The effects of porosity and permeability on fluid flow and heat transfer of multi walled carbon nano-tubes suspended in oil (MWCNT/Oil nano-fluid) in a microchannel filled with a porous medium

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ABSTRACT

The forced convection heat transfer and laminar flow in a two-dimensional microchannel filled with a porous medium is numerically investigated. The nano-particles which have been used are multi walled carbon nano-tubes (MWCNT) suspended in oil as the based fluid. The assumption of no-slip condition between the base fluid and nano-particles as well as the thermal equilibrium between them allows us to study the nanofluid in a single phase. The nanofluid flow through the microchannel has been modeled using the Darcy–Forchheimer equation. It is also assumed that there is a thermal equilibrium between the solid phase and the nanofluid for energy transfer. The walls of the microchannel are under the influence of a fluctuating heat flux. Also, the slip velocity boundary condition has been assumed along the walls. The effects of Darcy number, porosity and slip coefficients and Reynolds number on the velocity and temperature profiles and Nusselt number will be studied in this research.

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1. Introduction

Due to significant advances in different sciences in recent decades, especially in the branches of electro mechanic sciences, is felt to control the heat exchanges between the components and the fluid. Therefore through this study, it is tried to find a better and more effective way to increase the rate of heat transfer and thus increasing the life of these components [1–7].

Hwang and Chao [8] experimentally investigated the heat transfer in a porous medium obtained from metal materials. Hadim [9] employed the porous medium formed of separate strips inside the channel and investigated the heat transfer. Huang and Vafai [10] considered porous blocks on the surface of the channel and analyzed the heat transfer and concluded that by properly selecting the parameters of the porous medium; it will be possible to increase the heat transfer with a slight decrease in the pressure.

There are two different methods for modeling the heat transfer in a porous medium: first the thermal equilibrium model and second the thermal non-equilibrium model [11–16]. Regarding to the thermal equilibrium model, it is assumed that the fluid phase and solid phase of a porous medium are in thermal equilibrium and thus only one energy equation is required to predict the behavior of heat transfer. Through the modeling of thermal non-equilibrium, the fluid and solid phases are not in a thermal equilibrium condition and therefore the fluid and solid have different temperatures. In this case, two energy equations have been considered; one for the fluid and the other for the solid matrix, which have been paired by converting some terms between them. The assumption of thermal non-equilibrium will be valid, if the temperature difference between the two phases within the system is much less than the temperature difference generated in the entire intended system [17–21].

Beavers and Joseph [22] studied the empirical equation for the velocity gradient in porous media and compared it with that in media without porosity. Jang and Chen [23] conducted a numerical study on a forced flow inside a parallel channel partly filled with a porous medium based on the Darcy, Brinkman and Forchheimer law and saw an increase in heat transfer in the porous medium. Using an analytical method, Chikh et al. [24] studied an extended flow inside a concentric tube partly filled with a porous material.

Taking into account a channel filled with a porous material and with the constant heat flux boundary condition, Jang and Ren [25] analyzed the effects of viscous losses, boundary layer assumptions, distribution of heat flux, diameter of particles and variable properties of oil. Mohamad [26] investigated the heat transfer in channels and tubes fully and partially filled with a porous material. Many researchers studied and analyzed the issue of heat transfer...
and fluid flow at different conditions such as through the porous media and in the most cases they faced an increase in the heat transfer, compared with media without porosity [27–38].

Raisi et al. [39] studied the laminar flow forced convection of a nano fluid in a microchannel with slip and no-slip boundary conditions and evaluated the cooling power of pure water and water-copper nano fluid. They also studied the effects of changes in Reynolds numbers, volume fraction and slip coefficient on forced convection heat transfer. Li and Kleinstreuer [40] studied the thermal conductivity of pure water and water-copper nano fluid in a trapezoidal microchannel. Ahmed et al. [41] numerically analyzed the heat transfer and pressure drop of water-copper nano fluid in an isothermal channel using the numerical simulation through the finite difference method. Choi and Zhang [42] investigated the laminar flow forced convection of water-alumina nano fluid in a curved tube and showed that the Nusselt number increased with Reynolds and Prandtl numbers. Santra et al. [43] numerically studied the thermal performance of water-copper nano fluid in a warm isothermal channel; they showed that the heat transfer rate increased with more volume fraction of nanoparticles.

Karimipour et al. [44–48] studied the heat transfer of nano fluid flow in a microchannel with the slip velocity boundary condition, using the lattice Boltzmann method (LBM). More works can be addressed in this way by different researchers [49–57]. Esfe et al. [58–61] investigated the effect of different types of nano-particles on nano fluid heat transfer. Karimipour et al. [62,63] studied the gravity effects on the mixed convection heat transfer in a micro-channel and also in an inclined lid driven cavity by LBM. More other works are referred to investigate the effects of nanoparticles volume fraction on thermal conductivity and dynamic viscosity [64–68].

2. Problem statement

The problem being investigated is the incompressible laminar flow of MWCNT/Oil nano fluid in a horizontal two-dimensional

<table>
<thead>
<tr>
<th>Nomenclature</th>
<th>V Non-dimensional vertical velocity</th>
</tr>
</thead>
<tbody>
<tr>
<td>MWCNT</td>
<td>Multi walled carbon nanotubes</td>
</tr>
<tr>
<td>B</td>
<td>Non-dimensional slip coefficient ($\beta/h$)</td>
</tr>
<tr>
<td>$c_p$</td>
<td>Specific heat (J/kg K)</td>
</tr>
<tr>
<td>Da</td>
<td>Darcy number ($=K/h^2$)</td>
</tr>
<tr>
<td>F</td>
<td>Inertia coefficient</td>
</tr>
<tr>
<td>h</td>
<td>Microchannel height (m)</td>
</tr>
<tr>
<td>$h_c$</td>
<td>Convection heat transfer coefficient (W/m² K)</td>
</tr>
<tr>
<td>H</td>
<td>Non-dimensional microchannel height</td>
</tr>
<tr>
<td>k</td>
<td>Thermal conductivity (W/m K)</td>
</tr>
<tr>
<td>K</td>
<td>Permeability (m²)</td>
</tr>
<tr>
<td>l</td>
<td>Microchannel length (m)</td>
</tr>
<tr>
<td>L</td>
<td>Non-dimensional microchannel length (m)</td>
</tr>
<tr>
<td>$Nu_x$</td>
<td>Local Nusselt number</td>
</tr>
<tr>
<td>p</td>
<td>Pressure (Pa)</td>
</tr>
<tr>
<td>Pe</td>
<td>Peclet number ($=PrRe$)</td>
</tr>
<tr>
<td>Re</td>
<td>Reynolds number ($=u_e h/\nu_nf$)</td>
</tr>
<tr>
<td>Pr</td>
<td>Prandtl number ($=\nu_nf/\alpha_nf$)</td>
</tr>
<tr>
<td>T</td>
<td>Temperature (K)</td>
</tr>
<tr>
<td>TC</td>
<td>Temperature of cold inlet nano fluid (K)</td>
</tr>
<tr>
<td>$u_e$</td>
<td>Horizontal velocity (m s⁻¹)</td>
</tr>
<tr>
<td>$\dot{q}_c$</td>
<td>Heat flux, (W/m²)</td>
</tr>
<tr>
<td>$\dot{q}_b$</td>
<td>Amplitude heat flux, (W/m²)</td>
</tr>
<tr>
<td>U</td>
<td>Non-dimensional horizontal velocity</td>
</tr>
<tr>
<td>Us</td>
<td>Non-dimensional slip velocity</td>
</tr>
<tr>
<td>v</td>
<td>Vertical velocity (m s⁻¹)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Greek symbols</th>
<th>V Non-dimensional vertical velocity</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$</td>
<td>Thermal diffusivity ($=(k/\rho c_p)$ m² s⁻¹)</td>
</tr>
<tr>
<td>$\beta$</td>
<td>Slip coefficient (m)</td>
</tr>
<tr>
<td>$\epsilon$</td>
<td>Porosity</td>
</tr>
<tr>
<td>$\phi$</td>
<td>Volume fraction of nanoparticles</td>
</tr>
<tr>
<td>$\mu$</td>
<td>Dynamic viscosity (N s m⁻²)</td>
</tr>
<tr>
<td>$\Theta$</td>
<td>Non-dimensional temperature ($=(T-T_c)/\Delta T$)</td>
</tr>
<tr>
<td>$\rho$</td>
<td>Density (kg m⁻³)</td>
</tr>
<tr>
<td>$\nu$</td>
<td>Kinematic viscosity (m² s⁻¹)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Subscripts</th>
<th>V Non-dimensional vertical velocity</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e$</td>
<td>Effective</td>
</tr>
<tr>
<td>$f$</td>
<td>Fluid</td>
</tr>
<tr>
<td>$m$</td>
<td>Averaged value</td>
</tr>
<tr>
<td>$nf$</td>
<td>Nanofluid</td>
</tr>
<tr>
<td>$s$</td>
<td>Solid</td>
</tr>
<tr>
<td>$x$</td>
<td>Local value in X-direction</td>
</tr>
</tbody>
</table>

Fig. 1. The microchannel physical configuration.
and after cooling the walls of

\[ \phi = 0.0\% \]

\[ \phi = 0.1\% \]

\[ \phi = 0.2\% \]

\[ \phi = 0.4\% \]

as

\[ \varepsilon \]

porosity

been assumed to be Newtonian and incompressible and the

and steady. The physical properties of the nano

ature of 40

B

Darcy number is assumed to be in the interval

and the walls are under the in

fi

used to establish a relationship between the velocity and pressure

3. Numerical procedure

The finite volume approach beside the SIMPLE algorithm is

used to establish a relationship between the velocity and pressure

fields. As the values of all the parameters becomes less than 10^{-8},

the problem solution becomes convergent and the calculations

will give a result. The second-order upwind scheme has been used

to discretize the permeability and convection terms in the governing equations [48–52].

3.1. Governing equations

Continuity equation:

\[ \frac{\partial}{\partial x}(\rho_\text{nf} \bar{u}_x) + \frac{\partial}{\partial y}(\rho_\text{nf} \bar{c}_x) = 0 \]  

(1)

Momentum equation in X direction:

\[ \frac{\partial}{\partial x}(\rho_\text{nf} \bar{u}_x \bar{u}_x) + \frac{\partial}{\partial y}(\rho_\text{nf} \bar{c}_x \bar{u}_x) = -\frac{\partial p}{\partial x} + \frac{\partial}{\partial y}(\mu_\text{nf} \frac{\partial \bar{u}_x}{\partial x}) + \frac{\partial}{\partial y}(\mu_\text{nf} \frac{\partial \bar{u}_x}{\partial y}) - \frac{\mu_\text{nf} \bar{u}_x}{K} - \frac{\rho_\text{nf} F}{K} \bar{u}_x \bar{c}_x \]  

(2)

Momentum equation in Y direction:

\[ \frac{\partial}{\partial x}(\rho_\text{nf} \bar{u}_y \bar{c}_x) + \frac{\partial}{\partial y}(\rho_\text{nf} \bar{c}_y \bar{c}_x) = -\frac{\partial p}{\partial y} + \frac{\partial}{\partial y}(\mu_\text{nf} \frac{\partial \bar{c}_x}{\partial x}) + \frac{\partial}{\partial y}(\mu_\text{nf} \frac{\partial \bar{c}_x}{\partial y}) - \frac{\mu_\text{nf} \bar{c}_x}{K} - \frac{\rho_\text{nf} F}{K} \bar{u}_y \bar{c}_x \]  

(3)

Energy equation:

\[ \frac{\partial}{\partial x}(\rho_\text{nf} \bar{c}_x \bar{T}_x) + \frac{\partial}{\partial y}(\rho_\text{nf} \bar{c}_y \bar{T}_x) = \frac{\partial}{\partial x}(k_\text{nf} \frac{\partial \bar{T}_x}{\partial x}) + \frac{\partial}{\partial y}(k_\text{nf} \frac{\partial \bar{T}_x}{\partial y}) \]  

(4)

It is necessary to write Eqs. (1)–(4) in dimensionless form. Thus,

<table>
<thead>
<tr>
<th>Wt% (MWCNT/Oil)</th>
<th>( c_p ) (J/KgK)</th>
<th>( \rho ) (Kg/m^3)</th>
<th>( K ) (W/m K)</th>
<th>( \mu ) (Pa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0%</td>
<td>2010.57</td>
<td>867.50</td>
<td>0.1324</td>
<td>0.02900</td>
</tr>
<tr>
<td>0.1%</td>
<td>1588.43</td>
<td>868.62</td>
<td>0.1388</td>
<td>0.03161</td>
</tr>
<tr>
<td>0.2%</td>
<td>1381.00</td>
<td>868.82</td>
<td>0.1423</td>
<td>0.03531</td>
</tr>
<tr>
<td>0.4%</td>
<td>1200.87</td>
<td>868.95</td>
<td>0.1438</td>
<td>0.04832</td>
</tr>
</tbody>
</table>
they will be as follows:

Non-dimensional continuity equation:

\[ \frac{\partial U}{\partial X} + \frac{\partial V}{\partial Y} = 0 \]  

(5)

Non-dimensional momentum equation in X direction:

\[ \frac{\partial}{\partial X} (UU) + \frac{\partial}{\partial Y} (UV) = -\frac{\partial P}{\partial x} + \frac{\partial}{\partial X} \left( \frac{U^2}{2} \right) + \frac{\partial}{\partial Y} \left( \frac{UV}{2} \right) - \frac{U}{DaRe} \]  

(6)

Non-dimensional momentum equation in Y direction:

\[ \frac{\partial}{\partial X} (UV) + \frac{\partial}{\partial Y} (VV) = -\frac{\partial P}{\partial y} + \frac{\partial}{\partial X} \left( \frac{UV}{2} \right) + \frac{\partial}{\partial Y} \left( \frac{V^2}{2} \right) - \frac{V}{DaRe} + \frac{F}{\sqrt{Da}} \frac{U}{V} \]  

(7)

Non-dimensional energy equation:

\[ \frac{\partial}{\partial X} (U\theta) + \frac{\partial}{\partial Y} (V\theta) = \frac{1}{Pe} \left( \frac{\partial^2 \theta}{\partial X^2} \right) + \frac{1}{Pe} \frac{\partial}{\partial Y} \left( \frac{\partial \theta}{\partial Y} \right) \]  

(8)

In the equations above, the dimensionless numbers are all defined based on the properties of the nanofluid.

In Eqs. (1)–(8), the following parameters have been used:
Darcy’s law states that the pressure drop per unit length for a flow in a porous medium is proportional to the product of the fluid velocity and its dynamic viscosity.

Later the inverse proportionality constant was added to Darcy’s law and this constant of permeability, which was shown by \( K \), became a measure of the resistance of fluid faces in a porous medium.

\[
\frac{dp}{dx} = \frac{\mu u}{K} \quad \text{(10)}
\]

\[
\frac{dp}{dx} = \frac{\mu u}{K} + \frac{C_s \rho u^2}{\sqrt{K}} \quad \text{(11)}
\]

where \( \frac{dp}{dx} \), \( u \), \( \mu \), \( K \), are the pressure gradient, average velocity, dynamic viscosity of the fluid and Permeability of the porous medium. This law can be used at low Reynolds numbers (low velocities). As the Reynolds number increases, deviation from the Darcy equation increases due to the effect of the inertial term in the momentum balance equation. It has been proved that for all the media studied, the axial pressure drop is expressed as a sum of two terms, one of which is a linear function of velocity (the viscous

3.1.1. Darcy’s law

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Later the inverse proportionality constant was added to Darcy’s law and this constant of permeability, which was shown by \( K \), became a measure of the resistance of fluid faces in a porous medium.
share) and the other is a quadratic function of velocity (inertial share). The inertial term in the pressure drop equation is referred to as Forchheimer’s modification of Darcy’s law [53, 54]. The inertia coefficient ($C_F$) is considered to be zero at low velocities.

3.1.2. Porosity

The ratio of the empty volume inside a porous medium to the total volume is known as porosity and shown by ε, and its value is variable between zero and one [53, 54].

3.2. Hydrodynamic and thermal boundary conditions

It is obvious that the no-slip boundary condition should be used at the macroscopic level. But in the slip flow regime inside the microchannel, the slip boundary condition must be used which indicates the presence of slip in the fluid particles located on the wall of the microchannel. The value of slip velocity can be estimated from the following equation [56]:

$$u_s = \frac{\tau}{\rho} \left( \frac{\partial u}{\partial y} \right)_{y=0}$$

where $\beta$ represents the slip coefficient. The dimensionless form of Eq. (12) for the walls can be expressed as follows:

$$U_s = \frac{\beta}{h} \left( \frac{\partial U}{\partial Y} \right)_{Y=0}$$

where $B = \frac{\beta}{h}$ is called the dimensionless slip coefficient. The other dimensionless boundary conditions are as follows:

$$U = 1, V = 0 \text{ and } \theta = 0 \text{ for } X = 0 \text{ and } 0 \leq Y \leq 1$$

$$V = 0 \text{ and } \frac{\partial U}{\partial X} = 0 \text{ for } X = 32 \text{ and } 0 \leq Y \leq 1$$

Fig. 7. (a) Variations of temperature profiles along the horizontal microchannel centerline ($Y=H/2$) at $\phi=0.4\%$, $B=0.1$, $Re=1$, $Da=0.1$ for different values of $\varepsilon$. (b) Variations of temperature profiles along the horizontal microchannel centerline ($Y=H/2$) at $\phi=0.4\%$, $B=0.1$, $Re=0.1$, $Da=0.1$ for different values of $\varepsilon$.

Fig. 8. (a) Dimensionless slip velocity along the microchannel wall at $\phi=0.4\%$, $Re=1$, $Da=0.1$ and $\varepsilon=0.9$ for various $B$. (b) Dimensionless slip velocity along the microchannel wall at $\phi=0.4\%$, $Re=0.1$, $Da=0.1$ and $\varepsilon=0.9$ for various $B$. 


The walls of the microchannel have been put under a fluctuating heat flux $q$. The numerical value of the heat flux amplitude $q_0$ is calculated with the aid of dimensionless parameters in Eq. (9).

$$q''(x) = 2q_0 + q_0' \sin\left(\frac{\alpha x}{4}\right)$$  \hspace{1cm} (15)

Eqs. (5)-(8) are numerically solved under the aforesaid boundary conditions by using the SIMPLE algorithms. The local Nusselt number is as follows:

$$Nu_{x=0, h} = \frac{q_0 h}{(T(x)-T)K_e}$$  \hspace{1cm} (16)

where, $T(x)$ is the temperature of the wall surface of the microchannel. $h$ is the convection heat transfer coefficient here. The dimensionless form of the Eq. (16) is shown below by using introduced parameters in the Eq. (1):

$$Nu_{x}(X) = \frac{1}{\partial_j(X)}$$  \hspace{1cm} (17)

The effective thermal conductivity of the porous medium, $K_e$, is presented in two different correlations as follows [13,57]:

$$K_e = \varepsilon K_f + (1-\varepsilon)K_s$$  \hspace{1cm} (18)

$$K_e = K_f^{1-\varepsilon}$$  \hspace{1cm} (19)
4. Results and discussion

4.1. Grid study and validation

Table 2 shows the results related to the calculation of velocity in the middle of the microchannel for three models of meshing of 40x400, 50x500, 60x600 for Da=0.1, ε=0.9, B=0.001, ϕ=0.2%, and Re=0.1, 1. The obtained numbers are slightly different. Therefore, in this study, the 50x500 grid is selected.

Suitable validate is presented in Fig. 2a versus Ref. [57]. The velocity is drawn in two modes of Da=0.2 and Da=0.0002. Results are well consistent with those of Teamah et al. [57]. Also, more validation is presented versus Radiom et al. [36] for Da=0.01 and Da=0.0001 in Fig. 2b. The obtained results are slightly different from those of Ref. [36].

4.2. The effects of slip coefficient and Darcy number

Fig. 3a and b show the effect of different values of slip coefficient and Darcy number on the velocity profiles along the vertical line in the middle of the microchannel at ϕ=0.4%, Da=0.1, Re=10, and ε=0.9, respectively. Due to the slip boundary condition on the walls, the nanofluid on the walls moves faster. Due to the small Darcy number, the velocity profiles along the vertical line in the middle of the microchannel will not be parabolic and the maximum values on the vertical line for different slip coefficients are close together.

Dimensionless temperature profiles in different cross sections of the microchannel at ϕ=0.4%, B=0.1, Re=1 and ε=0.9 for Da=0.1, 0.0001 are drawn in Fig. 4a and b. Temperature profiles for different cross-sections are more uniform at Da=0.0001 than those at Da=0.1, because of the higher heat balance between the nanofluid and the walls of the microchannel. Also, dimensionless temperature profiles in different cross sections of the microchannel at ϕ=0.4%, B=0.01, Re=1 and ε=0.9 for Da=0.1, Da=0.0001 are drawn in Fig. 5a and b.

Fig. 6a shows the effect of different values of slip coefficient on dimensionless velocity along the horizontal line in the middle of the microchannel without a porous medium at ϕ=0.4% and Re=1. The velocity profile show that within a short distance from the inlet of the microchannel, the velocity increases with X and then reaches a constant value and the flow becomes hydraulically de-
veloped. Along the horizontal line in the middle of the micro-
channel, as the slip coefficient increases, the velocity decreases. Fig. 6b shows the effect of different values of slip coefficient on the dimensionless velocity along the horizontal line in the middle of the microchannel at ϕ=0.4%, Re=1, Da=0.1 and ε=0.9. In addition to the reasons mentioned for Fig. 6a, which represented a decrease in the dimensionless velocity in the horizontal line in the middle of the microchannel, this time the presence of a porous medium causes further decrease in the velocity compared with the state of no porous media.

4.3. The effects of porosity and Reynolds number

Fig. 7a and b shows the effect of different values of Reynolds and porosity on the values of dimensionless temperature along the horizontal line in the middle of the microchannel. The
temperature profiles in Fig. 7b show that due to its heat exchange with the walls of the microchannel, the microchannel inlet fluid temperature increases in a fluctuating way with $X$. The effects of the fluctuating flux are not significant in Fig. 7a due to more Reynolds number. It can be said that reductions in Reynolds and porosity will totally increase the heat exchange.

Dimensionless slip velocity along the microchannel wall at $\phi = 0.4\%$, $Re = 1$, $Da = 0.1$, and $\varepsilon = 0.9$ for various $B$ are illustrated in Fig. 8a and b, respectively. Moreover, Fig. 9a and b shows the effect of different values of slip coefficient on the slip velocity along the microchannel for different values of Reynolds number at $\phi = 0.4\%$, $Da = 0.0001$ and $\varepsilon = 0.9$. Looking at the charts, it can be seen that the slip velocity has maximum value near the wall at the inlet and within a very short distance from the inlet; it decreases with $X$ and then reaches a constant value. We can conclude from comparing Fig. 8a and b with Fig. 9a and b that reducing the Darcy number causes difference among the values of slip velocity for different slip coefficients and also reduces the length of inlet.

Fig. 10 shows the effect of slip coefficient and Darcy number on slip velocity. As can be seen, slip velocity increases with the increased slip coefficient. Also, a reduction in the Darcy number will intensify increase the amount of slip velocity.

The effects of Reynolds number and porosity on streamlines and isotherms are shown in Fig. 11a and b and also in Fig. 12a and b. It is observed that streamlines are almost parallel along the microchannel. Moreover for both values of Reynolds and Porosity, the flow becomes fully developed after passing a short distance from the inlet of the microchannel. The isotherms show that the temperature of the nanofluid increases along the microchannel, due to the imposed the heat flux; this temperature increasing will be higher for low Reynolds numbers. On the other hand, by comparing Fig. 11a with Fig. 11b as well as Fig. 12a with Fig. 12b, we find out that the effect of porosity on the rate of heat
development is more significant.

4.4. Effects of all parameters involved volume fraction of nanoparticles

To better study the mechanism of heat transfer in the microchannel, the values of local Nusselt numbers along the wall of the microchannel have been investigated for different conditions and the effect of each parameter has been studied in Figs. 13 and 14. The local Nusselt number has the maximum value at the inlet due to the highest temperature difference between the nanofluid and the walls and changes in a fluctuating way along the microchannel with X. Figs. 13a and 14a show that the local Nusselt number decreases at low Reynolds numbers; so the nanofluid has more time for heat exchange with the walls. Figs. 13b and 14b show that the velocity of the nanofluid increases with an increased Reynolds number; hence there is less time for heat transfer between the nanofluid and the walls which increases the local Nusselt number. Moreover in Figs. 13a to 14b, the effects of porosity and Darcy number are also been investigated for different conditions. It can be concluded that a decrease in porosity has greater impact on local Nusselt numbers. Therefore, for high Reynolds numbers and low porosity and Darcy, the amount of increase in the Nusselt number would be greater.

Fig. 15a and b shows the local Nusselt number for \( B = 0.1 \), \( Da = 0.1, Da = 0.0001, \varepsilon = 0.5 \) and \( Re = 10 \), respectively. It is seen that by adding nanoparticles with a volume percentage of 0.4%, the local Nusselt number increases. Also, by adding nanoparticles with volume fraction percentage of 0.1% and 0.2%, a decrease in the local Nusselt number is seen due to the way of definition of Nusselt number based on the nanofluid (and not the base fluid). A comparison between Figs. 15a and b in the same conditions shows that less Darcy number corresponds to higher local Nusselt number.

5. Conclusion

The forced convection heat transfer of a nanofluid composed of oil and nano-particles of multi walled carbon nano-tubes (MWCNT) in a two-dimensional microchannel is numerically investigated. The walls of the microchannel are under the influence of a fluctuating heat flux. Also, the slip velocity boundary condition is assumed along the walls. The microchannel is completely filled with a porous medium.

The investigations show that the local Nusselt number decreases at low Reynolds numbers which is due to the low flow velocities. Hence the nanofluid has more time for heat exchange with the walls. The velocity of the nanofluid increases with an increased Reynolds number so there is less time for heat transfer between the nanofluid and the walls which increases the local Nusselt number. Also, a decrease in porosity has greater impact on Nusselt numbers; hence for high Reynolds numbers and low porosity and Darcy, the amount of increase in the local Nusselt number would be greater.

References


