Advanced Powder Technology 26 (2015) 1423–1434

Contents lists available at ScienceDirect

Advanced Powder Technology

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

Original Research Paper

Buongiorno's model for double-diffusive mixed convective stagnation-point flow of a nanofluid considering diffusiophoresis effect of binary base fluid

Saeed Dinarvand [a,*], Reza Hosseini [b], Milad Abulhasansari [c], Ioan Pop [d]

[a] Young Researchers and Elite Club, Central Tehran Branch, Islamic Azad University, Tehran, Iran
[b] Department of Mechanical Engineering, Amirkabir University of Technology, 424 Hafez Avenue, Tehran, Iran
[c] Department of Mechanical and Aerospace Engineering, University of Texas at Arlington, Arlington, TX 76019, USA
[d] Department of Mathematics, University of Cluj, R-3400 Cluj, CP 253, Romania

ARTICLE INFO

Article history:
Received 10 April 2015
Received in revised form 20 July 2015
Accepted 25 July 2015
Available online 4 August 2015

Keywords:
Boundary layer
Double-diffusive mixed convection
Nanoparticle concentration
Buongiorno's model
Nanofluid

ABSTRACT

The development of double-diffusive mixed convective boundary layer flow of a nanofluid near stagnation point region over a vertical surface has been investigated. Buongiorno's model is used to incorporate the effects of Brownian motion and thermophoresis for the nanofluid, when the base fluid of the nanofluid is itself a binary fluid such as salty water. In addition the thermal energy equations include regular diffusion and cross-diffusion terms. Using the local similarity method, it is shown that a set of suitable similarity transformations reduces the non-linear coupled PDEs governing on the problem into a set of non-linear coupled ODEs. The analysis shows that velocity, temperature, solutal concentration and nanoparticle concentration profiles in the respective boundary layers depend on ten dimensionless physical parameters, namely the mixed convection parameter λ, the regular double-diffusive buoyancy parameter Nc, the nanofluid buoyancy ratio Nr, the Brownian motion parameter Nb, the thermophoresis parameter Nt, the modified Dufour parameter Nd, the regular Schmidt number Sc, the nanofluid Schmidt number Sc_n, Prandtl number Pr, and the Dufour-solutal Lewis number Ld. The results are presented in graphical form illustrating the effects of these parameters on boundary layer behavior. A sensitivity analysis of model is tabulated where the difference in each graph can be quantified in terms of root mean square deviation (RMSD) with respect to that with the default parameters. These results are supplemented with the data for the reduced Nusselt number and the two reduced Sherwood numbers, one for the solute and the other for the nanoparticles. It is found that for assisting flow regime the reduced Nusselt number is a decreasing function of each of Nr, Nb and Nt, and an increasing function of each of λ, Nc and Nd. The results demonstrate that the highest heat transfer rate is obtained for the situation that the thermophoresis effects are negligible. Moreover, a reduction in the reduced Sherwood number of nanoparticle is observed with increase in each of Nc and Nt, while this quantity increases with Nb.

1. Introduction

Convective heat transfer in nanofluids is a topic of major contemporary interest in the heat transfer research community [1–4]. The word "nanofluid" coined by Choi [5] describes a liquid suspension containing ultra-fine particles (diameter less than 50 nm). With the rapid advances in nano manufacturing, many inexpensive combinations of liquid/particle are now available. These include particles of metals such aluminum, copper, gold, iron and titanium or their oxides. The base fluids used are usually water, ethylene glycol, toluene and oil. A comprehensive survey of convective transport in nanofluids was made by Buongiorno [6], who says that a satisfactory explanation for the abnormal increase of the thermal conductivity and viscosity is yet to be found. He focused on the further heat transfer enhancement observed in convective situations. Buongiorno notes that several authors have suggested that convective heat transfer enhancement could be due to the dispersion of the suspended nanoparticles but he argues that this effect is too small to explain the observed enhancement. Buongiorno also concludes that turbulence is not

* Corresponding author. Tel.: +98 912 4063341; fax: +98 21 66419736.
E-mail addresses: saeed_dinarvand@yahoo.com, dinarvand@aut.ac.ir (S. Dinarvand).

http://dx.doi.org/10.1016/j.apt.2015.07.017
0921-8831/

Nomenclature

C	solutal concentration
C_∞	ambient solutal concentration
C_f	friction coefficient
D_B	Brownian diffusion coefficient
D_T	thermophoretic diffusion coefficient
D_{CT}	Soret-type diffusivity
D_{TC}	Dufour-type diffusivity
D_S	solutal diffusivity
f	dimensionless nanoparticle concentration
g	acceleration due to gravity
k	thermal conductivity
Ld	Dufour-solutal Lewis number
Nr	nanofluid buoyancy ratio
Nb	Brownian motion parameter
Nc	regular double-diffusive buoyancy parameter
Nd	modified Dufour parameter
Nt	thermophoresis parameter
Nu_x	local Nusselt number
Nur	reduced Nusselt number
Sh_x	local regular Sherwood number
Sh_x^n	local nanofluid Sherwood number
Shr	reduced regular Sherwood number
Shr_n	reduced nanofluid Sherwood number
s	dimensionless stream function
Sc	regular Schmidt number
Sc_n	nanofluid Schmidt number
Pr	Prandtl number
q_w	wall heat flux
q_w^s	wall solutal mass flux
q_w^{np}	wall nanoparticle mass flux
Re_x	local Reynolds number
T	fluid temperature
T_∞	ambient temperature
x, y	Cartesian coordinates
u, v	velocity components

Greek symbols

α	thermal diffusivity
β_T	volumetric thermal expansion coefficient
β_C	volumetric solutal expansion coefficient
λ	mixed convection parameter
γ	dimensionless solutal concentration
ϕ	nanoparticle concentration
ϕ_∞	ambient nanoparticle concentration
η	similarity variable
θ	dimensionless temperature
ν	kinematic viscosity
μ	dynamic viscosity
ρ_f	fluid density
ρ_p	nanoparticles density
$(\rho c)_f$	heat capacity of fluid
$(\rho c)_p$	effective heat capacity of nanoparticle
τ	nanofluid heat capacity ratio
ψ	stream function

affected by the presence of the nanoparticles so this cannot explain the observed enhancement. Particle rotation has also been proposed as a cause of heat transfer enhancement, but Buongiorno calculates that this effect is too small to explain the effect. With dispersion, turbulence and particle rotation ruled out as significant agencies for heat transfer enhancement, Buongiorno proposed a new model based on the mechanics of the nanoparticle/base-fluid relative velocity. Buongiorno [6] noted that the nanoparticle absolute velocity can be viewed as the sum of the base fluid velocity and a relative velocity (that he calls the slip velocity). He considered in turn seven slip mechanisms: inertia, Brownian diffusion, thermophoresis, diffusiophoresis, Magnus effect, fluid drainage, and gravity settling. After examining each of these in turn, he concluded that in the absence of turbulent effects it is the Brownian diffusion and the thermophoresis that will be important. Buongiorno proceeded to write down conservation equations based on these two effects. It is worth to mentioning that the nanofluid model proposed by Buongiorno [6] was recently used by Nield and Kuznetsov [7], Bachok et al. [8], Pop and Khan [9], Kuznetsov and Nield [10], and other researchers [11–15] in their papers.

Free convection is caused by the temperature difference of the fluid at different locations and forced convection is the flow of heat due to the cause of some external applied forces. The combination of free convection and forced convection is called as mixed

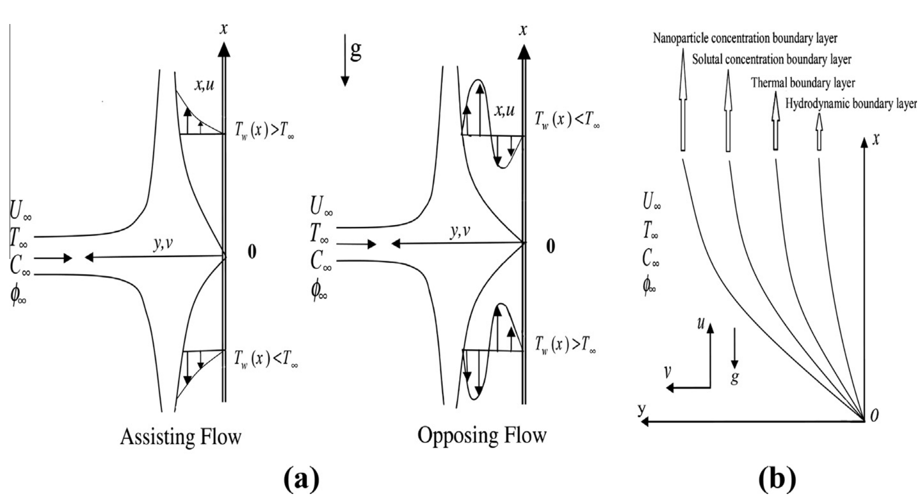

Fig. 1. (a) Schematic diagram of the physical model and coordinate system; and (b) typical patterns of boundary layers.