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Soret effect on mixed convection flow in a nanofluid under convective boundary condition

Ch. RamReddy [a,*], P.V.S.N. Murthy [b], Ali J. Chamkha [c], A.M. Rashad [d,e]

[a] Department of Mathematics, National Institute of Technology, Rourkela 769008, Odisha, India
[b] Department of Mathematics, Indian Institute of Technology, Kharagpur 721302, India
[c] Manufacturing Engineering Department, Public Authority for Applied Education and Training, Shuweikh 70654, Kuwait
[d] Department of Mathematics, Aswan University, Faculty of Science, Aswan 81528, Egypt
[e] Department of Mathematics, Salman Bin Abdul Aziz University, College of Science and Humanity Studies, AL-Kharj, Saudi Arabia

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ABSTRACT

In this investigation, we intend to present the influence of the prominent Soret effect on mixed convection heat and mass transfer in the boundary layer region of a semi-infinite vertical flat plate in a nanofluid under the convective boundary conditions. The transformed boundary layer ordinary differential equations are solved numerically using the implicit iterative finite difference method. Consideration of the nanofluid and the convective boundary conditions enhanced the number of non-dimensional parameters considerably thereby increasing the complexity of the present problem. A wide range of parameter values is chosen to bring out the effect of Soret parameter on the mixed convection process with the convective boundary condition. The effect of mixed convection, Soret and Biot parameters on the flow, heat and mass transfer coefficients is analyzed. The numerical results obtained for the velocity, temperature, volume fraction, and concentration profiles, as well as the local skin-friction coefficient, local wall temperature, local nanoparticle concentration and local wall concentration reveal interesting phenomenon, some of these qualitative results are presented through plots and tables.

1. Introduction

The process of heat and mass transfer caused by the simultaneous effect of free and forced convection is known as mixed convection flow. Considerable attention has been paid to the theoretical and numerical study of mixed convection boundary layer flow along a vertical plate in the recent past as it plays a crucial role in diverse applications, such as electronic devices cooled by fans, nuclear reactors cooled during an emergency shutdown, a heat exchanger placed in a low-velocity environment, solar collectors and so on. In the study of fluid flow over heated surfaces, the buoyancy force is neglected when the flow is horizontal. However, for vertical or inclined surfaces, the buoyancy force exert strong influence on the flow field. Extensive studies on mixed convection heat and mass transfer from isothermal and non-isothermal vertical surface under usual boundary layer approximation for viscous fluids have been undertaken by several researchers. Somers [1] analyzed theoretical results for combined thermal and mass transfer from a flat plate. The theoretical solution of heat transfer by mixed convection about a vertical flat plate has been obtained by Kliegel [2]. Merkin [3] investigated the mixed convection boundary layer flow on a semi-infinite vertical flat plate when the buoyancy forces aid and oppose the development of the boundary layer. Lloyd and Sparrow [4] used a local similarity method to solve the mixed convection flow on a vertical surface and showed that the numerical solutions ranged from pure forced convection to mixed convection. Kafoussias [5] presented analysis of the effects of buoyancy forces in a laminar uniform forced-convective flow with mass transfer along a semi-infinite vertical plate. An analysis is carried out by Chamkha et al. [6] to study the effects of localized heating (cooling), suction (injection), buoyancy forces and magnetic field for the mixed convection flow on a heated vertical plate. A detailed review of mixed convective heat and mass transfer can be found in the book by Bejan [7]. Recently, Subhashini et al. [8] discussed the simultaneous effects of thermal and concentration diffusions on a mixed convection boundary layer flow over a permeable surface under convective surface boundary condition.

The diffusion of mass due to temperature gradient is called Soret or thermo-diffusion effects and this effect might become significant when large density differences exist in the flow regime. For example, Soret effect can be significant when species are introduced at a surface in fluid domain, with a density lower than the surrounding fluid. The Soret parameter has been utilized for isotope separation and in a mixture between gases with very light molecular weight

* Corresponding author.
E-mail addresses: chramreddy@nitrkl.ac.in, chittetiram@gmail.com (Ch. RamReddy).

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Nomenclature

Bi	Biot number
C	solutal concentration
C_w	solutal concentration at the wall
C_f	skin friction coefficient
C_∞	ambient solutal concentration
c	constant
D_B	Brownian diffusion coefficient
D_S	solutal diffusivity
D_T	thermophoretic diffusion coefficient
D_{CT}	soret diffusivity
f	dimensionless stream function
g	gravitational acceleration
Gr_x	local Grashof number
h_f	convective heat transfer coefficient
$\mathcal{J}$	ratio between the effective heat capacity of the nanoparticle material and heat capacity of the fluid
k	thermal conductivity of the nanofluid
Le	Lewis number
Nb	Brownian motion parameter
Nc	regular buoyancy ratio
Nr	nanoparticle buoyancy ratio
Nt	thermophoresis parameter
Nu_x	local Nusselt number
Pr	Prandtl number
q_m	regular mass flux at the wall
q_n	nanoparticle mass flux at the wall
q_w	heat flux at the wall
Re_x	local Reynolds number
S	dimensionless concentration
Sc	Schmidt number
Sh_x	local Sherwood number
NSh_x	local nanoparticle Sherwood number
S_T	Soret number
T	temperature
T_f	temperature of the hot fluid
T_∞	ambient temperature
u_∞	characteristic velocity
u,v	velocity components in x and y directions
x,y	coordinates along and normal to the plate
α_m	thermal diffusivity
β_T,β_C	volumetric thermal and solutal expansion coefficients of the base fluid
η	similarity variable
γ	dimensionless volume fraction
λ	mixed convection parameter
θ	dimensionless temperature
ϕ	nanoparticle volume fraction
ϕ_w	nanoparticle volume fraction at the wall
ϕ_∞	nanoparticle volume fraction at large values of y (ambient)
μ	dynamic viscosity of the base fluid
ν	kinematic viscosity
ρ	density of the fluid
$\rho_{f\infty}$	density of the base fluid
ρ_p	nanoparticle mass density
$(\rho c)_f$	heat capacity of the fluid
$(\rho c)_p$	effective heat capacity of the nanoparticle material
τ_w	wall shear stress
ψ	stream function

Subscripts

w	wall condition
∞	ambient condition
C	concentration
T	temperature

Superscript

$'$	differentiation with respect to η

(H_2,He) and of medium molecular weight (N_2,air). Dursunkaya and Worek [9] studied diffusion-thermo and thermal-diffusion effects in transient and steady natural convection from a vertical surface, whereas Kafoussias and Williams [10] presented the same effects on mixed convective and mass transfer steady laminar boundary layer flow over a vertical flat plate with temperature dependent viscosity. The linear stability analysis of Soret-driven thermosolutal convection in a shallow horizontal layer of a porous medium subjected to inclined thermal and solutal gradients of finite magnitude has been investigated theoretically by Narayana et al. [11]. Recently, the effect of melting and/or thermodiffusion on convective transport in a non-Newtonian fluid saturated non-Darcy porous medium are presented by Kairi and Murthy [12] and Srinivasacharya and RamReddy [13].

In recent times, the flow analysis of nanofluids has been the topic of extensive research due to its characteristic in increasing thermal conductivity in heat transfer process. Several ordinary fluids including water, toluene, ethylene glycol and mineral oils etc. in heat transfer processes have rather low thermal conductivity. The nanofluid (initially introduced by Choi [14]) is an advanced type of fluid containing nanometer sized particles (diameter less than 100 nm) or fibers suspended in the ordinary fluid. Undoubtedly, the nanofluids are advantageous in the sense that they are more stable and have an acceptable viscosity and better wetting, spreading and dispersion properties on a solid surface. Nanofluids are used in different engineering applications such as microelectronics, microfluidics, transportation, biomedical, solid-state lighting and manufacturing. The research on heat and mass transfer in nanofluids has been receiving increased attention worldwide. Many researchers have found unexpected thermal properties of nanofluids, and have proposed new mechanisms behind the enhanced thermal properties of nanofluids. Excellent reviews on convective transport in nanofluids have been made by Buongiorno [15] and Kakac and Pramuanjaroenkij [16]. Kuznetsov and Nield [17] studied analytically the natural convective boundary-layer flow of a nanofluid past a vertical plate. The model used for the nanofluid incorporates the effects of Brownian motion and thermophoresis. Also, it is interesting to note that the Brownian motion of nanoparticles at molecular and nanoscale levels is a key nanoscale mechanism governing their thermal behaviors. In nanofluid systems, due to the size of the nanoparticles, the Brownian motion takes place, which can affect the heat transfer properties. As the particle size scale approaches to the nanometer scale, the particle Brownian motion and its effect on the surrounding liquids play an important role in the heat transfer. The steady boundary-layer flow of a nanofluid past a moving semi-infinite flat plate in a uniform free stream is analyzed by Bachok et al. [18]. Recently, the double-diffusive natural convective boundary-layer flow of a nanofluid past a vertical plate has been studied analytically by Kuznetsov and Nield [19]. Gorla et al. [20] presented a boundary layer analysis for the mixed convection past a vertical wedge in a porous medium saturated with a nanofluid. But, very little attention has been paid to study