Simulation the effects of cross-flow injection on the slip velocity and temperature domain of a nanofluid flow inside a microchannel

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Abstract
Purpose – In this paper, the forced convection heat transfer of the nanofluid composed of water and AL2O3 nanoparticles is simulated in a two-dimensional horizontal microchannel by injecting the lower wall. The upper wall of the microchannel is 303 K at temperature TH. On the lower wall of the microchannel, there are three holes for flow injection. Other parts of the wall are insulated. In this paper, the effect of parameters such as Reynolds number, slip coefficient and volume fraction of nanoparticles is investigated.

Design/methodology/approach – The boundary condition of the slip velocity is considered on the upper and lower walls of the microchannel. In this work, the flow of nanofluid in the microchannel is considered to be slow, permanent and Newtonian. In the present study, the effect of injection through the microchannel wall on the slip velocity is examined for the first time.

Findings – The results are also presented as velocity profiles and Nusselt number diagrams. It was found that the Nusselt number increases with increasing the amount of slip coefficient of velocity and the weight percentage of solid nanoparticles. The rate of this increase is higher in the high values of the Reynolds number.

Originality/value – A novel paper concerned the simulation of cross-flow injection effects on the slip velocity and temperature domain of a nanofluid flow inside a microchannel.

Keywords Forced convection, Slip velocity, Cross-flow injection, Micro flow

Paper type Research paper

1. Introduction
Cooling is one of the major issues of the basic industries, including power generation, micro-electricity, transportation, construction and metallurgy facing. Heat transfer today faces two major challenges: the cooling of equipment with high thermal flux and the problem of reducing the size of the equipment. Air cooling is the most common cooling method today, but it does not work well for the transmission of heat flux. Cooling fluids often include water, ethylene glycol, various types of refrigerants and other coolants depending on efficiency. These fluids often have poor heat transfer properties, which has led scientists to make a lot of effort to improve the low thermal conductivity of liquids by adding solid particles in the nanoscale. As the metal solid has a higher thermal conductivity than the fluid, it is expected that the suspension of solid metal particles in the fluid will increase its thermal conductivity. At first, Maxwell demonstrated in his theoretical work that the addition of a percentage of suspended particles in the fluid would lead to an increase in the heat conductivity of the mixture, because of the high thermal conductivity of the metallic and nonmetallic particles added to the fluid regarding the thermal conductivity of the base fluid. Nanofluids have been described as the potential coolants in numerous theoretical and
Microchannels are used in various engineering and scientific applications, and the inkjet printer is a classic example. Owing to its small size and high efficiency, it is widely used in medical applications and micro electromechanical systems such as micro-heat exchangers, micro-pumps, micro-turbines and sensors. Several studies have been carried out on fluid flow in the duct and microchannel (Shamshirband et al., 2015; Sajadifar et al., 2017; Akbari et al., 2016; Hemmat Esfe et al., 2015; Alipour et al., 2017; Afrand et al., 2015; Karimipour et al., 2013; Alipour et al., 2017; Afrand et al., 2015; Karimipour et al., 2017; Karimipour, 2015; Karimipour et al., 2015; Akbari et al., 2016; Hemmat Esfe et al., 2015; Chamkha et al., 2015; Chamkha and Rashad, 2012; Chamkha and Khaled, 2000; Kumar et al., 2010). Behzadmehr et al. (2007) studied the forced convection heat transfer of a turbulent flow in a circular tube, numerically, with water/copper oxide nano fluid. They used a two-phase mixture model, and by comparing the calculated results with experimental values, they showed that the two-phase mixture model is more accurate than the single-phase model.

Kamali and Binesh (2010) numerically investigated the forced convection heat transfer of water/copper oxide nano fluid in a microtube with constant heat flux boundary conditions. The results showed that the heat transfer coefficient and Nusselt number were increased. Li and Kleinstreuer (2008) showed that the presence of copper nanoparticles in the water as the based fluid would increase thermal performance by studying the heat transfer in a trapezoidal microchannel using a water/copper nano fluid. Maiga et al. (2004) numerically studied the thermal and hydrodynamic properties of the nano fluids passing through a tube that is uniformly moved in a slow flow with a single-phase model. They showed that addition of nanoparticles significantly increased the heat transfer compared to the base fluid. Anoop et al. (2012) empirically investigated the forced convection heat transfer of water/silica nanoparticles in a microchannel. The nano fluid exhibited Newtonian behavior and more volume fraction of nanoparticles would increase the nano fluid viscosity.

Nemati et al. (2012) examined the effect of the magnetic field on the free convection transfer of nano fluid in a rectangular chamber. The results of their study indicated that the averaged Nusselt number increased with higher volume fraction and decreased with larger magnetic field. Some researchers numerically examined the nano fluid heat transfer in a microchannel and observed that the heat transfer increased by increasing the volume percentage of nanoparticles. They also showed that increasing the Reynolds number corresponded to larger Nusselt number (Esfandiary et al., 2016; Goodarzi et al., 2014; Jung et al., 2009).

Karimipour et al. (2016) studied the forced convection heat transfer of water/PMWCNT nano fluid in a two-dimensional microchannel under a magnetic field. They observed that increasing the strength of the magnetic field led to a significant increase in the amount of slip velocity. Nazari et al. (2014) experimentally investigated the heat transfer of water and water/alumina nano fluid in a constant temperature tube containing a porous material in the Reynolds number of 700-5,000. The results indicated an increase in nano fluid heat transfer rate compared to the base fluid; numerous studies can be referred here (Mahmoodi et al., 2015; Bahrami et al., 2016; Afrand et al., 2015; Esfe et al., 2015; Esfe et al., 2014; Afrand et al., 2016).
2. Problem description
The problem is a two-dimensional horizontal microchannel according to Figure 1. The width and length of the microchannel are $h$ and $l$, and the dimensionless height and length are $H = \frac{h}{h} = 1$ and $L = \frac{l}{h} = 30$, respectively. The upper wall of the microchannel has a temperature of $T_H = 303$ K. On the lower wall, three holes with diameter of $D = 0.07$ L are embedded. Injection is done in these parts. The other parts between the holes as well as the edges of the lower wall inlet and outlet are insulated. The nanofluid contains water and $\text{Al}_2\text{O}_3$ solid nanoparticles ($D_p = 40$ nm). The nanofluid with a temperature of $T_C = 293$ K and velocity inlet of $U_C$ enters the microchannel and after cooling the microchannel walls, exits from its end. The nanofluid flow within the microchannel is considered to be slow, steady and Newtonian. The thermophysical properties of water/$\text{Al}_2\text{O}_3$ nanofluid are presented in Table I. The slip velocity condition is considered on the upper and lower walls. The Reynolds number of the microchannel inlet and the lower wall holes are assumed as $Re = 1, 10, 100$. The various amounts of slip coefficients are $B = 0.001, B = 0.01$ and $B = 0.1$. The volume fraction of solid nanoparticles are also as $\varphi = 0$, $\varphi = 2$ and $\varphi = 4$ per cent.

3. Governing equations
The dominant nondimensional equations include the continuity, momentum and energy for the steady Newtonian nanofluid (Sajadifar et al., 2017; Akbari et al., 2016; Karimipour et al., 2012; Karimipour, 2015; Karimipour et al., 2015; Akbari et al., 2016):

\[
\frac{\partial U}{\partial X} + \frac{\partial V}{\partial Y} = 0 \quad (1)
\]

\[
U \frac{\partial U}{\partial X} + V \frac{\partial U}{\partial Y} = - \frac{\partial P}{\partial X} + \frac{\mu_{nf}}{\rho_{nf} \nu_l} \left( \frac{1}{Re} \right) \left( \frac{\partial^2 U}{\partial X^2} + \frac{\partial^2 U}{\partial Y^2} \right) \quad (2)
\]

![Microchannel schematic](image)

**Table I.**

<table>
<thead>
<tr>
<th>$\varphi$ (%)</th>
<th>$\rho$ (kg/m$^3$)</th>
<th>$\mu$ (Pa·s)</th>
<th>$K$ (w/mk)</th>
<th>$c_\varphi$ (J/kg·K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermophysical</td>
<td>0</td>
<td>997.1</td>
<td>$8.91 \times 10^{-4}$</td>
<td>0.613</td>
</tr>
<tr>
<td>properties of water/$\text{Al}_2\text{O}_3$ nanofluid</td>
<td>2</td>
<td>1056.5</td>
<td>$9.37 \times 10^{-4}$</td>
<td>0.663</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>1116</td>
<td>$9.87 \times 10^{-4}$</td>
<td>0.695</td>
</tr>
</tbody>
</table>
The equations to compute the nanofluid properties are presented as follows:

**Density:**

\[ \rho_{nf} = (1 - \varphi)\rho_f + \varphi \rho_s \]  \hspace{1cm} (6)

**Thermal diffusivity:**

\[ \alpha_{nf} = \frac{k_{eff}}{(\rho C_p)_{nf}} \]  \hspace{1cm} (7)

**Special heat capacity:**

\[ (\rho C_p)_{nf} = (1 - \varphi)(\rho C_p)_f + \varphi(\rho C_p)_s \]  \hspace{1cm} (8)

**Dynamic viscosity:**

\[ \mu_{nf} = \frac{\mu_f}{(1 - \varphi)^{2.5}} \]  \hspace{1cm} (9)

**Effective thermal conductivity:**

\[ K_{eff} = k_{f} \left( 1 + \frac{k_s A_s}{k_f A_f} + ck_s P R_0 \frac{A_s}{k_f A_f} \right) \]  \hspace{1cm} (10)

In equation (10), the experimental constant is \( c = 25,000 \), the solid thermal conductivity is \( K_s = 40 \text{ w/mk} \) and the thermal conductivity of the fluid is \( K_f = 0.613 \text{ w/mk} \).
In equations (11) and (12), $d_f = 2\, \text{Å}$ is the diameter of the water molecule, and $d_s = 40\, \text{nm}$ is the diameter of the nanoparticles. $A_S$ is the solid molecular area and $A_f$ is the area of the fluid molecule. The amount of the nanoparticle Brownian motion rate is obtained by the following equation:

$$u_s = \frac{2K_bT}{\pi \mu_f d_s^2} \quad (13)$$

In equation (13), $k_b = 1.3807 \times 10^{-23}\, \text{J/K}$.

Local Nusselt number ($\text{Nu}_x$) and averaged Nusselt number ($\text{Nu}_m$) are as follows:

$$\text{Nu}_x(x) = -\frac{K_{\text{eff}}}{K_f} \left( \frac{\partial \theta}{\partial Y} \right)_{Y=0} \quad (14)$$

$$\text{Nu}_m = \frac{1}{L} \int_0^L \text{Nu}_x \, dx \quad (15)$$

4. Boundary conditions
The amount of dimensionless slip velocity is obtained by the following equation:

![Figure 2. Nusselt number of the present study in comparison with the results of Ref. (Raisi et al., 2012)](image-url)
\[ U_s = \pm B \frac{\partial U}{\partial Y} \bigg|_{y=0.1} \]  

(16)

In which, \( B \) represents the dimensionless slip coefficient. In general, the governing boundary conditions for the supposed problem are as follows:

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

\[ V = 0 \quad \text{and} \ \frac{\partial U}{\partial X} = \frac{\partial \theta}{\partial X} = 0 \quad \text{for} \ X = 30 \ \text{and} \ 0 \leq Y \leq 1 \]

\[ V = 0, \ U = U_s \quad \text{and} \ \frac{\partial \theta}{\partial Y} \quad \text{for} \ Y = 0 \ \text{and} \ 0 \leq X \leq 30 \]

\[ V = 0 \quad \text{for} \ Y = 1 \ \text{and} \ 0 \leq \theta \leq 1 \quad \text{and} \ \leq X \leq 30 \]

\[ U = U_s \]

Figure 3.

Velocity profile of the present study in comparison with the results of references (Raisi et al., 2012; Nikkhah et al., 2015)
5. Grid study
In Table II, the dimensionless velocity and dimensionless temperature values in the middle line of the microchannel at different grids were investigated for Reynolds number of $\text{Re} = 10$ at $\varphi = 2$ per cent and $B = 0.01$. There was a negligible difference between grids of $60 \times 600$ and $70 \times 700$. Therefore, the $60 \times 600$ meshes were found proper to continue the calculations.

6. Validation
Validation of the present problem was provided with the results of Raisi et al. (2012) (see Figures 2 and 3) and Nikkhah et al. (2015) (see Figure 3) which they studied the fluid flow and heat transfer through a two-dimensional microchannel. The Nusselt number was compared in Figure 2 at different Reynolds numbers, and the fully developed velocity profile was compared in Figure 3. There was a good match between the results.

7. Results and discussion
The forced convection heat transfer of water/Al$_2$O$_3$ nanofluid is studied numerically in a two-dimensional horizontal microchannel as shown in Figure 1. The boundary condition of
the slip velocity along the microchannel walls is considered for different values of slip coefficient.

Figure 4 shows the streamlines and isotherms for Reynolds numbers 1, 10 and 100 for $\phi = 2$ per cent and $B = 0.1$. For each of the three Reynolds numbers, it is observed that the flow after passing a small part of the length of the microchannel inlet reaches the developed state until the injection takes place at each stage of the holes. Then, after the last injection, the flow reaches full development. The isotherms indicate that the higher Reynolds number causes the higher flow velocity which leads to inadequate time to exchange heat between the nanofluid and the microchannel wall which means there will be less heat exchange. Therefore, the flow can reach the fully developed state later.

In this section, the effects of slip coefficient on microchannel thermal performance are investigated. Figure 5 shows the velocity and temperature profiles on the vertical line of the microchannel ($X = 0.6$ L), for $Re = 10$ and $\phi = 2$ per cent at different values of slip
coefficient. The nanofluid flow is developed as a parabolic profile. The nanofluid on the walls of the microchannel has velocity because of the slip boundary condition on the walls. As the slip coefficient increases, the nanofluid velocity on the microchannel walls increases. The maximum velocity on the vertical line in the middle of the microchannel also decreases with increasing the slip coefficient. Moreover, the temperature on the vertical line of the microchannel also increases with increasing the slip coefficient.

In Figure 6, the dimensionless temperature profiles along different sections of the microchannel are specified at Re = 10, \( \varphi = 2 \) per cent and \( B = 0.1 \). As can be seen, the amount of dimensionless temperature increases along the microchannel with increasing the cross-section. The nanofluid temperature in the fully developed region is also exceeded by increasing the cross-section. Also, with increasing the slip coefficient, there is a little change in the temperature of the nanofluid.

Figure 6.
Temperature profiles on different sections of the microchannel at Re = 10 and \( \varphi = 0.02 \)

Figure 7.
Dimensionless slip velocity along the microchannel wall at Re = 10, \( \varphi = 0.02 \) and various slip coefficients
In Figure 7, the effect of different slip coefficients on the slip velocity is determined at Re = 10 and $\varphi = 2$ per cent. It can be seen that the slip velocity is maximum at the microchannel inlet. It decreases in a small part of the length by increasing $X$. Then, with each injection through the wall holes, the slip velocity increases a little. Finally, it decreases and tends to a constant value. The slip coefficient has a significant effect on the slip velocity of the nanofluid near the microchannel walls. By increasing the Reynolds number, the nanofluid velocity increases near the walls of the microchannel. As a result, the slip velocity reaches the fully developed state later. Figure 7 shows the effect of injection through the microchannel wall, which is discussed in this paper. That increases the slip velocity, especially at higher slip coefficients; this diagram is reviewed and drawn for the first time in the present work (Umavathi et al., 2005; Chamkha et al., 2002; Reddy and Chamkha, 2018;)

![Figure 8](image1)

**Figure 8.** Local Nusselt number changes along the microchannel walls at $\varphi = 0.02$ for different slip coefficients

![Figure 9](image2)

**Figure 9.** Temperature profiles on the vertical line of microchannel ($X = 0.6$ L) at Re = 10, $B = 0.1$ and various volume fractions
The effect of different values of the slip coefficient on the Nusselt number is shown in Figure 8 for Re = 100 and \( \phi = 2 \) per cent. Nusselt number increases with increasing Reynolds number and slip coefficient. At the microchannel inlet, the Nusselt number is maximum because of the high temperature difference between the nanofluid and the microchannel walls. Along the microchannel, as \( X \) increases, it decreases because of the increase in the nanofluid temperature.

Figure 9 shows the effects of volume fraction of nanofluid on the dimensionless temperature profiles on the vertical line of the microchannel (\( X = 0.6 \) L), for Re = 10 and \( B = 0.1 \) at different volume fractions of nanoparticles. Increase in volume fraction of solid nanoparticles leads to an increase in the nanofluid dimensionless temperature because of more thermal conductivity coefficient of the nanofluid. This improve in temperature is because of heat transfer from the microchannel wall to the nanofluid flow along the microchannel.

Figure 10 shows the effect of different volume fractions of nanoparticles on Nusselt number at Re = 100 and \( B = 0.01 \). The Nusselt number increases with higher Reynolds number and volume fractions. More volume fraction corresponds to more thermal performance of nanofluid because of high thermal conductivity coefficient of the nanoparticles. In the low Reynolds numbers, the increase in Nusselt number is less affected by higher amounts of volume fraction.

In Figure 11, the averaged Nusselt number values on the microchannel wall are shown for different slip coefficients. The averaged Nusselt number increases with more slip coefficient. As the slip coefficient increases, the temperature gradient grows along the microchannel heated wall which leads to higher Nusselt number; however that fact is occurred less severely at low values of Reynolds number.

8. Conclusion
The forced convection heat transfer of a nanofluid composed of water and aluminum oxide nanoparticles is numerically investigated in a two-dimensional horizontal microchannel. The upper wall of the microchannel is under constant temperature. On the lower wall of the
microchannel, there are three holes for the flow injection. Other parts of the lower wall are insulated.

The Nusselt number increases with more Reynolds number and the volume fraction of nanoparticles. The averaged Nusselt number increases with more slip coefficient. As the slip coefficient increases, the temperature gradient grows along the microchannel heated wall which leads to higher Nusselt number; however, that fact is occurred less severely at low values of Reynolds number.

Slip velocity increases with larger slip coefficient, but the Nusselt number decreases in the microchannel outlet. Maximum Nusselt number occurs at microchannel inlet. Slip coefficient has a significant effect on slip velocity of nanofluid near the microchannel.
walls. The injection increases the slip velocity along the microchannel walls. In the present research, considering the injection through the wall and flow in the slip flow regime, the effect of cross-flow injection on the slip velocity has been studied for the first time.

References


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