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ORIGINAL ARTICLE

Effect of thermal radiation on mixed convection of a nanofluid from an inclined wavy surface embedded in a non-Darcy porous medium with wall heat flux

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Abstract This article focuses on the effect of radiation on mixed convection in a nanofluid along an inclined wavy surface embedded in a non-Darcy porous medium. A coordinate transformation is employed to transform the complex wavy surface to a smooth surface. The governing equations are transformed into a set of partial differential equations using the non-similarity transformation and then a local similarity and non-similarity method is applied to obtain coupled ordinary differential equations. These resulting equations are linearized using the successive linearization method and then solved by the Chebyshev spectral method. The effects of radiation, non-Darcy parameter, Brownian motion parameter, thermophoresis parameter, the amplitude of the wavy surface, angle of inclination of the wavy surface on the non-dimensional heat and nanoparticle mass transfer rates are studied and presented graphically.

1. Introduction

Suspensions of nanometer sized particles into the conventional heat transfer fluids is referred to as nanofluids which was pioneered by Choi [1]. It has been shown experimentally [2–5] that nanofluids can have anomalously

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higher thermal conductivities compared to that of the base fluid. The main goal of nanofluids is to achieve the highest possible thermal properties at the smallest possible concentrations (preferably $<$ 1% by volume) by uniform dispersion and stable suspension of nanoparticles (preferably <10 nm) in the conventional liquids. To achieve this goal it is important to understand how nanoparticles enhance energy transport in liquids. The nanoparticles suspended in a conventional liquid are in random motion under the influence of several acting forces, such as the Brownian force. This random motion of the suspended nanoparticles strengthens energy transport inside the liquid. Nanofluids have several engineering applications in microelectronics, microfluidics, transportation, biomedical, solid-state lighting, manufacturing, high-power X-rays, scientific measurement, material processing, medicine and material synthesis. The detailed review on nanofluids can be found in the book by Das et al. [6].

The mixed convective heat transfer is considered as an important phenomenon in engineering systems owing to its wide applications in electronics cooling, heat exchangers, double pane windows, solar energy collectors, geothermal and hydrocarbon recovery. A review of convective heat transfer in porous medium is presented in the book by Nield and Bejan [7]. Thermal Radiation on convective heat and mass transfer has received much attention for the last several decades due to its wide range of applications involving high temperatures such as nuclear power plant, gas turbines missiles, satellites, space vehicles and aircraft etc. Chen and Yang [8] studied the effects of thermal radiation on laminar forced and free convection along a wavy surface. Chamkha et al. [9] presented the non-similar solution of steady mixed convection of a nanofluid in the presence of thermal radiation. Hady et al. [10] studied the effect of radiation on viscous flow of a nanofluid and heat transfer over a non-linearly stretching sheet. Rahman [11] numerically investigated the problem of thermal radiation on unsteady magnetohydrodynamic (MHD) flow of a nanofluid in stretching porous medium. Akbar et al. [12] analysed the effect of thermal radiation on the MHD stagnation point flow of nanofluid towards a stretching surface with convective boundary condition. Agha et al. [13] studied the influence of thermal radiation on natural convection boundary layer flow for heat and mass transfer in a porous medium saturated with a nanofluid past a semi-infinite vertical plate, via a model in which Brownian motion and thermophoresis are taken into account.

The study of heat and mass transfer from irregular surfaces is often encountered in many engineering applications to enhance heat transfer such as micro-electronic devices, flat-plate solar collectors and flat-plate condensers in refrigerators, and geophysical applications (e.g., flows in the earth's crust), underground cable systems, electric machinery, cooling system of micro-electronic devices, etc. Moreover, roughened surfaces could be used in the cooling of electrical and nuclear components where the wall heat flux is known. The presence of roughness elements disturbs the flow past a flat surface and alters the heat transfer rate. Tashtoush and Al-Odat [14] used finite difference method to investigate the effect of magnetic field on forced convection heat and fluid flow along a wavy surface with prescribed heat flux and found that the magnetic parameter has a significant effect on velocity flow field and temperature gradient. Molla et al. [15] studied the natural convection boundary layer flow along a vertical complex wavy surface with uniform surface heat flux. Rahman et al. [16] employed implicit finite difference method to study the natural convection flow along a vertical wavy cone with uniform surface heat flux. They have shown that the thickness of thermal boundary layer increased almost twice with the variation of viscosity variation parameter from 0.0 to 1.0. Neagu [17] reported the analysis of the natural convective heat and mass transfer induced by a constant heat and mass fluxes along a vertical wavy wall in a non-Darcy double stratified porous medium. Mahdy and Ahmed [18] analyzed the problem of laminar free convection over a vertical wavy surface embedded in a porous medium saturated with a nanofluid. Ahmed and Abd El-Aziz [19] studied the effect of local thermal non-equilibrium on unsteady heat transfer by natural convection of a nanofluid over a vertical wavy surface. Recently, Srinivasacharya and Kumar [20] used successive linearization method to studied the effect of radiation on natural convective boundary layer flow over an inclined wavy surface embedded in a non-Darcy porous medium saturated with nanofluid. They have seen that the temperature and local heat transfer increases with increasing values of the radiation parameter.

The preceding literature reveals that the problem of radiation effect on free convection of nanofluid along an inclined wavy surface embedded in a non-Darcy porous medium with uniform surface heat and nanoparticle fluxes has not been considered so far. The present study mainly focused on exploring the effects of radiation, non-Darcy parameter, Brownian motion, thermophoresis, amplitude and angle of inclination of the wavy plate on mixed convection in non-Darcy porous medium saturated with nanofluid.

2. Mathematical formulation

Consider the steady laminar incompressible two-dimensional boundary layer mixed convection flow along a semi-infinite inclined wavy surface embedded in a nanofluid saturated non-Darcy porous medium. The wavy plate is inclined at an angle A $(0^\circ \leq A \leq 90^\circ)$ to the horizontal. The inclination angle is 0° (for horizontal plate), 90° (for vertical plate) and $0^\circ < A < 90^\circ$ (for inclined plate). The coordinate system is shown in Figure 1. The wavy surface is described by

$$y = \delta(x) = a \sin(\pi x / l)$$

where a is the amplitude of the wavy surface, and $2l$ is the characteristic length of the wavy surface. The wavy surface is maintained at uniform heat and nanoparticle volume fraction