



Magnetohydrodynamic in partially heated square cavity with variable properties: Discrepancy in experimental and theoretical conductivity correlations



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ABSTRACT

Natural convection nanofluid heat transfer enhancement in a partially heated cavity is considered under the effect of an external Lorentz force exerted through interaction of the nanoparticles and the applied constant magnetic field. The aluminum oxide (Al_2O_3 or alumina) nanofluid is considered to be with variable properties (i.e. thermal conductivity, viscosity and electric conductivity) and the cavity is partially heated from its left top corner. The effect of the inclination angle of the applied magnetic field is studied and analyzed. The Nusselt number is calculated at the heater to probe the heat transfer enhancement. Both effective thermal and electric conductivities have been investigated in their respective theoretical and experimental correlations. Numerical experiments are presented to show the discrepancy in heat transfer with the use of such correlations. A substantial difference in the heat transfer is noticed for the use of different correlations. An adverse effect is identified and analyzed with the increase of Hartmann number, the nanoparticle volume fraction, and the position of the heater within the cavity.

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1. Introduction

Natural convection in enclosures is encountered in many applications including chemical reactors, heat exchangers, nuclear reactor cooling, electronics cooling, solar energy applications, and phase changes processes [1–3]. Researchers are continually searching for innovative techniques to enhance the heat transfer in natural convection applications. For example, magnetohydrodynamics (MHD) has been used extensively during the last decades to control the heat transfer rates generated in natural convection. Ghassemi et al. [4] investigated effect of magnetic field on natural convection in enclosure with two isolated baffles. They found that the magnetic field significantly has an inversely impact on heat transfer within the cavity and the effect was more severe at low Rayleigh numbers. Sathiyamoorthy and Chamkha [5] analyzed natural convection of electrically conducting liquid gallium in a square cavity and they reported a sensitivity of the heat transfer to the direction of the applied magnetic field for moderate values of Hartmann number. Pirmohammadi and Ghassemi [6] investigated the effect

of magnetic field on natural convection heat transfer inside a tilted enclosure and showed that the heat transfer depends significantly on magnetic field and inclination angle. Revnic et al. [7] examined the effects of an inclined magnetic field and heat generation on unsteady free convection within a square cavity filled with a fluid-saturated porous medium. They found that for a fixed value of the Rayleigh number, the average Nusselt number decreases to the steady case when the Hartmann number is increased. Likewise, other studies considered MHD on natural convection are found elsewhere [8–15].

On the other hand, researchers recently investigated the impact of nanofluids on heat transfer enhancement in natural convection applications (see [16–23] and the references therein). Nanofluids have emerged as a promising fluids in enhancing the intrinsic thermophysical properties of heat transfer fluids (HTF) by suspension of nanoparticles in the base fluid [16,17]. However, the role of nanoparticles in enhancing the heat transfer in natural convection, in the absence of MHD, is still a debate where there is inconsistency between theoretical predictions and experimental findings [18–22]. For example, Abu-Nada et al. [22], Abu-Nada [23] related such discrepancies to the use of classical models for nanofluids thermophysical properties (such as Brinkman model for viscosity and Maxwell–Garnett model for thermal conductivity), which are

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Nomenclature*Roman letters*

$\vec{B}$	uniform magnetic field ($\text{N m}^{-1} \text{A}^{-1}$)
B	magnitude of magnetic field ($\text{N m}^{-1} \text{A}^{-1}$)
B_x, B_y	components of magnetic field along x - and y -axis ($\text{N m}^{-1} \text{A}^{-1}$)
C	nanoparticles concentration
C_0	initial nanoparticles concentration
c_p	specific heat at constant pressure ($\text{J kg}^{-1} \text{K}^{-1}$)
D_B	dimensional Brownian diffusion coefficient ($\text{m}^2 \text{s}^{-1}$)
D_B	dimensionless Brownian diffusion coefficient
D_T	dimensional thermophoretic diffusion coefficient ($\text{m}^2 \text{s}^{-1}$)
D_T	dimensionless thermophoretic diffusion coefficient
d_p	nanoparticle diameter (m)
$\vec{e}_x, \vec{e}_y$	unit vectors in the Cartesian coordinate system
$\vec{F}$	magnetic Lorentz force (N)
$\vec{g}$	gravitational acceleration vector (m s^{-2})
H	length and height of the cavity (m)
Ha	Hartmann number
$\vec{J}$	electric current (A)
K	dimensionless thermal conductivity
k	dimensional thermal conductivity ($\text{W m}^{-1} \text{K}^{-1}$)
Le	Lewis number
M	dimensionless dynamic viscosity
Nt	thermophoresis parameter
Nu	local Nusselt number
$\bar{Nu}$	average Nusselt number
$\bar{p}$	dimensional pressure (Pa)
Pr	Prandtl number
Ra	Rayleigh number
Re	Reynolds number
T	dimensional temperature (K)
t	dimensional time (s)
T_c	low temperature (K)

T_h	high temperature (K)
u, v	dimensionless velocity components
$\bar{u}, \bar{v}$	dimensional velocity components (m s^{-1})
$\vec{V}$	dimensional velocity (m s^{-1})
x, y	dimensionless Cartesian coordinates
$\bar{x}, \bar{y}$	dimensional Cartesian coordinates (m)

Greek symbols

α	thermal diffusivity ($\text{W m}^{-2} \text{K}^{-1}$)
β	thermal expansion coefficient (K^{-1})
γ	magnetic field inclination angle
Δ'	dimensional length of a heater section along x -axis (m)
Δ	dimensionless length of a heater section along x -axis
θ	dimensionless temperature
$\bar{\mu}$	dimensional dynamic viscosity (Pa s)
ρ	density (kg m^{-3})
ρc_p	heat capacitance ($\text{J m}^{-3} \text{K}^{-1}$)
$\rho \beta$	buoyancy coefficient ($\text{kg m}^{-3} \text{K}^{-1}$)
Σ	dimensionless electrical conductivity
σ	dimensional electrical conductivity ($\Omega^{-1} \text{m}^{-1}$)
τ	dimensionless time
ϕ	nanoparticles volume fraction
ψ	dimensionless stream function
ω	dimensionless vorticity

Subscripts

c	cold
f	fluid
h	hot
$\max$	maximum value
nf	nanofluid
p	(nano) particle

shown to underestimate the viscosity and thermal conductivity of nanofluids. This reveals the importance of using robust and accurate models for nanofluid thermophysical properties estimation.

The combination of nanofluids and MHD on natural convection has also recently attracted many researchers [24–37] without being exhaustive. For example, Sheikholeslami et al. [27], investigated heat flux boundary condition for nanofluid filled enclosure in presence of magnetic field and reported a inversely relation of heat transfer in the enclosure with Hartmann number and an enhancement in heat transfer due to the addition of nanoparticles. More recently, Sheremet et al. [28] studied MHD free convection in a wavy open porous cavity filled with nanofluids. They reported a reduction in heat transfer with Hartmann number and the magnetic field inclination angle affects non-monotonically the heat transfer rate. Kefayati [29] studied the effect of MHD on natural convection in an open enclosure which subjugated to water- Al_2O_3 nanofluid and showed that the heat transfer is inversely proportional to Hartmann number for various volume fractions of nanoparticles. Mejri and Mahmoudi [30] investigated natural convection in an open enclosure filled with a water- Al_2O_3 nanofluid using Lattice Boltzmann method (LBM). Bondareva et al. [31] studied transient MHD natural convection of nanofluid in a trapezoidal enclosure using a two-phase nanofluid model. Other studies on MHD in nanofluids are also found elsewhere [32–37] and references therein.

Based on the literature search presented above, all of MHD studies on nanofluids are using theoretical correlations for electrical conductivity for nanofluids. The most adopted theoretical

model to estimates the electrical conductivity of nanofluid is the MG model. Most recently, measurements of electrical conductivity of nanofluids revealed that the experimental measured values of electrical conductivity of nanofluid are much higher than those estimated from theoretical models [38–40]. Actually, the ratio between the electrical conductivity measurements and theoretical predictions is in the order of hundreds. Such huge difference cannot be neglected in any robust numerical simulation of MHD in nanofluids.

Therefore, the main scope of this work is to use a more robust electrical conductivity model for a nanofluid in MHD natural convection flow and to estimate the discrepancies between theoretical predictions and experimental electrical conductivity correlations on heat transfer. In addition to electrical conductivity, the current work will employ consistently robust models for thermal conductivity and viscosity of the nanofluid based on experimental correlations, which means that the current model uses more realistic experimental correlations for the main thermo-visco-electrical properties of the nanofluid (electrical conductivity, thermal conductivity, and viscosity of the nanofluid). Furthermore, a two-phase nonhomogeneous model is used to account for Brownian motion and thermophoresis mechanisms of heat transfer within nanofluids. Besides, thermo-visco-electrical properties of the nanofluids are considered dual function of temperature and volume fraction of nanoparticles. The streamlines, isotherms, nanoparticles volume fraction distribution within the enclosure as well as distributions of average Nusselt number are demonstrated for different values of governing non-dimensional param-

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