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Effect of Water Based Nanofluids on Laminar Convective Heat Transfer in Developing Region of Rectangular Channel

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ABSTRACT

Researches involving mixing very little amount of nano-sized solid additives to base fluid have gained popular interest to develop enhanced convective heat transfer techniques. The dispersion of solid particles in such nanofluids changes the thermo physical properties of the working fluid such as viscosity, thermal conductivity, density and specific heat. Therefore, nanofluids have enhancement potential in heat transfer performance compared to normal working fluids. Additionally, most of the researches regarding heat transfer enhancement by using nanofluids considered circular tube as the geometry conducted on developed region. However, in many industry or heat generated equipment, rectangular channels are generally used as a flow path for fluid flowing to conduct heat transfer application. Therefore, the analysis of heat transfer through the entire section of channel (both developing and developed region) is important to understand flow behavior along with heat transfer performance of the entire section for industrial operation. In this study, convective heat transfer of laminar nanofluids in developing region of a rectangular channel was numerically investigated using finite volume method and single-phase approach with ANSYS Fluent software. Four nanoparticles (Al_2O_3, CuO, SiC and TiO_2) with different volume fraction (1% - 5%) were used to mix with water to produce water based nanofluids. The heat transfer was analysed for a constant Reynolds numbers 700 with a constant heat flux 500 W/m^2 applied on the channel wall. Results demonstrated 2% to 13.38% enhancement in heat transfer coefficient with the presence of 1 to 5% nanoparticles concentration, respectively, in comparison to pure water. Meanwhile, results in terms of Nusselt number showed an increase of 1.5% to 13.36% as compared to pure water for the same range of nanoparticles concentration, respectively. From these results, it can be deduced that higher nanoparticles volume fraction results in higher heat transfer coefficient and Nusselt number. Moreover, CuO-water nanofluid provides the highest enhancement in terms of both heat transfer coefficient and Nusselt number while Al_2O_3-water nanofluid provides lowest enhancement in terms of both heat transfer coefficient and Nusselt number among all nanofluids considered in this study. From this study, it can be concluded that water-based nanofluids provide enhancement of heat transfer coefficient and Nusselt number for laminar developing region of a rectangular channel.

Keywords:
Nanofluids; Nusselt Number; heat transfer coefficient; developing region

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1. Introduction

Deals with excessively generated thermal load are of high interest for several industrial fields which are usually associated with high or medium viscosity fluids. Generally, this excessive heat inevitably penalizes the thermal efficiency and lifetime of heat generated apparatuses. Therefore, effective heat transfer techniques which introduce enhanced heat transfer are in high interest of these industries. One of the most common practices of heat transfer techniques is the use of liquid coolant to control overheating. However, the heat transfer rate of traditional liquid coolants such as engine oil, water and ethylene glycol are inherently limited due to their poor thermal and fluid dynamic properties. Therefore, to improve thermo-fluid properties of these fluids, suspension of micro or millimeter sized solid additive to liquid has gained popularity from the last few decades which was first observed by Ahuja [1]. Although this early study introduced some enhancement in heat transfer, it experienced few problems such as channel clogging, poor suspension stability, erosion and high-pressure loss. Hereafter, Choi (1995) [2] first introduced a new class of fluids which is consisting of equally dissolved and suspended nanoparticles into base fluids. This new class of fluids is called nanofluids.

Meanwhile, the flow of fluid through a channel or circular object can be described or divided into two sections, developing region (boundary layer of the flow is not created completely) and fully developed region (boundary layer of the flow is fully developed). Because of boundary layer condition, most of the researchers have carried out their investigation on the convective heat transfer rate at fully developed flow section whereas very few researches have been carried out on developing flow section. However, entry length is an important characteristic in industrial sectors especially those deal with fluid flow and heat transfer for numerous applications of internal flow of stream through a conduit or tube. Moreover, it can also influence the operation of a mechanical segment or technical gadget [3]. Meanwhile, in industrial sectors the investigation and analysis of the entry length is a valuable parameter for quality control, management of flow behavior and flow straightening. One of the practical examples is the flow meter’s establishment location, which is necessary for precise and optimum flow information at the location where fluids rate is usually steady [4]. Additional functions of estimating the entry length are nevertheless evolving which encourage further investigations on entry length and developing region. Therefore, this study mainly focuses on the improvement of heat transfer rate in developing region at the presence of nanoparticles concentration in water as the working fluid.

In this regard, Yihe Huang *et al.,* [5] studied numerically entry flow of convective heat transfer through tube and channel by using nanofluids wherein CuO-H_2O, CNT-H_2O and Al_2O_3-H_2O nanofluids were used for the purpose of investigating the Nusselt number and coefficient of heat transfer in terms of axial length. The results indicated that nanofluids offered extra enhancement of heat transfer for both developed and developing regions in comparison to natural water whereby CNT/H_2O presents extra enhancement in comparison to others. Another study conducted by M. Izadi and D. Jalali [6] on heat transfer of developing laminar flow by using Al_2O_3/H_2O nanofluid. According to the study, the boundary layer of the flow was not changing significantly with the variation of volume fraction of nanoparticles whereas profile of temperature and coefficient of convective heat transfer were increased with presence of nanoparticles. Wael Al-Kouz *et al.,* [7] carried out their investigation at a constant wall temperature with low-pressure gaseous nanofluid through the entry area of a circular tube. They demonstrated that there was no significant impact on the heat transfer characteristics at the presence of nanoparticles volume concentration less than 3%. Hence, by increasing this volume concentration beyond 3%, an enhancement of average Nusselt number was obtained. Sadaghiani *et al.,* [8] studied on thermally developing convective heat exchange of alumina-water nanofluid inside a micro tube and they observed that the presence of nanoparticles in working fluid changed the profile of velocities and enhanced the heat transfer rate significantly. Moreover, mixing of 3% volume concentration of alumina provides 50% enhancement of heat transfer. Jung *et al.,* [9] studied on the coefficient of heat exchange and friction factor for forced convection of nanofluids and their results indicated that 1.8% volume concentration provided 32% enhancement of heat exchange. Another researcher Karim zadehkhouei *et al.,* [10] investigated the effect of inlet temperature for alumina-water nanofluid for thermally developing and hydro dynamically developed zone of laminar fluid flow. Their results indicated that the effect of inlet temperature was more significant for thermally developing region. The studies by previous researchers were among others who also examined the effect of nanofluids on laminar convective heat transfer and their results indicate the enhancement and improvement of heat transfer characteristics using nanofluids [11-17].

From the above literature review, it can be observed that most of the researches regarding heat transfer enhancement by using nanofluids in developing region considered circular tube as the geometry. However, in many industry or heat generated equipment, rectangular channels are generally used as a flow path for fluid flowing to conduct heat transfer application. Therefore, the analysis of heat transfer through the entire section of channel (both developing and developed region) is important to understand flow behavior along with heat transfer performance of the entire section for industrial operation. Additionally, most of the researches on heat transfer analysis of channels were conducted on developed region. Only few researches conducted on developing region and entire channel section. Therefore, this study investigates numerically the effect on laminar convective heat transfer characteristics in developing region of a rectangular channel with presence of four different water based nanofluids which are Al_2O_3-H_2O, SiC- H_2O, TiO_2- H_2O and CuO-H_2O. Comparisons are made in terms of heat transfer coefficient and Nusselt number enhancement among these nanofluids and both regions.

2. Methodology

For the purpose of investigating the heat transfer characteristics of water based nanofluids through a rectangular channel, a computational fluid dynamics (CFD) analysis has been carried out by employing Ansys Fluent software. The advent of fast and inexpensive computers enables CFD to be the most effective approach for most researchers including Wael Al-Kouz *et al.,* [7], Insiat *et al.,* [17], Hassan *et al.,* [18], Ong *et al.,* [19], and Mahmood *et al.,* [20]. The simulation approach for present study is described next.

2.1 Computational Model and Boundary Conditions

A steady laminar single-phase flow through a two-dimensional channel is considered as shown in Figure 1. At the wall of the channel a constant heat flux of 500 W/m^2 has been applied with stationary wall boundary condition whereas uniform velocity with a constant temperature of 303K is considered at channel inlet. Pressure outlet is considered at the outlet with a presumption of no slip condition on the channel surface. To determine the heat transfer characteristics in the developing region, the surface and bulk temperatures have been examined at an interval of 50 mm from the inlet to outlet.

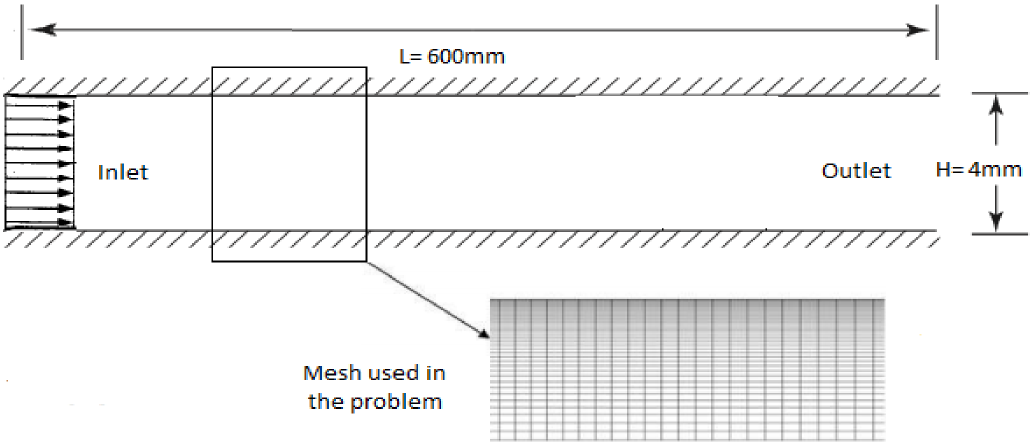


Fig. 1. Computational geometry of the rectangular channel and mesh

2.2 Numerical Method

For this numerical modeling, commercial ANSYS Fluent software was used for computational fluids dynamics approach of the 2D symmetric channel. A control volume approach was solved for the second order unpinned governing equation of energy, momentum, mass and laminar quantities. A simple algorithm and least squares cell-based gradient was used for velocity-pressure coupling purpose. The relaxation factors for pressure, momentum, energy and density were set to be 0.4, 0.785, 1 and 0.8, respectively. Nanoparticles considered in this study were CuO, Al_2O_3, SiC and TiO_2 with 1-5% volume concentration while water was chosen as the base fluid. The nanofluids were tested for a constant Reynolds numbers 700 and results were compared in terms of heat transfer coefficient and Nusselt number enhancement.

2.3 Governing Equations

The governing equations for continuity, momentum and energy for laminar steady flow conditions of forced convection are described as follows.

Continuity equation: For two-dimensional steady flow condition, the amount of mass within the control volume remains constant, and thus the conversation of mass can be written as

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

where, u and v are the fluids velocity at x and y directions, respectively.

Momentum equation: The momentum equation for laminar fluid flow is expressed by

X- Momentum Equation

$$\rho\left(u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}\right)=-\frac{\partial p}{dx}+\mu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right) \qquad (2)$$

Y-Momentum Equation

$$\rho\left(u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}\right)=-\frac{\partial p}{dy}+\mu\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right) \tag{3}$$

where, ρ is the density and μ is the viscosity of fluids.

Energy Equation: Energy can be exchanged or converted by heat, mass and work only, therefore for a steady-flow control volume the energy balance can be described as

$$\rho C_p\left(u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}\right)=k\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right) \tag{4}$$

where, C_p is the specific heat at constant pressure, k is the thermal conductivity and T is the temperature of fluids.

2.4 Thermal and Fluid Dynamics Properties

The Reynolds number for water based nanofluids flow is expressed as

$$Re=\frac{\rho_{nf}U_{av}D_h}{\mu_{nf}} \tag{5}$$

where, U_{av} is the average inlet velocity, ρ_{nf} is the density and μ_{nf} is the viscosity of nanofluids whereas D_h is the hydraulic diameter of channel.

The heat transfer rate is expressed as

$$Q_{nf}=\dot{m}_{nf}C_{P_{nf}}\Delta T \tag{6}$$

where, $\dot{m}_{nf}$ is the mass flow rate of nanofluids and ΔT is the log mean temperature difference which is calculated as

$$\Delta T=\frac{(T_W-T_O)-(T_W-T_i)}{\ln\left(\frac{T_W-T_O}{T_W-T_i}\right)}, \tag{7}$$

where, T_w is the wall temperature whereas T_i and T_o are the inlet and outlet temperature of the nanofluids.

The average heat transfer coefficient h is given by

$$h=\frac{\dot{Q}_{nf}}{A_w(\Delta T)} \tag{8}$$

where, A_w is the surface area of channel.

The average Nusselt number is defined as follows

$$Nu = \frac{h\,D_h}{k_{nf}} \tag{9}$$

where, k_{nf} is the thermal conductivity of nanofluids.

Dynamic viscosity: There are several empirical equations for dynamic viscosity of nanofluids. For this study, we employed Pak and Cho [21] equation for TiO_2, Nguyen *et al.,* [22] equation for CuO, Maiga *et al.,* [23] equations for Al_2O_3 and Chein *et al.,* [24] equation for SiC. The equations are given as follows

For TiO_2 –water [21]

$$\mu_{nf} = \mu_{bf}(1.0683 + 4.70\emptyset + 167.7\emptyset^2) \tag{10}$$

where, μ_{bf} is the viscosity of base fluid which is water and $\emptyset$ is the volume concentration of nanoparticles.

For CuO –water [22]

$$\mu_{nf} = \mu_{bf}(1.475 - 0.319\emptyset + 0.051\emptyset^2 + 0.009\emptyset^3) \tag{11}$$

For Al_2O_3–water [23]

$$\mu_{nf} = (1 + 7.3\emptyset + 123\emptyset^2)\mu_{bf} \tag{12}$$

For SiC–water [24]

$$\mu_{nf} = \mu_{bf}[1 + 10.6\emptyset + (10.6\emptyset)^2] \tag{13}$$

Thermal conductivity: For this study, we employed Pak and Cho [21] equation for thermal conductivity of TiO_2-water, CuO-water and Al_2O_3-water, meanwhile Maxwell *et al.,* [25] equation was used for thermal conductivity of SiC-water. The equations are as follows

For TiO_2 –water [21]

$$k_{nf} = (1.0084 + 2.1796\emptyset) \tag{14}$$

For CuO –water [21]

$$k_{nf} = k_w(.53785 + .7644815\emptyset + .018689) \tag{15}$$

where, k_w is the thermal conductivity of water which is base fluid (i.e., $k_w = k_{bf}$).

For Al_2O_3–water [21]

$$k_{nf} = k_{bf}(1.0021 + 7.3349\emptyset) \tag{16}$$

For SiC–water [25]

$$k_{nf} = \frac{k_p+2k_{bf}+2(k_p-k_{bf})\emptyset}{k_p+2k_{bf}-(k_p-k_{bf})\emptyset\times k_{bf}} \tag{17}$$

where, k_p is particle's thermal conductivity.

Density: In this study, Xuan and Roetzel [26] equation for density of nanofluids has been used. The equation is given below

$$\rho_{nf} = \rho_p\emptyset + \rho_{bf}(1-\emptyset) \tag{18}$$

where, ρ_{nf} is the density of nanofluids and $\rho_p$is the density of nanoparticles whereas ρ_{bf} is the density of base fluid.

Specific heat: Pak and Cho [21] equation was also used for the nanofluid's specific heat calculation. The equation is given below

$$C_{nf} = (1-\emptyset)C_{bf} + \emptyset C_p \tag{19}$$

where, C_{nf}, C_{bf} and C_p are the specific heat capacity of nanofluids, water which is base fluid and nanoparticles respectively while $\emptyset$ is the volume concentration of the nanoparticles.

2.5 Validation of Simulation Model

For validation of the simulation model, the Nusselt number has been obtained for flow of water and the values were compared with the empirical equation of Nusselt number of entry region provided by Edwards *et al.,* [27]. The results show good agreement with only deviation of 5% from the empirical equation as shown in Figure 2.

The empirical equation that has been established by Edwards *et al.,* [27] for developing region of laminar parallel plates flow is given below

Entry region laminar

$$Nu = 8.22\ \frac{0.03\left({}^{D_h}/_{L}\right)\times Re\times Pr}{1+0.016\left[\left({}^{D_h}/_{L}\right)\times Re\times Pr\right]^{2/3}}, Re \leq 2800 \tag{20}$$

where, Re is the Reynolds number while Pr is the Prandtl number

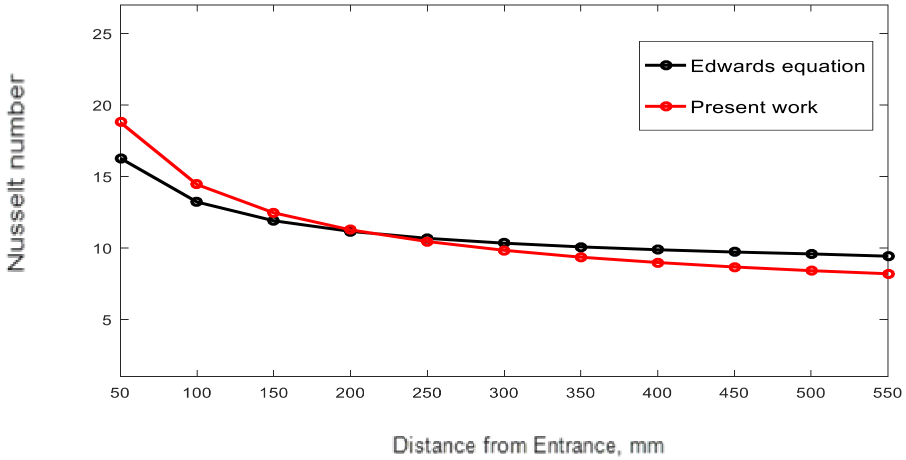


Fig. 2. Comparison of Nusselt number between Edwards *et al.,* [27] correlation and present study with water for different Reynolds numbers

2.6 Grid Independence Test

For grid independence investigation, working substance has been taken as water and the simulation was run at Reynolds number 700. Grid independence test was carried out to discover the optimum grid size for the present study. Five different grid sizes (500×15, 800×30, 900×40, 1000×45 and 1200×50) for rectangular channel were tested to find out the effect on the Nusselt number calculated at a distance 590 mm from the inlet which is shown in Figure 3.

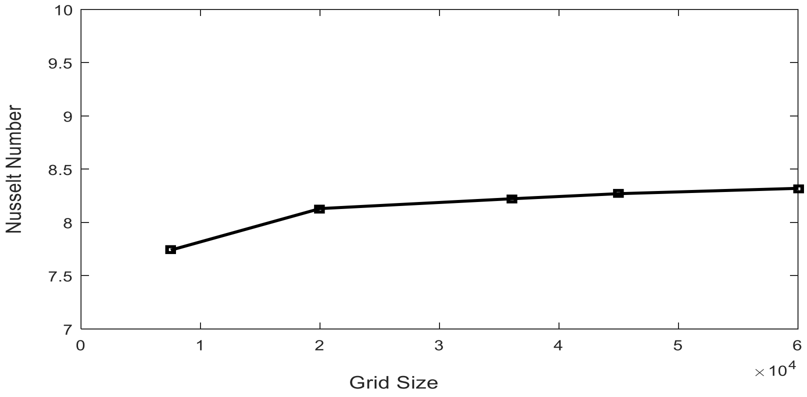
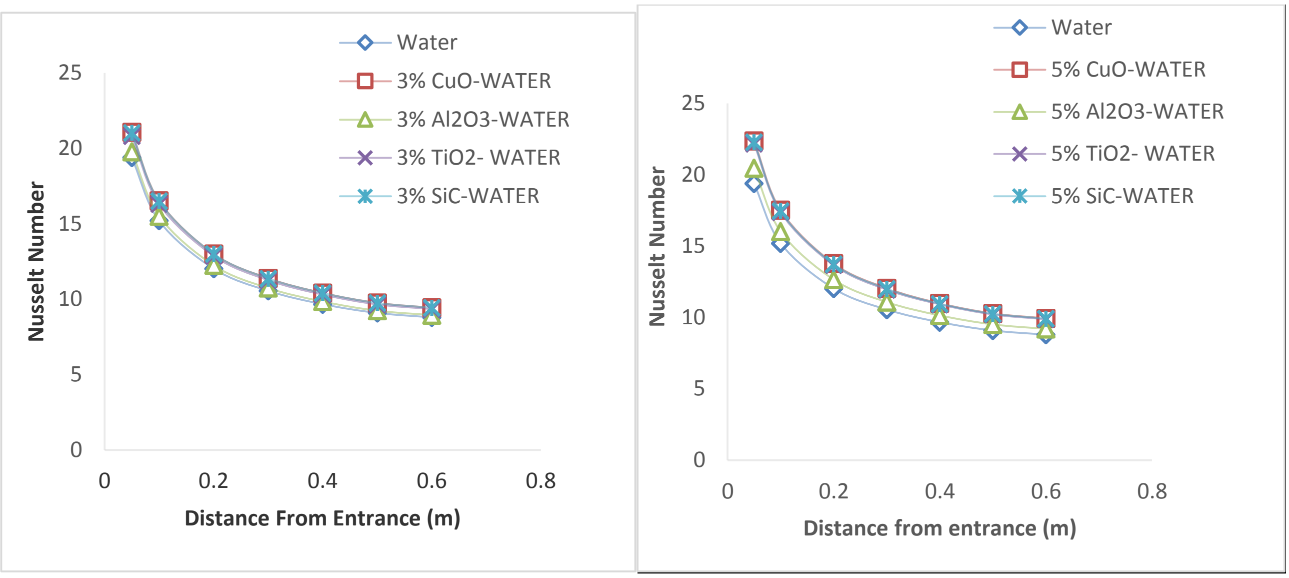


Fig. 3. Variation of Nusselt Number for different grid sizes

From Figure 3, it was found that there is no significant change in Nusselt Number beyond the grid size of 900×40 and at this grid the Nusselt number is very close to 8.23. Therefore, for the present study, the grid size of 36000 was used to perform all the simulation.

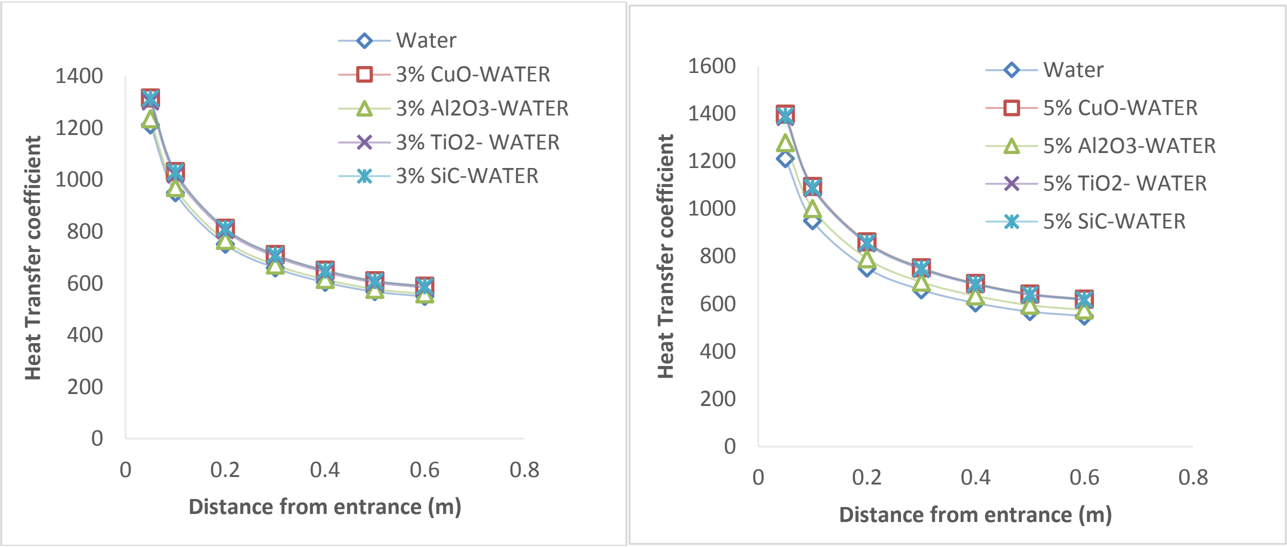
3. Results and Discussions

The effects of nanoparticles volume fraction on Nusselt number and heat transfer coefficient along with axial distance for 3% and 5% volume concentrations of nanoparticles at constant Reynolds number of 700 are shown in Figures 4 and 5, respectively. From Figure 4, after 400 mm distance from entrance, the Nusselt number variation has been very limited. It remains almost constant which indicates that after this distance the developed region has started. Similar observation can be seen in Figure 5. Since this paper focuses on heat transfer characteristics in developing region of the rectangular channel, these observations provide the necessary relevance.



(a) (b)

Fig. 4. Variation of Nusselt number along with axial distance from entrance for (a) 3% and (b) 5% volume fraction of all water based nanofluids



(a) (b)

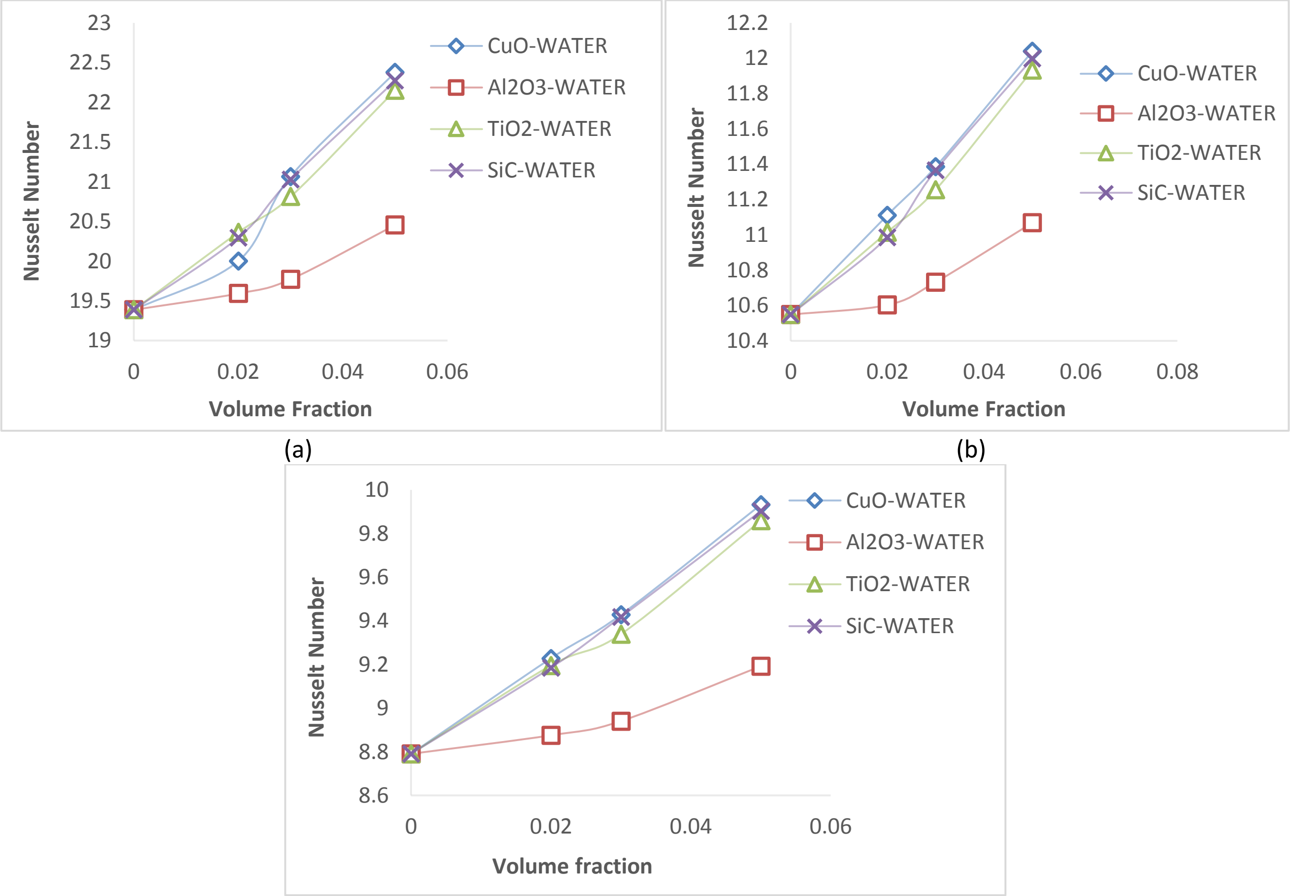
Fig. 5. Variation of heat transfer coefficient along with axial distance from entrance for (a) 3% and (b) 5% volume fraction of all water based nanofluids

These figures (Figures 4 and 5) also demonstrate that the value of Nusselt number increases with the presence of nanoparticles in water flow. The Nusselt number is observed to decrease with the variation of axial position along with the channel length from entry section to outlet at constant Reynolds number.

Meanwhile, Figures 6 and 7 represent the effects of different nanoparticles volume fraction on Nusselt number and heat transfer coefficient, respectively, at different locations, (a) 0.05 m, (b) 0.3 m and (c) 0.6 m from entrance. The former two locations (0.05 m and 0.3 m distance) were both developing region while the later (0.6 m) was a developed region. These figures also indicate the comparison among different nanoparticles which assist to analyse the performance and identify the best nanoparticle as well. It can be observed from Figures 6 and 7 that CuO-water provides the highest enhancement for both Nusselt number and heat transfer coefficient compared to the other nanofluids. On the other hand, Al_2O_3-water results in the lowest enhancement in terms of both Nusselt number and heat transfer coefficient.

The results from Figures 6 and 7 also show that at distance 0.05 m from entrance for 2% volume fraction, CuO provides lower enhancement compared to SiC and TiO_2 for both Nusselt number and heat transfer coefficient. This might be due to the location being very close to inlet which affected the performance of CuO at this distance. However, at distance 0.3 m and 0.6 m from entrance CuO provides highest enhancement compared to others. Therefore, CuO-water is considered as the overall highest enhancement provider in terms of Nusselt number and heat transfer coefficient compared to other considered nanofluids in this study.

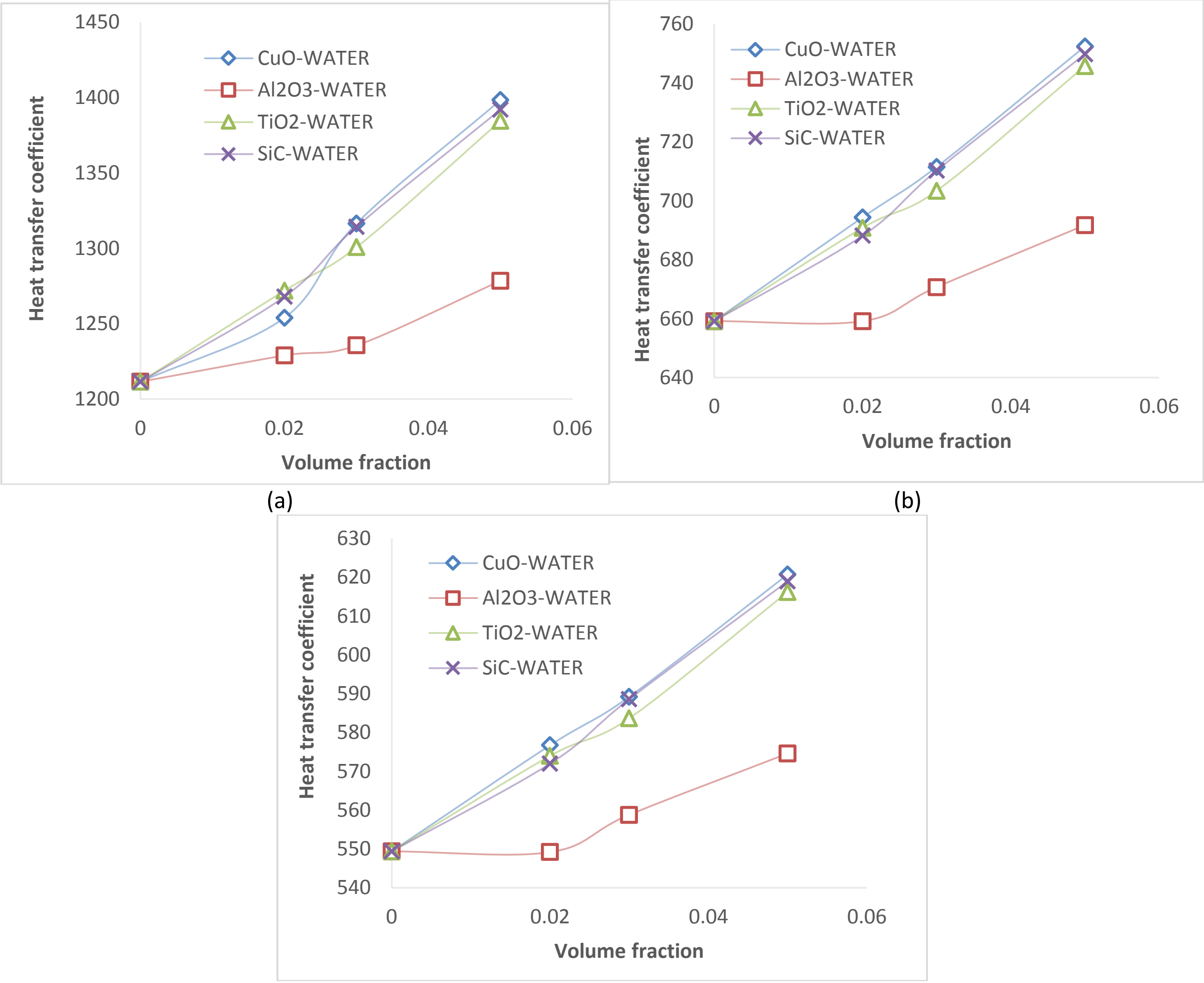
Additionally, for better understanding of the different volume fraction Ø effect on the Nusselt number and heat transfer coefficient enhancement, the results for CuO-water nanofluid are presented in Figure 8 for Ø = 1-5%. For this analysis, CuO-water nanofluid was considered as it provides the overall highest enhancement in both Nusselt number and heat transfer coefficient as shown and discussed above. From Figure 8(a), at position *x* = 50 mm which is developing region, the Nusselt number for CuO-water increases from 1.5% to 13.36% for Ø= 1-5%, respectively, compared to water. Meanwhile, at *x* = 600 mm which is developed region, the enhancement was 1.15% to 11.48% for Ø = 1-5%, respectively.



(a) (b)

(c)

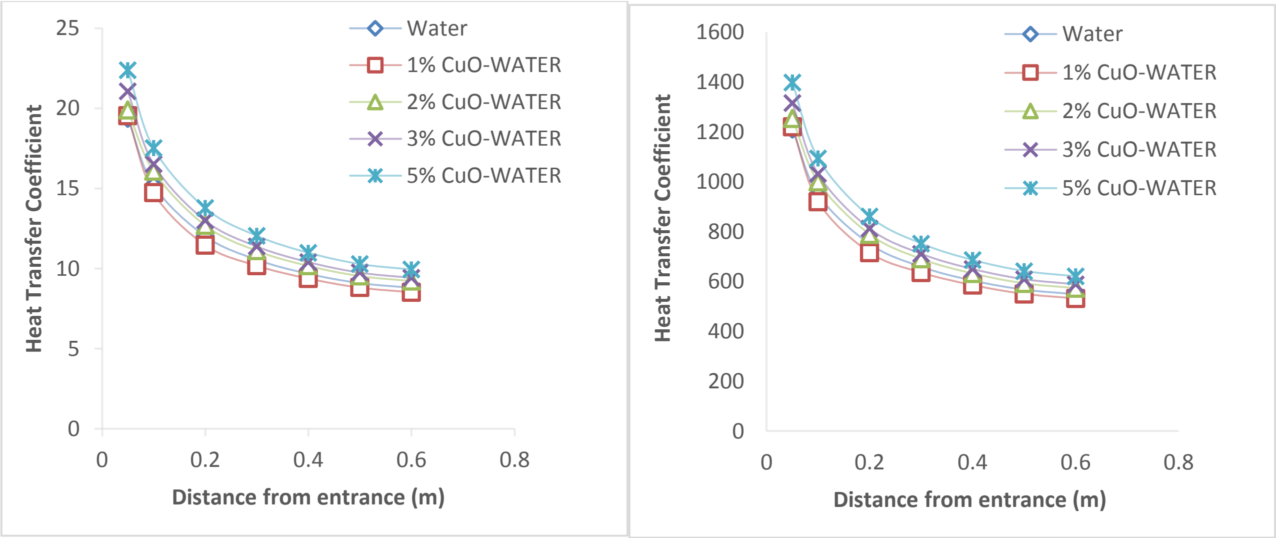
Fig. 6. Variation of Nusselt number with volume fraction of all water based nanofluids at distance (a) 0.05 m, (b) 0.3 m and (c) 0.6 m from entrance



(a) (b)

(c)

Fig. 7. Variation of heat transfer coefficient with volume fraction of all water based nanofluids at distance (a) 0.05 m, (b) 0.3 m and (c) 0.6 m from entrance



(a) (b)

Fig. 8. Effect of volume fraction on (a) Nusselt number and (b) heat transfer coefficient along axial distance from entrance for CuO-water nanofluid

Meanwhile, Figure 8(b) demonstrates that the coefficient of heat transfer increases with the presence of CuO nanoparticles while decreases with the variation of axial location from inlet to outlet. At location *x* = 50 mm the enhancement for heat transfer coefficient is 2% to 13.38% for 1-5% volume fraction compared to that of water, whereas at location x = 600 mm the enhancement reduces a little to 1.6% to 11.45% as seen in Figure 8(b).

Table 1 shows enhancement (%) of the Nusselt number and heat transfer coefficient among the different nanofluids for both developing and developed regions. Observation from Table 1 indicates that in both regions, the presence of CuO nanoparticles provides the highest enhancement for both heat transfer coefficient and Nusselt number which is almost 14% for developing region and 12% for developed region, both with 5% volume fraction.

Table 1
Comparison of enhancement in terms of Nusselt number and heat transfer coefficient among the water-based nanofluids

Nano-Particles	Volume fraction	Nusselt number enhancement percentage compared to water		Heat transfer coefficient enhancement percentage compared to water	
		Developing region (at 0.05 m distance from entrance)	Developed region (at 0.6 m distance from entrance)	Developing region (at 0.05 m distance from entrance)	Developed region (at 0.6 m distance from entrance)
CuO	3%	7.79%	6.79%	7.98%	6.79%
Al_2O_3		1.94%	1.68%	1.94%	1.61%
TiO_2		6.85%	5.89%	6.85%	5.83%
SiC		7.82%	6.69%	7.84%	6.63%
CuO	5%	13.36%	11.48%	13.38%	11.45%
Al_2O_3		5.23%	4.35%	5.24%	4.36%
TiO_2		12.49%	10.85%	12.50%	10.88%
SiC		12.96%	11.21%	13.00%	11.17%

4. Conclusions

This study focuses on the numerical investigation of laminar convective heat transfer characteristics of four different water based nanofluids flowing through the developing region of a rectangular channel. For this purpose, Al_2O_3, CuO, SiC and TiO_2 nanoparticles with 1-5% volume fraction are used to mix with pure distilled water. Results from Ansys Fluent simulations demonstrate 2% to 13.38% enhancement in heat transfer coefficient with the presence of 1 to 5% nanoparticles concentration, respectively, in comparison to pure water. Meanwhile, results in terms of Nusselt number show an increase of 1.5% to 13.36% as compared to pure water for the same range of nanoparticles concentration, respectively. From these results, it can be deduced that higher heat transfer coefficient and Nusselt number can be obtained with higher nanoparticles volume fraction. Moreover, the results show that CuO-water nanofluid provides the highest enhancement in terms of both heat transfer coefficient and Nusselt number while Al_2O_3-water nanofluid provides lowest enhancement among all nanofluids considered in this study. From this study, it can be concluded that water-based nanofluids provide enhancement of heat transfer coefficient and Nusselt number for laminar developing region of a rectangular channel.

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