Investigation of permeability effect on slip velocity and temperature jump boundary conditions for FMWNT/Water nanofluid flow and heat transfer inside a microchannel filled by a porous media

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ABSTRACT

The fluid flow and heat transfer of a nanofluid is numerically examined in a two dimensional microchannel filled by a porous media. Present nanofluid consists of the functionalized multi-walled carbon nanotubes suspended in water which are enough stable through the base fluid. The homogenous mixture is in the thermal equilibrium which means provide a single phase substance. The porous media is considered as a Darcy- Forchheimer model. Moreover the slip velocity and temperature jump boundary conditions are assumed on the microchannel horizontal sides which mean the influences of permeability and porosity values on theses boundary conditions are presented for the first time at present work. To do this, the wide range of thermo physical parameters are examined as like Da = 0.1 to 0.001, Re = 10,100, dimensionless slip coefficient from 0.001 to 0.1 at different mass fraction of nanoparticles. It is observed that less Darcy number leads to more local Nusselt number and also applying the porous medium corresponds to higher slip velocity.

1. Introduction

The cooling system is one of the important issues to which many base industries are exposed including electric energy, micro-electrics, transportation, construction, and metallurgy. Today, heat transfer encounters two major challenges: On the one hand, cooling of equipment with high thermal flux; and on the other hand, problem of minimizing size of equipment. Nowadays, aerial cooling is the most prevalent cryogenic technique but this method is not too efficient for transfer of huge thermal fluxes. Thus, engineers have tended to cooling techniques using fluids. The coolant fluids often such as water, ethylene glycol, type of coolants including liquid nitrogen and other cooling agents may be utilized depending on their specific use. These fluids often possess weak property for heat transfer and surely they will be too inefficient for transfer of huge amounts of heat. So far, scientists and researchers have carried out wide studies about effect of suspended nanoparticles in base fluids their findings showed improvement in heat transfer process [1–6].

Sheikholeslami et al. [7–9] examined effect of magnetic field on nanofluid convection heat transfer in a semi annulus. Their finding indicate that Nusselt number has a direct relationship whit Reynolds number while it has reverse relationship whit the Hartmann number and Lewis number. Sheikholeslami and Ganji [10] studied heat transfer of nanofluid Fe3O4-Ethylene glycol in presence of electric field. The results indicated that coulomb force would increase temperature gradient. Sheikholeslami and Ganji [11–14] studied heat transfer of nanofluid in a porous medium in presence of magnetic field the results show Nusselt number has a direct relationship whit Darcy number and Rayleigh number also temperature gradient enhance with rise of Darcy number, Rayleigh number and nanofluid mass fraction. Sheikholeslami et al. [15–17] studied heat transfer of nanofluid in presence of magnetic field Their finding indicate that temperature gradient enhance with rise of Hartmann number, Eckert number while it decrease with rise of Reynolds number results show enhance of Lorentz force causes decrease of nanofluid velocity and enhance of Reynolds number causes decrease of...
plates in presence of magnetic
eenhance of Hartmann number and Eckert number causes rise of Nusselt
friction coefficient of unsteady nano
containing aluminum oxide. Sheikholeslami et al. [28] studied heat and
possesses higher effective thermal conductivity than nano
thermal conductivity. Alternately, nano
which ethylene glycol is used. The
results show that heat transfer augmentation
grows with rise of buoyancy forces and radiation parameter while it
decrease with rise of Lorentz forces. Maiga et al. [31] examined heat
transfer of nano fluid inside a tube numerically and two calm and chaotic
regimes. The result of their work indicated that rate of heat transfer in
Al2O3-ethylene glycol nano fluid was higher than in Al2O3-water. Zhu
[32] has proposed a model for effective heat transfer of nano fluid based
on the findings and Maxwell technique. Al2O3-water and nanotube was
used by him as nano fluids. The offered model showed abnormal increase
in effective thermal conductivity of oil nano fluid and nanotube as well as
nonlinear effective thermal conductivity along with amount of nanotube.
Many researchers examined effect of suspended nanoparticles in base
fluids and their impact on potential for rise of heat transfer. They studied
volumetric percent of suspended nanoparticles in base fluid as well as
kind of nanoparticles. Most of findings showed that the rise of volumetric
percent of nanoparticles in base fluid would increase potential for heat
transfer. The studies indicated type and size of nano fluids might
noticeably impact on potential for heat transfer in nano fluid [33–38].
Wu et al. [39] studied numerically flow passing through a micro
channel under slip boundary conditions on the walls. The results showed
the presence of slip boundary conditions might be highly different from
each other in terms of behavior of flow in various areas with pressure.
Duan et al. [40] examined slip regime in a microchannel with
non-circular surface. They posited the given findings for prediction of
mass rate of flow and pressure distribution in slip regime. Zhang et al.
[41] studied on 2-D slip flow between two parallel planes analytically.
The normal differential equation may describe this problem that has been
derived using change in isotropic deformation. Based on this analysis,
Navier-Stocks equations are not appropriate under the current slip

Table 1
Thermo-physical properties of FMWNT/Water at 20 °C [86].

<table>
<thead>
<tr>
<th>Wt.% (FMWNT/Water)</th>
<th>ρ (kg m⁻³)</th>
<th>μ (Pa s)</th>
<th>K (W/mk)</th>
<th>ζ (W/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
<td>995.80</td>
<td>0.00980</td>
<td>0.59</td>
<td>4178</td>
</tr>
<tr>
<td>0.12</td>
<td>1003.00</td>
<td>0.00991</td>
<td>0.65</td>
<td>4178</td>
</tr>
<tr>
<td>0.25</td>
<td>1008.00</td>
<td>0.00104</td>
<td>0.69</td>
<td>4178</td>
</tr>
</tbody>
</table>

Table 2
Grid independence test for Re = 10 and Re = 100 at η = 0.25%, B = 0.001 and Da = 0.1.

<table>
<thead>
<tr>
<th>Grid points</th>
<th>500 × 25</th>
<th>600 × 30</th>
<th>700 × 35</th>
</tr>
</thead>
<tbody>
<tr>
<td>Re = 10</td>
<td>1.438</td>
<td>1.440</td>
<td>1.435</td>
</tr>
<tr>
<td>Re = 100</td>
<td>1.440</td>
<td>1.443</td>
<td>1.437</td>
</tr>
</tbody>
</table>

Fig. 1. The microchannel physical configuration.
boundary conditions to describe flow in passing area. Rahman et al. [42] studied two-dimensional, stable and slipping flow numerically under a magnetic field. They utilized two different nanofluids in their work. Their findings indicated that velocity of nanofluid was lesser than speed of base fluid. Similarly, nanofluid flow includes thinner hydrodynamic boundary layer and thicker thermal boundary layer than flow of base fluid. They found this point by comparing two types of nanofluid that the rate of heat transfer in copper-water nanofluid was greater than in aluminum oxide-water nanofluid. Rise of heat transfer caused by increase in slip coefficient is one of the other findings. Buonomo et al. [43] studied natural displacement in a vertical microchannel in numerical form. Walls of vertical microchannel in this work were put under uniform thermal flux. They examined effect of various values of Knudsen number and Rayleigh number on temperature of walls, mass discharge of flow, velocity profiles and Nusselt number. The results indicated that as Knudsen number was increased, it was added to temperature profiles and discharge of flow while Nusselt number was decreased.

Yarmand et al. [44] explored numerically heat transfer in chaotic regime in a quadrangular tube. Likewise, they examined effect of volumetric percent of nanoparticles on Nusselt number. In their survey they used nanoparticles, CuO, ZnO, Al2O3, and SiO2. The findings have shown that SiO2-water nanofluid has been studied for greatest Nusselt number compared to other nanofluids. Similarly, it has been observed that following to increase in Reynolds number and volumetric percent of solid

Fig. 2. Present work fully developed velocity profiles with those of Karimipour and Afrand [84] for different values of B.

Fig. 3. Present work θ profiles with those of Karimipour and Afrand [84] for different values of B.
nanoparticles, the Nusselt number was increased. Alkam et al. [45] studied heat transfer of compressible displacement in developed area for a channel filled with porous matter. They examined effect of Darcy number, ratio of thermal conductivity coefficient, microscopic inertia coefficient, and thickness (diameter) of porous layer on heat transfer. The findings indicated that effect of Darcy number would be 1000 times greater than for inertia coefficient and at the same time Nusselt number might be increased in a porous medium. Alkam and Al-Mimr [46] used porous blocks in inner walls to improve efficiency of concentric tubular converters. Their findings showed this operation might increase heat transfer in converters although presence of porous blocks would increase pressure drop. Sheikholeslami [47] studied natural convection of a CuO-water nanofluid in a permeable cavity is simulated using the Darcy

Fig. 4. a. Present work fully developed velocity profiles with those of Teamah et al. [77] for different Da, b. Present work fully developed velocity profiles with those of Radion et al. [61] for different Da, c. Variation of heat transfer coefficient with Re from present work versus of experimental study [86] for different values of bulk temperature.

Fig. 5. a. U profiles of nanofluid at vertical centerline of microchannel (X = L/2) at φ = 0.25, and Re = 10 for different values of B, b. U profiles of nanofluid at vertical centerline of microchannel (X = L/2) at φ = 0.25, Da = 0.001 and Re = 10 for different values of B.
law. The results indicated that Nusselt number decrease with rise of Hartmann number and while it enhances with rise of Rayleigh number and nano fluid mass fraction. Sheikholeslami [48,49] examine nano fluid forced convection in existence of uniform Lorentz forces by means of Lattice Boltzmann Method. Results show Lorentz force causes rise of heat transfer also temperature gradient enhance with rise of Darcy number and Rayleigh number. Lorentz forces make the enhance the thermal boundary layer thickness. Temperature gradient enhances with increase of Rayleigh number Darcy number, and, nano fluid mass fraction, while it decrease with rise of Hartmann number. Mohammad [51] studied heat transfer in channel and tube under filled and half-filled conditions in porous material. The results indicated that the presence of porous material at the center of channel might increase length of developed thermal area at level 50%. Alternately, at this mode heat transfer is increased with logical ratio to rise of pressure drop. Although use of porous medium causes pressure drop along channel, we will observe noticeable rise in Nusselt number versus optimal thickness in porous matter (6% of channel height). One of his other findings is omission of inertia phrase for Darcy number lesser than 0.0001 from equations. His studied conclusion shows the half-filled channel may transfer heat more than in the filled channel.

Pavel and Mohammad [52] explored heat transfer in a channel under boundary conditions with fixed and uniform flux on walls and metallic porous material in lattice form that is placed at the center of channel in numerical and empirical form. The study was conducted for both calm and chaotic regimes with range of Reynolds numbers (40–1000) and the effect porosity, diameter of porous material, thermal heat transfer conductivity coefficient, and Reynolds number was explored on heat transfer. Their findings indicated that under the condition when diameter of porous material was near the diameter of channel i.e. the channel was assumed as filled with porous material, rise of heat transfer would be acceptable with respect to rising pressure drop. Nusselt number will be about 5.2 times greater than one without porous medium. The researchers explored many techniques to achieve empirical relations for velocity gradient in a porous medium and comparing it with non-porous medium. They generalized their studies in calm and chaotic regimes through analysis of Darcy number and the range of their reliability and also use if Brinkman–Forchheimer rules. Use of filled and half-filled channels with porous material and application of porous barriers in channels as well as their impacts on heat transfer and pressure drop were some of important subjects noticed by researchers [53–60].

Radoim et al. [61] explored partially compressible flow of a fluid inside channel that was filled by porous material with different values of Darcy number and drew variance of axial velocity due to change in Darcy's number at high speeds. Karimipour et al. [62] explored heat transfer of copper-water nano fluid flow in a microchannel under boundary conditions of slip velocity using lattice Boltzmann technique. The findings indicated that addition of nanoparticles to base fluid would lead to rise of Nusselt number. Karimipour et al. [63] examined heat transfer of copper-water nano fluid flow in a cavity given gravitational

Fig. 7. a. Dimensionless temperature profiles, $\theta$, at different cross sections of microchannel at $\varphi = 0.25$ and $Re = 10$ for different values of $B$. b. Dimensionless temperature profiles, $\theta$, at different cross sections of microchannel at $\varphi = 0.25$ and $Re = 10$ for different values of $B$. 

![Fig. 7. a. Dimensionless temperature profiles, $\theta$, at different cross sections of microchannel at $\varphi = 0.25$ and $Re = 10$ for different values of $B$. b. Dimensionless temperature profiles, $\theta$, at different cross sections of microchannel at $\varphi = 0.25$ and $Re = 10$ for different values of $B$.](image)
force at different angles of cavity displacement by means of lattice Boltzmann technique. Their findings indicated that by increase in angle in respective of horizontal axis, the effect of gravitational force would be increased further on velocity-temperature diagram. Karimipour et al. [64] studied heat transfer in a microchannel assuming gravitational force assuming gravitational force by lattice Boltzmann technique. Their results showed the gravitational force in slip velocity might be effective on lower wall. Karimipour [65] explored compressible heat transfer of silver-water, copper-water, aluminum oxide-water nanofluids in a microchannel under boundary conditions of slip velocity and temperature jump by means of lattice Boltzmann technique. Their findings indicated that addition of nanoparticles would increase heat transfer in nanofluid as well as rise in rate of temperature jump at microchannel input.

It is seen that there is lack of research article concerns the slip velocity and temperature jump boundary conditions of a nanofluid in a microchannel filled by a porous medium which is presented for the first time at this work (to the best knowledge of authors).

2. Problem statement

The studied problem includes a two-dimensional microchannel with dimensions ratio (AR = L/H = 20) according to Fig. 1. The given nanofluid contains of water and FMWNT carbon nanotubes. The cold nanofluid enters into microchannel at porous medium filled with porosity (0.9) at temperature Tc = 293 K and constant velocity uc and after cooling
of microchannel walls which are placed at temperature $T_H = 303$ K exits from the other end. Thermophysical properties of water-carbon nanotubes (FMWNT/Water) are given at fixed temperature $T = 20$ °C according to Table 1. The sizes of nanoparticles are almost $d_p = 30 \pm 5$ nm after dispersion.

Fig. 10. a) Slip velocity, $U_s$ along the microchannel wall at different values of $B$ for $\varphi = 0.25\%$ and $Re = 10$. b) Slip velocity, $U_s$ along the microchannel wall at different values of $B$ for $\varphi = 0.25\%$, $Re = 10$ and $Da = 0.001$.

3. Numerical procedure

In this study, finite volume method has been employed for discreteness of the used governing equations and for solution of the governing and discreteness equations of the solved area in the organized system [68,69]. SIMPLE algorithm has been utilized to solve velocity field and pressure [66–70]. Lesser values of parameters as number $10^{-8}$ has been considered as convergence condition in solution of the governing discrete equations. The second-order upwind design has been utilized for discretization of permeability phrase and displacement of the governing equations.

3.1. Governing equations

Continuity equation:

$$\frac{\partial}{\partial x} (\rho_n u_i) + \frac{\partial}{\partial y} (\rho_n v_i) = 0$$

Momentum equation in X direction:

$$\frac{\partial}{\partial x} (\rho_n u_i u_i) + \frac{\partial}{\partial y} (\rho_n v_i u_i) = -\frac{\partial p}{\partial x} + \frac{\partial}{\partial x} \left( \mu_n \frac{\partial u_i}{\partial x} \right) + \frac{\partial}{\partial y} \left( \mu_n \frac{\partial u_i}{\partial y} \right) - \frac{\mu_n u_i}{K} - \frac{\rho_n F}{\sqrt{K}} |u_i| u_i$$

Momentum equation in Y direction:

$$\frac{\partial}{\partial x} (\rho_n u_i v_i) + \frac{\partial}{\partial y} (\rho_n v_i v_i) = -\frac{\partial p}{\partial y} + \frac{\partial}{\partial x} \left( \mu_n \frac{\partial v_i}{\partial x} \right) + \frac{\partial}{\partial y} \left( \mu_n \frac{\partial v_i}{\partial y} \right) - \frac{\mu_n v_i}{K} - \frac{\rho_n F}{\sqrt{K}} |u_i| v_i$$

In above equations, $\rho_n$ denotes nanofluid density, $u_i$ is momentary component of velocity along with x- De Cartesian coordinates, $v_i$ as momentary component of velocity along with y- De Cartesian coordinates, and $\mu_n$ is viscosity of nanofluid, $T_c$ temperature of cold nanofluid, $u_i$ is momentary component of velocity along with x- De Cartesian coordinates, and $F$ is adjusted Forchheimer coefficient. Similarly, $K$ is permeability coefficient of porous medium.

Energy equation:

$$\frac{\partial}{\partial x} (\rho_n u_i c_{fl} T_i) + \frac{\partial}{\partial y} (\rho_n v_i c_{fl} T_i) = \frac{\partial}{\partial x} \left( k \frac{T_i}{\partial x} \right) + \frac{\partial}{\partial y} \left( k \frac{T_i}{\partial y} \right)$$

In above equation, $c_{fl}$ denotes specific heat capacity of nanofluid and $K_n$ is effective thermal conductivity coefficient. Equations (1)–(4) should be written dimensionless to examine the results.

$$\frac{\partial}{\partial x} (U) + \frac{\partial}{\partial y} (V) = 0$$

$$\frac{\partial}{\partial x} (UU) + \frac{\partial}{\partial y} (VV) = -\frac{\partial p}{\partial x} + \frac{\partial}{\partial x} \left( \frac{\partial U}{\partial x} \right) + \frac{\partial}{\partial y} \left( \frac{\partial U}{\partial y} \right) - \frac{U}{DaRe} - \frac{F}{\sqrt{Da}} |U| U$$

$$\frac{\partial}{\partial x} (UV) + \frac{\partial}{\partial y} (VW) = -\frac{\partial p}{\partial y} + \frac{\partial}{\partial x} \left( \frac{\partial V}{\partial x} \right) + \frac{\partial}{\partial y} \left( \frac{\partial V}{\partial y} \right) - \frac{V}{DaRe} - \frac{F}{\sqrt{Da}} |U| V$$

$$\frac{\partial}{\partial x} (U0) + \frac{\partial}{\partial y} (V0) = \frac{1}{Pe} \left( \frac{\partial^2 \theta}{\partial x^2} \right) + \frac{1}{Pe} \frac{\partial}{\partial y} \left( \frac{\partial \theta}{\partial y} \right)$$

$Da$ denotes Darcy number and $Pe$ is Peclet number in above equation.
Non-dimensionality of all above equations has been defined according to properties of nanofluid and also dimensionless parameters have been utilized in Equations (1)–(8) as follows:

\[
X = \frac{x}{h}, \quad Y = \frac{y}{h}, \quad U = \frac{u}{u_k}, \quad V = \frac{v}{u_k}, \quad p = \frac{\rho_f u_k^2}{\mu_f} H = \frac{h}{H} = 1, \quad L = \frac{l}{H},
\]

\[
\theta = \frac{T - T_C}{T_H - T_C}, \quad \text{Re} = \frac{\rho_f u_k h}{\mu_f}, \quad \text{Pr} = \frac{\mu_f}{\alpha_f}, \quad \text{Pe} = \text{RePr}.
\]

With respect to thermal equilibrium among porous medium and nanofluid, the effective heat transfer coefficient \(k_e\) can be calculated by the following equation \([77, 78]\):

\[
k_e = \varepsilon K_f + (1 - \varepsilon) K_v
\]

### 3.2. Darcy’s law

The flow has been already noticed and studied in porous media and the given results have been presented as different models to describe fluid flow inside porous medium. Thermal and hydraulic effects are considered as two important subjects in analysis of flow in porous medium. The first investigation was carried out by Darcy \([79]\) and Darcy’s law was recorded under his title. Targui et al. \([80]\) added constant reciprocal proportion to Darcy’s law where this constant is called permeability and it is a criterion for fluid resistance when passing through a porous medium. Darcy’s law has been defined as follows.

\[
\frac{dp}{dx} = \frac{\mu}{k} u
\]

Where \(\frac{dp}{dx}\) denotes pressure gradient, \(u\) is average velocity, \(\mu\) as dynamic viscosity of fluid, and \(k\) is permeability of porous medium. Darcy’s law is applicable only when value of Reynolds number for flow is low and viscosity and compressive forces prevail. In fact, this equation is only restricted to low-speed flow and saturated media with low-porosity. The porosity is one of the parameters in porous medium that is defined as follows:

\[
\varepsilon = \frac{\text{Empty volume inside porous medium}}{\text{Total volume of porous medium}}
\]

### 3.3. Hydrodynamic boundary conditions

The no-slip condition of is the simplest boundary conditions at macroscopic scale that denotes a fluid adjacent to solid surface possesses the same velocity of surface. Recently, researchers have shown that no-slip boundary condition may not be appropriate to flow in channels at micro scale since compared at micro scale; the flow of a fluid may differ from flow at macro scale. In fact, there is regional wall in slip regimes at neighborhood in which fluid molecules are fluctuated. Therefore, Navier-Stokes equation will be applicable only by consideration of slip boundary condition. To solve slip velocity, \(L_s\), \(u_{wall}\), and \(u_{fluid}\) will be defined respectively as slip length, wall velocity, and fluid velocity \([81]\):

\[
\Delta u_{wall} = u_{fluid}(y \rightarrow \text{wall}) - u_{wall} = L_s \frac{\partial u_{fluid}(y)}{\partial y}_{\text{wall}}
\]

As a result, nanofluid slip velocity \((L_s)\) is computed on mobile wall as follows \([82]\):

\[
u_s = \pm \beta \frac{\partial y}{\partial y_{\text{wall}}} = -h
\]

In above equation, parameter \(\beta\) is called slip coefficient and...
dimension form of Equation (16) is defined as follows:

$$U_s = \pm B \frac{\partial U}{\partial Y}_{y=0.1}$$

(17)

where, $B = \frac{\nu}{\mu}$ is called the dimensionless slip coefficient.

3.4. Thermal boundary conditions

The presence of slip conditions near the walls may cause different temperature in fluid adjacent to walls compared to wall temperature. Given temperature of walls of microchannels has been assumed as fixed in this study; this effect will be visible more. The effect of temperature jump can be modeled in this study similar to Equation (15). Temperature jump is defined along with wall of microchannel as follows [83].

$$\Delta T_{wall} = T_{fluid}(y \rightarrow \text{wall}) - T_{wall} = \xi \frac{\partial T_{fluid}(y)}{\partial Y}_{y=0.1}$$

(18)

$$\theta_s = abc(\theta - \theta_{wall})$$

(20)

Other dimensionless boundary conditions are also shown as follows [84]:

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

$$V = 0 \text{ and } \frac{\partial U}{\partial X} = \frac{\partial \theta}{\partial X} = 0 \text{ for } X = 20 \text{ and } 0 \leq Y \leq 1$$

(21)

$$V = 0, U_s = B \frac{\partial U}{\partial Y}, \theta_s = B \frac{\partial \theta}{\partial Y}_{y=0.1} \text{ and for } Y = 0 \text{ and } 0 \leq X \leq 20$$

$$V = 0, U_s = B \frac{\partial U}{\partial Y}, \theta_s = B \frac{\partial \theta}{\partial Y}_{y=0.1} \text{ and for } Y = 1 \text{ and } 0 \leq X \leq 20$$

Nusselt number:

$$\langle Nux \rangle_{\text{lower wall}} = \frac{K_e}{K_f} \left( \frac{\partial \theta}{\partial Y} \right)_{Y=0}$$

(22)

$$\langle Nux \rangle_{\text{upper wall}} = \frac{K_e}{K_f} \left( \frac{\partial \theta}{\partial Y} \right)_{Y=1}$$

(23)

$\lambda$ is the convection heat transfer coefficient [85]:

$$\lambda = \frac{q}{T_s - T_c}$$

(24)

4. Results

4.1. Grid independency

Table 2 shows values of number to nanofluid velocity among microchannel for three meshing models in different meshes (500 × 25, 600 × 30, and 700 × 35) and for $Re = 10$ at $\phi = 0.12\%$ and $B = 0.001$. It is seen there is small difference between meshes in the given results. Consequently, mesh (600 × 30) has been selected to continue calculations.
To validate the conducted operation, velocity profiles of copper-water nanofluid are shown inside a microchannel at $\phi = 0.4\%$ and $Re = 10$ based on findings from Karimipour and Afrand [78] in Fig. 2. Similarly, Fig. 3 indicates temperature profile in vertical axis at the middle of microchannel under conditions of $\phi = 0.4\%$ and $Re = 10$. Karimipour and Afrand have studied numerically on compressible displacement of calm flow of nanofluid in a microchannel. Likewise, profiles of air velocity inside a channel have been compared at different Darcy values with the findings of Mohammad [53] in Fig. 4a. Mohammad has studied numerically compressible displacement of calm air flow through a half-filled channel with porous material. More validation is presented versus those of Ref. [61] concerned numerical calculation of air flow through an open channel linked to a porous media for $Da = 0.01$ and $Da = 0.0001$ in Fig. 4b. The achievements are similar in a suitable way.

Heat transfer coefficient of convection in a horizontal tube filled by water/FMWCNT nanofluid at $\phi = 0.12\%$ was compared with those of Amrollahi et al. [86] in Fig. 4c. Amrollahi et al. experimentally measured convective heat transfer coefficient of 0.12 wt% nanofluids to that of base fluid in entrance region of laminar and turbulent flow as a function of Reynolds number in different temperatures. Reynolds number was chosen in the wide range of $1592 \leq Re \leq 4778$.

### 4.2. Analysis of effect of slip coefficient and Darcy number

Fig. 5a indicates impact of various values of slip coefficient along with vertical axis at the middle of microchannel at $\phi = 0.25\%$ and $Re = 10$ in the absence of porous medium. Due to presence of slip boundary conditions on walls, nanofluid possesses velocity on the walls and rate of velocity of walls is added by increase in slip coefficient.

In Fig. 5b similar to Fig. 5a, velocity profile has been shown along with vertical axis at the middle of microchannel at $\phi = 0.25\%$; $Da = 0.001$, and $Re = 10$. Due to slip boundary conditions on walls, nanofluid possesses certain velocity on the walls in which by addition to slip coefficient, value of slip velocity is also increased on the walls. Here
due to presence of porous medium, velocity profile will not become parabolic form and also rate of slip velocity will be increased near the wall.

Fig. 6 shows effect of slip coefficient on temperature profiles along with vertical axis in the middle of microchannel at \( \varphi = 0.25\% \) and \( Re = 10 \) in the absence of porous medium. Due to presence of slip boundary conditions on the walls, nanofluid possesses velocity on the walls and such slip may prevent from exchange of total heat of nanofluid with microchannel walls. Thus, it is observed as slip coefficient is added, the rate of temperature difference is increased in microchannel walls.

Fig. 7a shows dimensionless temperature profile along with vertical axes in different cross-sections of microchannel at \( \varphi = 0.25\% \), \( B = 0.1 \), and \( Re = 10 \) and in the absence of porous medium. As it observed, following to rise in X-value, nanofluid temperature rate is added along microchannel and nanofluid temperature approaches to temperature of walls. Nanofluid temperature at section \( (X = 0.8 L) \) has further approached to temperature of walls than in section \( (X = 0.2 L) \). Similarly, temperature jump is more effective at input of microchannel and it is decreased with rising X-value.

Fig. 7b indicates dimensionless temperature profile along with vertical axis in different sections of microchannel at \( \varphi = 0.25\% \), \( B = 0.001 \), and \( Re = 10 \) and in the absence of porous medium. One can observe effect of slip coefficient dimensionless temperature profile by comparing of Fig. 7a with Fig. 7b. As it seen, rise of slip coefficient causes increase in temperature jump and this increase rate is at maximum level in microchannel input at section \( (X = 0.2 L) \). The effect of slip coefficient on temperature jump is decreased as rate of fluid advancement is increased in microchannel.

Fig. 8a shows dimensionless temperature profile along with vertical axis in the middle of microchannel at \( \varphi = 0.25\% \) and \( Re = 10 \) and for different Darcy's values. Due to presence of porous medium and higher thermal equilibrium among nanofluid and microchannel walls caused by reduced permeability effect, and subsequently decreased velocity of fluid, temperature profiles are more uniform than \( D_a = 0.1 \). The presence of porous medium has caused lessening temperature jump. Through comparison among Fig. 8a and b the rate of temperature jump is revealed further near the microchannel walls following to rise of slip coefficient.

In Fig. 9a, effect of various Darcy's values are shown on velocity profile along with vertical axis in the middle of microchannel at \( \varphi = 0.25\% \), \( B = 0.001 \), and \( Re = 10 \). Microchannel exists from parabolic form following to decrease in Darcy's number for velocity along with vertical axis at the middle of microchannel and the maximum value of nanofluid velocity is reduced on vertical axis.

The impact of slip coefficient is visible on dimensionless velocity profile in comparison of Fig. 9a with Fig. 9b. The slip velocity is added near the walls by increase in slip coefficient and with respect to mass-energy conservation principle velocity is increased along with horizontal axis. Likewise, presence of porous medium will increase slip velocity near the walls.

Fig. 10a indicates the effect of slip coefficient along microchannel at \( \varphi = 0.25\% \) and \( Re = 10 \) and in the absence of porous medium. With respect to the diagram, it is seen the slip velocity is at maximum level near the wall at microchannel input and it is reduced very slightly from input wall of microchannel by rise of \( X \) and then it approaches to a fixed level. We may conclude from comparison of Fig. 10b with Fig. 10a that the presence of porous medium with low permeability or in other words reduction in Darcy number causes difference between values of slip velocity for various slip coefficients as well as reduced input length to slip velocity to achieve constant value.

Fig. 11a and b indicate diagram of temperature jump along with microchannel wall. The temperature jump is at maximum level in microchannel input and then it is reduced with gradient proportional to slip coefficient and finally it approaches to a fixed value. As slip coefficient is added, the rate of temperature jump is also increased. As it seen, the value of temperature jump is greater for slip coefficient \( B = 0.1 \) than \( B = 0.001 \). Darcy's effect has been shown on temperature jump value in Fig. 11b. Following to decrease in permeability gradient of diagram is increased further and value of temperature jump is reduced more quickly along with microchannel compared to in a state without porous medium.

### 4.3. Effect of Reynolds, Darcy, and volumetric percent of carbon nanotubes

As we know, analysis of local Nusselt values along with microchannel wall is one of the methods to examine heat transfer mechanism. The rate of local Nusselt number is at maximum level in microchannel input because of the maximum difference in temperature among nanofluid and microchannel walls and it is reduced along with microchannel by rise of \( X \) and it approaches to a fixed level. Fig. 12a and b indicate local Nusselt diagram for various slip coefficients and Darcy number. As it identified in Fig. 12a, rise of slip coefficient in the absence of porous medium has caused increase in value of local Nusselt number and in Fig. 12b, local Nusselt number will be increased by reducing Darcy number.

Fig. 12b and c indicate local Nusselt number is reduced more quickly at lower Reynolds numbers and this is because of lower velocity of flow and therefore nanofluid may have longer time to exchange heat transfer with microchannel walls and its temperature approaches more rapidly to temperature in microchannel walls. By comparing Fig. 12a and b it is seen that presence of porous medium and reduction of Darcy number will increase local Nusselt number. Fig. 13a and Fig. 13b shows nanofluid temperature contours for different Reynolds values along with microchannel. Rise of Reynolds number causes nanofluid to have lesser opportunity for heat exchange with microchannel walls. Thus, nanofluid will achieve thermal development later. On the other hand, by comparing Fig. 13a with Fig. 13b, we find out that the effect of porous media and Darcy number on the rate of heat.

In Fig. 14, effect of volumetric percent has been shown in carbon nanotubes added to base fluid. 12% increase in carbon nanotubes will have not too effect on rise of local Nusselt value but rise of carbon nanotubes up to 0.25% will noticeably increase local Nusselt value.

### 5. Conclusion

The subjects of heat transfer, compressible displacement of nanofluid composed of water and carbon nanotube particles (FMWNT) in a 2-D microchannel were numerically examined. Microchannel walls are placed at fixed temperature and higher than nanofluid input.
temperature. Likewise, the slip velocity and temperature jump boundary conditions have been designated along with the microchannel. Nanofluid has been filled totally by a porous medium.

The studies indicated that local Nusselt number was more quickly reduced at lower Reynolds numbers and this may be due to low velocity of flow and therefore nanofluid may have more time for exchange of heat transfer with microchannel walls and its temperature would approach more rapidly to temperature of microchannel walls. Nanofluid velocity is increased as Reynolds number is added and therefore the shorter time is needed for heat transfer among nanofluid and walls and it causes increase in local Nusselt number. Similarly, reduced permeability will lead to rise of local Nusselt number. Also slip coefficient is assumed as one of efficient parameters in rise of local Nusselt number. In this survey, rise of slip coefficient will cause increase in local Nusselt number. Thus, the rate of increase will be further in local Nusselt number for higher Reynolds numbers and in lower Darcy numbers with greater slip coefficient. Local Nusselt number is increased by addition at level 0.25 in volumetric percent of nanoparticles. Thus, under the same conditions, Darcy number will causes increase in local Nusselt number. The phenomenon of temperature jump is visible at microchannel input and near the walls. Temperature jump is increased due to rise of slip coefficient and in contrast it is decreased by reducing Darcy number.

References
