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International Journal of Thermal Sciences 47 (2008) 1043–1054

International Journal of Thermal Sciences

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Effects of chemical reaction on free convective flow of a polar fluid through a porous medium in the presence of internal heat generation

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Received 5 January 2007; received in revised form 12 March 2007; accepted 27 July 2007

Available online 25 October 2007

Abstract

This paper is focused on the study of combined effects of free convective heat and mass transfer on the steady two-dimensional, laminar, polar fluid flow through a porous medium in the presence of internal heat generation and chemical reaction of the first order. The highly non-linear coupled differential equations governing the boundary layer flow, heat and mass transfer are solved by using two-term perturbation method with Eckert number E as perturbation parameter. The parameters that arise in the perturbation analysis are Eckert number E (viscous dissipation), Prandtl number Pr (thermal diffusivity), Schmidt number Sc (mass diffusivity), Grashof number Gr (free convection), solutal Grashof number Gm, chemical reaction parameter Δ (rate constant), internal heat generation parameter Q, material parameters α and β (characterizes the polarity of the fluid), C_f (skin friction coefficient), Nusselt number Nu (wall heat transfer coefficient) and Sherwood number Sh (wall mass transfer coefficient). Analytical expressions are computed numerically. Numerical results for the velocity, angular velocity, temperature and concentration profiles as well as for the skin friction coefficient, wall heat transfer and mass transfer rate are obtained and reported graphically for various conditions to show interesting aspects of the solution. Further, the velocity distribution of polar fluids is compared with the corresponding flow problems for a viscous (Newtonian) fluid and found that the polar fluid velocity is decreasing.

Keywords: Chemical reaction; Free convection; Polar fluid; Porous medium; Internal heat generation; Couple stress

1. Introduction

Many transport processes occurring both in nature and in industries involve fluid flows with the combined heat and mass transfer. Such flows are driven by the multiple buoyancy effects arising from the density variations caused by the variations in temperature as well as species concentrations. Convective flows in porous media have been extensively examined during the last several decades due to many practical applications which can be modeled or approximated as transport phenomena in porous media. References of comprehensive literature surveys regarding the subject of porous media can be had in most recent books by Ingham and Pop [1], Nield and Bejan [2], Vafai [3], Pop and Ingham [4] and Ingham et al. [5]. Coupled heat and mass transfer problems in presence of chemical reaction are of importance in many processes and have, therefore, received considerable amount of attention in recent times. In processes such as drying, distribution of temperature and moisture over agricultural fields and groves of fruit trees, damage of crops due to freezing, evaporation at the surface of a water body, energy transfer in a wet cooling tower and flow in a desert cooler, heat and mass transfer occur simultaneously. Possible applications of this type of flow can be found in many industries. For instance, in the power industry, among the methods of generating electric power is one in which electrical energy is extracted directly from a moving conducting fluid. Chemical reactions can be modeled as either homogeneous or heterogeneous processes. This depends on whether they occur at an interface or as a single phase volume reaction. A homogeneous reaction is one that occurs uniformly throughout a given phase. The species generation in a homogeneous reaction is the same as internal source of heat generation. On the other hand, a heterogeneous reaction takes place in a restricted area or within the boundary of a phase.

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1290-0729/$ – see front matter © 2007 Published by Elsevier Masson SAS.
doi:10.1016/j.ijthermalsci.2007.07.013

Nomenclature

C'	species concentration
C'_w	surface concentration
C'_∞	species concentration far from the surface
C_a, C_d	are coefficients of couple stress viscosities
C_f	skin friction co-efficient
D	the effective diffusion co-efficient
E	Eckert number
C_p	specific heat at constant pressure
Gm	solutal Grashof number
Gr	Grashof number
g	acceleration due to gravity
I	a constant of dimension equal to that of the moment of inertia of unit mass
K'	permeability of the porous medium
K	dimensionless permeability
k_1	first order chemical reaction rate
Nu	Nusselt number
Pr	Prandtl number
Q_0	heat generation co-efficient
Q	heat generation parameter
Sc	Schmidt number
Sh	Sherwood number
T'	temperature in the boundary layer
T'_∞	temperature of the fluid far away from the plate
T'_w	temperature at the wall
U'_∞	free-stream velocity
u', v'	components of velocities along and perpendicular to the plate, respectively
u	dimensionless velocity
u_0	zeroth order velocity
u_1	first order velocity
v_0	suction velocity
X', Y'	co-ordinate system
y	dimensionless co-ordinate normal to the plate

Greek symbols

α, β	material parameters characterizing the polarity of the fluid
β_c	volumetric co-efficient of thermal expansion
β_t	volumetric co-efficient of expansion with concentration
Δ	chemical reaction parameter
γ	spin gradient velocity
λ	thermal conductivity of the fluid
ν	kinematic viscosity of the fluid
ν_r	rotational kinematic viscosity of the fluid
ρ	density of the fluid
ρ_∞	density of the fluid far away from the surface
Φ	dimensionless concentration
Θ	dimensionless temperature
Θ_0	zeroth order temperature
Θ_1	first order temperature
ω'	angular velocity component
ω	dimensionless angular velocity
ω_0	zeroth order angular velocity
ω_1	first order angular velocity

It can therefore be treated as a boundary condition similar to the constant heat flux condition in heat transfer. The study of heat and mass transfer with chemical reaction is of great practical importance to engineers and scientists because of its almost universal occurrence in many branches of science and engineering. Das et al. [6] have studied the effects of mass transfer on the flow past impulsively started infinite vertical plate with constant heat flux and chemical reaction. Diffusion of a chemically reactive species from a stretching sheet is studied by Andersson et al. [7]. Anjalidevi and Kandasamy [8,9] have analyzed the effects of chemical reaction, heat and mass transfer on laminar flow without or with MHD along a semi infinite horizontal plate. Muthucumaraswamy and Ganeshan [10–12] have studied the impulsive motion of a vertical plate with heat flux/mass flux/suction and diffusion of chemically reactive species. The flow and mass transfer on a stretching sheet with a magnetic field and chemically reactive species are examined by Takhar et al. [13]. Muthucumaraswamy [14] has analyzed the effects of a chemical reaction on a moving isothermal vertical surface with suction. Prasad et al. [15] have studied the effects of diffusion of chemically reactive species of a non-Newtonian fluid immersed in a porous medium over a stretching sheet. Ghaly and Seddeek [16] have discussed the Chebyshev finite difference method for the effects of chemical reaction, heat and mass transfer on laminar flow along a semi infinite horizontal plate with temperature dependent viscosity. Seddeek [17] has studied the finite element method for the effects of chemical reaction, variable viscosity, thermophoresis and heat generation/absorption on a boundary layer hydromagnetic flow with heat and mass transfer over a heat surface. Effects of chemical reaction, heat and mass transfer along a wedge with heat source and concentration in the presence of suction or injection are examined by Kandasamy et al. [18]. Raptis and Perdikis [19] have discussed the viscous flow over a non-linearly stretching sheet in the presence of chemical reaction and magnetic field.

Quite a number of physical phenomena involve free convection driven by heat generation. The study of heat generation in moving fluids is important in view of several physical problems such as those dealing with chemical reactions and those concerned with dissociating fluids. Possible heat generation effects may change the temperature distribution and, therefore, the particle deposition rate. This may occur in such applications related to nuclear reactor cores, fire and combustion modeling, electronic chips and semi conductor wafers. In fact, the literature is replete with examples dealing with heat transfer in laminar flow of viscous fluids. Vajravelu and Hadjinicolaou [20] have studied heat transfer characteristics in a laminar boundary layer flow of a viscous fluid over a linearly stretching contin-