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Soret and Dufour effects on free convection boundary layer over a vertical cylinder in a saturated porous medium☆

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ABSTRACT

This paper deals with an analysis of the Soret and Dufour effects on the boundary layer flow due to free convection heat and mass transfer over a vertical cylinder in a porous medium saturated with Newtonian fluids with constant wall temperature and concentration. A suitable coordination transformation is used to derive the similar governing boundary-layer equations, and the cubic spline collocation method is then employed to solve the similar governing boundary-layer equations. The variation of the Nusselt number and the Sherwood number with the Dufour parameter and the Soret parameter for various Lewis numbers and buoyancy ratios have been presented in this work. Results show that an increase in the Soret number leads to a decrease in the local Sherwood number and an increase in the local Nusselt number. The local Nusselt number tends to decrease as the Dufour parameter is increased. Moreover, an increase in the Lewis number enhances the effect of the Dufour parameter on the local Nusselt number.

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1. Introduction

The heat and mass transfer due to free convection and mixed convection in fluid-saturated porous media has been considered by theoretical and experimental studies during the last several decades because of its great practical applications in modern industry, such as geothermal systems, drying technology, heat insulation, catalytic reactors, compact heat exchangers, solar power collectors and food industries.

Bejan and Khair [1] studied the heat and mass transfer by free convection in a porous medium. Lai [2] examined the heat and mass transfer by free convection from a horizontal line source in a saturated porous medium. Chamkha and Khaled [3] studied the hydromagnetic heat and mass transfer by mixed convection from a vertical plate embedded in a uniform porous medium. Cheng [4] uses an integral approach to study the heat and mass transfer by free convection from truncated cones in porous media with variable wall temperature and concentration. Khanafer and Vafai [5] studied the double-diffusive mixed convection in a lid-driven enclosure filled with a fluid-saturated porous medium. Rathish Kumar et al. [6] examined the effect of thermal stratification on double-diffusive free convection in a vertical porous enclosure. Moreover, Cheng [7] studied the double-diffusive free convection along a vertical wavy surface in non-Newtonian fluid-saturated porous media with thermal and mass stratification.

The free convection about a vertical cylinder embedded in porous media is of much interest. Minkowycz and Cheng [8] examined the heat transfer in free convection flow from a vertical cylinder in a saturated porous medium, where the surface temperature of the cylinder varies as a power function of distance from the leading edge. Kumari et al. [9] used the Keller box method and improved perturbation method to study the problem of free convection on a vertical cylinder embedded in a saturated porous medium. Merkin [10] presented an asymptotic solution for the free convection from an isothermal cylinder embedded in a saturated porous medium. Bassom and Rees [11] used the Keller box method to study the problem of free convection on a vertical cylinder embedded in a saturated porous medium with variable wall temperature. Yih [12] presented numerical solutions for the effect of radiation on free convection about an isothermal cylinder embedded in porous media.

There are a few studies about the Soret and Dufour effects in a Darcy or non-Darcy porous medium. Postelnicu [13] studied the heat and mass characteristics of free convection about a vertical surface embedded in a saturated porous medium subjected to a magnetic field by considering the Dufour and Soret effects. Partha et al. [14] examined the Soret and Dufour effects in a non-Darcy porous medium. Mansour et al. [15] studied the multiplicity of solutions induced by thermosolutal convection in a square porous cavity heated from below and submitted to horizontal concentration gradient in the presence of Soret effect. Lakshmi Narayana et al. [16] studied the Soret and Dufour effects in a doubly stratified Darcy porous medium. Lakshmi Narayana and Murthy [17] examined the Soret and Dufour effects on free convection heat and mass transfer from a horizontal flat plate in a Darcy porous medium. Mahdy [18] studied the problem of

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Nomenclature

C	concentration
D	Dufour parameter
$\overline{D}$	Dufour coefficient
D_M	mass diffusivity of the porous medium
f	dimensionless stream function
g	acceleration due to gravity
K	permeability of the porous medium
Le	Lewis number
N	buoyancy ratio
Nu	local Nusselt number
r	radial coordinate
r_0	radius of the cylinder
S	Soret parameter
$\overline{S}$	Soret coefficient
Ra	Rayleigh number
Sh	Sherwood number
T	temperature
u	velocity component in x-direction
v	velocity component in r-direction
x	axial coordinate

Greek symbols

α	thermal diffusivity of the porous medium
β_C	coefficient of concentration expansion
β_T	coefficient of thermal expansion
η	similarity variable
θ	dimensionless temperature
ν	kinematic viscosity
ϕ	dimensionless concentration
Ψ	stream function

Subscripts

w	condition at wall
∞	condition at infinity

MHD non-Darcian free convection from a vertical wavy surface embedded in porous media in the presence of Soret and Dufour effect.

The literature review shows that the previous studies have considered the Soret and Dufour effects on the steady boundary layer flow by free convection heat and mass transfer over a horizontal and vertical surfaces embedded in a Darcy or non-Darcy porous medium. The present study, however, considers the free convection heat and mass transfer boundary layer flow over a vertical cylinder in a Darcy porous medium saturated with Newtonian fluid considering Soret and Dufour effects. A suitable coordination transformation is used to derive the similar governing boundary-layer equations. The coupled similarity boundary-layer solutions are then solved by the cubic spline collocation method to study the effects of the Dufour parameter, Soret parameter, Lewis number, and buoyancy ratio on the heat and mass transfer characteristics for the free convection about a vertical cylinder in a porous medium saturated with Newtonian fluids.

2. Basic equations and similarity analysis

Consider the boundary layer flow due to free convection heat and mass transfer from a vertical cylinder of radius r_0 embedded in a porous medium saturated with a Newtonian fluid with Soret and Dufour effects. The surface of the cylinder is maintained at a constant temperature T_w, which is different from the porous medium temperature sufficiently far from the surface of the cylinder. The concentration of a certain constituent in the solution that saturated the porous medium varies from C_w on the fluid side of the surface of the cylinder to C_∞ sufficiently far from the surface of the cylinder.

The fluid properties are assumed to be constant except for density variations in the buoyancy force term. The governing equations for the flow, heat and mass transfer within the boundary layer near the vertical cylinder can be written in two-dimensional cylindrical (x,r) as [12,19]

$$\frac{\partial(ru)}{\partial x} + \frac{\partial(rv)}{\partial r} = 0 \tag{1}$$

$$u = \frac{gK}{\nu}[\beta_T(T-T_\infty) + \beta_C(C-C_\infty)] \tag{2}$$

$$u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial r} = \frac{\alpha}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right) + \frac{\overline{D}}{r}\frac{\partial}{\partial r}\left(r\frac{\partial C}{\partial r}\right) \tag{3}$$

$$u\frac{\partial C}{\partial x} + v\frac{\partial C}{\partial r} = \frac{D_M}{r}\frac{\partial}{\partial r}\left(r\frac{\partial C}{\partial r}\right) + \frac{\overline{S}}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right) \tag{4}$$

where the x-axis is measured the surface of the cylinder and the r-axis is measured in the radial direction. u and v are the volume-averaged velocity components in the x and r directions, respectively. T and C are the volume-averaged temperature and concentration, respectively. Property ν is kinematic viscosity of the fluid, and K is the permeability of the porous medium. Furthermore, β_T and β_C are the coefficient of thermal expansion and the coefficient of concentration expansion, respectively. α and D_M are the thermal diffusivity and mass diffusivity of the porous medium, respectively. $\overline{D}$ and $\overline{S}$ are the Dufour coefficient and Soret coefficient of the porous medium, respectively. g is the gravitational acceleration.

The boundary conditions are given by

$$r = r_0 : v = 0 \quad T = T_w \quad C = C_w \tag{5}$$

$$r \to \infty : u \to 0 \quad T \to T\infty \quad C \to C\infty \tag{6}$$

We introduce the similarity variables

$$\eta = \frac{r_0 Ra^{1/2}}{2x}\left(\frac{r^2}{r_0^2}-1\right), \xi = \frac{2x}{r_0 Ra^{1/2}}, f(\eta) = \frac{\psi}{\alpha r_0 Ra^{1/2}}, \quad \theta(\xi,\eta) = \frac{T-T_\infty}{T_w-T_\infty}, \phi(\xi,\eta) = \frac{C-C_\infty}{C_w-C_\infty} \tag{7}$$

where ψ is the stream function defined as:

$$u = \frac{1}{r}\frac{\partial\psi}{\partial r}, v = -\frac{1}{r}\frac{\partial\psi}{\partial x} \tag{8}$$

and the Rayleigh number is given by

$$Ra = \frac{gK\beta_T x(T_w-T_\infty)}{\nu\alpha} \tag{9}$$

Upon using these variables, the basic equations of the boundary layer for the problem under consideration can be written in non-dimensional form as

$$f' = \theta + N\phi \tag{10}$$

$$(1+\xi\eta)\theta'' + \left(\xi + \frac{1}{2}f\right)\theta' + D(1+\xi\eta)\phi'' + D\xi\phi' = \frac{\xi}{2}\left(f'\frac{\partial\theta}{\partial\xi} - \theta'\frac{\partial f}{\partial\xi}\right) \tag{11}$$

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