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Radiation effects on Marangoni convection flow and heat transfer in pseudo-plastic non-Newtonian nanofluids with variable thermal conductivity

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A B S T R A C T

In this paper, we examine radiation effects on Marangoni convection flow and heat transfer in pseudo-plastic non-Newtonian nanofluids driven by a temperature gradient. The surface tension is assumed to vary linearly with temperature. Four different types of nanoparticles; namely, Cu, Al_2O_3, CuO and TiO_2, are considered with sodium carboxymethyl cellulose (CMC)–water used as a base fluid. The effects of power-law viscosity on temperature field are taken into account by assuming that the temperature field is similar to the velocity field and that the thermal conductivity of the non-Newtonian fluids is power-law-dependent on the velocity gradient. The governing partial differential equations are reduced to a series of ordinary differential equations using similarity transformations, the solutions are obtained numerically by the shooting method. The effects of the solid volume fraction, the Power-law Number, the Marangoni Number and the Radiation Number on the velocity and temperature fields are analyzed and discussed in detail.

1. Introduction

The term “nanofluid” is defined as a solid–liquid mixture consisting of nanoparticles and a base liquid [1]. Choi is the first to use the term “nanofluids” to refer to fluids with suspended nanoparticles [2]. Studies have shown that adding nanoparticles to a base fluid can effectively improve the thermal conductivity of the base fluid and enhance heat transfer performance of the liquid. This is why nanofluids have found such a wide range of applications in so many fields: energy, power, aerospace, aviation, vehicles, electronics, etc.

Since the 1990s, the basic mechanism of the enhanced heat transfer characteristics in nanofluids has been extensively investigated. Wang and Mujumdar [3] presented an overview of the literature with regards to recent developments in the study of heat transfer using nanofluids. Based on previous studies they found that researchers had paid much more attention to the thermal conductivity of nanofluids than their heat transfer characteristics. Fan and Wang [4] also offered an overview of the recent research and development on heat conduction in nanofluids. Their emphasis is on nanofluid thermal conductivity (experiment data, proposed mechanisms responsible for conductivity enhancement and predicting models). In addition, Mahbubul et al. analyzed different characteristics of the viscosity of nanofluids including nanofluid preparation methods, temperature particle size and shape and volume fraction effects [5].

In regards to the convective heat transfer in nanofluids this past decade alone has witnessed extensive research. Abu-Nada [6] presented numerical solutions of heat transfer over a backward facing step (BFS) with nanofluids. The finite volume technique was used to solve the momentum and energy equations. Santra et al. [7,8] presented the effect that copper-water (i.e. Cu-water) nanofluid has on heat transfer due to natural convection in a differentially heated square cavity, treating the nanofluid as non-Newtonian in nature. The first paper, Santra et al. [7,8], used the control volume approach to discrete the governing equations or used Artificial Neural Network (ANN). Another paper using ANN is Kargar et al. [9]. They developed a series of feed-forward multilayer ANNs to analyze natural convection in a Cu-water nanofluid-filled enclosure. Further, Santra et al. [10] presented heat transfer due to laminar flow of Cu-water nanofluid through a two-dimensional channel with constant temperature walls, using a control volume approach to solve the governing equations. Hamad [11] examined the convective flow and heat transfer of an incompressible viscous nanofluid past a semi-infinite vertical stretching sheet in the

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Nomenclatures:

A	positive constant
M	the Marangoni number
T	temperature
n	the power law index
f	similar stream function
u, v	x- and y-component of the dimensional velocity, respectively
x, y	Cartesian coordinates
Pr	the Prandtl number
Nr	the radiation number
Nu_x	the local Nusselt number

Greek symbols

δ	surface tension
δ_0	the minimum value of the surface tension, a positive constant
ρ	density
C_p	heat capacity
ϕ	the solid volume fraction
k	thermal conductivity
μ	viscosity of fluid
α	thermal diffusivity
η	location similarity variable
δ^*	the Stefan–Boltzmann constant
k^*	the mean absorption
q	heat flux
q_r	the radiative heat flux
γ_T	surface tension on the second derivative of the temperature
θ	temperature similarity variable
ψ	stream function

Subscripts

nf	nanofluid
f	base fluid
s	solid
w	for $\eta = 0$ or $y = 0$
∞	for $\eta \to \infty$

presence of a magnetic field. Esfahani and Bordbar [12] investigated the flow and heat transfer characteristics of a nanofluid in a square enclosure exposed to both temperature and concentration gradients. Nasrin and Parvin [13] numerically analyzed the problem of natural convection in a trapezoidal enclosure filled with Cu-water nanofluids. Bachok et al. [14] examined the extended Blasius and Sakiadis problems in nanofluids by considering a uniform free stream parallel to a fixed or moving flat plate. Avramenko et al. [15] studied the flow and heat and mass transfer of a nanofluid in a boundary layer over a flat plate. The equations were obtained based on symmetry properties (Lie groups). Hamad et al. [16] discussed similarity reductions for problems of magnetic field effects on free convection flow of a nanofluid past a semi-infinite vertical flat plate. Bachok et al. [17] studied the steady and axially symmetric flow of an incompressible viscous fluid due to a rotating porous disk in a nanofluid.

There have also been several experimental investigations to better understand the mechanism of heat transfer enhancement during convection heat transfer in nanofluids [18–24]. It should be noted that nanofluids, as well as the base fluid, show shear-thinning (pseudoplastic) rheological behavior. This is best seen in Putra et al. [18], Zhou et al. [20] and Hojjat et al. [23]. Further, theoretical and experimental research investigations are needed to understand the heat transfer characteristics of nanofluids and identify new and unique applications for these fields [3].

In addition to nanofluids, it is also important to examine the role that convection plays. The dissipative layers, which may occur along the liquid–gas or liquid–liquid interfaces, are called Marangoni boundary layers. Marangoni flow, induced by surface tension, appears in many practical projects such as aerospace, materials science, crystal growth, etc. There have been several recent papers published on the mechanism of Marangoni convection. Christopher and Wang [25,26] presented a similarity solution for Marangoni induced flow over a flat surface due to an imposed temperature gradient. The analysis assumed a boundary layer develops along the surface due to coupled Marangoni convection. Zheng et al. [27] presented a theoretical analysis for Marangoni convection induced flow over a free surface due to an imposed temperature gradient. The Adomian analytical decomposition technique was used to solve the governing equations. Magyari and Chamkha [28] investigated the exact analytical solution for thermosolutal MHD Marangoni boundary layers due to imposed temperature and concentration gradients in the presence of a constant magnetic field. Zhang and Zheng [29] studied two-dimensional steady laminar boundary layer flow of an incompressible viscous electrically conducting fluid over a plate surface in the presence of surface tension due to temperature and concentration gradients at the wall. The double-parameter transformation perturbation expansion method and Pade approximants technique were used to solve the similarity equations. Hamid et al. [30] studied the Marangoni flow over a permeable flat surface with the effect of thermal radiation and suction/injection. In essence it can be regarded as an extension of [25–27]. Arifin et al. [31] studied the problem of Marangoni convection boundary layer flow past a flat plate in a nanofluid when the wall is permeable (suction/injection) using different types of nanoparticles. Hamid et al. [32] presented similarity solutions for the Marangoni convection boundary flow over a flat plate in a nanofluid with radiation effect.

In this paper we consider radiation effects on the steady two-dimensional Marangoni convection flow driven by a power-law temperature gradient in CMC–water-based non-Newtonian nanofluids containing different types of nanoparticles; namely, copper (Cu), aluminum oxide (Al_2O_3), copper oxide (CuO) and titanium oxide (TiO_2). The surface tension is assumed to vary linearly with temperature. The effects of power-law nanofluid viscosity on the temperature field are taken into account by assuming that the temperature field is similar to the velocity field [33–40]. The Navier–Stokes equations and the heat equation with a modified Fourier's law heat conduction for power-law fluid media is reduced to two nonlinear ordinary differential equations and the solutions are presented numerically.

2. Governing equations and problem formulation

In this paper we consider radiation effects on the steady Marangoni convection flow driven by a temperature gradient in CMC–water-based nanofluid containing different type of nanoparticles. Experimental studies show that the CMC–water is a pseudoplastic fluid; namely, it is a non-Newtonian fluid. In this study, the CMC–water with low concentration (0.1–0.4%) is used as a base