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Natural convection of CuO-water micropolar nanofluids inside a porous enclosure using local thermal non-equilibrium condition

Mohsen Izadi[a], S.A.M. Mehryan[b,*], Mikhail A. Sheremet[c]

[a] Mechanical Engineering Department, Faculty of Engineering, Lorestan University, Khorramabad, Iran
[b] Young Researchers and Elite Club, Yasooj Branch, Islamic Azad University, Yasooj, Iran
[c] Laboratory on Convective Heat and Mass Transfer, Tomsk State University, 634050 Tomsk, Russia

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ABSTRACT

The present paper deals with numerical investigation of natural convection of a micropolar nanofluid inside a porous enclosure using thermal non-equilibrium model. Rates of the heat transfer and micropolar nanofluid flow are widely considered by presenting contours of nanofluid flow, isotherms of fluid and solid phases, and contours of micro-rotation. Numerical results have been validated with previous references and good concordance has been observed. The results confirm that the thermal non-equilibrium model of the porous medium approaches the thermal equilibrium one by increasing thermal conductivity ratio parameter as well as the heat transfer interface parameter. The strength of convection inside pores of porous medium arises from augmenting H that can result in micro-rotations amplification. The characteristic equations of a micropolar fluid flow are transformed into classic Navier–Stokes equations by increasing porosity and the dimension of pores. Results indicate that the reduction of the thermal resistance of the fluid phase due to an increment of K_r can enhance the heat transfer rate through porous media. Finally, the permeability is important and influences the Nusselt numbers of both the solid matrix and the nanofluid when the nanofluid particles rotate around the center of their gravity.

1. Introduction

The micropolar fluid [1,2] is an improvement of Navier–Stokes theory, which transforms the classical continuum fluid mechanics to micro continuum by taking into account the effects of microrotation of fluid molecules. This approach represents those rigid-form molecules of micropolar fluids could physically spin independent of main stream and their local velocity. It seems that numerous discrepancy of experimental and numerical data arises from such micro structure effects. Therefore, micropolar theory uses from concept of vortices to describe flow characteristics. They represent a key physical mechanism related to suspensions, liquid crystal, biological fluid and nanofluids.

Hsu [3] numerically studied natural convection flow of a micropolar fluid in an enclosure. Also, numerical study of natural convection flow in an inclined cavity filled with micropolar fluids is another work of Hsu et al. [4]. Hsu and Hong [5] corroborated the research done by Aydin and Pop [6] that micropolar fluids presented lower heat transfer values than those of the Newtonian fluids. Also, Aydin and Pop [7] analyzed the steady laminar natural convective flow and heat transfer of micropolar fluids using a two-dimensional numerical simulation. Because of decreasing overall heat transfer, Zadravec et al. [8] showed that microrotation of particles in suspension should not be neglected when computing heat and fluid flow of micropolar fluids.

Recently, many studies have focused on the convection mechanism of micropolar fluid [9,10]. For example, Gibanov et al. [9] performed an analysis of natural convective flow inside of a cavity filled by a micropolar fluid. They stated that the microrotation and fluid velocity increase and decrease respectively while the vortex viscosity parameter increases. Also it was concluded that the form of streamlines is dependent on the value of vortex viscosity parameter. The study on laminar natural convective of micropolar fluid inside a trapezoidal cavity was numerically fulfilled by Gibanov et al. [10]. The authors considered the effects of Rayleigh number, Prandtl number and vortex viscosity parameter. The outcomes showed that an increase in the vortex viscosity parameter and the Prandtl number results in debilitation and intensification of the convective heat transfer and fluid flow, respectively. Saleem et al. [11] performed the study of transient natural convection associated with a micropolar fluid flow in a rectangular enclosure having a heated bottom wall and two cold vertical walls. They showed that

* Corresponding author.
E-mail addresses: izadi.m@lu.ac.ir (M. Izadi), michael-sher@yandex.ru (M.A. Sheremet).

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Nomenclature

c_p	specific heat (J/kg/K)
Da	Darcy number
g	gravitational acceleration (m/s^2)
H	Nield number
h_{nfs}	convection coefficient at the interface of solid and nanofluid phases (W/K/m^3)
j	micro-inertia density (m^2)
K	permeability of porous medium (m^2)
K_r	thermal conductivity ratio
k	thermal conductivity (W/m/K)
L	cavity size (m)
$\boldsymbol{N^*}$	dimensional microrotation vector (s^{-1})
$\boldsymbol{N}$	dimensionless microrotation vector
Nu	average Nusselt number
p^*	dimensional pressure (Pa)
Pr	Prandtl number
Q_{nf}	dimensionless overall heat transfer
Q_r	dimensionless overall heat transfer ratio
Ra	Rayleigh number
T^*	dimensional temperature (K)
$T_h{}^*$	dimensional hot wall temperature (K)
$T_c{}^*$	dimensional cold wall temperature (K)
T	dimensionless temperature
$\boldsymbol{V^*}$	dimensional velocity vector (m/s)
u^*, v^*	dimensional components of velocity in x^* and y^* directions, respectively
x^*, y^*	dimensional Cartesian coordinates (m)
x, *y*	dimensionless Cartesian coordinates

Greek symbols

α	thermal diffusivity (m^2/s)
β	thermal expansion coefficient (K^{-1})
Δ	vortex to molecular viscosity ratio
ε	porosity
κ	vortex viscosity (kg/m/s)
μ	dynamic viscosity (kg/m/s)
μ_r	dynamic viscosity ratio
ν	kinematic viscosity (m^2/s)
ρ	density (kg/m^3)
φ	nanoparticles volume fraction
ψ^*	dimensional stream function (m^2/s)
ψ	dimensionless stream function

Subscripts

c	cold
bf	base fluid
h	hot
nf	nanofluid
np	nanoparticles
r	relative
s	solid

Superscripts

*	dimensional variables

the heat transfer rate of non-Newtonian micropolar fluid is less than that of the Newtonian fluid. More studies on flow of micropolar fluid can be seen in works performed by Sheremet et al. [12], Miroshnichenko et al. [13].

As a new category of thermal fluids, for the first time, Choi and Eastman [14] presented concept of nanofluids which refer to the class of fluid with suspended nanoparticles made of different materials by chemical and physical processes. These new generation of fluids have attracted numerous interests in order to manifest their hydrodynamic and thermal performance. Lee et al. [15], Pak and Cho [16], Xuan and Li [17–20], Mehryan et al. [21,22], Izadi et al. [23–28] and Mohebbi et al. [29,30] have provided insights into the thermal behavior of nanofluid flows and have confirmed their superior improvement of thermal performance. The periodic natural convection in an enclosure filled with nanofluids was considered by Ghasemi and Aminossadati [31]. The results indicate that adding Cu nanoparticles into base fluid enhances the heat transfer especially at low Rayleigh numbers. Using two-phase mixture model, Toosi and Siavashi [32] considered natural convection of a nanofluid inside a square cavity filled with porous layer. They showed that optimal volume fraction and porous layer thickness could achieve maximize *Nu* for different values of *Ra* and *Da*. Yousaf and Usman [33] presented the numerical results of natural convection in a two-dimensional square cavity in the presence of roughness on vertical walls. It was shown when the sinusoidal roughness elements were located on both the hot and cold walls simultaneously the maximum reduction in the average heat transfer was 28%.

On the other hand, some researchers have shown a gap between the numerical and experimental findings of natural convection throughout nanofluid flows. It is possible that disagreement between numerical and experimental results could be due to neglecting the effect of microrotation in the Navier–Stokes theory. Therefore, a new model of nanofluids as micropolar fluid has been represented by authors. Bourantas and Loukopoulos [34] investigated the flow of MHD micropolar nanofluid of Al_2O_3-water driven by natural convection inside a tilted square cavity. Bourantas and Loukopoulos [35] theoretically modeled the natural convective flow of micropolar nanofluids. They stated that the microrotations in general reduce overall heat transfer from the heated wall and should not therefore be neglected. The theoretical model was validated by comparing with available experimental and theoretical data.

A porous medium is distinguished by a material consisting of a solid matrix and pore space. Later allows the flow of fluid through the solid matrix. Natural convection throughout porous medium has been applied in various problems including post-accident heat removal from pebble-bed nuclear reactors, high-performance building insulation, geothermal energy, multishield structures used in the insulation of nuclear reactors, solar power collector. The Darcy law was still used to express the relationship between the superficial velocities of flow with the pressure drop in porous media. Earlier researches manifest that the steady-state Darcy model is acceptable to predict flow through porous media, especially at low velocity values and porosity.

Many studies of convection heat transfer inside heated porous enclosures filled with a nanofluid have been considered [36–41]. Using a meshless technique, Bourantas et al. [36] numerically studied the convection of a nanofluid in a porous square cavity. The results confirm as the solid volume fraction increases, the average Nusselt number also enhances at the presence of a porous medium. However, in the present study flowing fluid and the porous medium are everywhere in local thermal non-equilibrium. Natural convection heat transfer in a three-dimensional porous enclosure filled with a nanofluid using the Buongiorno model has been investigated by Sheremet et al. [37]. Last recently, Mehryan et al. [42] numerically done the analysis related to heat transfer of free convection of Al_2O_3-Cu hybrid nanofluid in a porous square cavity. In this study, the experimental values of thermal conductivity and dynamic viscosity of the hybrid nanofluid were used.

In brief, although numerous researches have singly done on the natural convection of nanofluid, porous medium and micropolar fluids, only one study was reported on the natural convection of a micropolar nanofluid inside the porous medium which has completely modeled the governing equation [43]. In fact, before the