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Original Research Paper

Double diffusive flow of a hydromagnetic nanofluid in a rotating channel with Hall effect and viscous dissipation: Active and passive control of nanoparticles

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ABSTRACT

The investigation of simultaneous effects of Hall current and viscous dissipation on three-dimensional magnetohydrodynamic nanofluid flow in a horizontal rotating channel with active and passive control of nanoparticles, is carried out. The lower sheet is considered stretching while the upper sheet is kept fixed. Mathematical model is developed using boundary layer and scale analysis approach. Similarity transformation technique is employed to translate the governing partial differential equations into ordinary differential equations. The **bvp4c** solver of MATLAB is employed to solve transformed equations. Computations for nanofluid velocity, nanofluid temperature distribution and distribution of nanoparticles along with skin friction co-efficient and Nusselt number, are carried out for a range of values of pertinent flow parameters. A comparative analysis of effect of CuO and Al_2O_3 nanoparticles on velocity, temperature, nanoparticle distribution, skin friction coefficient and Nusselt number is carried out. Rate of heat transfer at the lower sheet is observed to be a decreasing function of magnetic field whereas this physical quantity is getting enhanced as the volume fraction of nanoparticles are increased.

1. Introduction

In the recent past, nanofluids, which are liquids containing colloidal suspension of nanoparticles are found to have significantly greater thermal conductivity than expected from the effective medium theories. A small fraction of nanoparticles, when diffused homogeneously in the base fluid, can result in remarkable enhancement in the thermal properties of fluids. This makes nanofluids very attractive as heat transfer fluids in many applications. Thus, the nanofluid technology is proving to be worthy of an investigation in order to alleviate the heat consumption. Nanofluids can be used as coolants in the electronics and automobile industries. A comprehensive survey of analytical and experimental studies can be found in the works of Kakac and Pramuanjaroenkij [1] who systematically reviewed the enhancement of forced convection heat transfer with nanofluids. Beg et al. [2] simulated the transport phenomena for the flow of Al_2O_3-water bio-nanofluid inside a tube and performed a comparative study of single phase and three different two-phase models. Khalili et al. [3] considered the unsteady flow of a power-law pseudoplastic nanofluid and found that the effect of unsteadiness parameter on the velocity boundary layer thickness is more pronounced compared to the concentration and temperature boundary layer thicknesses. Kherbeet et al. [4] conducted an experimental analysis of nanofluid flow over a microscale forward-facing step (MFFS) and microscale backward-facing step (MBFS). They observed that Nusselt number is higher when we use the MFFS as compared to MBFS for which the Nusselt number is half of that in case of MFFS. Bhatti and Rashidi [5] analyzed the effects of thermal radiation and thermo diffusion on the flow of Williamson nanofluid past a permeable stretching/shrinking sheet. Chamkha et al. [6] reviewed the studies dealing with the physical properties of nanofluid under the influence of magnetic field over different geometries. Sheikholeslami et al. [7] used the Differential Transform Method to investigate the effects of thermophoresis and Brownian motion on the flow of nanofluid flow in a channel and found that Nusselt number is an increasing function of Hartmann number. Seth and Mishra [8] highlighted the need to consider the effect of thermal radiation on the hydromagnetic nanofluid flow induced by nonlinearly stretching sheet. Seth et al. [9] considered the hydromagnetic viscoelastic nanofluid flow, incorporating

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Nomenclature

b	constant (s^{-1})
$\Omega = (0, \Omega_0, 0)$	angular velocity (s^{-1})
B	magnetic field ($kg\,s^{-2}\,A^{-1}$)
B_0	constant magnetic field ($kg\,s^{-2}\,A^{-1}$)
m	hall current parameter
D_B	Brownian diffusion coefficient ($m^2\,s^{-1}$)
D_T	thermophoretic diffusion coefficient ($m^2\,s^{-1}$)
f, g	dimensionless stream functions
k_p	thermal conductivity of nanoparticle ($W\,m^{-1}\,K^{-1}$)
k_{nf}	thermal conductivity of nanofluid ($W\,m^{-1}\,K^{-1}$)
$(C_p)_p$	specific heat at constant pressure for nanoparticles ($J\,K^{-1}\,kg^{-1}$)
$(C_p)_f$	specific heat at constant pressure for base fluid ($J\,K^{-1}\,kg^{-1}$)
K	rotation parameter
M	magnetic parameter
R	Reynolds number
E_c	Eckert number
Pr	Prandtl number
Nb	Brownian motion parameter
Nt	thermophoresis parameter
Le	Lewis number
C_{f_x}	skin friction coefficient
$q = (u, v, w)$	velocity component along x, y and z-directions respectively (ms^{-1})
s	nanoparticle volume fraction
s_h	nanoparticle volume fraction at upper sheet
T	temperature of nanofluid (K)
T_l, T_h	temperature at lower and upper sheets respectively (K)
t	time (s)
Nu_x	Nusselt number

Greek symbols

ρ_{nf}	density of nanofluid ($kg\,m^{-3}$)
μ_{nf}	dynamic viscosity of nanofluid ($kg\,m^{-1}\,s^{-1}$)
μ_f	dynamic viscosity of base fluid ($kg\,m^{-1}\,s^{-1}$)
$(\rho C_p)_{nf}$	heat capacity of nanofluid ($J\,K^{-1}$)
ρ_p	density of nanoparticles ($kg\,m^{-3}$)
ρ_f	density of base fluid ($kg\,m^{-3}$)
σ_p	electrical conductivity of nanoparticle (Sm^{-1})
σ_f	electrical conductivity of base fluid (Sm^{-1})
σ_{nf}	electrical conductivity of nanofluid (Sm^{-1})
ϕ	dimensionless nanoparticle concentration
θ	dimensionless temperature
ψ	stream function (m^2 s)
η	similarity variable

the effect of thermal radiation under convective surface boundary condition.

The Magnetohydrodynamic flows in a channel can be observed in a variety of ways in the scientific and industrial applications. Moreover, the flow of liquid metals in a channel, under the effect of magnetic field has several applications viz. the continuous casting of steel and the crystal growth, the production of cast parts at the semiconductor industry, in the fabrication of complex microstructures in 3-dimensions, in nuclear power industry, the application of liquid metal flows can be found in fusion reactors and at fast breeder power plants. Also, the renewable energy industry may find application of liquid metals flow in a channel such as the application of liquid metal coolants at concentrated solar power plants. The study of Tao [10] was concerned with the formation of Couette flow in the presence of magnetic field and he observed that magnetic field helps the flow to attain the steady state. Nigam and Singh [11] figured out the magnetohydrodynamic heat transfer problem for the forced flow between two parallel walls. They observed that the average mixed temperature at any point gets reduced due to the ionic conductivity of liquid. The work of Attia and Kotb [12] discussed the heat transfer aspect of flow of an electrically conducting fluid between two insulated parallel plate channels. Moreover the flow of nanofluids in a channel under magnetic field's influence has numerous applications in engineering. With the application of magnetic field in the flow region, the flow of nanofluids provides ample elucidations of heat transfer and hydromagnetic characteristics. Considering all the important applications of such study, Sheikholeslami et al. [13] presented the solution of hydromagnetic laminar flow through semi-porous channel by means of optimal Homotopy asymptotic method. Hatami and Ganji [14] analyzed the hydromagnetic flow of nanofluid in a convergent and divergent channel, using three analytical and one numerical technique. The main emphasize of their study was to check the suitability of Weighted Residual Methods on the boundary layer flows. Servati et al. [15] discussed the Lattice Boltzman Solution for the hydromagnetic flow of a nanofluid in a channel and observed that, with the enhancement in the nanoparticle volume fraction, the effect of magnetic field on average Nusselt number diminishes. Sheikholeslami and Ganji [16] discussed the hydrothermal nature of nanofluids in a squeezing flow under the influence of variable magnetic field. The rate of heat transfer in this study was observed to get enhanced on intensifying the magnetic field. Akbar et al. [17] analyzed numerically, the effects of magnetic field on the flow of nanofluids between two parallel plates filled with porous materials and found that the heat transfer profile can significantly be controlled by the magnetic field.

The purpose of all the above conferred research studies made on nanofluids, was to understand and exploit the heat transfer mechanism, offered by nanofluids. One more thing which affects the heat transfer mechanism considerably, is the viscous dissipation effect. Temperature distribution in the boundary layer is significantly affected by the viscous dissipation, which works as an internal heat source, caused by shearing of the layers of fluids. Brinkman [18] is considered to be the first person, describing the generation of heat due to viscous dissipation. One thing which makes the study of viscous dissipation effect in the nanofluid flow dynamics worthwhile is that the solid particles present in the fluid brings out supplementary disturbance in the stream, and consequently, the flow field gets altered which gives rise to an enhancement in the dissipation of heat [19]. Effect of viscous dissipation is even more pronounced in the situations where fluid flows through a microchannel. Inspired by the importance of viscous dissipation effects, Hung [20] presented an analysis of viscous dissipation effect on forced convection flow of nanofluids in a microchannel with isoflux boundary condition. He also presented the Nusselt number plot, through which he examined the interrelationship between nanoparticle volume fraction and viscous dissipation. Mah et al. [21] reported the viscous dissipation effect on entropy generation in forced convection flow of water-Al_2O_3 nanofluid in a microchannel and learned the fact that viscous dissipation has an adverse effect on the thermal performance for forced convection of nanofluids in the channel. Ting et al. [22] studied the exponential wall heat flux effect on the water-Al_2O_3 nanofluid in a microchannel and observed that the viscosity and effective thermal conductivity of nanofluid can significantly be enhanced with the