THERMOPHORESIS PARTICLE DEPOSITION AND VARIABLE VISCOSITY EFFECTS ON NON-DARCY FREE CONVECTION IN A FLUID SATURATED POROUS MEDIA WITH UNIFORM SUCTION/INJECTION

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***Abstract*— The main purpose of this investigation is to study the effect of thermophoresis particle deposition in natural convection heat and mass transfer over a vertical flat plate embedded in a fluid-saturated porous medium with variable viscosity effect. The viscosity of the fluid is assumed to be an inverse linear function of the fluid temperature. A boundary-layer analysis is employed to derive the non-dimensional governing equations. The governing equations for this contribution are transformed into a set of non-similar equations and solved numerically using an implicit finite difference technique. Comparisons with previously published work on special cases of the problem are performed and the results are found to be in excellent agreement. A parametric study illustrating the influence of the thermophoresis parameter, thermophoretic coefficient, viscosity-variation parameter, buoyancy ratio the Lewis number, Prandtl number, transpiration parameter and Grashof number on the fluid velocity, temperature and solute concentration profiles as well as the Sherwood number and the wall thermophoretic deposition velocity is conducted.**

Keywords — **Thermophoresis, Porous media, Variable viscosity, Natural convection, Non-Darcy, Suction or injection.**

I. INTRODUCTION

Double-diffusive convection caused by buoyancy due to temperature and concentration gradients in a fluid-saturated porous medium occurs in a lot of geophysical, geothermal and industrial applications, such as the migration of moisture through air contained in fibrous insulations and the underground spreading of chemical contaminants through water- saturated soil.

Moreover, thermophoresis is a phenomenon which causes small particles to be driven away from a hot surface and towards a cold one. Small particles, such as dust, when suspended in a gas with a temperature gradient, experience a force in the direction opposite to the temperature gradient. This phenomenon has many practical applications in removing small particles from gas streams, in determining exhaust gas particle trajectories from combustion devices, and in studying the particulate material deposition on turbine blades. It has been shown that thermophoresis is the dominant mass transfer mechanism in the modified chemical vapor deposition process used in the fabrication of optical fiber perform and is also important in view of its relevance to postulated accidents by radioactive particle deposition in nuclear reactors. In many industries the composition of processing gases may contain any of an unlimited range of particle, liquid, or gaseous contaminants and may be influenced by uncontrolled factors of temperature and humidity. When such an impure gas is bounded by a solid surface, a boundary layer will develop, and energy and momentum transfer gives rise to temperature and velocity gradients. Mass transfer caused by gravitation, molecular diffusion, eddy diffusion, and inertial impact results in deposition of the suspended components onto the surface.

Goren (1977) was one of the first to study the role of thermophoresis in laminar flow of a viscous incompressible fluid. He used the classical problem of flow over a flat plate to calculate the deposition rates and showed that substantial changes in surface deposition can be obtained by increasing the difference between the surface and free stream temperature. Shen (1989) studied the problem of thermophoretic deposition of small particles on to cold surfaces in two-dimensional and axisymmetric cases. Mahdy and Hady (2009) reported the effect of thermophoretic deposition in non-Newtonian free convection flow over a vertical plate with magnetic field effect. Jayaraj *et al.* (1999) analyzed thermophoresis in natural convection with variable properties for a laminar flow over a cold vertical flat plate. Chamkha *et al.* (2006) analyzed the effect of heat generation or absorption on thermophoretic free convection boundary layer from a vertical flat plate embedded in a porous medium. Seddeek (2006) studied the influence of viscous dissipation and thermophoresis on Darcy Forchheimer mixed convection in a fluid-saturated porous media. Selim *et al.* (2003) studied the effect of surface mass flux on mixed convective flow past a heated vertical flat permeable plate with thermophoresis. Epstein *et al.* (1985) investigated the thermophoretic transport of small particles through a free convection boundary layer adjacent to a cold, vertical deposition surface in a viscous incompressible fluid. Garg and Jayaraj (1988) analyzed the thermophoretic transport of small particles in forced convection flow over an inclined plate. Chamkha and Pop (2004) looked to the effect of thermophoresis particle deposition in free convection boundary layer from a vertical flat plate embedded in a porous medium; the steady free convection over an isothermal vertical circular cylinder embedded in a fluid-saturated porous medium in the presence of the thermophoresis particle deposition effect was analyzed in Chamkha *et al.* (2004). Wang (2006) studied the combined effects of inertia and thermophoresis on particle deposition onto a wafer with wavy surface. Opiolka *et al.* (1994) analyzed the combined effects of electrophoresis and thermophoresis on particle deposition onto flat surface. Alam *et al.* (2008, 2009) reported the effects of variable suction and thermophoresis on steady MHD combined free-forced convective heat and mass transfer flow over a semi-infinite permeable inclined plate in the presence of thermal radiation. On the other hand, the impetuous research on convective flows in porous media is surveyed in the books by Ingham and Pop (1998, 2002) and Nield and Bejan (1999).

The objective of the present paper is to study the effects thermophoresis particle deposition in free convective heat and mass transfer flow over a vertical flat plate embedded in porous media saturated with a Newtonian fluid considering a viscosity proportional to an inverse linear function of temperature.

II. MATHEMATICAL DESCRIPTION

Consider the problem of steady-state two-dimensional, non-Darcian boundary-layer flow over a vertical flat plate embedded in a fluid-saturated porous medium driven by buoyancy due to temperature and concentration gradients. The x–axis is measured along the surface from the point where the surface originates and the y–axis is measured normal to it. Moreover, the fluid properties are assumed to be constant except for the density variations in the buoyancy force term and the viscosity variations with temperature. Fluid suction or injection is imposed at the plate surface. The temperature of the surface is held uniform at T_w which is higher than the ambient temperature T_∞. The species concentration at the surface is maintained uniform at C_w, and that of the ambient fluid is assumed to be C_∞. The effect of thermophoresis is being taken into account to help in the understanding of the mass deposition variation on the surface. Invoking the boundary-layer and Boussinesq approximations, the governing equations which are based on the balance laws of mass, momentum, energy and species for non-Darcy's flow over a vertical flat plate in a homogenous porous medium saturated with a Newtonian fluid with temperature-dependent viscosity can be written as:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \tag{1}$$

$$\frac{\partial(\mu u)}{\partial y}+\rho_\infty \tilde{K}\frac{\partial u^2}{\partial y}=\rho_\infty K g\left(\beta\frac{\partial T}{\partial y}+\tilde{\beta}\frac{\partial C}{\partial y}\right) \tag{2}$$

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\alpha\frac{\partial^2 T}{\partial y^2} \tag{3}$$

$$u\frac{\partial C}{\partial x}+v\frac{\partial C}{\partial y}=D\frac{\partial^2 C}{\partial y^2}-\frac{\partial C v_t}{\partial y} \tag{4}$$

here, u, v are the volume-averaged velocity components in the x- and y- directions, respectively, such that are defined as $u=\partial\psi/\partial y$, $v=-\partial\psi/\partial x$, where ψ is the stream function, g is the acceleration due to gravity, β and $\tilde{\beta}$ are the coefficient of volume expansion and the volumetric coefficient of expansion with concentration respectively, K and $\tilde{K}$ are the permeability of the porous medium and inertial coefficients, α and D are the effective thermal diffusivity and mass diffusivity of the saturated porous medium. Furthermore, T and C are the temperature of the fluid and concentration. The effect of thermophoresis is usually prescribed by means of the average velocity, which a particle will acquire when exposed to a temperature gradient. In boundary layer flow, the temperature gradient in y–direction is very much larger than in the x–direction, and therefore only the thermophoretic velocity in y–direction is considered. In consequence the themophretic velocity can be expressed in the following form

$$v_t=-k\frac{\nu}{T}\frac{\partial T}{\partial y} \tag{5}$$

where k is the thermophoretic coefficient which ranges in value from 0.2 to 1.2 as indicated by Batchelor and Shen (1985) and is defined from the theory of Talbot *et al.* (1980) by

$$\frac{2C_s(\lambda_g/\lambda_p+C_t Kn)\left\{1+Kn(C_1+C_2e^{-C_3/Kn}\right\}}{(1+3C_m Kn)(1+2\lambda_g/\lambda_p+2C_t Kn)}$$

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

In addition, the property μ is the dynamic fluid viscosity proportional to an inverse linear function of temperature, and ρ is the fluid density. Following Lings and Dybbs (1992), it is assumed that the viscosity varies with temperature in the following form

$$\mu=\frac{\mu_\infty}{1+a(T-T_\infty)} \tag{6}$$

where a is a viscosity-variation constant and μ_∞ is the viscosity of the ambient fluid.

The appropriate boundary conditions are given by

$$y=0;\ v=-v_w,\ T=T_w,\ C=C_w \tag{7a}$$

$$y\to\infty;\ u\to 0,\ T\to T_\infty,\ C\to C_\infty \tag{7b}$$

It is convenient to transform the governing equations into dimensionless form. This can be done by introducing the following dimensionless variables

$$\xi=\frac{x}{l},\ \eta=\frac{y}{l}\left(\frac{Ra}{\xi}\right)^{1/2},\ \psi=\alpha(\xi Ra)^{1/2}f(\eta) \tag{8a}$$

$$\theta(\eta)=\frac{T-T_\infty}{T_w-T_\infty},\quad \phi(\eta)=\frac{C-C_\infty}{C_w-C_\infty} \tag{8b}$$

Substituting this transformation into governing Eqs. (2)-(5) turn into

$$\frac{1}{1+\gamma\theta}f''-\frac{\gamma}{(1+\gamma\theta)^2}f'\theta'+2Grf'f''=\theta'+N\phi' \tag{9}$$

$$\theta''+\frac{1}{2}f\theta'=0 \tag{10}$$

$$Le^{-1}\phi''+\frac{1}{2}f\phi'+\frac{1}{1+\gamma\theta}\frac{kPr}{N_t+\theta}\times\left(\theta'\phi'+\phi\theta''-\frac{\phi\theta'^2}{N_t+\theta}-\frac{\gamma\phi\theta'^2}{1+\gamma\theta}\right)=0 \tag{11}$$

In previous equations the primes denote partial derivative with respect to η only, and $\gamma=a(T_w-T_\infty)$ is the viscosity-variation parameter, $N=\tilde{\beta}(C_w-C_\infty)/\beta(T_w-T_\infty)$ is the buoyancy ratio parameter, $Ra=\rho_\infty Kg\beta(T_w-T_\infty)l/(\mu_\infty\alpha)$ is the Rayleigh number, $Le=\alpha/D$ is the Lewis number, $Pr=v_\infty/\alpha$ is the Prandtl number, $Ra=K\tilde{K}g\beta(T_w-T_\infty)/(v_\infty)^2$ is the Grashof number, $N_t= T_\infty/(T_w-T_\infty)$ is the thermophoresis parameter.

The applied boundary conditions for the problem under consideration are

$$\eta=0;\ f(\eta)=f_w,\ \theta(\eta)=1,\ \phi(\eta)=1 \tag{12a}$$

$$\eta\to 0;\ f'(\eta)\to 0,\ \theta(\eta)\to 0,\ \phi(\eta)\to 0 \tag{12b}$$

where f_w is the dimensionless transpiration parameter, which is positive for suction and negative for blowing of the fluid through the surface. The results of practical interest in many applications are the wall thermophoretic deposition velocity at the wall V_{tw}, concentration profiles and mass transfer coefficient. The local mass transfer coefficient is expressed in term of local Sherwood number, which is given by

$$Sh_x=\frac{xq_m}{D(C_w-C_\infty)} \tag{13}$$

where q_m is the local mass transfer rate per unit surface area and q_m is defined as

$$q_m=-D\left.\frac{\partial C}{\partial y}\right|_{y=0} \tag{14}$$

Employing Eqs. (8) and (14), we get the Sherwood number in the following form

$$Sh_x Ra^{1/2}=-\xi^{1/2}\phi'(0) \tag{15}$$

The wall thermophoretic deposition velocity V_{tw} is given by

$$V_{tw}=-\frac{kPr}{N_t+1}\left(\frac{\partial\theta}{\partial\eta}\right)_{\eta=0} \tag{16}$$

III. RESULTS AND DISCUSSION

Since the governing boundary layer Eqs. (9)–(11) are highly nonlinear, a numerical treatment would be more appropriate. The system of transformed Eqs. (9)-(11) together with the boundary conditions (12) is numerically solved by employing an implicit finite difference method. The procedure is repeated until we get the results up to the desired degree of accuracy, namely 10^{-6}. In addition, in order to verify the accuracy of the present numerical method, the results are compared with those reported earlier by Chamkha and Pop (2004), Bejan and Khair (1985) and Cheng and Minkowycz (1977). The results of these comparisons are shown in Table 1. It can be seen from this table that an excellent agreement between the results exists. This lends confidence in the numerical results reported below. A number of results is obtained throughout this contribution. A representative set of results is presented graphically in Figures 1-18 in order to explore the various physical aspects of the problem. The default values of the other parameters considered are $N=1$, $Pr=6.2$, $k=0.7$, $Gr=5.0$, $Le=6.0$, $\gamma=1.0$, $Nt=100$ and $f_w=-1.0,1.0$ unless otherwise specified.

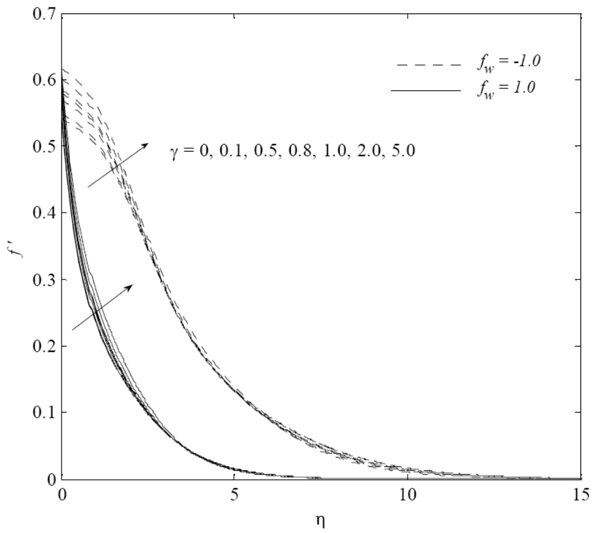

Fig. 1. Effect of viscosity-variation parameter (γ) on the fluid velocity distribution

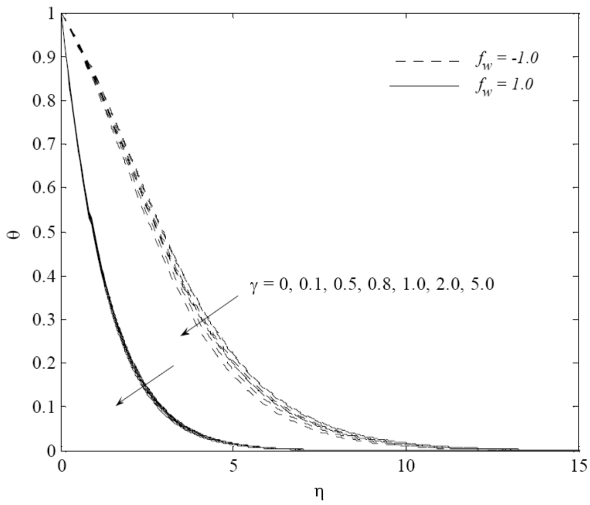

Fig. 2. Effect of viscosity-variation parameter (γ) on the temperature distribution

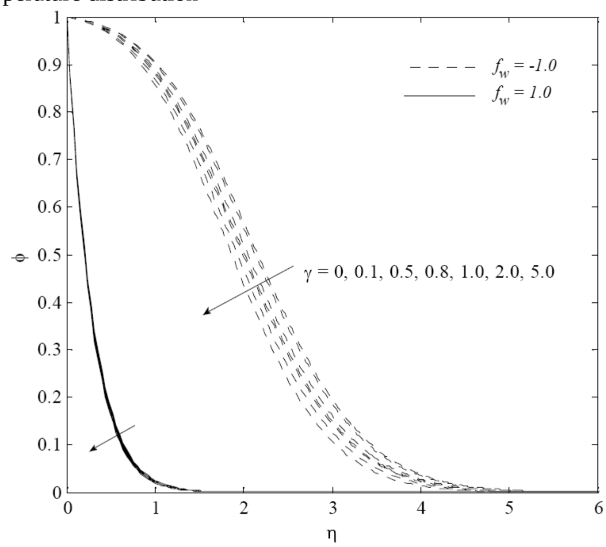

Fig. 3. Effect of viscosity-variation parameter (γ) on the concentration distribution

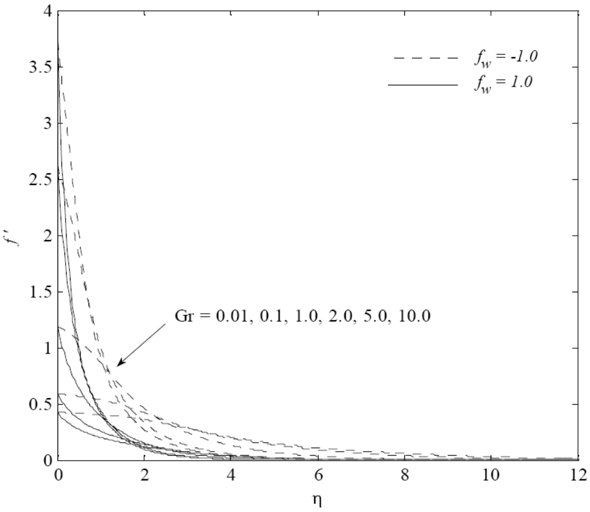

Fig. 4. Effect of Grasho number (*Gr*) on the velocity distribution

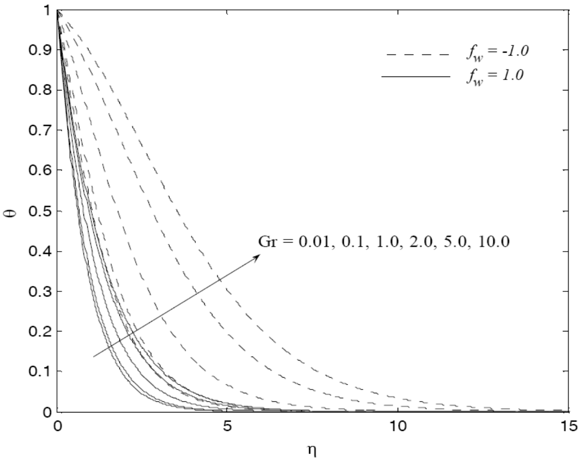

Fig. 5. Effect of Grasho number (*Gr*) on the temperature distribution

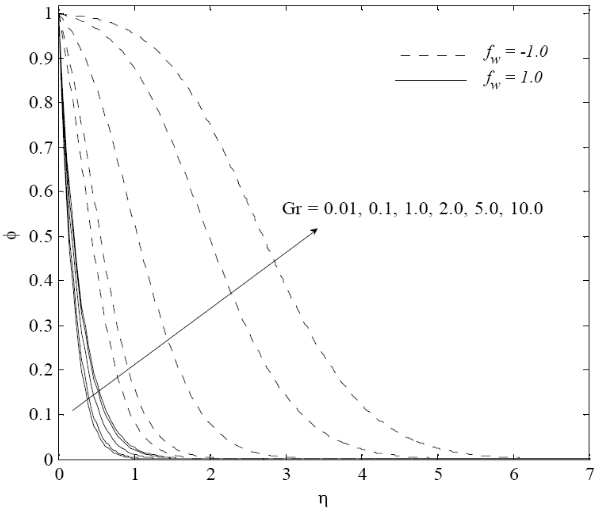

Fig. 6. Effect of Grasho number (*Gr*) on the concentration distribution

Figures 1-3 depict the effects of the viscosity-variation parameter γ on the fluid velocity, temperature and solute concentration profiles for both suction f_w>0 and injection f_w<0 cases, respectively. Figure 1 illustrates that an increase in the value of the viscosity-variation parameter tends to increase the peak of the velocity at the wall. Furthermore, Fig. 2 shows that a porous medium saturated with a fluid of higher viscosity-variation parameter has thinner thermal boundary layer and higher temperature gradient at the wall, thus

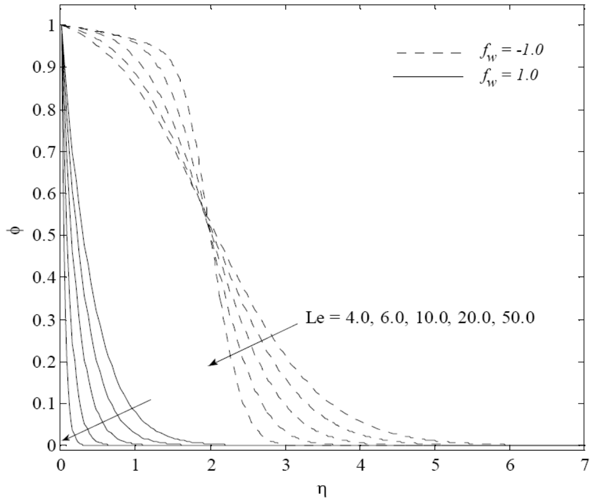

Fig. 7. Effect of Lewis number (*Le*) on the concentration distribution

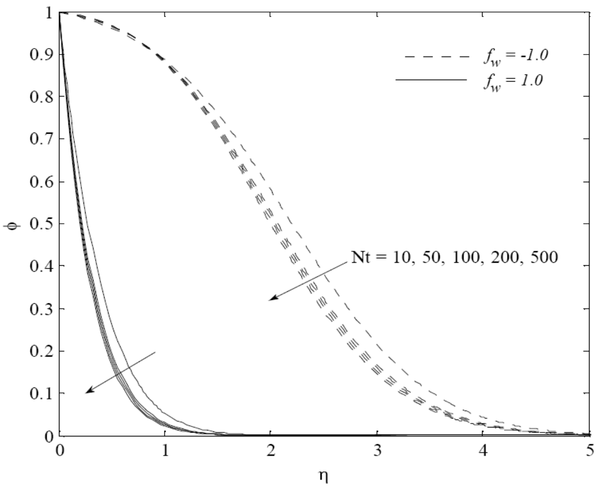

Fig. 8. Effect of thermophoresis parameter (*Nt*) on the concentration distribution

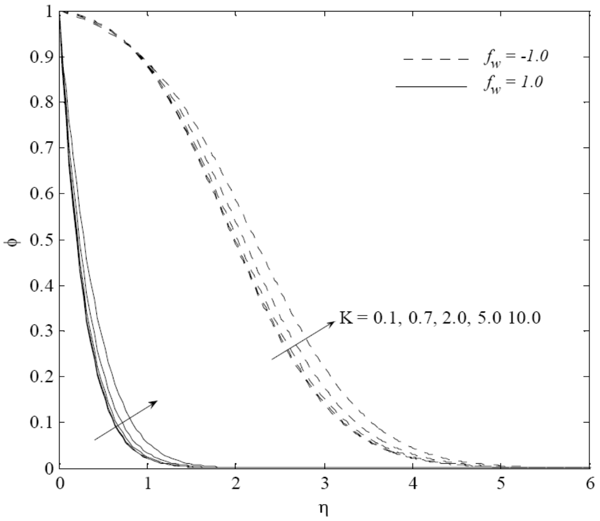

Fig. 9. Effect of themophoretic coefficient (*k*) on the concentration distribution

leading to higher heat transfer rate between the porous medium and the surface. Figure 3 shows that increasing the viscosity-variation parameter tends to decrease the concentration boundary-layer thickness, thus increasing the concentration gradient at the wall and increasing the mass transfer rate between the porous medium and the surface. Furthermore, higher values of transpiration parameter f_w produce lower values of fluid velocity, temperature and solute concentration distributions.

The effect of Grashof number on the fluid velocity, temperature and solute concentration distributions is illustrated through Figures 4-6. As it is shown that increasing Grashof number leads to decrease the peak of the velocity which occurs at the wall. This happens because the inertia term begins to have a pronounced effect for high Grashof numbers. Moreover increase in Grashof number leads to increase both of temperature and solute concentration distributions. Consequently the thermal and solutal boundary layer thicknesses reduced.

Figure 7 displays the effect of Lewis number Le on the concentration profiles for both suction and injection cases. The Lewis number is an important parameter in heat and mass transfer processes as it characterizes the ratio of thicknesses of the thermal and concentration boundary layers. Its effect on the species concentration has similarities to the Prandtl number effect on the temperature. Therefore, as expected, it is observed that as the Lewis number increases, the solute concentration decreases. In addition, increasing the Lewis number tends to decrease the concentration boundary layer thickness, thus increasing the mass transfer rate between the porous medium and the surface. The influences of the thermophoresis parameter *Nt* is plotted in Fig. 8, as it is observed from this figure that as the *Nt* increases, the solute concentration decreases, while increasing in thermophoretic coefficient *k* tends to increase of the solute concentration as shown in Fig. 9.

Figures 10-12 illustrate the effects of the buoyancy ratio parameter *N* on the fluid velocity, temperature and concentration profiles for both of suction and injection cases, respectively. It is observed that as the buoyancy ratio parameter increases, the peak of the velocity at the

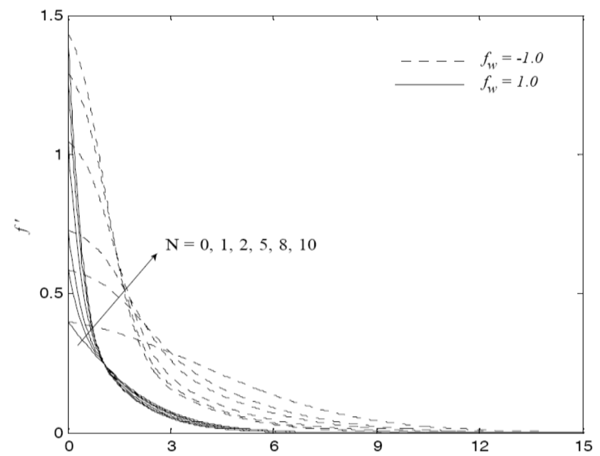

Fig. 10. Effect of buoyancy ratio parameter (*N*) on the fluid velocity distribution

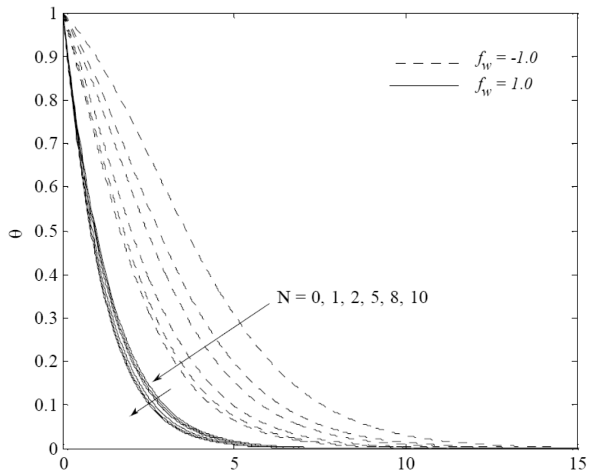

Fig. 11. Effect of buoyancy ratio parameter (*N*) on the temperature distribution

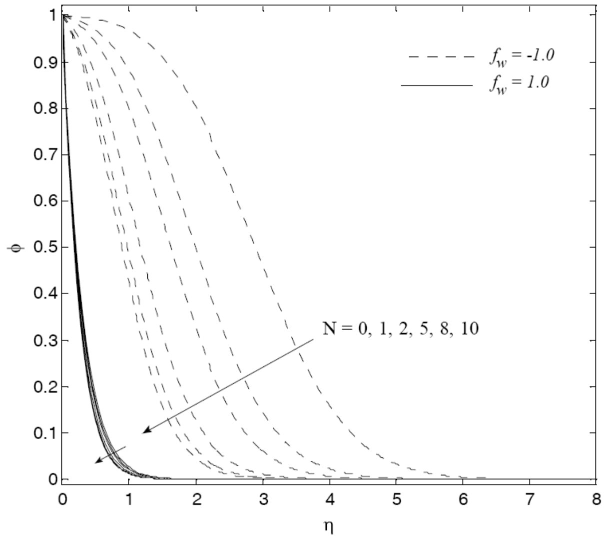

Fig. 12. Effect of buoyancy ratio parameter (*N*) on the concentration distribution

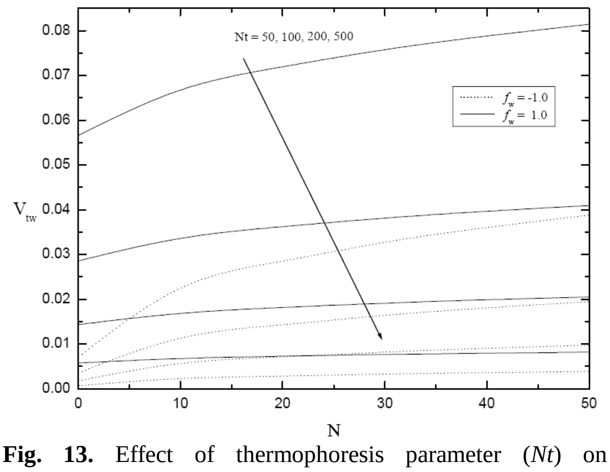

Fig. 13. Effect of thermophoresis parameter (*Nt*) on thermophoretic deposition velocity

Table 1. Comparison of $-\theta'(0)$

N	Cheng and Minkowycz (1977)	Bejan, and Khair (1985)	Chamk and Pop (2004)	Present
0	0.444	-------	0.44325	0.443748
1	-------	0.628	0.62783	0.627554

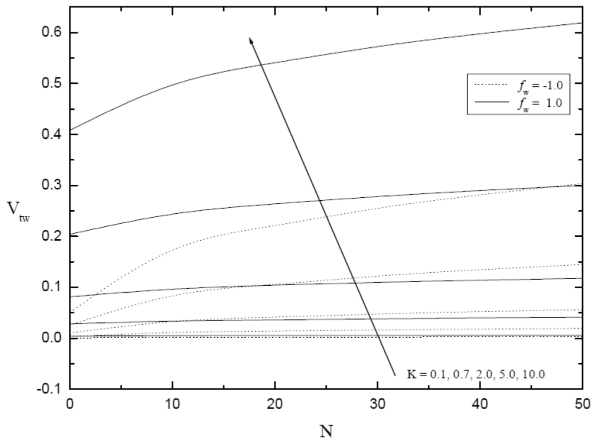

Fig. 14. Effect of thermophoretic coefficient (k) on thermophoretic deposition velocity

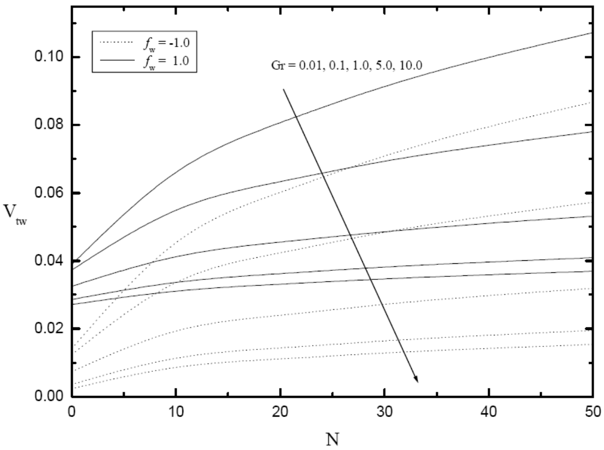

Fig. 15. Effect of Grashof number (Gr) on thermophoretic deposition velocity.

wall increases while both of the temperature profile and solute concentration profile decrease.

The variations of the thermophoretic deposition velocity at the wall V_{tw} against the buoyancy ration N for various values of the thermophoresis parameter, Nt=50, 100, 200 and 500 for both suction and injection cases is illustrated in Fig. 13. As shown, the thermophoretic deposition velocity at the wall tends to increase rapidly at first and gradually levels off the buoyancy ratio parameter are increased. It is clear from this figure that the thermophoretic deposition velocity at the wall decreases with increasing value of the buoyancy ration parameter. The same effect for Grashof number on the thermophoretic deposition velocity at the wall as it is observed from Fig. 15, that is, increase in Grashof number leads to decrease the thermophoretic deposition velocity at the wall. The effect of thermophoretic coefficient on the variations of the thermophoretic deposition velocity at the wall is depicted in Fig. 14. It is clear that the thermophoretic deposition velocity at the wall increases with increasing thermophoretic coefficient. Moreover the same effect for both of viscosity-variation parameter and Prandtl number as displayed in Figures 16 and 18.

Figure 17 depicts the variations of the local Sherwood number $-\phi'(0)$ against the buoyancy ratio parameter for various values of the Lewis number Lc= 1.0, 4.0, 6.0,

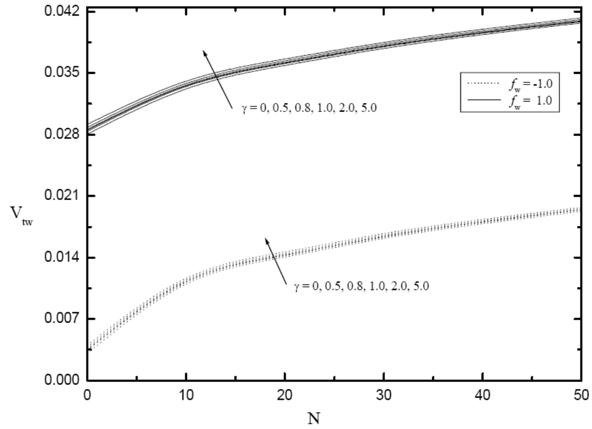

Fig. 16. Effect of viscosity-variation parameter (γ) on thermophoretic deposition velocity

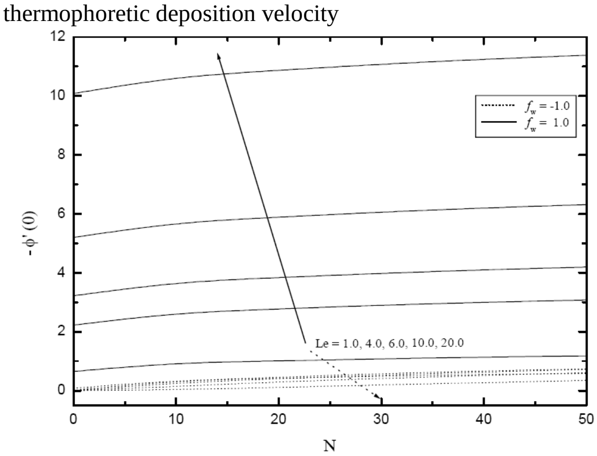

Fig. 17. Effect Lewis number (Le) on the local Sherwood number

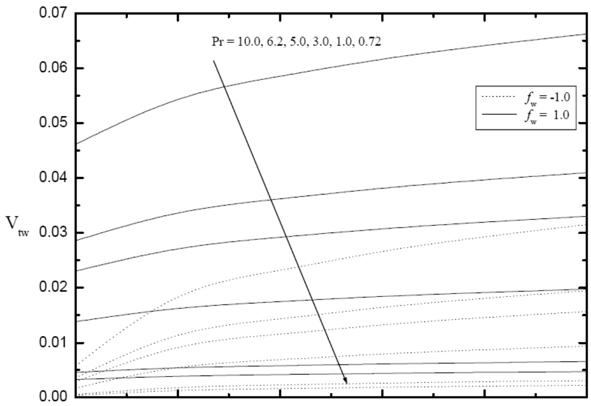

Fig. 18. Effect of Prandtl number (Pr) on thermophoretic deposition velocity

10.0 and 20.0 for both cases, namely, suction and injection. It is observed that the local Sherwood number increases with increasing values of the Lewis number for suction of fluid through the surface case, while the local Sherwood number decreases with increasing the Lewis number for blowing of fluid through the surface (injection) case.

IV. CONCLUDING REMARKS

The present contribution helps us understanding numerically as well as physically the thermophoresis phenomenon on heat and mass transfer of non-Darcian flow of Newtonian fluid past a permeable when viscosity proportional to an inverse linear function of temperature. A representative set of numerical results for the velocity, temperature and solutal concentration profiles as well as the thermophoretic deposition velocity at the wall was presented graphically and discussed in details. Based on the obtained graphical results, it is found that the thermophorsis parameter leads to decrease while thermophoretic coefficient tends to increase the solute concentration profile. Moreover, the particle concentration level as well as the concentration boundary layer thickness decreased due to increases in either of Lewis number or the buoyancy ratio parameter. The thermophoretic deposition velocity at the wall increases with increasing Prandtl number, thermophoretic coefficient, viscosity-variation parameter while it decreases with increasing both of thermophoresis parameter and Grashof number.

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