe} - k_l)(1+\beta)^3\varphi} k_l \qquad (2)$$

In our study, the thermal conductivity of the nanofluid has calculated by using Yu and Choi's equation.

If we assume that nanoparticles are uniformly distributed in the base fluid, the density and specific heat of two-phase nanofluids at different temperatures and concentrations are specified in Equation 3 and Equation 4 [18-20].

$$p_{nf} = \varphi p_p + (1-\varphi)p_{bf} \qquad (3)$$

$$C_{p_{nf}} = (1-\varphi)\frac{p_{bf}}{p_{nf}}C_{p_{bf}} + \varphi\frac{p_p}{p_{nf}}C_{p_p} \qquad (4)$$

'nf' refers to nanofluid, 'p' particles, and 'bf' refers to the base fluid used as a sub-index. In order to calculate the dynamic viscosity, the formulation has specified in Equation 5 has been used [18,21,22].

$$\mu_{nf} = (123\varphi^2 + 7.3\varphi + 1)\mu_{bf} \qquad (5)$$

In order to calculate the effective thermal conductivity, Equation 6 has published by Maxwell in 1881 based on the weighted average of the conductivity of the liquid and the solid has used [23].

$$\frac{k_{eff}}{k_f} = 1 + \frac{3(k_p/k_f - 1)\varphi}{\left(\frac{k_p}{k_f} + 2\right) - (\frac{k_p}{k_f} - 1)\varphi} \qquad (6)$$

The formula is given in Equation 7 (Nu Ther. Dev) is used to calculate the Nusselt number. 'Nu' denotes Nusselt number, 'Re' Reynolds number, 'Pr' Prandtl number, 'D' diameter and 'L' length of the channel [24].

$$Nu = \frac{3.657 + (0.19(Re.Pr.\frac{D}{L})^{0.8})}{1 + 0.117(Re.Pr.\frac{D}{L})^{0.467}} \qquad (7)$$

In theoretical calculations, mass flow rate (ṁ) is shown with Reynolds number (Re) and heat transfer (q) and the specified values have been calculated in Equation 8, Equation 9 and Equation 10, respectively [24].

$$\dot{m} = \rho u_m A_c \qquad (8)$$

$$Re_D = \frac{4\dot{m}}{\pi D\mu} \qquad (9)$$

$$q = \dot{m}C_p(T_{out} - T_{in}) \qquad (10)$$

The continuity equation, mass conservation equation, momentum conservation and energy conservation are given by Equation 11, Equation 12, Equation 13 and Equation 14, respectively.

$$\frac{\partial_u}{\partial x} + \frac{\partial_v}{\partial y} + \frac{\partial_w}{\partial z} = 0 \qquad (11)$$

$$(\frac{\partial_p}{\partial t} + \nabla.(\rho\vec{V})) = S_m \qquad (12)$$

$$\frac{\partial_p}{\partial t}(\rho\vec{V}) + \nabla.(\rho\vec{V}\vec{V}) = -\nabla p + \nabla.(\bar{T}) + \rho\vec{g}) + \vec{F} \qquad (13)$$

$$\frac{\partial_{pE}}{\partial t} + \nabla.\left(\vec{V}(\rho E + \rho)\right) = \nabla.[k_{eff}\nabla T - \sum_j h_i j_i + (\bar{T}_{eff}.\vec{V})] + S_h \qquad (14)$$

2.3. Computational Fluid Dynamics and Theoretical Calculations Analysis Results

Nanofluids with different volume ratios and different nanoparticles have used in our study are shown in Table 3. Outlet temperatures, thermal conductivity ratios and convective heat transfer coefficients of nanofluids at 100, 250, 500 and 1000 Reynolds (Re) numbers have been investigated. A constant heat flux of 100000 W/m^2 has been applied along the channel and the inlet temperature of the nanofluids has been determined as 293.15K. Outlet temperatures have been compared with both computational fluid dynamics (CFD) and theoretical calculations. Ansys R18.2-Fluent software has been used for computational fluid dynamics (CFD) calculations. For the mesh modeling; 201370 elements have been used, the minimum orthogonal quality is 0.11 and the maximum skewness value is 0.84. Different mesh structures and element numbers have been analyzed, and it has been accepted as the optimum value since there was no significant change in the results after the number of elements 201370. The COUPLED algorithm is used as a solution method. It is assumed that the flow is fully developed, incompressible, continuous, and the channel is smooth. The results of the values have obtained using computational fluid dynamics are given in Table 3.

Table 3. Outlet temperatures of nanofluids with percent volume ratios calculated by CFD

OUTLET TEMPERATURES (K)				
Nanofluids	REYNOLDS (Re)			
	100	250	500	1000
Water (293.15 K)				
Water	312.91	301.691	297.899	295.909
Al_2O_3				
0.01 Al_2O_3	309.236	300.326	297.663	295.722
0.02 Al_2O_3	308.155	299.932	297.411	295.581
0.03 Al_2O_3	307.15	299.47	297.142	295.431
0.04 Al_2O_3	306.016	299.023	296.87	295.279
CuO				
0.01 CuO	309.546	300.456	297.738	295.759
0.02 CuO	308.701	300.2	297.546	295.65
0.03 CuO	307.898	299.783	297.325	295.526
0.04 CuO	306.897	299.404	297.091	295.399
Fe_2O_3				
0.01 Fe_2O_3	309.4	300.399	297.704	295.745
0.02 Fe_2O_3	308.319	300.086	297.439	295.582
0.03 Fe_2O_3	307.555	299.645	297.244	295.487
0.04 Fe_2O_3	306.623	299.277	297.034	295.343
TiO_2				
0.01 TiO_2	309.277	300.342	297.676	295.73
0.02 TiO_2	308.232	299.94	297.432	295.589
0.03 TiO_2	307.247	299.514	297.17	295.447
0.04 TiO_2	306.256	299.081	296.907	295.301
SiO_2				
0.01 SiO_2	309.139	300.294	297.653	295.72
0.02 SiO_2	308.122	299.857	297.395	295.578
0.03 SiO_2	307.068	299.401	297.124	295.429
0.04 SiO_2	306.023	298.948	296.859	295.281

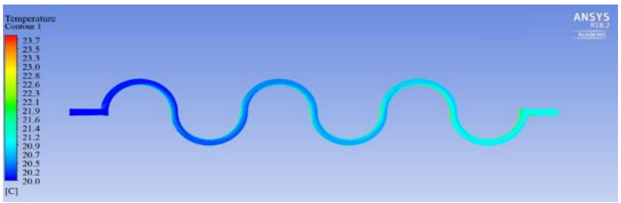

Figure 3. 0.04% SiO_2-Water temperature distribution across the wavy micro-channel

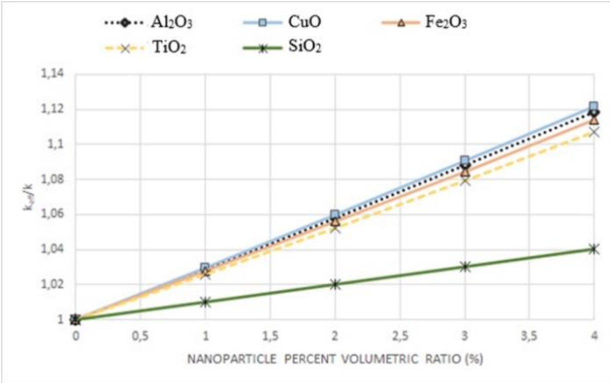

Figure 4. Thermal Conductivity Efficiency based on nanoparticle percent volumetric ratio (Maxwell)

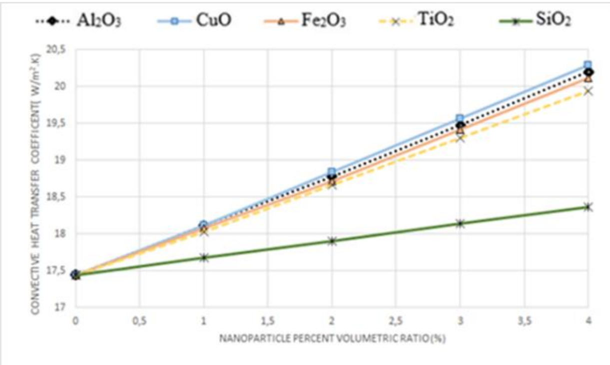

Figure 5. Convective Heat Transfer Coefficient change depending on nanoparticle percent volumetric ratio

In Figure 4, the thermal conductivity efficiencies of the nanofluids are given. In these calculations, the formulation specified in Equation 6 has been used.

Figure 5 shows the change in the nanoparticle percentage volumetric ratios and convective heat transfer coefficient of nanofluids. The formulation has been specified in Equation 7 has used in these calculations.

Nanofluids with different volume ratios and different nanoparticles have used in our study are shown in Table 4. They have been calculated with the formulations specified in Section 2.2. Reynolds numbers have been selected as 100, 250, 500 and 1000 and the outlet temperatures, thermal conductivity efficiency and convective heat transfer coefficients of nanofluids in laminar flow in a wavy microchannel have been investigated.

Table 4. Outlet temperatures of nanofluids with percentage volume ratios specified by theoretical calculations

OUTLET TEMPERATURES (K)				
Nanofluids	REYNOLDS (Re)			
	100	250	500	1000
Water (293.15 K)				
Water	313.15	301.15	297.15	295.15
Al_2O_3				
0.01 Al_2O_3	310.92	300.25	296.7	294.92
0.02 Al_2O_3	309.78	299.8	296.47	294.81
0.03 Al_2O_3	308.55	299.31	296.23	294.69
0.04 Al_2O_3	307.3	298.81	295.98	294.56
CuO				
0.01 CuO	311.34	300.42	296.78	294.96
0.02 CuO	310.55	300.11	296.63	294.89
0.03 CuO	309.58	299.72	296.43	294.79
0.04 CuO	308.53	299.3	296.22	294.68
Fe_2O_3				
0.01 Fe_2O_3	311.14	300.34	296.74	294.94
0.02 Fe_2O_3	310.19	299.96	296.55	294.85
0.03 Fe_2O_3	309.09	299.52	296.33	294.74
0.04 Fe_2O_3	307.95	299.07	296.11	294.63
TiO2				
0.01 TiO_2	310.96	300.27	296.71	294.93
0.02 TiO_2	309.86	299.83	296.49	294.82
0.03 TiO_2	308.65	299.35	296.25	294.7
0.04 TiO_2	307.42	298.85	296,00	294.57
SiO_2				
0.01 SiO_2	310.69	300.16	296.65	294.9
0.02 SiO_2	309.37	299.63	296.39	294.77
0.03 SiO_2	307.99	299.08	296.11	294.63
0.04 SiO_2	306.64	298.54	295.84	294.49

3. RESULTS AND DISCUSSION

In our study, nanoparticles of different percentage volume ratios have been used together with the base fluid water. The flow regime is laminar, and Reynolds numbers are 100, 250, 500 and 1000. The outlet temperatures, convective heat transfer coefficients and thermal conductivity efficiency of nanofluids have been compared. In the micro-channel, where constant heat flux has been applied along the channel of 100000 W/m^2, it has been observed that the outlet temperature has decreased as the nanoparticle percentage volume ratio increased in nanofluids with the same Reynolds number. In theoretical calculations, the highest increase in heat transfer amount has been observed at 0.04% SiO_2 volumetric rate in 100 Reynolds number and this increase is 16.26%. In Ansys R18.2-Fluent calculations made with computational fluid dynamics, two different nanofluids have the highest heat transfer amount. These nanofluids are 17.33% increase for 0.04% Al_2O_3 and 17.32% for 0.04% SiO_2 at 100 Reynolds value.

As seen in Figure 4 and Figure 5, when the convective heat transfer coefficients and thermal conductivity efficiencies of nanofluids are compared, the highest increase is seen in 0.04% CuO as 14.04% and 12.18%, respectively. However, when the outlet temperatures are compared with other nanoparticles, the least increase in the amount of heat transfer has been observed in CuO. This is because the density of CuO is higher than other nanoparticles. CuO has a lower inlet velocity than other nanofluids at the same Reynolds number because it has a higher density than other nanoparticles. Since CuO have a lower inlet velocity than other nanoparticles at the same Reynolds number, the increase in heat transfer amount is less than other nanoparticles. Unlike CuO, SiO_2 has a higher inlet velocity at the same Reynolds number thanks to its lower density. When the nanoparticles' convective heat transfer coefficients and thermal conductivity efficiencies are compared, the lowest values belong to 0.04% SiO_2 as 5.06% and 4.05%, respectively. However, due to its low density, SiO_2 has the best increase in heat transfer amount in theoretical calculations compared to other nanoparticles since it will have a higher input velocity at the same Reynolds number. For Ansys R18.2-Fluent calculations, Al_2O_3 and SiO_2 have approximately the same increased values in the amount of heat transfer. As a result of these situations, it has been observed that the density of the nanoparticle to be used is an important factor.

As shown in Table 3 and Table 4, a significant decrease has been observed in the outlet temperatures as the nanofluids will have higher inlet velocities with the increase of the Reynolds number. It has been observed in Figure 4 and Figure 5 that the thermal conductivity efficiency and convective heat transfer coefficient increase with the amount of nanoparticle increase.

Figure 6 and Figure 7 show the Nusselt number of the wavy-microchannel. It is observed that the Nusselt number increases as the amount of nanoparticles and the Reynolds number increase.

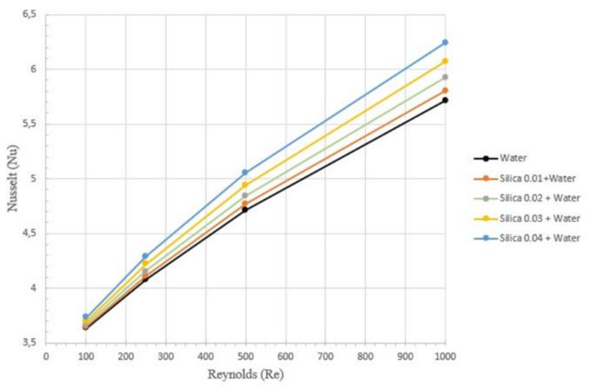

Figure 6. Variation of Nusselt number of microchannel with Reynolds numbers for SiO_2-Water

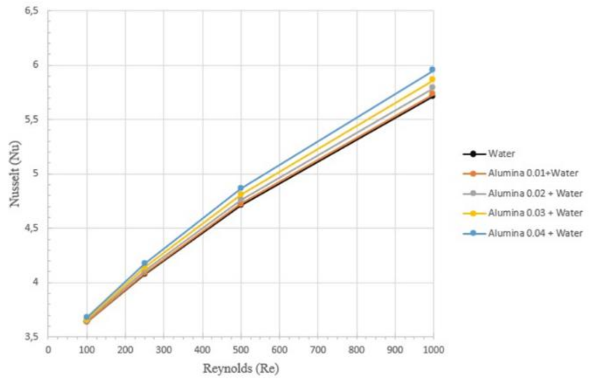

Figure 7. Variation of Nusselt number of microchannel with Reynolds numbers for Al_2O_3-Water

The results showed similar values when compared with the studies in the literature. Topuz et al. [25] have been investigated the heat transfer performance in a circular microchannel in both laminar and turbulent flow. Water as the base fluid and 0-1% Al_2O_3, TiO_2 and SiO_2 as nanoparticles have been used. The maximum increase in the heat transfer performance of the nanofluid has been specified as 15.3%. Azizi et al. [9] have been used water as the base fluid in laminar flow and nanofluid containing 0.05-0.3% CuO with 25 nm particle diameter as a nanoparticle. They have stated that the maximum increase in the heat transfer performance of the microchannel with cylindrical geometry is 23%. In the study of Duangthonsuk and Wongwises [10], the heat transfer performance of the nanofluid consisting of 0.3-0.8% SiO_2 with a diameter of 15 nm and de-ionized water as the base fluid in turbulent flow have been investigated. The enhancement in heat transfer in the microchannel with zigzag geometry has been stated as 15%. Putra et al. [26] have been used water as base fluid and 0-5% Al_2O_3 as nanoparticles in a rectangular microchannel in laminar flow. The increase in heat transfer has been observed as 13%. Wu et al. [27] have been stated that the heat transfer performance of Al_2O_3-Water nanofluid with 0-0.26% nanoparticles in laminar flow increased by 15.8% in the trapezoidal microchannel.

4. CONCLUSIONS

In our study, the outlet temperatures of nanofluids have been compared with both computational fluid dynamics (CFD) and theoretical calculations. As a result of the calculations, the highest error among the outlet temperatures is 5.5%, and the nanofluid with the highest percentage error value is detected in a 100 Reynolds value nanofluid with a concentration of 2% Fe_2O_3 by volume and is shown in Figure 8. Maximum percent error for Al_2O_3-Water; At 1% volume ratio, 4.46% at 100 Reynolds value, maximum percentage error for CuO-Water; 4.95% at 100 Reynolds value at 2% volume ratio, maximum percentage error for TiO_2-Water; 4.45% at 100 Reynolds value at 1% volume ratio and maximum percentage error for SiO_2-Water; It is 4.44% at 500 Reynolds value at 4% volume ratio. It has been determined that the theoretical and CFD outlet temperatures results are close to each other.

In this study, the heat transfer performance of nanofluids in laminar flow in the wavy microchannel has been numerically investigated, and it is planned to be studied experimentally in the future.

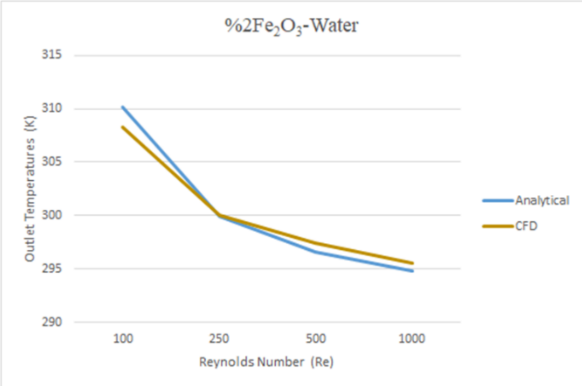

Figure 8. 2% Fe_2O_3-Water comparison of theoretical and CFD calculations outlet temperatures

DECLARATION OF ETHICAL STANDARDS

The author(s) of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

AUTHORS' CONTRIBUTIONS

Mutlu Tarık ÇAKIR: Analysed the results and wrote the manuscript.

Deniz AKTÜRK: Analysed the results and wrote the manuscript.

CONFLICT OF INTEREST

There is no conflict of interest in this study.

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