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Numerical Study of the Thermal and Hydraulic Characteristics of the SiO_2 –Water Nanofluid through a Backward-Facing Step

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Abstract: The work of this paper is devoted to the two-dimensional numerical investigation of the turbulent forced convection through backward-facing step. Two cases are taken into account. For the first, the bottom wall is smooth; but for the second case, it is corrugated with a triangular base containing ten corrugations. A uniform heat flux is imposed on the bottom wall. A flow of a nanofluid consisting of silicon dioxide SiO_2 nanoparticles dispersed in a base fluid (water) flows through this step.The flow equations were discretized by the finite volume method. For modeling turbulence, the K-ε-RNG model was applied to analyze Reynolds number effect, the volume fraction and the size of the particle. Numerical simulations were conducted for various Reynolds between 10,000 and 40,000; volume fractions of nanoparticles which vary from 0 to 5% and particle diameter dp equal to 30; 50 and 70 nm. We noted that the obtained findings are in good conformity with those of the literature.

Keywords: Forced convection, Turbulent flow, Backward-facing step channel, Corrugated channel, SiO_2 – water Nanofluid.

Introduction

The improvement of heat transfer is a key objective in several applications, and to do this, a large number of researchers have conducted a multitude of numerical and experimental tests relating to the description of the phenomena governing the modes of heat transfer. Chronologically, ideas for improvement began to affect mainly the geometry of systems at the macroscopic scale, and the physico-chemical nature of convective media fields. Attempts at improvement have sometimes touched on the microscopic aspect of the process. But the emergence and rapid expansion of nanoscience and nanotechnology in the second half of the 20th century meant that convection became a major part of this new trend, and thus another aspect of improvement. It is at the nanometric dimension of the material, of the convective medium, that much of the recent work has focused on developing a more efficient heat transfer fluid to reduce energy consumption. Among the topical solutions found, note that of nanofluids (Choi & Eastman, 1995). These nanofluids are colloidal solutions formed by particles of nanometric size (1 to 100 nm), with metal bases or metal oxides suspended in a basic liquid (pure water; E-G; oils; etc…). The presence of nanoparticles in base fluids changes their thermal conductivity and viscosity. A great deal of work has been carried out in this area by many authors. They have experimentally and numerically studied nanofluids; convection and heat exchange in various corrugated channels.

Hilo et al. (2020) have numerically investigated a turbulent forced convection flow in a straight and wavy channel using three bases (zigzag, triangular and trapezoidal) on two backward-facing step channel with pure water as the working fluid. The authors investigated the effects of corrugated design and geometric parameters like the pitch of the channel, amplitude and Re number on velocity vectors, temperature contours, pressure drop and mean Nu number. The results indicate that the combination of a wavy wall and a backward-facing step increases Nu by up to 62% at a Reynolds number of 5000, with a slight increase in pressure drop. This study also showed that the greatest enhancement in heat transfer rate compared to a backward-facing step could be achieved using a trapezoidal wavy bottom with an amplitude height and channel pitch of 4 mm and 20 mm, respectively.

A numerical study of laminar flow by forced convection in an isothermally heated wavy channel with a triangular base, utilizing Cu-water nanofluid, has been conducted (Ahmed et al., 2011). Simulations are performed for volume fractions varying from 0 to 5% and Re from 100 to 1000. The findings reveal that the average Nu number rises with the Re number and nanoparticles volume fractions; but this increase is associated with an increase in the pressure drop. It was also found that the use of nanofluid in wavy channels can be suggested as an appropriate method for achieving enhanced heat exchange efficiency, which may lead to the design of more compact heat exchangers. In (Ahmed et al., 2013(a)), the authors have performed a numerical simulation of the laminar forced convection heat exchange of Cu-water nanofluid in a trapezoidal corrugated channel. They were interested in the effect of concentration in the range of 0% to 5%, the Reynolds number varying between 100 and 700 and the geometric parameters effect such as amplitude and wavelength of the channel corrugation on the pressure drop and the mean Nu. Numerical findings show that the mean Nusselt value increases with nanoparticle volume fraction, Reynolds number and amplitude of the corrugated channel, while the pressure drop also increases. In addition, as the wavelength of the wavy channel rises, the mean Nu decreases and the pressure drop increases. These findings also reveal that the utilization of the copper-water nanofluid in place of conventional fluids using the trapezoidal channel can lead to a further improvement in heat exchange. It may therefore be possible to design more compact, thermally efficient heat exchangers. Ahmad et al. (2013b) considered a numerical study of a forced convection laminar flow using the Al_2O_3-water nanofluid in a triangular channel. The study was conducted for Re ranging from 100 to 800, nanoparticle volume fractions between 0% and 5% and diameters equal to 30, 50 and 70 nm. The findings showed that the Nu increases with the Re and volume fraction of the nanoparticles, but that the pressure drop also increases. Similarly, as nanoparticle size reduces, the Nu increases, while nanoparticle size has no effect on pressure drop. In (Ahmed et al., 2014), the authors have investigated heat exchange numerically in a straight, wavy channel with three bases (trapezoidal, triangular and sinusoidal) using the CuO-water nanofluid. These researchers examined the effect of concentration in the 0-5% range, with Re in the 100-800 range. The findings indicate an improvement in the heat exchange with the increased nanoparticles volume fraction of and increased Re for all shapes of the channel. This study also showed that the trapezoidal channel offers the highest Nu, followed by the sinusoidal, then the triangular and finally the straight channel.. Furthermore, dimensionless pressure drop rises with nanoparticle volume fraction, while it decreases with increasing Re for all shapes of the channel. Khoshvaght-Aliabadi (2014) has numerically investigated forced convection heat transfer and flow in an undulating sinusoidal channel by using the Al_2O_3-water nanofluid. The author examined the influence of geometric factors such as channel height and length, the wavelength, the amplitude of the corrugations, the angles of phase shift for different Reynolds numbers varying from 6000 to 22000 and volume fractions of the nanoparticles varying from 0% to 4%. The findings indicate that nanofluid flow inside sinusoidal channels provides greater values of the Nu relatively to the base fluid, while the values obtained for the nanofluid friction factor and the base fluid are practically the same. Ahmad et al. (2015) conducted an experimental investigation followed by a numerical study of convective heat exchange flow using a SiO2-water nanofluid with three wavy channel shapes (trapezoidal, sinusoidal and straight channel) for Re numbers ranging from 400 to 4000 and different volume fractions equal to 0%, 0.5% and 1%. Numerical and experimental results revealed that the average Nu increased as the nanoparticle volume fraction increased, and that the pressure drop also increased. The authors also found the first channel gave the greatest heat exchange, then the second and finally the third. In (Selimefendigil & Oztop, 2017), the authors have numerically analyzed the laminar forced convection heat exchange of Cu-water nanofluid in a V-shaped channel via a backward-facing step. The authors studied the influences of Re, wave length and height, nanoparticle volume fraction, flow pulsation amplitude and frequency, and heat exchange. The findings demonstrate that the mean Nu rises with Re, as well as with corrugation length and height. The mean Nu increases with the addition of nanoparticles, although the degree of improvement is related to the volume fraction of nanoparticles. The forced convection and turbulent flow characteristics of various kinds of nanoparticles (Al_2O_3, CuO, SiO_2, ZnO) and water as a basic fluid in a straight channel and two configurations of trapezoidal symmetry and zigzag shape have been investigated (Ajeel et al., 2018). Simulations are performed for volume fractions ranging from 0% to 8%; particle diameter varies from 20 nm to 80 nm and Re between 10000 and 30000. The results show that the best nanofluid was SiO_2, monitoring of Al_2O_3, ZnO and CuO-water and that also the symmetry profile of the trapezoidal channel has a significant effect on thermal efficiency in comparison with the zigzag profile. Ajeel et al. (2019a) have carried out a simulation of turbulent flow by forced convection using the ZnO-water nanofluid in a wavy channel with various rib shapes (semicircular, trapezoidal and house). Simulations are carried out for Re in the range 10,000 - 30,000 and volume fractions varying from 0% to 8%. The findings obtained by the study indicate that the Nu and the pressure drop are 1 to 4 times higher for the wavy channels than for the straight channel and that also among wavy channels, the trapezoidal offers the best thermal efficiency, followed by semicircular and triangular. Experimental and numerical investigations were conducted by Ajeel et al., (2019b). The authors focused the improvement of heat exchange in various shapes of wavy channels (semicircular, trapezoidal and straight) using Al_2O_3 as nanoparticles for Re varying from 10000 to 30000 and volume fractions of the Al_2O_3 nanofluid of 0%, 1% and 2%. The results showed that the Nu, the pressure drop for all mid-channel shapes, increases with increasing Re and nanoparticle volume fractions. The research also showed that the new type of trapezoidal corrugated channel is experimentally and numerically confirmed as the best choice for obtaining thermal enhancement in heat exchange devices. Ajeel et al. (2020) studied the heat exchange characteristics of SiO_2-water nanofluid flowing through a house-shaped corrugated channel under a uniform heat flux equal to $10\,kW/m^2$ and Re varying from 10000 to 30000. In their study, the nanoparticle concentration varies from 0% to 8%. The effect of geometric parameters, involving height-to-width ratio (h/W), height-to-length ratio (p/L) and ratio (e/r) on temperature and flow characteristics were the focus of the study. The results demonstrated that increasing the Re and the height/width ratio of the wavy channel had a marked influence on enhancing the mean Nu and the pressure drop. Also, when p/L increases the heat transfer decreases. Mohammed et al. (2016) conducted numerical study on laminar flow and heat exchange of distilled SiO_2-water nanofluid through a wavy channel backward facing step, using the finite difference method for a range of Re varying between 100 and 1500 and a volume fraction of nanoparticles from 0 to 1%. The findings showed that the Nu and the coefficient of friction increase when the amplitude of the wavy channel increases. The study also demonstrated that as the volume fraction of nanoparticles increases, the Nu also rises considerably, with only a modest increase in the friction coefficient.

Our study involves the numerical simulation of two-dimensional forced convection turbulent flow using the Ansys-Fluent computer code, on the one hand, and the K-ε-RNG turbulence model, on the other, through a smooth, then undulating, downward step. The bottom surface is exposed to a constant flow of heat, during a turbulent flow using water as the base fluid for a nanofluid in which spherical nanoparticles of SiO_2 are dispersed at different diameters ($dp = 30$, 50 and 70 nm) and different volume fractions equal to 0%; 1%; 3% and 5%. The principal objective of our research is to demonstrate the influence of nanofluids on thermal efficiency in forced convection, for Reynolds numbers of 10,000, 20,000, 30,000 and 40,000.

Mathematical Modeling

Physical Model

The investigated physical model is depicted in figures 1 and 2. It is a symmetrical, triangular-based wave channel with total channel length, $L_{Total} = 0.2\,m$, including the heights, Hmin and Hmax. The wavelenght of the corrugation is denoted by λ. In addition, the length of the upstream and downstream undulations is $L = 0.04\,m$.

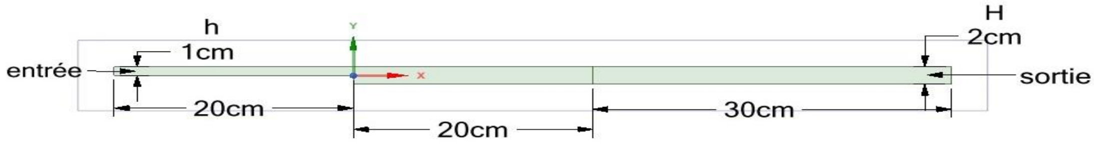


Figure 1. Smooth channel with backward-facing step

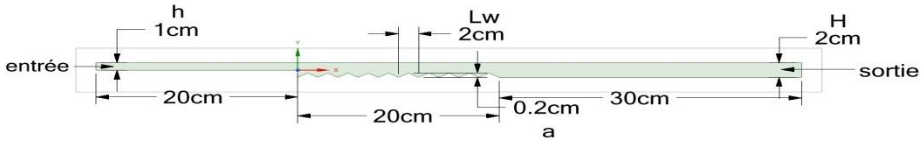


Figure 2. Triangular based corrugated channel with backward-facing step

Flow Equations

The nanofluid under consideration is supposed to be Newtonian and incompressible; viscous dissipation is negligible ($\Phi = 0$) and the fluid's physical characteristics (ρ, u, k, C_p) are constant. The flow equations can be formulated as:

Continuity equation

$$\frac{\partial \bar{U}}{\partial x} + \frac{\partial \bar{V}}{\partial y} = 0 \quad (1)$$

x - Momentum equation

$$\bar{U}\frac{\partial \bar{U}}{\partial x} + \bar{V}\frac{\partial \bar{U}}{\partial y} = -\frac{1}{\rho_{eff}}\frac{\partial \bar{P}}{\partial x} + \frac{\partial}{\partial x}\left[2(\nu_{eff} + \nu_t)\frac{\partial \bar{U}}{\partial x}\right] + \frac{\partial}{\partial y}\left[(\nu_{eff} + \nu_t)\left(\frac{\partial \bar{V}}{\partial x} + \frac{\partial \bar{U}}{\partial y}\right)\right] \quad (2)$$

y - Momentum equation

$$\bar{U}\frac{\partial \bar{V}}{\partial x} + \bar{V}\frac{\partial \bar{V}}{\partial y} = -\frac{1}{\rho_{eff}}\frac{\partial \bar{P}}{\partial y} + \frac{\partial}{\partial y}\left[2(\nu_{eff} + \nu_t)\frac{\partial \bar{V}}{\partial y}\right] + \frac{\partial}{\partial x}\left[(\nu_{eff} + \nu_t)\left(\frac{\partial \bar{V}}{\partial x} + \frac{\partial \bar{U}}{\partial y}\right)\right] \quad (3)$$

Energy equation

$$\bar{U}\frac{\partial \bar{T}}{\partial x} + \bar{V}\frac{\partial \bar{T}}{\partial y} = \frac{\partial}{\partial \mathrm{x}}\left[\left(\frac{\nu_{eff}}{Pr} + \frac{\nu_t}{\sigma_t}\right)\frac{\partial \bar{T}}{\partial \mathrm{x}}\right] + \frac{\partial}{\partial \mathrm{y}}\left[\left(\frac{\nu_{eff}}{Pr} + \frac{\nu_t}{\sigma_t}\right)\frac{\partial \bar{T}}{\partial \mathrm{y}}\right] \quad (4)$$

Equation l'énergie cinétique turbulente.

$$\bar{U}\frac{\partial k}{\partial x} + \bar{V}\frac{\partial k}{\partial y} = \frac{\partial}{\partial \mathrm{x}}\left[\left(\nu_{eff} + \frac{\nu_t}{\sigma_k}\right)\frac{\partial k}{\partial \mathrm{x}}\right] + \frac{\partial}{\partial \mathrm{y}}\left[\left(\nu_{eff} + \frac{\nu_t}{\sigma_k}\right)\frac{\partial k}{\partial \mathrm{y}}\right] + P_k - \varepsilon \quad (5)$$

Equation taux de dissipation de l'énergie cinétique.

$$\bar{U}\frac{\partial \varepsilon}{\partial x} + \bar{V}\frac{\partial \varepsilon}{\partial y} = \frac{\partial}{\partial \mathrm{x}}\left[\left(\nu_{eff} + \frac{\nu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial \mathrm{x}}\right] + \frac{\partial}{\partial \mathrm{y}}\left[\left(\nu_{eff} + \frac{\nu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial \mathrm{y}}\right] + (C_{\varepsilon 1}(P_k) - C_{\varepsilon 2}\varepsilon)\frac{\varepsilon}{k} \quad (6)$$

Where $P_k = \nu_t\left(\frac{\partial \overline{U_i}}{\partial x_j} + \frac{\partial \overline{U_j}}{\partial x_i}\right)\frac{\partial \overline{U_i}}{\partial x_j}$

Dimensionless Numbers

Reynolds Number

$$Re = \frac{UD_h}{\nu} \quad (7)$$

Nusselt Number

$$Nu = \frac{hD_h}{K} \quad (8)$$

Boundary Conditions

- Inlet of the channel

A velocity is imposed at the inlet of the channel, given by:

$$U_{eff} = \frac{Re \times \mu_{eff}}{D_h \times \rho_{eff}} \tag{9}$$

A constant temperature is subject at the inlet $T_{eff} = 300°K$

Turbulent kinetic energy k and turbulent dissipation rate ε are expressed as follows:

$$k = \frac{3}{2} U^2 I^2 \tag{10}$$

Where $I = 0.16 Re^{-1/8}$ and $Re = \frac{UD_h}{\nu}$

$$\varepsilon = C_\mu^{3/4} \frac{k^{3/2}}{l} \tag{11}$$

Where $l = 0.07L$ and $L = D_h$

- Outlet the of channel

$\frac{\partial U}{\partial x} = 0$;$\frac{\partial V}{\partial x} = 0$; $\frac{\partial T}{\partial x} = 0$; $\frac{\partial \mathrm{k}}{\partial \mathrm{x}} = 0$; $\frac{\partial \varepsilon}{\partial \mathrm{x}} = 0$

A heat flux $\varphi = 4000 w/m^2$ is imposed on the bottom wall of the backward-facing step.

Property of the Nanofluid

The thermo-physical characteristics of the SiO2-Water nanofluid employed in this research are:

Density

$$\rho_{nf} = (1 - \varphi)\, \rho_f + \varphi \rho_P \tag{12}$$

Heat Capacity

Model of Xuan & Roetzel (2000):

$$(\rho Cp)_{nf} = (1 - \varphi)\, (\rho Cp)_f + \rho Cp)p \tag{13}$$

Effective Dynamic Viscosity

Model of Corcione (2010):

$$\frac{\mu_{nf}}{\mu_f} = \frac{1}{1 - 34{,}87 (\frac{dp}{df})^{-0.3} \varphi^{1.03}} \tag{14}$$

Where d_p is the diameter of the SiO_2 particle and df is the diameter of the water.

Effective Thermal Conductivity

Model of Maxwell (1882):

$$K_{eff} = K_{statistique} + K_{brownien} \tag{15}$$

Where: $$K_{statistique} = \frac{K_p+2K_{bf}+2\phi(K_p-K_{bf})}{K_p+2K_f-\phi(K_p-K_{bf})}K_{bf} \tag{16}$$

$$K_{brownien} = 5\times10^4\beta\phi\rho_{bf}Cp_{bf}\sqrt{\frac{K_BT}{\rho_p d_p}}f(T,\phi) \tag{17}$$

$$f(T,\phi) = (2.8217\times10^{-2}\phi + 3.917\times10^{-3})\left(\frac{T}{T_0}\right) + (-3.0669\times10^{-2}\phi - 3.391123\times10^{-3})$$

Numerical Modeling

The flow equations and heat exchange are solved by the finite volume method. In order to simulate and calculate the fluid flow properties of the studied problem, the CFD calculation code ANSYS FLUENT 2019 was used. This code offers extensive solutions for the most complicated geometries. The precision and stability of the results of our simulation depends on the quality of the mesh, so a mesh independence test has been carried out for different numbers of nodes.

Discretization Schemes

The discretization schemes used in this study are presented in the table1.

Table1. Discretization schemes

Variable	Nature of scheme
Pressure	Standard
Velocity and pressure coupling	Simple
Momentum Quantity	Second order upwind
Energy	Second order upwind

Mesh Effect and Validation

Mesh Effect

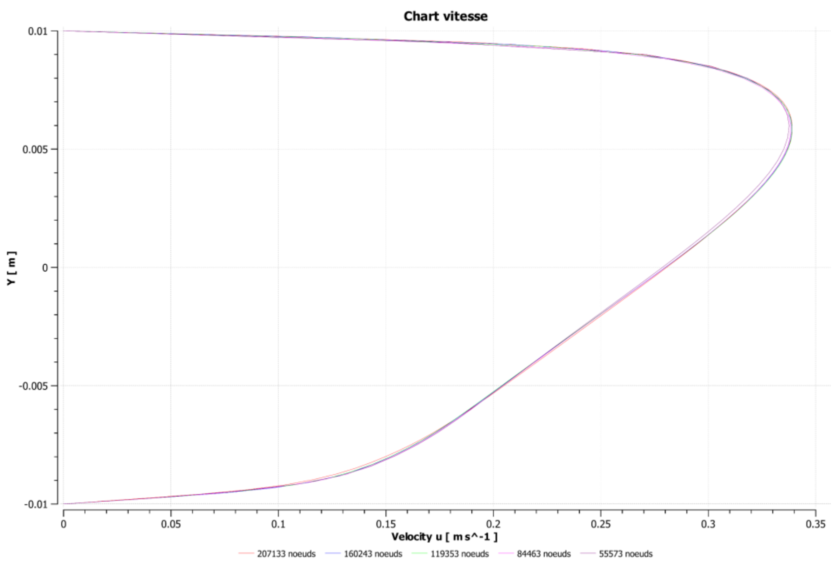


Figure 03. Velocity profiles for different mesh sizes, at Re=10000 and ϕ=0% at station x=10cm.

To demonstrate the influence of the mesh size on the solution, five mesh sizes were examined 55573; 84463; 119353; 160243 and 207133 for Re = 10000 and $\phi = 0\%$. The effect of the nodes number on the solution is expressed by the profile of the axial velocity. Figure 3 illustrates the change in the axial component of the velocity. It is noticed that the curves of the various meshes have an identical pace and that the profiles not dependent on the number of nodes.So our choice fell on mesh 4; to save time and preserve computer capacity. Note also that this mesh captures better the dynamic and thermal boundary layers near solid walls.

Validation of the Results

The numerical simulation validation is required to verify the precision of the numerical findings obtained by the ANSYS FLUENT 2019 calculation code. Our results were compared with the Dittus Boelter correlation. Figure 4 shows the change in the average Nu versus Re for a smooth channel filled with water. It can be seen that average Nusselt values rise with Re, and that there is also good concordance between our findings and the calculation by the Dittus Boelter correlation.

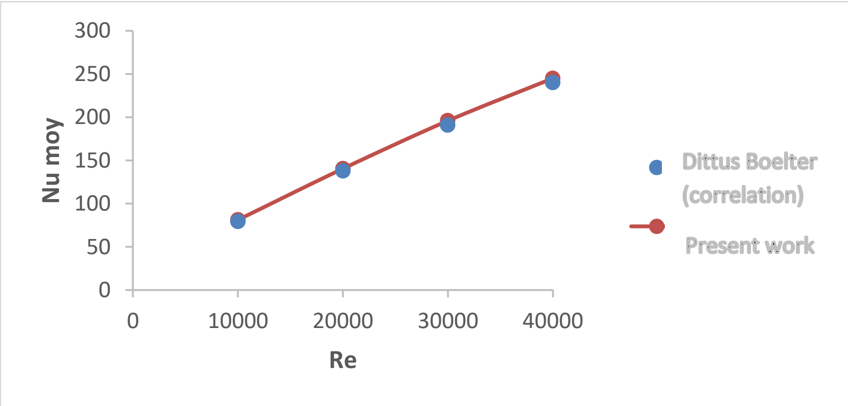


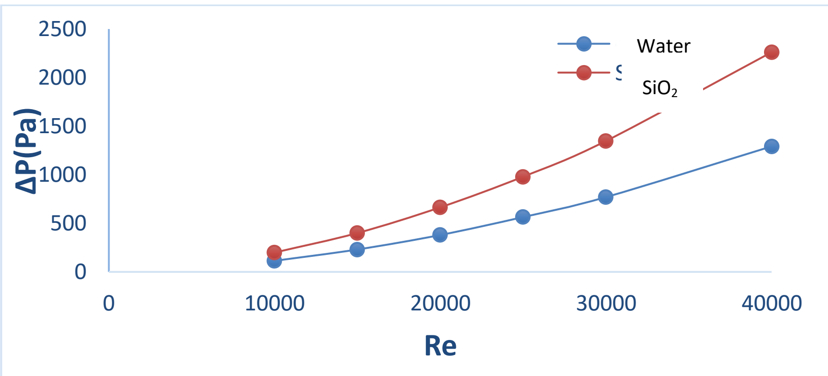
Figure 04. Variation of average Nu versus Re

Results Discussion

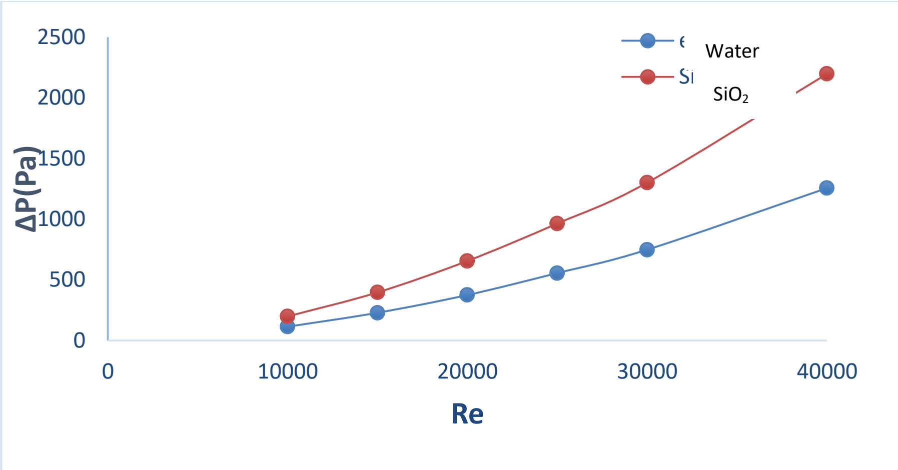
This section is devoted to showing the findings obtained by numerical simulation using the Ansys-Fluent computer code, where the impact of Re, volume fraction and particle size will be studied.

Reynolds Number Effect

The pressure drop of the nano-fluid SiO_2 and water for different Re in the smooth and corrugated backward facing step is shown in Figure 5 (a) and (b). These figures show an increase in pressure drop with rising Re.. This is caused by an increase in the average velocity, which translates into a greater velocity gradient near the walls, and hence into greater shear stress. We also note that the pressure drop values are very high for SiO_2, especially for Re values of 30000 and 40000.



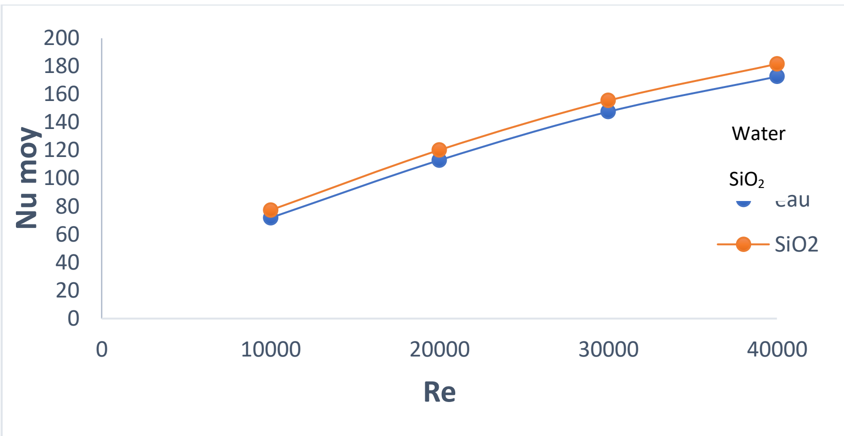
(a)



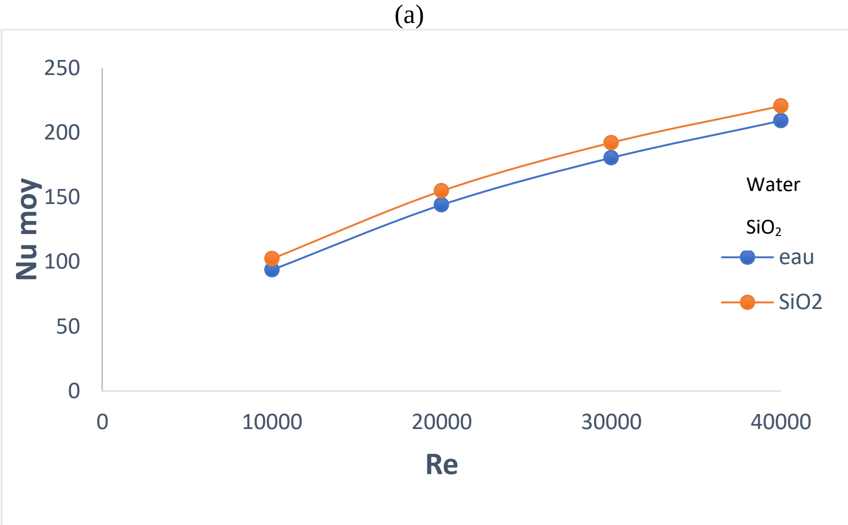
(b)

Figure 5. Pressure drop versus Reynolds : (a) Smooth backward facing step, (b) Corrugated backward-facing step

Figure 6 shows the change of the average Nu versus Re for water and SiO_2 with volume fraction equal to 3% and diameter $dp = 30nm$. We can see that the Nu rises proportionally with the Re due to the improved fluid particle motion, where we can clearly see that the Nu values are high for $Re = 40000$ compared to those for Re =10000. We can therefore say that the rate of heat exchange is improved.. These figures also show that the mean Nu for SiO_2 is higher than for water in both the smooth and corrugated backward facing step cases.



(a)

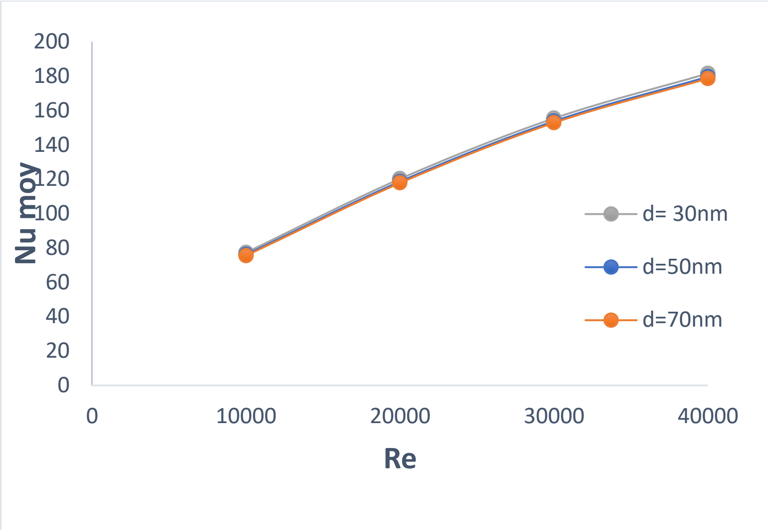


(b)

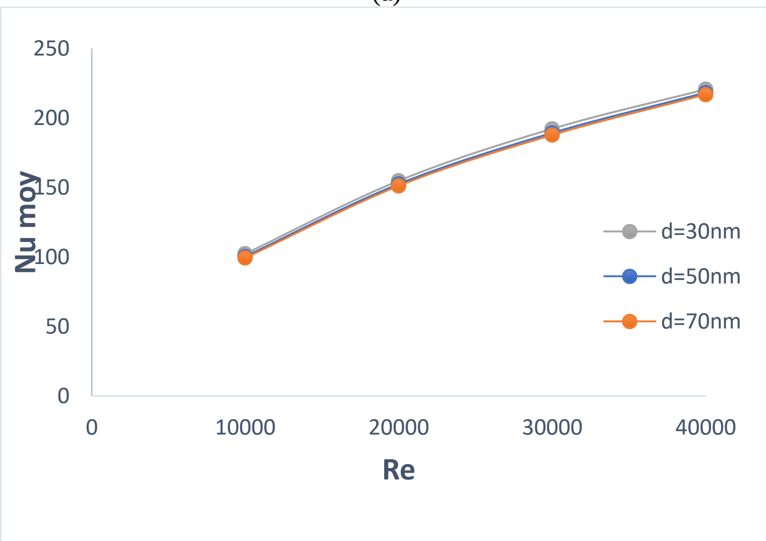
Figure 6. Mean Nu versus Re

Size of the Particle Effect

Figure 7 illustrates the influence of particle diameter on the average Nu versus Re with various particle diameters ($dp = 30nm$, 50nm and 70nm) and $\phi = 3\%$, in a smooth and corrugated channel with a triangular base. In the case of the smooth channel, the Nu rises with increasing Re and decreasing particle size; the Nusselt number values are much higher for $dp = 30nm$ than those corresponding to $dp = 30nm$ and 70nm. This is due to the increased exchange surface, nanoparticle aggregation and stronger Brownian motion for smaller nanoparticle diameters, leading to higher nanofluid thermal conductivity. The larger the nanoparticles, the weaker this Brownian motion will be, as they will be more difficult to move due to their greater inertia, and will have a lower displacement speed and therefore more efficient heat transfer when the particle size decreases. The same applies to the corrugated channel, but at higher values.



(a)



(b)

Figure 7. Average Nu for various particle diameters with $\phi = 3\%$: (a) Smooth backward facing step, (b) corrugated backward facing step

Conclusion

In this work, we have numerically investigated the two-dimensional heat exchange by turbulent forced convection for water and the SiO_2-water nanofluid inside a smooth, corrugated channel with a triangular base whose bottom wall is subjected to a constant heat flow. The effect of Re and oxide particle size on thermal and hydraulic behavior through the smooth, corrugated channel with two backward-facing steps has been investigated. The obtained findings show that:

- An increase in Reynolds number results in an increase in Nu and pressure drop.
- The SiO_2-water nanofluid with the 3% fraction provides the best heat transfer enhancement, and oxide nanoparticles offer a high performance for increasing the Nu compared with water.
- Nu is affected by Re, an increase in the latter leads to a rise in the Nu, and the corrugated channel provides the highest Nu values compared with the smooth channel.
- Particle diameter has a significant influence on the Nu. Smaller particle diameters tend to increase both Nusselt number and pressure drop.

Scientific Ethics Declaration

The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Acknowledgements or Notes

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