Powder Technology 325 (2018) 78–91

Contents lists available at ScienceDirect

Powder Technology

journal homepage: www.elsevier.com/locate/powtec

Numerical investigation of laminar flow and heat transfer of non-Newtonian nanofluid within a porous medium

Pouya Barnoon, Davood Toghraie *

Department of Mechanical Engineering, Khomeinishahr Branch, Islamic Azad University, Khomeinishahr, Iran

ARTICLE INFO

Article history:
Received 9 August 2017
Received in revised form 19 September 2017
Accepted 19 October 2017
Available online xxxx

Keywords:
Laminar flow
Heat transfer
Non-Newtonian nanofluid
Porous

ABSTRACT

In this study, comprehensive study of laminar flow and heat transfer of pseudo-plastic non-Newtonian nanofluid (Al_2O_3 + CMC) within the porous circular concentric region is presented. The effect of volume fraction of nanoparticles, Reynolds number, Darcy number, thickness ratio is studied. Simulations for different Reynolds numbers and Darcy numbers in the range of $100 \leq Re \leq 300$ and $10^{-4} \leq Da \leq 10^{-2}$ are done. The results show that the effect of the porous layer on increasing the convective heat transfer coefficient is larger than the Reynolds number, since, at a given volume fraction, the porous medium plays a greater role in increasing the heat transfer compared to the increasing Reynolds number. Also, at a given volume fraction and for a fixed porosity, decreases in the permeability leads to increased Darcy velocity and, consequently, velocity profile. As the thickness of the porous layer increases at fixed values of permeability and porosity, the velocity of the nanofluid is also increased in a constant Reynolds number, by increasing the thickness of the porous media, heat transfer coefficient increases. In addition, at a specified thickness and constant Reynolds number, by increasing the Darcy number, the heat transfer coefficient and the Nusselt number increases. Moreover, as the thickness of the porous layer increases at fixed values of permeability and porosity, the velocity of the nanofluid is also increased; this consequently maximizes the pressure drop.

1. Introduction

A non-Newtonian fluid is a fluid that does not follow Newton's law of viscosity. Shear thinning is the non-Newtonian behavior of fluids whose viscosity decreases under shear strain [1,2]. In fluid mechanics, fluid flow through porous media is the manner in which fluids behave when flowing through a porous medium. The concept of porous media is used in many areas of applied science and engineering [3]. Nanofluids are fluids containing nanoparticles. They are engineered colloidal suspensions of nanoparticles in a base fluid. They exhibit enhanced thermal conductivity and the convective heat transfer coefficient compared to the base fluid [4–13].

Hatami and Ganji [14] analyzed heat transfer and flow for non-Newtonian nanofluid passing through the porous media between two coaxial cylinders. They showed that increasing the thermophoresis parameter caused an increase in temperature values in whole domain.

Nield and Kuznetsov [15] studied the forced convection in a channel occupied by a nanofluid or a porous medium saturated by a nanofluid. They found that the combination of Brownian motion and thermophoresis has the effect of reducing the Nusselt number.

Uphill et al. [16] investigated flow of nanofluids through porous media. They showed that nanofluids containing particles smaller than 60 nm flowed well through timber.

Bourantas et al. [17] studied heat transfer and natural convection of nanofluids in porous media. They found that higher Rayleigh number values strengthen the natural convection flows.

Sheremet and Pop [18] investigated the potential of nanofluids to enhance the heat transfer rate due to natural convection in a porous annulus. Their findings showed that Brownian motion parameter has the minimum influence on Nusselt number.

Mahdi et al. [19] reviewed heat transfer and fluid flow in porous media with nanofluid. They investigated the effects of several parameters in porous media geometry and thermophysical properties of nanofluid, thermal boundary conditions and types of nanofluids.

Kefayati [20] studied heat transfer and entropy generation of natural convection on non-Newtonian nanofluids in a porous cavity. He concluded that the addition of the nanoparticle enhances the average Nusselt number.

Sivasankaran and Narrein [21] investigated the two-phase laminar pulsating nanofluid flow in helical microchannel filled with a porous medium. They observed that the presence of porous media led to improvement in heat transfer performance.

Ghalambaz et al. [22] studied free convection in a square cavity filled by a porous medium saturated by a nanofluid. They concluded that the

* Corresponding author.
E-mail address: davoodtoghraie@gmail.com (D. Toghraie).

https://doi.org/10.1016/j.powtec.2017.10.040
0032-5910/

Nomenclature

Re	Reynolds number
T	temperature (K)
U	dimensionless velocity
Greek symbols	
ε	porosity
φ	volume fraction
ρ	density $[^{kg}/_{m^3}]$
Super- and sub-scripts	
f	fluid
nf	nanofluid
p	particle
bf	base fluid
s	solid
ave	average
o	outer
i	inner
C_p	specific heat capacity $[^{J}/_{kg\cdot K}]$
Da	Darcy number
f	friction factor
f_s	friction factor in smooth pipe
h	heat transfer coefficient $[^{W}/_{m^2\cdot K}]$
D_i	inner diameter [m]
D_o	outer diameter [m]
K	consistency index $[Pa\cdot s^n]$
k	thermal conductivity $[^{W}/_{m.K}]$
K^{**}	permeability $[m^2]$
K^{*}	modified permeability $[m^{n+1}]$
k_{eff}	effective thermal conductivity $[^{W}/_{m\cdot K}]$
L	length [m]
Nu	Nusselt number
Nu_s	Nusselt number in smooth pipe
n	power law index
Pr	Prandtl number

increase of Lewis number and buoyancy ratio parameter, respectively, increases and decreases the average Nusselt number.

Devakar et al. [23] simulated fully developed flow of non-Newtonian fluids in a straight uniform square duct through porous medium. They observed that, the velocity and volume flow rate decrease with an increase in couple stress parameter and porosity parameter.

Kasaeian et al. [24] reviewed the latest developments Nanofluid flow and heat transfer in porous media. They found that Tiwari and Das, and Buongiorno models were the most popular models used to simulate the nanofluid flow in porous media.

Selimefendigil et al. [25] simulated mixed convection in superposed nanofluid and porous layers in square enclosure. They found that the averaged heat transfer enhances almost linearly with nanoparticle volume fraction for different cylinder sizes.

Solomon et al. [26] investigated natural convection enhancement in a porous cavity with Al_2O_3-Ethylene glycol/Water nanofluids. They found that at a volume concentration of 0.05%, the heat transfer capability of porous cavity is enhanced to a maximum of 10% compared to the base fluids.

Reddy et al. [27] investigated boundary layer flow, heat and mass transfer over a rotating disk through porous medium saturated by Cu-Water and Ag-Water nanofluid with chemical reaction. They concluded that the temperature profiles elevated with the increasing values of nanoparticle volume fraction parameter.

Hashemi et al. [28] studied natural convection within a porous enclosure occupied by Cu-Water micropolar nanofluid at the presence of the heat generated in both solid and fluid phases of the porous medium. They found that as external Darcy-Rayleigh number increases, the strength of vortices formed and micro-rotation of particles increases.

Aly [29] studied natural convection over circular cylinders in a porous enclosure filled with a nanofluid under thermo-diffusion effects. He found that, the size and formation of cells inside the enclosure strongly depend on the Rayleigh number with Darcy parameter, and sizes and locations of the inner circular cylinders.

The present study includes three key elements: nanofluid, non-Newtonian fluid, and porous medium. In this study, comprehensive study of laminar flow and heat transfer of pseudo-plastic non-Newtonian nanofluid (Al_2O_3 + CMC) within the porous circular concentric region is presented.

2. Statement of the problem

Comprehensive study of laminar flow and heat transfer of pseudo-plastic non-Newtonian nanofluid (Al_2O_3 + CMC (0.5% wt)) within the porous circular concentric region is investigated numerically by using of finite volume method. The schematic of the problem in this study is shown in Fig. 1. The channel length $L = 3$ m, the outer diameter is $D_o = 5$ cm and inner diameter is $D_i = 4$ cm. The walls of the channel are under a constant flux of $q'' = 6000\ W/m^2$. The inlet temperature of the nanofluid is $T_{in} = 298$ K. Water and Al_2O_3 nanoparticles (particle diameter 20 nm) are in thermal equilibrium. The Reynolds and Darcy numbers ranges are $100 < Re < 300$ and $10^{-4} < Da < 10^{-2}$. The intended range for Al_2O_3 nanoparticles volume fraction has been selected by Hojjat et al. [33]. The minimum volume fraction considered in their paper was 0% and the maximum volume fraction was 1.5%. So, In this study the volume fraction of the nanoparticles is $\varphi = 1$–1.5% and the porous layer thickness range is $0 \geq R_p \geq 0.6$,

3. Governing equations

In this study, a single-phase model has been considered to analyze heat transfer and the flow of the non-Newtonian nanofluid within the porous circular concentric region. The resulting equations over the fluid flow include equations of conservation of mass, momentum and energy.

Continuity equation:

$$\rho_{nf}\left(\frac{1}{r}\left(\frac{\partial(ru_r)}{\partial r}\right)+\frac{1}{r}\left(\frac{\partial u_\theta}{\partial \theta}\right)+\left(\frac{\partial u_z}{\partial z}\right)\right)=0 \tag{1}$$

Momentum equations:

$$\rho_{nf}\left(u_r\frac{\partial u_r}{\partial r}+\frac{V_\theta}{r}\frac{\partial u_r}{\partial \theta}-\frac{u_\theta^2}{r}+u_z\frac{\partial u_r}{\partial z}\right) = -\frac{\partial P}{\partial r}+\eta\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial u_r}{\partial r}\right)-\frac{u_r}{r^2}+\frac{1}{r^2}\frac{\partial^2 u_r}{\partial \theta^2}-\frac{2}{r^2}\frac{\partial u_\theta}{\partial \theta}+\frac{\partial^2 u_r}{\partial z^2}\right]+S_r \tag{2}$$

$$\rho_{nf}\left(u_r\frac{\partial u_\theta}{\partial r}+\frac{u_\theta}{r}\frac{\partial u_\theta}{\partial \theta}+\frac{u_\theta u_r}{r}+u_z\frac{\partial u_\theta}{\partial z}\right) = -\frac{1}{r}\frac{\partial P}{\partial \theta}+\eta\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial u_\theta}{\partial r}\right)-\frac{u_\theta}{r^2}+\frac{1}{r^2}\frac{\partial^2 u_\theta}{\partial \theta^2}+\frac{2}{r^2}\frac{\partial u_r}{\partial \theta}+\frac{\partial^2 u_\theta}{\partial z^2}\right]+S_\theta \tag{3}$$

$$\rho_{nf}\left(u_r\frac{\partial u_z}{\partial r}+\frac{u_\theta}{r}\frac{\partial u_z}{\partial \theta}+u_z\frac{\partial u_z}{\partial z}\right) = -\frac{\partial P}{\partial z}+\eta\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial u_z}{\partial r}\right)+\frac{1}{r^2}\frac{\partial^2 u_z}{\partial \theta^2}+\frac{\partial^2 u_z}{\partial z^2}\right]+S_z \tag{4}$$