Effect of Mass transfer and thermal diffusion on unsteady MHD flow of a dusty gas through permeable boundary

M. Chitra[1], M.Suhasini[2]
[1] Associate Professor, [2] Research scholar, Department of Mathematics,
Thiruvalluvar University, Vellore-632 115, Tamilnadu, India

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AbstractIn this paper,We investigate the effect of unsteady MHD flow of a dusty gas through permeable boundary with mass transfer and thermal diffusion. The flow is assumed to be free convective flow and it is induced by the motion of a semi infinite plate. The closed forms of analytical solution are obtained for the saffman's equation of motion of the dusty gas along the x-axis. The effect of various parameters like soret number, permeability parameter, Schmidt number, magnetic parameter on velocity profile, temperature, concentration, wall shear stress and the rate of heat and mass transfer are obtained and their behaviour are discussed through the graphs.
Keywords: MHD, Convective flow, Dusty flow, Mass transfer ,Thermal diffusion.

1.Introduction

Many transport processes exist in nature and industrial application in which the transfer of heat and mass occurs simultaneously as a result of combined buoyancy effects of thermal diffusion and diffusion of chemical species. In the last few decades several efforts have been made to solve the problems on heat and mass transfer in view of their application to astrophysics, geophysics and engineering.Chemical reaction can be codified either heterogeneous or homogeneous processes. Its effect depends on the nature of the reaction whether the reaction is heterogeneous or homogeneous. A reaction is of order n, if the reaction rate is proportional to the n^th power of concentration. In particular, a reaction is of first order, if the rate of reaction is directly proportional to concentration itself.
Experimental and theoretical works on MHD flow with thermal diffusion and chemical reaction have been done extensively in various areas i.e. sustain plasma confinement for controlled thermonuclear fusion, liquid metal cooling of nuclear reactions and electromagnetic casting of metals.The study of radiation in thermal engineering is of great interest for industry point of view. Many processes in thermal engineering areas occur at high temperature and radiative heat transfer becomes very important for the design of pertinent equipment. Nuclear power plants, gas turbines and the various propulsion devices for air craft, missiles, satellites and space vehicles are example of such engineering areas.
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. 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.In many transport processes and industrial applications, transfer of heat and mass simultaneously as a result of combined buoyancy effects of thermal diffusion and diffusion of chemical species. Unsteady natural-convection of heat and mass transfer is great importance in designing control systems for modern free convection heat exchangers.

P. G. Saffman (1962) studied on the stability of laminar flow of a dusty gas.J.T.C. Liu (1972) discussed the flow of a dusty gas through a channel arbitrary time varying pressure gradient.W.Gretler and R. Regenfelder (2002) studied about the similarity solution for laser-driven shock waves in a dust-laden gas with internal heat transfer effects.N.K.Varshney and Ram Prakash (2004) discussed about MHD free convective flow of a visco-elastic(Kuvshiniski type) dusty gas through a porous medium induced by the motion of a semi-infinite flat plate moving with velocity decreasing exponentially with time.N. K. Varshney and Ram Prakash (2004) discussed about the MHD free convection flow of a visco elastic dusty gas through a porous medium induced by the motion of a semi- infinite flat plate moving with velocity decreasing exponentially with time. D.Kumar et.al (2006) have discussed on the MHD free convective flow of a visco-elastic (Kuvshiniki type) dusty gas through a porous medium induced by the motion of a semi-infinite flat plate moving with time and heat source. I. U. Mbeledogu and A. Ogulu (2007) discussed on the effect of heat and mass transfer of an unsteady MHD natural convection flow of a rotating fluid past a vertical porous flat plate in the presence of radiative heat transfer. P. M. Patil and P. S. Kulkarni (2008) discussed on the effects of chemical re-action on free convective flow of a polar fluid through a porous medium in the presence of internal heat generation. A. A. Afify (2009) studied on similarity solution in MHD effects of thermal diffusion on free convective heat and mass transfer over a stretching surface considering suction or injection.
P.Singh et.al (2010)studied on the effect of mass transfer in MHD free convective flow of a viscoelastic (Kuvshiniki type) dusty gas through a porous medium with heat source/sink.O. D. Makinde and T. Chinyoka (2010) discussed about the MHD transient flows and heat transfer of dusty fluid in a channel with variable physical properties and Navier slip condition.Om Prakash et .al (2010) studied the effects of thermal diffusion and chemical reaction on MHD Flow of dusty visco-elastic (Walter's Liquid Model-B) fluid. V.K Sharma et.al (2011) studied the effect of Dusty viscous fluid on MHD free convection flow with heat and mass transfer past a vertical porous plate. Rajesh Kumar et.al (2011) studied the thermal diffusion and mass transfer effects on MHD flow of a dusty gas through porous medium.
In this chapter, We have studied the effect of unsteady MHD flow of a dusty gas through permeable boundary with mass transfer and thermal diffusion. The flow is assumed to be free convective flow and it is induced by the motion of a semi – infinte plate. The closed forms of analytical solution are obtained for the saffman's equation of motion of the dusty gas and the dust particles along the x-axis. The effect of various parameters like soret number, permeability parameter, Schmidt number, magnetic parameter on velocity profile, temperature ,concentration, wall shear stress and the rate of heat and mass transfer are obtained and their behaviour are discussed graphically.

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2.Mathematical formulation

Consider the unsteady incompressible dusty gas to be confined in the space y >0 and the flow is produced by the motion of the finite flat plate moving with the velocity $\vartheta e^{-\lambda^2 t}$ in x direction. The gas has small electrical conductivity and the electromagnetic force produced is also very small.
According to Saffman (1962) the equation of motion of the dust gas and the dust particles along $x-$axis are given by

$$\frac{\partial u}{\partial t} = \vartheta \frac{\partial^2 u}{\partial y^2} + \frac{K_0 N_0}{\rho}(v-u) \tag{1}$$

$$\frac{\partial v}{\partial t} = \frac{K_0}{m}(u-v) \tag{2}$$

$$\frac{\partial T}{\partial t} = \frac{K_T}{\rho C_p}\frac{\partial^2 T}{\partial y^2} \tag{3}$$

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial y^2} + D_T \frac{\partial^2 T}{\partial y^2} \tag{4}$$

Where u and v denotes the velocity of gas and dust particles respectively. ϑ is the kinematic coefficient of viscosity of the gas, K_0 is the stokes resistance coefficient. N_0 is the number density of the dust particles which is taken to be constant, ρ is the density of the gas, m is the mass of the dust partical, K_τ is the thermal conductivity, D is the molecular diffusivity and D_τ is the thermal diffusivity.C_p is the specific heat at the constant pressure.
Applying the magnetic field, free convection, mass transfer and thermal diffusion along the $x-$ axis the equation of motion (7.1) reduces to

$$\frac{\partial u}{\partial t} \quad = \vartheta \tfrac{\partial^2 u}{\partial y^2} + \tfrac{K_0 N_0}{\rho}(v-u) - \tfrac{\sigma B_0^2 u}{\rho} + g\beta\theta + g\beta'\phi \tag{5}$$

Where $\theta = T - T_1, \phi = C - C_1$
The initial and boundary conditions are given as

$$\left.\begin{array}{l} u = u_p \text{ and } \dfrac{\partial u}{\partial y} = \dfrac{\alpha}{\sqrt{Da}}(u_B - u_p) \ ; v = \vartheta e^{-\lambda^2 t}; \theta = \vartheta e^{-\lambda^2 t}; \ \ \phi = \vartheta e^{-\lambda^2 t} \quad at \ \ y = \sqrt{\vartheta\tau} \\ \dfrac{\partial u}{\partial y} = 0 \ ; v = 0; \theta = 0; \ \ \phi = 0 \quad at \ \ y = 0 \end{array}\right\} \tag{6}$$

Introducing the following non-dimensional quantities

$$\left. y^* = \frac{y}{\sqrt{(\vartheta\tau)}}; u^* = \frac{u}{\vartheta}; v^* = \frac{v}{\vartheta}; t^* = \frac{t}{\tau}; \tau = \frac{m}{k_0}; \theta^* = \frac{\theta}{\vartheta}; \phi^* = \frac{\phi}{\vartheta} \right\} \tag{7}$$

using the above non- dimensional quantities, equations (2) to (5) can be reduced to the following dimensionless forms (dropping the stars)

$$\frac{\partial u}{\partial t} = \vartheta \frac{\partial^2 u}{\partial y^2} + f(v-u) - Mu + \beta_1 \theta + \beta_2 \phi \tag{8}$$

$$\frac{\partial v}{\partial t} = (u-v) \tag{9}$$

$$\frac{\partial \theta}{\partial t} = \frac{1}{Pr} \frac{\partial^2 \theta}{\partial y^2} \tag{10}$$

$$\frac{\partial \phi}{\partial t} = \frac{1}{Sc} \frac{\partial^2 \phi}{\partial y^2} + \frac{1}{S_1} \frac{\partial^2 \theta}{\partial y^2} \tag{11}$$

where $f = \frac{mN_0}{\rho}$ is the mass of concentration of dust particles, $M = \frac{m\sigma B_0^2}{K_0 \rho}$ is the magnetic parameter,, $\beta_1 = g\beta\tau$ is the volumetric expansion parameter , $\beta_2 = g\beta'\tau$ is the mass expansion parameter,$Sc = \frac{\vartheta}{D}$ is the Schmidt number, $Pr = \frac{\rho\vartheta C_p}{K_\tau}$ is the prandtl number, $S_1 = \frac{\vartheta}{D_\tau}$ is the thermal diffusion parameter as soret number.
Now the boundary conditions becomes

$$\left.\begin{aligned} &u = u_p \text{ and } \frac{\partial u}{\partial y} = \frac{\alpha}{\sqrt{Da}}(u_B - u_p) \ ;\theta = e^{-\lambda^2 t};\ \ \phi = e^{-\lambda^2 t} \quad at \ \ y = 1 \\ &\frac{\partial u}{\partial y} = 0 \ \ ;\theta = 0;\ \ \phi = 0 \quad at \quad y = 0 \end{aligned}\right\} \tag{12}$$

3.Solution of the problem

To solve the equations (8) to (11) subject to the boundary conditions (6), we assume solutions of the form

$$u = F(y)e^{-\lambda^2 t} \tag{13}$$

$$v = G(y)e^{-\lambda^2 t} \tag{14}$$

$$\theta = H(y)e^{-\lambda^2 t} \tag{15}$$

$$\phi = I(y)e^{-\lambda^2 t} \tag{16}$$

Substituting the equations (13) to (16) in to the equations (8) to (11), we get

$$\frac{\partial^2 F}{\partial y^2} + fG + F(\lambda^2 - f - M) = -\beta_1 H - \beta_2 I \tag{17}$$

$$G(1-\lambda^2) = F \tag{18}$$

$$\frac{\partial^2 H}{\partial y^2} + \lambda^2 HPr = 0 \tag{19}$$

$$\frac{\partial^2 I}{\partial y^2} + \frac{\partial^2 H}{\partial y^2} + \lambda^2 IS_1 Sc = 0 \tag{20}$$

Now the boundary conditions becomes

$$\left.\begin{aligned} &\frac{\partial F}{\partial y} = \frac{\alpha}{\sqrt{Da}}[u_B - u_P]; G = 1; H = 1; I = 1 \quad \text{at } \ y = 1 \\ &\frac{\partial F}{\partial y} = 0; G = 0; H = 0; I = 0; \quad \text{at } \ y = 0 \end{aligned}\right\} \tag{21}$$

Using the equation(18), equation (17)becomes

$$\frac{\partial^2 F}{\partial y^2} + {c_3}^2 F = -\beta_1 H - \beta_2 I \tag{22}$$

solving the equation (19) using the boundary conditions (21),The temperature distribution is

$$H = \frac{\sinh(c_1 y)}{\sinh(c_1)} \tag{23}$$

$$\theta = \left[\frac{\sinh(c_1 y)}{\sinh(c_1)}\right] e^{-\lambda^2 t} \tag{24}$$

solving the equation (20) using the boundary condition (21), The concentration distribution is

$$I = A_3 e^{c_2 y} + A_4 e^{-c_2 y} - \frac{c_1^2 \sinh(c_1 y)}{(c_1^2 - c_2^2)\sinh c_1} \tag{25}$$

$$\phi = \left[A_3 e^{c_2 y} + A_4 e^{-c_2 y} - \frac{c_1^2 \sinh(c_1 y)}{(c_1^2 - c_2^2)\sinh c_1}\right] e^{-\lambda^2 t} \tag{26}$$

solving the equation (25) using the boundary condition (21), The velocity of the gas is

$$\begin{aligned} F = {} & A_5 \cos c_3 y + A_6 \sin c_3 y - \frac{\beta_1}{c_1^2 + c_3^2}\frac{\sinh(c_1 y)}{\sinh c_1} - \frac{\beta_2}{(c_1^2 - c_2^2)} \\ & \left(\frac{2c_1^2 - c_2^2}{c_2^2 + c_3^2}\frac{\sinh(c_2 y)}{2\sinh c_2} - \frac{c_1^2}{c_1^2 + c_3^2}\frac{\sinh(c_1 y)}{\sinh c_1}\right) \end{aligned} \tag{27}$$

$$\begin{aligned} u = {} & \Bigg[A_5 \cos c_3 y + A_6 \sin c_3 y - \frac{\beta_1}{c_1^2 + c_3^2}\frac{\sinh(c_1 y)}{\sinh c_1} - \frac{\beta_2}{(c_1^2 - c_2^2)} \\ & \left(\frac{2c_1^2 - c_2^2}{c_2^2 + c_3^2}\frac{\sinh(c_2 y)}{2\sinh c_2} - \frac{c_1^2}{c_1^2 + c_3^2}\frac{\sinh(c_1 y)}{\sinh c_1}\right)\Bigg] e^{-\lambda^2 t} \end{aligned} \tag{28}$$

solving the equation (18) using the boundary condition (21), The velocity of the dusty particles is

$$\begin{aligned} G = {} & \frac{1}{(1-\lambda^2)}\Bigg[A_5 \cos c_3 y + A_6 \sin c_3 y - \frac{\beta_1}{c_1^2 + c_3^2}\frac{\sinh(c_1 y)}{\sinh c_1} - \frac{\beta_2}{(c_1^2 - c_2^2)} \\ & \left(\frac{2c_1^2 - c_2^2}{c_2^2 + c_3^2}\frac{\sinh(c_2 y)}{2\sinh c_2} - \frac{c_1^2}{c_1^2 + c_3^2}\frac{\sinh(c_1 y)}{\sinh c_1}\right)\Bigg] \end{aligned} \tag{29}$$

$$\begin{aligned} v = {} & \frac{1}{(1-\lambda^2)}\Bigg[A_5 \cos c_3 y + A_6 \sin c_3 y - \frac{\beta_1}{c_1^2 + c_3^2}\frac{\sinh(c_1 y)}{\sinh c_1} - \frac{\beta_2}{(c_1^2 - c_2^2)} \\ & \left(\frac{2c_1^2 - c_2^2}{c_2^2 + c_3^2}\frac{\sinh(c_2 y)}{2\sinh c_2} - \frac{c_1^2}{c_1^2 + c_3^2}\frac{\sinh(c_1 y)}{\sinh c_1}\right)\Bigg] e^{-\lambda^2 t} \end{aligned} \tag{30}$$

Using the boundary condition equation (21), the values of the co- efficient A1, A2, A3, A4, A5 and A6 are obtained and their values are mentioned in Appendix
Using the equation (28), The skin friction of the gas is

$$\tau = \left[\frac{\partial u}{\partial y}\right]_{y=1} \tag{31}$$

$$\begin{aligned} \tau = {} & \Bigg[-c_3 A_5 \sin(c_3) + c_3 A_6 \cos(c_3) - \frac{\beta_1}{c_1^2 + c_3^2}\frac{c_1\cosh(c_1)}{\sinh c_1} - \frac{\beta_2}{(c_1^2 - c_2^2)} \\ & \left(\frac{2c_1^2 - c_2^2}{c_2^2 + c_3^2}\frac{c_2\cosh(c_2)}{2\sinh c_2} - \frac{c_1^2}{c_1^2 + c_3^2}\frac{c_1\cosh(c_1)}{\sinh c_1}\right)\Bigg] e^{-\lambda^2 t} \end{aligned} \tag{32}$$

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using the equation (30), The skin friction of the dust particles is

$$\tau_p = \left[\frac{\partial v}{\partial y}\right]_{y=1} \tag{33}$$

$$\tau_p = \left[\frac{1}{(1-\lambda^2)}\left[-c_3A_5\sin(c_3) + c_3A_6\cos(c_3) - \frac{\beta_1}{c_1^2+c_3^2}\frac{c_1\cosh(c_1)}{\sinh c_1} - \frac{\beta_2}{(c_1^2-c_2^2)}\right.\right.$$
$$\left.\left.\left(\frac{2c_1^2-c_2^2}{c_2^2+c_3^2}\frac{c_2\cosh(c_2)}{2\sinh c_2} - \frac{c_1^2}{c_1^2+c_3^2}\frac{c_1\cosh(c_1)}{\sinh c_1}\right)\right]e^{-\lambda^2 t} \tag{34}$$

Using the equation (24) The rate of heat transfer of the dusty gas is

$$Nu = \left[\frac{\partial \theta}{\partial y}\right]_{y=1} \tag{35}$$

$$Nu = \left[\frac{c_1\sinh c_1}{\sinh c_1}\right]e^{-\lambda^2 t} \tag{36}$$

Using the equation (26) The rate of mass transfer of the dusty gas is

$$Sh = \left[\frac{\partial \phi}{\partial y}\right]_{y=1} \tag{37}$$

$$Sh = \left[A_3c_2e^{c_2} - A_4c_2e^{-c_2} - \frac{c_1^2\cosh c_1}{(c_1^2-c_2^2)\sinh c_1}\right]e^{-\lambda^2 t} \tag{38}$$

4.Results and discussion

In this paper, We studied the effect of unsteady MHD flow of a dusty gas through permeable boundary with mass transfer and thermal diffusion. The flow is assumed to be free convective flow. The closed forms of analytical solution are obtained for the saffman's equation of motion of the dusty gas and the dust particles along the x-axis. The effect of various parameters like magnetic parameter(M), thermal diffusion parameter as soret number(S_1), Schmidt number(Sc),Prandtl number(Pr),mass concentration of dust particles(f),volumetric expansion parameter (β_1),mass expansion parameter (β_2),Darcy number(Da) on velocity profile, temperature ,concentration, skin friction and the rate of heat and mass transfer are obtained and their behavior are discussed graphically.

Figures 1 and 2 shows that an increase in Magnetic parameter (M) leads to decrease in both the velocities u and v.This is because there exist a resistive type force called Lorentz force similar to drag force which has tendency to slow down the the motion of the dusty gas.so the velocity decreases while increasing the magnetic parameter. Figures 3 and 4 shows that an increase in mass concentration (f) leads to decrease in both the velocities u and v.Figures 5 and 6 shows that an increase in volumetric expansion parameter (β_1) leads to increases in both the velocities u and v.Figures 7 and 8 shows that an increase in mass expansion parameter (β_2) leads to decrease in both the velocities u and v. Figure 9 shows that an increase in the Schmidt number (Sc) leads to decrease in the velocity u. Figure 10, shows that an increase in the λ decreases the temperature profile(θ) of the dusty gas.Figures 11 and 12, shows that the concentration profile(ϕ) of the dusty gas decreases while increasing the values of Schmidt number(Sc) and the thermal diffusion parameter as soret number(S_1).

Figures 13 and 14, shows that the skin friction of the gas(τ) and the skin friction of the dust particles (τ_p) decreases while increasing the values of the thermal diffusion parameter as soret number(S_1).Figures 15 and 16, shows that the skin friction of the gas(τ) and the skin friction of the dust particles (τ_p)

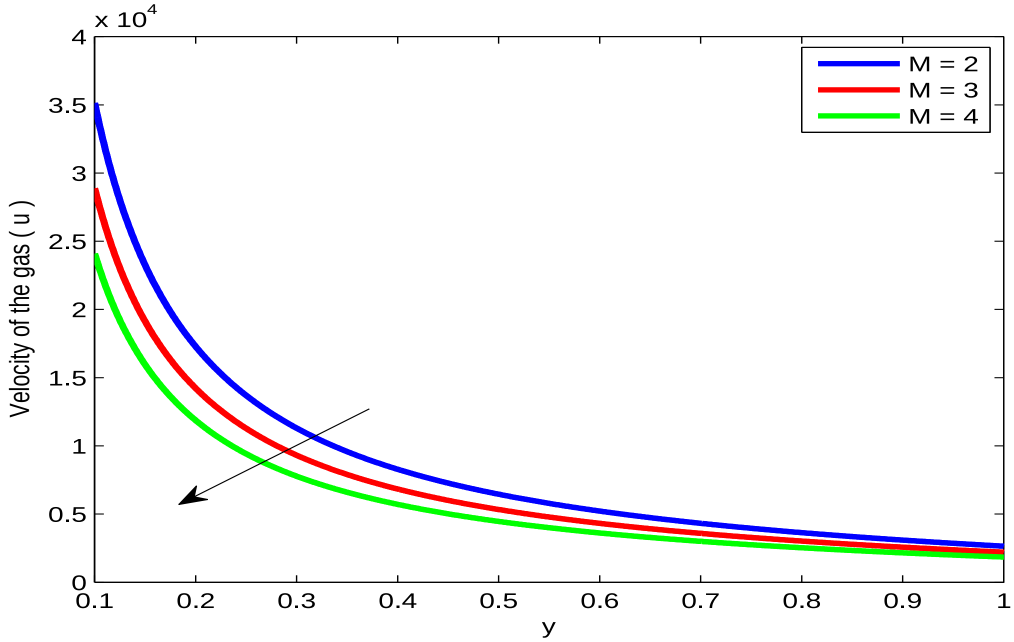

Figure 1: Variation of velocity of the gas (u) for different values of Magnetic parameter (M) for fixed $Sc = 3, \lambda = 0.5, S_1 = 0.5, Pr = 0.71, t = 0.3, \beta_1 = 0.5, \beta_2 = 2, f = 0.4, Da = 2$.

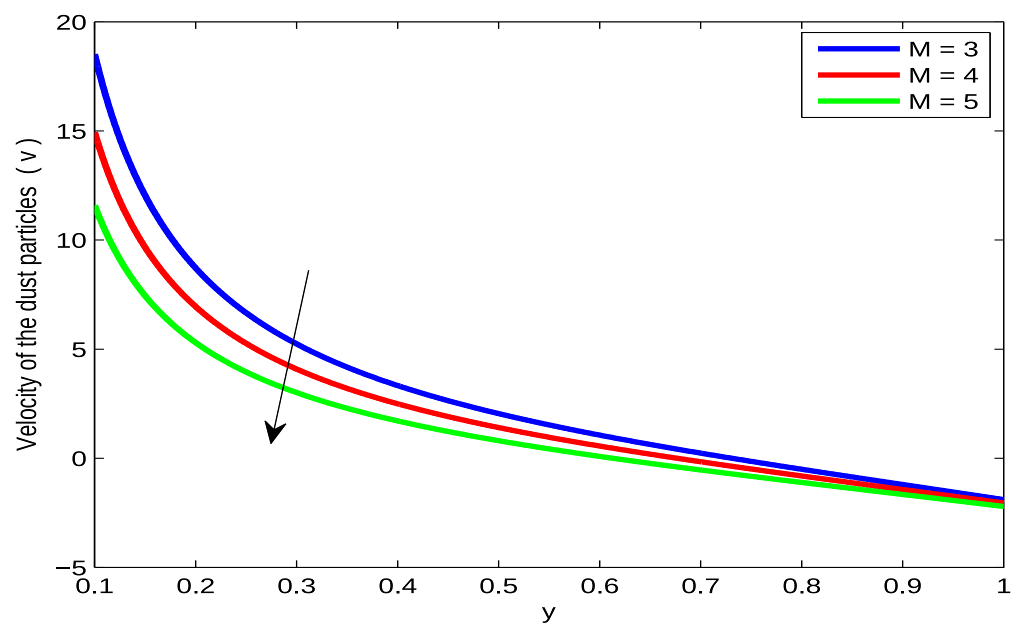

Figure 2: Variation of velocity of the dust particles (v) for different values of Magnetic parameter (M) for fixed $Sc = 3, \lambda = 0.5, S_1 = 0.5, Pr = 0.71, t = 0.5, \beta_1 = 0.5, \beta_2 = 2, f = 0.4, Da = 2$.

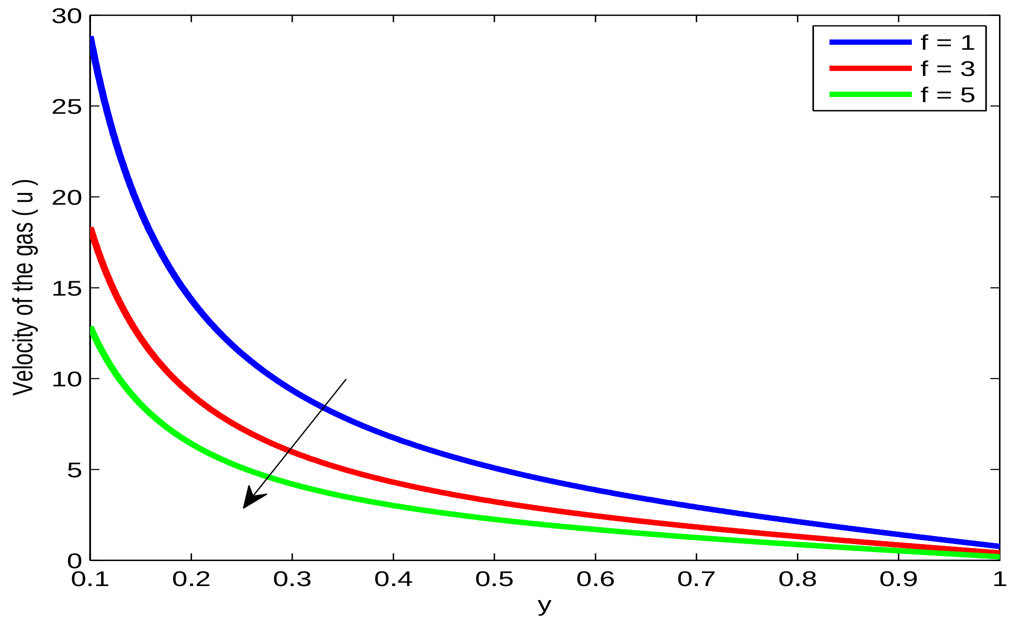

Figure 3: Variation of velocity of the gas (u) for different values of mass concentration (f) for fixed $Sc = 3, \lambda = 0.5, S_1 = 0.5, Pr = 0.71, t = 0.3, \beta_1 = 0.5, \beta_2 = 2, M = 3, Da = 2$.

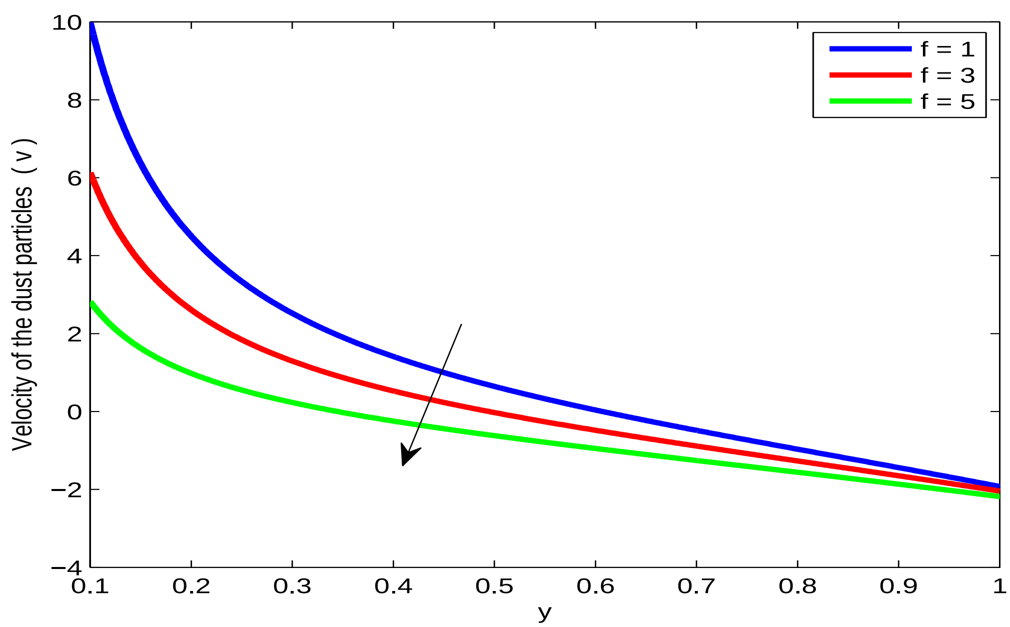

Figure 4: Variation of velocity of the dust particles (v) for different values of mass concentration (f) for fixed $Sc = 3, \lambda = 0.5, S_1 = 0.5, Pr = 0.71, t = 0.5, \beta_1 = 0.5, \beta_2 = 2, M = 3, Da = 2$.

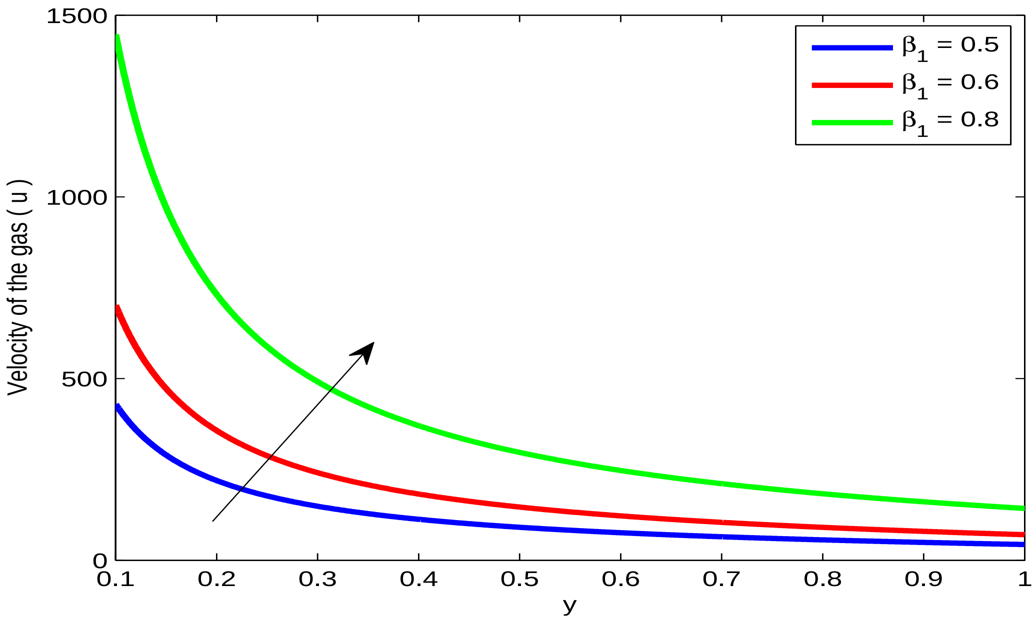

Figure 5: Variation of velocity of the gas (u) for different values of volumetric expansion parameter (β_1) for fixed $Sc = 3, \lambda = 0.5, S_1 = 0.5, Pr = 0.71, t = 0.3, M = 3, \beta_2 = 2, f = 0.4, Da = 2$.

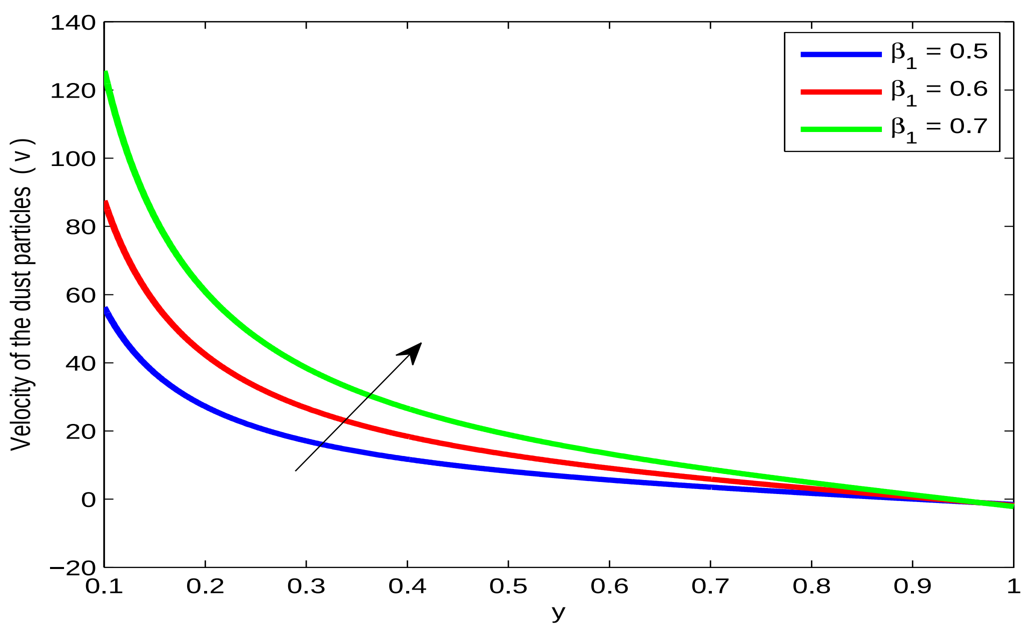

Figure 6: Variation of velocity of the dust particles (v) for different values of volumetric expansion parameter (β_1) for fixed $Sc = 3, \lambda = 0.5, S_1 = 0.5, Pr = 0.71, t = 0.5, M = 3, \beta_2 = 2, f = 0.4, Da = 2$.

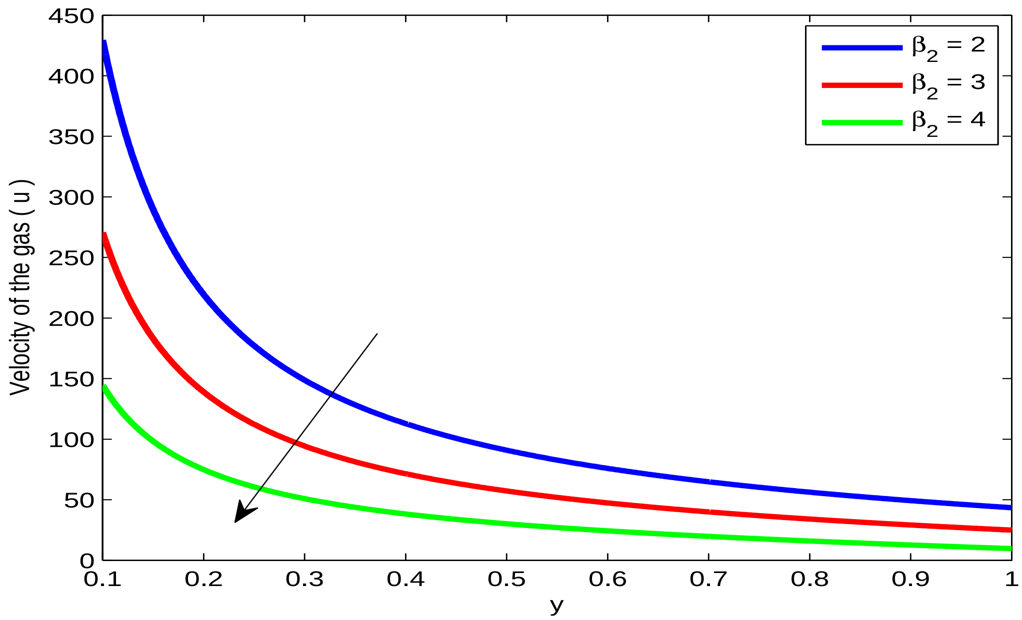

Figure 7: Variation of velocity of the gas (u) for different values of mass expansion parameter (β_2) for fixed $Sc = 3, \lambda = 0.5, S_1 = 0.5, Pr = 0.71, t = 0.3, M = 3, \beta_1 = 0.5, f = 0.4, Da = 2.$

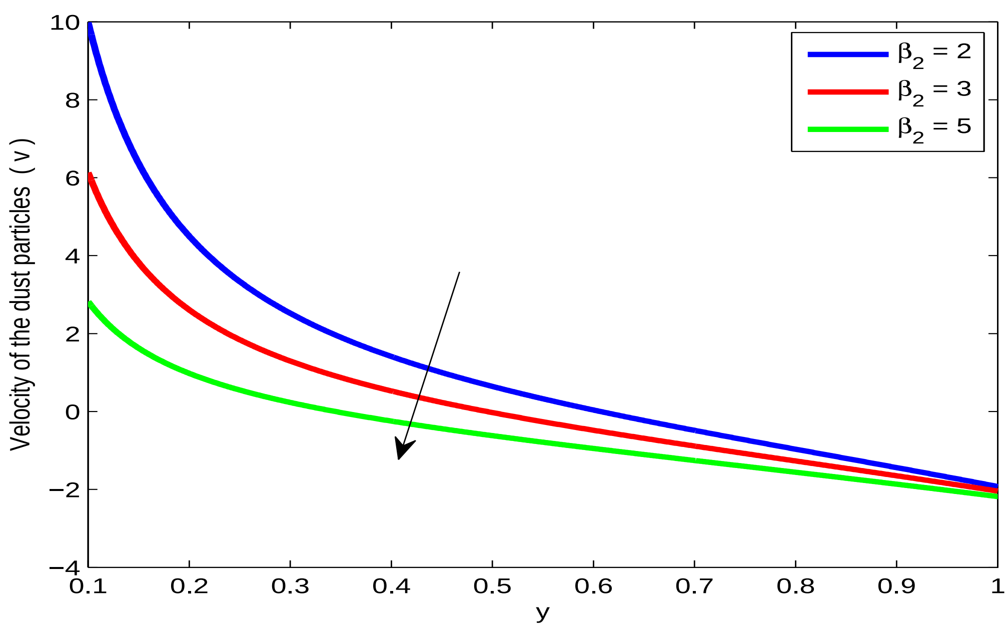

Figure 8: Variation of velocity of the dust particles (v) for different values of mass expansion parameter (β_2) for fixed $Sc = 3, \lambda = 0.5, S_1 = 0.5, Pr = 0.71, t = 0.5, M = 3, \beta_1 = 0.5, f = 0.4, Da = 2.$

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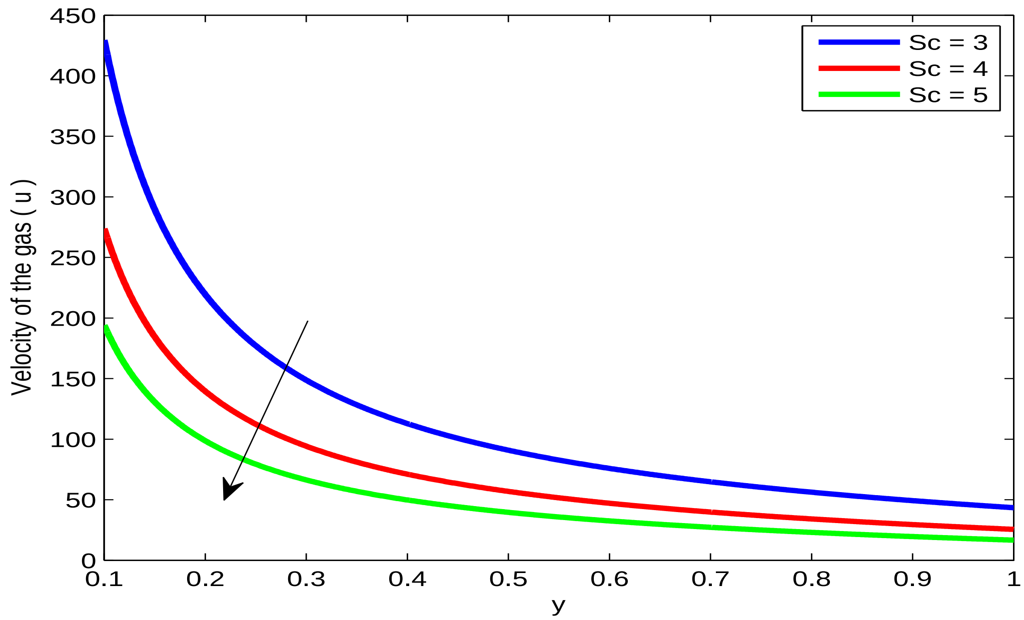

Figure 9: Variation of velocity of the gas (u) for different values of Schmidt number (Sc) for fixed $Da = 2, \lambda = 0.5, S_1 = 0.5, Pr = 0.71, t = 0.5, M = 3, \beta_2 = 2, \beta_1 = 0.5, f = 0.4$

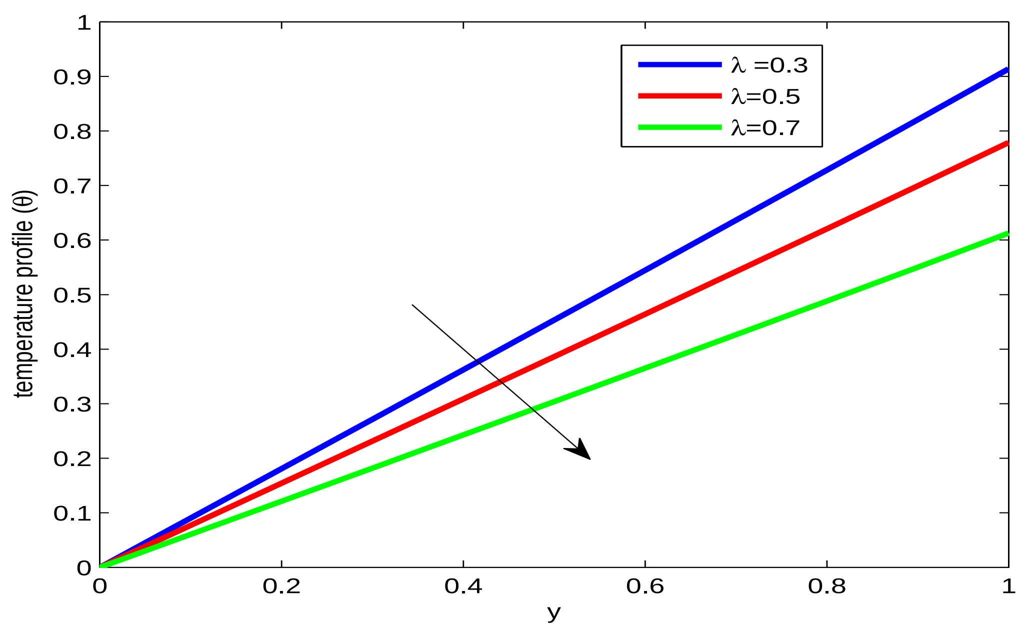

Figure 10: Temperature profile (θ) for different values of λ for fixed $Pr = 0.71, t = 1$.

decreases while increasing the values of the mass expansion parameter (β_2).Figure 17 shows that an increase in the mass concentration (f) leads to decrease in the skin friction of the gas (τ).Figure 18

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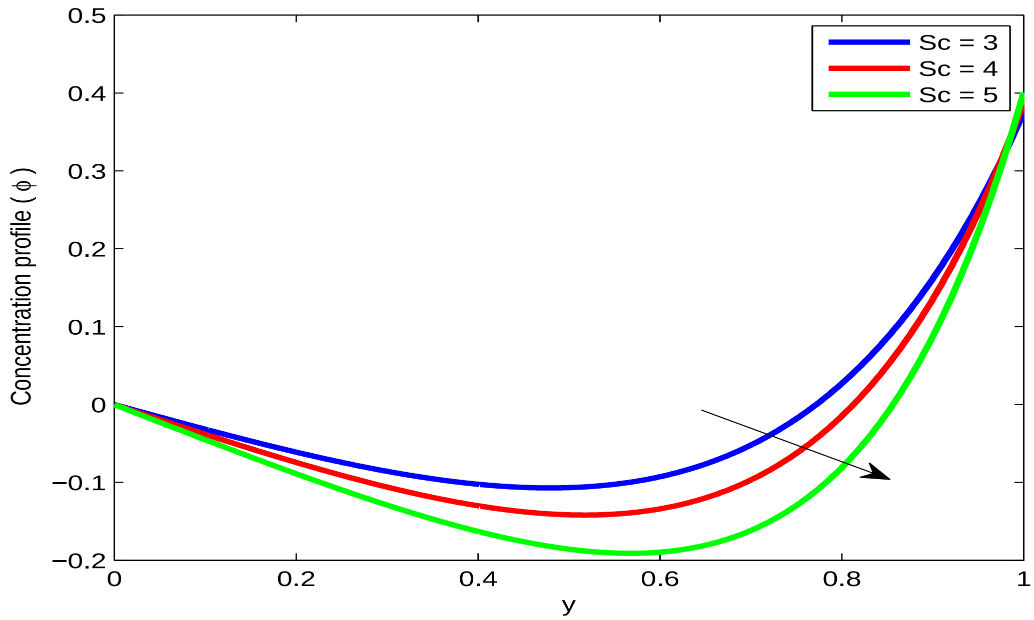

Figure 11: Concentration profile (ϕ) for different values of Schmidt number (Sc) for fixed $\lambda = 3, S_1 = 5, Pr = 0.71, t = 0.3$

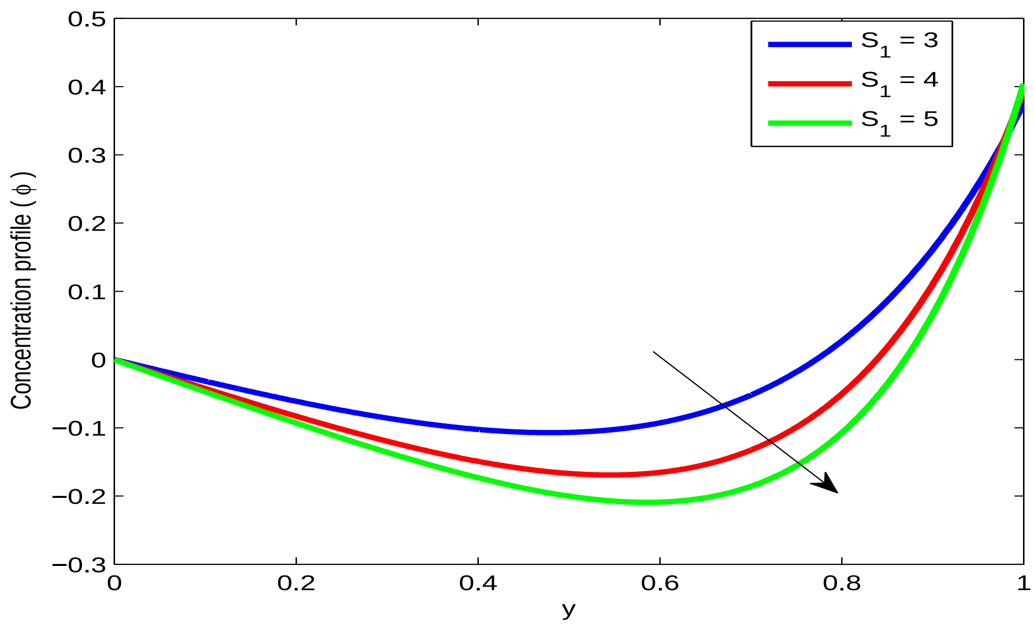

Figure 12: Concentration profile (ϕ) for different values of thermal diffusion parameter (S_1) for fixed $Sc = 3, \lambda = 3, Pr = 0.71, t = 0.3$

shows that an increase in the λ leads to decrease the Nusselt number (Nu).

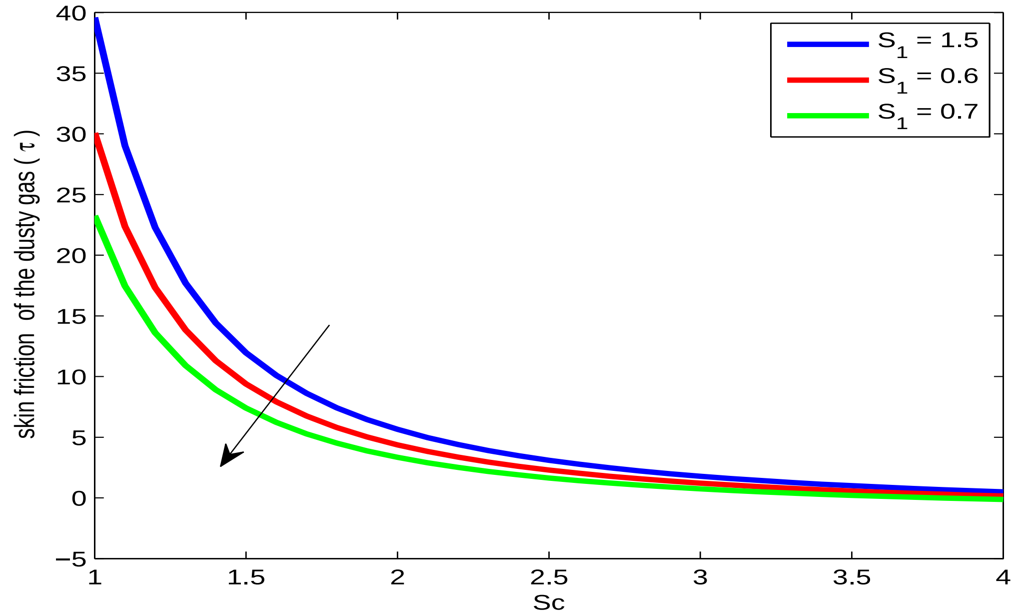

Figure 13: Skin friction of the gas(τ) for different values of thermal diffusion parameter (S_1)for fixed $Sc = 3, \lambda = 0.5, Pr = 0.71, t = 0.5, \beta_1 = 0.5, \beta_2 = 2, f = 0.4, Da = 2$.

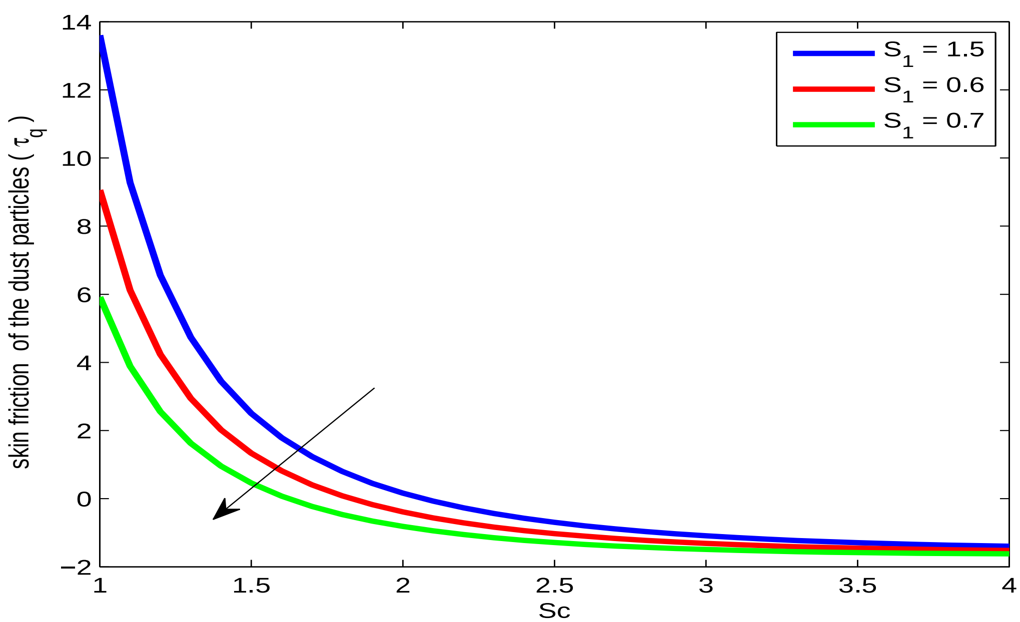

Figure 14: Skin friction of the dust particles (τ_p) for different values of thermal diffusion parameter (S_1)for fixed $Sc = 3, \lambda = 0.5, S_1 = 0.5, Pr = 0.71, t = 0.5, \beta_1 = 0.5, \beta_2 = 2, f = 0.4, Da = 2$.

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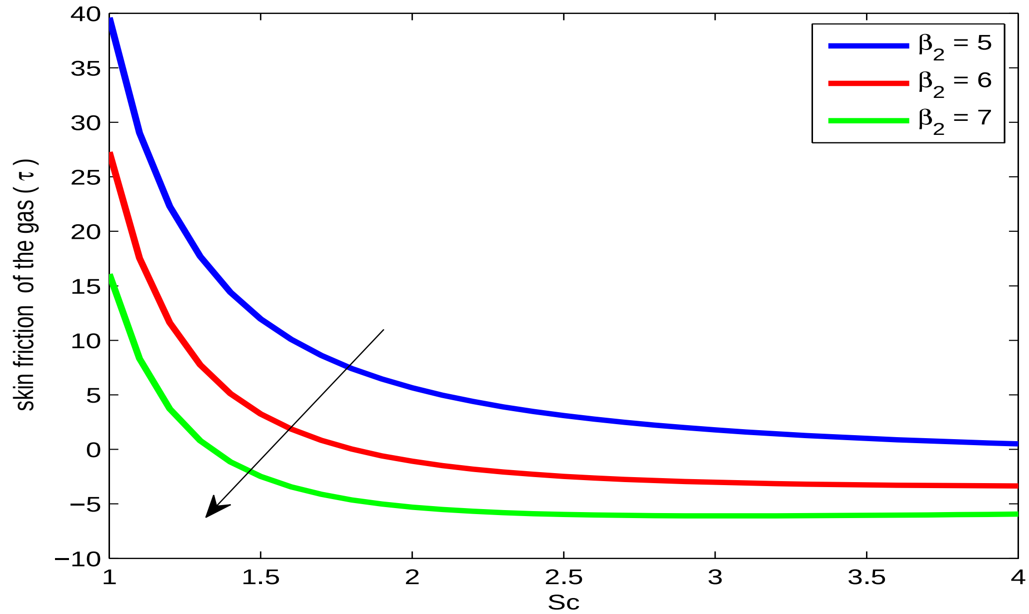

Figure 15: Skin friction of the gas(τ) for different values of mass expansion parameter (β_2) for fixed $Sc = 3, \lambda = 0.5, S_1 = 0.5, Pr = 0.71, t = 0.5, M = 3, \beta_1 = 0.5, f = 0.4, Da = 2$.

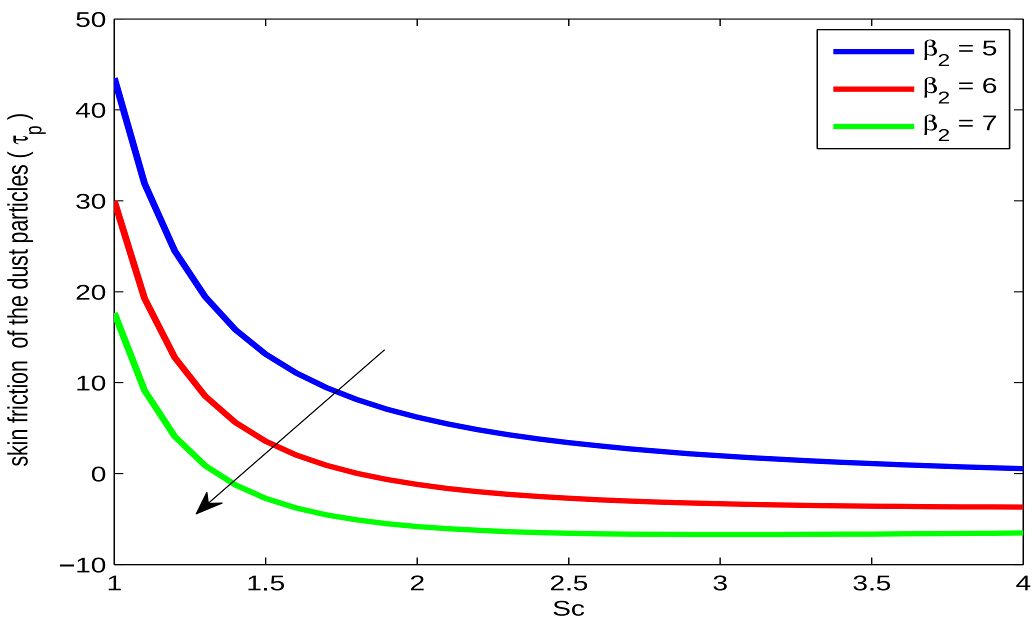

Figure 16: Skin friction of the dust particles (τ_p) for different values of mass expansion parameter (β_2) for fixed $Sc = 3, \lambda = 0.5, S_1 = 0.5, Pr = 0.71, t = 0.5, M = 3, \beta_1 = 0.5, f = 0.4, Da = 2$.

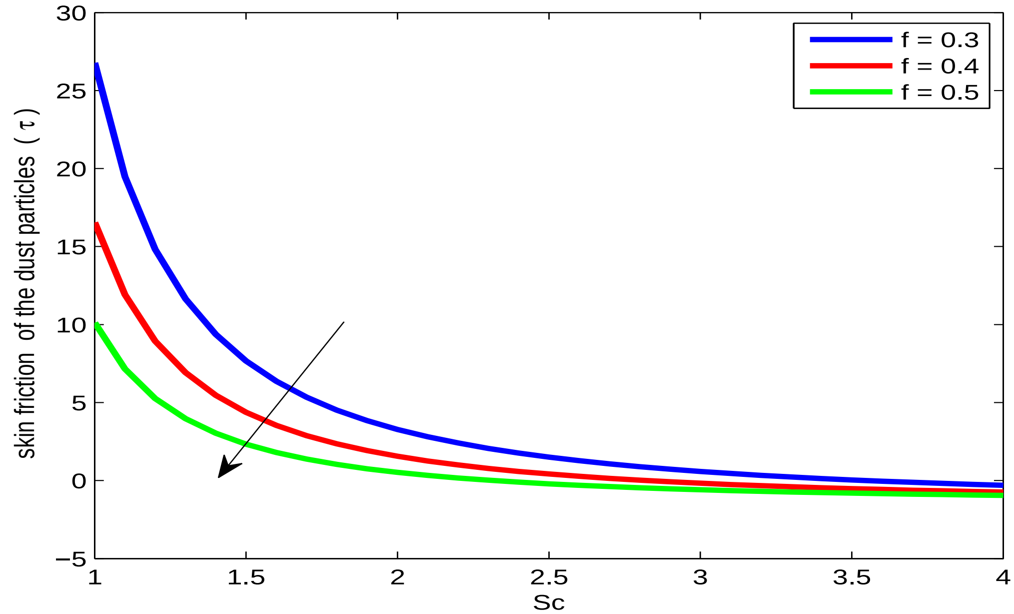

Figure 17: Skin friction of the gas (τ) for different values of mass concentration (f) for fixed $Sc = 3, \lambda = 0.5, S_1 = 0.5, Pr = 0.71, t = 0.5, M = 3, \beta_1 = 0.5, Da = 2$.

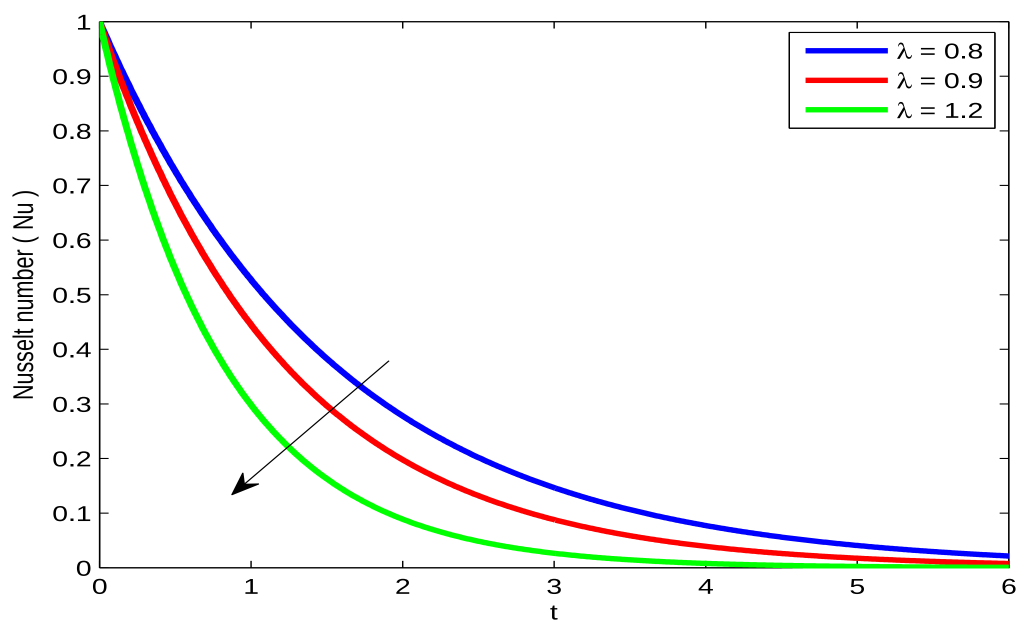

Figure 18: Variation of Nusselt number (Nu) for the different values of λ for fixed $Pr = 0.71, t = 1$

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Appendix

$$A_1 = \frac{1}{2\sinh(c_1)}$$
$$A_2 = -\frac{1}{2\sinh(c_1)}$$
$$A_3 = \frac{1}{2\sinh(c_2)}\frac{2c_1^2 - c_2^2}{c_1^2 - c_2^2}$$
$$A_4 = -\frac{1}{2\sinh(c_2)}\frac{2c_1^2 - c_2^2}{c_1^2 - c_2^2}$$
$$A_5 = -\frac{1}{C_3\sin C_3}\frac{\alpha}{\sqrt{Da}}[u_B - u_P] - \cos C_3[\frac{\beta_1}{C_1^2 + C_3^2}\frac{C_1}{\sinh C_1}$$
$$-\frac{\beta_2}{C_1^2 - C_2^2}\{\frac{2C_1^2 - C_2^2}{C_1^2 + C_3^2}\frac{C_2}{\sinh C_2} - \frac{C_1^3}{C_1^2 + C_3^2}C_2\frac{1}{\sinh C_1}\}] - \frac{\cosh C_1}{\sinh C_1}[\frac{\beta_1}{C_1^2 + C_3^2}$$
$$+\frac{\beta_2}{C_1^2 - C_2^2}\{\frac{2C_1^2 - C_2^2}{C_2^2 + C_3^2}C_2 + \frac{C_1^2}{C_2^2 + C_3^2}\}]$$
$$A_6 = \frac{1}{C_3}[\frac{C_1}{(C_1^2 - C_2^2)\sinh C_1}\{\beta_1 + \frac{\beta_2 C_1^2}{C_1^2 - C_2^2}\} + \{\frac{\beta_2}{C_1^2 - C_2^2}\frac{2C_1^2 - C_2^2}{C_2^2 + C_3^2}C_2 + \frac{C_1^2}{C_2^2 + C_3^2}\}]$$
$$c_1 = \lambda\sqrt{Pr}$$
$$c_2 = \lambda\sqrt{S_1 Sc}$$
$$c_3 = \frac{f}{(1-\lambda^2)} + \lambda^2 - f - M$$

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AUTHORS

First Author - M.Chitra,M.sc.,M.phil.,Ph.D, Thiruvalluvar University, chitratvu@gmail.com
Second Author - M.Suhasini,M.sc.,M.phil., Thiruvalluvar University,suhasinim54@gmail.com,9894596402.