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MODELING ELECTRIFICATION OF SPM ON THE THERMAL RADIATIVE BOUNDARY LAYER FLOW OF A PARTICULATE SUSPENSION OVER A STRETCHING SHEET IN PRESENCE OF HEAT SOURCE/SINK

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ABSTRACT
Thermal radiative boundary layer flow of particulate suspension due to an exponential stretching sheet in presence of electrification of particles and internal heat source/sink is considered in this study. Similarity transformation followed by shooting technique using Runge-Kutta 4^{th} order method is adopted for analyzing this problem. Particle electrification and the effect of a heat source/sink are included in the set of influencing parameters to understand the flow characteristics. From this investigation it is observed that the higher electrification parameter is to reduce the normalized fluid temperature and to enhance the normalized particle temperature in the presence of heat source, whereas the trend is reversed in the presence of heat sink.

KEYWORDS: Particulate suspension, Electrification of SPM, Thermal Radiation, Heat source & sink

I. INTRODUCTION
The theoretical study of boundary layer flows induced by a stretching sheet is of considerable interest because of their applications in fibers spinning, manufacturing of plastic and rubber sheets, the aerodynamics extrusion of plastic sheets, hot rolling and cooling of an infinite metallic plate in a cooling bath. It has also numerous applications in industrial manufacturing processes such as wire drawing, glass-fiber and paper production, crystal growing, cable coating and many other to get end product of desired quality and parameter.

Sakiadis [1] has investigated the boundary layer flow on a moving continuous solid surface. Crane [2] has extended this concept to a linearly stretching plane whose velocity is linearly proportional to the distance from the slit and produced an exact analytical solution for two dimensional flow problems. Dutta et. al. [3] have investigated the temperature field in the flow over a stretching surface with uniform heat flux. Chen & Char [4] have studied the heat transfer of a continuous stretching surface with suction or blowing. Kumaran & Ramanaiah [5] have explained their work on boundary layer fluid flow over a general quadratic stretching sheet. Magyari & Keller[6] have studied the heat and mass transfer in the boundary layers on an exponentially stretching continuous surface. Vajravelu & Rollins[7] have studied the hydro magnetic flow of a second grade fluid over a stretching sheet. Partha et.al.[8] have studied the effect of viscous dissipation on the mixed convection heat transfer from an exponentially stretching surface. Vyas & Ranjan[9] have investigated the dissipative MHD boundary-layer flow in a porous medium over a nonlinearly stretching sheet in the presence of radiation. Pal[10] has discussed about the mixed convection heat transfer in the boundary layers over an exponentially stretching surface with magnetic field. Gireesha et.al[11] have studied the boundary layer flow and heat transfer of an unsteady dusty fluid over a stretching sheet with non-uniform heat source/sink. Sreenivasulu & Bhaskar Reddy[12] have analyzed the thermo-diffusion as well as the diffusion-thermo effects on MHD boundary layer flow past an exponential stretching sheet with thermal radiation and viscous dissipation. Barik et.al.[13] have investigated the heat and mass transfer on MHD flow through a porous medium over a stretching surface with heat source. Ramesh et.al.[14] have studied the MHD flow of a dusty fluid near the stagnation point over a permeable stretching sheet with non-uniform source/sink. Gireesha et.al.[15] have studied the Mixed convective flow of a dusty fluid over a vertical stretching sheet with non-

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uniform heat source/sink and radiation. Jat & Chand[16] have analyzed the MHD flow and heat transfer over anexponential stretching sheet with viscous dissipation and radiation effects. Pavithra & Gireesha [17] have studied the boundary layer flow and heat transfer of a dusty fluid over an exponentially stretching surface in the presence of viscous dissipation and internal heat generation/absorption. Mohammed [18] has studied the heat and mass transfer effects on steady two-dimensional flow of a viscous incompressible, electrically conducting dissipating fluid past an exponentially stretching surface in presence of magnetic field, heat generation and radiation. Mukhopadhyay [19] has studied MHD boundary layer flow and heat transfer over an exponentially stretching sheet embedded in a thermally stratified medium subject to suction. Gireesha et.al.[20] have discussed on the effect of radiation on boundary layer flow and heat transfer over a stretching sheet in the presence of a free stream velocity. Pal & Mondal[21] have investigated the effects of temperature-dependent viscosity and variable thermal conductivity on MHD non-Darcy mixed convective diffusion of species over a stretching sheet. Renuka Devi et al. [22] have studied the radiation and mass transfer effects on MHD boundary layer flow of a viscous incompressible fluid over an exponentially stretching sheet with heat source. Dakshinamoorthy et al. [23] have studied the effect of radiation on magneto hydrodynamic (MHD) boundary layer flow of a viscous fluid over an exponentially stretching sheet. Rudraswamy & Gireesha [24] have investigated the influence of chemical reaction and thermal radiation on MHD boundary layer flow and heat transfer of a nano-fluid over an exponentially stretching sheet.

No consulted effort has been done to study the effect of radiation along with electrification of particles on boundary layer flow characteristics of fluid-particle suspension over an exponentially stretching sheet in presence of heat source/sink by the previous investigators. Further, The fluid is in neutral medium, whereas the particles are electrically charged due to particle-particle and particle-wall interactions producing an effective drag force on the ions, Soo [25], which significantly affect the dynamics of flow of fluid-particle suspension. In this problem, the influencing parameters like thermal radiation, force due to electrification of particles, buoyancy force in addition to heat source and sink along with the momentum equation for particulate phase in the normal direction are simultaneously considered to study their effects on the convective viscous boundary layer flow of fluid with SPM over an exponentially stretching sheet. The force due to electrification of particles are included in the momentum equations of both phases, whereas the energy sources due to electrification of particles, the terms pertaining to heat source/sink, radiative heat flux are included in the energy equations of both phases for better understanding of the boundary layer characteristics and heat transfer phenomena.

II. MATHEMATICAL FORMULATION OF THE PROBLEM

A steady two- dimensional laminar boundary layer flow of an incompressible viscous fluid-particle suspension past an exponential stretching sheet is considered in presence of radiation field with uniform heat source and sink. While the *x*-axis is taken along the stretching surface in the direction of the motion, *y*-axis is perpendicular to it. A steady uniform stress leading to equal and opposite forces is applied along the *x*-axis so that the sheet is stretched keeping the origin fixed in the fluid of ambient temperature T_∞. The flow is generated by stretching of the sheet from a slit with a velocity $U_w(x)$ which is in exponential order of the coordinate *x*, measured along the stretching surface. Electrification of SPM is considered in the direction of flow.

Under these above assumptions, the governing equations of the flow and energy fields after the boundary layer simplifications are given by

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

$$\frac{\partial}{\partial x}\left(\rho_p u_p\right)+\frac{\partial}{\partial y}\left(\rho_p v_p\right)=0 \tag{2}$$

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=\nu\frac{\partial^2 u}{\partial y^2}-\frac{1}{1-\varphi}\frac{1}{\tau_p}\frac{\rho_p}{\rho}\left(u-u_p\right)+g\beta^*(T-T_\infty)+\frac{1}{1-\varphi}\frac{\rho_p}{\rho}\left(\frac{e}{m}\right)E_x \tag{3}$$

$$u_p\frac{\partial u_p}{\partial x}+v_p\frac{\partial u_p}{\partial y}=\nu_s\frac{\partial^2 u_p}{\partial y^2}+\frac{1}{\tau_p}\left(u-u_p\right)+\left(1-\frac{\rho}{\rho_s}\right)g+\left(\frac{e}{m}\right)E_x \tag{4}$$

$$u_p\frac{\partial v_p}{\partial x}+v_p\frac{\partial v_p}{\partial y}=\nu_s\frac{\partial^2 v_p}{\partial y^2}+\frac{1}{\tau_p}\left(v-v_p\right) \tag{5}$$

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\frac{k}{\rho c_p}\frac{\partial^2 T}{\partial y^2}+\frac{1}{1-\varphi}\frac{\rho_p}{\rho}\frac{c_s}{c_p}\frac{1}{\tau_T}\left(T_p-T\right)+\frac{1}{1-\varphi}\frac{1}{\tau_p}\frac{\rho_p}{\rho}\frac{1}{c_p}\left(u-u_p\right)^2$$

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$$+\frac{\mu}{\rho c_p}\left(\frac{\partial u}{\partial y}\right)^2+\frac{1}{1-\varphi}\frac{\rho_p}{\rho}\frac{1}{c_p}\left(\frac{e}{m}\right)E_x u_p-\frac{1}{\rho c_p}\frac{\partial q_{rf}}{\partial y}+\frac{1}{\rho c_p}Q(T-T_\infty) \quad (6)$$

$$u_p\frac{\partial T_p}{\partial x}+v_p\frac{\partial T_p}{\partial y}=\frac{k_s}{\rho_s c_s}\frac{\partial^2 T_p}{\partial y^2}-\frac{1}{\tau_T}(T_p-T)-\frac{1}{\tau_p c_s}(u-u_p)^2$$

$$+\frac{\mu_s}{\rho_s c_s}\left[u_p\frac{\partial^2 u_p}{\partial y^2}+\left(\frac{\partial u_p}{\partial y}\right)^2\right]+\frac{1}{c_s}\left(\frac{e}{m}\right)E_x u_p-\frac{1}{\rho_s c_s}\frac{\partial q_{rp}}{\partial y}+\frac{1}{\rho_s c_s}Q_p(T_p-T_\infty) \quad (7)$$

The boundary conditions are:

$$y=0\ : u=U_w(x)=U_0e^{x/L},\ v=0,\ T=T_w(x)=T_\infty+T_0e^{c_1x/2L}$$

$$y\to\infty : u=0, u_p=0,\ v_p=v,\ T=T_\infty,\ T_p=T_\infty \quad (8)$$

where the terms $Q(T-T_\infty)$ and $Q_p(T_p-T_\infty)$ are the amount of heat generated or absorbed per unit volume of fluid and particle phases respectively. Q and Q_p are constants and treated as heat sources if $Q\ \&\ Q_P>0$, whereas heat sinks if $Q\ \&\ Q_P<0$.

III. SIMILARITY TRANSFORMATIONS

The following non-dimensional similarity transformation variables are introduced to convert the governing equations (1) to (7) into a set of similarity equations.

$$\frac{\rho_p}{\rho}=H(\eta),\ \ \eta=\sqrt{\frac{U_0}{\nu L}}e^{x/L}y,\ \ u=U_0e^{2x/L}f'(\eta),\ \ u_p=U_0e^{2x/L}F(\eta),\ v=-\sqrt{\frac{U_0\nu}{L}}e^{x/L}[f(\eta)+\eta f'(\eta)],$$

$$v_p=-\sqrt{\frac{U_0\nu}{L}}e^{x/L}G(\eta), T-T_\infty=T_0e^{4x/L}\theta(\eta),\ T_p-T_\infty=T_0e^{4x/L}\theta_p(\eta) \quad (9)$$

The continuity equation (1) is identically satisfied by introducing a stream function $\psi(x,y)=\sqrt{c\nu}\,xf(\eta)$ such that $u=\frac{\partial\psi}{\partial y}$ and $v=-\frac{\partial\psi}{\partial x}$. (10)

Using Rosseland approximation for thermal radiation, the radiation heat flux q_{rf} for the fluid phase in the energy equation (6) (Brewster [26]) is given by

$$q_{rf}=-\frac{4\sigma^*}{3\kappa^*}\frac{\partial T^4}{\partial y} \quad (11)$$

where σ^* and κ^* are Stephan Boltzman constant and mean absorption coefficient respectively.

The temperature difference within the flow is assumed to be sufficiently small so that T^4 can be expressed as a linear function of temperatureT_∞. Using a truncated Taylor series about the free stream temperature T_∞ yields

$$T^4=4T_\infty^3T-3T_\infty^4 \quad (12)$$

Substituting equation (9) into equation (8), we obtain

$$q_{rf}=-\frac{16T_\infty^3\sigma^*}{3\kappa^*}\frac{\partial T}{\partial y} \quad (13)$$

Similarly, the radiation heat flux q_{rp} for the particle phase in the energy equation (7) is given by

$$q_{rp}==-\frac{16T_\infty^3\sigma^*}{3\kappa^*}\frac{\partial T_p}{\partial y} \quad (14)$$

Upon substitution of the similarity transformation variables (9), the governing boundary layer equations (2) to (7) are transformed to the following non-linear ordinary differential equations:

$$H'=\frac{2HF+\eta HF'-HG'}{G-\eta F} \quad (15)$$

$$f''' = 2f'^2 - ff'' + \frac{1}{1-\varphi}\vartheta H(f' - F) - Gr\theta - \frac{1}{1-\varphi}HM \tag{16}$$

$$F'' = \frac{1}{\epsilon}\left[2F^2 + \eta FF' - GF' - \vartheta(f' - F) - \frac{1}{Fr}\left(1 - \frac{1}{\gamma}\right) - M\right] \tag{17}$$

$$G'' = \frac{1}{\epsilon}[FG + \eta FG' - GG' - \vartheta(f + \eta f' - G)] \tag{18}$$

$$\theta'' = \frac{1}{1+Ra}\begin{bmatrix} Pr(4f'\theta - f\theta') - \frac{2}{3}\frac{1}{1-\varphi}\vartheta H(\theta_p - \theta) - \frac{1}{1-\varphi}\vartheta PrEcH(f' - F)^2 \\ - PrEcf''^2 - \frac{1}{1-\varphi}MPrEcHF - \lambda Pr\theta \end{bmatrix} \tag{19}$$

$$\theta_p'' = \frac{1}{\left(\frac{\epsilon}{Pr} + \frac{3}{2}\frac{Ra}{\gamma}\right)}\begin{bmatrix} 4F\theta_p + \eta F\theta_p' - G\theta_p' + \vartheta(\theta_p - \theta) + \frac{3}{2}\vartheta PrEcH(f' - F)^2 \\ -\frac{3}{2}\epsilon PrEc\left(FF'' + F'^2\right) - \frac{3}{2}PrEcMF - \frac{3}{2}\frac{Pr}{\gamma}\lambda_p \end{bmatrix} \tag{20}$$

with the boundary conditions

$$\eta = 0 \ : \ f' = 1,\ f = 0,\ \theta = 1$$

$$\eta \to \infty : \ f' = 0,\ F' = 0,\ G = f(\infty),\ F = 0,\ \theta = 0,\ \theta_p = 0 \tag{21}$$

where prime denotes the differentiation with respect to η, $\gamma = \rho_s/\rho$ is the material density of the particle, $\rho_r = \rho_p/\rho$ is the relative density, $\vartheta = \frac{L}{U_0\tau_p e^{2x/L}}$ is the fluid-particle interaction parameter, $\epsilon = \nu_s/\nu$ is the Diffusion parameter, $Gr = g\beta^* T_0 L/U_0^2$ is the Grashoff number, $Fr = \frac{U_0^2 e^{4x/L}}{gL}$ is the Froude number, $M = \left(\frac{e}{m}\right)\frac{EL}{U_0^2 e^{4x/L}}$ is the Electrification parameter, $Ra = \frac{16T_\infty^3\sigma^*}{3k^*k}$ is the Radiation parameter, $Ec = \frac{U_0^2}{c_p T_0}$ is the Eckret number, $Pr = \frac{\mu c_p}{k}$ is the Prandtl number, $\lambda = \frac{QL^2}{\mu c_p e^{2x/L}}\frac{\nu}{LU_0} = \frac{QL^2}{\mu c_p e^{2x/L}}\frac{1}{Re}$ is the Heat Source/Sink parameter for the fluid phase, and $\lambda_p = \frac{Q_p L^2}{\mu c_p e^{2x/L}}\frac{\nu}{LU_0} = \frac{Q_p L^2}{\mu c_p e^{2x/L}}\frac{1}{Re}$ is the Heat Source/Sink parameter for the particle phase.

IV. NUMERICAL SIMULATION

The numerical solutions of non-linear differential equations (15) to (20) under the boundary conditions (21) have been solved by applying fourth order Runge-Kutta method along with Shooting technique. First of all these highly non-linear differential equations (15) to (20) are converted into simultaneous linear differential equations of first order as

$$F_1 = f' \tag{22}$$

$$F_2 = f'' \tag{23}$$

$$F_3 = f'''(\eta) = f''' = 2f'^2 - ff'' + \frac{1}{1-\varphi}\vartheta H(f' - F) - Gr\theta - \frac{1}{1-\varphi}HM \tag{24}$$

$$F_4 = G' \tag{25}$$

$$F_5 = G'' = \frac{1}{\epsilon}[FG + \eta FG' - GG' - \vartheta(f + \eta f' - G)] \tag{26}$$

$$F_6 = F' \tag{27}$$

$$F_7 = F'' = \frac{1}{\epsilon}\left[2F^2 + \eta FF' - GF' - \vartheta(f' - F) - \frac{1}{Fr}\left(1 - \frac{1}{\gamma}\right) - M\right] \tag{28}$$

$$F_8 = H' = \frac{2HF + \eta HF' - HG'}{G - \eta F} \tag{29}$$

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$$F_9 = \theta' \tag{30}$$

$$F_{10} = \theta'' = \frac{1}{1+Ra}\begin{bmatrix} Pr(4f'\theta - f\theta') - \frac{2}{3}\frac{1}{1-\varphi}\vartheta H(\theta_p - \theta) \\ -\frac{1}{1-\varphi}\vartheta PrEcH(f' - F)^2 - \ PrEcf''^2 \\ -\frac{1}{1-\varphi}MPrEcHF - \lambda Pr\theta \end{bmatrix} \tag{31}$$

$$F_{11} = \theta_p' \tag{32}$$

$$F_{12} = \theta_p'' = \frac{1}{\left(\frac{\epsilon}{Pr}+\frac{3}{2}\frac{Ra}{\gamma}\right)}\begin{bmatrix} 4F\theta_p + \eta F\theta_p' - G\theta_p' + \vartheta(\theta_p - \theta) \\ +\frac{3}{2}\vartheta PrEcH(f' - F)^2 - \frac{3}{2}\epsilon PrEc\left(FF'' + F'^2\right) \\ -\frac{3}{2}PrEcMF - \frac{3}{2}\frac{Pr}{\gamma}\lambda_p \end{bmatrix} \tag{33}$$

With boundary conditions

$$f'(\infty) = 0,\ F(\infty) = 0,\ G(\infty) = -f(\infty),\ H(\infty) = \omega,\ \theta(\infty) = 0,\ \theta_p(\infty) = 0\ . \tag{34}$$

In order to integrate the equations (22) to (33) as initial value problems, the values of $f''(0)$, $F(0)$, $G(0)$, $H(0)$, $\theta'(0)$, $\theta_p(0)$ are obtained utilizing linear interpolation formula followed by Runge-Kutta method. The appropriate finite value for η_∞ is determined as $\eta_\infty = 10$ to carry out the integration. Series values for unknown boundary conditions are taken to apply fourth order Runge-Kutta method with step size $h = 0.01$. The above procedure is repeated until the results up to the desired accuracy with an error of 10^{-5} are obtained.

V. RESULTS AND DISCUSSION

A parametric study is conducted to illustrate the effects of different governing physical parameters viz., the radiation parameter(Ra), electrification parameter(M) and source/sink parameters for both fluid & particle phases(λ, λ_p) on the nature of flow and the numerical results are depicted through graphs.
It is inferred from fig.1 that the normalized fluid temperature(θ) at any distance η increases with the increase of radiation parameter (Ra) in the presence of heat sink, whereas θ slowly increases at the plate up to a distance $\eta \approx 1.1$ from the plate and then starts decreasing up to $\eta \approx 4.0$ across the boundary layer and there after falls sharply to zero with the increase of radiation parameter (Ra) in the presence of heat source. The normalized particle temperature(θ_p) is observed to increase in the presence of heat sink and to decrease in the presence of heat source with increase of radiation parameter (Ra) across the boundary layer (fig.2).

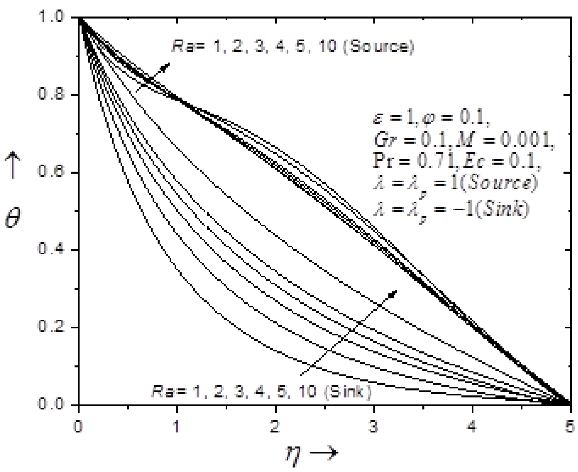

Figure 1: Normalized fluid temperature (θ) for various Ra in source/sink

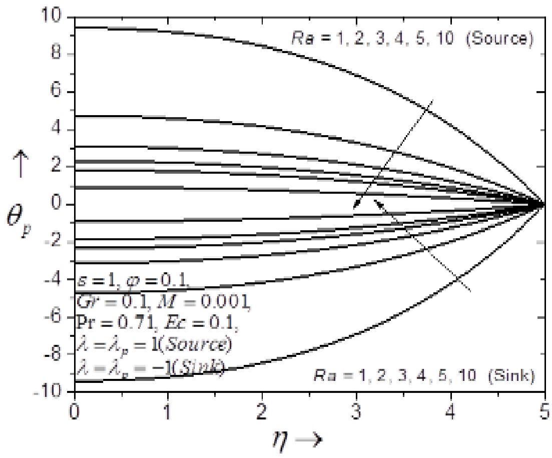

Figure 2: Normalized particle temperature(θ_p) for various Ra in source / sink

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From figs. 3 and 4 it is observed that there is no significant change in the non-dimensional fluid velocity profiles with increase of electrification parameter (M) in presence of both source & sink. But the magnification of these figures in the range of η = 3 to 5 depicts that the non-dimensional fluid velocity in this region increases in the presence of heat source and decreases in the presence of heat sink across the boundary layer with the increase of electrification parameter (M). The non-dimensional particle velocity is seen to decrease with the increase of electrification parameter (M) in presence of a heat source as well as a sink across the boundary layer (figs.5 and 6).

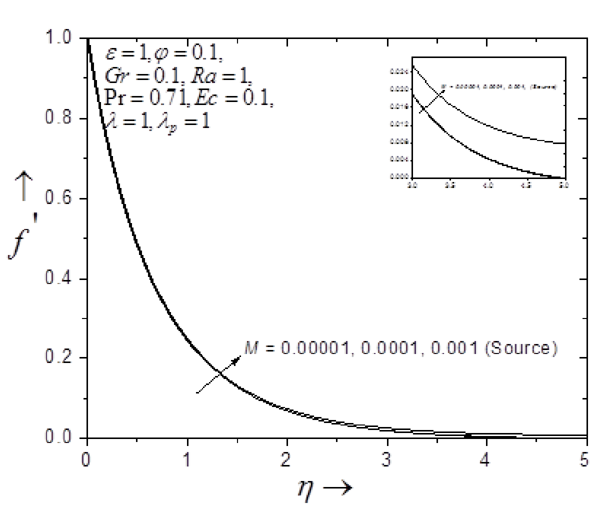

Figure 3: Non-dimensional fluid velocity(f') for various M in source

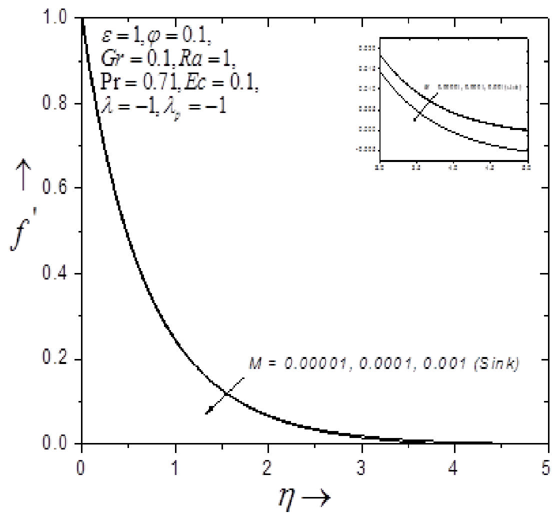

Figure 4: Non-dimensional fluid velocity(f') for various M in sink

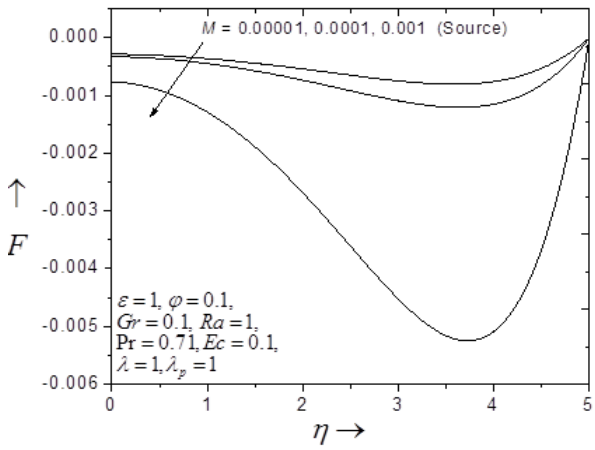

Figure 5: Non-dimensional particle velocity(F) for various M in source

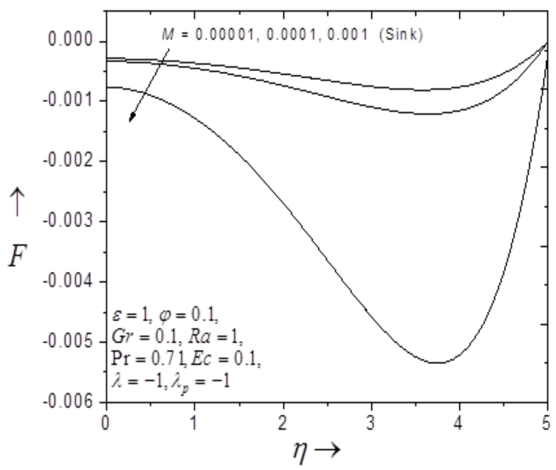

Figure 6: Non-dimensional particle velocity(F) for various M in sink

As regards to the effect of electrification parameter (M), it is seen that normalized fluid temperature θ at any η is decreasing with an increase of M in case of a heat source (Fig.7) and that the same is increasing with an increase of M in case of heat sink (Fig.8). From fig.9, it is revealed that the normalized particle temperature (θ_p) increases with increase in the value of electrification parameter (M) in presence of a heat source, while it is decreasing with an increase of M in presence of a heat sink in the direction of increasing η. It is observed from the figs.10, 11 & 12 that in the thermal boundary layer, the fluid temperature (θ) and particle temperature (θ_p) increase with the increase of both heat source and sink parameters for both fluid & particle phases λ & λ_p across the boundary layer.

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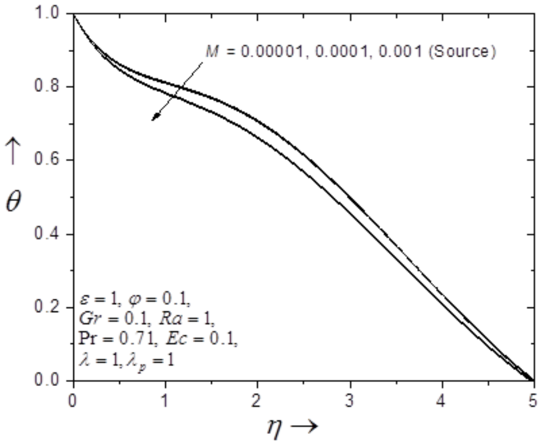

Figure 7: Normalized fluid temperature(θ) for various M in source

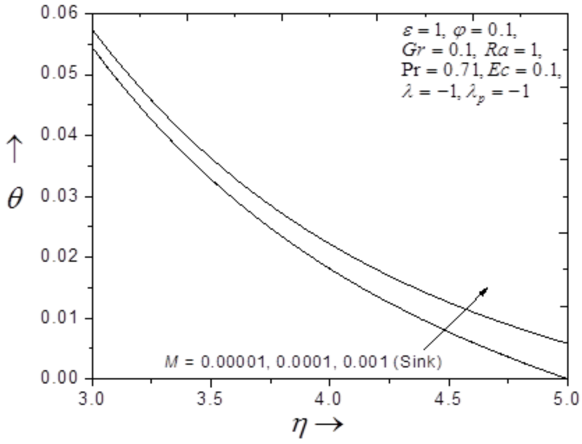

Figure 8: Normalized fluid temperature(θ) for various M in sink

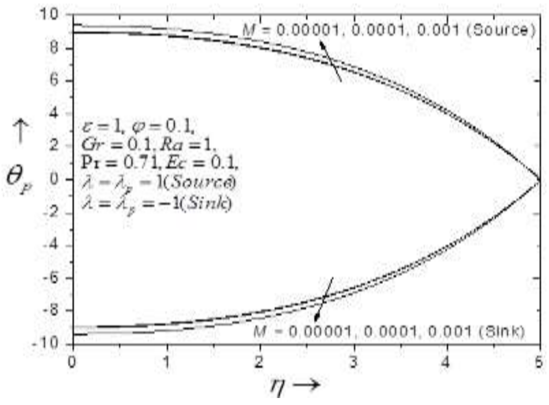

Figure 9: Normalized particle temperature(θ_p) for various M in source/sink

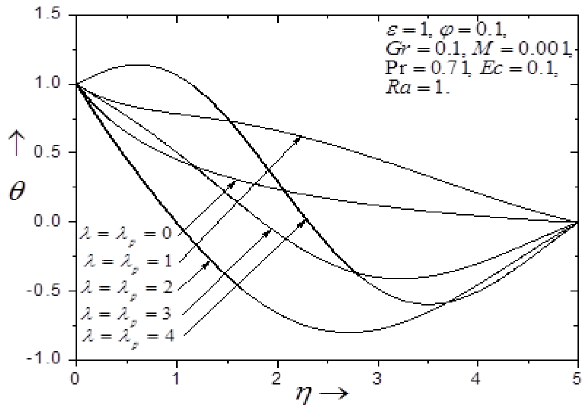

Figure 10: Normalized fluid temperature(θ) for various heat source parameters λ & λ_p

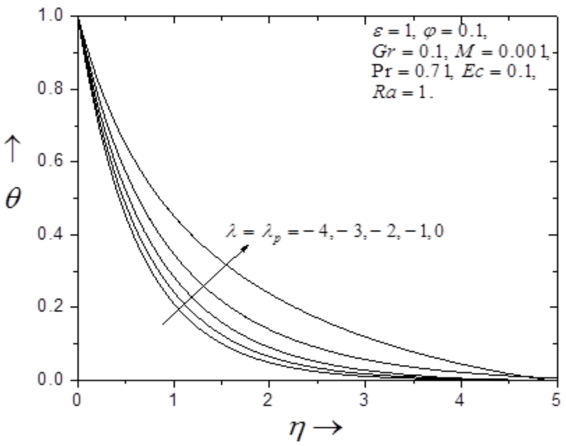

Figure 11: Normalized fluid temperature(θ) for various heat sink parameters λ & λ_p

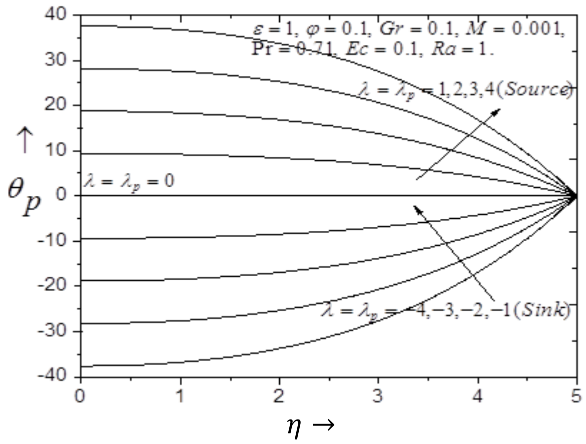

Figure 12: Normalized particle temperature(θ_p) for various heat source / sink parameters λ & λ_p

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VI. CONCLUSION

i. The normalized temperature of fluid and particle phases increase in presence of heat sink and decrease in the presence of heat source with the higher radiation parameter.
ii. The electrification parameter has a mild effect on non-dimensional fluid velocity profiles, whereas it has an effect to decrease the non-dimensional particle velocity in presence of both source & sink.
iii. The effect of electrification parameter is to decrease the normalized fluid temperature and to increase the normalized particle temperature in the presence of heat source, whereas the effect is just reverse in the presence of heat sink.
iv. The normalized temperature of fluid and particle phases increase with the increase of both heat source and sink parameters for fluid & particle phases across the boundary layer.

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