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Effect of Thermophoresis on Heat and Mass Transfer by Convective Flow along a Sinusoidal Wavy Surface

B. Mallikarjuna*[1], S.V.S.S.N.V.G. Krishna Murthy[2] and Ali. J. Chamkha[3]
[1]Department of Mathematics, BMS College of Engineering, Bangalore, Karnataka -560019
[2] Department of Applied Mathematics, Defense Institute of Advanced Technology, Deemed University, Pune, India-411025
[3]Manufacturing Engineering Department, Public Authority for Applied Education and Training, Shuweikh, Saudi Arabia, 70654 Kuwait

Corresponding author e-mail: mallikarjunab.maths@bmsce.ac.in

Abstract - A mathematical model has been developed for multi-physical transport of free and mixed convective heat and mass transfer flow of a viscous fluid near sinusoidal wavy surface in a fluid saturated porous medium by taking into account of thermophoresis effect. The Darcy's law can be used to describe the saturated porous medium. The governing nonlinear coupled equations representing transport of mass, momentum, energy and species are transformed into a smooth surface by using a suitable transformation. Then the transformed partial differential equations are converted into coupled nonlinear ordinary differential equations and then solved numerically by using shooting technique. The numerical results compared with previously published work and the results are approximately found to be a very good agreement. It is noted that concentration distribution is more pronounced due to the effect of thermophoresis and it is more significant with varying values of the parameters in both cases of assisting flow and opposing flow. The numerical results reported for fluid velocity, temperature and concentration profiles and the local Nusselt number and Sherwood number reveal interesting phenomenon, and some of these qualitative results are illustrated through graphs.

Keywords - Vertical wavy surface; thermophoresis effect; free and mixed convection; Darcy porous media

I. INTRODUCTION

The prediction of heat transfer from irregular surfaces is a topic of fundamental importance. Irregular geometries in manufacturing frequently occur in practice. Irregular surfaces are encountered in many practical applications for which convective heat transfer is of interest. For instance: condensation process, heat transfer devices such as flat plate solar collectors and flat plate condensers in refrigerators, grain storage container where walls are buckled. The presence of roughness elements disturb the flow and alter the heat transfer rate. At first, Yao [1]-[2] investigated free and mixed convection along a vertical wavy surface with uniform wall temperature and heat flux and he proposed a simple coordinate transformation to transform the effect of wavy surface on governing equations. Recently, Lakshminarayana and Sibanda [3] and Rathish Kumar and Krishna Murthy [4] considered Darcy and non-Darcy principle respectively to investigate Soret and Dufour effects on free convection along a vertical wavy surface. Siddiqa and Anwar [5] studied natural convective boundary layer flow over a wavy horizontal surface. Bhuvanavijaya and Mallikarjuna [6] investigated double dispersion effects on double diffusive flow along a vertical wavy surface in a porous medium. Srinivasacharya et.al [7] investigated radiation effect on convective flow of a viscous fluid over a wavy surface in a Darcy porous medium.

The study of thermophoresis plays a vital role in the species transport mechanism of several devices consists of small micron sized particles and large temperature gradient. The effect of the thermophoresis is so widespread in many practical applications in removing small particles from gas streams, in studying particulate material deposition on turbine blades and in determining exhaust gas particle trajectories from combustion devices. This shows that the thermophoresis is the dominant mass transfer mechanism in the modified chemical vapor deposition process which is utilized in germanium dioxide optical fiber performs and graded index silicon dioxide. Bakier and Reddy [8] considered the effects of thermophoresis and radiation on laminar flow along a semi-infinite vertical plate. Das [9] studied thermophoresis and chemical reaction effects on MHD micropolar fluid flow with variable properties. Kameswaran et.al [10] studied thermophoresis and non-linear effects on convective flow in a non-Darcy porous medium. Rashad et.al [11] studied thermophoresis effect on heat and mass transfer over a rotating cone in a porous medium.

In view of above applications, the authors envisage to investigate combined free and forced convection along a vertical wavy surface embedded in a fluid saturated porous medium under the influence of thermophoresis.

II. FORMULATION OF THE PROBLEM

We consider laminar, incompressible, steady-state two dimensional, boundary layer free and mixed convective flows over a vertical wavy surface embedded in a viscous fluid saturated porous medium. The wavy surface configuration along the vertical plate is defined as

$$\bar{y} = \bar{\sigma}(\bar{x}) = \bar{a}\sin\left(\frac{\pi\bar{x}}{l}\right)$$

where l is the characteristic length of the wavy surface and a is the amplitude of the wavy surface. The plate is maintained with constant temperature T_w and concentration C_w which are higher than the ambient fluid temperature T_∞ and concentration C_∞ at any arbitrary reference point in the medium. The porous medium is assumed to be isotropic and homogeneous and is saturated with viscous fluid which is locally thermodynamic equilibrium with the solid matrix. Darcy law states that pressure gradient is linearly proportional to volume averaged fluid velocity. Moreover, thermophoresis effect is incorporated. The fluid and porous media properties are assumed to be constant except the density in the buoyancy term in momentum equation. Under the above assumptions and using the Oberbeck-Boussinesq approximation, Darcy law model, the governing boundary layer equations for the conservation of mass, momentum, energy and concentration in two dimensional Cartesian forms $\left(\bar{x}, \bar{y}\right)$ are as follows:

$$\frac{\partial \bar{u}}{\partial \bar{x}} + \frac{\partial \bar{v}}{\partial \bar{y}} = 0 \qquad (1)$$

$$\frac{\partial \bar{u}}{\partial \bar{y}} = \frac{\partial \bar{v}}{\partial \bar{x}} + \frac{Kg}{\upsilon}\left(\beta_t \frac{\partial T}{\partial \bar{y}} + \beta_c \frac{\partial C}{\partial \bar{y}}\right) \qquad (2)$$

$$\bar{u}\frac{\partial T}{\partial \bar{x}} + \bar{v}\frac{\partial T}{\partial \bar{y}} = \alpha\left(\frac{\partial^2 T}{\partial \bar{x}^2} + \frac{\partial^2 T}{\partial \bar{y}^2}\right) \qquad (3)$$

$$\bar{u}\frac{\partial C}{\partial \bar{x}} + \bar{v}\frac{\partial C}{\partial \bar{y}} = D\left(\frac{\partial^2 C}{\partial \bar{x}^2} + \frac{\partial^2 C}{\partial \bar{y}^2}\right) - \frac{\partial}{\partial \bar{x}}\left(U_T C\right) - \frac{\partial}{\partial \bar{y}}\left(V_T C\right) \qquad (4)$$

The corresponding boundary conditions are

$$\left.\begin{array}{l} \text{at } \bar{y} = \bar{\sigma}(\bar{x}) = \bar{a}sin\left(\frac{\pi \bar{x}}{l}\right), \quad \bar{u} = 0;\ \bar{v} = 0;\ T = T_w;\ C = C_w \\ \text{as } \bar{y} \to \infty, T \to T_\infty; C \to C_\infty;\ \bar{u} \to 0 \quad \text{(for free convection)} \\ \qquad \bar{u} \to U_\infty \text{ (for mixed convection)} \end{array}\right\}$$

(5)

where $\bar{u}$ and $\bar{v}$ are the volume averaged velocity components in $\bar{x}$ and $\bar{y}$ directions, respectively. Properties μ is the variable viscosity, $\nu = \frac{\mu}{\rho}$ is the kinematic viscosity of the fluid, ρ is the fluid density and K is the permeability of the porous medium, β_t is the coefficients of thermal expansion, β_c is the coefficient of concentration expansion, D is the mass diffusivity of the saturated porous medium and g is the acceleration due to gravity. In Eq. (4) U_T and V_T are thermophoretic velocities which can be written as (Wu and Greif [12])

$$U_T = -\frac{k\nu}{T_r}\frac{\partial T}{\partial \bar{x}} \text{ and } V_T = -\frac{k\nu}{T_r}\frac{\partial T}{\partial \bar{y}} \qquad (6)$$

where k is the thermophoretic coefficient which ranges in the values between 0.2 and 1.2 and is defined as (Talbot et al. [13])

$$k = \frac{2C_s\left(\lambda_g/\lambda_p + C_t Kn\right)\left[1 + Kn\left(C_1 + C_2 e^{-C_3/Kn}\right)\right]}{\left(1 + 3C_m Kn\right)\left(1 + 2\lambda_g/\lambda_p + 2C_t Kn\right)}$$

where C_1, C_2, C_3, C_m, C_s, C_t are constants, λ_g and λ_p are thermal conductivities of fluid and diffused particles, respectively and Kn is the Knudsen number.

We define the stream function $\bar{\psi}$, which is to be satisfied the continuity equation (1) such that $\bar{u} = \frac{\partial \bar{\psi}}{\partial \bar{y}}, \bar{v} = -\frac{\partial \bar{\psi}}{\partial \bar{x}}$. In order to write the governing boundary layer equations in non-dimensional form, we introduce the following dimensionless variables

$$\left.\begin{array}{l} x = \bar{x}/l, \quad y = \bar{y}/l, \quad a = \bar{a}/l, \quad \sigma = \bar{\sigma}/l \\ \psi^* = \bar{\psi}/\alpha, \quad \theta = \dfrac{T - T_\infty}{T_w - T_\infty}, \quad \phi = \dfrac{C - C_\infty}{C_w - C_\infty} \end{array}\right\} \qquad (7)$$

Using Eqs. (6) and (7), Eqs. (2) - (4) becomes

$$\frac{\partial^2 \psi^*}{\partial y^2} + \frac{\partial^2 \psi^*}{\partial x} = Ra\left(\frac{\partial \theta}{\partial y} + N\frac{\partial \phi}{\partial y}\right) \qquad (8)$$

$$\frac{\partial \psi^*}{\partial y}\frac{\partial \theta}{\partial x} - \frac{\partial \psi^*}{\partial x}\frac{\partial \theta}{\partial y} = \frac{\partial^2 \theta}{\partial x^2} + \frac{\partial^2 \theta}{\partial y^2} \qquad (9)$$

$$Le\left(\frac{\partial \psi^*}{\partial y}\frac{\partial \phi}{\partial x} - \frac{\partial \psi^*}{\partial x}\frac{\partial \phi}{\partial y}\right) = \frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial y^2} - Sc\tau\left(\frac{\partial^2 \theta}{\partial x^2}\phi + \frac{\partial^2 \theta}{\partial y^2}\phi + \frac{\partial \theta}{\partial x}\frac{\partial \phi}{\partial x} + \frac{\partial \theta}{\partial y} \cdots\right.$$

(10)

where $Ra = \frac{g\beta_t K(T_w - T_\infty)l}{\alpha\nu}$ is the local Darcy-Rayleigh number, $N = \frac{\beta_c(C_w - C_\infty)}{\beta_t(T_w - T_\infty)}$ is the buoyancy ratio, $Le = \frac{\alpha}{D}$ is the Lewis number, $\tau = -\frac{k}{T_r}(T_w - T_\infty)$ is the thermophoretic parameter, and $Sc = \frac{\nu}{D}$ is the Schmidt number.

The associated boundary conditions are given by

$$\left.\begin{array}{l} \text{at } y = a\ sin(x), \quad \theta = 1, \quad \phi = 1, \quad \psi^* = 0 \\ \text{as } y \to \infty, \quad \theta \to 0, \quad \phi \to 0, \quad \psi_y^* \to 0 \quad \text{(for free convection),} \\ \qquad \psi_y^* \to \dfrac{\alpha}{l}U_\infty \text{ (for mixed convection).} \end{array}\right\}$$

(11)

We can transfer the effect of wavy surface from the boundary conditions into governing equations by employing suitable coordinate transformation with boundary layer scaling, for the case of free and mixed convection. The Cartesian coordinates (x, y) are transformed into the new variables (ξ, η).

Free Convection

We incorporate the effect of wavy surface and the usual boundary layer scaling into the governing equations (8) – (11) for free convection, using the transformations:

$$x = \xi, \quad \eta = \frac{y - asin(x)}{\xi^{1/2}\left(1 + a^2cos^2\xi\right)Ra^{-1/2}}, \quad \psi^* = \xi^{1/2}Ra^{1/2}f. \qquad (12)$$

and letting Ra→∞, we obtain the following boundary layer equations:

$$f'' = \left(\theta' + N\phi'\right) \qquad (13)$$

$$\theta'' + \frac{1}{2} f \theta' = 0 \quad (14)$$

$$\phi'' + \left(\frac{1}{2} Le\, f - Sc\, \tau\, \theta'\right)\phi' - Sc\, \tau\, \phi\, \theta'' = 0 \quad (15)$$

where prime denotes differentiation with respect to $\hat{\eta}$.

The associated boundary conditions are

$$\left.\begin{array}{l} f = 0, \quad \theta = 1, \quad \text{and} \quad \phi = 1 \quad \text{at} \quad \hat{\eta} = 0 \\ f' \to 0, \quad \theta \to 0 \quad \text{and} \quad \phi \to 0 \quad \text{as} \quad \hat{\eta} \to \infty \end{array}\right\} \quad (16)$$

Mixed Convection

We incorporate the effect of wavy surface and the usual boundary layer scaling into the governing equations (8) – (11) for mixed convection, using the transformations

$$x = \xi, \quad \eta = \frac{y - a\sin(x)}{\xi^{1/2}\left(1 + a^2 cos^2 \xi\right) Pe^{-1/2}}, \quad \psi^* = \xi^{1/2} Pe^{1/2} f(\eta).$$

(17)

and letting Pe→∞, we obtain the following boundary layer equations:

$$f'' = \Delta\left(\theta' + N\phi'\right) \quad (18)$$

$$\theta'' + \frac{1}{2} f \theta' = 0 \quad (19)$$

$$\phi'' + \left(\frac{1}{2} Le\, f - Sc\, \tau\, \theta'\right)\phi' - Sc\, \tau\, \phi\, \theta'' = 0 \quad (20)$$

where prime denotes differentiation with respect to η.

The associated boundary conditions are

$$\left.\begin{array}{l} f = 0, \quad \theta = 1, \quad \text{and} \quad \phi = 1 \quad \text{at} \quad \eta = 0 \\ f' \to 1, \quad \theta \to 0 \quad \text{and} \quad \phi \to 0 \quad \text{as} \quad \eta \to \infty \end{array}\right\} \quad (21)$$

The engineering design quantities of physical interest include the Nusselt number and the Sherwood number which are defined as

$$Nu_\xi = \frac{-\theta'(0) Ra_\xi^{1/2}}{(1 + a^2\cos^2(\xi))^{1/2}} \quad and \quad Sh_\xi = \frac{-\phi'(0) Ra_\xi^{1/2}}{(1 + a^2\cos^2(\xi))^{1/2}}$$

(for free convection)

$$Nu_\xi = \frac{-\theta'(0) Pe_\xi^{1/2}}{(1 + a^2\cos^2(\xi))^{1/2}} \quad and \quad Sh_\xi = \frac{-\varphi'(0) Pe_\xi^{1/2}}{(1 + a^2\cos^2(\xi))^{1/2}}$$

(for mixed convection) (22)

III. NUMERICAL METHOD

The flow governing nonlinear non-homogeneous coupled differential equations (13) – (15) and (18) – (20) together with boundary conditions (16) and (22) are locally similar and then solved numerically by employing the shooting technique (Srinivasacharya et.al [14] and Mallikarjuna et al. [15]) that uses RK4 and Newton method. In the present study the edge of the boundary layer (η at ∞) has been taken between 4.0 and 8.0, where velocity, temperature and concentration profiles approach 1 or 0 as given in the boundary conditions. The computation values has been taken with the first step size Δη=0.001. A convergence criterion based on the relative difference between two consecutive iterations for the variation of velocity, temperature and concentration distribution is employed. When the difference reaches 10^{-6}, the solution is assumed to be converged and the iteration process is terminated. The numerical method is not described for brevity. The present results are compared with those in Cheng [16] for free convection in the absence of thermophoresis parameter by neglecting waviness (*a*, i.e. vertical flat surface) and these results are found to be good agreement, as shown in Table 1 (for free convection).

IV. RESULTS AND DISCUSSIONS

The numerical solutions are presented graphically for various physical parameters, the Schmidt number and the thermophoresis parameter on the non-dimensional flow velocity, temperature and concentration distributions as well as the Nusselt number and the Sherwood number, as shown in Figs. (1) – (4).

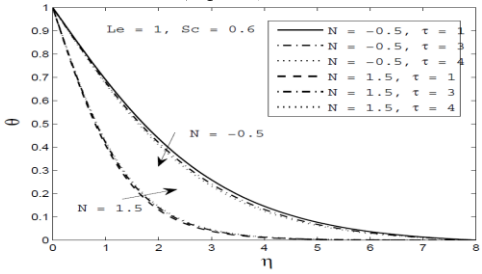
Table 1: Comparison of Nusselt and Sherwood numbers for, τ=0 at N=1, and Le=0.5.

Parameters		$Nu_x Ra_x^{-1/2}$	$Sh_x Ra_x^{-1/2}$	$Nu_x Ra_x^{-1/2}$	$Sh_x Ra_x^{-1/2}$
Le	**N**	**Cheng [16]**	**Present**	**Cheng [16]**	**Present**
1	4	0.992	0.9923	0.992	0.9923
10	4	0.681	0.6811	3.290	3.2913
4	2	0.650	0.6509	1.624	1.6238
4	3	0.728	0.7285	1.852	1.8519

Free convection

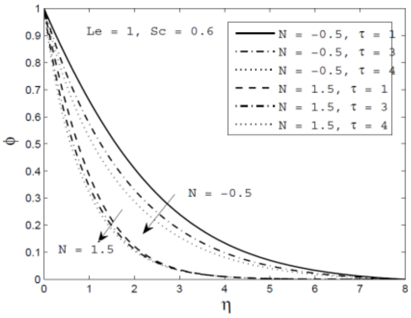
Figure 1 shows the velocity, temperature and concentration distributions for different values of the thermophoresis parameter (τ). It is worth mentioning here that the thermophoresis parameter τ indicates cold and hot surfaces for positive and negative values, respectively. A hot surface repels the sub-micron sized particles from it, and therefore, the thermophoresis parameter causes to blow the concentration boundary layer away from the surface for hot surfaces. Increasing the thermophoresis parameter leads to enhance the hydrodynamic velocity boundary layer thickness for N < 0 but for N < 0 opposite results are obtained and reported as shown in Fig.1a. Conversely, the temperature distribution is decreased significantly for the cases of N < 0 (Fig. 1b) while it is enhanced for N > 0 with an increase in the value of τ. This means that the effect of increasing the thermophoresis parameter τ is limited to increasing the wall slope of the concentration profile, while decreasing the concentration. This is true only for lesser values of the Schmidt number for which the Brownian diffusion effect is more pronounced than the convection effect. Hence, the influence of the thermophoresis parameter alters the concentration boundary layer significantly. From Fig. 1c, we observe that the concentration distribution is decreased with an increase in the thermophoresis parameter for both cases of N > 0 and N < 0. Thus, small particles suspended in a gas over a turbine blade surface can cause erosion and surface roughness, particularly increasing the particle size.

Figures 2 illustrate the axial distributions of the Nusselt number and the Sherwood number for different values of the thermophoresis parameter (τ). Fig. 2a shows that an increase in the value of τ results in a strong increase in the Nusselt number for N < 0 but the Nusselt number reduces strongly with an increase in the value of τ for N > 0. The amplitude of the Sherwood number increases for both cases of N > 0 and N < 0 (fig. 2b).



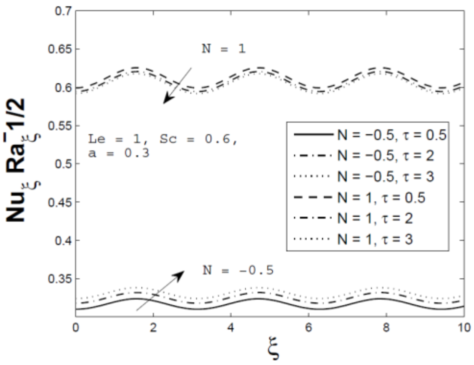
a) Velocity profile

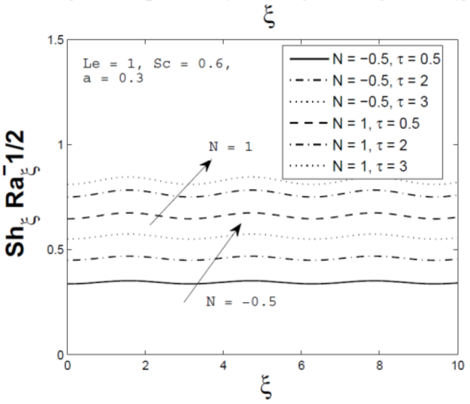
b) Temperature profile



c) Concentration profile

Fig. 1: Velocity, Temperature and Concentration profiles for different values of τ.



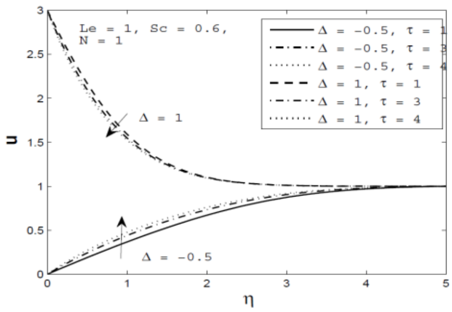


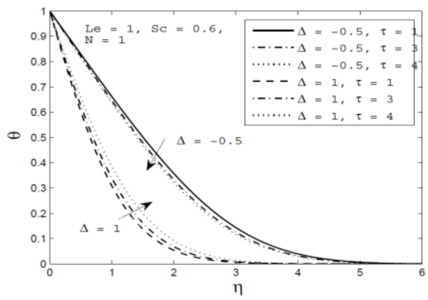
a) Nusselt number
b) Sherwood number

Fig. 2: Axial distribution of Nusselt number and Sherwood number for different values of τ.

Mixed Convection

The mixed convective parameter $\Delta = \dfrac{Ra}{Pe}$ in Eq. (18) produces two opposite signs because buoyancy can be assisting the external flow (aiding flow) and in the other case it can be opposing the flow (opposing flow). It is important to note that the flow is dominated by free convection when $\Delta \gg 1$, while the flow is dominated by forced convection when $\Delta \ll 1$, and the case when $\Delta = 1$ where free and forced convection are of equal importance is dominated by the mixed convection regime. The effects of the thermophoresis parameter (τ) on the velocity, temperature and the concentration distributions are presented in Figs. 3. As the value of τ increases, there is a strong increment in the velocity with a distance from boundary layer, i.e. it accelerates the flow for the case of opposing flow but this phenomenon is reversed for the case of aiding or assisting flow as shown in Fig. 3a. The velocity in all cases reaches a maximum value at the wall and then decreases smoothly up to reach unity in the free stream. The progression from τ=1 through τ=3 up to τ=4 results in a distinct deceleration in the temperature profile, i.e. the thermal boundary thickness is reduced strongly, as seen in Fig. 3b for the case of opposing flow while a clear acceleration is produced in the temperature profile with the increase in τ for the aiding or assisting flow case. Fig. 3c shows that the concentration is significantly reduced in the boundary layer regime for both cases of assisting and opposing flows with increasing values of τ.





a) Velocity profile b) Temperature profile

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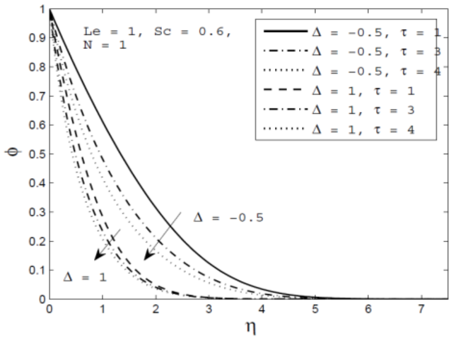
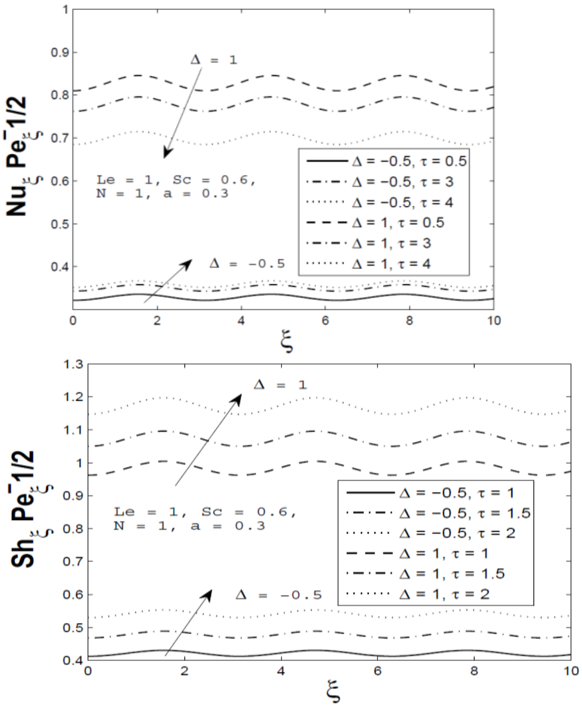


c) Concentration profile

Fig. 3: Velocity, Temperature and Concentration profiles for different values of τ.



a) Nusselt number

b) Sherwood number

Fig. 4: Axial distribution of Nusselt number and Sherwood number for different values of τ.

The influence of the thermophoresis parameter on the Nusselt number and the Sherwood number with the stream-wise coordinate is depicted in Figs. 4. From Fig. 4a, increasing the value of τ is observed to strongly accelerate the Nusselt number for the opposing flow case while the Nusselt number reduces with the increase in the value of τ for the aiding or assisting flow case. As shown in Fig. 4b, the Sherwood number increases with increasing values of τ for both cases of assisting and opposing flows.

V. CONCLUSION

An investigation of the effect of thermophoresis on free and mixed convection flow along a sinusoidal wavy surface embedded in a porous medium is carried out in the present work. Numerical method is employed to solve the governing boundary layer equations. The results are reported graphically for various physical parameters. The main results of this investigation are summarized as follows:

1. **For free convection:** Increases in the values of the thermophoresis parameter result in higher fluid velocities and Nusselt numbers but lower values of the temperature profile in the boundary layer for N < 0 whereas the opposite results are noted for N > 0. However, increasing the thermophoresis parameter results in depreciation in the concentration profile while it accelerates the flow mass transfer rate for both cases of N > 0 and N < 0.
2. **For mixed convection:** Increasing the thermophoresis parameter causes the velocity profile and the Nusselt number to increase while the temperature profile results are conversely decreased with the increase in the value of τ for the opposing flow case but the opposite results are noted for the aiding or assisting flow case. An increase in the value of τ suppresses the actual mass and accelerates the mass transfer rate for both cases of assisting and opposing flows.

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