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Soret and Dufour effects on natural convection heat and mass transfer near a vertical wavy cone in a porous medium with constant wall temperature and concentration ☆

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ABSTRACT

This work studies the heat and mass transfer characteristics of natural convection near a vertical wavy cone in a fluid saturated porous medium with Soret and Dufour effects. The surface of the wavy cone is kept at constant temperature and concentration. The governing equations are transformed into a set of coupled differential equations, and the obtained boundary layer equations are solved by the cubic spline collocation method. The heat and mass transfer characteristics are presented as functions of Soret parameter, Dufour parameter, half angle of the cone, Lewis number, buoyancy ratio, and dimensionless amplitude. Results show that an increase in the Dufour parameter tends to decrease the local Nusselt number, and an increase in the Soret parameter tends to decrease the local Sherwood number. Moreover, a greater half angle of the cone leads to a greater fluctuation of the local Nusselt and Sherwood numbers with the streamwise coordinates.

1. Introduction

The problem of heat and mass transfer near irregular surfaces is very important because it is often met in many practical applications. Yao [1] examined the natural convection heat transfer from isothermal vertical wavy surfaces, such as sinusoidal surfaces, in Newtonian fluids. Rees and Pop [2] studied the natural convection flow over a vertical wavy surface with constant wall temperature in porous media saturated with Newtonian fluids. Rees and Pop [3] studied the free convection induced by a vertical wavy surface with uniform heat flux in a porous medium Hossain and Rees [4] examined the heat and mass transfer in natural convection flow along a vertical wavy surface with constant wall temperature and concentration in Newtonian fluids. Cheng [5] presented the solutions of natural convection heat and mass transfer near a wavy cone with constant wall temperature and concentration in a porous medium. Molla et al. [6] examined the natural convection flow along a vertical wavy surface with uniform surface temperature in presence of heat generation or absorption. Rathish Kumar and Shalini [7] studied the non-Darcy free convection induced by a vertical wavy surface in a thermally stratified porous medium. Wang and Chen [8] studied the mixed convection boundary layer flow on inclined wavy plates including the magnetic field effect. Molla and Hossain [9] studied the radiation effect on mixed convection laminar flow over a vertical wavy surface. Cheng [10] examined the double diffusive convection near a frustum of a wavy cone in porous media. Cheng [11] studied the double diffusive natural convection along a vertical wavy truncated cone in non-Newtonian fluid saturated porous media with thermal and mass stratification. Cheng [12] studied the heat and mass transfer in natural convection flow from a vertical wavy surface in a power-law fluid saturated porous medium with thermal and mass stratification. Cheng [13] studied the double diffusive natural convection along an inclined wavy surface in a porous medium.

The Soret effect referred to species differentiation developing in an initial homogeneous mixture submitted to a thermal gradient. The Dufour effect referred to heat flux produced by a concentration gradient. Postelnicu [14] examined 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. [15] studied the Soret and Dufour effects in a non-Darcy porous medium. Lakshmi Narayana and Murthy [16] studied the Soret and Dufour effects on free convection heat and mass transfer from a horizontal flat plate in a Darcy porous medium. Mahdy [17] examined the problem of MHD non-Darcian free convection from a vertical wavy surface embedded in porous media in the presence of Soret and Dufour effect. Cheng [18] studied the Soret and Dufour effects on natural convection heat and mass transfer from a vertical cone in a porous medium. Cheng [19] presented the solutions of the free convection boundary layer over a vertical cylinder in a saturated porous medium by considering the Soret and Dufour effects. Cheng [20] examined the problem of heat and mass transfer by natural convection from a vertical truncated cone in a fluid-saturated porous medium with variable wall temperature and concentration with Soret and Dufour effects.

This work aims to study the Soret and Dufour effects on natural convection heat and mass transfer near a vertical wavy cone in a

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Nomenclature

$\bar{a}$	amplitude of the wavy cone
A	half angle of the cone
C	concentration
D	Dufour parameter
$\overline{D}$	Dufour coefficient
D_M	mass diffusivity of the porous medium
g	gravitational acceleration
f	dimensionless stream function
K	permeability of porous medium
l	half wavelength of the wavy cone
Le	Lewis number
N	buoyancy ratio
$Nu_{\bar{x}}$	local Nusselt number
Ra	modified Rayleigh number
r	local radius of the corresponding smooth cone
S	Soret parameter
$\overline{S}$	Soret coefficient
$Sh_{\bar{x}}$	local Sherwood number
T	temperature
$\bar{u}, \bar{v}$	velocity components
$\bar{x}, \bar{y}$	Cartesian coordinates

Greek symbols

α	thermal diffusivity of the porous medium
β_T	coefficient of concentration expansion
β_C	coefficient of thermal expansion
η, ξ	dimensionless coordinates
θ	dimensionless temperature
ν	kinematic viscosity
ϕ	dimensionless concentration
ψ	stream function

Subscripts

w	condition at wall
∞	condition at infinity

porous medium. The surface of the cone is kept at constant temperature and concentration. The governing equations are transformed into a set of coupled differential equations, and the obtained boundary layer equations are solved by the cubic spline collocation method [21]. The effects of Soret parameter, Dufour parameter, Lewis number, buoyancy ratio, half angle of the cone, and dimensionless amplitude on the heat and mass transfer characteristics near a vertical wavy cone in a porous medium saturated with a Newtonian fluid are carefully examined.

2. Analysis

Consider the boundary layer flow driven by natural convection with temperature and concentration gradients near a vertical wavy cone in a porous medium saturated with a Newtonian fluid as shown in Fig. 1. The profile of the surface of the wavy cone is given by

$$\bar{y} = \bar{\sigma}(\bar{x}) = \bar{a}\,\sin(\pi\bar{x}/l) \tag{1}$$

where A is the half angle of the corresponding smooth cone, $\bar{a}$ is the amplitude of the wavy cone, and $2l$ is the characteristic length of the wavy cone. The surface of the wavy cone is maintained at a constant temperature T_w greater than the porous medium temperature T_∞ sufficiently far from the wavy cone. The concentration of a certain constituent in the solution that saturates the porous medium varies from a higher concentration C_w on the fluid side of the surface of the wavy cone to a lower concentration C_∞ sufficiently far from the wavy cone.

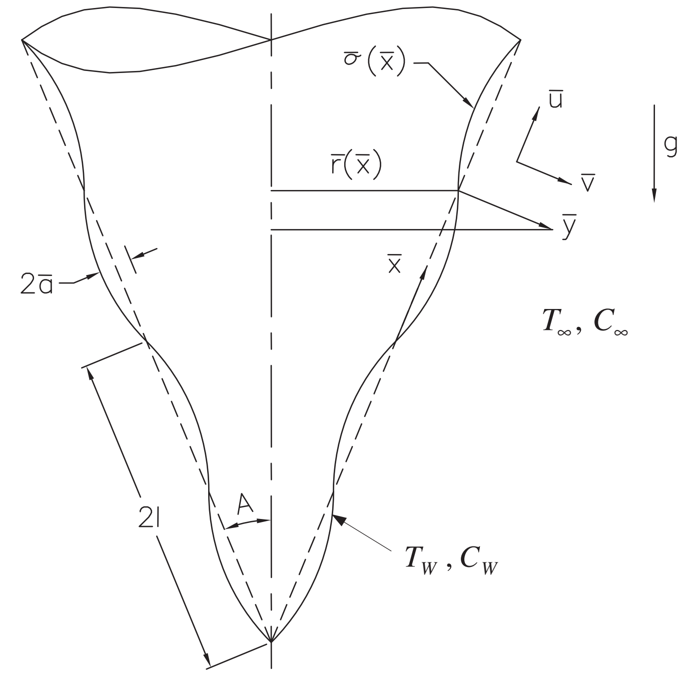

Fig. 1. Physical model and coordinates.

Based on the boundary layer and Boussinesq approximations, we can write the governing equations for boundary layer Darcy flow by free convection of a Newtonian fluid embedded in a porous medium near a vertical wavy cone with Soret and Dufour effects in two-dimensional Cartesian coordinates $(\bar{x}, \bar{y})$ as [5,22]

$$\frac{\partial(\bar{r}\bar{u})}{\partial\bar{x}} + \frac{\partial(\bar{r}\bar{v})}{\partial\bar{y}} = 0 \tag{2}$$

$$\frac{\partial\bar{u}}{\partial\bar{y}} - \frac{\partial\bar{v}}{\partial\bar{x}} = \frac{gK}{\nu}\left[\beta_T\frac{\partial T}{\partial\bar{y}}\cos A + \beta_C\frac{\partial C}{\partial\bar{y}}\cos A + \beta_T\frac{\partial T}{\partial\bar{x}}\sin A + \beta_C\frac{\partial C}{\partial\bar{x}}\sin A\right] \tag{3}$$

$$\bar{u}\frac{\partial T}{\partial\bar{x}} + \bar{v}\frac{\partial T}{\partial\bar{y}} = \alpha\left(\frac{\partial^2 T}{\partial\bar{x}^2} + \frac{\partial^2 T}{\partial\bar{y}^2}\right) + \overline{D}\left(\frac{\partial^2 C}{\partial\bar{x}^2} + \frac{\partial^2 C}{\partial\bar{y}^2}\right) \tag{4}$$

$$\bar{u}\frac{\partial C}{\partial\bar{x}} + \bar{v}\frac{\partial C}{\partial\bar{y}} = D_M\left(\frac{\partial^2 C}{\partial\bar{x}^2} + \frac{\partial^2 C}{\partial\bar{y}^2}\right) + \overline{S}\left(\frac{\partial^2 T}{\partial\bar{x}^2} + \frac{\partial^2 T}{\partial\bar{y}^2}\right) \tag{5}$$

The boundary conditions are written as

$$T = T_w, C = C_w, \bar{v} = 0 \text{ on } \bar{y} = \bar{\sigma}(\bar{x}) = \bar{a}\,\sin(\pi\bar{x}/l) \tag{6}$$

$$C \to C_\infty, T \to T_\infty, \bar{u} \to 0 \text{ as } \bar{y} \to \infty. \tag{7}$$

Here $\bar{u}$ and $\bar{v}$ are the volume-averaged velocity components in the $\bar{x}$ and $\bar{y}$ directions, respectively. T and C are the volume-averaged temperature and concentration, respectively. β_T and β_C are the coefficients for thermal expansion and for concentration expansion of the saturated porous medium, respectively. ν and K are the kinematic viscosity of the fluid and the permeability of the porous medium, 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