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CFD ANALYSIS OF LAMINAR FORCED CONVECTIVE HEAT TRANSFER FOR TiO_2/WATER NANOFLUID IN A SEMI-CIRCULAR CROSS-SECTIONED MICRO-CHANNEL

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ABSTRACT

In this study, forced convection flow and heat transfer characteristics of TiO2/water nanofluid flow with different nanoparticle volume fractions (1.0%, 2.0%, 3.0% and 4.0%) in semi – circular cross – sectioned micro – channel was numerically investigated. The three - dimensional study was conducted under steady state laminar flow condition where Reynolds number changing from 100 to 1000. CFD model has been generated by using ANSYS FLUENT 15.0 software based on finite volume method. The flow was under hydrodynamically and thermally developing flow condition. Uniform surface heat flux boundary condition was applied at the bottom surface of the micro – channel. The average and local Nusselt number and Darcy friction factor values were obtained using numerical results. Also, the effects of using nanofluid on local values of Nusselt number and Darcy friction factor were investigated. Numerical results indicate that the increasing of nanoparticle volume fraction of nanofluid, the average Nusselt number increases; however, there is no significant variation in average Darcy friction factor.

Keywords: *CFD, Semi – Circular Cross – Sectioned Micro – Channel, Forced Convection, Nanofluid*

INTRODUCTION

Micro and mini – channel applications play very important role for developing cooling capacity in microelectronic equipment such as micro – reactors, refrigeration systems and micro fuel cells. Micro – channels are identified to be one of the fundamental components to transport fluid within a tiny area. Increasing heat transfer rate in microelectronic components becomes very important for scientists. Hence, the researches on this area are mostly carried out for obtaining more efficient working fluids. Nowadays, the most efficient developed working fluids are nanofluids. The dispersed nanoparticle into a base fluid process was explored and called nanofluid. Nanofluids consist of solid metallic or nonmetallic nanoparticles and base fluid such as water, ethylene glycol etc. There is significant enhancement of convective heat transfer using nanofluids as working fluids.

In the past numerical and experimental studies, it was obtained that the flow characteristics in micro – channels are mostly different from macro – channels. The friction factor in micro – channel under laminar flow condition is higher than in macro – channel [1]. An extensive review of forced convection flow in circular and non – circular duct cross – sections were presented by Shah and London [2], Kakaç et al. [3] and Kakaç and Liu [4]. An experimental investigation was made by Berbish et al. [5] for turbulent forced convection heat transfer and pressure drop characteristics of air flow inside a macro – level horizontal semi – circular cross – sectioned duct. Throughout the duct, variations of surface and mean temperatures, local heat transfer coefficient, local Nusselt number and local friction factor were presented. Empirical correlations were obtained for the average Nusselt number and Darcy friction factor as a function of Reynolds number. Manglik and Bergles [6] analyzed numerically constant property, laminar flow heat transfer in a semi – circular tube with a uniform wall temperature. A steady state turbulent flow in a smooth semi – circular cross – sectioned duct was numerically investigated by Arslan [7]. Flow was hydrodynamically and thermally developing under uniform surface heat flux with uniform peripheral wall heat flux in that study. Local heat transfer coefficient and local Darcy friction factor were obtained through the duct length. Languri and Hooman [8] investigated numerically a slip flow in micro – channel for various cross – sections under forced convection condition. Velocity slip and temperature

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jump boundary conditions were applied at the uniformly heated walls. A numerical analysis has been conducted by Geyer et al. [9] for fully developed laminar flow and heat transfer in periodic semi – circular cross – sectioned trapezoidal channels. It is obtained that the semi – circular geometry provides high rate of heat transfer with relatively small pressure drop with respect to straight pipe.

Investigations conducted on nanofluids are mostly about their thermophysical properties; however, experimental and numerical investigations have been performed for flow and heat transfer characteristics of nanofluids. The investigations in literature about nanofluids using TiO_2 nanoparticle are presented here. Hussein et al. [10] numerically analyzed the effect of cross - sectional area of tube for friction factor and heat transfer using water with TiO_2 nanoparticles. Volume fractions of nanoparticles were 1.0%, 1.5%, 2.0% and 2.5%, respectively. Circular, elliptical and flat tubes were used and the results were compared with experimental data in literature. Parallel results were obtained with deviation of 2.0%. An experimental investigation was conducted by Duangthongsuk and Wongwises [11] about forced convection heat transfer and flow characteristics of TiO_2/water (0.2%) nanofluid in a double – tube counter flow heat exchanger. It was obtained that the convective heat transfer coefficient was higher about 6 – 11% than the base fluid and also it was seen that variation in pressure drop of nanofluid was very little. Kayhani et al. [12] experimentally investigated the convective heat transfer and pressure drop of TiO_2/water (nanoparticle volume fractions of 0.1%, 0.5%, 1.0%, 1.5% and 2.0%) nanofluid flow through a circular tube. The tube was flat, uniformly heated and the flow is under turbulent flow condition. An increase was observed in Nusselt number about 8% for 2.0% nanoparticle volume fraction of nanofluid. CFD analysis was conducted by Moraveji et al. [13] about the effect of nanofluid on cooling performance and pressure drop in mini – channel heat sink. TiO_2 and SiC nanoparticles were used with 0.8, 1.6, 2.4, 3.2 and 4.0% nanoparticle volume fractions for five inlet velocities and acceptable correlations were obtained for Nusselt number and friction factor. Celen et al. [14] studied on a two – dimensional numerical model of TiO_2/water nanofluid flow in plain and enhanced pipes in order to investigate pressure drop. They compared the numerical results with their previous experimental data. The results were presented with graphically for local and average values of temperature, pressure and velocity distribution. Also, pressure drop results were given according to nanoparticle volume fractions and tube types. An experimental analysis of heat transfer characteristics and friction factor of TiO_2 and SiO_2 water based nanofluids was carried out by Azmi et al. [15]. They determined the effect of nanoparticle volume fractions of nanoparticles of TiO_2 and SiO_2 on viscosity and thermal conductivity. The results indicate the enhancements in viscosity and thermal conductivity of TiO_2/water nanofluid were greater than SiO_2/water nanofluid. In addition, they observed a maximum enhancement of 26% in heat transfer coefficients with TiO_2/water nanofluid at 1.0% nanoparticle volume fraction, while there was 33% enhancement of SiO_2/water nanofluid at 3.0% nanoparticle volume fraction. Arani and Amani [16] investigated experimentally convective heat transfer and pressure drop of TiO_2/water nanofluid with nanoparticle volume fraction of 0.002 – 0.02 and the range of Reynolds number was 8000 – 51000. They observed that increasing the Reynolds number or nanoparticle volume fraction, the Nusselt number increases. It was obtained that at the higher Reynolds number greater than 30,000, there was no significant variation in Nusselt number with changing nanoparticle volume fractions. Also, effect of nanoparticle diameter on heat transfer performance was experimentally studied [17]. Experiments were carried out for fully developed turbulent flow condition using TiO_2/water nanofluid. The diameters of TiO_2 nanoparticles were 10, 20, 30 and 50 nm with the nanoparticle volume fractions were from 0.01 to 0.02. It was observed that there was no increment in Nusselt number, with decreasing the diameter of nanoparticles. The highest value of amount of heat transfer was observed for 20 nm nanoparticle diameter. A numerical study was carried out by Peng et al. [18] for heat transfer characteristics under turbulent flow condition in a horizontal circular tube using TiO_2/water nanofluids. Single – phase and multi – phase models were used for numerical computations. The new empirical correlation of nanoparticle viscosity for multi – phase model was suggested and indicated that it was more accurate than traditional ones. An experimental analysis about forced convective heat transfer characteristics and pressure drop of TiO_2/water nanofluid has been reported by Kahani et al. [19]. The geometry of the model was helical coiled tube and nanoparticle volume fractions of nanofluid was between 0.25 – 2.0% with a range of Reynolds number of 500 – 4500. It was observed that the heat transfer coefficient increases with increasing volume fraction and Reynolds number. The maximum thermal performance was obtained at 2.0% nanoparticle volume fraction and Reynolds number was 1750. Uysal et al. was numerically investigated flow characteristics of ZnO/Ethylene glycol nanofluid with φ=1.0 – 4.0% volumetric concentrations in rectangular micro-chanells. Laminar flow conditions were used and the dimensionless properties temperatures, convective heat transfer coefficient, Nusselt number, pressure drop, and

Darcy friction factor values were detrmined [20]. A numerical study was conducted by Makinde [21] about nanofluid flow over a plate with Cu/water, TiO_2/water and Al_2O_3/water nanofluids with low volume fractions. The effects of viscous dissipation and Newtonian heating on boundary flow were numerically determined by using Runge-Kutta-Fehlberg method. He has beern reported that the maximum heat transfer rate on the plate surface had obtained with Cu/water nanofluid. Khamis et al. [22] has reported a numerical analysis about water-based Cu and Al_2O_3 nanofluids flowing in a permeable cylindrical pipe with Navier slip. Unsteady flow conditions were taken into account with variable thermophysical properties along the saturated porous medium in the cylinder. They obtain the increase in volume fraction and Grashof number cause the temperature and velocity enhancement.

Energy and momentum analysis in semi – circular cross – sectioned micro - channels are a little complicated. In order to designing of mini or micro thermal equipment, fundamental knowledge of flow and heat transfer in semi – circular cross - sectioned micro - channel is needed. This geometry is used in heat exchanger in general [7]. In other respects, semi – circular geometry for laminar flow has not been sufficiently investigated in detail. The geometrical properties are very significant for heat removing systems. The channels on the CPU's or any electronic chips need to be heat rejection under higher heat flux. This paper proposes using nanofluids these types of micro-chanells. The novelty of this study is the numerical approach for nanofluid flow in a semi-circular cross sectioned micro-channel for influence of geometry. In this paper, TiO_2/water nanofluid flow inside a horizontal straight semi – circular cross – sectioned micro – channel under hydrodynamically and thermally developing laminar flow condition was numerically analyzed. TiO_2/water nanofluids with nanoparticle volume fractions of 1.0%, 2.0%, 3.0% and 4.0% were used as the heat transfer medium. The significant enhancements in heat transfer for nanofluids take place at under 5.0% nanoparticle volume fraction. It was determined that the enhancements in heat transfer above this value have remained lower values because of the viscosity and shear stress [27-29]. The continuity, momentum and energy equations for three - dimensional flow in semi – circular cross - sectioned micro – channel were solved using finite volume method. The variation of average and local Nusselt number and Darcy friction factor values with Reynolds number and channel length were investigated. Applicable empirical engineering correlations for average Nusselt number and average Darcy friction factor were presented. This study was carried out in order to emphasize the effect of channel geometry and nanoparticle volume fraction on flow and thermal performance of semi – circular micro – channel geometry.

MATHEMATICAL MODEL AND VALIDATION

The micro-channel is thought to be located over a hot surface like a CPU or microchip to disappear heat generation as mentioned before. In order to allow us to figure out more clearly the structure of the case the schematic diagram illustrating the geometry and coordinate system with boundary conditions is given in Figure. 1. Mathematical modeling of semi – circular cross – sectioned micro – channel was performed to solve the case. Three – dimensional Navier – Stokes and energy equations were used to identify the flow and heat transfer in micro – channel. The length and the diameter of the micro - channel are $L = 3x10^4$ µm and $D_i = 1.5x10^2$ µm, respectively. The thermophysical properties of nanofluids were obtained at the bulk temperature.

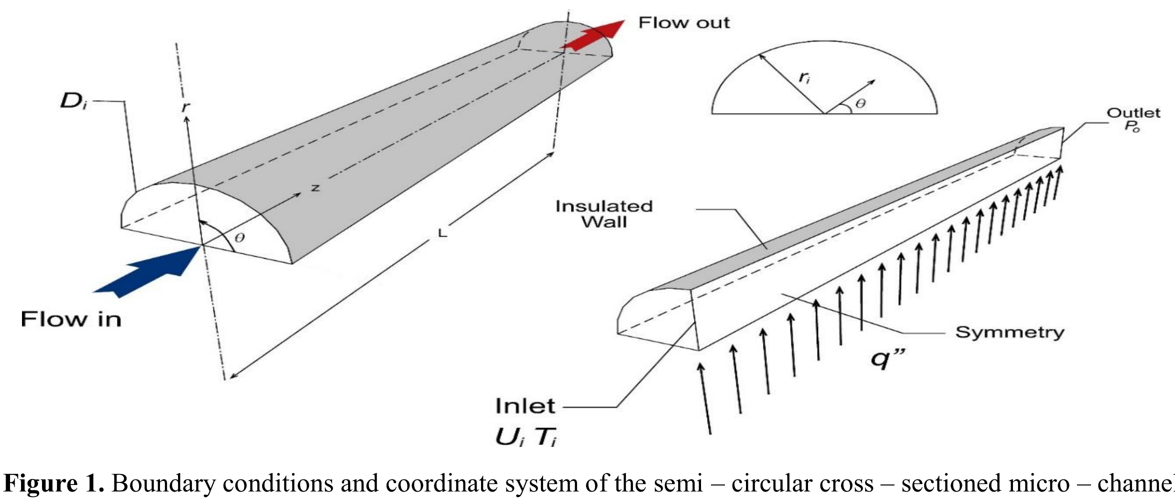


Figure 1. Boundary conditions and coordinate system of the semi – circular cross – sectioned micro – channel

The continuity, momentum and energy equations in cylindrical coordinate system [23]:

Continuity equation:

$$\nabla \vec{V}^* = 0 \tag{1}$$

Momentum equation

$$(\vec{V}^* \nabla^*)\vec{V}^* = -Eu \nabla^* P^* + \mathrm{Re}\, \nabla^{*2} \vec{V}^* \tag{2}$$

Energy equation:

$$\frac{1}{\mathrm{Re}\,\mathrm{Pr}} \nabla^{*2} T^* + \frac{E_c}{\mathrm{Re}} \Phi^* = 0 \tag{3}$$

where the dimensionless parameters in the Eqns. (1) – (3);

$$\vec{V}^* = \frac{\vec{V}}{U_m}, \quad \vec{\nabla}^* = \vec{\nabla} D_h, \quad \mathrm{Re} = \frac{\rho V D_h}{\mu}, \quad P^* = \frac{P - P_\infty}{P_0 - P_\infty}, \quad g^* = \frac{\vec{g}}{g}, \quad T^* = \frac{T - T_\infty}{T_w - T_\infty}, \quad \mathrm{Pr} = \frac{\mu c_p}{k},$$

$$Ec = \frac{U_m^2}{c_p (T_0 - T_m)}, \quad Eu = \frac{P_0 - P_\infty}{\rho V^2}$$

The ANSYS FLUENT 15.0 solves the problems by computing the Navier-Stokes equations according to designated flow type and boundary conditions. Thus continuity, momentum and energy equations were solved using this software. The momentum equation is used for calculating the pressure drop, friction coefficient and shear stress for the flow. Also, the energy equation is used for obtaining the outlet temperature values according to given heat flux and inlet temperature. In order to solve the case, uniform velocity and temperature profiles of TiO_2/water nanofluid was performed at the inlet of the micro-channel. The no slip boundary condition was applied on the micro - channel walls. The bottom surface of the micro-channel is affected by the heat generation of an electronic device. Therefore, a uniform heat flux was applied on the bottom surface of the micro-channel, while the rest of the micro – channel was thermally isolated from the environmental effects since the working conditions of microchips and micro heat exchangers. These types of micro-channels work under constant heat flux effect in general [20]. Also, the thermophysical properties of nanofluids are completely dependent with temperature. Thus, given heat flux were used to avoid from higher temperature differences. Velocity inlet boundary condition was used for indicating the flow regime that was mentioned as laminar before. Moreover, nanofluid flow enters the micro - channel at T_i=300 K and ANSYS FLUENT 15.0 pressure outlet boundary condition was performed at the outlet of the micro - channel. The symmetry boundary condition was applied on the symmetry plane of the micro-channel.

Single phase approach is considered in this study since the nanoparticle diameters of TiO_2/water nanofluid used in this study are smaller than 100 nm (d_p = 25 - 50 nm) [16]. The fluid flow has been modelled as continuous phase. The flow is assumed to be three-dimensional and steady state. Also, the following assumptions were made that, incompressible and laminar flow conditions, temperature independent thermophysical properties and negligible buoyancy and radiation effects.

The thermophysical properties of TiO_2/water nanofluid were obtained using the expressions as follows [10]:

$$\rho_{nf} = \left(\frac{\phi}{100}\right)\rho_p + \left(1 - \frac{\phi}{100}\right)\rho_f \tag{4}$$

$$C_{nf} = \frac{\frac{\phi}{100}(\rho C)_p + \left(1 - \frac{\phi}{100}\right)(\rho C)_f}{\rho_{nf}} \tag{5}$$

$$k_{nf}=k_f(0.8938)\left(1+\frac{\phi}{100}\right)^{1.37}\left(1+\frac{T_{nf}}{70}\right)^{0.2777}\left(1+\frac{d_p}{150}\right)^{-0.0336}\left(\frac{\alpha_p}{\alpha_f}\right)^{0.01737} \tag{6}$$

$$\mu_{nf}=\mu_f\left(1+\frac{\phi}{100}\right)^{11.3}\left(1+\frac{T_{nf}}{70}\right)^{-0.038}\left(1+\frac{d_p}{170}\right)^{-0.061} \tag{7}$$

The thermophysical properties of püre water and TiO_2 nanoparticle are presented in Table 1 [24].

Table 1. Thermophysical properties of water and TiO_2 nanoparticle

	Pure Water	**TiO_2**
k [W/m.K]	0.613	8.4
c_p [J/kg.K]	4179	710
ρ [kg/m^3]	997	4157
μ*10^6 [kg/m.s]	855	-

The convective heat transfer coefficient, average Nusselt number, average Darcy friction factor and Reynolds number were determined as follows:

$$h=\frac{\dot{m}C_{nf}(T_o-T_i)}{A_s(T_w-T_b)} \tag{8}$$

$$\mathrm{Re}=\frac{4\dot{m}}{\pi D_h\mu} \tag{9}$$

$$Nu=\frac{hD_h}{k} \tag{10}$$

$$f=\frac{2\Delta p\left(\frac{D_h}{L}\right)}{\rho U^2} \tag{11}$$

In order to compute the non-dimensional properties, the hydraulic diameter, D_h, for the semi – circular micro-channel was chosen as the characteristic length and obtained from the Eq. (12) [7]. Average heat transfer coefficient was also obtained from Eq. (13) [23].

$$D_h=\frac{\pi D_i}{\pi+2} \tag{12}$$

$$h=\frac{q''}{T_w-T_b} \tag{13}$$

Furthermore, all nanofluid properties were taken at the bulk temperature of nanofluid [25]:

$$T_b=\left(T_i+T_o\right)/2 \tag{14}$$

In this study, in order to perform the numerical analysis, a general finite – volume based commercial CFD software ANSYS FLUENT 15.0 was used. The code provides the mesh flexibility by structured and unstructured meshes. Computations were conducted under laminar flow condition and the energy equation was solved by neglecting radiative effects. The Navier – Stokes and energy equations were solved numerically until the residuals lower than 10-6 through the iterative process.

In order to prove the reliability of the numerical model the grid independence study was conducted since the mesh structure has vital importance in CFD investigations. For this reason, mesh structure was constituted with the following specifications. Tetrahedron cells were generated with a fine mesh near the plate walls. To obtain fine mesh distribution, boundary layer mesh type was used adjacent to the surfaces of the micro – channel. As depicted in Figure 2, the non – uniform grid distribution was performed to the plane perpendicular to the main flow direction. In order to enhance the resolution and accuracy, the number of grid points close to each wall was increased.

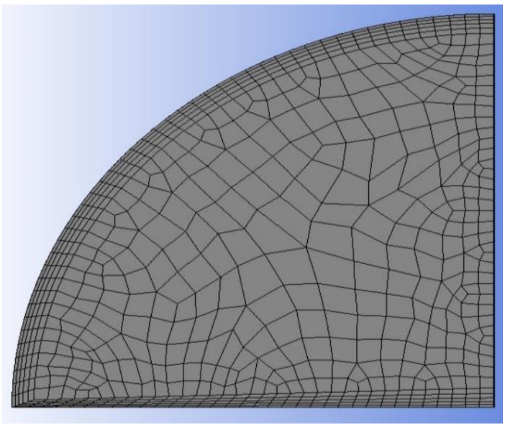


Figure 2. Mesh distribution of the computational domain

The mesh independence study was carried out until the variation in both average Nusselt number and average Darcy friction factor were less than 1%. To provide the certainty of results, a grid independence study was performed for pure water flow using ten different grid sizes changing from $1.36\text{x}10^5$ to $1.74\text{x}10^6$ for Re = 1000. This process gave the effects of grid size on flow and heat transfer. It is illustrated in Figure 3 that there was no remarkable variation on average Nusselt number and average Darcy friction factor between $9.07\text{x}10^5$ and $1.74\text{x}10^6$ grid sizes. According the mesh independence process, the grid size $9.07\text{x}10^5$ was chosen and used for Reynolds number 100 – 1000. Also, same procedure was applied for other nanoparticle volume fractions.

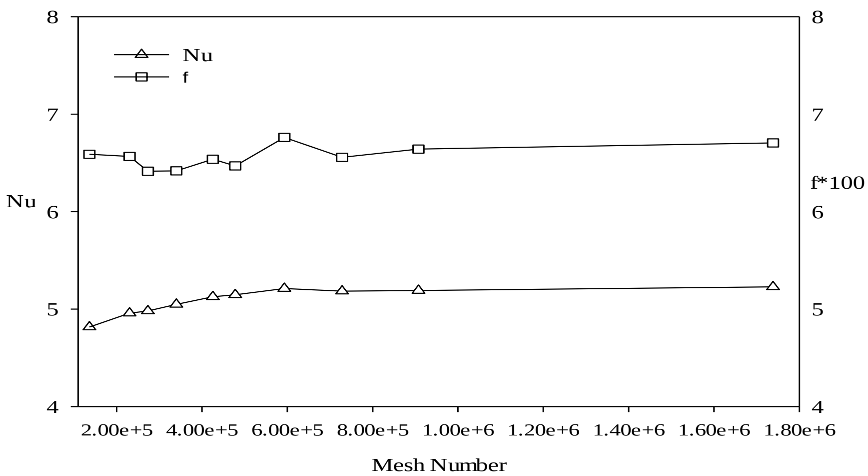


Figure 3. Variation of average Nusselt number and average Darcy friction factor with mesh number

RESULTS AND DISCUSSION

In this study, the fluid flow and heat transfer characteristics of TiO_2/water nanofluid flow in a semi – circular cross – sectioned micro-channel was numerically analyzed as mentioned before. Different nanoparticle volumetric concentrations (ϕ= 1.0%, 2.0%, 3.0% and 4.0%) were used in the computations. The Reynolds number was changed from 100 to 1000. The results were presented with average and local Nusselt number and Darcy friction factor. Moreover, the velocity and temperature profiles in the micro-channel were given with contur graphical representation.

In order to test the numerical code, results for numerical analysis were compared with the Hausen equation in the literature. The results of pure water flow in micro - channel were compared with Hausen equation which was obtained by means of experimental studies [26], used for calculating average Nusselt number under laminar flow condition in pipes, given with Eq. (15).

$$Nu = 3.66 + \frac{0.0668(D/L)\,\mathrm{Re}\,\mathrm{Pr}}{1 + 0.04\left[\left(D/L\right)\mathrm{Re}\,\mathrm{Pr}\right]^{2/3}} \qquad (15)$$

It is seen in Figure 4 that the current numerical study is harmonious with Hausen equation. The maximum deviation between the numerical and literature results [26] was obtained nearly ±7%. The validation was assumed to be in acceptable range and then calculations of nanofluid flow was carried out.

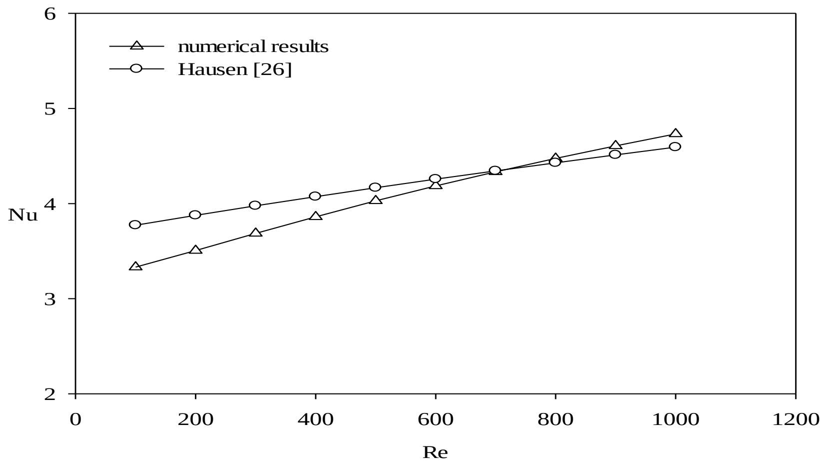


Figure 4. Comparison of current numerical analysis and Hausen equation in literature

Nusselt number is a measure of convective heat transfer coefficient and it is reliable to comparison of heat transfer characteristics since it is dimensionless. In this case the effect of volume fractions (1.0 – 4.0%) of the nanofluid on average Nusselt number and average Darcy friction factor are presented in Figure 5 and Figure 6. It can be seen in Figure 5 that the average Nusselt number increases with increasing Reynolds number and nanoparticle volume fraction. It is indicated that the movements of nanoparticles in base fluid provide higher energy exchange rates.

The highest value of average Nusselt number was observed in nanofluid has 4.0% nanoparticle volume fraction at the same boundary conditions. It represents that the convection heat transfer rate of nanofluid for nanoparticle volume fraction of 4.0% is more effective. Figure 5 represents that increasing the volume fraction of nanofluid increases the convective heat transfer capacity in micro-channel. The enhancement in Nusselt number at low Reynolds number remains lower values as opposed to high Re numbers. The Nusselt number increases with the increase in nanoparticle volume fraction of TiO_2/water nanofluid. The enhancements in the Nusselt number for 4.0% TiO_2/water nanofluid compared to pure water is 3.06% and 17.85% at Re = 100 and Re = 1000, respectively. Figure 6 shows that the changing of average Darcy friction factor with Reynolds number for different nanoparticle volume fractions. It can be seen from the figure that there is no significant effect of changing volume fractions of nanoparticles on Darcy friction factor in micro – channel as reported for Al_2O_3/Water and Al_2O_3/Water-EG nanofluids by Ref.[30-32]. Because at lower velocity values of fluid, the shear stress near the walls of micro-channel is higher values. The value of obtained Darcy friction factor at Re=100 is almost 10 times higher than at Re=1000. Adding nanoparticle to base fluid absolutely increases the pressure drop but the friction factor indicates dimensionless pressure drop.

The velocity and temperature profiles in channels are important for identifying the flow in the channel. The velocity and temperature distributions in micro - channel are shown in Figure 7 – 10. The contours of flow velocity magnitude for 4.0% vol. TiO_2/water nanofluid with different Reynolds numbers are given in Figure 7. It is seen that the velocity profile does not change with Reynolds number. Maximum velocity is obtained at the center of the micro-channel and diminishing through the radial direction since the shear stress is maximum close the walls. Additionally, the temperature distributions of the TiO_2/water nanofluid flow at the outlet of the channel for different Reynolds number are given in Figure 8. Temperature profiles are almost the same distribution for each Reynolds number. Gradually reduction of the temperature values is observed from bottom surface to top of the micro-channel since the bottom surface is exposed to heat flux.

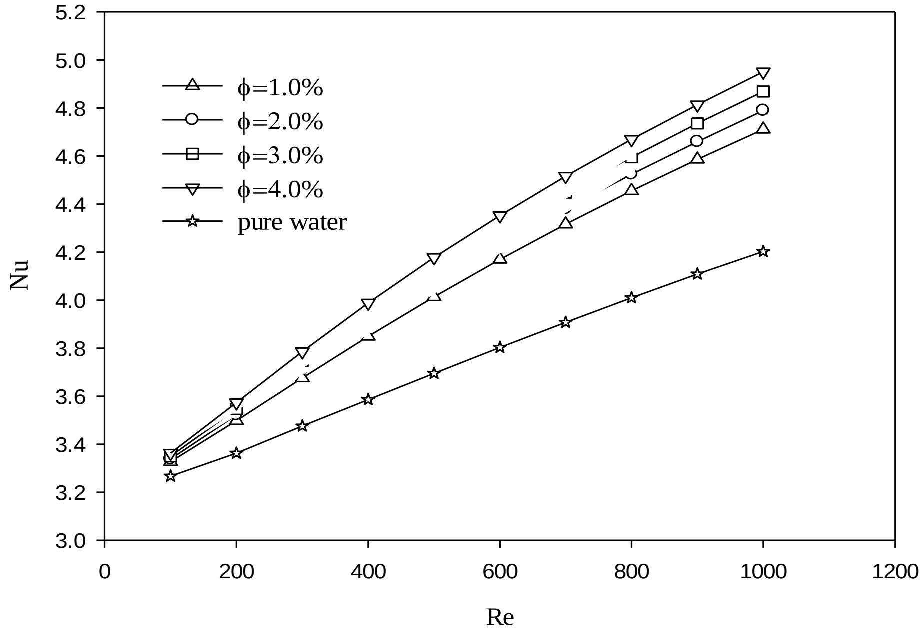


Figure 5. Variation of average Nusselt number with Reynolds number for different nanoparticle volume fractions

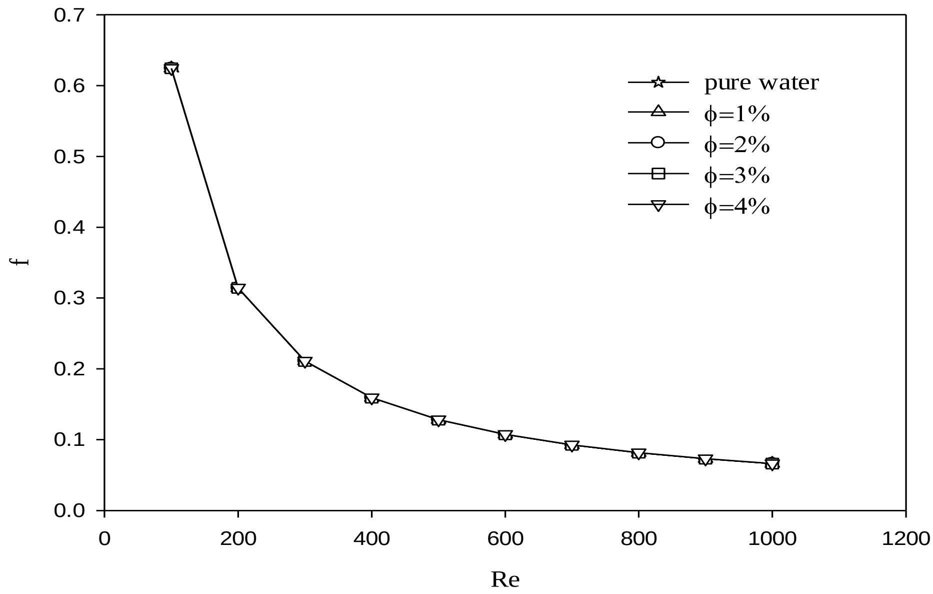
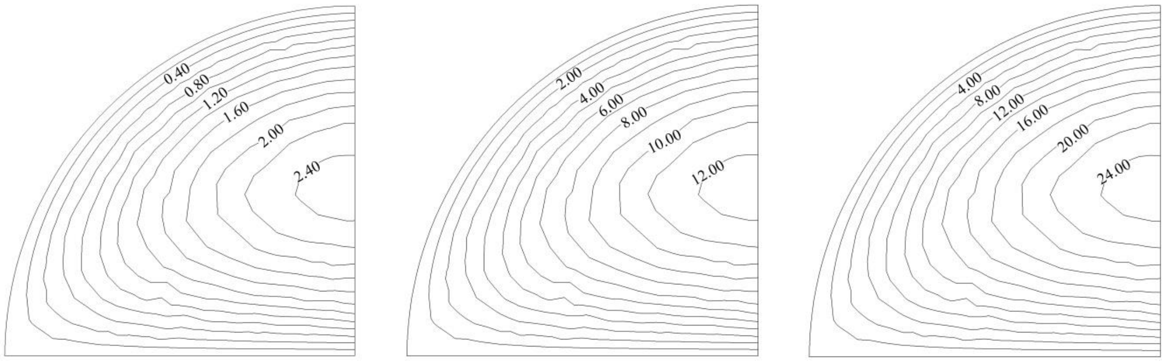
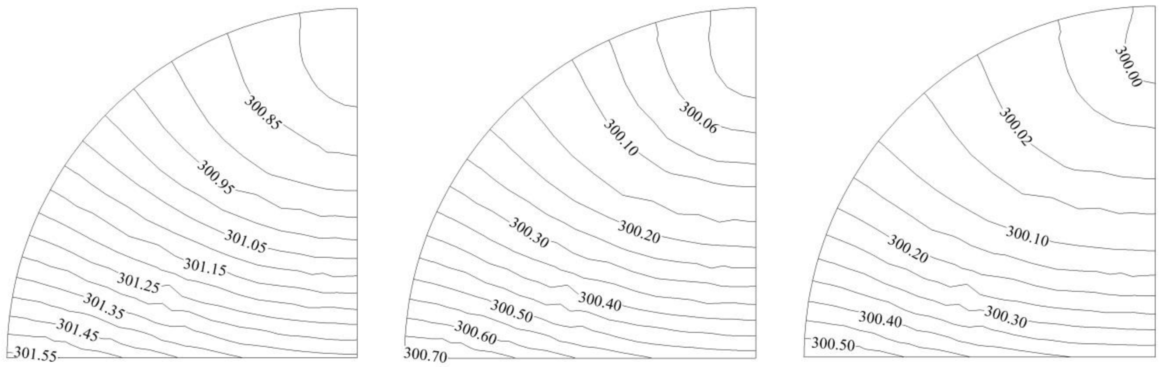


Figure 6. Variation of Darcy friction factor with Reynolds number for different nanoparticle volume fractions



(a) (b) (c)

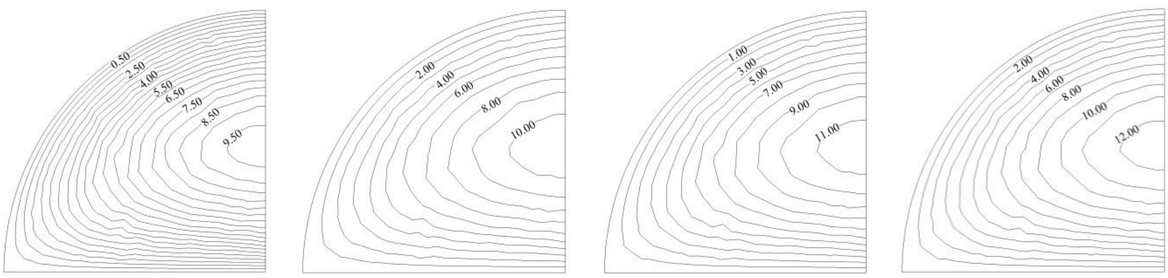
Figure 7. Velocity distributions at the outlet of the micro-channel for 4.0% nanoparticle volume fraction of TiO_2/water nanofluid (a) Re=100, (b) Re=500, (c) Re=1000



(a) (b) (c)

Figure 8. Temperature distributions at the outlet of the micro-channel for 4.0% nanoparticle volume fraction of TiO_2/water nanofluid (a) Re=100, (b) Re=500, (c) Re=1000

In order to determine the effect of nanoparticle volume concentration on temperature and velocity profiles in the micro-channel contours was constituted at Re=500. Figure 9 shows the flow velocity magnitude with different nanoparticle volume fractions at the outlet of the micro-channel and it is seen that the same profile is obtained. The center velocity of 4.0% volume fraction TiO_2/water nanofluid is calculated as 12 m/s which is 26.3% higher than 1.0% volume fraction TiO2/water nanofluid. The temperature contours at the outlet of the micro-channel are presented in Figure 10 for different nanoparticle volume fractions of nanofluids at Re = 500. It is obtained from the figure that the temperature distribution is not affected too much by changing nanoparticle volume fraction.



(a) (b) (c) (d)

Figure 9. Velocity distributions at the outlet of the micro - channel for different nanoparticle volume fractions of TiO_2/water nanofluid at Re=500 (a) 1.0% (b) 2.0% (c) 3.0% (d) 4.0%

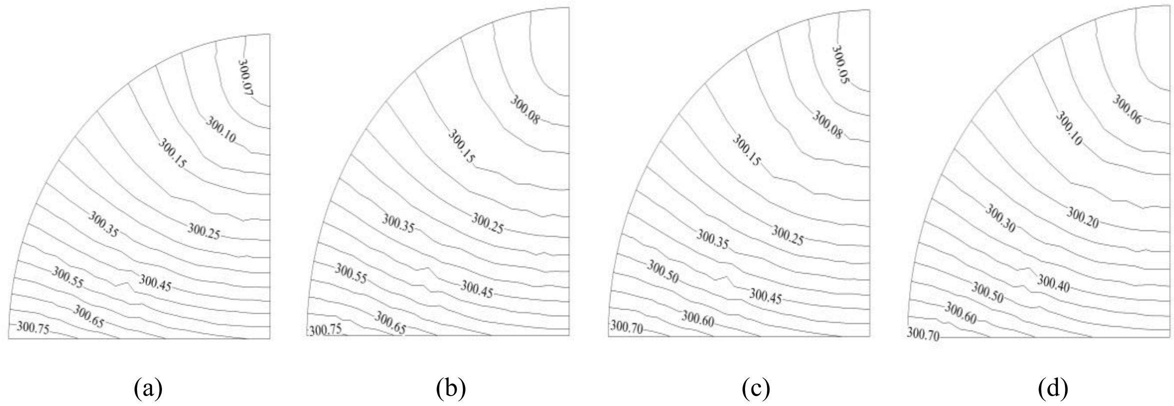


Figure 10. Temperature distributions at the outlet of the micro-channel for different nanoparticle volume fractions of TiO_2/water nanofluid at Re=500 (a) 1.0% (b) 2.0% (c) 3.0% (d) 4.0%

After the all computations for this case, the applicable correlations of average Nusselt number and average Darcy friction factor changing with Reynolds number and nanoparticle volume fraction were obtained from the numerical results of TiO_2/water nanofluid flow in a semi – circular cross – sectioned micro-channel. The empirical correlations are given in Eq. (16) and (17) for average Nusselt number and average Darcy friction factor, respectively. Average Nusselt number is directly dependent with Reynolds number and volume fraction of nanofluid as indicated in Eq. (16). Prandtl number is not used as a variable parameter in the Nusselt number equation. The reason of absence of the Prandtl number in the equation (16) is using only one type of nanofluid in the calculations.

$$Nu = 1.58\, Re^{0.17}\, \phi^{0.03} \tag{16}$$

$$f = 62.88 / Re \tag{17}$$

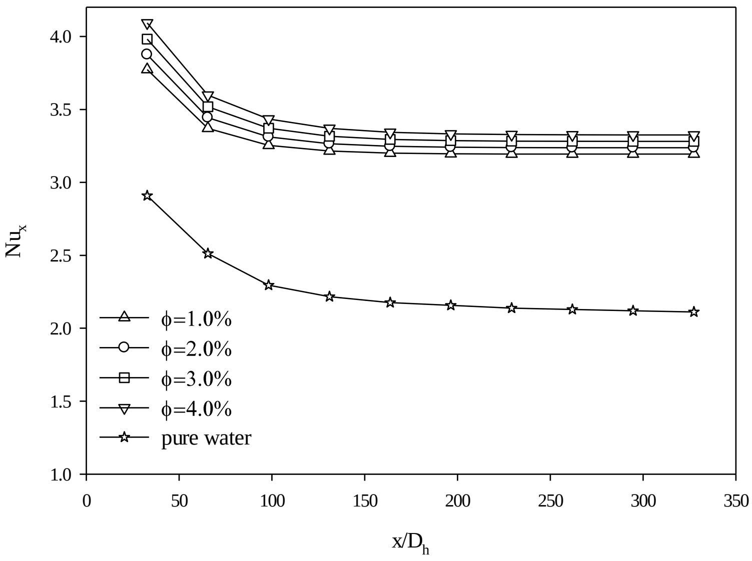
Local values of dimensionless parameters are very significant for observing the variation of flow characteristics along the channels. Therefore, variation of local Nusselt number according to dimensionless length of micro - channel for different nanoparticle volume fractions and Reynolds numbers is presented on Figure 11. It is determined that the local Nusselt number increases with increasing nanoparticle volume fraction; however, it decreases along with micro-channel length. Also, it can be seen that flow reaches thermally fully developed condition in the micro – channel for lower Reynolds numbers. At higher Reynolds numbers, flow is under thermally developing condition.

Figure 12 represents that the variation of local Darcy friction factor with dimensionless micro - channel length for different nanoparticle volume fractions and Reynolds numbers. Local Darcy friction factor can be evaluated as follows:

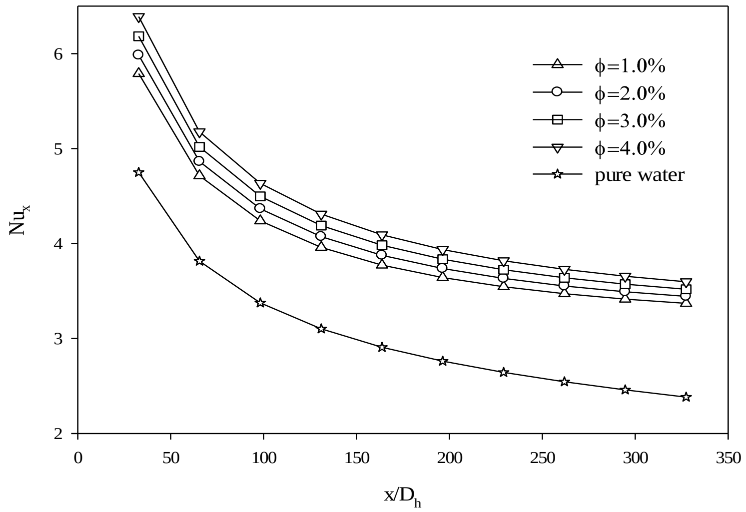
$$f_x = \frac{8\tau_x}{\rho U_{in}^2} \tag{18}$$

where τ_x is the local shear stress.

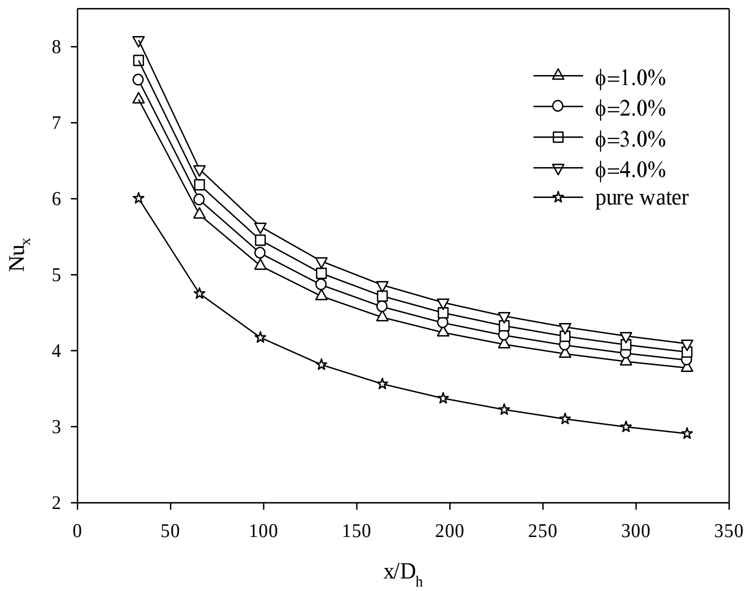
The maximum values of local Darcy friction factor were obtained at the inlet of the microchannel at each Reynolds number. Local Darcy friction factor values decreases until about x/D_h=30 and then become constant along the micro - channel length. Also, flow reaches hydrodynamically developing condition at x/D_h=30. The values of flow velocity and local shear stress increase with increase in Reynolds number, but the enhancement in velocity is higher than local shear stress. Hence, it decreases with increasing Reynolds number as seen in Figure 12. As a result, it can be said that the nanofluid flow reaches hydrodynamically fully developed flow condition inside the micro - channel.



(a)



(b)



(c)

Figure 11. The variation of local Nusselt Number with dimensionless length of micro - channel for (a) Re=100, (b) Re=500, (c) Re=1000

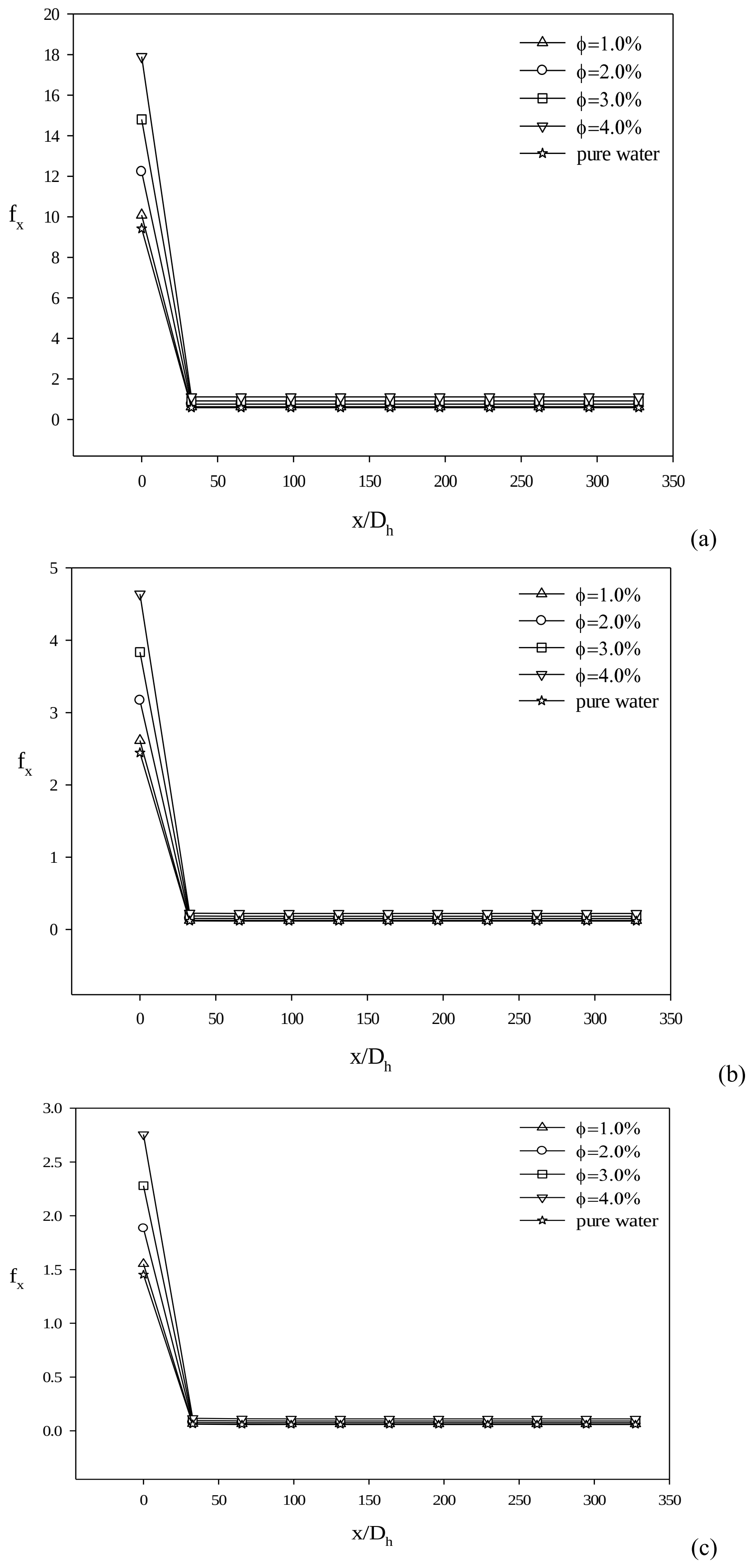


Figure 12. The variation of local friction factor with dimensionless length of micro - channel for (a) Re=100, (b) Re=500, (c) Re=1000

CONCLUDING REMARKS

In the present three – dimensional numerical investigation, TiO_2/water nanofluid flow in a semi – circular cross – sectioned micro – channel for different nanoparticle volume fractions was investigated. Flow characteristics were under hydrodynamically and thermally developing, steady laminar flow condition. Computations were conducted for different Reynolds numbers ($100 \leq Re \leq 1000$) and different nanoparticle volume fractions (1.0%, 2.0%, 3.0% and 4.0%). The results of numerical calculations showed that the increase of nanoparticle volume fraction increases the average Nusselt number up to 10% according to base fluid. However, there is no significant variation for average Darcy friction factor with changing nanoparticle volume fraction. Furthermore, the increment is observed for average Nusselt number with increasing Reynolds number, notwithstanding, average Darcy friction factor decreases. Velocity and temperature distribution at the outlet of the micro - channel were also presented graphically for different Reynolds number and different nanoparticle volume fractions of nanofluid. According to the numerical computations of laminar flow in semi – circular micro - channel, new engineering correlations were determined for average Nusselt number and average Darcy friction factor depends on Reynolds number and nanoparticle volume fraction for TiO_2/water nanofluid flow in semi – circular micro – channel.

NOMENCLATURE

C	specific heat [J/kgK]
ϕ	volumetric concentration
ρ	density [kg/m^3]
k	thermal conductivity [W/mK]
T	temperature [K]
d	particle diameter [m]
α	thermal diffusivity [m^2/s]
μ	viscosity [kg/ms]
$\dot{m}$	mass flow rate [kg/s]
U	velocity [m/s]
h	convection heat transfer coefficient [W/m^{2}K]
Nu	Nusselt number
f	friction factor
p	pressure [Pa]
L	length [m]
q	heat flux [W/m^2]
Re	Reynolds number
Pr	Prandtl number
D	channel diameter [m]
τ	shear stress [Pa]
Ec	Eckert number
Eu	Euler number
Φ	viscous dissipation
x	local values
nf	nanofluid
p	solid particle
f	liquid phase
h	hydraulic diameter
i	inlet
o	outlet
w	wall
b	bulk

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