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The effect of velocity and dimension of solid nanoparticles on heat transfer in non-Newtonian nanofluid

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ABSTRACT

In this investigation, the behavior of non-Newtonian nanofluid hydrodynamic and heat transfer are simulated. In this study, we numerically simulated a laminar forced non-Newtonian nanofluid flow containing a 0.5 wt% carboxy methyl cellulose (CMC) solutionin water as the base fluid with alumina at volume fractions of 0.5 and 1.5 as the solid nanoparticle. Numerical solution was modelled in Cartesian coordinate system in a two-dimensional microchannel in Reynolds number range of $10 \le Re \le 1000$. The analyzed geometrical space here was a rectangular part of whose upper and bottom walls was influenced by a constant temperature. The effect of volume fraction of the nanoparticles, Reynolds number and non-Newtonian nanofluids was studied. In this research, the changes pressure drop, the Nusselt number, dimensionless temperature and heat transfer coefficient, caused by the motion of non-Newtonian nanofluids are described. The results indicated that the increase of the volume fraction of the solid nanoparticles and a reduction in the diameter of the nanoparticles would improve heat transfer which is more significant in Reynolds number. The results of the introduced parameters in the form of graphs drawing and for different parameters are compared.

1. Introduction

The resulted increase in thermal conductivity and improvement in thermal conductivity behavior in form of the so-called "nanofluids" heralds their future use as operational fluids in various industries as well as tools. In order to use nanofluids in scientific and industrial functions, we must realize their convection heat transfer features. Thus, a plethora of researchers have conducted research on heat transfer function of nanofluids [1–7]. The research on convection heat transfer using nanofluids specifically began a decade ago. The recent studies on nanofluids indicate that the suspending nanoparticles base fluid bring about changes in thermophysical features of the cooling fluid and also in the heat transfer by the dissolution [8–10].

Generally speaking, convection heat transfer can improve through a geometrical change in the flow, boundary conditions, or an increase in the thermal conductivity of the fluid. Different methods have been offered to improve heat transfer capacity of the fluids. Researchers have also tried to improve thermal conductivity of fluids through adding suspending particles in the scale of micro or bigger to the fluids. However, the big size and density of the particles lead to instability and therefore an increase in the resistance which results in corrosion. For the same reason, the fluids containing large particles have not been commercialized so far. Modern nanotechnology has introduced modern methods of producing materials in average size and crystals below 50 nm. Fluids containing these particles are called nanofluids which have been dramatically considered as nanoparticles because they have been proved to be more efficient in heat transfer than pure fluids. The relative area of the bigger surface, in comparison with the previous particles, will improve stability in addition to heat transfer capacity. The use of nanoparticles leads to a reduction in dimensions leading to smaller and higher designs of heat transfer systems. Over the past few years, much numerical and experimental research has been done on convection heat transfer in both turbulent and laminar flows. Zeinali Herris et al. [11] numerically investigated fluid flow and the heat transfer of the nanofluid in a spiral pipe.

They concluded that adding a nanoparticle powder to the operational fluid results in a drastic increase in heat transfer. Akbari et al. [12] numerically simulated heat transfer and a turbulent flow of a nanofluid, contains water copper-oxide in a rectangular microchannel with semi-adhesive dents. They figured out that the upside of using semi-adhesive dents rather than fully-adhesive ones is to the surface of the channel is elimination of hot areas with lower heat transfer and

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Nomenclature

A	cross section, m^2
C_p	heat capacity, J/kg K
D_h	hydraulic diameter, m
d_p	nanoparticle diameter, nm
h	convection heat transfer coefficient, W/m^2 K
k	thermal conductivity coefficient, W/m K
K	Consistency index, N s^n m^{-2}
K_b	Boltzmann constant, J/K
L	length, m
n	exponent of power-law
Nu	Nusselt number
p	pressure, Pa
Pe	Peclet number
Pr	Prandtl number
q''	thermal flux, W/m^2
Re	Reynolds number
T	temperature, K
U	dimensionless velocity
u	input velocity, m/s

Greek symbols

Δ	different
α	thermal diffusivity coefficient, m^2/s
φ	volume fraction, %
λ	main free path, nm
ν	cinematic viscosity, m^2/s
π	phi number 3.14
θ	dimensionless temperature
ρ	density, kg/m^3

Super- and Sub-scripts

b	bulk
br	Brownie
eff	effective
f	fluid
in	input
nf	nanofluid
P	particle
s	solid
w	wall

improving heat transfer. Moreover, these dents caused a significant reduction in pumping power friction coefficient, and the pressure loss in the microchannel which, in turn, increases the fluidal thermal function of these dents.

Studies conducted by Ahmed et al. [13] on the nanofluid flow in channels and ducts indicated that heat transfer in nanofluids depends on the kind of solid particles. Chen et al. [14] investigated the heat transfer behavior of the non-Newtonian fluid in a microchannel using power-law method. They also studied parameters belonging to heat transfer and the flow of the fluid for various behavioral indexes.

Hojjat et al. [15] experimentally studied forced convection heat transfer for 3 different nanoparticle fluids in a round pipe under a turbulent flow and boundary conditions of fixed flux. The findings showed that local heat transfer and the average hat transfer of the nanoparticles were bigger than the base fluid. The heat transfer of nanofluids was also proved to increase in higher concentrations of nanoparticles. In this study, an equation was also recommended for the Nusselt number of non-Newtonian fluids in which Nusselt was a function of Reynolds and Prandtl number.

Soltani et al. [16] experimentally studied nucleate boiling heat transfer in non-Newtonian fluids. Their results indicated that the nucleate boiling heat transfer increased due to an added concentration of nanoparticles in non-Newtonian fluids.

Ozerinc et al. [17] conducted a numerical analysis on convection heat transfer in a turbulent flow of aluminum-oxide and water through a round pipe under two distinct boundary conditions of fixed thermal flux and temperature on the walls using a thermal scattering model and finite different method. In agreement with other studies, this one also resulted in a higher rate of heat transfer in nanofluids compared with base fluids. Tahir and Mital [18], studied forced convection heat transfer in laminar nanofluid flow of water–aluminum oxide in channel with a round cross section through a numerical simulation Navier–Stokes equations. They compared the effects of nanoparticles size, volume fraction of them and Reynolds number on the increase in nanofluids heat transfer and proved the Reynolds number to be the most effective. They also observed that as the size of the particles increased, heat transfer function decreased. Xi-Wen et al. [19] studied the flow of water in micro pipes, through this experiment they found out the move from laminar to turbulent flow in micro pipes happens in the Reynolds number range for 1700–1900. In recent decades, studies of non-Newtonian using nanofluids as coolant is done [20–22]. Industrial use of non-Newtonian nanofluids in order to significantly increase heat transfer in the chemical, petrochemical, polymer and pharmaceutical by Chhabra and Richardson [23] is investigated.

In this research, fluid behavior of a laminar flow, heat transfer of the non-Newtonian water-carboxy methyl cellulose nanofluid with a 0.5% weight concentration as well as solid alumina nanofluids with a volume fraction of 0.5% and 1.5% were numerically studied in a two-dimensional microchannel with hydrodynamic fixed boundary conditions and fixed temperature boundary conditions on the walls of the microchannel. The supposed microchannel was 25 μm high 100 μm long. The rheological behavior of the operating nanofluid is analyzed, from a non-Newtonian point of view, using the Power-Law regarding coefficients of power-law with K (consistency index) and n (power law index) for each volume fraction. In order to predict the fluid behavior and laminar flow heat transfer non-Newtonian fluids, Reynolds number is to be between 10 and 1000. The diameters of these nanoparticles are 25, 40 and 10 μm. The results must be reported in the form of comparative figures containing the average Nusselt number, pressure loss, and Peclet number for the diameter of each nanoparticle and different Reynolds number.

2. Mathematical model

2.1. Statement of the problem

In this numerical research, laminar forced flow of the nanofluid for volume fraction of 0.5% and 1.5% of the solid nanoparticle alumina suspended in a non-Newtonian fluid which is a 0.5% dissolution of CMC in water was analyzed numerically in a comparative analysis. The analysis was done on two-dimensional rectangular microchannel. In this article, heat transfer and the fluid dynamics of a non-Newtonian fluid have been calculated in different volume fractions and diameters of nanoparticles. Moreover, the study of velocity and temperature fields in each of the mentioned conditions were analyzed in different Reynolds number. Fig. 1 shows a schematic view of the rectangular microchannel analyzed the length of which is 2500 μm and the height D_h=h=25 μm. In order to consider the hydrodynamic expansion length in the beginning of the channel, the length of the upper and lower wall of the channel has been insulated along 750 μm of the length. The fixed temperature of T_h=303 K has been inserted on the upper and lower walls. The cooling fluid enters in an input temperature T_{in}=T_c=293 K.

Table 1
The thermophysical properties of the base fluid, nanofluid and nanoparticles.

Material	*Pr*	ρ (kg/m^3)	*Cp* (J/kg K)	*k* (W/m K)		
Pure water	6.2	997.1	4179	0.613		
Al_2O_3	–	3970	765	40		
				dp=25 nm	*dp*=45 nm	*dp*=100 nm
CMC (0.5%)+1% Al_2O_3	–	1013.5	4121	0.6262	0.6211	0.6157
CMC (0.5%)+1.5-% Al_2O_3	–	1040.5	4012	0.660	0.648	0.6356

The flow in the laminar mode is analyzed for Reynolds number of 10, 100, 500 and 1000. The base fluid includes a non-Newtonian dissolution of water and CMC with concentration of 0.5% and the solid nanoparticles including alumina powder are added in volume fraction of 0.5% and 1.5%. The molecular diameter of the base fluid is 2 Å and the diameters of the solid particles are 25, 45 and 100 nm and they are hemispheric and homogeneous. The thermophysical properties of the base fluid and particles of the alumina powder are presented in Table 1.

In this analysis the flow is two-dimensional, incompressible, non-Newtonian, laminar and single-phase and the properties of the nanofluid are considered in affixed temperature. The fluid enters the microchannel in the entrance constantly and the nanoparticles are considered to be round. The n and K coefficients along the microchannel are fixed in relation to the temperature for each volume fraction.

3. The governing equations

For this research a single-phase model for the analysis of heat transfer and the flow of the non-Newtonian nanofluid is of importance. The predominant equations on the flow of the fluid are those of conservation of mass, momentum, and energy [24].

$$\nabla.\ (\rho_{nf} V_m) = 0 \tag{1}$$

$$\nabla.\ (\rho_{nf} V_m V_m) = -\nabla P + \nabla.\ (\mu_{nf} \nabla V_m) \tag{2}$$

$$\nabla.\ (\rho_{nf}\ C\ V_m T) = \nabla.\ (k_{nf} \nabla T) \tag{3}$$

Since a non-Newtonian method (power-law) has been used, shear stress is defined as follows based on Ref. [25]:

$$\tau = K\dot{\gamma}^n \tag{4}$$

In this equation K, γ, and n are respectively shear stress, shear rate and power-law indice (exponent of power-law). In order to define the Reynolds number for the non-Newtonian fluid, the role of the power-law indice and coefficient is important in determination of the Reynolds number and the beginning velocity of the fluid in the entrance of the pipe. The Reynolds number for a non-Newtonian fluid is defined as [26]

$$Re = \frac{\rho u^{2-n} D^n}{K} \tag{5}$$

where K is the power-law coefficient. The Peclet number defines thermal diffusivity. Also, the Prandtl number in the non-Newtonian fluid is defined as follows [27]:

$$Pe = Re.Pr = \frac{\rho_{nf}.\ C_{p_{nf}}.\ \ u.\ D_h}{k_{nf}} \tag{6}$$

$$Pr = \frac{Cp_{nf}.\ r}{k_{nf}}\left(\frac{u}{D_h}\right)^{n-1} \tag{7}$$

In this numerical study, the power-law model has been used to study the rheological behavior of a fluid. Therefore, instead of determining the viscosity of the nanofluid, n and K which are respectively the constant and the indice of the power-law have been calculate through Hojjat et al. [28] study for the concentration of 0.5% and 1.5% volume fractions of alumina in a fluid of water and CMC (0.5 wt%). Fig. 2 shows the values of n and K for nanofluid used.

To reach the properties of the nanofluid, experimental relationships proposed by researchers are used. The following are used to calculate the density of the nanofluid [29,30] and the special thermal capacity [31]:

$$\rho_{nf} = (1-\varphi)\rho_f + \varphi\rho_s \tag{8}$$

$$(\rho C_p)_{nf} = (1-\varphi)(\rho C_p)_f + \varphi(\rho C_p)_s \tag{9}$$

where φ indice is the volume fraction of the solid nanoparticle and f, s, nf are respectively fluid, solid and nanofluid. To determine thermal conductivity coefficient Chon et al. [32] equation has been used [33]:

$$\frac{k_{nf}}{k_f} = 1 + 64.7\varphi^{0.7460}\left(\frac{d_f}{d_p}\right)^{0.3690} * \left(\frac{k_p}{k_f}\right)^{0.7476} \mathrm{Pr}^{0.9955}\mathrm{Re}^{1.2321} \tag{10}$$

In Eq. (10), Pr and Re are defined as [34]

$$Pr = \frac{\mu_f}{\rho_f \alpha_f} \tag{11}$$

$$Re = \frac{\rho_f V_{Br} d_p}{\mu_f} = \frac{\rho_f k_B T}{3\ \pi\ \mu_f{}^2\ \lambda_f} \tag{12}$$

In Eq. (11), α_f is thermal diffusivity coefficient of the base fluid and the dynamic viscosity of the fluid is calculated like

$$\mu_f = A \times 10^{\frac{B}{(T-c)}} \tag{13}$$

In Eq. (13) A, B, and C are fixed which are respectively equal to 2.414×10^{-5} Pa s, 247.8 K, and 140 K. Parameter T is on the scale of Kelvin and V_{Br} is the Brownian velocity of the nanoparticle which is

$$V_{Br} = \frac{k_B T}{3\ \pi\ \mu\ d_p\ \lambda_f} = \frac{k_B}{3\ \pi\ \mu\ d_p \lambda_f}\frac{T}{A.10^{\frac{B}{(T-c)}}} \tag{14}$$

where λ_f is the molecular free path. The above-mentioned only count for particles with dimensions of 11–150 nm in the temperature range of 1–71 °C. In Eq. (14), the effect of Brownian movement, the diameter of the solid particles and the molecules of the base fluid are considered to calculate thermal conductivity. To calculate the local and mean Nusselt number, the following are used [35–37]:

$$Nu(X) = -\frac{k_{eff}}{k_f}\left(\frac{\partial\theta}{\partial Y}\right)_{Y=0} \tag{15}$$

$$Nu_m = \frac{1}{L}\int Nu(X)\,dX \tag{16}$$

The parameters of coefficient of local heat transfer are defined as

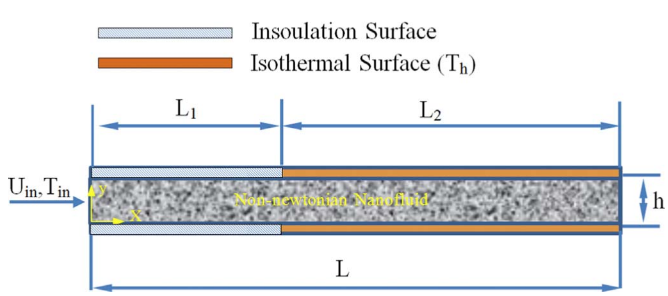

Fig. 1. Schematic view of the microchannel.

[38]

$$h = \frac{q''}{T_w - T_m} \tag{17}$$

$$h_{ave} = \frac{1}{L}\int_0^L h(z)\,dz \tag{18}$$

In Eqs. (17)–(20), parameters m, ΔP, A, u_{in}, T_w, T_m, q'' are respectively mass flow, pressure loss, input flow cross-section, the local temperature of flow wall, the average mass temperature, and the heat flux on the wall of the microchannel. To calculate the mean friction coefficient the following equation is used [39]:

$$Pe = Re.\,Pr \tag{19}$$

$$f = \frac{2\ .\ \Delta P.\ D_h}{L\ .\ \rho\ .\ {u_{in}}^2} \tag{20}$$

In this paper to calculate parameters, the dimensionless value used as follows [40–44]:

$$X = \frac{x}{h},\quad Y = \frac{y}{h},\quad U = \frac{u}{u_c},\quad V = \frac{v}{u_c},\quad H = \frac{h}{h} = 1,\quad \theta = \frac{T - T_c}{T_h - T_c} \tag{21}$$

4. Properties and methods

In this study, finite volume method are used. In the numerical simulation, coupled equations of velocity–pressure are implemented. To reach a suitable accuracy in the numerical solution, second order discretization as well as Simple C algorithm are taken into consideration. In all cases for all Reynolds number and volume frictions, to occupy less memory space on the computer and to economize the numerical solution process, the maximum 10^{-6} remainder is used.

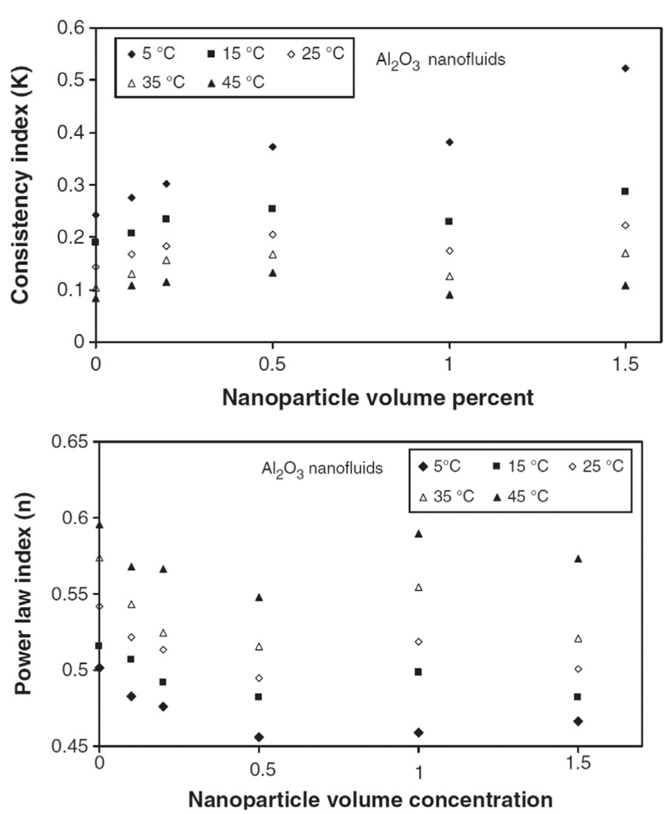

Fig. 2. The values of n and K for nanofluid used in volume fraction and different temperatures [28].

Table 2
Grid-independence for this study.

Mesh size	)ΔP)	(Nu_{ave})
30×300	198,766	3.151
50×500	211,324.08	3.4987
50×1000	212,031	3.6776
50×1500	213,552.1	3.9021
70×1800	213,600	3.9112

5. Grid-independence study

Regarding the fact that the supposed geometric space of the micropipe is two-dimensional, an organized rectangular grid is used. In this study, the number of grids is analyzed in accordance with Table 2 regarding criteria including acceptable number of numerical faults and suitable number of grids to calculate mean Nusselt number and pressure loss in Table 2, grid independence is reviewed for Re=500 for a non-Newtonian nanofluid in a volume friction of 0.5% for a solid nanoparticle with a diameter of dp=25 nm. In a revision of grid-independence, the fault for mean Nusselt number and pressure loss are considered in proportion to more accurate answers (number of grids 50×1500). Since the fault is less than 10%, the number of grids is smaller and less memory and processing time is spent, an organized rectangular grid is used for the supposed space with 50×1500 dimensions.

6. Analysis of the results

6.1. Validation

Fig. 3 shows the validation of the current numerical solution in the 2D (a) [45] and 3D (b) [46] microchannel by Newtonian fluid and non-Newtonian nanofluid. It has also been verified through the numerical work of Leng et al. [46] and Santra et al. [45]. Fig. 4 shows the Nusselt number figures for the Nusselt number10, 100, 500, and 1000 for volume frictions of 0.5% and 1.5% for the solid nanoparticles. The Nusselt number increased rapidly with an increase in volume friction of the nanoparticle and the Reynolds number. The variations in the increase in heat transfer are little in lower Reynolds number. Thus, the figures for lower Reynolds number are lower than those of higher number. The reason for better heat transfer in higher Reynolds number is the better blending of the areas and the layers of the fluid and the boost in heat transfer mechanisms. In all figures of Nusselt number on the input to channels, the number along the entrance of the pipe is of high levels since the effects of expansion have not affected the flow of the fluid completely.

Fig. 5 shows the average heat transfer coefficient for different Reynolds number and volume fractions 0.5 and 1.5 of the solid nanoparticle. In the case of a solid non-Newtonian fluid, bigger Reynolds number lead to bigger heat transfer coefficients. The increase in this trend is also upwards with a rise in volume fraction. An increase in the volume fraction of nanoparticles also has a significant effect on heat transfer behavior of the fluid. The more the volume frictions of the nanoparticles are, the higher the figures go. The effect of the decrease in the diameter of the nanoparticles distinguishes the figures for average heat transfer coefficient from others. The decrease in the diameter of the particles results in a bigger molecular surface a bigger number of solid nanoparticles for fixed mass and volume friction which in turn causes an increase in the heat transfer surface and more contact in molecular levels which eventually improves heat transfer and prevents the impacts of settlement and lumping of the solid nanoparticles. The effect of the use of solid nanoparticles with a bigger volume friction and a smaller diameter on the Reynolds number is obvious.

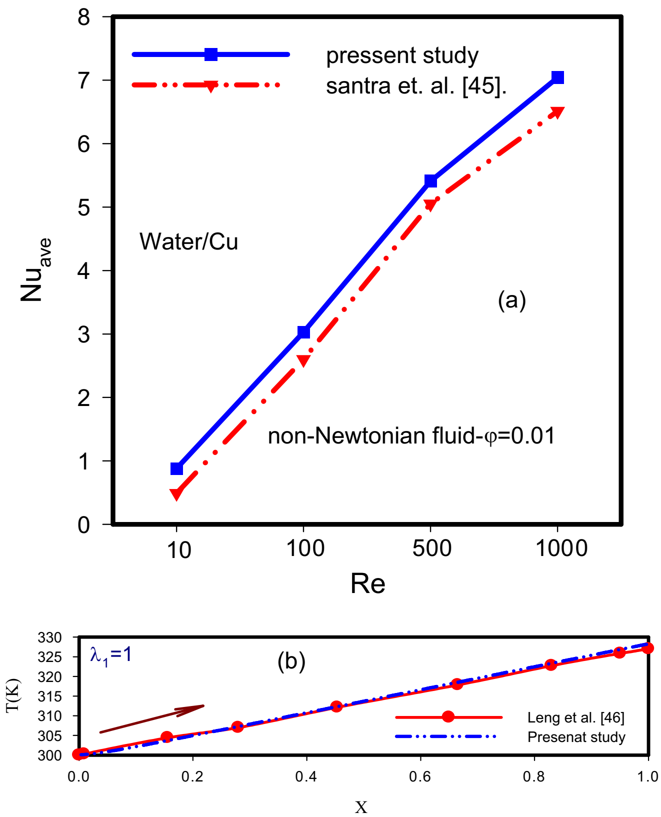

Fig. 3. Validation of the current numerical solution with Santra et al. [45] and Leng et al. [46] work.

Fig. 6 shows the mean heat transfer coefficient for various Peclet number and diameters of nanoparticles. It can be seen that for the same Peclet number, the coefficient of heat transfer increases for higher concentrations of nanoparticles. This increase in Peclet number significantly affects the coefficient of convection heat transfer in a non-Newtonian heat transfer positively. The upward trend of the coefficient of mean heat transfer with the increase in volume fraction is dramatic which can be due to the increase in convection heat transfer of the nanofluid in higher concentrations in higher volume fractions. Nanoparticle in a non-Newtonian fluid results in an increase in temperature gradient in the walls of the walls of the microchannel which boosts heat transfer.

Fig. 7 shows mean pressure loss for different Reynolds number and volume fractions of nanoparticles for a fixed diameter of 100 nm for the nanoparticle. This parameter for non-Newtonian nanofluid with a higher volume fraction has a significant trend. Because a nanofluid with more nanoparticles loses velocity along the walls of the microchannel and the decrease in volume fraction of the nanoparticle leads to more contact with the walls. An increase in volume fraction results in an increase in dynamic viscosity and density of the nanofluid which brings about changes in the velocity of the fluid. Heavier fluids with higher viscosity cause bigger momentum corrosion.

Fig. 8 shows dimensionless temperature for *Re*=10 and volume fraction of 1.5% of solid nanoparticle in comparison with the base fluid. This figure depicts the changes in this temperature for different cross sections of the microchannel. Using non-Newtonian fluids with higher volume fractions causes big changes in the distribution of dimensionless temperature along the microchannel height. In fact, nanoparticles involved in heat transfer boost the process. Thus, with the introduction of the fluid to the microchannel and in the entrance sections of the channel, the variations in the dimensionless temperature are significant due to lack of expansion. After the flow through the channel and

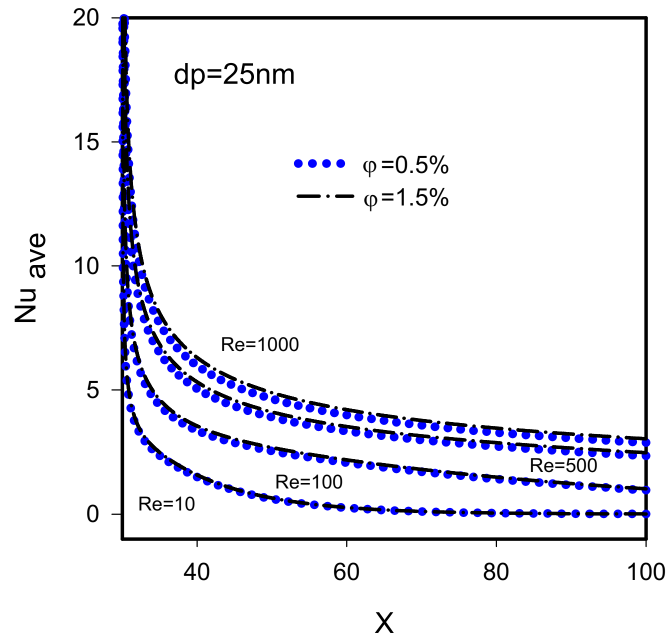

Fig. 4. Figures for the average Nusselt number based on the Reynolds number for different volume frictions.

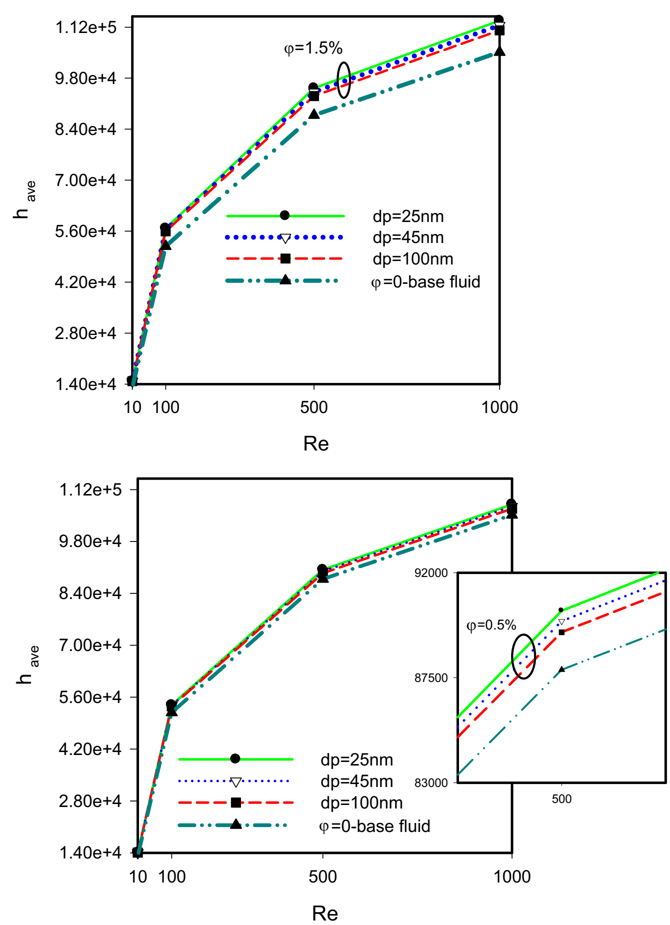

Fig. 5. Convection heat transfer coefficient based on Reynolds number for volume fractions of 0.5 and 1.5 for the solid nano-particle.

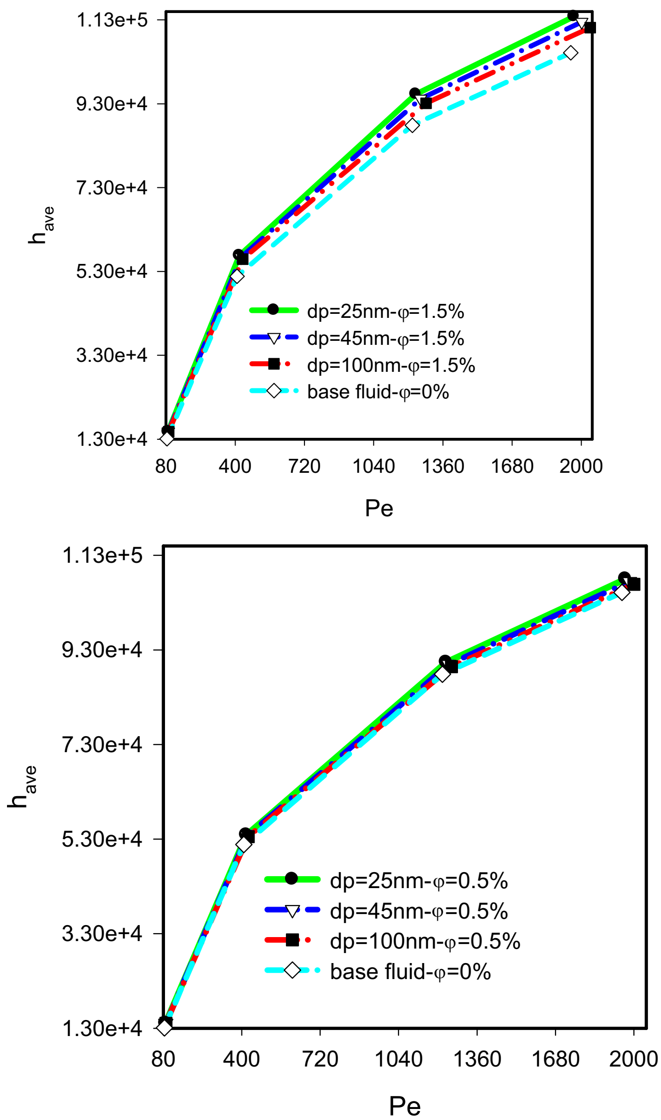

Fig. 6. Coefficient of convection heat transfer in proportion to Peclet number for various diameters and volume fractions of solid nanoparticles.

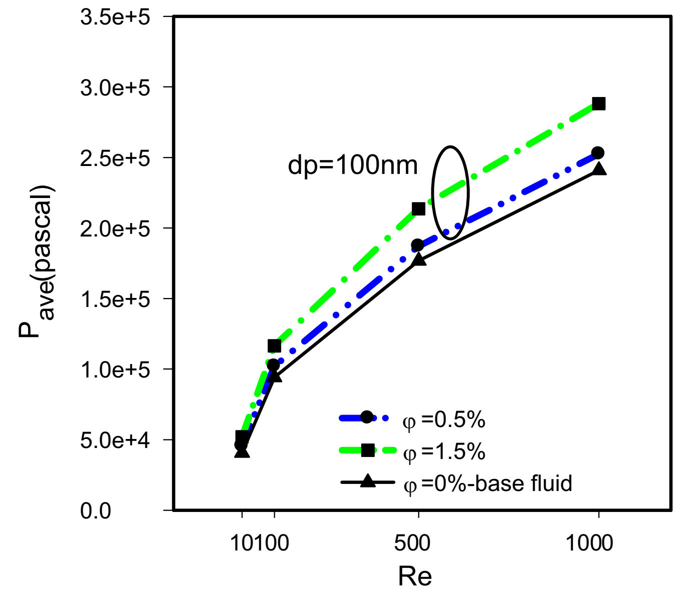

Fig. 7. Mean pressure loss for different Reynolds number and volume fractions of solid nanoparticles.

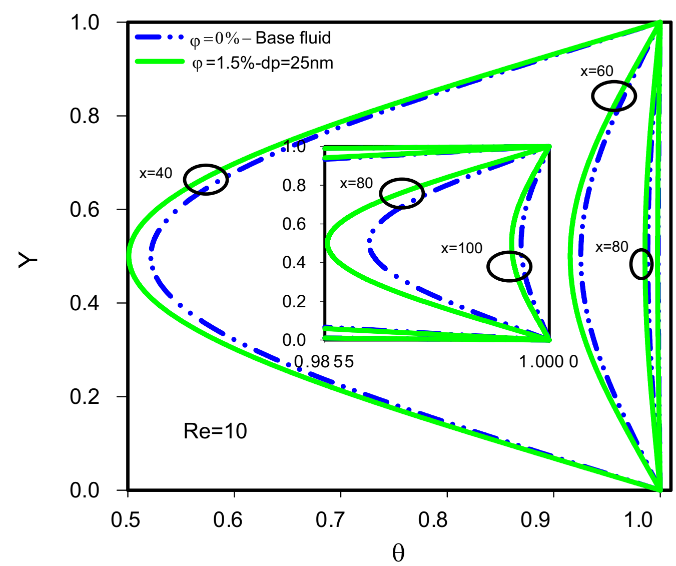

Fig. 8. Dimensionless temperature for Re=10 and volume fraction of 1.5% of solid nanoparticle.

the occurrence of expansion, the variations take a steady and almost stable trend.

Fig. 9 illustrates dimensionless temperature for Re=100 and 1000 and a volume fraction of 1.5% of the nanoparticles and their various diameters in cross sections of X=60, 80 and 100. Regarding its definition, dimensionless temperature allows for a better heat transfer in its lower amounts closer to zero. The use of nanoparticle powders with smaller diameters has been proved to be the most effective in heat transfer. Also the higher velocity of the fluid implements changes in the trend of the dimensionless temperature. To sum up, the variations of dimensionless temperature in the entrance of the channel are high and increase in proportion to higher Reynolds number.

7. Conclusion

The laminar flow of the fluid water/CMC-alumina for volume fractions of 0.5% and 1.5% of solid nanoparticle (alumina) suspended in a non-Newtonian dissolution made of 0.5% concentration of CMC was studied. In this research, calculative fluid dynamics and laminar heat transfer behavior of the non-Newtonian fluid in rectangular two-dimensional using an organized mesh and Simple C algorithm and second order discretization were all studied. To determine a more accurate viscosity of the fluid, the power-law was used to draw the non-Newtonian fluid. The results indicated that an increase in volume fraction of the solid nanofluid lead to an upward trend in heat transfer, rate, Nusselt number and pressure loss. Furthermore, the presence of solid nanoparticle had a great impact on the increase of the above-mentioned especially Reynolds number which can be a result of boosting micronic heat transfer mechanisms and a better combination of nanofluid flow in higher Reynolds number. The use of solid nanoparticles with a smaller diameter had a good effect on the increase in heat transfer, decrease in pressure loss, and economized variation of dimensionless temperature in different sections of the microchannel. The extension of this paper for nanofluids according our previous works [47–62] affords engineers a good option for turbulent jet impingement simulation.

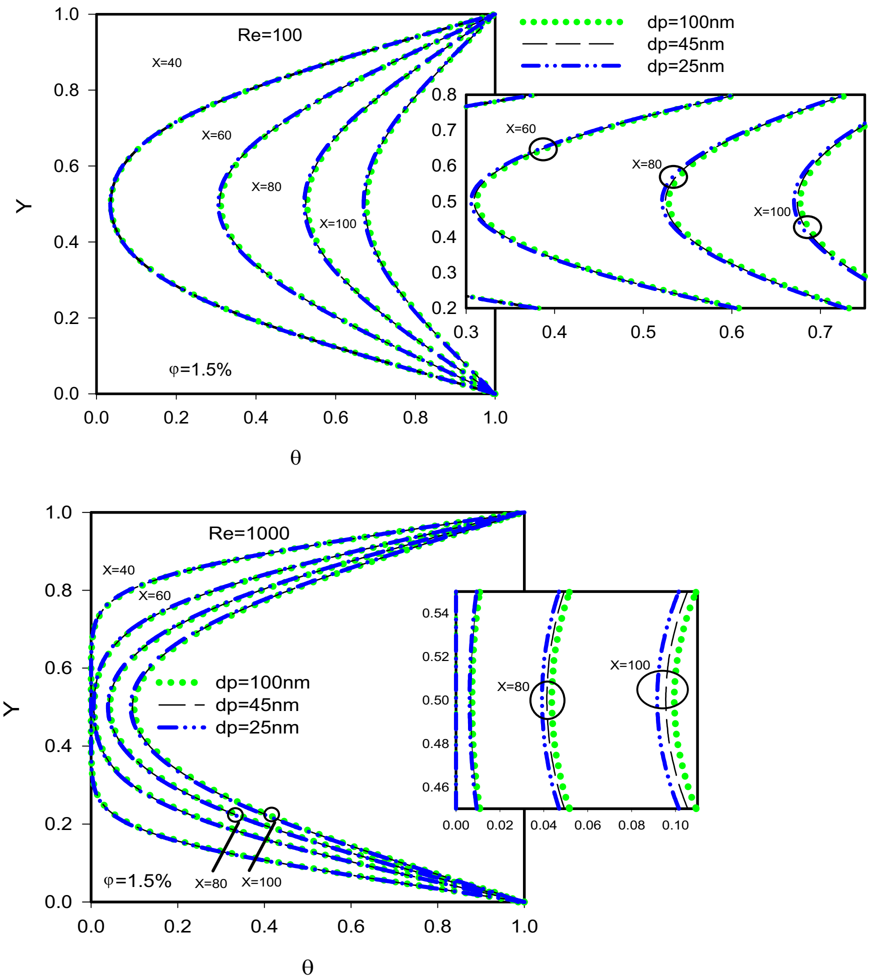

Fig. 9. Dimensionless temperature for various Reynolds number and diameters of nanoparticles.

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