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Exact Solution for Heat Transfer of Hydromagnetic Oscillatory Dusty Fluid Through a Porous Plate with Uniform Suction and Injection

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Abstract: The flow of an unsteady incompressible, viscous, electrically conducting dusty fluid moving through a non-conducting vertical porous plate is under consideration. A magnetic field is applied externally in a uniform manner and is perpendicular to the plate where as the motion of the fluid is maintained with uniform suction and injection through the both ends of the plate. The governing equations are framed using Navier Stokes conditions for dusty fluids. The exact solution for heat transfer is estimated for fluid and particle phase separately. The effects of different dimensionless parameters are discussed elaborately using graphs.

Keywords: exact solution, suction, dusty fluid, porous medium, vertical plate, MHD, oscillatory

Introduction

The role of suction and injection in Fluid Dynamics, especially Heat and Mass Transfer problems is essential, because of its applications in MHD stirring of molten metal, electronic packages, microelectronic devices, thermal insulation, petroleum reservoirs, MHD marine propulsion etc.

In the arena of aerodynamics and space sciences, the theory of injection is important to study the effect of boundary layer control. Braslow [1] made a detailed study on suction in laminar flow of flight research control. Shojaefard et al. [2] administered injection process to regulate the air ow on the outward surface of subsonic aircraft. They concluded that by regulating the suction and injection

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process, the fuel utilisation could be minimised by 30%, a remarkable reduction in pollutant emission could also be attained, and the running costs of commercial aeroplanes could be optimised by atleast 8%.

Hazem A. Attia [3] explored the impact of same injection in arotating disk with heat transfer. Devi et al. [4] investigated the impacts of non-linear MHD laminar ow such as chemical reaction, mass and heat transfer on along with injection. Kandasamy et al. [5] worked on the impacts of chemical reaction which occurs inside the fluid, heat and mass transfer, thermal radiation along with injection. The study on unsteady MHD coquette flow with heat transfer and constant suction and injection was carried out by Hazem Attia [8]. Singh et al. [9] made an examination on the influence of injection and suction on an MHD oscillatory flow through a rotating horizontal channel with porous medium. Uwanta et al. [12] discussed the effect of suction and injection on unsteady MHD viscous fluid with thermal diffusion.

Saffman [6] presented the theory of stable nature of dusty laminar flow. Hazem Attia [7] also conducted a detailed research on the impact of suction and injection on unsteady ow of a dusty conducting fluid in a rectangular channel. By varying mass diffusion, Sivaraj et al. [13] explored the unsteady hydromagnetic dusty viscoelastic fluid couette flow through an irregular channel by changing mass diffusion. For a non-grey gas, the differential estimation for heat transfer through radiation was given by Cogley et al. [10].

Hartmann et al. [15] analysed the influence of transverse magnetic field on a conducting fluid owing through two parallel insulated plates. Ibrahim et al. [14] also studied the hydromagnetic impacts of dusty viscous fluid with volume fraction. In addition to these works, Vijayalakshmi et al. [16-20] made a detailed investigation about the physical nature of dusty fluid moving under various conditions. To be more specific, Prakash et al. [11] thoroughly examined the MHD oscillatory couette flow of dusty fluid through porous medium.

It is quite notable to say that the topic Exact Solution for Heat Transfer through a Hydromagnetic Oscillatory Dusty Fluid with Uniform Suction and Injection was not taken by any researcher for their research work. Additionally, the importance of dust particles mass per unit volume of the fluid is taken into account. In this research work, the temperature of dust particles is also estimated separately.

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Mathematical Formulation

In this research work, the flow of viscous, incompressible, MHD oscillatory couette dusty fluid passing through a plate containing small minute pores is considered. The ends of the plates are insulated and are separated by distance h as shown in **Figure 1**. A Cartesian co-ordinate system is taken with origin (0, 0) at the stationary plate, maintained with a constant injection velocity V_0. The other plate oscillates with a nonzero constant mean velocity U and is maintained with the same constant suction velocity V_0. Hence all the physical properties of the fluid are functions of y and t except the pressure.

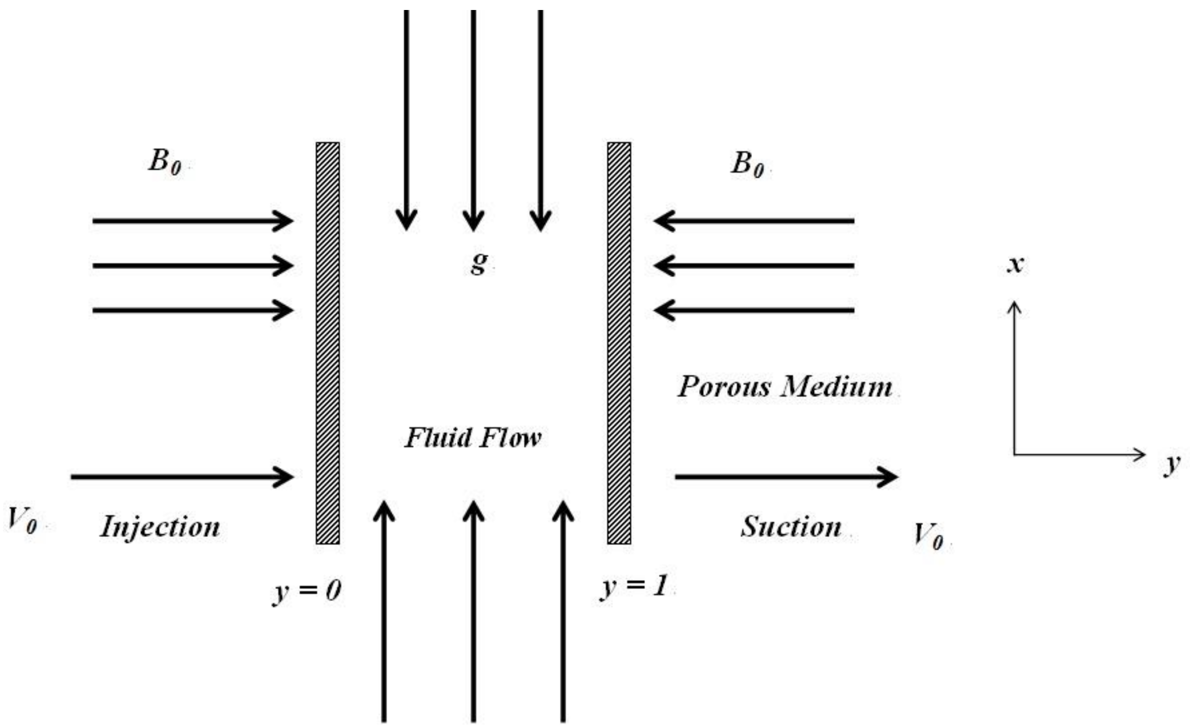

Figure 1 Geometry of Flow

Governing Equations

$$\frac{\partial v^*}{\partial y^*} = 0 \Rightarrow v^* = -V_0 \tag{1}$$

Fluid Phase

Momentum Equation

$$\frac{\partial u^*}{\partial t^*} - V_0 \frac{\partial u^*}{\partial y^*} = -\frac{1}{\rho}\frac{\partial p^*}{\partial x^*} + \nu \frac{\partial^2 u^*}{\partial y^{*2}} - \frac{\nu}{K^*} u^* - \frac{\sigma B_0^2 u^*}{\rho} + g\,\beta_T (T^* - T_0^{\ *}) + \frac{K_0 N_0 (u_d^{\ *} - u^*)}{\rho} \qquad (2)$$

Temperature (Energy) Equation

$$\frac{\partial T^*}{\partial t^*} - V_0 \frac{\partial T^*}{\partial y^*} = \frac{k}{\rho C_p}\frac{\partial^2 T^*}{\partial y^{*2}} + \frac{1}{\rho C_p}\frac{\partial q^*}{\partial y^*} + \frac{\rho_d C_d (T_d^{\ *} - T^*)}{\rho C_p \gamma_T} \qquad (3)$$

Particle Phase

Momentum Equation

$$m_d \frac{\partial u_d^{\ *}}{\partial t^*} = K_0 (u^* - u_d^{\ *}) \qquad (4)$$

Temperature (Energy) Equation

$$\frac{\partial T_d^{\ *}}{\partial t^*} = -\frac{1}{\gamma_T}(T_d^{\ *} - T^*) \qquad (5)$$

Boundary Conditions

$$\begin{aligned} &u^* = 0, u_d^{\ *} = 0, \\ &T^* = T_0^{\ *}, T_d^{\ *} = T_0^{\ *} \qquad \text{at } y^* = 0 \end{aligned} \qquad (6)$$

$$\begin{aligned} &u^* = 0, u_d^{\ *} = U(1 + \varepsilon e^{i\omega^* t^*}), \\ &T^* = T_0^{\ *} + (T_w^{\ *} - T_0^{\ *}), (1 + \varepsilon e^{i\omega^* t^*}), T_d^{\ *} = T_0^{\ *} + (T_w^{\ *} - T_0^{\ *}), (1 + \varepsilon e^{i\omega^* t^*}) \quad \text{at } y^* = h \end{aligned} \qquad (7)$$

where ε is small oscillation amplitude.

Here the term $\varepsilon e^{i\omega t}$ reduces the governing coupled equations into simple equations corresponding to various powers of ε, that is, to the steady and unsteady parts.

According to Cogley [10],

$$\frac{\partial q^*}{\partial y^*} = 4\alpha^2 (T^* - T_0^{\ *}) \qquad (8)$$

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Dimensionless Parameters

$$x=\frac{x^*}{h}, y=\frac{y^*}{h}, t=\frac{t^* U}{h}, \omega=\frac{\omega^* h}{U}, u=\frac{u^*}{U}, u_d=\frac{u_d^{\ *}}{U}, \mathrm{Re}=\frac{U h}{\upsilon}, \theta=\frac{T^*-T_0^{\ *}}{T_w^{\ *}-T_0^{\ *}},$$
$$\theta_d=\frac{T_d^{\ *}-T_0^{\ *}}{T_w^{\ *}-T_0^{\ *}}, Da=\frac{K^*}{h^2}, s^2=\frac{1}{Da}, M^2=\frac{\sigma B_0^{\ 2} h^2}{\rho\upsilon}, p=\frac{p^* h}{\rho\upsilon U}, \mathrm{Pr}=\frac{\gamma\rho C_p}{k},$$
$$N^2=\frac{4\alpha^2 h^2}{k}, Gr=\frac{g\beta_T (T_w^{\ *}-T_0^{\ *})h^2}{\upsilon U}, R=\frac{K_0 N_0 h^2}{\rho\upsilon}, G=\frac{m_d\upsilon}{K_0 h^2}, L_0=\frac{h}{U\gamma_T},$$
$$\gamma_T=\frac{3\mathrm{Pr}\gamma_p C_d}{2C_p}, \gamma_p=\frac{2\rho_s D^2}{9\mu}, \rho_s=\frac{3\rho_d}{4\pi D^3 N_0}, S=\frac{V_0 h}{\upsilon} \tag{9}$$

Solution of the Problem

Apply equations (8) and (9) in equations (2 - 7).

Fluid Phase

$$\mathrm{Re}\frac{\partial u}{\partial t}-S\frac{\partial u}{\partial y}=-\frac{\partial p}{\partial x}+\frac{\partial^2 u}{\partial y^2}-(s^2+M^2+R)u+Gr\,\theta+R\,u_d \tag{10}$$

$$\mathrm{Re}\,\mathrm{Pr}\frac{\partial\theta}{\partial t}-S\,\mathrm{Pr}\frac{\partial\theta}{\partial y}=\frac{\partial^2\theta}{\partial y^2}+N^2\theta+\frac{2R}{3}(\theta_d-\theta) \tag{11}$$

Particle Phase

$$\mathrm{Re}\,G\frac{\partial u_d}{\partial t}=u-u_d \tag{12}$$

$$\frac{\partial\theta_d}{\partial t}=-L_0(\theta_d-\theta) \tag{13}$$

Boundary Conditions

$$u=0, u_d=0, \theta=0, \theta_d=0 \quad \text{at } y=0 \tag{14}$$

$$u=1+\varepsilon e^{i\omega t}, u_d=1+\varepsilon e^{i\omega t}, \theta=1+\varepsilon e^{i\omega t}, \theta_d=1+\varepsilon e^{i\omega t} \quad \text{at } y=1 \tag{15}$$

For pulsatile flow, let

$$-\frac{\partial P}{\partial x}=A+\varepsilon e^{i\omega t}; u(y,t)=u_0(y)+\varepsilon u_1(y)e^{i\omega t}$$
$$u_d(y,t)=u_{d_0}(y)+\varepsilon u_{d1}(y)e^{i\omega t}$$
$$\theta(y,t)=\theta_0(y)+\varepsilon\theta_1(y)e^{i\omega t}$$
$$\theta_d(y,t)=\theta_{d0}(y)+\varepsilon\theta_{d_1}(y)e^{i\omega t} \tag{16}$$

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Here A is the amplitude of pressure gradient.

Apply equations (16) in equations (10 - 15).

Fluid Phase

$$\frac{d^2\theta_0}{dy^2} + S\,\mathrm{Pr}\frac{d\theta_0}{dy} + N^2\,\theta_0 = 0 \tag{17}$$

$$\frac{d^2u_0}{dy^2} + S\,\frac{du_0}{dy} - m_2^2\,u_0 = -A - Gr\,\theta_0 \tag{18}$$

$$\frac{d^2\theta_1}{dy^2} + S\,\mathrm{Pr}\frac{d\theta_1}{dy} + m_1^2\,\theta_1 = 0 \tag{19}$$

$$\frac{d^2u_1}{dy^2} + S\,\frac{du_1}{dy} - m_3^2\,u_1 = -1 - Gr\,\theta_1 \tag{20}$$

Particle Phase

$$\theta_{d_0} = \theta_0 \tag{21}$$

$$u_{d_0} = u_0 \tag{22}$$

$$\theta_{d_1} = \left(\frac{L_0}{L_0 + i\,\omega}\right)\theta_1 \tag{23}$$

$$u_{d_1} = \left(\frac{1}{1 + i\,\omega\,\mathrm{Re}\,G}\right)u_1 \tag{24}$$

Boundary Conditions

$$u_0 = u_{d_0} = u_1 = u_{d_1} = 0, \theta_0 = \theta_{d_0} = \theta_1 = \theta_{d_1} = 0 \text{ at } y = 0 \tag{25}$$

$$u_0 = u_{d_0} = u_1 = u_{d_1} = 1, \theta_0 = \theta_{d_0} = \theta_1 = \theta_{d_1} = 1 \text{ at } y = 1 \tag{26}$$

where

$$m_1^2 = N^2 - \frac{2R}{3} + \frac{2R}{3}\left(\frac{L_0}{L_0 + i\,\omega}\right) - i\,\omega\,\mathrm{Re}\,\mathrm{Pr}$$

$$m_2^2 = s^2 + M^2$$

$$m_3^2 = s^2 + M^2 + R + i\,\omega\,\mathrm{Re} - \frac{R}{1 + i\,\omega\,\mathrm{Re}\,G}$$

Equations (17 – 24) are solved using equations (25) and (26) to get the temperature and hence the velocity of fluid and dust particles.

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TEMPERATURE

Fluid Phase

$$\theta=\left(\frac{e^{t_1 y}-e^{t_2 y}}{e^{t_1}-e^{t_2}}\right)+\varepsilon\left(\frac{e^{t_3 y}-e^{t_4 y}}{e^{t_3}-e^{t_4}}\right)e^{i\omega t} \tag{27}$$

Particle Phase

$$\theta_d=\left(\frac{e^{t_1 y}-e^{t_2 y}}{e^{t_1}-e^{t_2}}\right)+\varepsilon\left(\frac{L_0}{L_0+i\omega}\right)\left(\frac{e^{t_3 y}-e^{t_4 y}}{e^{t_3}-e^{t_4}}\right)e^{i\omega t} \tag{28}$$

VELOCITY

Fluid Phase

$$u(y,t)=u_0+\varepsilon u_1 e^{i\omega t} \tag{29}$$

Particle Phase

$$u_d(y,t)=u_{d_0}+\varepsilon u_{d_1} e^{i\omega t}$$

$$u_d(y,t)=u_0+\varepsilon\left(\frac{1}{1+i\omega \operatorname{Re} G}\right)u_1 e^{i\omega t} \tag{30}$$

where

$$u_0=C_1 e^{t_5 y}+C_2 e^{t_6 y}+t_9-t_{10}\left(\frac{e^{t_1 y}}{t_7}-\frac{e^{t_2 y}}{t_8}\right),$$

$$u_1=C_3 e^{t_{11} y}+C_4 e^{t_{12} y}+t_{13}-t_{14}\left(\frac{e^{t_3 y}}{t_{15}}-\frac{e^{t_4 y}}{t_{16}}\right),$$

and the constants involved in the above equations are given below:

$$t_1=\frac{-S\Pr+\sqrt{(S\Pr)^2-4N^2}}{2},t_2=\frac{-S\Pr-\sqrt{(S\Pr)^2-4N^2}}{2},t_3=\frac{-S\Pr+\sqrt{(S\Pr)^2-4m_1^2}}{2},$$

$$t_4=\frac{-S\Pr-\sqrt{(S\Pr)^2-4m_1^2}}{2},t_5=\frac{-S+\sqrt{S^2+4m_2^2}}{2},t_6=\frac{-S-\sqrt{S^2+4m_2^2}}{2},$$

$$t_7=t_1{}^2+S\,t_1-m_2{}^2,t_7=t_2{}^2+S\,t_2-m_2{}^2,t_9=\frac{A}{m_2{}^2},t_{10}=\frac{Gr}{e^{t_1}-e^{t_2}},$$

$$t_{11}=\frac{-S+\sqrt{S^2+4m_3^2}}{2},t_{12}=\frac{-S-\sqrt{S^2+4m_3^2}}{2},t_{13}=\frac{1}{m_3^2},t_{14}=\frac{Gr}{e^{t_3}-e^{t_4}},t_{15}=t_3^2+S\,t_3-m_3^2,$$

$$t_{16}=t_4^2+S\,t_4-m_3^2,$$

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$$C_1=\frac{e^{t_6}\left(-t_9+\frac{t_{10}}{t_7}-\frac{t_{10}}{t_8}\right)-\left(1-t_9+\frac{t_{10}\,e^{t_1}}{t_7}-\frac{t_{10}\,e^{t_2}}{t_8}\right)}{e^{t_6}-e^{t_5}},C_2=\frac{\left(1-t_9+\frac{t_{10}\,e^{t_1}}{t_7}-\frac{t_{10}\,e^{t_2}}{t_8}\right)-e^{t_5}\left(-t_9+\frac{t_{10}}{t_7}-\frac{t_{10}}{t_8}\right)}{e^{t_6}-e^{t_5}}$$

$$C_3=\frac{\left(-t_{13}+\frac{t_{14}}{t_{15}}-\frac{t_{14}}{t_{16}}\right)e^{t_{12}}-\left(1-t_{13}+\frac{t_{14}\,e^{t_3}}{t_{15}}-\frac{t_{14}\,e^{t_4}}{t_{16}}\right)}{e^{t_{12}}-e^{t_{11}}},C_4=\frac{\left(1-t_{13}+\frac{t_{14}\,e^{t_3}}{t_{15}}-\frac{t_{14}\,e^{t_4}}{t_{16}}\right)-e^{t_{11}}\left(-t_{13}+\frac{t_{14}}{t_{15}}-\frac{t_{14}}{t_{16}}\right)}{e^{t_{12}}-e^{t_{11}}}$$

SKIN FRICTION (SHEAR STRESS ACTING ON FLUID)

Fluid Phase

$$\tau=\left[\mu\frac{\partial u}{\partial y}\right]\text{at } y=(0,1).$$

$$\tau=\left[\mu\frac{\partial}{\partial y}\left(u_0+\varepsilon u_1\,e^{\,i\omega t}\right)\right]\text{at } y=(0,1).$$

Particle Phase

$$\tau_d=\left[\mu\frac{\partial u_d}{\partial y}\right]\text{at } y=(0,1).$$

$$\tau_d=\left[\mu\frac{\partial}{\partial y}\left(u_{d_0}+\varepsilon u_{d_1}\,e^{\,i\omega t}\right)\right]\text{at } y=(0,1).$$

NUSSELT NUMBER (Rate of Heat Transfer)

Fluid Phase

$$Nu=-\left[\frac{\partial\theta}{\partial y}\right]\text{at } y=(0,1).$$

$$Nu=-\left[\frac{\partial}{\partial y}\left(\theta_0+\varepsilon\,\theta_1\,e^{\,i\omega t}\right)\right]\text{at } y=(0,1).$$

Particle Phase

$$Nu=-\left[\frac{\partial\theta_d}{\partial y}\right]\text{at } y=(0,1).$$

$$Nu=-\left[\frac{\partial}{\partial y}\left(\theta_{d_0}+\varepsilon\,\theta_{d_1}\,e^{\,i\omega t}\right)\right]\text{at } y=(0,1).$$

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Graphical Results and Discussions

The above set of mathematical equations is solved to get the analytical expressions for temperature as well as the velocity of the fluid. The graphs are plotted to show the variation in fluid and dust particle phase using MATLAB 8.3 software. It is noteworthy to take Pr = 0.71 (Air at 20°C). The remaining values are selected such that **$t = 0.5$; $\varepsilon = 0.1$; $\omega = 1$; $s = 0.1$; $N = 2$; $G = 1$; $R = 1$; $L_0 = 1$; $S = 1$; $Gr = 1$; $A = 0.1$; $M = 1$.** The values are selected in such a way that the parameter which is under consideration is only to be varied and all the other remaining values are fixed as mentioned above.

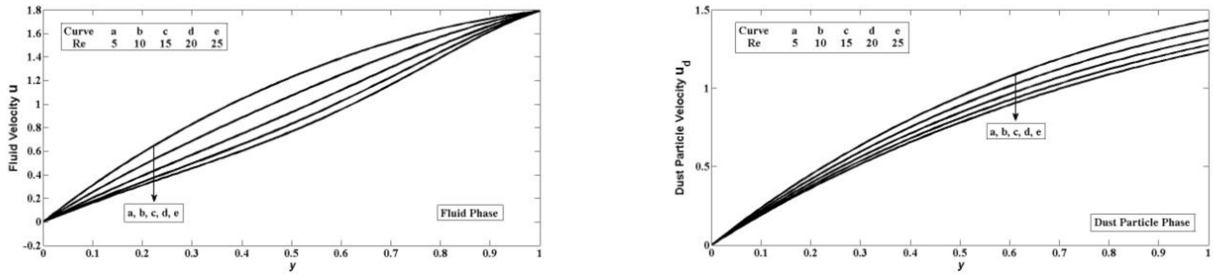

Figure 2: Effect of Re on (a) u (b) u_d

It is noteworthy to mention that accelerating Reynolds number (Re) diminishes the velocity of fluid as well as dust particles. This fact coincides with that of the result obtained by Prakash et al. [11] for the same flow geometry in the absence of suction / injection parameter.

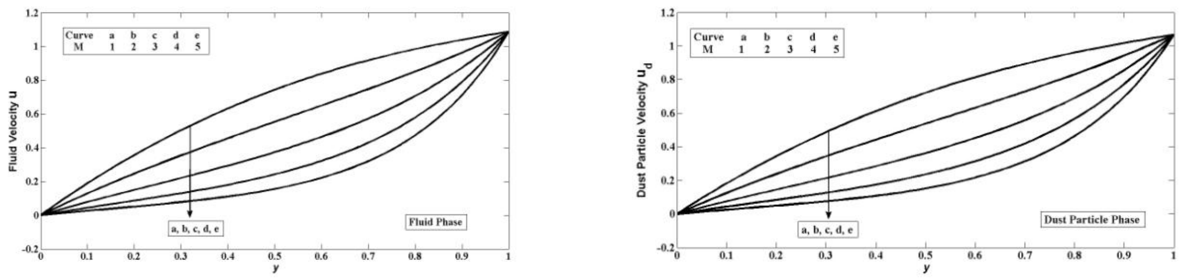

Figure 3: Effect of M on (a) u (b) u_d

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It is explicit to say that Hartmann number (M) has similar impact on velocity of fluid as well as dust particles. This result coincides with that of the result obtained by Prakash et al. [11] for the same flow geometry in the absence of suction / injection parameter.

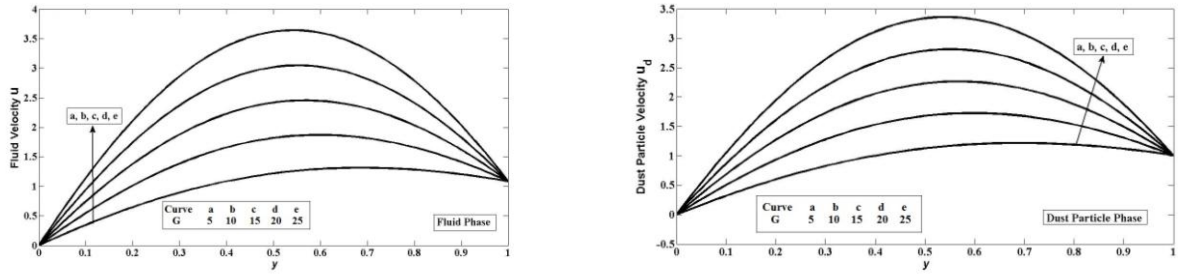

Figure 4: Effect of G on (a) u (b) u_d

It is understood from the figures that particle mass parameter (G) has remarkable effect on velocity of fluid as well as dust particles.

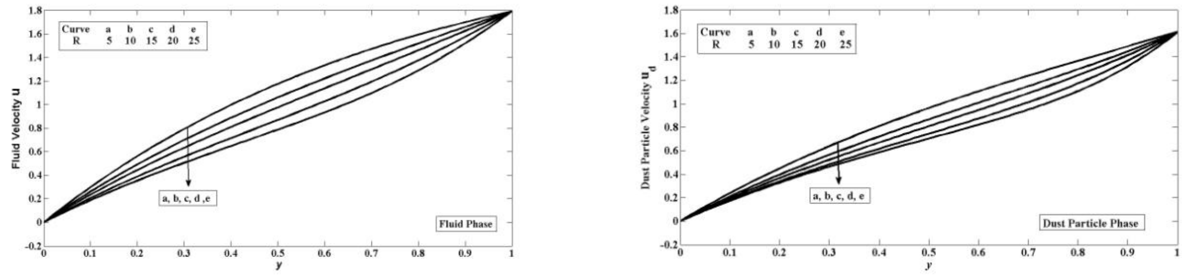

Figure 5: Effect of R on (a) u (b) u_d

It is apparent to say that particle concentration parameter (R) has minor influence on velocity of fluid as well as dust particles.

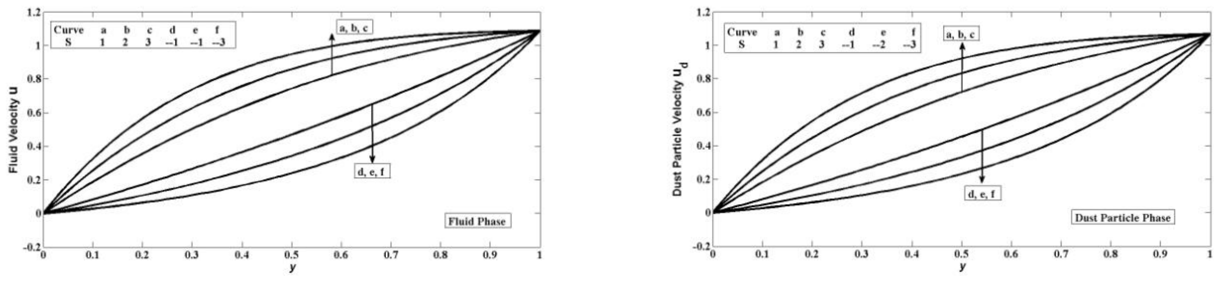

Figure 6: Effect of S on (a) u (b) u_d

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Positive values of suction / injection parameter (S) increase the velocity of fluid and dust particles, whereas the negative values show a reverse trend. This result agrees with Uwanta et al. [12] for the same flow geometry.

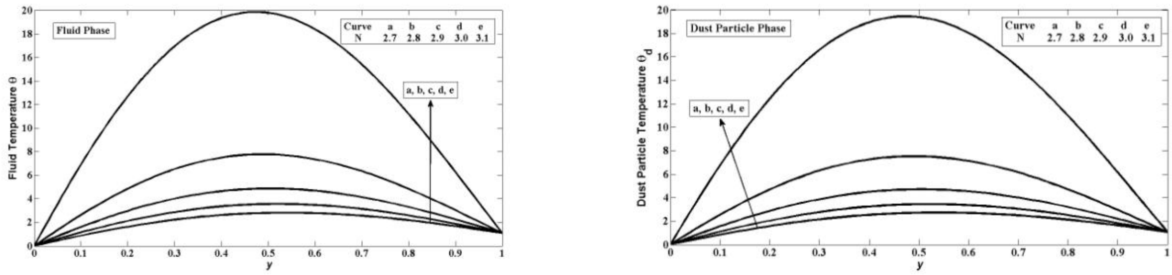

Figure 7: Effect of N on (a) θ (b) θ_d

It is noticeable that the temperature of fluid as well as dust particles accelerates with a raise in radiation parameter (N). This result matches with the result obtained by Prakash et al. [11] for the same flow geometry in the absence of suction / injection parameter.

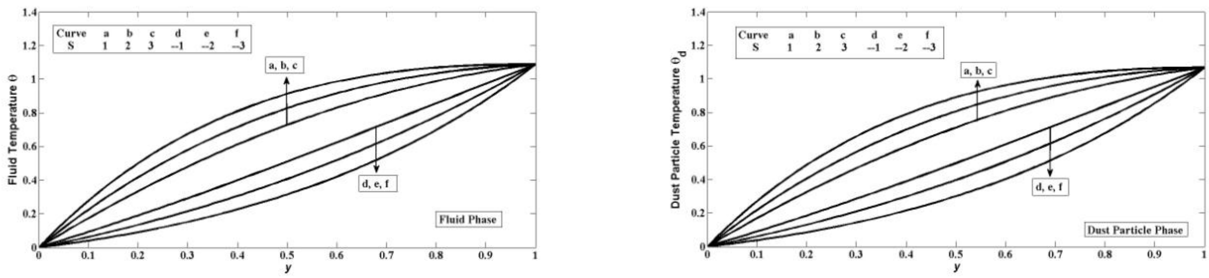

Figure 8: Effect of S on (a) θ (b) θ_d

The temperature of fluid as well as dust particles enhance for positive values of suction / injection parameter (S), whereas the trend is opposite for negative values.

Conclusion

- Enhancement in Reynolds number (Re), Hartmann number (M) and particle concentration parameter (R) diminish the velocity of fluid as well as dust particles.
- Increase in particle mass parameter (G) accelerates the velocity of fluid as well as dust particles.

- Positive values of suction / injection parameter (S) increase the velocity and temperature of both the fluid as well as dust particles, whereas the negative values of (S) exhibit a reverse effect.
- Increase in radiation parameter (N) enhances the temperature of fluid and dust particles.

Limiting Case

In the removal of suction / injection parameter ($S \rightarrow 0$) and heat transfer from the particle to the fluid ($(T_d - T) \rightarrow 0$), the remarkable results got in this paper merge with those of Prakash [11] for a vertical porous plate.

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Appendix

Nomenclature

B_0	Electromagnetic induction
C_p	Specific heat at constant pressure
D_m	Mass diffusion coefficient
g	Gravitational force
Gr	Grashof number due to the transfer of heat
M	Hartmann number
k	Thermal conductivity
N	Radiation parameter
p	Pressure
Pe	Peclet number
q	Radiative heat flux
Re	Reynolds number
t	Time variable
T	Fluid Temperature
T_0	Temperature at y = 0
T_1	Temperature at y = h
u	Axial velocity
u	Mean flow velocity
x	Axial distance
y	Transverse distance
μ	Dynamic viscosity
α	Mean radiation absorption coefficient
β	Volume expansion coefficient due to temperature
λ	Real constant

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σ	Conductivity of the fluid
ω	Frequency of the oscillation
ρ	Fluid density
θ	Temperature