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ORIGINAL RESEARCH PAPER

Heat Transfer Analysis of Nanofluid in a Sine Wave Plate Heat Exchanger

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ABSTRACT: Heat transfer is one of the most critical processes in the industry, and by increasing the efficiency of the heat exchanger, energy consumption of systems will be reduced. Very tiny particles in nanoscale dimensions, when uniformly dispersed and stably suspended in the base fluid, efficiently improve the thermal properties of the base fluid. With the help of nanofluids, the heat transfer rate increase. The purpose of this research is to investigate the thermal and hydraulic characteristics of nanofluid in turbulent flow regime in a plate heat exchanger with a sine pattern in which cold and hot flows alternately pass through the plates. First, problem geometry is modeled and simulated in ANSYS-FLUENT software. All properties of nanoparticles are dependent on temperature, velocity, and particles diameter, and are added to software in the form of a separate code. Simulations are for different parameters such as wavelength to amplitude ratio (L/A), Reynolds number, volume fractions of nanoparticles and nanoparticle diameter. The results indicate that the best shape of the wave for the highest heat transfer rate in the heat exchanger is gained for equal wave amplitude and wave length.

KEYWORDS*: Computational Fluid Dynamics; Nanofluid; plate heat exchanger; sinusoidal plate*

INTRODUCTION

In the last few decades, to save energy and raw materials, and taking into account economic and environmental issues, many efforts have been made to build high-performance heat exchangers, and their primary purpose is to reduce the size of the system for a given heat load and increase the heat transfer capacity. An overview of the work done in this area can be divided into the following general methods: Passive methods that do not require external force; and active methods that need external power. Passive methods include the use of extended surfaces, compact heat exchangers, non-circular cross-sections, increasing the heat transfer by vortices, micro-channels, surface coating, surface irrigation, etc. Alternatively, mechanical stirring, rotating surfaces, fluid fluctuations, use of the electric field, injection and suction goes into active methods. Among the passive means of increasing heat transfer, the use of wavy channels due to the high increase in heat transfer and relatively low increase in pressure drop is of interest to researchers. The primary reason for enhanced heat transfer in the wavy channel is due to near wall recirculation flow. This recirculation flow exists at low Reynolds number. As the Reynolds number increases, the interaction between the core flow and near wall recirculation flow increases, and thus multiply the mixing behavior of this flow [1]. When Reynolds number is significant enough to move the flow regime to turbulent flow, the destabilization of thermal boundary layer allows more interaction between the core and near wall flows.

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So the flow become three-dimensional, and heat transfer will be increased considerably [2]. As plate heat exchangers are widely used in industry, works were made to enhance the heat transfer rate in these heat exchangers, while some changed the cross-section of the flow passage, others used Nanofluid as working fluid. Wavy channels can be divided into two major categories. Symmetric ducts (Raccon channels) in which the upper and lower walls have a phase difference of 180° and the alternating current passes through a convergent-divergent duct; and asymmetric walls (Serpentine Channels) in which the upper and lower waves have the same phase. Raccon and serpentine wavy channels were compared in laminar flow by Pati et al. [3] For small wall wavelength, the heat transfer rate does not differ in these two types of channels.

However, for the higher wavelength of the wall, the heat transfer rate in Raccon channel is more excellent than the serpentine channel. These results are entirely different considering pressure drop. By assessing thermo-hydraulic performance, serpentine channel overtaking Raccon channel for all wavelength and amplitude of wall and Reynolds number.

Asymmetric wavy channels with the sinusoidal wall were studied numerically by Mills et al. [4]. They considered three parameters in their both steady and unsteady simulation, the effect of driving pressure, the amplitude and period of wall waviness. The fluid flow was laminar. At lower mass flow rates, heat transfer is mainly affected by the amplitude of wall; while at higher flow rates, the effect of pressure drop is dominant.

	Nomenclature		
A	Wave Amplitude(m)	u_i	Velocity component (m/s)
C_P	specific heat (kJ/kg K)	V	velocity (m/s)
d_p	average diameter of nanoparticles (m)		**Greek Symbols**
d_f	average diameter of fluid (m)	Q	nanoparticle volume fraction (%)
h	Heat transfer coefficient ($W/m^2.K$)	ρ	density(kg/m^3)
i,j	indices	μ	Viscosity
k	thermal conductivity (W/m K)	μ_t	corrective viscosity coefficient
K	Turbulent energy	ρ	density
L	Wave Length(m)		
Nu	Nusselt number		**Subscripts**
Pr	Prandtl number	f	base fluid
Q	heat flux (W/m^2)	in	Inlet
Re	Reynolds number	nf	nanofluid
T	temperature (K)	p	particle

Ko et al. [5] numerically investigated entropy generation and optimal Reynolds number in a double-sine duct. Reynolds number was in the range of 86 to 2000, and the flow was laminar. Constant heat flux boundary condition was applied to the walls. He divided the total entropy generation into two section: the one produced by frictional irreversibility and the other generated by heat transfer irreversibility. He states that when Reynolds number is significant, and wall flux is low, frictional irreversibility mainly raises the total entropy generation and when the wall flux is high, and Re is small, heat transfer irreversibility dominates it. Finally, he stated an optimal aspect ratio for different wall fluxes and Reynolds numbers. Harikrishnan and Tiwari[6] used Ansys-Fluent software to study the effect of skewness of wavy channel on thermodynamic and thermos-hydraulic performance. Giving skewness to the wavy channel makes stronger secondary flow. Increasing skewness angle to 35° results in the higher Nusselt number, while this angle alters to 30° for friction factor. Beyond these angles both Nusselt number and friction factor decrease. The effect of the corrugation of a wavy channel on heat transfer, pressure drop, and entropy generation was studied by Akbarzadeh et al.[7]. Three types of wavy surfaces were considered, sinusoidal, trapezoidal and triangular shapes. Flow regime was set to be laminar. Simulations revealed that triangular channels provide the lowest Nusselt number and highest entropy generation, while the trapezoidal channels served most top pressure drop. They recommended using sinusoidal channel since they offer the most top performance and smallest pressure drop.

With nanofluids advantages over the base fluid, the use of nanofluid in heat exchangers can provide a proper perspective for industries. Kumar et al. [8] reviewed nanofluid applications in plate heat exchangers in a review paper. In numerical and experimental documents examined, nanofluids showed a high potential for increasing the efficiency of heat exchangers. They also provided a variety of models for nanofluids properties. Ahmed et al. numerically simulated Al_2O_3 nanofluid in a sinusoidal wavy channel. They analyzed the effect of curved wall phase shift on local and average Nusselt number and friction factor. They showed that when the phase shift is 0° for the examined ranges of Reynolds number and nanoparticles volume fractions, the performance is optimized. Nanofluid has been used as a working fluid in plate heat exchangers both experimentally and numerically. Zamzamian et al. [9] used Al_2O_3/EG and CuO/EG nanofluid at 0.1-1wt% and reported that heat transfer coefficient increased up to 49%. Kabeel et al. [10] and Jokar et al. [11] mixed Al_2O_3 in water at 1-4 vol.%, and nanoparticles diameter was 47 and 36nm respectively. Kabeel et al. [10] stated that heat transfer coefficient increased up to 13%, while Jokar et al. [11] reported that the enhancement was not considerable. The effectiveness of SiO_2/water and ZnO/water nanofluid in a trapezoidal plate heat exchanger was assessed by Abed et al. [12]. They stated that heat transfer coefficient increased about 12% at 4vol.%. By Huang et al.[13] the heat transfer and pressure drop of nanofluid, which is water and aluminum oxide mixture, were investigated numerically in a plate heat exchanger and compared with the results of pure water. The heat transfer was enhanced by using Nanofluids in a constant Reynolds number but did not improve significantly at a constant velocity. Besides, they reported that the pressure drop of the nanofluid was higher due to the higher viscosity than the base fluid.

In this study, two passive methods namely wavy surfaces and nanofluid have been used. The use of internal flows at the corrugated surfaces in the industry and heat exchangers makes it possible to consider ways to increase the heat transfer in this widely used geometry and to apply solutions to improve the heat transfer rate. The focus of this research is to investigate the effects of the use of nanofluids as energy transfer fluid in curved plate heat exchangers.

MODEL DESCRIPTION

The selected heat exchanger is a sine wave pattern plate heat exchanger. Figure 1 shows simulated geometry. The geometry of the heat exchanger is created, the proper mesh is generated, and boundary conditions of the problem are applied to it.

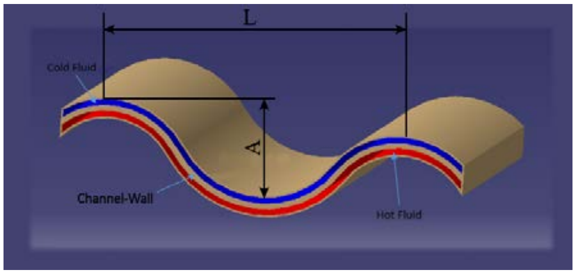

Fig. 1. Geometry and boundary condition of the problem

GOVERNING EQUATIONS

According to the flow range and the Reynolds number in this study, the flow regime is assumed to be turbulent. Numerical simulations are performed using the Ansys-Fluent Computational Fluid Dynamics software. The governing equations of fluid are as follows:

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

$$\rho(\vec{V}.\vec{\nabla})\vec{V} = -\vec{\nabla}p + \eta\vec{\nabla}^2\vec{V} \tag{2}$$

$$\rho(\vec{V}.\vec{\nabla})(c_pT\ \ ) - \vec{\nabla}.(k\vec{\nabla}T\ \ ) = \Phi \tag{3}$$

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + G_k - \rho\varepsilon + S_k \tag{4}$$

$$\frac{\partial}{\partial t}(\rho \varepsilon) + \frac{\partial}{\partial x_i}(\rho \varepsilon u_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right] + C_{1\varepsilon}\frac{\varepsilon}{k}G_k - C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} + S_\varepsilon \tag{5}$$

$$\mu_t = \rho C_\mu \frac{k}{\varepsilon^2} \tag{6}$$

In which Φ is the heat source Which mainly results in frictional losses in contact with parts. Turbulent constants C_μ, σ_k, σ_ε, $C_{1\varepsilon}$, $C_{2\varepsilon}$ are 0.09. 1.0, 1.3, 1.44 and 1.92, respectively. The three-dimensional flow is solved using the finite volume discretization technique. For the discretization of equations, the second-order upwind method and the coupling of the pressure and velocity equations, the SIMPLE algorithm is employed. The solution is converged when the residual of continuity, momentum, energy and turbulent equations become less than 10^{-5}.

DETERMINATION OF NANOFLUID PROPERTIES

One of the nanofluid related fields that attracted many researchers is the determination of the changed properties of the fluid due to the presence of nanoparticles.
density
According to the physics of mixture of two substances [14]:

$$\rho_{nf} = (1-\phi)\rho_f + \phi\rho_p \tag{7}$$

The density of water and alumina are 998.2 and 3880 kg/m^3 respectively[15].
Heat capacity [14]:

$$C_{p,nf} = \frac{(1-\phi)(\rho\ cp)_f + \phi(\rho\ cp)_p}{\rho_{nf}} \tag{8}$$

In these equations, φ is the volume fraction of the nanoparticles, and the subheadings f, nf, and p respectively represent the properties of the fluid, nanofluid and nanoparticles. The heat capacity of water and alumina are 4182 and 729 $W/kg.K$ respectively [15].
Thermal conductivity coefficient:

In this study, for the monophasic mode, thermal conductivity model which has been confirmed by Minsta et al.[16] is used:

$$\frac{k_{nf}}{k_f} = 1 + 64.7\,\phi^{0.746}\left(\frac{d_f}{d_p}\right)^{0.369}\left(\frac{k_p}{k_f}\right)^{0.7476}{Re_p}^{1.2321} \tag{9}$$

In the above equations, d_f and d_p are the diameter of the base fluid molecules and the average diameter of the nanoparticles. $\mathrm{Pr} = \frac{\mu_f}{(\rho\alpha)_f}$ and $\mathrm{Re} = \frac{\rho_f\,k_b T}{3\,\pi\,\mu_f{}^2\lambda_f}$ are respectively Prandtl and Reynolds numbers and α_f the thermal diffusion coefficient, Boltzmann's k_b constant and λ_f is the average free distance of water molecules, which was considered 17nm in this study according to Chon et al.[17]. They provided this model for aluminum, aluminum oxide, and copper oxide nanoparticles.
The viscosity:

The viscosity correlation proposed by Khanafer and Vafai is used for Al_2O_3/water nanofluid [18]:

$$\mu_{nf} = -0.4491 + \frac{28.837}{T} + 0.574\phi - 0.1634\phi^2 + 23.053\frac{\phi^2}{T^2} + 0.0132\phi^3 + 2354.735\frac{\phi}{T^3} - 23.498\frac{\phi^2}{d_p^2} \tag{10}$$

Where nanoparticles diameter is set to $d_p\ = 20\ nm$.

VERIFICATION AND GRID INDEPENDENCE

In this section, verification of grid system and solution procedure is done. For thermal validation, simulations are performed in two flow regime of laminar and turbulent flow. The results are compared with the work of Wang et al.[1] in the laminar flow regime, and with the work of Pham et al[19]. and Zhang et al.[20] in the turbulent regime. Pham et al. [19] studied the flow and heat transfer in a wide range of Reynolds numbers inside a wave channel using the LES turbulence model. Zhang et al. [20] examined the flow and heat transfer numerically, taking into account factors such as friction factor and Colburn j-factor in a channel for Reynolds number in the range of 100-1500.

In Figure 2, local Nusselt numbers are compared with the results of Wang et al. [1]. As the figure shows, there is a good match between the results of the present study and other researchers.

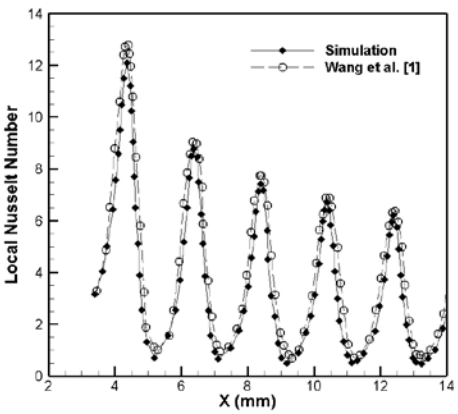

Fig. 2. Verification study for local Nusselt number for a wave channel in the laminar fluid flow

In turbulence regime, the Colburn factor j is also compared with the numerical values of Pham et al. [19] and the experimental values of Zhang et al. [20]. As it is seen in Figure 3, the results are in good agreement.

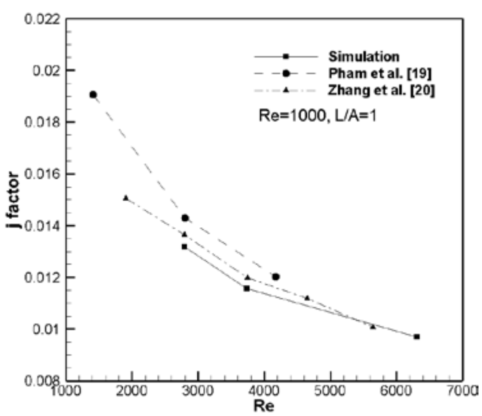

Fig. 3. Verification study for the Colburn factor j for a wave channel in turbulent fluid flow

Four sets of grid systems are examined for the sine wave plate heat exchanger.

The geometry and operating condition are fixed while the average Nusselt number from the heat exchanger is compared for three grid systems, and the results are presented in Figure 4.

It is observed that the system with about 2 million and 3 million cells produce an almost identical Nusselt number. Thus, a domain with 2 million cells was chosen in the present study.

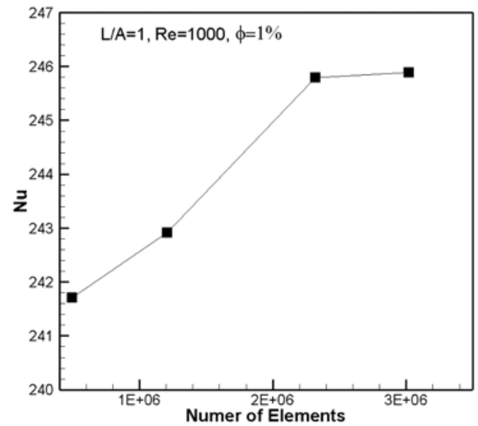

Fig. 4. Average Nusselt based on the number of computational cells

RESULTS AND DISCUSSION

The effects of channel shape

In this section, the average Nusselt value of pure water is given in Re = 500 for different geometries, L/A ratio. Concerning Figure 5, it is seen that the highest heat transfer rate occurs at $\frac{L}{A} = 1$. In $\frac{L}{A} = 0.5$, Nusselt is equal to 102. Reducing the wave amplitude, until the value of $\frac{L}{A} = 1$, the heat transfer rate will increase. However, a further decrease in the amplitude of the wave reduces heat transfer.

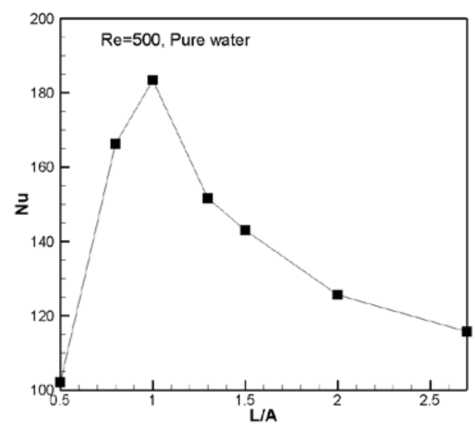

Fig. 5. The effect of plate sine wave pattern on average Nusselt number

The effect of Reynolds number

According to Figure 6, the average Nusselt value of pure water increases with increasing Reynolds number. In fact, increasing the Reynolds by increasing the heat transfer coefficient, improves heat transfer. Also, turbulence in these regions and frequent interactions between the wall and the fluid and sufficient time for energy exchange causes the heat transfer and consequently the Nusselt number to increase sharply. In the Reynolds calculation, the hydraulic diameter of the sinusoidal ducts is used which is obtained from the relation $D_h = 4A/P$. A is the cross-section area, and P is the perimeter of the wetted surface that is derived from the Gambit software.

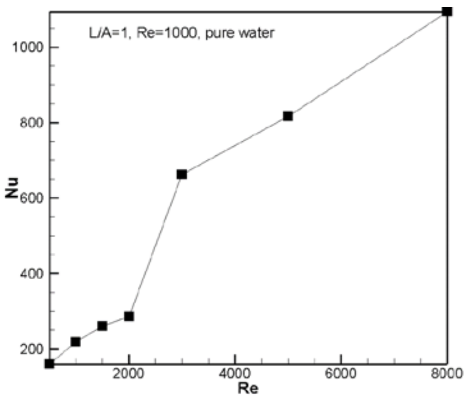

Fig. 6. The effect of Reynolds number on average Nusselt number

Figure 7 shows the pressure drop for pure water in different Reynolds in the channel. An increase in the average flow rate causes a higher gradient of velocity near the wall. Consequently, shear stress and pressure drop along the channel increases.

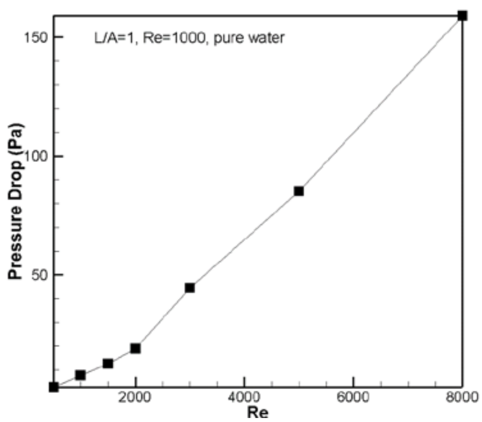

Fig. 7. The effect of Reynolds number on channel pressure drop

The effect of nanoparticles volume fraction

In this section, the result of the nanoparticle 's volume fraction on the average Nusselt has been investigated. As shown in Figure 8, the mean value of nanofluid Nusselt increases with increasing volume fraction of nanoparticles.

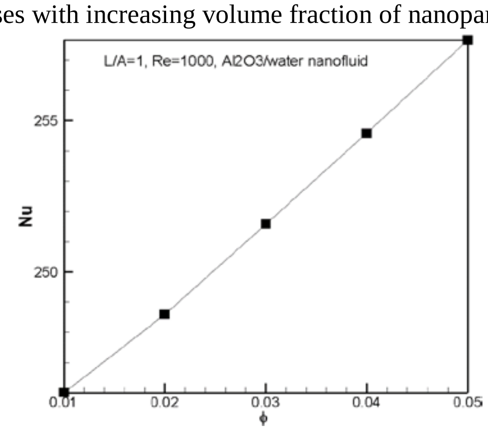

Fig. 8. The effect of volume fraction of nanoparticles on average Nusselt number

Indeed, increasing the volume fraction by enhancing the role of nanoparticles and effective thermal conductivity can improve heat transfer.

As we know, the Nusselt number depends on the temperature gradient, the thermal conductivity, and the mass flow rate of the fluid.

The direct impact of nanoparticles on the increase of the temperature gradient and the thermal conductivity, have the crucial role on enhancing heat transfer rate.

Improvement of heat transfer by increasing the volumetric fraction of nanoparticles in water is shown in Figure 9. The maximum recovery in the 2% volume is 18%.

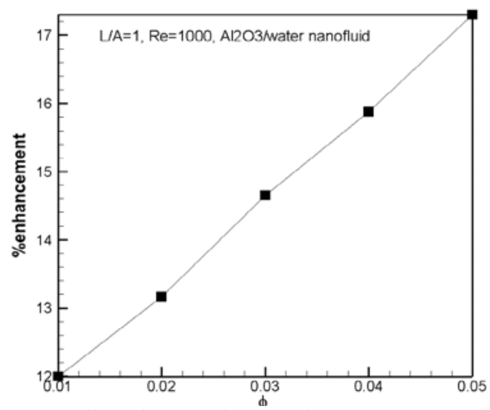

Fig. 9. The effect of volume fraction of nanoparticles on Nusselt number enhancement

Investigation of nanofluid pressure drop based on nanoparticle volume fraction is shown in Figure 10. An increase in the volume fraction of nanoparticles in the base fluid causes an increase in the pressure drop in the desired geometry

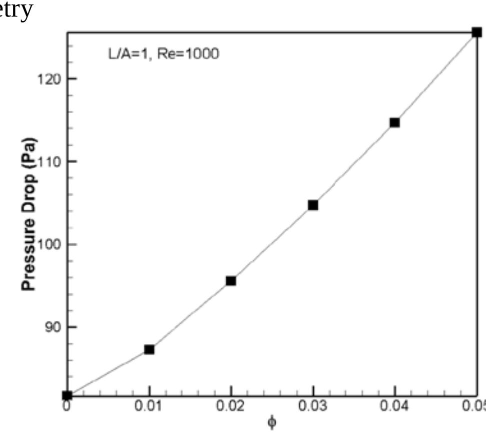

Fig. 10. The effect of volume fraction of nanoparticles on channel pressure drop

By increasing the volume fraction of nanoparticles, more energy is needed to move the liquid, and the pressure on the outlet is reduced further.

The effect of nanoparticles diameter

It is seen from Figure 11 that the decrease in the diameter of the nanoparticles leads to an increase in heat transfer. In fact, by reducing the diameter of the nanoparticles, the relation between the volume of particles and their surface area rise; this leads to a better interaction of particles and water and consequently higher thermal conductivity of Nanofluid. Decreasing the diameter results in enhancement of the browning motion of the nanoparticles and improve the heat transfer rate.

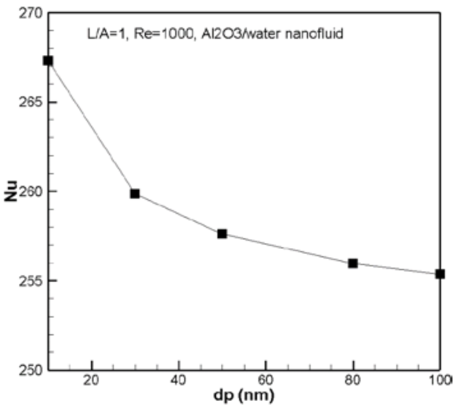

Fig. 11. The effect of nanoparticle's diameter on average Nusselt number

The effect of nanoparticle type

The impact of Al_2O_3 and CuO nanoparticles has been compared with each other on increasing the nanofluid heat transfer in Figure 12. As seen from the figure, the Al_2O_3 nanofluid has a better heat transfer than the CuO nanofluid. This suggests that aluminum oxide improves the thermodynamic properties in the desired geometry, and further increases the heat transfer.

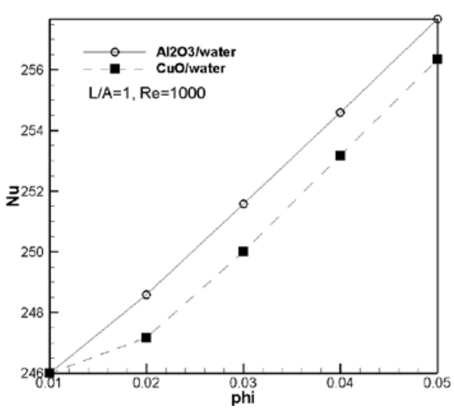

Fig. 12. The effect of nanoparticle's type on average Nusselt number

According to Figure 13, the skin friction factor increases with increasing volume fraction of nanoparticles. Also, the skin friction factor for CuO nanofluid is slightly higher than the Al_2O_3 nanofluid. As can be seen, the nanofluid friction factor is higher than that of pure water, but the amount of increase in the heat transfer of the nanofluid is so significant that this friction coefficient can be ignored.

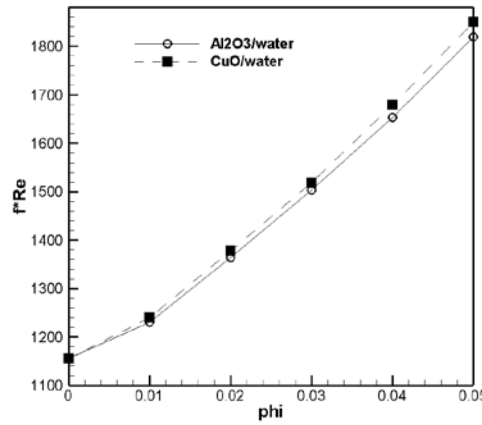

Fig. 13. The effect of nanoparticle's type on pressure drop

CONCLUSIONS

In this paper, the flow, pressure drop and heat transfer of nanofluid in a sine heat exchanger are numerically investigated for different values of Reynolds number, problem geometry, volume fraction, and diameter of nanoparticles. In this research, the governing equations are discriminated using a finite volume method. The SIMPLE algorithm is used to solve the velocity-pressure coupling. The use of nanofluids can improve heat transfer. For example, Al_2O_3/water nanofluid at 1%vol. and Re = 1000 can increases the Nusselt number by 12% relative to pure water. The average Nusselt number increases with increasing Reynolds number. The average Nusselt number increases with the volume fraction of the nanoparticles, the Nusselt number for the highest volume fraction (5%) is 6% higher than the one at 1% volume fraction. By keeping various parameters constant, it is concluded that the improvement of heat transfers in fluid increases with smaller nanoparticles. For example, heat transfer by nanoparticles with a diameter of 10 nm is 5% higher than nanoparticles with a diameter of 100 nm. It is also revealed that the shape of the sine wave is fundamental to its heat transfer rate. The best form of wave is the case that its length and amplitude of wave have the same values (L/A=1).

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