THERMOPHORESIS EFFECTS ON HEAT AND MASS TRANSFER IN A NON-DARCY POROUS MEDIUM

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Abstract— thermophoresis particle deposition in mixed convection on a vertical plate embedded in a fluid saturated non-Darcy porous medium is studied using similarity solution technique. The effect of thermophoresis parameter (τ), nonlinear convective parameters (σ , γ) on concentration distribution, heat and mass transfer is discussed in detail for different values of mixed convection parameter(Ra_x /Pe_x) and Lewis number (Le). The results indicate that there is a considerable reduction in concentration distribution for higher values of mixed convection parameter and Lewis number. Also there is a significant variation in heat and mass transfer with respect to different values of thermophoresis parameter, non linear convective parameters is seen.

Keywords— Porous medium, Thermophoresis, nonlinear convection, Lewis number, mixed convection.

I. INTRODUCTION

Transport phenomena involving the motion of small particles suspended in gaseous media and their deposition on immersed or containment solid surfaces occur often in industry and nature. When an impure gas is bounded by a solid surface, a boundary layer will develop and energy and momentum transfer will give rise to temperature and velocity gradients. Mass transfer caused by gravitation, molecular diffusion, eddy diffusion and inertial impact results in deposition of suspended components on to the surface. Small particles suspended in a nonisothermal gas acquire a mean velocity relative to the gas in the direction opposite to the temperature gradient. This phenomenon, known as thermophoresis, is of considerable practical importance as can be learned from the book by Fuchs [1].Prediction of the transport rates of aerosol particles is of immense importance in a wide variety of technologies like fabrication of optical wave guides, semiconductor devices, process gas cleaning, corrosion/fouling/erosion of combustion turbine and fossil-fuel-fired boiler components etc. Also, some physical process, require the deposition rates to the desired degree of accuracy by which the accurate prediction of heat and mass transfer rates are possible.

By varying the temperature gradient, the mechanism of capture of submicron particles on the surfaces and the repulsion of particles, is always possible since the thermophoretic velocity is relative independent of particle size. This phenomenon of capture of submicron particles is therefore utilized in air cleaning and aerosol devices and this has been sited as a cause for the deposition of particulate on heat exchange surfaces with the attendant reduction of the heat transfer coefficient. The reverse effect, namely, the repulsion of particles from a hot wall and the formation of dust free layer around hot objects has also been observed. It is likely that thermophoresis is important in the coagulation of condensing or evaporating aerosols, in determining particle trajectories in the exhaust gases from combustion devices, in the respiratory tract, in the modified chemical vapour deposition (MCVD) process and elsewhere. This subject is also important in view of its relevance to postulated accidents by radioactive particle deposition in nuclear reactors.

A detailed analysis on experimental and theoretical study of thermophoresis was reported by Derajaguin et al. [2, 3]. A Paper by Epstein et al. [4] deals with thermophoretic deposition in natural convection flow from a vertical plate. But the analysis was considered for the cold surface. Garg and Jayaraj [5] analyzed numerically the thermophoretic deposition of small particles due to impingement of a laminar slot jet on an inclined plate using an implicit finite difference scheme. The analysis was done for the cold, hot and adiabatic plate conditions. More discussions and applications of thermophoresis can be found in [6.7]. The study of thermophoresis particle deposition on a vertical plate was extended to porous medium by Chamkha and Pop [8]. Chamkha et al. [9] studied thermophoresis free convection form a vertical cylinder embedded in a porous medium. The governing partial differential equations are transformed into a set of non similar equations and they are solved using an implicit finite difference method.

The basis of the Boussinesq approximation is that there are flows in which the temperature varies a little. Therefore the density varies a little and the buoyancy drives the motion. Thus, the variation in density is neglected except in the buoyancy term. Assuming that the densities vary linearly with temperature variations, Cheng and Minkowcyz [11], Bejan and Khair [12] made an analysis for the natural convection. They assumed that the convection took place in a very thin layer around the heating surface. However, when the temperature and concentration difference between the plate and the ambient fluid was appreciably large, (e.g., the study of the heat transfer rate and size of the hot water zone around a dike) the mathematical model using a linear density temperature relation becomes more inaccurate. While, discussing the buoyancy induced boundary layer flows in geothermal reservoirs, Cheng [13] reported that with a maximum temperature of 1200^oC, the intrusive are most likely to be cooled.

There are several reasons for the density temperature relationship to become nonlinear. Thermal stratification and the heat released by the viscous dissipation, e.g., wall jet like profiles, induce significant changes in density gradients. In practice the used liquid metals have the Prandtl numbers ranging from 0.03 to 0.003. Densities of fluids with very small Prandtl numbers e.g., liquid sodium, change significantly. Therefore a large boundary layer thickness is encountered. In industrial and chemical engineering processes involving multi-component fluid, concentrations resulting from mass transfer vary from point to point. Heated jets or diffusion flames created by blowing combustible gases from a vertical pipe are controlled by the forced convection in the initial region by the buoyancy forces far from the jet or pipe. The simplest physical model of such flows is the two-dimensional laminar flow along a vertical flat plate. Recent applications of this model can be found in the area of reactor safety, combustion flames, and solar collectors.

It is obvious that when the temperature-concentration-dependant density relation is not accurate, the computation of the velocity of the fluid, non-dimensional heat and mass transfer coefficients are not accurate up to the desired degree of accuracy. Hence, the design of the thermal system will not be optimum. In fluidized bed technology, the fluid passes through a perforated or porous plate first, and then a bed of particles in a wide sized distribution. To achieve the desired thermal performance, the velocity of the air passing through the bed of particles should be calculated exactly. Some of the thermal systems need cooling of electronic components, turbine blades, etc.,) or drying of the surface, i.e., warm air blows along the surface to raise the local air temperature to evaporate water droplets and films. The removal heat by a coolant that sweeps or baths the warm surface is one of the most encountered cooling strategies in engineering systems. The layered porous media of high thermal conductivity architecture, e.g., metallic foams and sponges, for maximal cooling are distributed within the flow system. When the determination of non-dimensional heat and mass transfer coefficients is not accurate due to inaccurate temperature-concentration- dependent density relation, the transpiration process or drying of the surface is simply continued. This will increase the rate of clogging and thermophoretical deposition rates [14]. In this process, all kinds of contaminants presented in the fluid, such as lint, dust, moisture, and even oil, are deposited on the surface. It should be remembered that the dust settled on the electronic component acts as an insulation layer, which makes it very difficult for the heat generated in the components to escape. Verms [15] studied the deposition rates in cooled and uncooled turbine cascades. It was found that the temperature difference between the wall and the gas could cause a fifteen-fold increase in the deposition rate as compared with the case of adiabatic cascade.

Goren [16] established the necessity of using quadratic- density-temperature variation. Yen [17] conducted an experimental study to investigate the effect of density inversion on free convective heat transfer in a porous layer heated (the glass beads in water constituted porous medium.) from below. The motivation to use the temperature-concentration-dependent relation is as follows.

Some of the thermal systems, e.g., areas of reactor safety, combustion solar collectors, layered porous media of high thermal conductivity architecture (metallic foams and sponges), are operated at moderate and very high temperature. In such special cases the temperature-concentration-dependent is nonlinear and double dispersion effects are of immense importance. So far, the nonlinear temperature-concentration-dependant density has not been used to study the combined effect of the thermophoresis and double dispersion. The consequences due to the usage of linear temperature-concentration-dependent density as mentioned above are very serious. The applications related are of immense importance. It is relevant here to analyze the effect of the temperature-concentration-dependent density nonlinear relation and also, the effect of thermophoresis on the convective transport in a non-Darcy porous medium.

II. GOVERNING EQUATIONS

Mixed Convection Heat and mass transfer from an impermeable vertical wall in a fluid-saturated porous medium is considered for the study. The x-axis is taken along the plate and y-axis is normal to it. The wall is maintained at constant temperature and the concentration T_W and, C_W respectively, and these values are assumed to be greater than the ambient temperature and concentration T_∞ and C_∞ respectively.

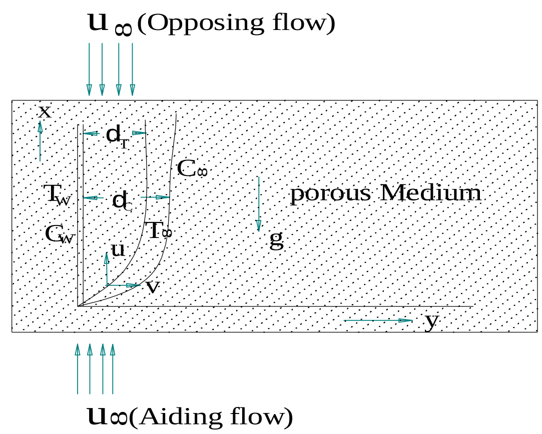

Fig. 3.1 Schematic drawing of the problem

The governing equations for the boundary layer flow, heat and mass transfer from the wall y = 0 into the fluid-saturated porous medium $x \geq 0$ and $y > 0$ are given by

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

$$u + \frac{c\sqrt{K}}{\upsilon}u^2 = -\frac{K}{\mu}\left(\frac{\partial p}{\partial x} + \rho g\right) \qquad (2)$$

$$v + \frac{c\sqrt{K}}{\upsilon}v^2 = -\frac{K}{\mu}\left(\frac{\partial p}{\partial x}\right) \qquad (3)$$

$$u\frac{\partial T}{\partial x} + v\frac{\partial C}{\partial y} = \frac{\partial}{\partial x}\left(\alpha_x\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(\alpha_y\frac{\partial T}{\partial y}\right) \qquad (4)$$

$$u\frac{\partial C}{\partial x} + v\frac{\partial C}{\partial y} = \frac{\partial}{\partial x}\left(D_x\frac{\partial C}{\partial y}\right) + \frac{\partial}{\partial y}\left(D_y\frac{\partial C}{\partial y}\right) - \frac{\partial}{\partial y}(V_T C) - \frac{\partial}{\partial y}(\ldots) \qquad (5)$$

$$\rho = \rho_\infty[1 - \beta_0(T-T_\infty) - \beta_1(T-T_\infty)^2 - \beta_2(C-C_\infty) - \beta_3(C-C_\infty)^2] \qquad (6)$$

$$\theta'' + \frac{1}{2}f\theta' + Pe_\gamma(f'\theta'' + f''\theta') = 0 \qquad (7)$$

With the boundary conditions

$$y = 0: \quad v = 0, \; T = T_w, \; C = C_w$$
$$y \rightarrow \infty: \quad u = u_\infty, \; T = T_\infty, \; C = C_\infty$$

Here x and y are the Cartesian coordinates, u and v are the averaged velocity components in x and y - directions, respectively, T is the temperature, C is the concentration, β_0 , β_1 are the coefficients of thermal expansion, β_2 , β_3 are the coefficients of solutal expansion, υ is the kinematic viscosity of the fluid, K is the permeability, c is an inertial coefficient, g is the acceleration due to gravity, here α_x , α_y are the components of the thermal dispersion, D_x , D_y are the components of solutal dispersion, in the x , y directions respectively. V_T represents thermophoretic velocity

Eliminating the pressure and by using the boundary layer approximations, also invoking non-Boussinesq approximation and using similarity transformations to convert the partial differential equations into ordinary differential equations we get

$$\frac{1}{Sc}\phi'' - \tau\left(\phi\theta'' + \phi'\theta' - \frac{\phi(\theta')^2}{\theta}\right) + \frac{1}{2Pr}f\phi' + \left(\frac{Le\,Pe_\xi}{Sc}\right)(f'\phi'' + f''\phi') = 0 \qquad (8)$$

$$f'' + (F)f'f'' = \frac{Ra_x}{Pe_x}[(1 + \alpha_1\theta)\theta' + N(1 + \gamma_1\phi)\phi'] \qquad (9)$$

And the boundary conditions are transformed into

$$\eta = 0: \quad f = 0, \quad \theta = 1, \; \phi = 1$$
$$\eta = \infty: \quad f' = 1, \quad \theta = 0, \; \phi = 0$$

The heat and mass transfer coefficients in their non dimensional form are written as

$$\frac{Nu_x}{Pe_x^{1/2}} = -[1 + Pe_\gamma f'(0)]\theta'(0) \qquad (10)$$

$$\frac{Sh_x}{Pe_x^{1/2}} = -[1 + Pe_\xi f'(0)]\phi'(0) \qquad (11)$$

III. ESULTS AND DISCUSSIONS

Using an implicit finite difference scheme the above set of ordinary differential equations are solved for different values of all the parameters, Le, F, Ra_x/Pe_x, α, γ, τ. It is a well known fact that the thermophoresis parameter, double dispersion parameters have significant effect on convective heat and mass transfer. Our aim is to discuss the effect of thermophoresis parameter in the presence of non-linear convective parameters α, γ. Hence heat and mass transfer is analysed in Non-Darcy porous media when thermophoresis parameter, nonlinear convective parameters assumes a range of values starting from very less values to higher values.

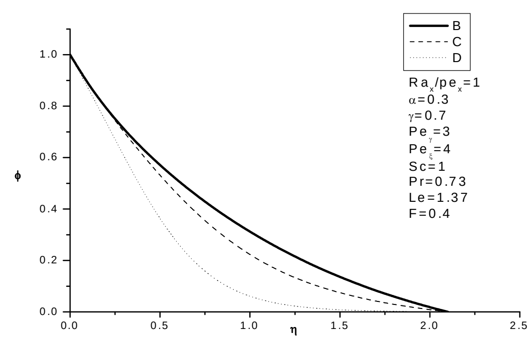

Fig. 1 Concentration distribution inside the boundary layer for various values of thermophoresis parameter

The effect of thermophoresis parameter on concentration distribution with the variation of η very well exhibited in Fig.1. As the thermophoresis parameter increases the concentration boundary layer thickness is observed to be decreasing drastically. Also it is seen that up to η = 0.5, concentration distribution is almost the same for all values of τ (τ = 0.1, τ = 0.5). But with the increase of η the concentration distribution is effected to a larger extent. Whereas the comparison between the curves corresponding to (τ = 0.1, τ = 6.0) clearly shows the different effect of τ on concentration distribution even in the range η = 0 to η = 0.5. Therefore we can conclude that very high values of τ have a significant effect on concentration distribution at every point η. whereas less values of τ have more effect on concentration distribution after a certain stage.

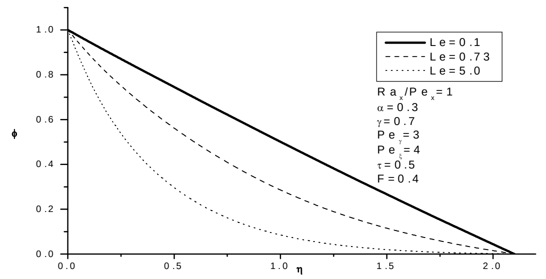

Fig. 2 Concentration distribution inside the boundary layer for different values of Lewis number

The Lewis number always has got its own role on concentration distribution. This is very well seen in Fig. 2. The effect of Le is to decrease the concentration distribution i.e., as Le takes higher values, concentration distribution decreases drastically. Fig.3. shows that when the mixed convection parameter assumes large values, concentration distribution boundary layer thickness reduces drastically. Whereas concentration distribution change marginally for very less change in the value of mixed convection parameter. Therefore it is very clear that with the increase of the parameters which controls thermophoresis, mixed convection, Lewis number, the concentration distribution decreases.

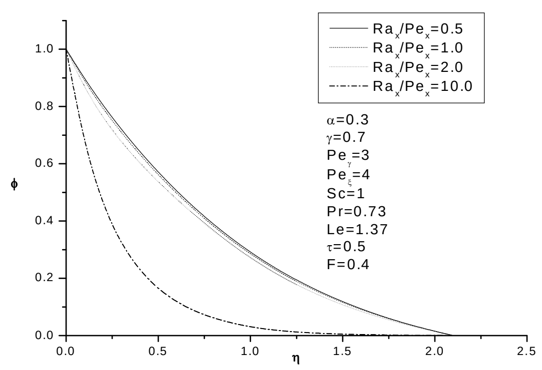

Fig. 3 Effect of Mixed convection parameter on concentration distribution

The variation of heat transfer with non-linear convective parameter α_1 for different values of mixed convection parameter is crystal clear from the Fig. 4.

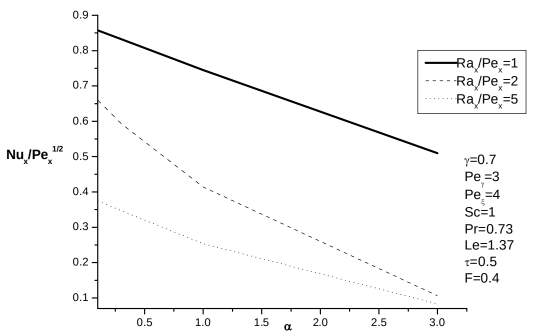

Fig. 4 Effect of γ on non dimensional heat transfer coefficient for different values of mixed convection parameter

An extensive decrease in heat transfer is not only due to the increase of α but also due to the increase of mixed convection parameter. Ra_x/Pe_x The above discussion clearly establishes the different effect of the parameters F, Pe_γ, Ra_x/Pe_x in the presence of non-linear convective parameters α, γ.

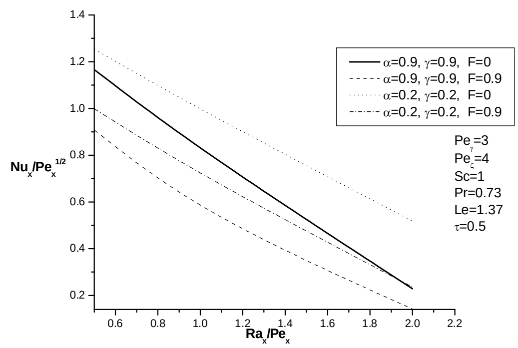

Fig. 5 Effect of non linear convective α, γ on heat transfer in Darcy and non-Darcy medium

The same behaviour that increases in α_1, γ_1 decreases the heat transfer rate in both Darcy and non-Darcy is clear in Fig. 5. A comparative study between the curves $\alpha = \gamma = 0.2$, F = 0, $\alpha = \gamma = 0.2$, F = 0.9 shows that the effect of α, γ on heat transfer in Darcy is very high than that of non-Darcy.

A linear relation (straight line behaviour) between mass transfer and Lewis number is observed from Fig. 6. Though the effect of τ is to increase the mass transfer rate is very clear, the linear relation between mass transfer and Le is not altered. But Fig. 7 is exhibiting a little different view. The mass transfer increase with the increase of τ is not linear for lesser values of γ while it is almost linear for higher values of γ This shows that the different values of α, γ, τ have a pronounced effect in the presence of other parameters like Le, Pe_ξ on mass transfer. Fig. 8 represents that the effect of τ on mass transfer is more in Darcy when compared to non-Darcy.

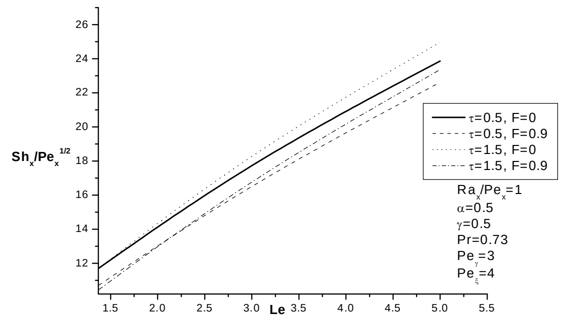

Fig. 6 Effect of Lewis number on mass transfer for different values of thermophoresis parameter

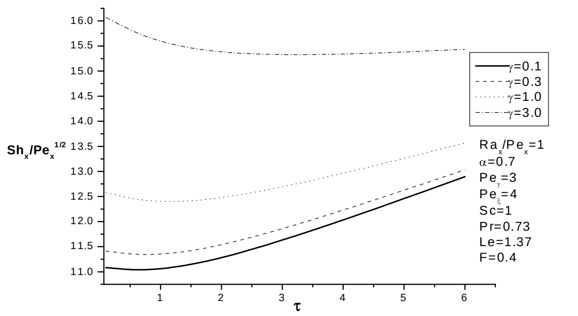

Fig. 7 Effect of thermophoresis parameter on mass transfer for different values of γ

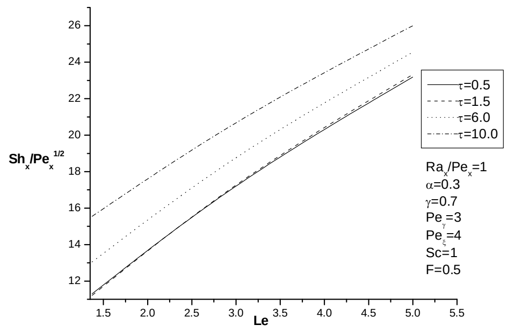

Fig. 8 Variation of mass transfer with Lewis number for different values of thermophoresis parameter in Darcy and non-Darcy medium

CONCLUSION

Mixed convection from a vertical plate embedded in a porous medium is studied considering the effect of thermophoresis, non linear convective parameters. Similarity transformation is used to convert the governing partial differential equations to ordinary differential equations and these are solved using an implicit finite difference scheme.

The usual behaviour that Decrease in concentration distribution with the increase of Lewis number, Mixed convection parameter, increase in heat transfer with the increase of thermal dispersion parameter, increase in mass transfer with the increase of solutal dispersion parameter, Lewis number is observed and significant variation in heat and mass transfer with respect to different values of thermophoresis parameter, non linear convective parameters is seen.

When the thermophoresis parameter assumes high values the concentration distribution is affected everywhere inside the boundary layer region. Whereas for lesser values of the thermophoresis parameter, the concentration distribution is affected in a region away from the leading edge of the plate.

The concentration distribution decreases with the increase of the thermophoresis parameter in Darcy as well as non-Darcy. But, concentration distribution increases more rapidly in the non-Darcy case when compared to Darcy case.

Though the usual behaviour that heat transfer decreases with the increase of inertial effect is observed, the combined effect of inertial parameter, non- linear convective parameters, mixed convection parameter amplifies the above behaviour. Though heat transfer increases with the thermal dispersion parameter even when the non linear convective parameters assumes less values, this trend changes whenever they assume high values.

The effect of non linear convective parameters on heat transfer is to decrease with their increase in Darcy as well as non-Darcy and this is more pronounced in Darcy.

Mass transfer increases with the increase of Lewis number. But the combined effect of thermophoresis parameter, non linear convective parameters, Lewis number, and mixed convection parameter enhances this effect more significantly.

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