Advanced Powder Technology 26 (2015) 224–235

Contents lists available at ScienceDirect

Advanced Powder Technology

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

Original Research Paper

Effects of nanoparticles diameter and concentration on natural convection of the Al_2O_3–water nanofluids considering variable thermal conductivity around a vertical cone in porous media

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ARTICLE INFO

Article history:
Received 30 July 2014
Received in revised form 22 September 2014
Accepted 1 October 2014
Available online 17 October 2014

Keywords:
Nanofluid
Variable viscosity
Variable thermal conductivity
Drift-flux model
Homogeneous model

ABSTRACT

The effects of nanoparticles diameter and concentration on natural convection heat transfer of a nanofluid around a vertical cone embedded in a Darcy porous medium is theoretically investigated utilizing the drift-flux model. The thermal conductivity and the viscosity of the nanofluid are assumed as simultaneous functions of temperature and local volume fraction of nanoparticles using experimental correlations. In addition, the flux of nanoparticles on the surface of the cone is assumed to be zero. An efficient mathematical approach with a self-similar solution is utilized to theoretically analyze the boundary layer heat and mass transfer of an Al_2O_3–water nanofluid. The reduced system of ordinary differential equations are general and can be solved for any arbitrary functions of thermal conductivity and viscosity. The analysis of the nanofluid natural convection flow is accomplished for two cases of (i) $T_w > T_\infty$ and (ii) $T_w < T_\infty$. The results show that using nanoparticles would not (would) enhance the heat transfer from the cone for the case of a cone with a hot surface (cold surface). A decrease in the size of nanoparticles or an increase in the volume fraction of nanoparticles causes a decline in the heat transfer rate from the cone when the cone surface is hot. Finally, a comparison between the non-homogenous model (drift-flux model) and the homogenous model of nanofluids is performed. The results demonstrate that the drift-flux model tends to the homogeneous model as the size and volume fraction of nanoparticles increase.

1. Introduction

Natural convection flow and heat transfer over embedded bodies in porous media has various engineering applications such as thermal energy storage, groundwater systems, flow through filtering media, and crude oil extraction [1]. Such versatile applications have attracted extensive research on natural convection phenomena over embedded bodies within porous media.

Nanofluids are widely used in various thermal systems to boost the heat transfer rate and the thermal efficiency. Nanofluids have been employed in different fields of thermal engineering such as heat exchangers, nuclear reactors, and cooling of electronic devices [2]. Utilizing nanofluids as the working fluid may enhance the heat transfer because of the enhancement in the thermal conductivity. However, other thermo-physical properties also may affect the enhancement of heat transfer of nanofluids. Some of these factors are the thermal conductivity, viscosity, density, heat capacity, dispersion and amorphous movement of nanoparticles, Brownian motion, and thermophoresis effects.

There are two known models for theoretical study of convective heat transfer of nanofluids: (i) homogeneous models and (ii) non-homogeneous models. In the homogeneous models, the nanofluid is uniform with no slip between the base fluid and nanoparticles. In the non-homogeneous models, the slip between nanoparticles and the base fluid is accounted for, and hence, the nanofluid would not be a uniform mixture of nanoparticles with a base fluid. Many researchers believe that the migration of nanoparticles within the base fluid is the significant reason behind the heat transfer enhancement of nanofluids. The migration of nanoparticles in the base fluid would transfer energy in the base fluid. Using scale analysis, Buongiorno [3] discussed seven possible mechanisms for drift flux of particles during convection of nanofluids. These are inertia, Brownian diffusion, thermophoresis, diffusion phoresis, Magnus effect, fluid

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http://dx.doi.org/10.1016/j.apt.2014.10.001
0921-8831/

Nomenclature

C	a constant
Cp	specific heat (J/kg K)
D_B	Brownian diffusion coefficient (m^2/s)
d_p	diameter of nanoparticle (m)
D_T	thermophoretic diffusion coefficient (m^2/s)
f	rescaled nanoparticles volume fraction, nanoparticles concentration
g	gravitational acceleration vector (m/s^2)
h	convective heat transfer coefficient
k	thermal conductivity (W/m K)
k_B	Boltzmann's constant (1.3807×10^{-23} J/K)
Le	Lewis number
Nb	Brownian motion parameter
Nr	buoyancy ratio
Nt	thermophoresis parameter
Nu	Nusselt number
P	pressure (Pa)
q_w	surface heat flux
Ra_x	local Rayleigh number
r	local radius of the cone
S	dimensionless stream function
T	temperature (K)
u, v	Darcy velocity components (m/s)
(x, y)	Cartesian coordinates

Greek symbols

(ρc)	heat capacity (J/m^3 K)
μ	viscosity (Pa s)
α	thermal diffusivity (m^2/s)
β	volumetric expansion coefficient of fluid (1/K)
ε	porosity
γ	cone half-angle
η	dimensionless distance
θ	dimensionless temperature
κ	permeability of porous medium (m^2)
ρ	fluid density (kg/m^3)
ϕ	nanoparticles volume fraction
ψ	stream function

Subscripts

∞	ambient
eff	effective property between porous medium and nanofluid
f	the base fluid
nf	nanofluid
p	nanoparticles
s	porous medium
w	wall

drainage, and gravity. However, only the thermophoresis and the Brownian diffusion effects were found to be important [3,4].

Nield and Kuznetsov [5] have extended the work of Buongiorno [3] to the heat transfer of nanofluids in porous media. They have analyzed the natural convection flow of nanofluids over an isothermal flat plate taking into account the Brownian motion and thermophoresis effects. They [5] found that the reduced Nusselt number is a decreasing function of the Brownian motion and thermophoresis parameters. Yih [6] numerically explored the effect of uniform lateral mass flux on natural convection around a cone embedded in a saturated porous medium using a similarity solution. Recently, Rashad et al. [7] have extended work of Yih [6] to the natural convection flow of nanofluids. They [7] have analyzed the heat transfer associated via migration of nanoparticles. They found that as the thermophoresis, Brownian motion and buoyancy ratio parameters increase, the reduced Nusselt number decreases. Natural convective boundary layer flow of a nanofluid over a horizontal plate embedded in a saturated porous medium has been examined by Gorla and Chamkha [8]. Chamkha et al. [9] presented a non-similar solution for natural convective boundary layer flow over a sphere embedded in a nanofluid-saturated porous medium. Rana et al. [10] analyzed the boundary layer heat transfer of nanofluids over an inclined plate embedded in a porous medium. In a recent work, Noghrehabadi et al. [11] have investigated non-Darcy flow and natural convection of nanofluids over a vertical cone embedded in a porous medium. They [11] have reported that the reduced Nusselt number decreases with an increase in the non-Darcy parameter. Noghrehabadi et al. [12] have studied natural convection heat and mass transfer of nanofluids over a vertical plate embedded in a porous medium by applying surface heat and nanoparticle fluxes as boundary conditions. Furthermore, Noghrehabadi and Behseresht [13] analyzed the flow and heat transfer of nanofluid over a cone placed in porous media. Considering the viscosity and thermal conductivity of nanofluids as a linear function of local volume fraction of nanoparticles, they studied the effect of variable properties on the flow and heat transfer of a nanofluid. The important outcome has shown that the reduced Nusselt number would increase with increase of viscosity parameter and decrease with an increase of thermal conductivity parameter [13]. In addition, Gorla et al. [14] have recently studied the nanofluid flow boundary layer for the natural convection over a non-dimensional vertical cone in a porous medium.

In the mentioned works [7–12], the effects of temperature and local volume concentration of nanoparticles on the thermal conductivity and viscosity of nanofluids were neglected. However, experiments demonstrate that the thermal conductivity and the dynamic viscosity of nanofluids strongly depend on both of the volume fraction of nanoparticles and temperature [4,15,16]. Indeed, although the effect of temperature on the thermal conductivity and the dynamic viscosity of conventional pure fluids can be neglected for small temperature differences, these effects cannot be neglected for nanofluids owing to the presence of nanoparticles [15]. Therefore, in the present study, experimental correlations as simultaneous functions of temperature and local volume fraction of nanoparticles are adopted to include the local effect of temperature and volume fraction of nanoparticles on the thermal conductivity and the dynamic viscosity of an Al_2O_3–water nanofluid.

Previous studies [7–12] have approximated the volume fraction of nanoparticles on the surface to be constant, but this constant is unknown and no effort was made to calculate it. Accomplishing a case study, however, requires the exact value of nanoparticles volume fraction on the surface. Furthermore, an approximation of constant value of nanoparticles volume fraction on the surface generally implies a non-zero value of particles mass flux at the surface. This is an unrealistic assumption since the particles cannot cross the surface. Hence, assuming a zero particle mass flux through the surface as a boundary condition makes a more physical sense.

In this paper, a zero particle flux through the cone surface is utilized as a new auxiliary boundary condition. Furthermore, using similarity variables, the governing partial differential equations are converted into a set of ordinary differential equations. A case study for an Al_2O_3–water nanofluid, as a typical nanofluid, is conducted. The experimental correlations in the literature are then used to evaluate the local values of the dynamic viscosity and the thermal conductivity. Moreover, the nanoparticles volume fraction at the cone surface is also evaluated.