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Short communication

Natural-convection heat and mass transfer from a vertical cone in porous media filled with nanofluids using the practical ranges of nanofluids thermo-physical properties

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ABSTRACT

The present study aims to analyze the effects of Brownian motion and thermophoresis forces on the natural convection heat transfer of nanofluids around a vertical cone placed in a saturated porous medium. The range of non-dimensional parameters and the definition of two important parameters of heat and mass transfer are discussed. The results show that the range of Lewis number as well as Brownian motion and thermophoresis parameters and also the definition of the reduced Nusselt and Sherwood numbers, used in the previous analyses, should be reconsidered. In the present study, reasonable definitions of reduced Nusselt and Sherwood numbers have been proposed and discussed in details. In contrast with previous researches, the present results show that the heat transfer associated with migration of nanoparticles is negligible compared with heat conduction and convection mechanisms.

Keywords: Natural convection; Porous media; Nanofluids; Brownian motion; Thermophoresis; Similarity solution

1. Introduction

Convective flow in porous media has a wide range of engineering applications, such as solar energy collectors, heat exchangers, geothermal and hydrocarbon recovery (Nield and Bejan, 2013; Vadasz, 2008; Gorla et al., 2011).

Nanofluids are produced by suspending nanoparticles, metallic or nonmetallic particles with the size of nanometers, in conventional heat transfer fluids such as water, oil, and ethylene glycol (Das et al., 2007). The thermal conductivity of conventional heat transfer fluids is low. However, presence of solid nanoparticles can enhance the thermal conductivity of base fluids (Ismay et al., 2013). The thermal conductivity and viscosity of seven nanofluids have been extensively examined by Buongiorno et al. (2009) and Venerus et al. (2010) in different laboratories. It is found that two of seven nanofluids showed shear-thinning behavior; the remaining five showed Newtonian behavior. Buongiorno (2006) has developed an analytical model for convective transport in nanofluids in which Brownian motion and thermophoresis effects are taken into account. Recently, Nield and Kuznetsov (2009) have used the Boungiorno's model (Buongiorno, 2006) to simulate the natural convection flow of nanofluids. Nield and Kuznetsov have examined the effect of nanoparticles on the natural convection boundary-layer flow past a vertical plate.

Very recently, Rashad et al. (2011) have investigated the natural convection boundary layer of a nanofluid about a permeable vertical full cone embedded in a saturated porous medium. Moreover, natural convective boundary layer flow over a horizontal plate embedded in porous media saturated with a nanofluid was investigated by Gorla and Chamkha (2011). In previous researches (Nield and Kuznetsov, 2009; Rashad et al., 2011; Gorla and Chamkha, 2011; Noghrehabadi et al., 2013a,b), the appropriate range of Brownian motion parameter, thermophoresis parameter, buoyancy ratio

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Nomenclature

D_B	Brownian diffusion coefficient (m^2/s)
D_T	thermophoretic diffusion coefficient (m^2/s)
f	rescaled nanoparticle volume fraction, nanoparticle concentration
g	gravitational acceleration vector (m/s^2)
κ	permeability of porous medium (m^2)
k	thermal conductivity (W/m K)
k_m	effective thermal conductivity of the porous medium (W/m K)
Le	Lewis number
Nb	Brownian motion parameter
Nr	buoyancy ratio
Nt	thermophoresis parameter
P	pressure (Pa)
Ra_x	local Rayleigh number
S	dimensionless stream function
T	temperature (K)
T_∞	ambient temperature (K)
T_W	wall temperature of the vertical cone (K)
U	reference velocity (m/s)
u, v	Darcy velocity components (m/s)
(x, y)	Cartesian coordinates (m)

Greek symbols

$(\rho c)_f$	heat capacity of the fluid (kg/m^3 K)
$(\rho c)_m$	effective heat capacity of porous medium (kg/m^3 K)
$(\rho c)_p$	effective heat capacity of nanoparticle material (kg/m^3 K)
μ	viscosity of fluid (Pa s)
α_m	thermal diffusivity of porous media (m^2/s)
β	volumetric expansion coefficient of fluid (1/K)
γ	cone half-angle (rad)
ε	porosity
η	dimensionless distance
θ	dimensionless temperature
ρ_f	fluid density (kg/m^3)
ρ_p	nanoparticle mass density (kg/m^3)
τ	parameter defined by Eq. (5)
φ	nanoparticle volume fraction
φ_∞	ambient nanoparticle volume fraction
φ_w	nanoparticle volume fraction at the cone surface
ψ	stream function

parameter and Lewis number have not been fully discussed. In addition, the effect of mass transfer on the reduced Nusselt number and the effect of temperature gradient on the reduced Sherwood number have not been taken into account.

In the present study, the influence of practical range of nanofluid parameters on the natural convection flow about a vertical cone placed in a saturated porous medium is analyzed. In addition, the practical range of non-dimensional nanofluid parameters and the reasonable definition of reduced Nusselt and Sherwood numbers are discussed.

2. Mathematical model

Consider a two-dimensional natural convection flow of a nanofluid about a vertical isothermal cone placed in a Darcy porous medium, in which the flow is incompressible and steady-state. It is assumed that the temperature and nanoparticle volume fraction (φ) at the cone surface ($y = 0$) have a fixed value of T_w and φ_w, respectively. The ambient values of T and φ, as y tends to infinity, are denoted by T_∞ and φ_∞, respectively.

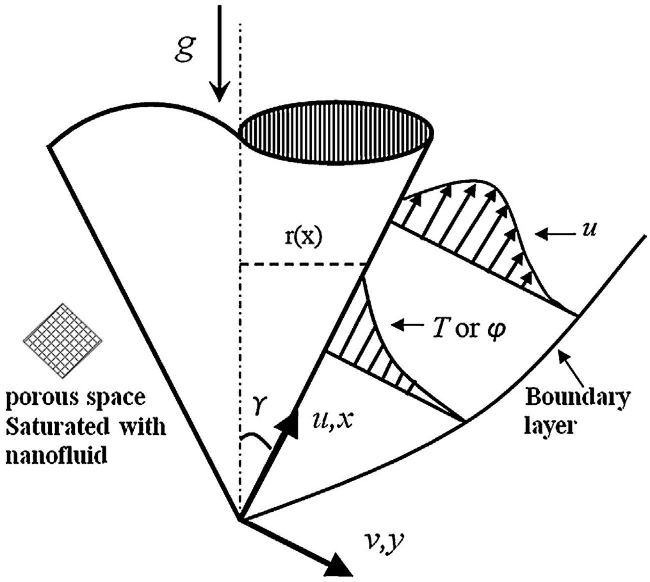

Fig. 1 – Schematic view and the coordinate system utilized to model the boundary layer configuration.

It has been demonstrated that the Brownian motion and thermophoresis forces induce slip velocities relative to the base fluid molecules (Buongiorno, 2006). Therefore, the concentration of nanoparticles in the convective heat transfer of nanofluids may not remain homogeneous. The thermophoresis force tends to move the particles in the direction opposite to the temperature gradient, and in contrast, the Brownian motion force tends to move the particles from high concentration to low concentration areas and homogeneous the fluid. As there is the temperature gradient in the boundary layer, the thermophoresis and Brownian motion forces appear, and hence, there is a boundary layer for concentration of nanoparticles.

The coordinate system is chosen such that x-axis is aligned with the flow on the cone surface. The physical model and coordinate system are shown in Fig. 1. There are three distinct boundary layers which are hydrodynamic boundary layer, thermal boundary layer and nanoparticle concentration boundary layer. It is worth noticing that the presence of hydrodynamic boundary layers is because of the thermal boundary layer. The thermal boundary layer induces the density difference in the fluid, and hence, the hydraulic boundary layer appears. Indeed, the presence of the hydraulic boundary layer is not because of the no-slip boundary condition or development of shear stresses due to the wall effects; it is because of the buoyancy forces. In addition, as the flow is buoyancy driven, and the practical temperature difference in the nanofluids is limited, the velocities are sufficiently low; hence the surface drag forces (Darcy term) are dominant, and they are in balance with the buoyancy forces. Therefore, in the present study, the flow in the porous medium with porosity ε and permeability κ is considered as Darcy flow, and the Oberbeck–Boussinesq approximation is applied.

Using the standard boundary layer approximations, the steady-state conservation of total mass, momentum and