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Flow and Heat Transfer of the Cu-Water Nanofluid in a Corrugated Channel

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ABSTRACT

This paper is devoted to study the influence of the Cu-water nanofluid on a two-dimensional laminar and incompressible flow and heat transfer in a corrugated triangular-based channel filled with homogeneous mixture of water and metallic nanoparticles. The equations governing the problem were solved using the finite volume method. ANSYS 15.0 FLUENT software was used to perform the numerical simulations. These numerical simulations were carried out for different values of the Reynolds number ranging from 100 to 1000 and for metallic nanoparticles of diameter $dp = 30\, nm$ with volume fractions of 0% and 5%. The effect of the Reynolds number, the nature of the nanofluid on the flow field and the heat transfer were studied. Note that the obtained results are in good agreement with the results existing in the literature.

Keywords: Cu-water nanofluid, Fluent, forced convection, Reynolds number, volume fraction

1. INTRODUCTION

The need to improve heat transfer by forced convection is the main goal of several studies. Improvements by increasing the exchange surfaces are a method already widely explored and have reached their limits. Generally, the effectiveness is limited by the thermophysical properties of the used fluids. With the emergence and rapid development of nanosciences and nanotechnologies during the second half of the 20th century, convection has taken a large part of this new domain. Scientists introduced nanoscale particles to the field and found that compared to millimeter and micrometer size particles, (nanoscale particles are suspended in conventional fluid) the associated systems are very stable. Later, Choi [20] conducted a study on the heat capacity of fluids using nanoscale particles dispersed in base fluids in the hope of increasing the effective thermal conductivity of the mixture resulting in the birth of nanofluids. Hence nanofluids, due to their excellent thermal performance compared to other heat transfer fluids, have occupied a very important place in various fields of application, such as heating of buildings, heat exchangers, automotive cooling applications etc.

During the last two decades, many authors have taken an interest in this field of application.

Ahmed et al. [1] presented a numerical study of nanofluid (Cu-water) flow flowing through an isothermally heated triangular-based corrugated channel. The simulations are carried out for volume fractions between 0 and 0.05 and a Reynolds number ranging from 10 to 1000. The results show that the average Nusselt number increases with the increase in the volume fractions of the nanofluid, but this improvement is accompanied by an increase in pressure drop and it was found that the improvement in heat transfer mainly depends on the volume fraction of the nanofluid and the Reynolds number.

Ajeel et al. [2] carried out a numerical study concerning a turbulent flow of forced convection in different configurations of corrugated and trapezoidal channels filled with four different types of nanofluids (Al_2O_3, CuO, SiO_2 and ZnO-water) at constant heat flux ($10KW\ /\ m^2$). The simulations are realized for a Reynolds number varying from 10000 to 30000. The results show that the SiO_2-water nanofluid exhibits an increase in heat transfer, the highest compared to the others for all the studied shapes. These authors also found that the adopted geometry of the corrugated and trapezoidal channel can improve the heat transfer by more than twice that of the straight channel.

Ahmed et al. [3] have studied numerically the heat transfer by forced convection of nanofluid (Cu-water) in a trapezoidal channel. This study also focused on the effects of geometric parameters such as channel wavelength, amplitude, Reynolds number and volume fractions of the nanofluid on velocity vectors, temperature contours, pressure drop and mean Nusselt number. The results show that the mean Nusselt number increases with increasing volume fractions of the nanofluid and with channel amplitude, but this improvement is accompanied by an increase in pressure drop. Also, the authors noted that as the wavelength decreases the Nusselt number increases and the pressure drop decreases.

Ahmed et al. [4] presented a numerical work to study heat transfer in a straight and corrugated channel at three different bases (trapezoidal, triangular and sinusoidal) filled with nanofluid (CuO-water). The authors studied the effects of volume fraction of nanoparticles and Reynolds number on temperature, velocity and Nusselt number. The authors conclude that the mean Nusselt number increases with increasing nanoparticle volume fractions and Reynolds number for the three considered corrugations. This study also showed that the trapezoidal base channel gives the best heat transfer compared to other channels.

Abed et al. [5] numerically studied the heat transfer characteristics in a corrugated V-form channel filled with four types of nanoparticles (Al_2O_3, CuO, SiO_2 and ZnO) and three different types of base fluid (water, glycerin and ethylene glycol). The authors have shown that SiO_2 gives the best improvement in heat transfer and particularly when it is dispersed in glycerin unlike other base fluids.

In order to improve heat transfer, Tokgoz et al. [6] have studied numerically the heat transfer characteristics of the water-based Al_2O_3nanofluid in a rectangular channel for different phase angles. The simulations are carried out for Reynolds number between 500 and 2000 and volume fractions ranging from 0 to 0.08. The results show that the addition of nanoparticles to the base fluid and the use of corrugated channels increase heat transfer.

Ahmed et al. [7] performed a numerical study of a turbulent flow of forced convection through a triangular channel with different volume fractions of nanoparticles (Al_2O_3, CuO, SiO_2 and ZnO) of varying diameter. The results show that the mean Nusselt number increases with increasing nanofluid volume fractions and decreasing nanoparticle diameter. In addition, the SiO_2-water nanofluid exhibits an increase in heat transfer and it is the highest compared to that of other nanofluids.

The characteristics of heat transfer and flow of different types of nanoparticles (Al_2O_3, CuO, SiO_2, ZnO) and three different types of base fluid (water, ethylene glycol, motor oil) in a triangular base channel studied numerically by Kuppusamy et al. [8]. The simulations are carried out for volume fractions between 0 and 0.04 and the diameter of the particle varying from 25 nm to 80 nm. The results show that the best base fluid and the best nanoparticle are H_2O and Al_2O_3, respectively. The authors also found that heat transfer increases with increasing nanofluid volume fractions and decreasing nanoparticle diameter.

Srinivas el al. [9] carried out a numerical study on the effects of the diameter of the nanoparticles and the volume fractions of the Au-water nanofluid, the amplitude of the channel and the Reynolds number on the heat transfer in different corrugated channels (triangular, trapezoidal, sinusoidal and square). The authors showed that the square-based corrugated channel gives the best heat transfer compared to the other channels.

An experimental study followed by a numerical study was carried out by Ahmed et al. [10]. The authors were interested in improving heat transfer in different forms of corrugated channels (trapezoidal, sinusoidal and straight channel) using SiO_2 as nanoparticles. The results show that the mean Nusselt number increases with increasing volume fraction of nanoparticles and that the trapezoidal channel gives the best heat transfer, followed by the sinusoidal, then the right channel.

Majdi and Abed [11] studied numerically a flow of the SiO_2-water nanofluid in a corrugated channel for a Reynolds number range varying from 5000 to 20,000; volume fractions between 0 and 0.04 and different diameters of nanoparticles varying from 20 nm to 80 nm. Simulation results indicate that the mean Nusselt number increases with increasing volume fraction and Reynolds number and decreasing nanoparticle diameter, but with this increase results an increase in pressure drop.

Vanaki and Mohammed [12] carried out a numerical study concerning a turbulent flow of a forced convection in a corrugated channel with different forms of ribs(rectangular, triangular, etc…) and four types of nanoparticles (Al_2O_3, CuO, SiO_2 and ZnO), with variable diameter. The authors showed that the Nusselt number across the ribbed channels increased with increasing volume fraction, Reynolds number and decreasing particle diameters. It was found that the SiO_2–water nanofluid provides the highest values of the Nusselt number with a particle diameter equal to 30 nm and for 4% concentration.

Ahmed et al. [13] considered a laminar flow of a forced convection of the Al_2O_3-water nanofluid with different volume fractions between 0 and 0.05 in a sinusoidal corrugated channel with corrugation angles varying from 0° to 180° and for a range of Reynolds number varying from 100 to 800. The results show that the mean Nusselt number increases with increasing Reynolds number, volume fractions of nanoparticles and also with the decrease in the corrugation angle.

A numerical study concerning a turbulent flow of forced convection with four types of nanoparticles (Al_2O_3-CuO-SiO_2 and ZnO) in different forms of corrugated channels was carried out by Al-Shamani et al. [14]. The simulations are realized for a Reynolds number varying from 10,000 to 40,000; volume fractions between 1 and 0.04 and different diameters of nanoparticles varying from 25 nm to 70 nm. The results show that the mean Nusselt number increases with increasing volume fraction and Reynolds number and decreasing nanoparticle diameter. Also, the SiO_2-water nanofluid exhibits an increase in heat transfer, the highest, followed by Al_2O_3; ZnO; CuO and finally by pure water.

Ajeel et al. [15] studied numerically the effects of geometric parameters such as ratio (height / length) and ratio (height / width), Reynolds number on mean Nusselt number, pressure drop and performance factor thermal for a turbulent flow of the nanofluid SiO_2–water in a trapezoidal channel. The results show that the mean Nusselt number increases with increasing Reynolds number and ratio (height / width), but this improvement is accompanied by an increase in pressure drop. Also, the authors noticed that the mean Nusselt number decreases and that the pressure drop increases as the ratio (height / length) increases and that the ratios (height / width), (height / length) of 0.075 are the optimal parameters, with values equal to 0.05 and 0.075; respectively. In addition, these authors have shown a significant improvement in the thermal performance factor.

The heat transfer characteristics of the SiO_2-water nanofluid flowing through a semi-circular symmetry channel under a turbulent regime have been investigated numerically by Ajeel et al. [16]. In their study, the authors considered that the concentration of nanoparticles varies between 0% and 8% and for a row of the Reynolds number varying from 10000 to 30000. The results show that the average Nusselt number increases with the increase in the Reynolds number and with the height of the corrugated channel, but this increase is accompanied by an increase in the pressure drop. This study also showed that the highest Nusselt values are evaluated for the corrugated height of $2.5\,mm$ with a longitudinal corrugation wavelength of 15.0 mm.

Ajeel et al. [17] carried out a numerical study concerning turbulent flow of a forced convection with different types of nanoparticles (ZnO, Al_2O_3, CuO and SiO_2), of variable diameter, in a corrugated channel. The simulations are carried out for Reynolds number between 10000 and 30000, volume fractions varying from 0.02 to 0.08 and nanoparticle diameters varying from 20 nm to 80 nm. The obtained results show that the use of corrugated channel in a zigzag shape semicircle plays an important role in increasing heat transfer. In addition, the authors noticed that the SiO_2-water nanofluid gives the best improvement in heat transfer followed by Al_2O_3, ZnO and finally CuO. Also, the adopted geometry of the semi-circle corrugated channel can increase the heat transfer with a rate of 1.5 to 2.7 times higher than that of the straight channel.

Ajeel et al. [18] studied numerically the heat transfer characteristics and flow of different types of nanoparticles (Al_2O_3, CuO, SiO_2, ZnO) in a trapezoidal channel of different types shapes for volume fractions varying between 0% and 8 % and nanoparticle diameters ranging from 20 nm to 80 nm and Reynolds ranging between 10,000 and 30,000. The authors have shown that the adopted geometry of the trapezoidal channel can increase heat transfer with a rate of 2.3 to 3.7 times higher compared to right channel. Also, it was found that the mean Nusselt number increases with the increase in Reynolds number and the volume fraction and the decrease in the diameter of nanoparticles. In addition, the authors showed that SiO_2-water gives the highest values of the Nusselt number compared to others.

Salman [19] carried out a numerical study concerning a turbulent flow of forced convection in a corrugated channel with different rib shapes (rectangular, triangular and trapezoidal) filled with four different types of nanofluids (SiO_2, CuO, Al_2O_3 and ZnO-water) at constant heat flow. The results obtained by the study indicate that the Nusselt number through the ribbed channels was increased with increasing volume fractions, Reynolds number and decreasing particle diameters and it was also found that the Maximum improvement in heat transfer is about 1.66 for SiO_2 nanoparticles of size 30 nm and volume fraction of 4% with the use of the triangular ribs at a Reynolds number of 10,000.

2. MATHEMATICAL MODELING

2.1 Physical model

The studied physical model is represented in figure1. It is a corrugated channel with triangular base, symmetrical, which is characterized by a total length of the channel$L_{Total} = 0.2\,m$, a minimum height Hmin and maximum Hmax and a wavelenght of the corrugation λ. The upstream and downstream length of the corrugations is$L = 0.04m$.

The channel is filled with a homogeneous mixture of water and metallic nanoparticles, the thermophysical properties of the base fluid (water) and the nanoparticles are taken at $293\,°K$ and are summarized in table 1, below.

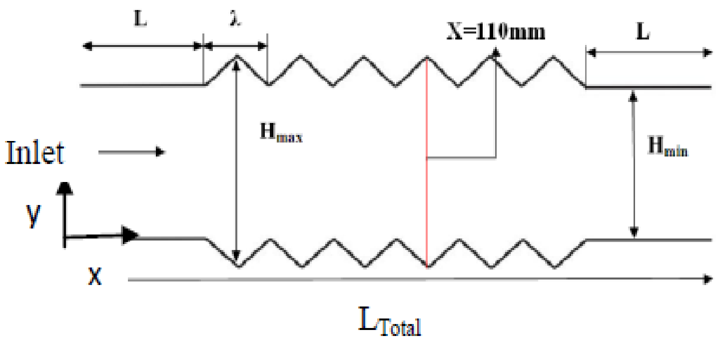

Figure 1.Studied configuration

2.2 Governing equations

- The considered nanofluid is assumed to be Newtonian and incompressible
- The viscous dissipation is negligible ($\Phi = 0$)
- The physical properties of the fluid (ρ, u, k, C_p) are constant.

The main governing equations can be written in the following form:

Continuity equation

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \qquad (1)$$

x - Momentum equation

$$\left(u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y}\right) = \frac{1}{\rho_{nf}}\left[-\frac{\partial P}{\partial x} + \mu_{nf}\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right)\right] \qquad (2)$$

y - Momentum equation

$$\left(u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y}\right) = \frac{1}{\rho_{nf}}\left[-\frac{\partial P}{\partial y} + \mu_{nf}\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right)\right] (3)$$

Energy equation

$$u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial Y} = \alpha_{nf}\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right) \qquad (4)$$

$\alpha_{nf} = \frac{K_{nf}}{\rho_{nf} Cp_{nf}}$: thermal diffusivity of the nanofluid

2.3 Dimensionless numbers

Reynolds numbers

$$Re = \frac{\rho V D_h}{\mu}$$

Nusselt numbers

$$Nu = \frac{h\, D_h}{k}$$

h: convective heat transfer coefficient [W/m^2.°K].

Friction coefficient

$c_f = \frac{\tau_w}{\frac{1}{2}\rho U^2}$, τ_w : Shear stress

2.4 Boundary conditions

Channel inlet

- An inlet velocity is imposed and it is calculated as follows:

$$u_{nf} = \frac{\mu_{nf} \times R_e}{D_h \times \rho_{nf}} \quad (5a)$$

-And a constant temperature of the fluid at the inlet of the channel$T_{nf} = 293\ °K$.

Channel outlet

The triangular configuration of the channel being formed of six corrugations, so the output is sufficiently far away, the flow can be assumed to be fully developed, which results in a normal zero gradient for all the physical quantities governed by a differential transport equation.

$$\frac{\partial u}{\partial x} = 0, \frac{\partial v}{\partial x} = 0, \frac{\partial T}{\partial x} = 0 \qquad (5b)$$

Treatment near the walls

Near the upper and lower solid walls, the impermeability and non-slip conditions are used. They imply that:

$$u = v = 0 \qquad (5c)$$

A warm temperature compared to that of the fluid in the channel is also imposed on the walls.

2.4 Nanofluid property

The thermo physical properties of the Cu-Water nanofluid used in this study are given as follows:

2.4.1 Density

$$\rho_{nf} = (1 - \varphi)\,\rho_f + \varphi \rho_P \qquad (6)$$

2.4.2 Heat capacity

The model proposed by Xuan et al. [21] is given by:

$$(\rho Cp)_{nf} = (1-\varphi)\,(\rho Cp)_f + \rho Cp)p \quad (7)$$

2.4.3 Effective dynamic viscosity

Several models are proposed in the literature for modeling the effective viscosity of nanofluids (Brinkman [22]; Corcione [23]; etc…). In this work, it is evaluated by the correlation proposed by Corcione [23] and expressed as follows:

$$\frac{\mu_{nf}}{\mu_f} = \frac{1}{1-34{,}87(\frac{d_p}{d_f})^{-0.3}\varphi^{1.03}} \quad (8)$$

Where: dp is the diameter of the Cuparticle and $df$is the diameter of the water base fluid.

2.4.4 Effective thermal conductivity

The thermal conductivity of the nanofluid is evaluated by the following correlation proposed by Patel et al.[24]

$$\frac{k_{eff}}{k_f} = 1 + \frac{k_p A_p}{k_f A_f} + c k_p p_e \frac{A_p}{k_f A_f} \quad (9)$$

Avec: $\frac{A_p}{A_f} = \frac{d_f}{d_p}\frac{\phi}{(1-\phi)}$, $p_e = \frac{u_p d_p}{\alpha_f}$

u_p : is the velocity of particles brownian motion, which is given by

$$u_p = \frac{2k_b T}{\pi\,\mu_f {d_p}^2}$$

k_b: Boltzmann constant (1.38064852×10^{-23} [J/k]), d_p: particle diameter, d_f : base fluid diameter.

Table1. Thermo-physical properties of base fluid (water) and metallic nanoparticles at 293 ° K

	$\rho(kg/m^3)$	C_p (J / Kg.°K)	K (W / m.°K)	μ (kg /m.s)
Eau	1000.52	4181.8	0.597	0.001
Cu	8954	383.1	386	-------

3. NUMERICAL MODELING

The equations governing flow and heat transfer are discretized using the finite volume method. To deal with the velocity-pressure coupling, the Simple Algorithm was used.

4. MESH EFFECT AND VALIDATION

To show the effect of the mesh on the solution, three meshes were tested 91688; 117085 and 158168 in flow regime for a Reynolds number $Re = 500$ and a volume fraction equal to 0%. Figures2 and 3 represent the variation of the local Nusselt number and friction coefficient for different meshes, respectively. It is noted that the mesh 117085 gives an independent solution of nodes number. The validation of the numerical simulation is necessary in order to verify the accuracy of the numerical results. A comparison of our results with the numerical results found by Ahmed [1] is carried out.

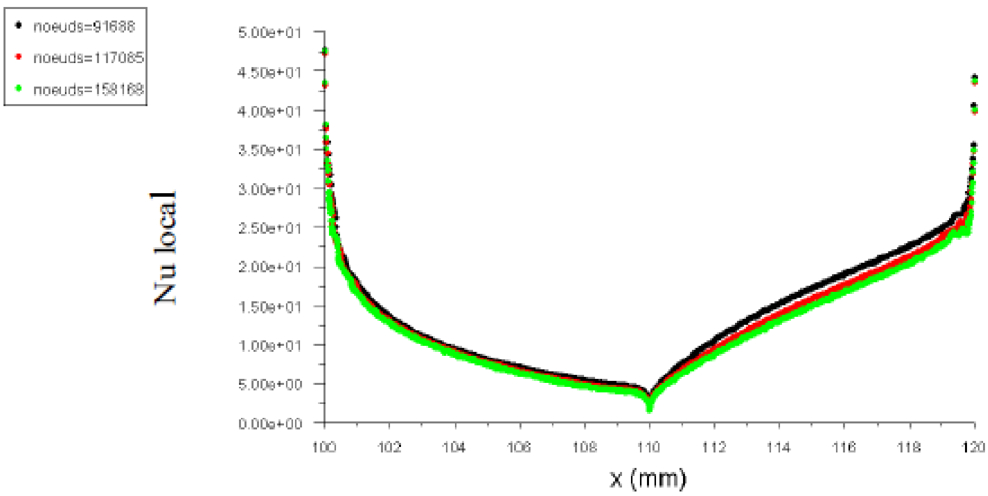

Figure2: Variation of the local Nusselt number with $\varphi = 0\%$ and $Re = 500$ for different Meshes.

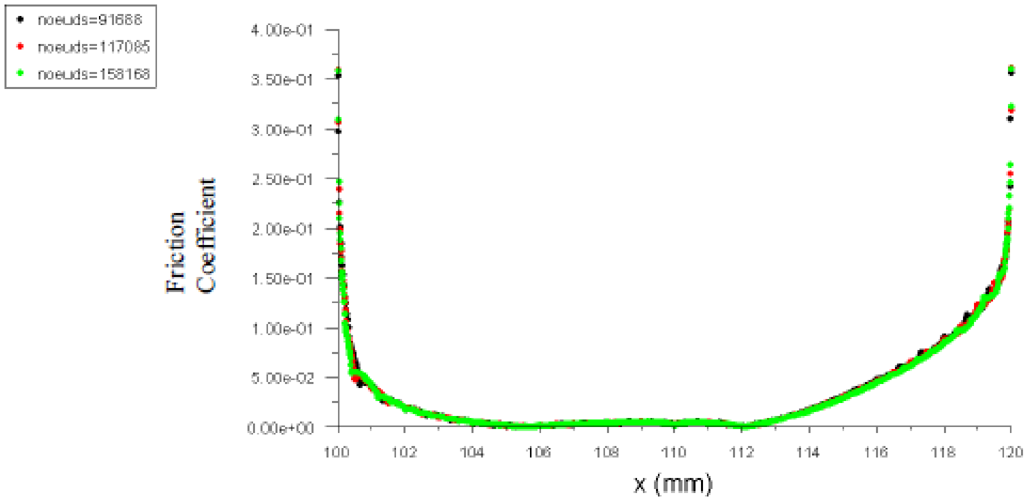

Figure 3: Variation of the local friction coefficient with $\varphi = 0\%$ and $Re = 500$ for different Meshes.

Figure 4 represents the variation of the mean Nusselt number as a function of the Reynolds number for a corrugated channel with a triangular base with a volume fraction φ = 0%. Note that the mean Nusselt values increase with increasing Reynolds number. Also, we note a good agreement between the results obtained by the present simulation and those of Ahmed [1].

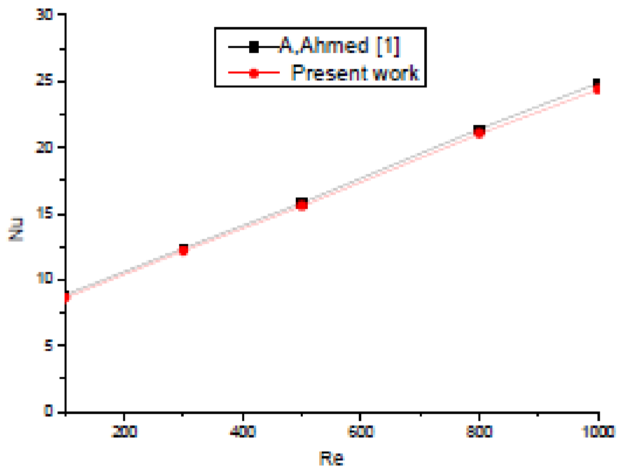

Figure 4: Variation of the mean Nusselt number for different Reynolds numbers with $\varphi = 0\%$

5. RESULTS AND DISCUSSION

In this section, we will present the results of the numerical simulation obtained by the Ansys-Fluent 15.0 computer code where we will study the effect of the Reynolds number which varies between 100 and 1000 for a volume fraction of 5% of a Cu-water nanofluid on the dynamic and thermal field.

Figure 5 represents the profiles of the axial velocity with φ = 0% and at station x = 110mm for different Reynolds numbers. We see that the velocity values increase with increasing Reynolds number and that the maximum velocity is located on the channel axis. Also, we notice the appearance of negative velocity values for different Reynolds numbers. This is due to the appearance of the recirculation zone. The zone corresponding to the negative value increases with the increase in the Reynolds number.

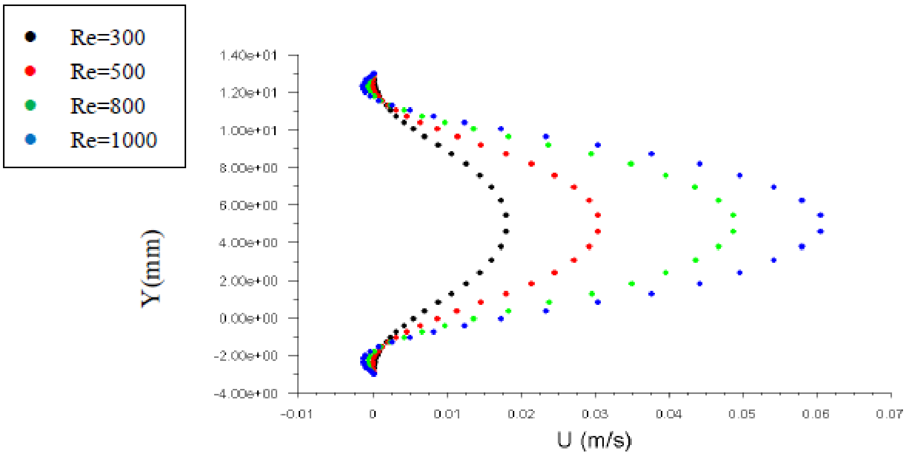

Figure 5: Profiles of the axial velocity with $\varphi = 0\%$ for different Reynolds numbers at station $x = 110mm$.

Static temperature profiles obtained for different Reynolds numbers with φ = 5% and at station $x = 110mm$ are shown in figure 6. We notice a minimum value corresponding to the temperature at the center of the channel, which increases when we are brings the upper and lower walls of the channel closer together. We also note that as we approach the hot walls, the temperature of the fluid increases gradually for low Reynolds numbers. This shows that the heat exchange between the fluid and the wall is better unlike large values of the Reynolds number where the heat exchange is poor. This is due to the appearance of recirculation zone whose size is more and more larger, with increasing flow regime.

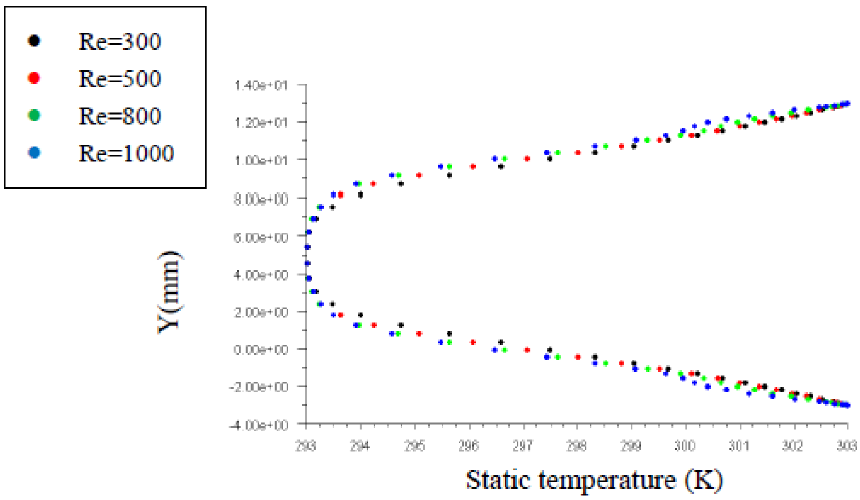

Figure 6: Static temperature profiles with $\varphi = 0\%$ for different Reynolds numbers at station $x = 110mm$.

Figure 7 shows the local distribution of Nusselt numbers as a function of Reynolds with φ = 0%. We note that the values of the local Nusselt number increase with increasing Reynolds number. In addition, we see that when the fluid is attached at walls where the velocities are very high, the Nusselt number has maximum values and therefore the heat transfer between the wall and the fluid is very important. Also, it is noted that at the level of the corrugation where there is the appearance of recirculation zones, the values of the Nusselt number are minimal, since in these zones the fluid is stagnant and therefore the heat transfer is minimal.

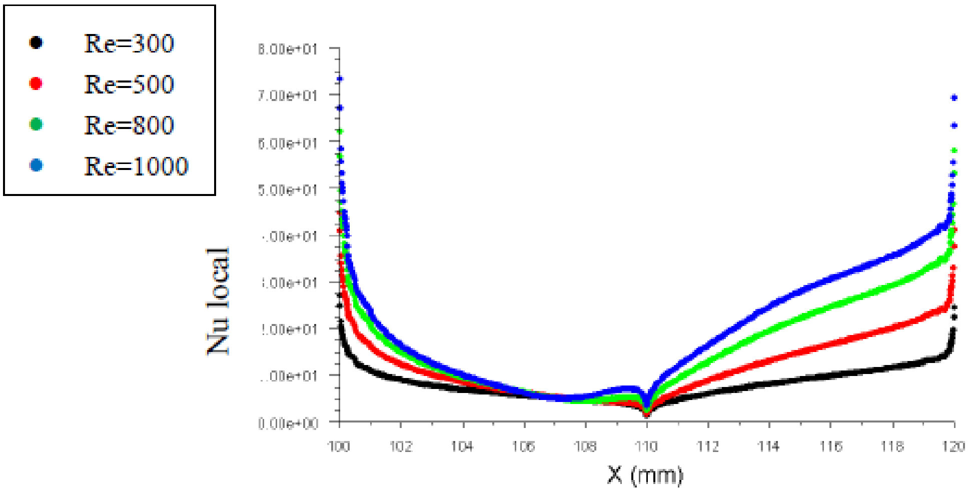

Figure 7: Variation of the local Nusselt number with $\varphi = 5\%$ for different Reynolds numbers

Figure 8 illustrates the local variation of the local Nusselt number with φ = 5%, for different Reynolds numbers. For all the higher corrugations, this figure clearly shows the periodicity of the phenomenon in the corrugated channel. Also, we note that the maximum value of the Nusselt number is reached at the level of the first corrugation where the heat exchange between the nanofluid and the heated walls begins, because upstream of the corrugations the walls are adiabatic.

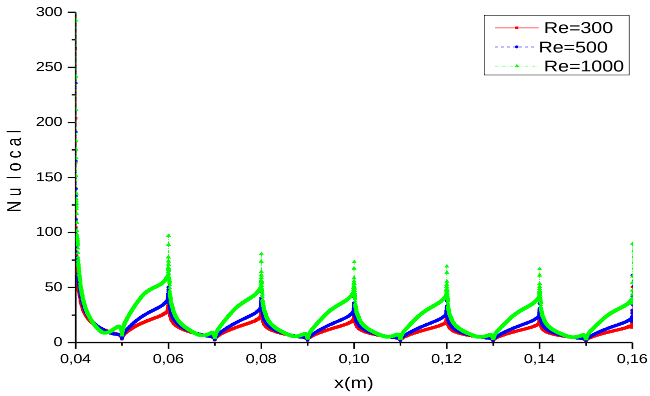

Figure 8: Variation of the local Nusselt number with $\varphi = 5\%$ for different Reynolds numbers for all the higher corrugations

CONCLUSION

The work presented in this paper concerns a numerical simulation study of heat transfer by forced convection in a corrugated channel with a triangular base filled with Cu metallic nanoparticles dispersed in pure water in stationary laminar flow. This study allowed us to see the effect of the Reynolds number on the flow and heat transfer of metal particles. The obtained results show that:

- The increase in Reynolds number results in an increase in recirculation zones.
- Nusselt numbers are influenced by the Reynolds number, an increase in the later leads to an increase in the Nusselt number.

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