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Numerical investigation of convective heat transfer of single wall carbon nanotube nanofluid laminar flow inside a circular tube

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Abstract This study presents the behavior of a single wall carbon nanotube (SWCNT)/water nanofluid for convective laminar flow inside a straight circular pipe heated by a constant heat flux. Five volume fractions of SWCNT were used to investigate their effect on the heat transfer coefficient, Nusselt number, temperature distribution and velocity field in comparison with pure water flow. One model for each property was tested to calculate the effective thermal conductivity, effective dynamic viscosity, and effective specific heat of the SWCNT/water mixture. The models were extracted from experimental data of a previous work. The outcomes indicate that the rheological behavior of SWCNT introduces a special effect on the SWCNT/water properties, which vary with SWCNT volume fraction. The results show an improvement in the heat transfer coefficient with increasing volume fraction of nanoparticles. The velocity of SWCNT/water nanofluid increased by adding SWCNT nanoparticles, and the maximum increase was registered at 0.05% SWCNT volume fraction. The mixture temperature is increased with the axial distance of the pipe but a reduction in temperature distribution is

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observed with the increasing SWCNT volume fraction, which reflects the effect of thermophysical properties of the mixture.

Keywords: Convective heat transfer; Reynolds number; Nanofluid; Single wall carbon nanotube SWCNT; Laminar flow

Nomenclature

C_p	–	specific heat, J/kgK
$C_{p.bf}$	–	specific heat of the base fluid, J/kgK
$C_{p.nf}$	–	specific heat of the nanofluid, J/kgK
$C_{p.p}$	–	specific heat of the nanoparticles, J/kgK
D	–	pipe diameter, m
d_p	–	nanoparticle diameter, m
h	–	heat transfer coefficient, W/m^{2}K
k_{bf}	–	thermal conductivity of base fluid, W/mK
k_{nf}	–	thermal conductivity of nanofluid, W/mK
k_p	–	thermal conductivity of nanoparticles, W/mK
q	–	heat flux, W/m^2
R	–	pipe radius, m
Re	–	Reynolds number
T	–	thermodynamic temperature, K
T_o	–	reference temperature, K
T_{fr}	–	freezing point of the base fluid, K
$\vec{v}$	–	velocity vector, m/s
V_x	–	velocity of the nanofluid, m/s
X	–	coordinate along the pipe axis, m

Greek symbols

μ_{bf}	–	dynamic viscosity of the base fluid, kg/ms
μ_{nf}	–	dynamic viscosity of the nanofluid, kg/ms
ρ_p	–	density of nanoparticles, kg/m^3
ρ_{bf}	–	density of the base fluid, kg/m^3
ρ_{nf}	–	density of the nanofluid, kg/m^3
ϕ	–	volume fraction of nanoparticles

Subscripts

bf	–	base fluid
nf	–	nanofluid
p	–	particles

Abbreviations

CNT	–	carbon nanotube
SWCNT	–	single wall carbon nanotube
MWCNT	–	multi-walled carbon nanotube

1 Introduction

Nanofluids can be considered an essential part of the advanced technologies to improve the thermophysical properties of numerous fluids used in many applications. Heat exchangers, electronic cooling, radiators, and nano lubricants are the techniques modified by using different types of nanoparticles such as AL_2O_3, TiO_2, and CuO, etc. Single wall carbon nanotube (SWCNT) is a special type of nanoparticles, which has high thermal conductivity and may give unusual properties if it is used as a nanofluid. Convective heat transfer of fluids can be improved by the addition of nanoparticles. Nanofluids containing various types of nanoparticles were tested to enhance the thermal behavior of the base fluid, as in the work of Choi *et al.* [1]. Multi-walled carbon nanotube (MWCNT) was used to enhance the thermophysical properties of poly α-olefin oil which resulted in a 160% improvement for 1% volume fraction [2]. Xie *et al.* [3] used MWCNT with three different base fluids - distilled water, ethylene glycol and decene to test the nanofluid thermophysical properties. They found an increase in thermal conductivity by about 7.0%, 12.7%, and 19.6%, respectively. Copper nanoparticles improved the heat transfer coefficient of pure water for a given Reynolds number by around 60% using 2% volume fraction as presented by Xuan *et al* [4]. Wen *et al.* [5] presented an experimental study to determine the convective heat transfer for γ-Al_2O_3/water flowing through a circular pipe using different quantities of nanoparticle volume fractions. They found an increase in the convective heat transfer with the addition of γ-Al_2O_3 nanoparticles, especially in the entrance region and reduced gradually with the axial distance. Aqueous carbon nanotube (CNT) was used to enhance the performance of a microchannel, which improved the forced convection heat transfer according to Faulkner *et al.* [6]. An extremely low Reynolds number was used in the work with a range of volume fraction CNT 1.1–4.4%. CNT improves the convective heat transfer of CNT nanofluid flowing through a horizontal tube in comparison with pure water to a significant amount as described by Ding *et al.* [7]. Tunneling nanotube (TNT) and carbon nanotube (CNT) was added by He *et al.* [8] to water to test the heat transfer behavior for the laminar fluid flow inside a tube. Their work was executed numerically considering the base fluid and the nanoparticles as a single phase. They found an enhancement in the thermal conductivity, as wel as convective heat transfer was augmented especially if the fluid flow was considered as a non-Newtonian one. On the other hand, He *et al.* [9] discussed the TiO_2/water nanofluid laminar flow inside a circular pipe, numerically. They studied the impact of nanoparticles volume fraction, Reynolds number and heat transfer coefficient. Their results indicated an improvement in the heat transfer with the increase in the nanoparticles volume fraction, and a good agreement was detected in comparison with the experimental results. Moreover, they demonstrated the effect of different parameters on their outcomes such as the effect of viscosity and thermal conductivity, and concluded that thermal conductivity affected the heat transfer coefficient more than viscosity. Garg *et al.* [10] studied the enhancement in heat transfer coefficient of the fluid flow inside a copper pipe. Nanofluid of multi-walled carbon nanotube/water was applied as a working fluid; the experiments were conducted at different values of Reynolds number and 1% volume fraction. They indicated an enhancement in the heat transfer coefficient at all Reynolds numbers and volume fractions. Kamali *et al.* [11] performed a numerical study on the effect of MWCNT/water to enhance the convective heat transfer for the fluid flow through a straight tube. The results showed an augmentation in the heat transfer coefficient with the addition of MWCNT at a constant Reynolds number. Mohammed *et al.* [12] studied the heat transfer through different nanofluids flowing through a heat exchanger of the microchannel. They found that the thermal performance of heat exchangers was improved by using nanofluids in general. SWCNT is a special type of nanoparticles, which have high thermal conductivity and may give unusual properties if used as a nanofluid. The cylindrical shape of CNT can explain the novel thermal properties such as high thermal conductivity; that shape effect has been discussed in many experimental and theoretical studies such as Harish *et al.*, Nasiri *et al.*, and Sadri *et al.* [13–15]. Single wall carbon nanotube/water was used in the double-layered microchannel heat sink to investigate the laminar flow and heat transfer coefficient in comparison with pure water. The investigations were performed numerically by Arani *et al.* [16]. They found that the heat transfer rate was improved with the addition of SWCNT and by increasing the SWCNT volume fraction.

The present work aims to investigate the performance of three models for calculating the effective thermal conductivity, effective specific heat and effective viscosity of SWCNT/water nanofluid; the models are based on experimental data achieved by another work to test the mentioned properties. A numerical study is performed by applying the presented models to evaluate the heat transfer coefficient, Nusselt number, temperature distribution and velocity field for the SWCNT/water nanofluid, flowing inside a circular pipe supplied by a constant heat flux. The mentioned properties are studied by applying various volume fractions of SWCNT, which shows the transformation in the SWCNT/water properties with a rising SWCNT concentration as a result of rheological behavior, achieved from the special shape of SWCNT.

2 Mathematical model

Single wall carbon nanotube/water nanofluid is considered as a single-phase medium, so the thermophysical properties of the mixture such as the effective thermal conductivity, effective specific heat and effective viscosity are described by specific models presented in this work and designed according to the experimental results of Sabiha *et al.* [17]. However, no experimental data mentioned about the effective density, so a general model for evaluating the effective density is used to calculate the effective density of SWCNT/water, Godson *et al.* [18], and by using SWCNT properties presented in Sabiha *et al.* The dimensional governing equations that cover the single-phase flow at steady state are [19–21]:

continuity equation

$$\nabla.\left(\rho_{nf}\,\vec{v}\,\right) = 0, \tag{1}$$

momentum equation

$$\nabla.\left(\rho_{nf}\,\vec{v}\,\vec{v}\,\right) = -\nabla p + \nabla.\left(\mu_{nf}\nabla\vec{v}\,\right), \tag{2}$$

energy equation

$$\nabla.\left(\rho_{nf}\,\vec{v}\,C_p\,T\right) = \left(\nabla.k_{nf}\nabla T\right). \tag{3}$$

3 Thermophysical properties of nanofluids

Three correlations are used in the present work for calculating the effective thermal conductivity, effective specific heat and effective viscosity. The correlations are based on the experimental data presented in the work of Sabiha *et al.* [17] where the mentioned properties for SWCNT/water nanofluid were measured as a function of temperature and with different volume fractions of SWCNT. The correlations specify each property as a function of temperature and volume fraction. The only property calculated according to the standard equation is the effective density.

3.1 Effective thermal conductivity correlation

The correlation which is used to calculate the effective thermal conductivity as a function of temperature and SWCNT volume fraction has the form

$$k_{nf} = 0.5 + (0.00363 + 0.01264\phi)\,(T - 273)\,. \tag{4}$$

3.2 Effective specific heat correlation

The correlation used to calculate the effective specific heat as a function of temperature and SWCNT volume fraction is as follows

$$C_{P.nf} = 3.5042 - 3.0940\phi + 0.01045\,(T - 273)\,. \tag{5}$$

3.3 Effective dynamic viscosity correlation

The correlation used to calculate the effective dynamic viscosity as a function of temperature and SWCNT volume fraction is

$$\mu_{nf} = 5(T - 273)^{-0.4993+0.2226\phi}\,. \tag{6}$$

3.4 Effective density correlation

The correlation which is used to calculate the effective density as a function of SWCNT volume fraction and constant temperature can be found from

$$\rho_{nf} = (1 - \phi)\,\rho_{bf} + \phi\rho_p\,. \tag{7}$$

4 Numerical method and simulation

The applied domain of the presented work achieved by following the work of He *et al.* [9] was represented by a pipe of 2 m in length and 0.004 m in diameter and heated by a constant heat flux equal to 4000 $\mathrm{W/m^2}$. Laminar flow condition at a fixed Reynolds number equal to 900 was applied in the present numerical procedure. The boundary conditions were fixed as follows: the applied temperature was 293 K and a uniform velocity field was present at the pipe inlet, a constant temperature gradient with zero velocity gradient at the pipe outlet and no-slip condition at the wall. The numerical procedure was built using commercial general-purpose simulation software COMSOL Multiphysics [28].

The used element type in simulation is that of a coarse-mesh type, with a minimum size equal to 0.0402 mm and maximum size equal to 0.899 mm, with a 1.2 element growth rate. The narrow region resolution is equal to the one with a curvature factor equal to 0.4. Figure 1 shows the schematic diagram for the domain geometry and the used mesh. The number of mesh vertices is equal to 59387, the number of triangles is 76190, quads 17024 and edge elements 8534. The number of mesh elements is 93214, the minimum element quality is 0.4254 and the average element quality is 0.8345, the element area ratio is 0.09751 and the total mesh area is 8000 mm^2. The triangle mesh area is 7071 mm^2, the quads mesh area is 929 mm^2 and the mesh edge length is 4008 mm.

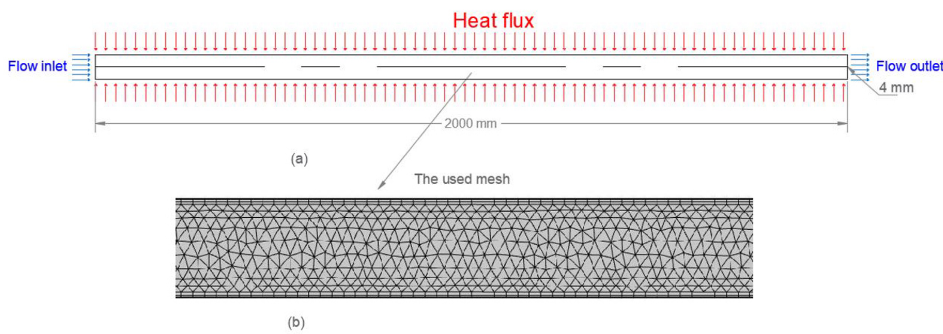

Figure 1: Schematic diagram for (a) the domain geometry, (b) the mesh used.

5 Validity of the model

A local heat transfer coefficient for pure water at different axial positions along the pipe used in this work has been calculated to validate the presented numerical solution in comparison with the experimental and numerical study performed by He *et al.* [9] as shown in Fig. 2. The simulation of the validity procedure is done for a laminar flow of water through a circular pipe at the Reynolds number of 900 and subject to a constant heat flux equal to 4000 W/m^2. Moreover, the Nusselt number at various axial positions along the pipe axis was also calculated and compared with the experimental and numerical data of He *et al.* [9] and the results of Shah equation [22] as shown in Fig. 3. From Figs. 2 and 3, it can be noticed that there is a good agreement between the present study and experimental as well as numerical data of He *et al.* [9], with a standard deviation of 8.17%, with respect to the experimental work. In addition, for the validity of the Nusselt number a good agreement was obtained between the present work and experimental, numerical and Shah equation data, with a standard deviation of 8.45%, to the experimental data.

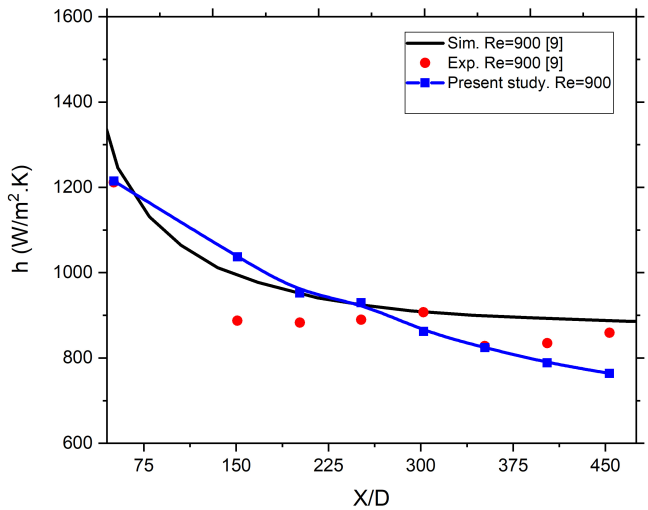

Figure 2: Heat transfer coefficient at various axial positions for the present study in comparison with reference data.

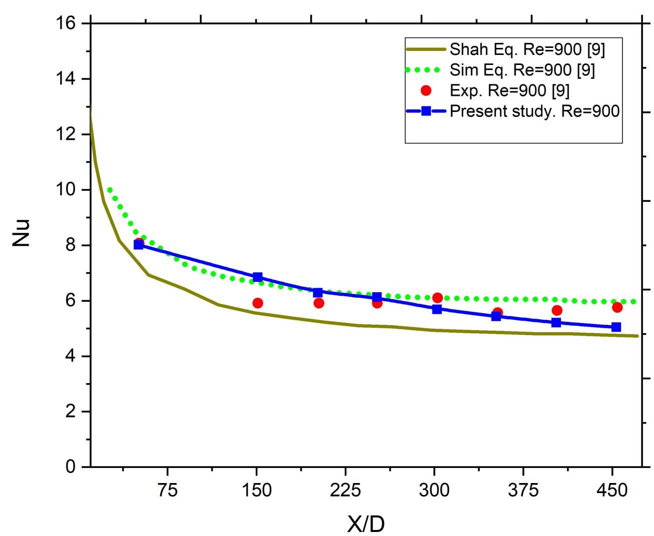

Figure 3: Nusselt number at various axial positions for the present study in comparison with reference data.

6 Results and discussion

6.1 Convective heat transfer coefficient at different axial points

Convective heat transfer coefficient behavior recorded at various nanoparticle volume fractions of SWCNT/water and for pure water at different axial positions is presented in Fig. 4a. The behavior exhibits a reduction in the value of convective heat transfer coefficient with the increasing axial distance. The explained demeanor applies to pure water and all used SWCNT volume fractions. Moreover, the SWCNT improves the convective heat transfer coefficient with all used ratios in the work.

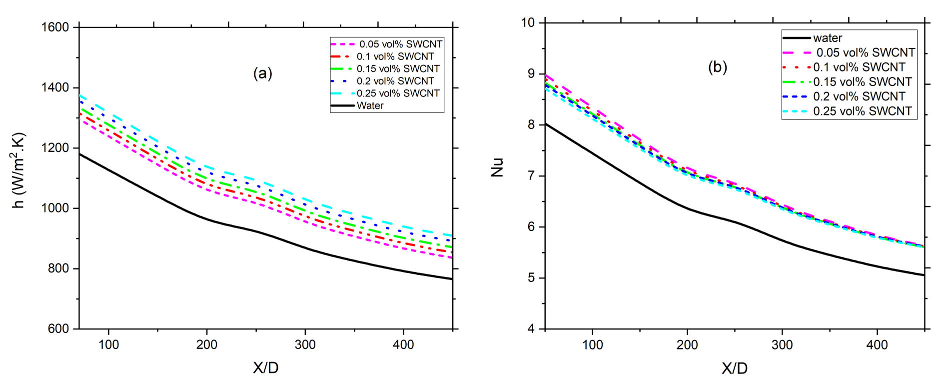

Figure 4: Axial profile of the convective heat transfer coefficient (a) and the Nusselt number (b).

6.2 Effect of volume fraction for SWCN

The impact of SWCNT addition to the pure water on the convective heat transfer coefficient is clarified in Fig. 4a, achieved at the Reynolds number of 900. It can be observed that SWCNT improves the convective heat transfer coefficient for all used volume fractions 0.05–0.25% in comparison with pure water. The maximum enhancement is detected at 0.25% volume fraction and reduced gradually with the decreasing volume fractions. The minimum improvement is indicated at 0.05% volume fraction.

6.3 Impact of SWCNT addition on Nusselt number

Figure 4b shows the impact of SWCNT on the Nusselt number, which was calculated at volume fractions 0.05–0.25% of SWCNT. The behavior exhibits an improvement in the Nusselt number with all used values of SWCNT. However, the maximum enhancement was recorded at 0.05% volume fraction and it was reduced gradually with the higher values. The interpretation for the reduction in the Nu number associated with an increase in the SWCNT volume fraction is related to the effective dynamic viscosity and the effective density, which dominate the velocity field of SWCNT/water at the constant Reynolds number equal to 900. The increase in volume fraction of SWCNT gives a rise in both the effective dynamic viscosity and effective density. However, the rising ratio in the effective dynamic viscosity is less than that of the effective density with the increasing SWCNT volume fraction, which minimizes the velocity field gradually and results in a limited increase in the convective heat transfer coefficient with the increasing the volume fraction of SWCNT in comparison with the improvement in the effective thermal conductivity of the SWCNT/water. The explained demeanor of the effective dynamic viscosity and effective density is connected directly to the SWCNT properties such as the density of 2100 kg/m^3, according to Sabiha *et al.* [17] and the special shape of SWCNT which produces the rheological behavior.

6.4 Rheological behavior effect

The rheological behavior of SWCNT/water has a direct impact on fluid flow, the convective heat transfer coefficient and Nusselt number, as shown in Fig. 4. The essential property responsible by the specific behavior of heat transfer coefficient and Nusselt number of SWCNT/water is the dynamic viscosity. The shear-thinning behavior produced from the special shape of SWCNT and MWCNT as presented by Nanda *et al.* [23] and Garg *et al.* [24], respectively, lead to a reduction in the dynamic viscosity with the raising shear rate. Therefore, whenever the SWCNT volume fraction increased, the shear-thinning effect enhanced and the dynamic viscosity of mixture decreased. The shear-thinning behavior effect is interpreted by the realignment of the SWCNT inside the base fluid with the shear force direction that minimizes the resistance to the flow [25,26] and decreases the fluid viscosity. According to the previous, a limited increase in the effective dynamic viscosity has been found in comparison to the effective density with the increasing SWCNT volume fraction, which results in a gradual decrease in the velocity field and a special behavior of the convective heat transfer coefficient and Nu number along the pipe. This special behavior of Nu number relevant to SWCNT shape and does not exist in another shape of nanoparticle [27].

6.5 Radial profiles of velocity

The radial profiles of axial velocity for SWCNT/water nanofluid for five volume fractions at 0.2 m and 1.6 m axial positions along the pipe are shown in Figs. 5a and b. The Reynolds number was fixed at 900 and the heat flux supplied to the pipe was equal to 4000 W/m^2. The laminar flow behavior was observed for the mixture, with the zero velocity at the pipe wall and increasing gradually reaching the maximum value at the center of the pipe. The velocity field improved with the addition of SWCNT volume fraction in comparison with pure water. The exegesis of this behavior is the change in the SWCNT volume fraction, which affects the effective dynamic viscosity and effective density of the mixture, and controls the applied velocity fields at the constant Reynolds number 900.

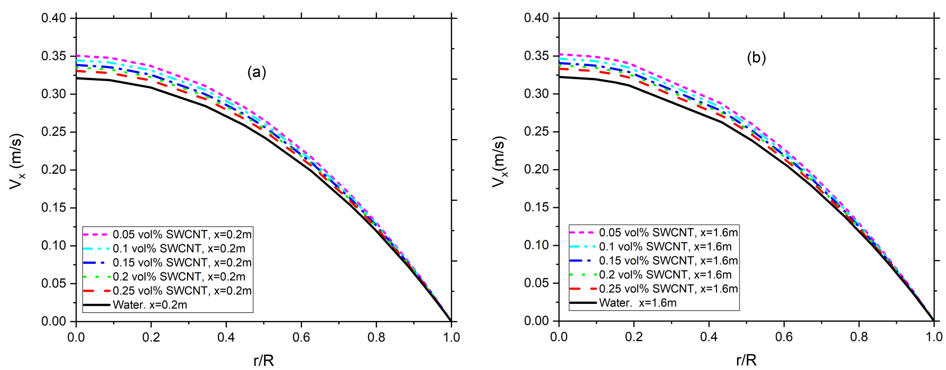

Figure 5: Radial profiles of local axial velocity at various volume fractions of SWCNT in comparison with pure water (a) at axial distance of 0.2 m and (b) 1.6 m.

Since the ratio of increase in the effective dynamic viscosity is less than the ratio of increase in the effective density for the reasons explained before, the maximum velocity field was found at 0.05% SWCNT volume fraction and decreased gradually with the higher SWCNT volume fractions. The minimum improvement in the velocity field was recorded at 0.25% volume fraction of SWCNT. Figure 6 shows details for the velocity field of SWCNT/water mixture at different axial positions and each volume fraction of SWCNT: (a) 0.05%, (b) 0.1%, and (c) 0.15%. One can observe the minimum velocity field recorded at the 1.6 m axial position, increasing gradually towards the 0.2 m position. However at the 0.2 m and 0.5 m positions the velocity fields seem to have the same values. This behavior is due to the fraction between the fluid layers, which reduces the velocity field with increasing distance along the pipe. The behavior at 0.2 m and 0.5 m gives intercepting results because the distance between these points is not very large so it is almost the same.

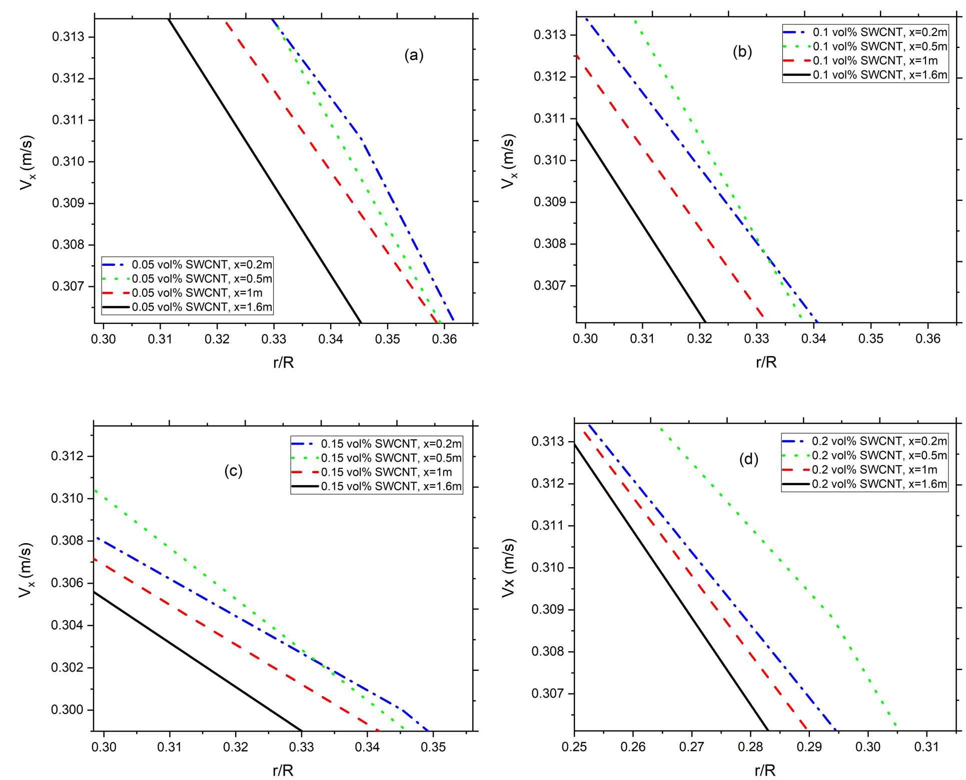

Figure 6: Radial profiles of local axial velocity at different axial positions and specific volume fractions of SWCNT: (a) 0.05 vol%, (b) 0.1 vol%, (c) 0.15 vol% and (d) 0.2 vol%.

6.6 Temperature distribution

The temperature distribution inside the pipe is shown in Figs. 7a and 7b. The general behavior exhibits a reduction in the temperature distribution with the increasing volume fraction of the SWCNT in comparison with the pure water so that the minimum temperature is noticed at 0.25% volume fraction of SWCNT and the maximum is observed at 0.05% volume fraction of SWCNT. This behavior is affected by two factors, the first one is the velocity field of the SWCNT/water flow, which broadly increases for all

SWCNT volume fractions in comparison to the pure water, and the second one is the effective thermal conductivity of the SWCNT/water, which increases with the addition of SWCNT. On the other side, the decrease in the velocity field with the increasing SWCNT volume fraction from 0.05 vol% to 0.25 vol% corresponds to a remarkable increase in the effective thermal conductivity of the SWCNT/water. The ratio of increase in the effective thermal conductivity with the addition of SWCNT is very significant, as compared to the decreasing ratio the velocity field with the increasing of SWCNT volume fraction, among the investigated SWCNT/water volume fractions.

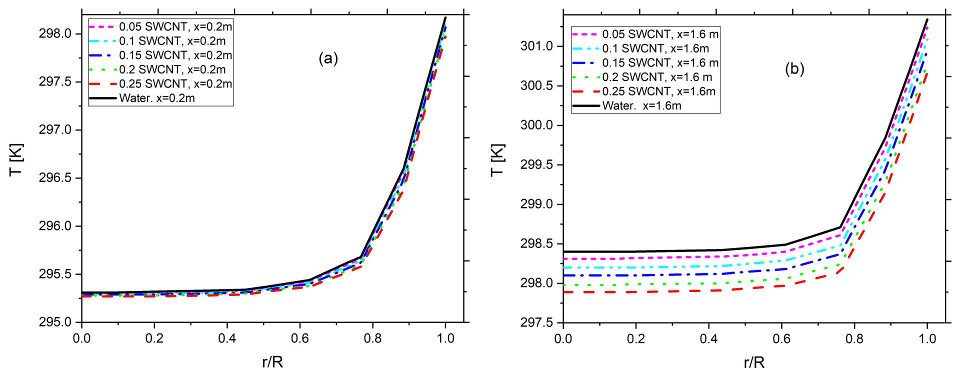

Figure 7: Temperature distribution at various volume fractions of SWCNT in comparison with pure water (a) at 0.2 m (b) at 1.6 m.

The temperature distribution at different volume fractions of SWCNT and at different axial positions is shown in Fig. 8. It follows from the figure that the temperature is increased toward the pipe axis, and the maximum temperature distribution was obtained at the 1.6 m axial distance, regardless of the volume fraction of SWCNT. The above rise in temperature is due to the long distance that the fluid travels inside the pipe, which allows delivering more heat to the SWCNT/water mixture. The reduction in temperature distribution with the increasing volume fraction of the nanoparticles, seen in Figs. 8a, b, c and d, can be explained by the decreasing velocity field of the SWCNT/water with the increasing SWCNT volume fractions, due to the reasons explained before. This is associated with the effective thermal conductivity of the mixture enhanced with the raising SWCNT concentration.

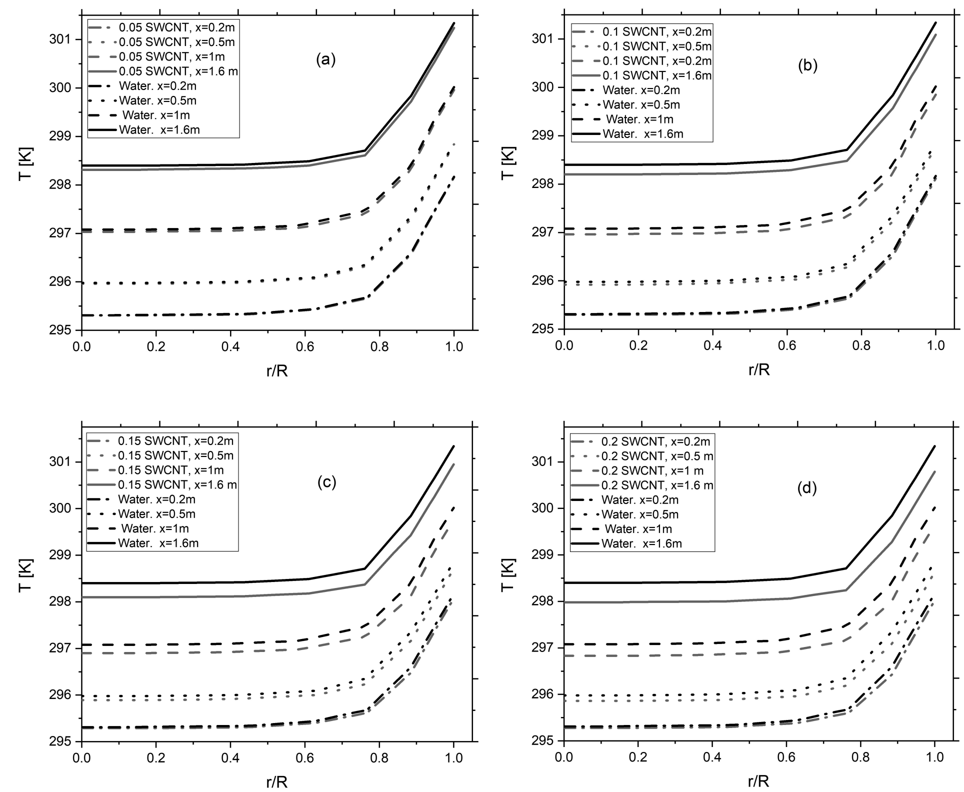

Figure 8: Temperature distribution at different axial positions for different volume fractions of SWCNT: (a) 0.05 vol%, (b) 0.1 vol%, (c) 0.15 vol%, and (d) 0.2 vol%.

7 Conclusions

Numerical investigation for convective heat transfer of SWCNT/water nanofluid laminar flow inside a circular tube using various volume fractions of the SWCNT has been studied. One model for each property to calculate the effective thermal conductivity, effective dynamic viscosity and effective specific heat of SWCNT/water has been proposed according to previous data of experimental work. Five volume fractions of SWCNT have been applied in the present study to indicate their effect on the heat transfer coefficient, velocity field and temperature distribution.

The results show a special behavior of SWCNT/water nanofluid related directly to its rheological properties, which affect the effective viscosity. The shear-thinning behavior produced from the special shape of SWCNT lead to a reduction in the dynamic viscosity with a raise in the shear rate. Therefore, whenever the SWCNT volume fraction increased, the shear-thinning effect enhanced and the dynamic viscosity of the mixture decreased. So, the ratio of increase in the effective dynamic viscosity with the addition of SWCNT to the basefluid is determined by the shape of SWCNT, and is limited in comparison to the increase in the effective density. The explained behavior controls the improvement in the heat transfer coefficient, which is associated with the increase in the velocity field of the SWCNT/water in comparison with the pure water and at the same time associated with a reduction in velocity within the investigated range of volume fractions of SWCNT. Moreover, the addition of SWCNT to the pure water improves the effective thermal conductivity to remarkable values. This behavior explains the temperature distribution indicated in the presented work. Finally, the limited improvement in the convective heat transfer in comparison to the thermal conductivity of the SWCNT/water affects directly the Nusselt number, which is improved generally with the addition of SWCNT, and reduced with the increasing volume fraction of SWCNT.

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