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Thermal diffusion and radiation effects on MHD convective chemically reactive dusty fluid-flow past a vertical porous plate with heat absorption

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ABSTRACT

An analytical solution of two-dimensional MHD free convective double diffusive dusty flow of a viscous, incompressible, electrically conducting and heat-absorbing fluid past a vertical permeable porous plate in presence of radiation and chemical reaction is presented. The plate is assumed to move with a constant velocity in the direction of fluid flow, while free stream velocity is assumed to follow the exponentially increasing small perturbation law. The Velocity, Temperature, Concentration, Skin friction, Nusselt number and Sherwood number distributions are derived and have shown through graphs and tables by using simple perturbation technique.

Introduction

The study of fluids having uniform distribution of solid spherical particles is of interest in a wide range of areas of technical importance. These areas include fluidization (flow through packed feds), flow in rockets, tubes, where small carbon or metallic fuel particles are present, environmental pollution, the process by which rain drops are formed by the coalescence of small droplets, which might be considered as solid particles for the purpose of examining their movement prior to coal scene, combustion and more recently blood flow in capillaries. Attia [1] studied unsteady flow of a dusty conducting fluid between parallel porous plates with temperature dependent viscosity. Reddy [2] studied the flow of dusty viscous liquid through rectangular channel. Work in this field has been carried out by several researchers [3-5]. Saffman [6] investigated the stability of a laminar flow of a dusty gas which is very useful for this work. The study of heat and mass transfer to chemical reacting MHD free convection flow with radiation effects on a vertical plate has received a growing interest during the last decades. Free convection arises in the fluid when temperature changes cause density variation leading to buoyancy forces acting on the fluid elements. Accurate knowledge of the overall convection heat transfer has vital importance in several fields such as thermal insulation, drying of porous solid materials, electrical conductors and geophysical, astrophysical applications such as polymer production, packed-bed catalytic reactors, aeronautics, cooling of nuclear reactors, underground energy transport, magnetized plasma flow, high speed plasma wind, geothermal reservoirs geothermal extractions and cosmic jets.

A clear understanding of the nature of interaction between thermal and concentration buoyancies is necessary. Consolidated effects of heat and mass transfer problems are of importance in many chemical formulations and reactive chemicals. More such engineering applications can be seeing in electrical power generation systems when the electrical energy is extracted directly from a moving conducting fluid. Further, the diffusion and chemical reaction in the above said applications occur simultaneously.

Sivaiah et.al [7] studied heat and mass transfer effects on MHD free convective flow past a vertical porous plate. Mass transfer effects on free convection flow of an incompressible viscous dissipative fluid were studied by Manohar and Nagarajan [8]. Chamkha [9] studied the unsteady MHD convective heat and mass transfer past a semi-infinite vertical permeable moving plate with heat absorption. The effects of chemical reaction, thermophoresis and variable viscosity on a study of hydro magnetic flow with heat and mass transfer over a flat plate in the presence of heat generation/absorption was examined by Seddeek [10]. Takhar et al. [11] investigated the radiation effects on MHD free convection flow of a radiating gas past a semi-infinite vertical plate. Muthukumaraswamy and Ganesan [12] studied the diffusion and first-order chemical reaction on impulsively started infinite vertical plate with variable temperature. The combined effect of buoyancy forces from thermal and mass diffusion on forced convection laws studied by Chen et.al [13]. Badruddin et al. [14] analyzed the free convection and radiation characteristics for a vertical plate embedded in a porous medium. The influence of chemical reaction on transient MHD free convection over a moving vertical plate was discussed by Al-Odat and Al-Azab [15].

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NOMENCLATURE

u^1 :	The component of velocity along x-axis	v^1 :	The component of velocity along y-axis
t :	Time	g :	The acceleration due to gravity
β_T :	Thermal expansion coefficient	β_c :	Concentration expansion coefficient
υ :	Kinematic viscosity	k^1 :	Permeability of the porous medium in non- dimensional form
k :	Stoke's resistance coefficient	N_0 :	Number density of the dust particles
m :	Mass of the dust particle	V :	Velocity of Dust particle
ρ :	Density of the dusty fluid	σ :	Electrical conductivity of the dusty fluid
B_0 :	Uniform magnetic field	Q :	Heat source
C_p :	Specific heat at constant pressure	q_r :	Radioactive heat flux
T^1 :	Temperature in non-dimensional form	C^1 :	Concentration in non-dimensional form
D :	Molecular diffusivity		
D_1 :	Thermal diffusivity	K_c^1 :	Chemical reaction parameter in non-dimensional form
G_r :	Grashof number	N :	Buoyancy ratio
B_1 :	Dusty fluid parameter	M :	Magnetic field parameter
K :	Permeability of porous medium	B :	Dust particles parameter
P_r :	Prandtl number	R :	Radiation parameter
H :	Heat source parameter	S_c :	Schimidt number
S_0 :	Soret number	Kc :	Chemical reaction parameter
K_λ :	Absorption coefficient at the plate	e_λ :	Plank's function.
T_∞^1 :	Temperature of the fluid far away from the plate	α :	Thermal diffusivity
C_∞^1 :	Concentration of the fluid far away from the plate		
T_w^1 :	Temperature of the wall as well as the temperature of the fluid at the plate		
C_w^1 :	Concentration of the wall as well as the concentration of the fluid at the plate		

MadhusudhanaRao B, Viswanathareddy G and Raju M.C [16] studied MHD transient free convection and chemically reactive flow past a porous vertical plate with radiation and temperature gradient dependent heat source in slip flow regime. The effect of chemical reaction and radiation absorption on free convection flow through porous medium with variable suction in the presence of uniform magnetic field was investigated by SudheerBabu and Satyanarayana [17]. Free convective flow past a vertical plate is studied by Ostrach [18]. Soundalgekar [19] studied the effects of viscous dissipation on the flow past an infinite vertical porous plate. Recently Sharma et.al [20] analyzed the effect of Dusty viscous fluid on MHD free convection flow with heat and mass transfer past a vertical porous plate.

This paper considered the problem of Sharma et.al [20] by introducing heat absorption, chemical reaction, radiation and thermal diffusion effects. The object of the present paper is to study MHD free convective heat and mass transfer double diffusive dusty fluid flow past an infinite vertical permeable moving plate with heat absorption, radiation, and chemical reaction. In obtaining the solution, the terms regarding radiation effect, temperature gradient, and dependent heat source are taken into account of energy equation and chemical reaction parameter, double diffusion effect are taken into account of concentration equation. The Permeability of the porous medium and the suction velocity are considered to be as exponentially decreasing function of time.

Mathematical Analysis

We consider a two-dimensional unsteady free convective heat and mass transfer flow of an incompressible dusty viscous fluid past an infinite vertical porous plate. In rectangular Cartesian coordinate system, we take *x*-axis along the plate in the direction of flow and *y*-axis normal to it. Further the flow is considered in presence of temperature gradient dependent heat source and effect of radiation and chemical reaction. For small velocity the viscous and Darcy's resistance terms are taken into account with constant permeability and constant plate temperature. Influence of density variation with temperature is considered. Introduce the boundary layer and Boussinesq's approximations. Under the above assumptions, the governing equations of continuity, momentum, Dust particle, energy and concentration can be written as follows

$$\frac{\partial v^1}{\partial y^1} = 0 \tag{1}$$

$$\frac{\partial u^1}{\partial t^1} + v^1\frac{\partial v^1}{\partial y^1} = g\beta_T(T^1 - T_\infty^1) + g\beta_C(C^1 - C_\infty^1) + \upsilon\frac{\partial^2 v^1}{\partial y^{1^2}} - \left(\frac{\upsilon}{k^1} + \frac{\sigma B_0^{\ 2}}{\rho} + \frac{kN_0}{\rho}\right)u^1 + \frac{kN_0}{\rho}V \tag{2}$$

$$\frac{\partial V}{\partial t^1} = \frac{k}{m}\left(u^1 - V\right) \tag{3}$$

$$\frac{\partial T^1}{\partial t^1} + v^1\frac{\partial T^1}{\partial y^1} = \frac{k}{\rho C_p}\frac{\partial^2 T^1}{\partial y^{1^2}} - \frac{1}{\rho C_p}\frac{\partial q_r}{\partial y^1} - \frac{Q}{\rho C_p}(T^1 - T_\infty^1) \tag{4}$$

$$\frac{\partial C^1}{\partial t^1}+v^1\frac{\partial C^1}{\partial y^1}=D\frac{\partial^2 C^1}{\partial y^{1^2}}+D_1\frac{\partial^2 T^1}{\partial y^{1^2}}-K_c{}^1(C^1-C^1_\infty) \tag{5}$$

With the boundary conditions

$$u^1=0,\quad T^1=T^1_w,\quad C^1=C^1_w \qquad \text{at} \quad y^1=0$$

$$u^1\to 0, T^1\to T^1_\infty, C^1\to C^1_\infty \qquad \text{as} \quad y^1\to\infty \tag{6}$$

Consider the fluid which is optically thin with a relatively low density and radioactive heat flux is given by Ede [21] is

$$\frac{\partial q_r}{\partial y^1}=4(T^1_w-T^1_\infty)I \tag{7}$$

Where $I=\int_0^\infty K_\lambda \frac{\partial e_\lambda}{\partial T^1_w}d\lambda$

Non-Dimensionlization

We introduce the non-dimensional quantities given below

$$u=\frac{u^1}{U_0},\ v=\frac{V}{U_0},\ y=\frac{y^1U_0}{\upsilon},\quad t=\frac{U_0{}^2t^1}{\upsilon},\ T=\frac{T^1-T^1_\infty}{T^1_w-T^1_\infty},\ C=\frac{C^1-C^1_\infty}{C^1_w-C^1_\infty},\ k=\frac{U_0{}^2k^1}{\upsilon^2} \tag{8}$$

Employing the above described non-dimensional quantities, the governing equations (2), (3), (4) & (5) reduce to

$$\frac{\partial u}{\partial t}-\frac{\partial u}{\partial y}=G_r(T+NC)+B_1(v-u)+\frac{\partial^2 u}{\partial y^2}-(M+\frac{1}{K})u \tag{9}$$

$$B\frac{\partial v}{\partial t}=u-v \tag{10}$$

$$\frac{\partial T}{\partial t}-\frac{\partial T}{\partial y}=\frac{1}{P_r}\frac{\partial^2 T}{\partial y^2}-(R+H)T \tag{11}$$

$$\frac{\partial C}{\partial t}-\frac{\partial C}{\partial y}=\frac{1}{S_c}\frac{\partial^2 C}{\partial y^2}+S_0\frac{\partial^2 T}{\partial y^2}-K_cC \tag{12}$$

Where,

$$G_r=\frac{g\beta_T\upsilon(T^1_w-T^1_\infty)}{U_0{}^3},\ N=\frac{g\beta_c\upsilon(C^1_w-C^1_\infty)}{\beta_T(T^1_w-T^1_\infty)},\ B_1=\frac{k\upsilon N_0}{\rho U_0{}^2},\ M=\frac{\upsilon\sigma B_0{}^2}{\rho U_0{}^2},\ K=\frac{k^1U_0{}^2}{\upsilon^2},\ B=\frac{mU_0{}^2}{\upsilon k},\ P_r=\frac{\upsilon}{\alpha}=\frac{\upsilon\rho C_p}{k},$$

$$R=\frac{4\upsilon I}{\rho C_pU_0{}^2},\ H=\frac{Q\upsilon}{\rho C_pU_0{}^2},\ S_c=\frac{\upsilon}{D},\ S_0=\frac{D_1}{\upsilon}\left(\frac{T^1_w-T^1_\infty}{C^1_w-C^1_\infty}\right),\ K_c=\frac{K_c{}^1\upsilon}{U_0{}^2},\ \alpha=\frac{k}{\rho C_p}.$$

Moreover, the boundary conditions (6) take the form

$$u=0,\quad v=0,\quad T=1,\quad C=1, \qquad \text{at} \quad y=0$$

$$u\to 0,\ v\to 0,\ T\to 0,\ C\to 0, \qquad \text{as} \quad y\to\infty \tag{13}$$

Method of Solution

The partial differential equations (9), (10), (11) and (12) cannot be solved in closed form. So we solve analytically by converting them into ordinary differential equations. Therefore, we assume the solution of these equations as

$$u(y,t)=e^{-nt}u_0(y)+O(\varepsilon)$$

$$v(y,t)=e^{-nt}v_0(y)+O(\varepsilon) \tag{14}$$

$$T(y,t)=e^{-nt}T_0(y)+O(\varepsilon)$$

$$C(y,t)=e^{-nt}C_0(y)+O(\varepsilon)$$

Substitute above expressions (14) in the equations (9), (10), (11) & (12) and by equating the constant terms, we get the ordinary differential equations.

$$u_0^{11}(y)+u_0^1(y)-\left[\left(M+\frac{1}{K}\right)-\frac{nBB_1}{1-nB}-n\right]u_0(y)=-G_rT_0(y)-NG_rC_0(y) \tag{15}$$

$$v_0(y)=\frac{u_0(y)}{1-Bn} \tag{16}$$

$$T_0^{11}(y)+P_rT_0^1(y)+P_r(n-R-H)T_0(y)=0 \tag{17}$$

$$C_0^{11}(y)+S_cC_0^1(y)+S_c(n-K_c)C_0(y)=-S_cS_0T_0^{11} \tag{18}$$

And the boundary conditions (13)

$$u_0=0,\ v_0=0,\ T_0=1,\ C_0=1, \quad at\ y=0$$

$$u_0\to 0,\ v_0\to 0,\ T_0\to 0,\ C_0\to 0, \quad as\ y\to\infty \tag{19}$$

On solving the 2nd order ordinary differential equations (15), (16), (17) and (18) with the boundary conditions (19), we obtain

$$u_0(y)=A_2e^{-m_1y}+A_3e^{-m_2y}-\left(A_2+A_3\right)A_3e^{-m_3y} \tag{20}$$

$$v_0(y)=\frac{1}{1-Bn}\left(A_2e^{-m_1y}+A_3e^{-m_2y}-\left(A_2+A_3\right)A_3e^{-m_3y}\right) \tag{21}$$

$$T_0(y)=e^{-m_1y} \tag{22}$$

$$C_0(y)=A_1e^{-m_1y}+(1-A_1)e^{-m_2y} \tag{23}$$

Where the constants are given in the appendix.

In view of the above solutions (20), (21), (22), (23) and the equations for *u*, *v*, *T* and *C* are given as

$$u(y,t)=\left(A_2e^{-m_1y}+A_3e^{-m_2y}-(A_2+A_3)e^{-m_3y}\right)e^{-nt} \tag{24}$$

$$v(y,t)=\left(\frac{A_2e^{-m_1y}+A_3e^{-m_2y}-(A_2+A_3)e^{-m_3y}}{1-nB}\right)e^{-nt} \tag{25}$$

$$T(y,t)=\left(e^{-m_1y}\right)e^{-nt} \tag{26}$$

$$C(y,t)=\left(A_1e^{-m_1y}+(1-A_1)e^{-m_2y}\right)e^{-nt} \tag{27}$$

Skin friction

The expression for skin-friction (τ) at the plate is,

$$\tau=\left(\frac{du}{dy}\right)_{y=0}=A_4e^{-nt} \tag{28}$$

Nusselt number

The expression for Nusselt number (N_u) is,

$$N_u=\left(\frac{dT}{dy}\right)_{y=0}=-m_1e^{-nt} \tag{29}$$

Sherwood number

The expression for the Sherwood number (S_h) is,

$$S_h=\left(\frac{dC}{dy}\right)_{y=0}=A_5e^{-nt} \tag{30}$$

Results and Discussion

To assess the physical depth of the problem, the effects of various parameters like Schmidt number S_c, Grashof number G_r, Magnetic parameter *M*, Permeability of Porous medium *K*, Heat source parameter *H*, Radiation parameter *R*, Chemical reaction parameter K_c, Soret effect number S_0, Dust particles parameter *B*, Dusty fluid parameter B_1, Prandtl number P_r on velocity profile, temperature profile and concentration profile are studied in figures (1)-(18), while keeping the other parameters as constants.

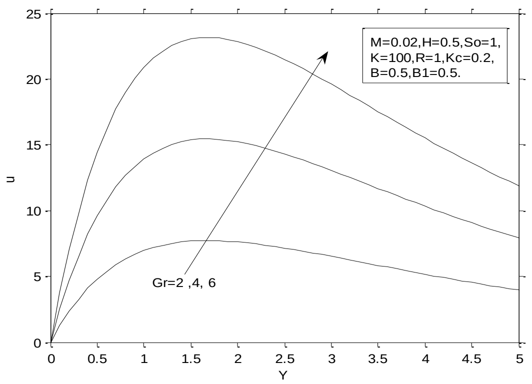

Fig 1. The effect of Gr on velocity of dusty fluid

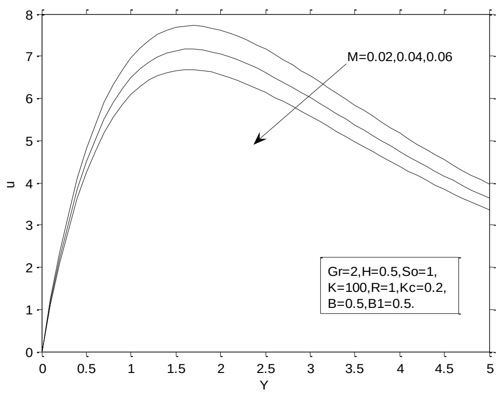

Fig 2. The effect of M on velocity of dusty fluid

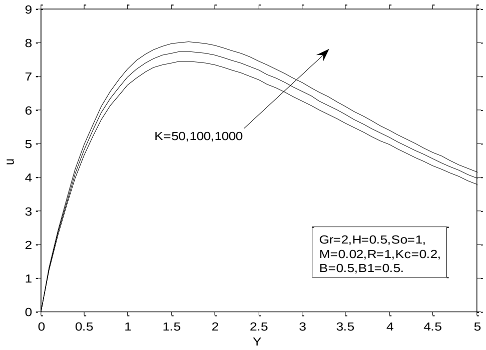

Fig 3. The effect of K on velocity of dusty fluid

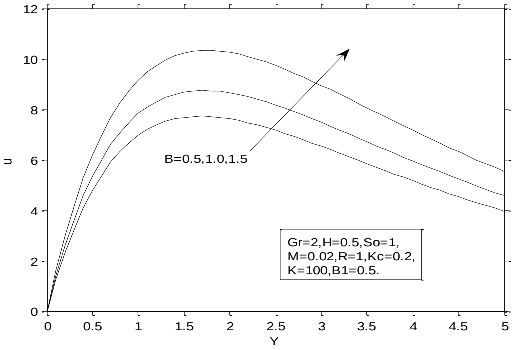

Fig 4. The effect of B on velocity of dusty fluid

The velocity profiles of dusty fluid and dust particles are shown in the figures (1)-(12) at $n=0.1$, $t=0.1$, $N=1.5$, $S_c=0.22$, $P_r=0.71$. From the figures (1)-(5)&(7)-(11), it is observed that velocity of dusty fluid and dust particles increase as G_r, K, B and B_1 increase, but it decreases with an increase in M, observed by Sharma et.al [20]. It indicates that the effect of G_r on the velocities of dusty fluid and dusty particles is directly proportional and also the Magnetic field suppresses the free convection. And from the figures (6) & (12), it is noticed that velocity of dusty fluid and dust particles increases with an increase in S_0.

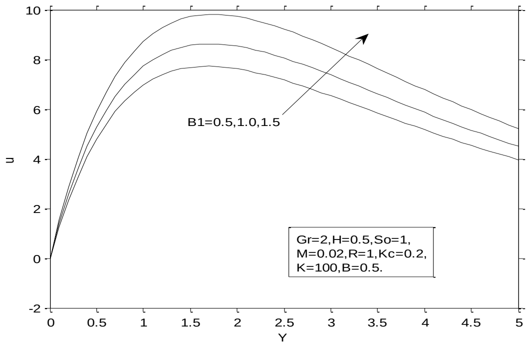

Fig 5. The effect of B_1on velocity profile of dusty fluid

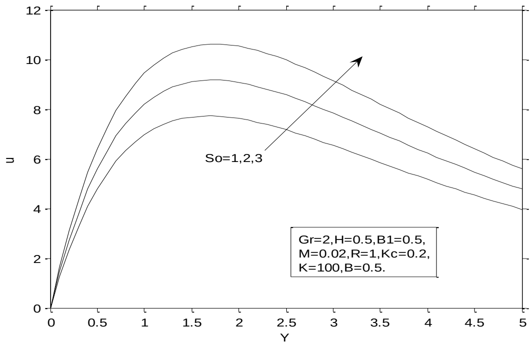

Fig 6. The effect of $S_o$on velocity profile of dusty fluid

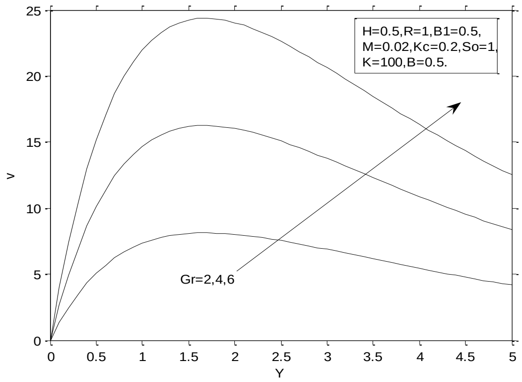

Fig 7. The effect of Gr on velocity of dust particles

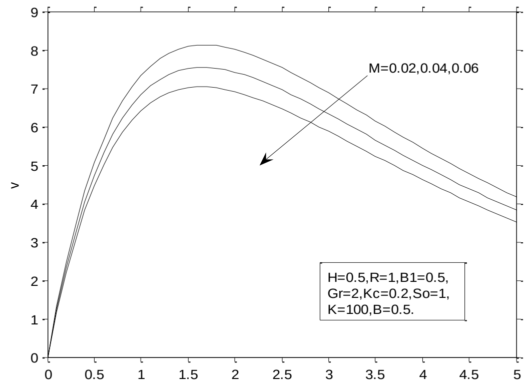

Fig 8. The effect of M on velocity of dust particles

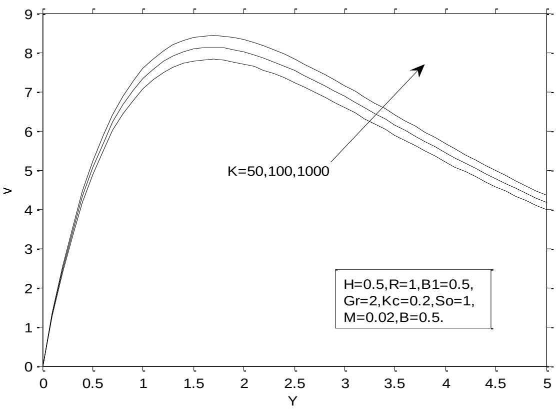

Fig 9. The effect of K on velocity of dust particles

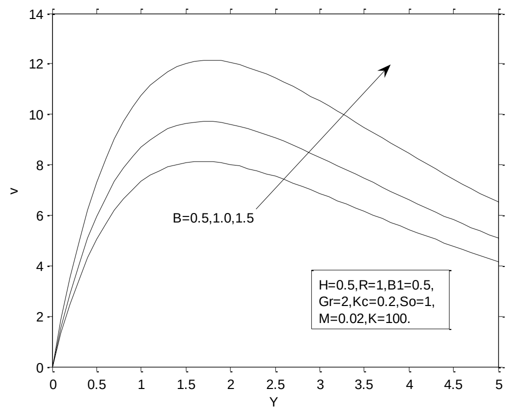

Fig 10. The effect of B on velocity of dust particles

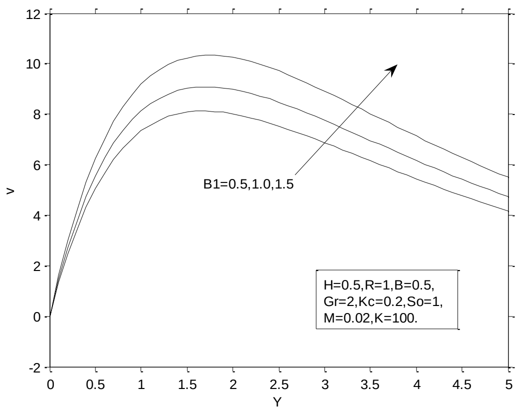

Fig 11. The effect of B_1 on velocity of dust particles

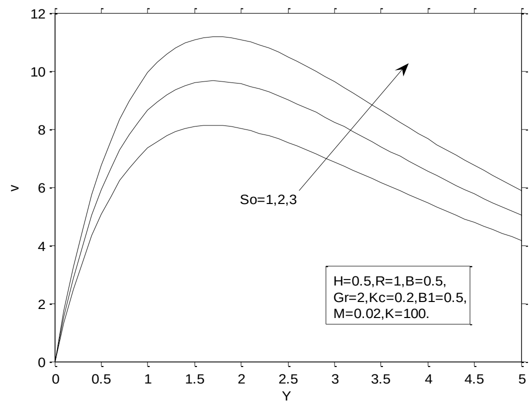

Fig 12. The effect of S_0 on velocity of dust particles

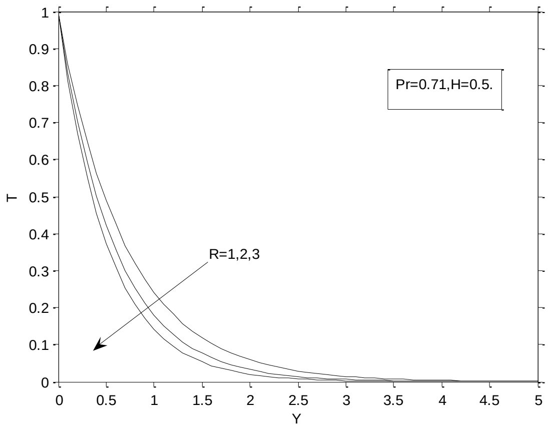

Fig 13. The effect of R on Temperature of dusty fluid

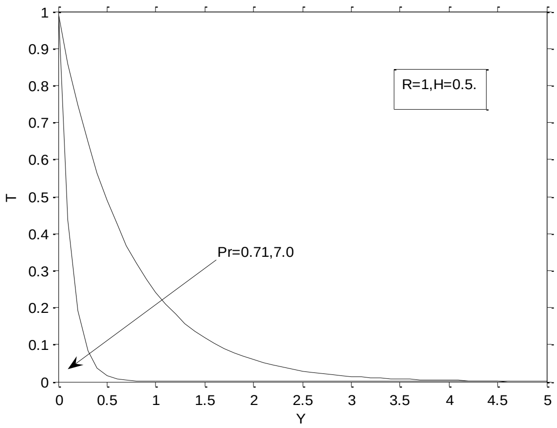

Fig 14. The effect of Pr on Temperature of dusty fluid

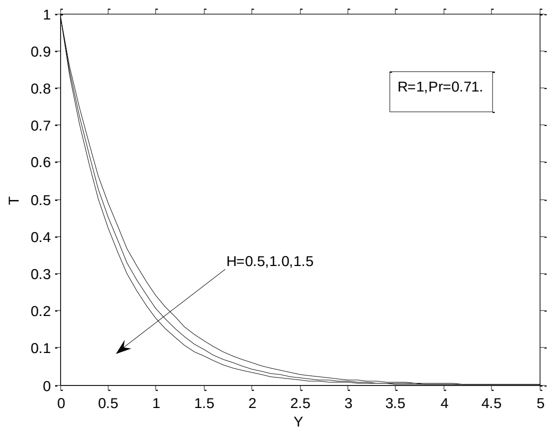

Fig 15. The effect of H on Temperature of dusty fluid

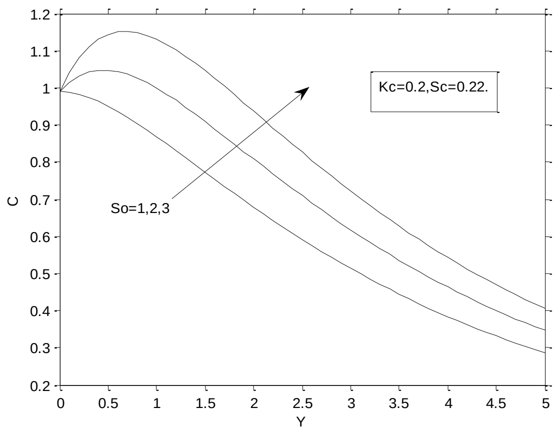

Fig 16. The effect of S_0 on Concentration of dusty fluid

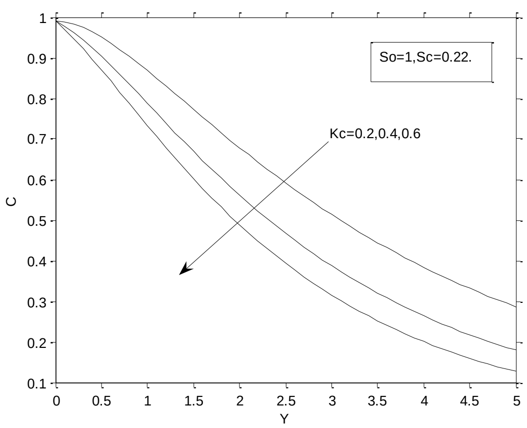

Fig 17. The effect of Kc on Concentration of dusty fluid

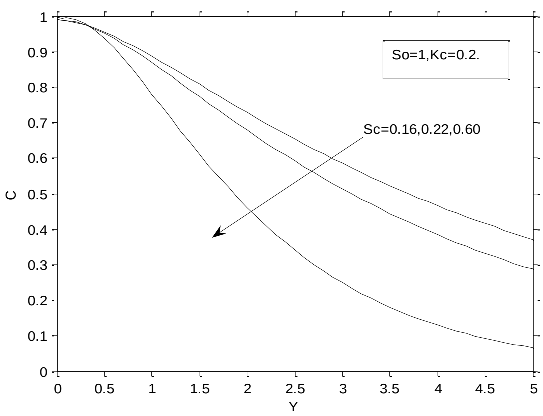

Fig 18. The effect of S_c on Concentration of dusty fluid

The temperature and concentration profiles do not change with the change in G_r, K, B, $B_1$and M, but for some other parameters like R, P_r, H, S_0 K_c, S_c, we can observe some changes. The Temperature profiles of dusty fluid are shown in the figures (13)-(15) at $n=0.1$, $t=0.1$, $N=1.5$, $S_c=0.22$, $G_r=2$, $M=0.02$, $K=100$, $B=0.5$, $B_1=0.5$, $S_0=1$ and $K_c=0.2$. From these figures it is seen that the temperature profile decreases as R, P_r and H increase. It is worth mentioning to note that Temperature is more for mercury than for electrolytic solution. The concentration profiles of dusty fluid are shown in the figures (16)-(18) at $n=0.1$, $t=0.1$, $N=1.5$, $Gr=2$, $M=0.02$, $K=100$, $B=0.5$, $B_1=0.5$, $R=1$, $P_r=0.71$ and $H=0.5$. From these figures it is observed that the concentration profile decreases as K_c, S_c increase, but it increases with an increase in S_0. The variations in Skin friction, Nusselt number and Sherwood number are studied through the tables (1) to (3).

Table 1. Variations in Skin-friction

Gr	M	K	B	B1	So	Kc	R	H	τ
2	0.02	50	0.5	0.5	1	0.2	1	0.5	13.0209
4	0.02	50	0.5	0.5	1	0.2	1	0.5	26.0419
2	0.04	50	0.5	0.5	1	0.2	1	0.5	12.2982
2	0.02	100	0.5	0.5	1	0.2	1	0.5	13.4282
2	0.02	50	1.0	0.5	1	0.2	1	0.5	14.3189
2	0.02	50	0.5	1.0	1	0.2	1	0.5	14.1733
2	0.02	50	0.5	0.5	2	0.2	1	0.5	15.0159
2	0.02	50	0.5	0.5	1	0.4	1	0.5	10.1927
2	0.02	50	0.5	0.5	1	0.2	2	0.5	12.8042
2	0.02	50	0.5	0.5	1	0.2	1	1.0	12.8959

Table 2. Variations in Nusselt number

R	Pr	H	Nu
1	0.71	0.5	-1.3992
2	0.71	0.5	-1.6908
3	0.71	0.5	-1.9294
1	7.0	0.5	-8.1142
1	0.71	1.0	-1.5539
1	0.71	0.5	-1.6908

Table 3. Variations in Sherwood number

S_0	Kc	Sc	Sh
1	0.2	0.16	-0.0140
2	0.2	0.16	0.1993
3	0.2	0.16	0.4127
1	0.4	0.16	-0.1081
1	0.6	0.16	-0.1758
1	0.2	0.22	-0.1206
1	0.2	0.60	-0.1413

To be realistic, the numerical values of Prandtl number P_r are chosen as $P_r=0.71$, and $P_r=7.00$, which correspond to air and water at 20^{o}C respectively. The numerical values of the remaining parameters are chosen arbitrarily.

Conclusions

- It is observed that the velocities of dusty fluid and dust particles decrease with the increase in magnetic parameter M, and increase as Grashof number G_r, Permeability of Porous medium K, Dust particles parameter B and Dusty fluid parameter B_1 increase. Further it is noticed that the velocity of the dusty fluid is more than that of dust particles.
- The temperature and concentration profiles do not change with the change in Grashof number, Permeability of Porous medium, Dust particles parameter, Dusty fluid parameter and magnetic parameter.
- The temperature profile decreases as Radiation parameter R, Prandtl number P_r, Heat source parameter H increase. The concentration profile decreases as Chemical reaction parameter K_c, Schmidt number S_c increase, but it increases with an increase in Soret number S_0.

Appendix

$$m_1 = \frac{P_r + \sqrt{P_r^{\,2} - 4P_r(n-R-H)}}{2} \qquad m_2 = \frac{S_c + \sqrt{S_c^{\,2} - 4S_c(n-K_c)}}{2}$$

$$m_3 = \frac{1 + \sqrt{1 + 4\left(M + \frac{1}{K} - \frac{nBB_1}{1-nB}\right)}}{2} \qquad A_1 = \frac{-S_o S_c m_1^{\,2}}{m_1^{\,2} - S_c m_1 + S_c(n-K_c)}$$

$$A_2 = \frac{-G_r N A_1 - G_r}{m_1^{\ 2} - m_1 - \left(M + \frac{1}{K} - \frac{nBB_1}{1-nB} \right)} \qquad A_3 = \frac{G_r N A_1 - G_r N}{m_2^{\ 2} - m_2 - \left(M + \frac{1}{K} - \frac{nBB_1}{1-nB} \right)}$$

$$A_4 = -m_1 A_2 - m_2 A_3 + m_3 A_2 + m_3 A_3 \qquad A_5 = -m_1 A_1 - m_2 (1 - A_1)$$

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