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Rotating frame analysis of radiating and reacting ferro-nanofluid considering Joule heating and viscous dissipation

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ABSTRACT

We investigated the role of vibrational rotations and slip conditions at liquid-sheet interface in maintaining the three dimensional flow of ferro-nanoliquid (water-Fe_3O_4) over a bi-directionally stretchable surface under the influence of magnetic field. It is assumed that chemical reactions prevail between two species *A* and *B* whose diffusion coefficients are unequal. Also, mass transfer is considered in the presence of homogeneous and heterogeneous reactions for species *A* and *B*. Influences of nonlinear thermal radiation along with viscous dissipation and Joule heating are also invoked into the analysis due to their predominance in the control of heat and mass transfer mechanism. Stability and convergence limitations are verified to ensure the accuracy of results. The outcome due to proposed explicit finite difference scheme is exhibited in the form of figures and tables to illustrate the influence of emerging parameters for two cases namely slip nanofluid (SNF) and no slip nanofluid (NSNF). Results reveal that vibrational rotations and slip at the surface of sheet substantially control flow, and heat and mass transfer phenomena.

1. Introduction

It is a well-known phenomenon in the study of nanofluids that nanoparticle suspension in the base fluid provides applications in transportation, power plant and manufacturing. Since common fluids (water, engine oil, ethylene glycol) have limited capabilities for heat transfer; and metals and metal oxides (Cu, Al_2O_3, CuO, TiO_2) have higher thermal conductivities. Therefore, nanofluids (suspension of nanoparticles in base fluid) with higher thermal conductivity property are suitable candidates to be used as heat transfer medium. Sheikholeslami and Shehzad [1] presented the effect of external magnetic field on nanofluid flow and heat transfer in a porous media. Sheikholeslami et al. [2] investigated nanofluid forced convection inside a cavity by means of lattice Boltzmann method. Sheikholeslami and Shehzad [3] employed control volume finite element method to examine the influence of external magnetic field on magnetic nanofluid in a porous cavity. The nanoparticle shape effect on the copper-water nanofluid flow inside a cavity was discussed by Sheikholeslami [4]. For the latest works dealing with the heat and mass transfer mechanisms of nanofluid flow, readers are referred to the following references [5–23].

The prominent aspects of heat and mass transfer can be regulated by non-linear radiative heat transfer and the combination of homogeneous and heterogeneous reactions as indicated by Hayat et al. [24]. Non-linear thermal radiation helps in those situations where large temperature differences exist between the temperature of the surface and ambient fluid temperature. In this situation, it is not possible to linearize the flow field temperature with respect to constant free stream temperature. Therefore, non-linear law is the necessity for radiative heat transfer analysis. Also, complex phenomenon of bonding between homogeneous and heterogeneous reactions needs its understanding at the basic level owing to the relevance in glass blowing, metallurgy, continuous casting, polymer technology, manufacture of plastic melt spinning, spinning of fibers and food production [24]. Some recent works in this field can be addressed through the investigations [25–28] and various references enlisted in them.

Simultaneously, heat generated by viscous dissipation and Joule heating is important in the design of numerous devices because sometimes this type of heating is not required at all. Work done by velocity against viscous stresses is known as viscous dissipation of energy, whereas Joule heating is substantial when conduction electrons transfer energy to conductor's atoms through the

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Nomenclature

a, c	stretching constants (s^{-1})
a_0	ambient species concentration
B_0	magnetic field strength (Wb m^2)
(c_{fX}, c_{fY})	local skin-friction coefficients
(c_{fx}, c_{fy})	skin-friction coefficients
c_p	specific heat at constant pressure (J kg^{-1} K^{-1})
D_A	diffusivity of species A (m^2 s^{-1})
D_B	diffusivity of species B (m^2 s^{-1})
Ec	Eckert number
Gr_T	thermal Grashof number
g	acceleration due to gravity (ms^{-2})
j_{wA}	wall mass flux due to species A (m^2 s^1)
j_{wB}	wall mass flux due to species B (m^2 s^1)
k	thermal conductivity (W/mK)
k^*	mean absorption coefficient
k_c	reaction rate of homogeneous species (L^2 mol^{-2} s^{-1})
k_h	reaction rate of heterogeneous species (s^{-1})
K_c	homogeneous species reaction parameter
K_s	heterogeneous species reaction parameter
L_1, L_2, L_3	slip lengths (m)
M	dimensionless magnetic field parameter
n	shape parameter
Nu	Nusselt number
Nu_x	Local Nusselt number
Pr	Prandtl number
q_r	radiative heat flux (W/m^2)
q_w	wall heat flux (W/m^2)
R	dimensionless rotation parameter
Ra	dimensionless radiation parameter
Sc	Schmidt number
(Sh_A, Sh_B)	Sherwood numbers
$(Sh_{\phi_f}, Sh_{\phi_s})$	Local Sherwood numbers
Sl_1, Sl_2	dimensionless velocity slip parameters
Sl_3	dimensionless temperature jump parameter
t	dimensional time (s)
T	nanofluid temperature (K)
(u, v, w)	velocity components (ms^{-1})
(U, V, W)	dimensionless velocity components

Greek symbols

α	thermal diffusivity (m^2 s^{-1})
β_T	thermal expansion coefficient (K^{-1})
δ	species diffusivity ratio
ε	velocity ratio parameter
ϕ	volume fraction of nanoparticles
μ	dynamic viscosity (Pas)
v	kinematic viscosity of base fluid (m^2 s^{-1})
$\bar{\omega}$	frequency of oscillation (s^{-1})
ω	dimensionless frequency of oscillation
ρ	density (kg/m^3)
τ	dimensionless time
$(\tau_{wx,}, \tau_{wy})$	wall shear stresses (Nm^{-2})
θ	dimensionless temperature
θ_w	temperature ratio parameter
σ	electrical conductivity (s/m)
σ^*	Stefan-Boltzmann constant (W/m^2 K^4)
ϕ_f	non-dimensional homogeneous concentration
ϕ_s	non-dimensional heterogeneous concentration

Subscripts

f	base fluid
nf	nanofluid
s	nanoparticle
w	condition at the wall
∞	free stream condition

collision process. To prevent the devices and their components from overheating, convection cooling effects are to be introduced in the design of equipments. Influence of viscous dissipation and first order chemical reaction on an unsteady flow of MHD fluid along a hot vertical plate was explored by Singh and Kumar [29]. The extension to this paper was presented by Ram et al. [30] with radiative heat transfer. Sheikholeslami and Sadoughi [31] studied the effect of melting surface heat transfer in presence of magnetic field. They utilized control volume base finite element method in their simulation. Sheikholeslami and Bhatti [32] investigated the effect of electric field on nanofluid heat transfer enhancement. Sheikholeslami [33] demonstrated the effect of Lorentz forces on nanofluid forced convection in a lid driven cubic cavity. Sheikholeslami and Rokni [34] examined a numerical simulation for two phase analysis of nanofluid in presence of induced magnetic field.

In above mentioned biochemical engineering processes, scientists and engineers have engaged themselves to manage efficient transport of mass and energy, to control the droplet and bubble size, to generate good mixing of different fluid-fluid and fluid-solid phases. This target is achieved if we deal with high velocity turbulent flow or mechanically agitating devices. But on the other side when flow velocity is low and distribution is laminar then oscillatory flow over the surface of object or fluctuating surface temperature or vibrating free stream velocity and temperature needs to be superimposed to enhance heat and mass transfer. Tubular oscillatory flow reactor and baffled tube are some examples.

Recently, the analysis of heat and mass transfer processes in the flow of nanofluid past deformable surfaces which are subjected to time dependent rotational oscillations have attracted researchers and scientists due to their enlarged range of applications in various fields such as polymer industry, fiber technology, food processing and metallurgical sciences. In the beginning, combined effects of fluctuating and stretching velocities (existing on the surface of the sheet) were examined by Wang [35] utilizing matched asymptotic expansions for large suction. Sheikholeslami et al. [36] studied the radiative heat transfer of nanofluid in existence of Lorentz forces. Sheikholeslami et al. [37] analyzed the EHD nanofluid force convective heat transfer considering electric field dependent viscosity. Javed et al. [38] achieved the numerical solution for the oblique stagnation flow due to a fluctuating plate through Keller box method. Sheikholeslami and Seyednezhad [39] utilized CVFEM for modelling of nanofluid flow in a porous cavity in existence of magnetic field. Recently, Kumar and Sood [40] highlighted the importance of unidirectional surface stretching forces in rotational environment when radiation and chemical reaction control the heat and mass transfer mechanism in the flow of nanofluid. This work was extended by Kumar et al. [41] by considering non-linear radiative heat transfer and bidirectional stretching forces.

Motivated by the above utility of vibrational rotations, we made an attempt to fill the gap in literature by examining their role in the three dimensional flow of ferro-nanoliquid along a stretchable surface considering viscous/Ohmic dissipations, and radiative/reactive environment.