ARTICLE IN PRESS
Alexandria Engineering Journal (2017) xxx, xxx–xxx

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ORIGINAL ARTICLE

Finite element study of radiative double-diffusive mixed convection magneto-micropolar flow in a porous medium with chemical reaction and convective condition

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Received 4 June 2015; revised 12 November 2016; accepted 15 December 2016

KEYWORDS
MHD;
Micropolar fluid;
Chemical reaction;
Convective boundary condition;
FEM;
Stretching cylinder

Abstract In this paper, the steady, two-dimensional, heat and mass transfer of a mixed convection magneto-micropolar fluid flow over a non-permeable linearly stretching cylinder embedded in a porous medium in the presence of thermal radiation and first order chemical reaction with convective boundary condition is investigated. Using similarity transformations, the governing boundary layer equations are transformed into a system of nonlinear ordinary differential equations which are solved numerically using the finite element method. Graphical variations of the velocity, micro-rotation, temperature and concentration functions across the boundary layer are presented to depict the influence of the controlling parameters. Numerical data for the skin friction, couple stress, rate of heat and mass transfer have also been tabulated for various values of the thermophysical parameters. A comparison of the present results with earlier studies shows excellent agreement, thereby demonstrating the accuracy of the present numerical code. The study finds applications in chemical reaction engineering processes, magnetic materials processing, solar collector energy systems, etc.

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1. Introduction

Convective heat and mass transport phenomena in porous media are of fundamental importance in many technological processes such as in extraction of geothermal energy, cooling of nuclear reactors and underground disposal of nuclear wastes, petroleum reservoir operations, building insulation, irrigation systems, cooling of electronic components and the spreading of chemical pollutants in saturated soil and so on. Comprehensive reviews of the much of the work communicated in porous media transport phenomena have been presented in the monographs by Nield and Bejan [1], Vafai [2] and Ingham and Pop [3]. In recent years, the effect of magnetic field on heat and mass transfer flows through a porous medium has stimulated considerable interest owing to diverse applications in film

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Peer review under responsibility of Faculty of Engineering, Alexandria University.

http://dx.doi.org/10.1016/j.aej.2016.12.001
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Please cite this article in press as: G. Swapna et al., Finite element study of radiative double-diffusive mixed convection magneto-micropolar flow in a porous medium with chemical reaction and convective condition, Alexandria Eng. J. (2017), http://dx.doi.org/10.1016/j.aej.2016.12.001

Nomenclature

Roman

b	constant
C	concentration of species in the boundary layer ($\mathrm{kmol\ m^{-3}}$)
C_∞	concentration of species far away from the surface ($\mathrm{kmol\ m^{-3}}$)
c_p	specific heat at constant pressure ($\mathrm{J\ kg^{-1}\ K^{-1}}$)
D	chemical molecular diffusivity ($\mathrm{m^2\ s^{-1}}$)
T_∞	temperature far away from the surface (K)
k_1	rate of chemical reaction ($\mathrm{mol\ m^{-1}\ s^{-1}}$)
k_p	permeability of the porous medium ($\mathrm{m^2}$)
f	dimensionless stream function
g	dimensionless micro-rotation
g_e	acceleration due to gravity ($\mathrm{m\ s^{-2}}$)
h	dimensionless velocity
h_f	heat transfer coefficient ($\mathrm{W\ m^{-2}\ K^{-1}}$)
j	microinertia per unit mass ($\mathrm{kg\ m^{-3}}$)
k_f	thermal conductivity of the fluid ($\mathrm{W\ m^{-1}\ K^{-1}}$)
k_p	permeability of the porous medium
N	micro-rotation component ($\mathrm{kg\ m^2\ s^{-1}}$)
T	temperature of the fluid in the boundary layer (K)
u_w	velocity of the stretching cylinder ($\mathrm{m\ s^{-1}}$)
q_r	radiative heat flux ($\mathrm{W\ m^{-2}}$)

Greek

β	thermal expansion coefficient ($\mathrm{K^{-1}}$)
β^*	concentration expansion coefficient ($\mathrm{K^{-1}}$)
σ	electrical conductivity ($\mathrm{s^3\ A^2\ kg^{-1}\ m^{-3}}$)
η	dimensionless coordinate
θ	dimensionless temperature
ϕ	dimensionless concentration
α	thermal diffusivity ($\mathrm{m^2\ s^{-1}}$)
ρ	fluid density ($\mathrm{kg\ m^{-3}}$)
ν	kinematic viscosity ($\mathrm{m^2\ s^{-1}}$)
κ	micro-rotation viscosity ($\mathrm{m^2\ s^{-1}}$)
γ	spin gradient viscosity ($\mathrm{m^2\ s^{-1}}$)
Ψ	stream function ($\mathrm{m^2\ s^{-1}}$)

Subscripts

w, f	condition at the surface and of the hot fluid, respectively
∞	condition far away from the surface

Superscript

$\prime$	differentiation with respect to η

vaporization in combustion chambers, transpiration cooling of re-entry vehicles, solar wafer absorbers, manufacture of gels, magnetic materials processing, astrophysical flows and hybrid MHD power generators. Porous media abound in chemical engineering systems and magnetic fields are frequently used to control transport phenomena in electrically-conducting fluent media. Convective flow with simultaneous heat and mass transfer in porous media under the influence of a magnetic field and chemical reaction has also stimulated extensive research owing to numerous applications in air and water pollutions, drying technologies, fibrous insulation, atmospheric flows, cooling of nuclear reactors and magnetohydrodynamic (MHD) power generators, and many other chemical engineering problems. Many processes in new engineering areas occur at high temperature and the knowledge of radiative heat transfer becomes very important for the design of the pertinent equipment. Radiation effects on convective heat transfer and MHD flow problems have assumed increasing importance in electrical power generation, astrophysical flows, solar power technology, space vehicle re-entry, gas turbines and various propulsion devices for aircraft and other industrial areas. In this regard, many researchers have contributed to the subject for different physical situations [4–9].

In recent years, flow transport phenomena from stretched cylindrical bodies have begun to attract the attention of many researchers owing to the fact that cylinders have been used in nuclear waste disposal, energy extortion in underground and catalytic beds. Wang [10] initiated the steady flow of a viscous and incompressible fluid outside of a stretching hollow cylinder. Ishak et al. [11] extended the work of Wang [10] by including suction and injection effects. Later, they [12] examined the magnetohydrodynamic flow and heat transfer due to a stretching cylinder and obtained the numerical solutions using Keller-box method. Using homotopy analysis method (HAM), Joneidi et al. [13] presented a study on the MHD flow and heat transfer of a viscous and incompressible electrically conducting fluid outside a stretching cylinder. Chamkha et al. [14] obtained the numerical solution of flow and heat transfer outside a stretching permeable cylinder with thermal stratification and uniform suction/blowing effects. Subsequently, many authors have examined numerous aspects of the stretching cylinder [15–21].

The above studies are all confined to the Navier Stokes fluid model. However, in various chemical engineering applications, material processing engineering, biomechanics, slurry technologies, etc., the fluid used exhibits microstructural characteristics i.e. rotary motions and also gyration of fluid microelements. Eringen in his pioneering paper [22] formulated the micropolar fluid model to simulate such effects. The micropolar model takes into account the inertial characteristics of the substructure particles which are allowed to sustain rotation and couple stress. Such type of flow finds applications in the purification of crude oil, polymer technologies, cooling tower dynamics, chemical reaction engineering, metallurgical drawing of filaments and solar energy systems. Eringen [23] later extended the theory to include thermal effects and developed the theory of thermo-micropolar fluids. An excellent discussion of the applications of micropolar fluids has been communicated in the recent monograph by Bég et al. [24]. Mohamed and Abo-Dahab [25] presented an analysis for the effects of chemical reaction and thermal radiation on hydromagnetic free convection heat and mass transfer for a micropolar fluid via a porous medium bounded by a semi-infinite vertical porous plate in the presence of heat generation. Das [26] studied the effects of thermal radiation and chemical reaction on unsteady MHD free convection heat and mass transfer

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