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Flow and Heat Transfer of Nanofluid in a Channel Partially Filled with Porous Media Considering Turbulence Effect in Pores

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Abstract: The flow and heat transfer of Al_2O_3-water nanofluid in a channel partially filled with porous media is investigated numerically. The turbulence effect in the porous media is taken under consideration in this article. A simple case is simulated first to evaluate the accuracy of the results in comparison with the available data. The turbulent kinetic energy profile is investigated at a flow cross section. The results show that the maximum of turbulent kinetic energy occurs at the clear fluid region in the vicinity of porous media region. The turbulent kinetic energy is decreasing function of the porosity of porous media. The effect of porosity on the variation of turbulent kinetic energy decreases with the increase in the porosity of porous media. The turbulent kinetic energy at clear fluid and porous media regions decreases with the increase in nanofluid concentration from 0.01 to 0.03, and it increases with the increase in nanofluid concentration from 0.03 to 0.05. The temperature of nanofluid increases with the increase in the nanofluid concentration and decrease in the porosity of porous media. It is shown that for this case, with the increase in nanofluid concentration and porosity of porous media, the skin friction coefficient increases and the Nusselt number decreases.

Keywords: Porous Media, Nanofluid, Turbulence Modelling, Heat Transfer, Computational Fluid Dynamics

1. Introduction

The flow and heat transfer of fluid in porous media has many applications in several engineering processes such as microelectronic cooling, chemical reactors, energy storage units and heat exchangers. Due to the vast applications, it has been studied by many researchers. The stated problem can be studied analytically, numerically and experimentally. More than one numerical method for investigation of the flow and heat transfer of fluid in porous media region can be found. Whitaker [1] investigated microscopic method and macroscopic method to study the flow of fluid in the porous medium region. Microscopic method is based on the belief that the regular Navier-Stokes equations should be solved for each pore. In other hand, the macroscopic method is based on the considering of all pores together. The definition of the boundary conditions of pores are completely complex in the microscopic method; so, the macroscopic method can be chosen to overcome the complexity. Most of the flow investigation in practical engineering situations have been made using macroscopic method; consequently, the macroscopic method is chosen in this article to study the flow and heat transfer of fluid in porous media.

The investigation of the fluid flow under the effects of porous media was experimentally initiated by Beavers and Joseph [2]. Vafai and Kim [3] revised the description of fluid behavior at interface region between the porous medium and clear fluid which had been studied by Beavers and Joseph. Since the pioneering work in 1967 by Beavers and Joseph [2], various aspects of the problem have been examined by many investigators [4-6]. Some of the investigations have been allotted to the analytical study of the fluid flow in the interface between porous medium and clear fluid regions. Kuznetsov [7] investigated the fluid flow in the interface region for the steady laminar fluid flow in the cylindrical channel and parallel-plate partially filled with porous medium. The Brinkman-extended Darcy equation was utilized to find the dependence of the velocity on the various parameters. In completing the previous work, Kuznetsov [8] presented an analytical solution for the fluid flow in a channel partially filled with porous medium considering the stress jump boundary condition at the interface region between porous medium and clear fluid which was suggested by Ochoa-Tapia and Whitaker [9,10]. Al-Nimr and Alkam [11] expected that the fluid flow was unsteady because of unexpected change in the pressure or velocity of the channel boundaries. They obtained analytical solution for unsteady fluid flow in a channel partially filled with porous media using Green's function method. Most of the previous studies were allocated to the investigation of heat transfer under the effects of porous media. The forced convection in a channel partially filled with porous media was investigated analytically by Karimi et al. [12] considering constant wall heat flux boundary condition. The local thermal non-equilibrium equation was employed, and exact solution for the temperature field was obtained using two fundamental models for the thermal boundary conditions at the interface between the porous medium and the clear region.

Computational fluid dynamics modeling of the fluid flow and heat transfer in the porous media becomes a significant research subject because of the comprehensive information that can be derived from the results. Alkam and Al-Nimr [13] made a numerical simulation of unsteady forced convection in a cylindrical channel partially filled with porous media to investigate the effects of porous media thickness and Darcy number on the hydrodynamic and thermal characteristics of the fluid flow. Mahdavi et al. [14] investigated the effects of the porous medium position on the entropy generation and convective heat transfer of steady incompressible flow of fluid in a pipe partially filled with porous medium. The Nusselt number and entropy generation rate were investigated under the effects of porous medium thickness and Darcy number for constant heat flux boundary condition. Mahmoudi and Karimi [15] studied the effects of inertia, Darcy number, conductivity ratio and porosity on the flow and heat transfer of fluid in a pipe partially filled with porous media with constant wall temperature boundary condition. They obtained optimum value for porous thickness with reasonable heat transfer rate and pressure drop.

In addition to the porous medium, nanofluids can be used as a way to increase the heat transfer rate. Nanofluid is made by adding very small suspended nanoparticles to a base fluid. Choi and Eastman [16] initiated to investigate nanofluids. Since the advent of the nanofluid concept, various studies have been done about using nanofluid to increase the heat transfer rate [17-20].

Sedighi [21] analytically studied the effects of magnetic field, viscous dissipation, heat source and thermal radiation on the flow and heat transfer of nanofluid over an exponentially stretching sheet. Sedighi and Deldoost [22] investigated the effects of thermal radiation and magnetic field on the Nusselt number and skin friction for the flow of nanolfuid over a plate. They found that Nusselt number is decreasing function of magnetic field and thermal radiation, whereas the skin friction is increasing function of magnetic field and it is constant by variation of thermal radiation. In the recent years, new accurate definitions for the properties of nanofluid have been found from experimental investigations. Sedighi and Mirzamohammad [23] used new correlation for the viscosity of Ag–H2O nanofluid to investigate the effects of magnetic field, thermal radiation, and nanofluid concentration on the skin friction coefficient and Nusselt number. In this paper, the accurate definition of the viscosity of nanofluid is chosen as a function of nanofluid concentration. Nanofluids and porous media can be used simultaneously to enhance the rate of heat transfer; therefore, the effects of various parameters on the stated problem have been investigated by many researchers. Abdollahzadeh et al. [24] investigated the steady stagnation flow of nanofluid toward a permeable stretching sheet under the effects of heat generation. They used Cu-water, Al_2O_3-water and TiO_2-water as nanofluid to present the effects of different nanoparticles dispersion and nanofluid concentration on the velocity and temperature profiles.

In this paper, temperature and turbulent kinetic energy of the Al_2O_3-water nanofluid flow in a channel partially filled with porous media are investigated numerically considering turbulence effect in pores. It can be found from the results that the turbulence effect in porous media is significant for high values of Reynolds number, especially by increasing of nanofluid concentration. Consequently, the turbulence effect is considered in the porous region which was ignored in the most of the previous works. The accurate definition for the viscosity of Al_2O_3-water nanofluid is used to investigate the effects of independent parameters on the Nusselt number and skin friction coefficient. The results can be used by mechanical engineering to evaluate the heat transfer rate in equipment that deals with heat transfer process.

2. Problem Definition and Boundary Conditions

The steady state flow and heat transfer of Al_2O_3-water nanofluid in a channel partially filled with porous is investigated numerically. Fig.1 shows that the domain consists of porous media and clear fluid regions. The channel has length and height of 25H and 2H, respectively. The symmetry boundary condition is defined at the channel center line to model half of the channel. The thickness of the porous medium is defined as H/2. The porous media is located near the walls and the clear fluid region is defined at the center of channel. The numerical results are obtained for constant heat flux boundary condition for wall, and velocity inlet boundary condition for inlet. Nanofluid enters the channel with uniform velocity and temperature. The Reynold number is defined as 50000 to have fully turbulence flow in domain.

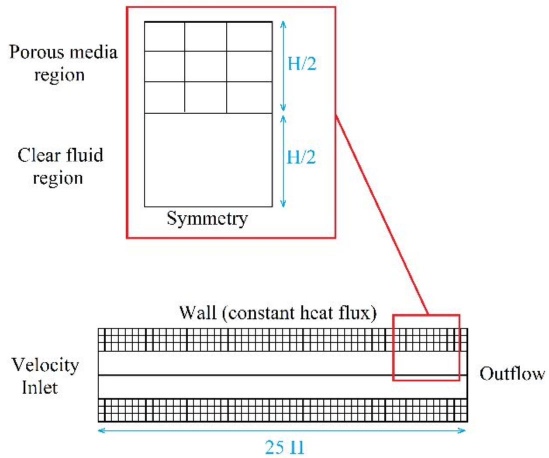


Fig.1 The geometry of computational domain

3. Governing equations

The governing equations of steady turbulent flow and heat transfer of Al_2O_3-water nanofluid in a channel partially filled with porous media need to be solved simultaneously. There are two sets of governing equations corresponding to the porous medium and clear fluid [25]. To express the flow of nanofluid in the porous medium and clear fluid regions, Brinkman–Forchheimer-extended Darcy model and Navier–Stokes equation are used, respectively. The equations for conservation of mass, momentum, and energy can be written as follow where the subscripts 1 and 2 designate the parameters in the porous medium and the clear fluid regions, respectively.

1– Continuity equation for porous region.

$$\frac{\partial u_1}{\partial x}+\frac{\partial v_1}{\partial y}=0 \tag{1}$$

2– Continuity equation for clear fluid region.

$$\frac{\partial u_2}{\partial x}+\frac{\partial v_2}{\partial y}=0 \tag{2}$$

Where u and v are the velocity of nanofluid in x and y direction, respectively.

1– Momentum equations for porous region.

$$\frac{1}{\beta^2}\left[u_1\frac{\partial u_1}{\partial x}+v_1\frac{\partial u_1}{\partial y}\right]=-\frac{1}{\rho_{nf}}\frac{\partial P_1}{\partial x}+\frac{\mu_{nf}}{\rho_{nf}}\left[\frac{\partial^2 u_1}{\partial x^2}+\frac{\partial^2 u_1}{\partial y^2}\right]-\frac{\mu_{nf}/\rho_{nf}}{K}u_1-\frac{C_F}{\sqrt{K}}\left|u_1\right|u_1 \tag{3}$$

$$\frac{1}{\beta^2}\left[u_1\frac{\partial v_1}{\partial x}+v_1\frac{\partial v_1}{\partial y}\right]=-\frac{1}{\rho_{nf}}\frac{\partial P_1}{\partial y}+\frac{\mu_{nf}}{\rho_{nf}}\left[\frac{\partial^2 v_1}{\partial x^2}+\frac{\partial^2 v_1}{\partial y^2}\right]-\frac{\mu_{nf}/\rho_{nf}}{K}v_1-\frac{C_F}{\sqrt{K}}\left|v_1\right|v_1 \tag{4}$$

2– Momentum equations for clear fluid region.

$$\left[u_2\frac{\partial u_2}{\partial x}+v_2\frac{\partial u_2}{\partial y}\right]=-\frac{1}{\rho_{nf}}\frac{\partial P_2}{\partial x}+\frac{\mu_{nf}}{\rho_{nf}}\left[\frac{\partial^2 u_2}{\partial x^2}+\frac{\partial^2 u_2}{\partial y^2}\right] \quad (5)$$

$$\left[u_2\frac{\partial v_2}{\partial x}+v_2\frac{\partial v_2}{\partial y}\right]=-\frac{1}{\rho_{nf}}\frac{\partial P_2}{\partial y}+\frac{\mu_{nf}}{\rho_{nf}}\left[\frac{\partial^2 v_2}{\partial x^2}+\frac{\partial^2 v_2}{\partial y^2}\right] \quad (6)$$

Where β is the porosity, P is pressure of fluid, μ is viscosity, ρ is density of fluid, K is permeability and C_F is the inertial coefficient.

1– Thermal energy equation for porous region.

$$(\rho C_P)_{nf}\left[u_1\frac{\partial T_1}{\partial x}+v_1\frac{\partial T_1}{\partial y}\right]=k_{nf}\left[\frac{\partial^2 T_1}{\partial x^2}+\frac{\partial^2 T_1}{\partial y^2}\right]+\lambda_1 \quad (7)$$

$$\lambda_1=\frac{\mu_{nf}}{K}\left(u_1^2+v_1^2\right)+\frac{\rho_{nf}C_F}{\sqrt{K}}\left(u_1^2+v_1^2\right)^{3/2}+\mu_{nf}\left[2\left(\frac{\partial u_1}{\partial x}\right)^2+2\left(\frac{\partial v_1}{\partial y}\right)^2+\left(\frac{\partial u_1}{\partial y}+\frac{\partial v_1}{\partial x}\right)^2\right]$$

2– Thermal energy equation for clear fluid region.

$$(\rho C_P)_{nf}\left[u_2\frac{\partial T_2}{\partial x}+v_2\frac{\partial T_2}{\partial y}\right]=k_{nf}\left[\frac{\partial^2 T_2}{\partial x^2}+\frac{\partial^2 T_2}{\partial y^2}\right]+\lambda_2 \quad (8)$$

$$\lambda_2=\mu_{nf}\left[2\left(\frac{\partial u_2}{\partial x}\right)^2+2\left(\frac{\partial v_2}{\partial y}\right)^2+\left(\frac{\partial u_2}{\partial y}+\frac{\partial v_2}{\partial x}\right)^2\right]$$

Where C_P is specific heat at constant pressure, T is temperature, k is conductivity and λ is the viscous heating due to viscous dissipation. The transport equations for the Realizable k – ε model are defined in the following forms. As stated before, the turbulence effect is considered in porous media region.

$$\rho_{nf}\left(\frac{\partial(k_t u)}{\partial x}+\frac{\partial(k_t v)}{\partial y}\right)=\frac{\partial}{\partial x}\left(\left(\mu_{nf}+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k_t}{\partial x}\right)+\frac{\partial}{\partial y}\left(\left(\mu_{nf}+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k_t}{\partial y}\right)+G_k-\rho_{nf}\varepsilon \quad (9)$$

$$\rho_{nf}\left(\frac{\partial(\varepsilon u)}{\partial x}+\frac{\partial(\varepsilon v)}{\partial y}\right)=\frac{\partial}{\partial x}\left(\left(\mu_{nf}+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x}\right)+\frac{\partial}{\partial y}\left(\left(\mu_{nf}+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial y}\right)+\rho_{nf}C_{1\varepsilon}S_\varepsilon-\rho_{nf}C_{2\varepsilon}\frac{\varepsilon^2}{k_t+\sqrt{\nu\varepsilon}} \quad (10)$$

Where G_k is the generation of turbulence kinetic energy due to the mean velocity gradient. $C_{1\varepsilon}$ and $C_{2\varepsilon}$ are constants of equations.

The effective density, the effective heat capacity and the effective thermal conductivity of nanofluid are defined in the following forms.

$$\rho_{nf}=(1-\phi)\rho_f+\phi\rho_p \quad (11)$$

$$C_{P_{nf}}=\frac{(1-\phi)(\rho C_P)_f+\phi(\rho C_P)_p}{\rho_{nf}} \quad (12)$$

$$\frac{k_{nf}}{k_f}=\frac{k_p+2k_f-2\phi\left(k_f-k_p\right)}{k_p+2k_f+2\phi\left(k_f-k_p\right)} \tag{13}$$

The effective viscosity of Al_2O_3-water nanofluid is defined as follows. The below correlation was derived from experimental data by use of curve which was fitted on the results [26].

$$\mu_{nf}=\mu_f\left(1+0.025\mu_f+0.015\mu_f^{\,2}\right) \tag{14}$$

The equations of mass, momentum, energy and the equations of k-ε turbulence model are solved numerically. The structured grids are used in the domain. The nodes are closer to each other near the wall and the border between the porous media and clear fluid regions. The discretization of equations is performed on the grids by a second order upwind scheme. A SIMPLE algorithm is applied to achieve the step-by-step correction of pressure. The treatment of the fluid flow near the wall is defined by applying standard wall function. The results are obtained by continuing the iteration to reduce the residuals to an acceptable level. The time of the calculation for each case was about 120 minute.

4. Results and Discussions

The numerical solution of the governing equations described in the previous section considering various boundary conditions yields the flow and heat transfer of Al_2O_3-water nanofluid in the channel partially filled with porous media. The independency of the results to the number of calculation cells needs to be investigated first. The variation of the numerical results with respect to the number of nodes reveals that any increase in the number of nodes does not affect the profile of non-dimensional velocity for the grid distribution containing 61061 nodes. Prior to presenting the results, the numerical model needs to be validated. Fig.2 shows that the obtained results are in good agreement with previous published data.

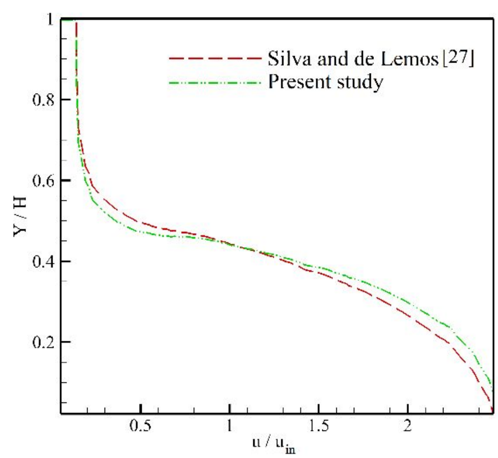


Fig.2 Comparison between the velocity profile of present study with those of Silva and de Lemos [27]

Fig.3 shows the variation of temperature with respect to the nanofluid concentration and the porosity of porous media. It can be found that the temperature of nanofluid is affected by nanofluid concentration and porosity in the porous media region; whereas, the variation of temperature with respect to the nanofluid concentration and the porosity of porous media is negligible in the clear fluid region. It is shown that the temperature of nanofluid is a decreasing function of the porosity for the all values of nanofluid concentration. The temperature of nanofluid is a nonlinear increasing function of nanofluid concentration. The variation of temperature with respect to the nanofluid concentration is higher for the lower values of nanofluid concentration.

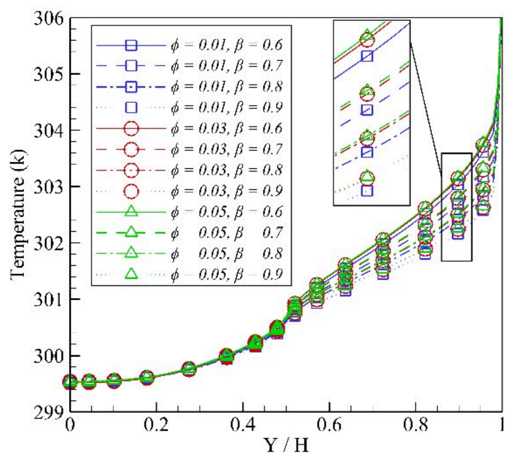
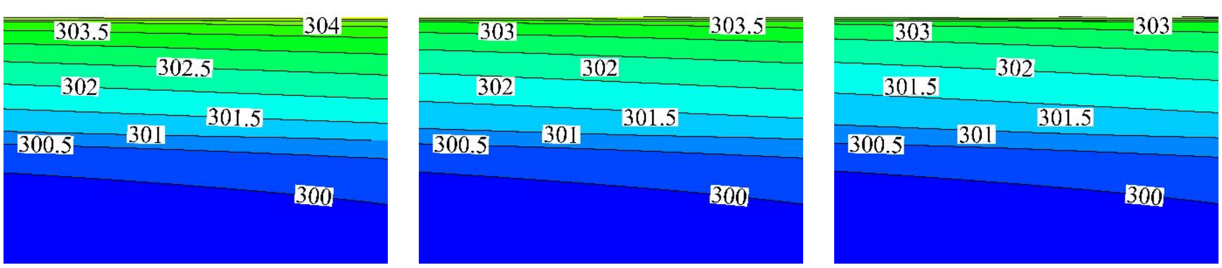


Fig.3 Temperature profiles for the various values of nanofluid concentration and porosity of porous media at x= 10H

Fig.4 shows the effects of nanofluid concentration and porosity of porous media on the contours of temperature in the domain. It can be found that the concluded results from Fig.3 at a flow cross section can be generalized to the other cross sections. Fig.4 shows that the temperature of nanofluid increases by passing through the channel. The temperature in the domain decreases with the increase in the porosity of porous media.



$\phi = 0.01, \beta = 0.6$ $\phi = 0.01, \beta = 0.7$ $\phi = 0.01, \beta = 0.8$

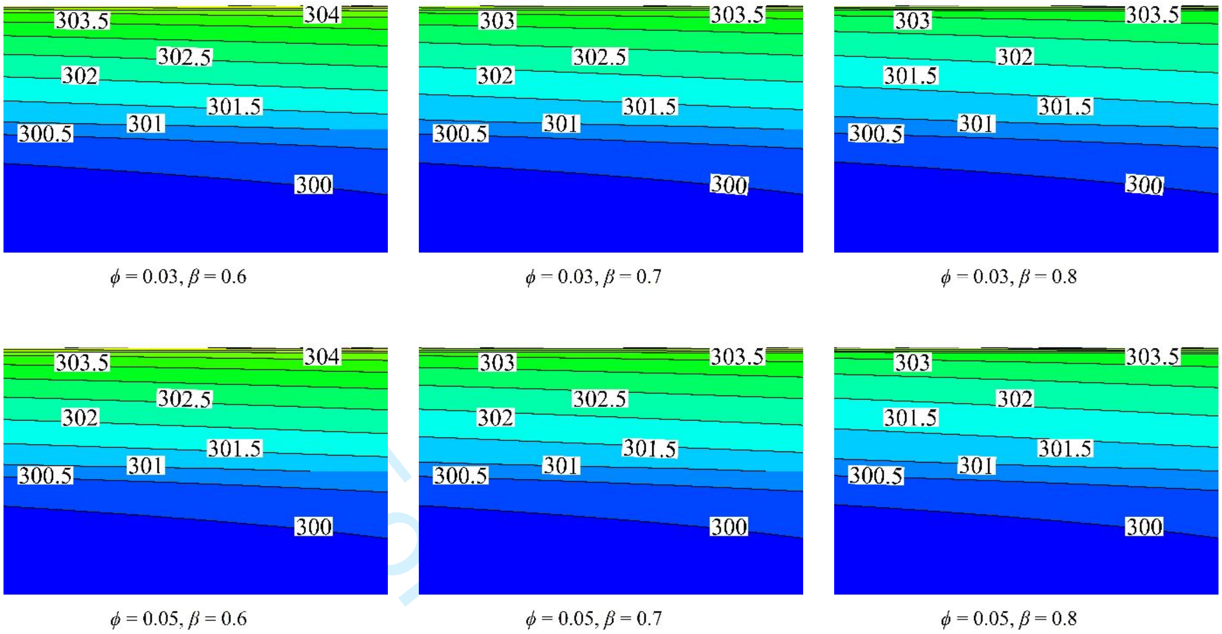


Fig.4 Contours of temperature for various values of nanofluid concentration and porosity of porous media

Fig.5 shows that the turbulent kinetic energy decreases with the increase in the porosity of the porous media. The effect of the porosity on the variation of turbulent kinetic energy increases for lower values of the porosity of porous media. The peaks of turbulent kinetic energy profiles occur in the clear fluid region near the porous media. The peaks of turbulent kinetic energy curves occur farther from the border between the porous media and clear fluid regions for lower values of the porosity of porous media. Moreover, it can be found that the turbulent kinetic energy is a nonlinear function of nanofluid concentration. The turbulent kinetic energy decreases by increasing of the nanofluid concentration from 0.01 to 0.03, and it increases with the increase in the nanofluid concentration from 0.03 to 0.05.

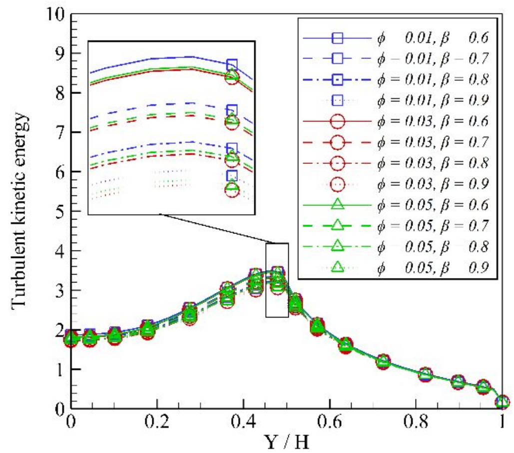


Fig.5 Turbulent kinetic energy profiles for various values of nanofluid concentration and porosity of porous media at x= 10H

Fig.6 shows effect of the porosity of porous media and the nanofluid concentration on the skin friction coefficient. It is found that the skin friction coefficient is an ascending function of the nanofluid concentration and the porosity of porous media. The rate of the variation of skin friction coefficient with respect to the porosity of porous media is constant for different values of nanofluid concentration. The variation of skin friction coefficient with respect to the nanofluid concentration is greater for higher values of the nanofluid concentration.

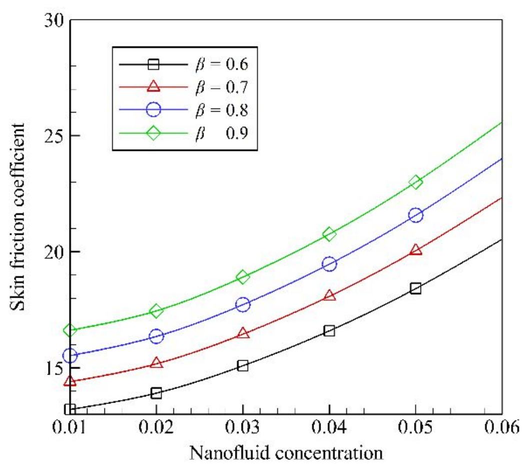


Fig.6 Variation of skin friction coefficient with respect to the nanofluid concentration and porosity of porous media

Fig.7 shows the variation of Nusselt number under the effects of the porosity of porous media and nanofluid concentration. It is found that the Nusselt number decreases with the increase in nanofluid concentration and porosity of porous media. The rate of variation of Nusselt number with respect to the porosity is ascending function of the porosity of porous media. It can be found that the Nusselt number decreases significantly by increasing of nanofluid concentration from 0.01 to 0.02. The variation of Nusselt number by growing of the nanofluid concentration from 0.02 to 0.06 is negligible with respect to the variation of Nusselt number by increasing of the nanofluid concentration from 0.01 to 0.02.

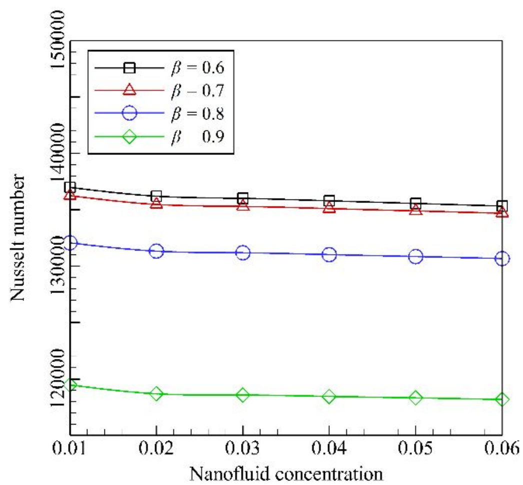


Fig.7 Variation of Nusselt number with respect to the nanofluid concentration and porosity of porous media

4. Conclusion

The flow and heat transfer of Al_2O_3-water nanofluid in a channel partially filled with porous media is studied considering turbulence effect in pores. The accurate definition of the Al_2O_3-water nanofluid viscosity is used. The numerical results are investigated in detail after making comparison between the present results and available published data. It can be found that the turbulent kinetic energy decreases with the increase in the porosity of the porous media and it changes from decreasing function of nanofluid concentration to increasing function of nanofluid concentration by growing the concentration of nanofluid. The variation of the turbulent kinetic energy with respect to the porosity of porous media decreases with the increase in the porosity of porous media. The results show that the curves of turbulent kinetic energy at a flow cross section have peaks in the clear fluid region near the porous media. The peaks of curves occur farther from the porous media by decreasing the porosity of porous media. It is shown that the skin friction coefficient is an ascending function of the nanofluid concentration and the porosity of porous media. Nusselt number decreases with the increase in nanofluid concentration and the porosity of porous media.

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