International Journal of Heat and Mass Transfer 79 (2014) 930–944

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

MHD natural-convection flow in an inclined square enclosure filled with a micropolar-nanofluid

G.C. Bourantas [a], V.C. Loukopoulos [b,*]

[a] MOSAIC Group, Max Planck Institute of Molecular Cell Biology and Genetics, Dresden, Germany
[b] Department of Physics, University of Patras, Patras, 26500 Rion, Greece

ARTICLE INFO

Article history:
Received 17 March 2014
Received in revised form 8 August 2014
Accepted 27 August 2014
Available online 19 September 2014

Keywords:
Micropolar
Nanofluids
Magnetohydrodynamics
Natural convection
Meshfree point collocation method

ABSTRACT

Transient, laminar, natural-convection flow of a micropolar-nanofluid (Al_2O_3/water) in the presence of a magnetic field in an inclined rectangular enclosure is considered. A meshless point collocation method utilizing a velocity-correction scheme has been developed. The governing equations in their velocity–vorticity formulation are solved numerically for various Rayleigh (*Ra*) and Hartman (*Ha*) numbers, different nanoparticles volume fractions (φ) and considering different inclination angles and magnetic field directions. The results show that, both, the strength and orientation of the magnetic field significantly affect the flow and temperature fields. For the cases considering herein, experimentally given forms of dynamic viscosity, thermal conductivity and electrical conductivity are utilized.

1. Introduction

Magnetohydrodynamic (MHD) flows, associated with heat transfer, have received considerable attention over the last decades since there is a growing interest of understanding the underlying physical processes occurring, that is natural convection under the influence of a magnetic field. This is due to their wide variety of application in engineering areas, such as crystal growth in liquid, cooling of nuclear reactor, electronic package, microelectronic devices, and solar technology. There has been an increasing interest to understand the flow behavior and the heat transfer mechanism of enclosures that are filled with electrically conducting fluids under the influence of a magnetic field [1–3]. For an electrically conducting fluid when the magnetic field is present, there are two body forces, a buoyancy force and a Lorentz force. These two forces interact with each other and influence the flow and heat transfer.

Numerical studies have been performed in order to evaluate the effect of the magnetic field on natural convection flow and heat transfer in cavities. Authors in [4] studied the steady state, laminar natural convection flow in the presence of a magnetic field, considering as a study case an inclined rectangular enclosure heated and cooled on adjacent walls. They stated that the magnetic field suppressed the convective flow and the heat transfer rate, while the orientation and the aspect ratio of the enclosure along with both the strength and direction of the magnetic field significantly affected the flow and temperature fields. Authors in [5] numerically studied natural convection occurring in a water filled square cavity under the influence of a magnetic field. They considered temperature dependent physical properties and they observed that both flow and temperature fields were affected by changing the reference temperature parameter when both thermal conductivity and viscosity were temperature dependent. Additionally, they stated that the heat transfer rate was influenced by the direction of the external magnetic field and decreased by an increase of the magnetic field. Authors in [6] conducted a numerical study concerning a magneto-convection flow in a cavity with partially active vertical walls. They found that the average Nusselt number decreases with an increase of Hartmann number (*Ha*), while it increases with the Rayleigh number (*Ra*). Authors in [7] considered the effect of the magnetic field on convection heat transfer inside a tilted square enclosure. Their study showed that the heat transfer mechanism and flow characteristics inside the enclosure depend strongly upon both magnetic field and inclination angle.

In applications where a significant amount of heat needs to be removed from a very small surface, the coolant should have more effective heat transfer characteristics. Due to technological achievements nanomaterials with size ranging from 1 to 100 nm, have been mainly used in the areas of heat transfer, electricity, magnetism and mechanics. These nanoscale particles, such as oxide ceramics, nitride ceramics, carbide ceramics, metals and

* Corresponding author.
E-mail addresses: bouranta@mpi-cbg.de (G.C. Bourantas), vxloukop@physics.upatras.gr (V.C. Loukopoulos).

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2014.08.075
0017-9310/

Nomenclature

C_p	specific heat at constant pressure (J kg^{-1} K^{-1})
$\mathbf{g}$	gravitational acceleration (m s^{-2})
Ra	Rayleigh number
L	length of the enclosure (m)
k	thermal conductivity (W m^{-1} K^{-1})
Nu	Nusselt number
p	pressure
Pr	Prandtl number
T	dimensional temperature (°C)
u,v	dimensional velocity (m s^{-1})
U,V	dimensionless velocity components
x,y	dimensional coordinates (m)
X,Y	dimensionless coordinates

Greek symbols

α	thermal diffusivity (m^2 s^{-1})
β	thermal expansion coefficient (K^{-1})
θ	dimensionless temperature
μ	dimensionless thermal conductivity
ρ	density (kg m^{-3})
φ	relative nanoparticle volumetric fraction
ω	dimensional vorticity (s^{-1})
Ω	dimensionless vorticity
γ	angle of inclination of the enclosure from the horizontal axis
ξ	angle of orientation of the magnetic field
τ	dimensionless time

Subscripts

avg	average
C	cold
H	hot
F	base fluid
P	particle
nf	nanofluid

semiconductors, when suspended in a base fluid such as water, ethylene, glycol, engine oil or refrigerant form the so-called nanofluids [8]. In the numerical studies for natural convective heat transfer of nanofluids conducted by several researchers, nanofluids were treated as a single-phase fluid and conventional equations of mass, momentum and energy were solved. Authors in [9] studied natural convection of Cu-water nanofluid in a two-dimensional enclosure assuming uniform volume fraction. The mass and momentum equations were solved in their stream function-vorticity formulation and it was stated that Nusselt number increases with an increase of the volume fraction of the nanoparticles. In [10] a study of natural convection in horizontal annuli using different nanofluids took place and showed that the heat transfer is enhanced by using nanofluids. In fact the Nusselt number increases with increasing nanoparticles volume fraction. In Oztop and Abu-Nada [11] authors studied the natural convection of a nanofluid being in a partially heated enclosures considering different aspect ratios. They found that the heat transfer was more pronounced at low aspect ratio and high volume fraction of nanoparticles. Aminossadati and Ghasemi [12] considered the effect of apex angle, position and dimension of heat source on fluid flow and heat transfer in a triangular enclosure using nanofluid. They found that at low Rayleigh numbers, the heat transfer rate continuously increases with the enclosure apex angle and decreases with the distance of the heat source from the left vertex.

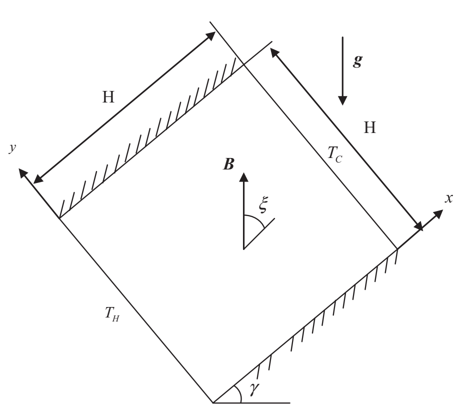

Fig. 1. Geometry and coordinate system.

Most of the studies which focus on the natural convection in enclosures with magnetic effects have considered an electrically conducting fluid with low thermal conductivity. This limits the enhancement of heat transfer in the enclosure especially when a magnetic field is applied. There are several studies dealing with the nanofluids heat transfer that state totally different findings. Most researchers argue that the addition of nanoparticles with relatively higher thermal conductivity to the base fluid results in an increase of the thermal performance of the resultant nanofluid [13–15]. On the other hand, some researchers argue that the dispersion of nanoparticles in the base fluid may result in a decrease of the heat transfer [16]. The numerical studies and experimental findings in the case of natural convection in enclosures are controversial. Therefore, it is possible that the assumptions made in the theoretical models lead to false outcomes. The enhancement or mitigation of the heat transfer of nanofluids may be because of the formulae used for their thermal properties. A comprehensive nanofluid simulation study should take account of the structure, shape, size, aggregation and anisotropy of the nanoparticles as well as the type, fabrication process, particle aggregation and deterioration of nanofluids. A fluid theory that potential can bridge the gap between the numerical and experimental finding is the micropolar flow theory. Micropolar fluids, introduced by Eringen [17], take into account the microstructure of the fluid along with the inertial characteristics of the substructure particles, which are allowed to undergo rotation. In such way nanofluids can be considered as a fluid medium whose properties and behavior are strongly influenced by the local motions of the material particles contained in each of its volume elements.

In the present paper we incorporate the micropolar flow theory to study the natural convection of an electrically conducted nanofluid in a square cavity subjected to a magnetic field. The work in

Table 1
Thermo-physical properties of water and nanoparticles.

	ρ(kgr/m^3)	C_p(J/kgrK)	k(W/mK)	$\beta \times 10^{-5}$(K^{-1})
Pure Water	997.1	4179	0.613	21
Alumina (Al_2O_3)	3970	765	40	0.85