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SORET AND DUFOUR EFFECTS ON MHD FLOW ABOUT A ROTATING VERTICAL CONE IN PRESENCE OF RADIATION

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Abstract: In this paper a numerical study of Soret and Dufour effect on MHD flow in presence of thermal radiation about a rotating vertical cone has been investigated. The governing equations are nonlinear partial differential equations and so by using similarity transformations they are converted to ordinary differential equations. MATLAB's built in solver `bvp4c` is employed to solve numerically the ODE's. The graph of velocity, temperature and concentration of the fluid are illustrated. To verify the accuracy of the numerical solution, a comparison for wall shear stress in tangential and circumferential direction with the present result and the one available in literature is done and the outcomes are in good match. Also local rate of surface heat transfer and mass transfer for different values of parameters are obtained.

Keywords: Dufour effect; radiation; rotating cone; Soret effect; `bvp4c`.

2010 AMS Subject Classification: 76D05, 76S05.

1. INTRODUCTION

Problems related to transfer of heat and mass are often seen in the field of engineering and

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geothermal applications because of its various uses in devices like turbines, numerous propulsion devices for aircrafts and missiles, power transformers, metallurgy, satellites and canisters for nuclear disposable wastes etc. The knowledge of heat transport and distribution of temperature is important in aeronautics, dams, multi-storied buildings and petroleum industries. Chemical reaction along with problems of exchange of heat and mass are encountered in chemical as well as metallurgical industries. Chemical reactions are classified into two type's viz. homogeneous and heterogeneous chemical reaction. Homogeneous reaction occurs at a uniform rate in the solution through a given phase whereas heterogeneous reaction happens at the restricted region or at interface of a solution.

Many researchers have studied MHD flow problems with heat transfer as well as mass transfer about a rotating cone. Hartnett and Deland [1] investigated rotating body problems and the consequences of heat flow due to Prandtl number. Sparrow and Cess [2] studied the heat flux on the fluid flow in presence of an axial magnetic field about a rotating disk. Tien and Tsuji [3] did an analytical investigation on exchange of heat on a steady laminar forced flow about a rotating cone. Kafoussias and Williams [4] investigated Soret and Dufour effects with temperature dependent viscosity with mixed convective heat and mass transfer. Postelnicu [5] examined the impact of magnetic field on a vertical surface with heat transfer as well as mass transfer. Anilkumar and Roy [6] investigated numerically the results of mass transfer and thermal diffusion in a rotating fluid due to rotating cone. Afify [7] analysed mass flux on free convective optically dense viscous flow and the influence of radiation and chemical reactions about an erect cone. Chamkha and Al-Mudhaf [8] studied numerically unsteady heat and mass transfer with heat production or absorption effects due to a cone in the existence of magnetic field. Pullepu et al. [9] studied the impact of heat production or absorption and chemical reaction on unsteady flow with free convection and variable temperature about a vertical cone. Sharma and Konwar [10] investigated numerically the transfer of heat and mass on MHD flow under the influence of radiation on a vertical rotating cone.

Siddiqa et al. [11] investigated nanofluid flow with gyrotactic microorganisms through a standing curvy cone with heat and mass transfer and bioconvection. They found that the amplitude

of the cone's curvy surface significantly affect the coefficient of heat and mass transfer as well as microorganisms density. Saleem et al. [12] examined theoretically using Homotopy Analysis Method nanofluid Walter's B flow with magnetic effects. They considered the flow to be time dependent and found notable effect of thermophoresis as well as Brownian motion parameters on heat and mass transfer rate. Verma et al. [13] investigated numerically heat transfer and mass transfer in porous medium considering Forchheimer model with Soret effect through a rotating disk. Theoretical analysis has been carried out to discuss the effect of chemical reaction on heat and mass transfer on magneto-nanofluid that are ionised partially by Nawaz et al. [14]. Nadeem et al. [15] investigated the effects of variable viscosity on an expanding curved body due to carbon nanotubes in the fluid flow containing nanoparticles. Israr-ur-Rehman et al. [16] obtained numerically dual solutions on porous extending/shrinking surface considering anisotropic slip on nanofluid flow near stagnation point under magnetic conditions. Verma et al [17] studied numerically Soret and Dufour effect with heat and mass transfer in porous medium near stagnation point through a stretching sheet considering radiation and chemical effects. Naqvi et al. [18] studied nanofluid flow due to extending/shrinking disk considering heat generation/absorption to be non-uniform. Verma et al. [19] investigated numerically the impact of thermophoresis, chemical reaction and external heat source on MHD micropolar fluid with nanoparticles through a shrinking sheet near stagnation point.

In the field of engineering like nuclear reactors and processes involving liquid metals, the process of separation of binary fluid mixture becomes very significant. The binary fluid mixture composition in any given volume can be expressed by concentration C , which is the ratio of mass of the lighter and rarer constituent to the total mass of the fluid mixture, while composition of the heavier and greater component is given by $\bar{C} = 1 - C$. Usually temperature gradient, concentration gradient and pressure gradient are responsible for diffusion of independent species in a fluid mixture. Diffusion flux \vec{j} stated by Landau and Lifshitz [20] is represented by

$$\vec{j} = -\rho D_m [\nabla C + k_p \nabla P + k_T \nabla T] \quad (1)$$

The present work focuses primarily on Soret and Dufour effects under the influence of

radiation on the separation process of the binary fluid mixture. Investigations have been done by many researchers on the process involving transport of heat and mass on a vertical cone and few of them have also worked on Soret and Dufour effect but none of the literatures studied above have discussed on the detachment process of the binary fluid mixture. The main motive of this paper is to discuss numerically Soret and Dufour effects on MHD flow with heat and mass transfer of a binary fluid mixture about a vertical rotating cone along with thermal radiation.

2. MATHEMATICAL FORMULATION

Consider a heated, permeable vertical rotating cone in an incompressible, boundary layer steady flow of a binary fluid mixture. The fluid is viscous, hydromagnetic, laminar, electrically conducting and chemically reacting and the cone is rotating around its axis with uniform angular velocity Ω . Curvilinear coordinate system (x, y, z) is considered where the x-axis, y-axis and z-axis are taken along the tangential, circumferential and normal direction respectively to the cone. The components of velocity along tangential, circumferential and normal to the cone are u, v and w respectively. Along z-axis, which is perpendicular to the surface of the cone, a uniform magnetic field B_0 is applied. The same magnetic field is acting all the points on the circular section on the surface of the rotating cone. The applied magnetic field is axisymmetric. The surface of the cone is experiencing a uniform suction/injection of the fluid with velocity w_0 .

The fluid is viscous and because of the rotation of the cone a velocity in the y-direction originates and due to centrifugal force, a velocity develops in the z-direction due to which fluid is thrown in the z-direction. To fill up the vacant place fluid moves from the vertex in x-direction and in this way a fully developed three-dimensional flow generates. At the surface of the cone, the fluid temperature is T_w and species concentration is C_w and both, temperature as well as concentration, are supposed to change linearly with distance x . Away from the surface, let the temperature of the fluid be T_∞ and species concentration be C_∞ .

The following assumptions are considered in the problem:

1. The cone is considered symmetric about the axis of rotation.

2. The induced magnetic field is neglected due to the small value of magnetic Reynolds number.
3. The Joule heating and Hall Effect of MHD are neglected .
4. The medium is considered to be optically thin with comparatively low density and the order of chemical reaction is one.

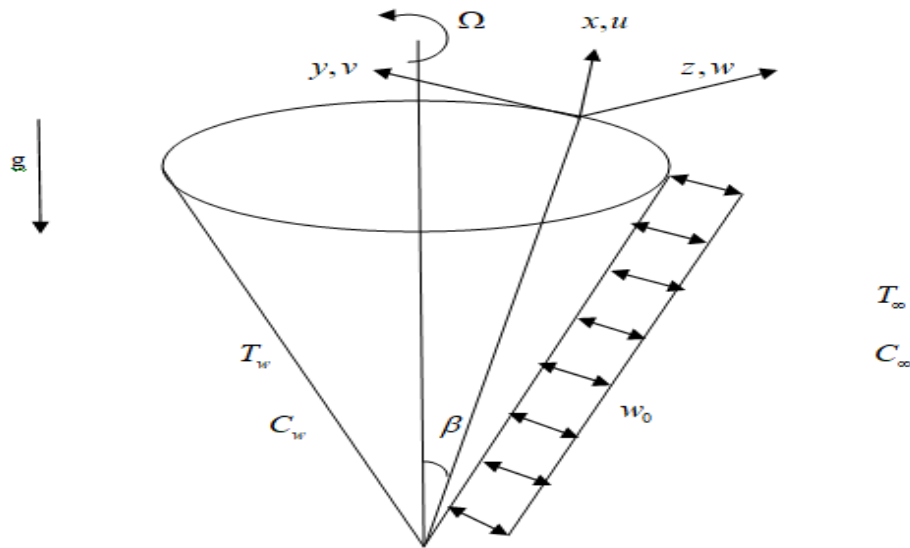


Fig. 1: Geometry of the problem

The governing equations under the above assumptions together with Boussinesq's approximation are:

$$\frac{\partial u}{\partial x} + \frac{u}{x} + \frac{\partial w}{\partial z} = 0, \quad (2)$$

$$u \frac{\partial u}{\partial x} + w \frac{\partial u}{\partial z} - \frac{v^2}{x} = \nu \frac{\partial^2 u}{\partial z^2} + g\beta_T(T - T_\infty)\cos\beta + g\beta_c(C - C_\infty)\cos\beta - \frac{\sigma B_0^2 u}{\rho}, \quad (3)$$

$$u \frac{\partial v}{\partial x} + w \frac{\partial v}{\partial z} + \frac{uv}{x} = \nu \frac{\partial^2 v}{\partial z^2} - \frac{\sigma B_0^2 v}{\rho}, \quad (4)$$

$$u \frac{\partial T}{\partial x} + w \frac{\partial T}{\partial z} = \frac{1}{\rho c_p} \left(k \frac{\partial^2 T}{\partial z^2} + \rho \frac{D_m K_T}{C_s} \left(\frac{\partial^2 C}{\partial z^2} \right) + Q_0(T - T_\infty) - \frac{\partial q_r}{\partial z} \right), \quad (5)$$

$$u \frac{\partial C}{\partial x} + w \frac{\partial C}{\partial z} = D_m \frac{\partial^2 C}{\partial z^2} + \frac{D_m K_T}{T_m} \left(\frac{\partial^2 T}{\partial z^2} \right) - K_c(C - C_\infty). \quad (6)$$

The conditions on the boundary are

$$u = 0, v = \Omega x \sin\beta, w = w_0, T = T_w(x), C = C_w(x) \text{ when } z = 0, \quad (7)$$

$$u \rightarrow 0, v \rightarrow 0, T \rightarrow T_\infty, C \rightarrow C_\infty \text{ when } z \rightarrow \infty. \quad (8)$$

To make equations (2) to (6) dimensionless the following similarity transformations have been used:

$$\begin{aligned} \eta &= \left(\frac{\Omega \sin \beta}{v}\right)^{\frac{1}{2}} z, \quad u(x, z) = -\frac{1}{2} \Omega x \sin \beta f'(\eta), \quad v(x, z) = \Omega x \sin \beta h(\eta), \\ w(x, z) &= (v \Omega \sin \beta)^{\frac{1}{2}} f(\eta), \quad T(x, z) = T_\infty + \frac{x}{L} (T_w - T_\infty) \theta(\eta), \\ C(x, z) &= C_\infty + \frac{x}{L} (C_w - C_\infty) \phi(\eta) \end{aligned} \quad (9)$$

where L represents the characteristics length along the cone's slant height.

The radiation heat flux is given by

$$\frac{\partial q_r}{\partial z} = -4a\sigma^*(T_\infty^4 - T^4) \quad (10)$$

Within the fluid flow region, the temperature differences are sufficiently small and so T^4 can be expanded using Taylor's series about T_∞ as

$$T^4 = 4T_\infty^3 T - 3T_\infty^4 \quad (11)$$

By the above transformations, equation of continuity (2) is identically satisfied and equations from (3) to (6) transform to the set of ordinary differential equations:

$$f''' - ff'' + \frac{1}{2}(f')^2 - 2h^2 - 2Ri(\theta + N\phi) - Mf' = 0, \quad (12)$$

$$h'' - (fh' - hf') - Mh = 0, \quad (13)$$

$$\theta'' - Prf\theta' + \frac{1}{2}Prf'\theta + \delta Pr\theta + D_f Pr\phi'' - R_d\theta = 0, \quad (14)$$

$$\phi'' - Scf\phi + \frac{Sc}{2}f'\phi + SrSc\theta'' - Sc\gamma\phi = 0. \quad (15)$$

The modified boundary conditions for (7) and (8) are

$$f' = 0, f = f_w, h = 1, \theta = 1, \phi = 1 \text{ when } \eta = 0 \quad (16)$$

$$f' = 0, h = 0, \theta = 0, \phi = 0 \text{ when } \eta \rightarrow \infty \quad (17)$$

where

$$\begin{aligned} Ri &= \frac{Gr}{Re^2}, \quad Gr = \frac{L^3(T_w - T_\infty)g\beta_T \cos \beta}{v^2}, \quad Re = \frac{L^2 \Omega \sin \beta}{v}, \quad Pr = \frac{\mu C_p}{k}, \\ N &= \frac{\beta_c(C_w - C_\infty)}{\beta_T(T_w - T_\infty)}, \quad M = \frac{\sigma B_0^2}{\rho \Omega \sin \beta}, \quad Sc = \frac{v}{D_m}, \quad R_d = \frac{16va\sigma^* T_\infty^3}{k \Omega \sin \beta}, \quad D_f = \frac{D_m K_T (C_w - C_\infty)}{v C_p C_s (T_w - T_\infty)}, \end{aligned}$$

$$Sr = \frac{D_m K_T (T_w - T_\infty)}{\nu T_m (C_w - C_\infty)}, \quad \delta = \frac{Q_0}{\rho c_p \Omega \sin \beta} \quad \text{and} \quad \gamma = \frac{K_c}{\Omega \sin \beta}. \quad (18)$$

The suction or injection velocity is

$$f_w = \frac{w_0}{(\nu \Omega \sin \beta)^{\frac{1}{2}}} \quad (19)$$

- where in case of
- (i) Impermeable rotating cone $f_w = 0$
 - (ii) Suction $f_w < 0$
 - (iii) Injection $f_w > 0$.

For heat absorption $\delta < 0$ and heat generation $\delta > 0$.

3. METHOD OF SOLUTION

We have used MATLAB'S built in solver bvp4c to solve numerically the non-linear equations (12) to (15) subject to the boundary conditions represented by equations (16) and (17).

4. RESULTS AND DISCUSSIONS

The outcomes for velocity, temperature and concentration profiles are represented graphically for different values of parameters R_d , Sr and D_f . To verify the precision of the numerical approach, the current result of wall shear stresses in tangential and circumferential direction are compared with the results obtained by Sparrow and Cess [2] in Table 1 and the present outcomes are in good match with the previous one. Local rate of heat and mass transfer of the present problem is calculated and is presented in Table 2.

Fig. 2-6 depicts the distribution of the components of velocity along tangential, normal and circumferential directions; temperature, and concentration for the values of $R_d = [0.5, 1, 1.5]$, $Sr = 1$, $\delta = 0.5$, $Pr = 0.72$, $M = 1$, $Ri = 1$, $Sc = 0.6$, $f_w = 0.1$, $D_f = 1$, $\gamma = 1$ and $N = 1$.

From the figures it is clear that due to the influence of radiation parameter R_d the tangential velocity component increases exponentially from the surface of the cone and reaches its peak at $\eta \approx 0.7$ and then decreases asymptotically and obtains its minimum value near the end of the boundary layer. The increase in the value of radiation parameter R_d i.e. with the increase in

absorption coefficient and temperature far away the surface (or decrease in speed of rotation and semi vertical angle), the normal velocity and circumferential velocity components increase. The radiation parameter also affects the temperature and concentration of the fluid, the temperature decreases with the increasing values of radiation parameter R_d whereas the concentration of the rarer constituent of the binary fluid mixture increases. It can be interpreted that the decrease in the energy flux reduces the buoyant forces with the larger values of radiation parameter which in turn increases the concentration of the rarer constituent. The speed of rotation is inversely proportional to the radiation parameter and so lesser the speed of rotation, the more will be the effect of radiation parameter on separation process. The accumulation of the lighter and rarer constituent of the mixture is more close to the cone's surface, which implies that the denser and heavier constituent is thrown away from the surface thereby helping in the process of separation of the binary fluid mixture.

Table 1: Comparison of local surface shear stresses by taking the following values

$$Ri = 0, N = 0, D_f = 0, Pr = 0.72, \delta = 0, Sr = 0, Sc = 0, \gamma = 0, R_d = 0 \text{ and } f_w = 0.$$

Present result

M	$-f''(0)$	$-h'(0)$
0	1.0161	0.6149
0.5	0.7695	0.8488
1	0.6184	1.0691
2	0.4611	1.4421
3	0.3810	1.7477
4	0.3314	2.0103

Previous result (Sparrow and Cess [2])

M	$-f''(0)$	$-h'(0)$
0	1.021	0.616
0.5	0.770	0.849
1	0.619	1.069
2	0.461	1.442
3	0.381	1.748
4	0.331	2.010

Fig. 7-11 depicts the distribution of the components of velocity along tangential, normal and circumferential directions; temperature, and concentration for values of $Sr = [0, 1, 2]$, $\delta = 0.5$, $Pr = 0.72$, $R_d = 0.5$, $M = 1$, $Ri = 1$, $Sc = 0.6$, $f_w = 0.1$, $D_f = 1$, $\gamma = 1$ and $N = 1$.

From the figures, it is seen that the tangential velocity component increases exponentially to attain the maximum value at $\eta \approx 0.7$ and then gradually decreases to attain its minimum value near the end of the boundary layer. The temperature decreases with the increasing values of Sr i.e. with the rise in temperature difference between the wall of the cone and free stream temperature (or decrease in difference in concentration between the wall of the cone and far away from the cone), while the normal velocity component, circumferential velocity component and concentration of the rarer constituent is seen to increase. Fig. 11 show that the accumulation of the lighter and rarer constituent of the binary fluid mixture is more surrounding the surface of the cone thereby helping the separation process. It is evident that the consequence of Soret number on concentration of the rarer constituent and temperature is opposite to each other. The Soret effect enables cooling of the binary fluid mixture by restricting the temperature and separation process and hence enables notable mass diffusion effect.

Fig. 12-16 depicts the velocity components along tangential, normal and circumferential directions; temperature, and concentration profiles for values of $D_f = [0, 1, 2]$, $\delta = 0.5$, $\gamma = 1$,

$Pr = 0.72, R_d = 0.5, M = 1, Ri = 1, Sc = 0.6, f_w = 0.1, Sr = 1$ and $N = 1$.

From the figures it is seen that the increasing values of Dufour number i.e. with the increase in concentration difference between the wall of the cone and far away from the cone (or decrease in temperature difference between the wall of the cone and far away from the cone), decreases tangential velocity component and concentration of the rarer constituent of the fluid whereas the normal and circumferential velocity components increase. Again in case of temperature distribution we have seen that temperature increases with increasing Dufour number till $\eta = 1$ and then a decreasing trend is seen. It is evident that the effect of Dufour number is profoundly seen near the surface of the cone where it helps the separation process by heating up the fluid but as we go away from the cone its effect on separation process decreases.

Table 2. Local rate of surface heat transfer and mass transfer for the values:

$Ri = 1, N = 1, Pr = 0.72, Sc = 0.6, M = 1, \gamma = 1, \delta = 0.5, \text{ and } f_w = 0.1$.

Sr	D_f	R_d	$-\theta'(0)$	$-\phi'(0)$
0	0.5	0.5	0.5485	0.9134
0.5	0.5	0.5	0.5692	0.8810
1	0.5	0.5	0.5917	0.8482
0.5	0	1	0.9482	0.7706
0.5	0.5	1	0.8629	0.8040
0.5	1	1	0.7632	0.8432
1	1	0.5	0.4428	0.9665
1	1	1	0.8340	0.7714
1	1	1.5	1.1488	0.6088

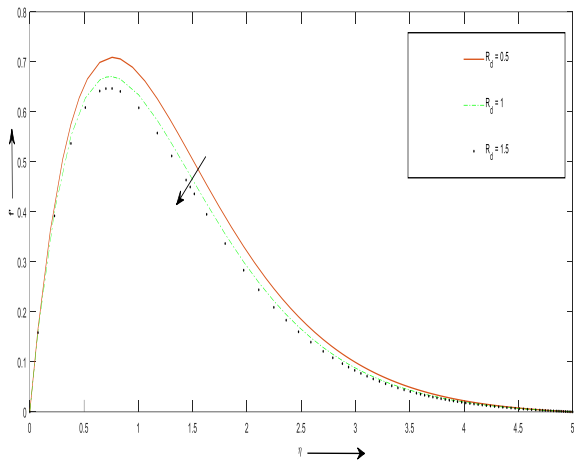


Fig. 2: Tangential velocity distribution due to R_d

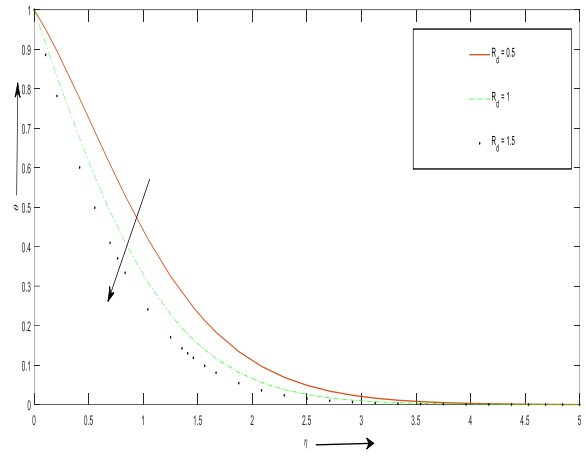


Fig. 5: Temperature distribution due to R_d

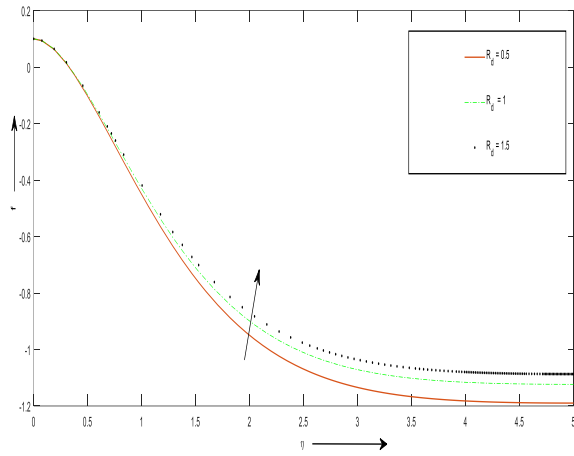


Fig. 3: Normal velocity distribution due to R_d

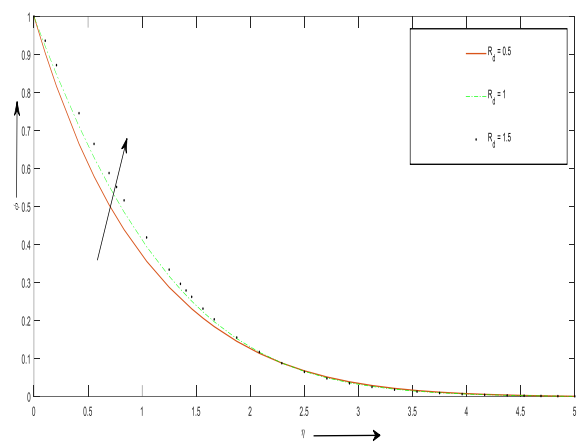


Fig. 6: Concentration distribution due to R_d

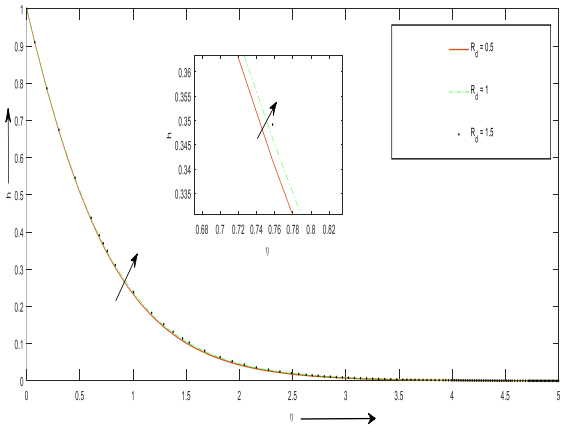


Fig. 4: Circumferential velocity distribution due to R_d

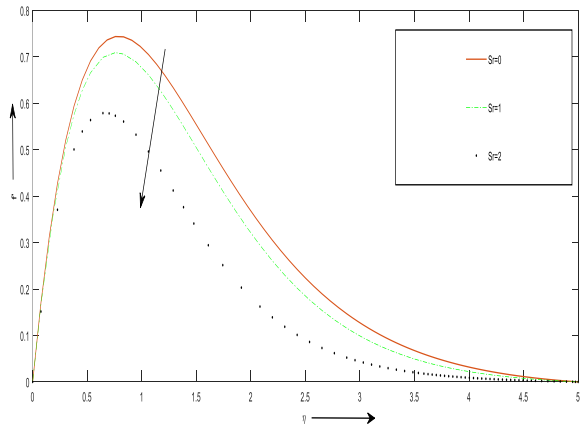


Fig. 7: Tangential velocity distribution due to S_r

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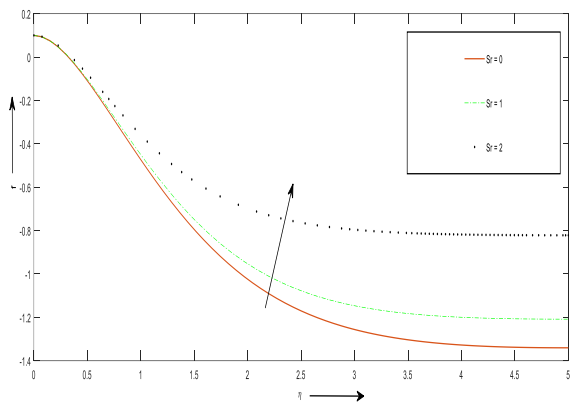


Fig. 8: Normal velocity distribution due to Sr

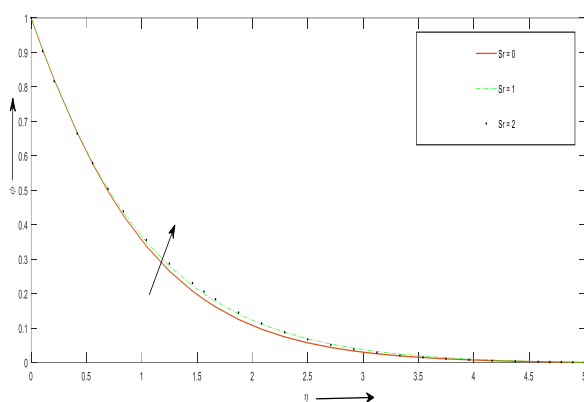


Fig. 11: Concentration distribution due to Sr

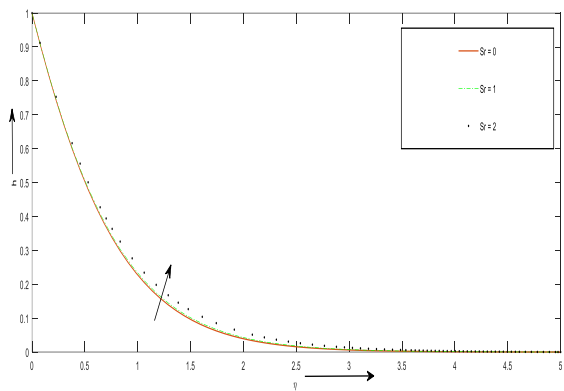


Fig. 9: Circumferential velocity distribution due to Sr

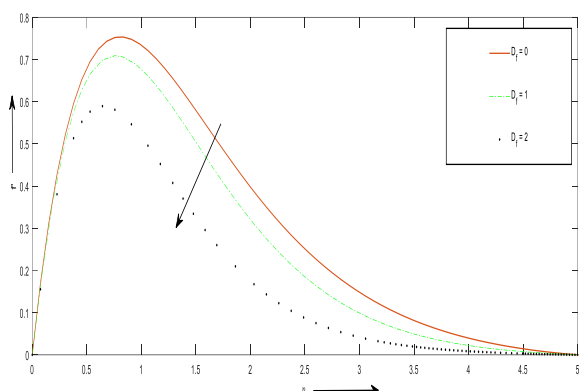


Fig. 12: Tangential velocity distribution due to D_f

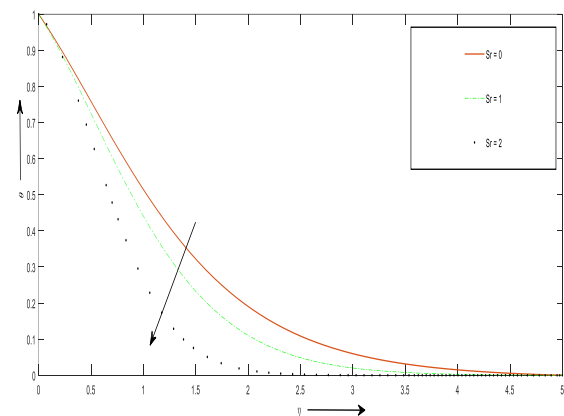


Fig. 10: Temperature distribution due to Sr

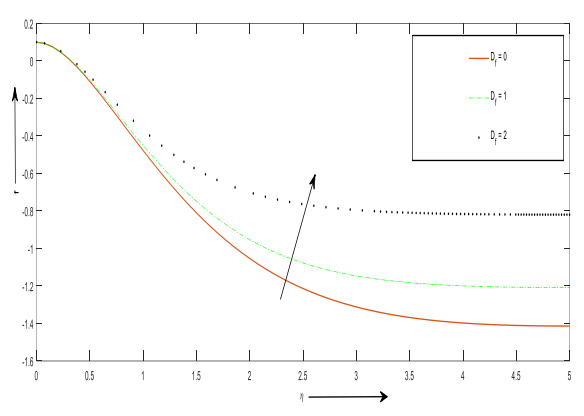
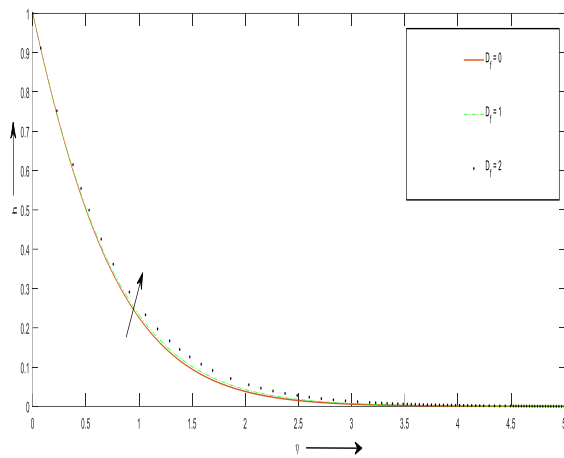
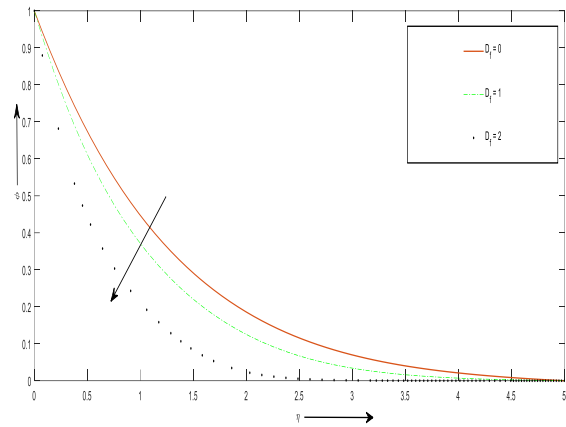
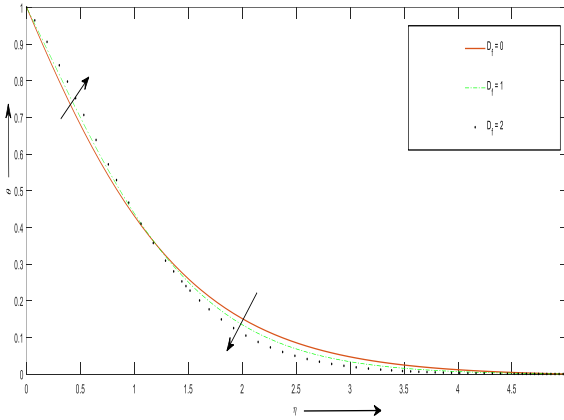


Fig. 13: Normal velocity distribution due to D_f

Fig. 14: Circumferential velocity distribution due to D_f Fig. 16: Concentration distribution due to D_f Fig. 15: Temperature distribution due to D_f

5. CONCLUSION

The three important parameters Sr , D_f and R_d play an important part in the separation process of the binary fluid mixture by assembling the lighter and rarer constituent of the mixture close to the surface of the cone and pushing the heavier and denser component apart from it. Other important results obtained are:

1. The increasing values of R_d , Sr and D_f decreases the velocity component along tangential direction.
2. The velocity components along normal and circumferential direction increases for the

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increasing values of parameters R_d , Sr and D_f .

3. The temperature of the fluid rises with the increasing values of D_f while the temperature falls with increasing values of R_d and Sr .

4. The concentration of the fluid increases with the increasing values of parameters R_d and Sr but decreases with increasing values of D_f .

5. With the increasing values of Soret number, Sr the local rate of surface heat transfer increases and mass transfer decreases but a reverse case happens with increasing values of Dufour number, D_f .

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NOMENCLATURE

a	Absorption coefficient	q_r	Radiation heat flux
B_0	Magnetic field strength	R_d	Dimensionless radiation parameter
C	Concentration of the rarer component	Re	Reynolds number
C_w	Species concentration at the cone's surface	Ri	Richardson number
C_∞	Species concentration away from the cone's surface	Sc	Schmidt number
C_p	Specific heat at constant pressure	Sr	Soret number
C_s	Concentration susceptibility	T	Temperature of the fluid
D_f	Dufour number	T_m	Mean temperature of the fluid
D_m	Mass diffusivity	T_∞	Fluid temperature away from the cone's surface

f	Similarity velocity function	u	Tangential velocity component
f_w	Dimensionless suction/injection velocity	v	Circumferential velocity component
g	Acceleration due to gravity	w	Normal velocity component
h	Similarity velocity function	w_0	Dimensionless suction/injection velocity
Gr	Grashof number	Ω	Angular velocity
k	Thermal conductivity	ρ	Fluid density
K_c	Dimensionless chemical reaction parameter	ν	Kinematic viscosity
K_T	Thermal diffusion ratio	β	Semi vertical angle
L	Characteristic length	β_T	Coefficient of thermal expansion
M	Magnetic parameter	β_c	Coefficient of mass expansion
N	Bouyancy parameter	γ	Chemical reaction parameter
Pr	Prandtl number	η	Similarity variable
Q_0	Heat generation/absorption coefficient	σ	Electrical conductivity
θ	Dimensionless temperature	σ^*	Stefen-Boltzmann constant
ϕ	Dimensionless species concentration	\vec{j}	Diffusion flux
δ	Dimensionless heat generation parameter		

CONFLICT OF INTERESTS

The authors declare that there is no conflict of interests.

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