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RESEARCH ARTICLE

DUFOUR, SORET AND DISSIPATION EFFECTS ON MAGNETOHYDRODYNAMIC FLOW PAST A STRETCHING PERMEABLE SHEET WITH RADIATIVE CHEMICAL REACTION ANDHEAT SOURCE

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Abstract

Present investigation explores the numerical solution of Magnetohydrodynamic laminar steady gray fluid flow with heat and mass transfer past a stretching permeable sheet, incorporating several factors such as heat source, viscous and joules dissipation effects, thermal radiation, chemical reactions, Soret and Dufour effects. The governing nonlinear PDE's are simplified into ODE's with the help of similarity transformations. Momentum equation is solved analytically. Non-Dimensional temperature and concentration calculated with the help of RK- shooting method with Nachtsheim-Swigert iteration method. Key results include the calculation of heat and mass transfer rates and Co-efficient of skin friction. The effects of various parameters such as magnetic field strength, suction, radiation, chemical reactions, internal heat generation and dissipative effects on the flow characteristics and other physical parameters are thoroughly investigated, highlighting their impact on the thermal and concentration profiles in the system. This comprehensive analysis provides insights into the behaviour of the fluid flow under the specified conditions, which can be useful for applications in engineering and industrial processes.

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Introduction:-

Current studies that incorporate chemical processes and thermal radiation into boundary layer, laminar gray fluid flow, and the impact of Dufour and Soret effects, has provided valuable insights into complex fluid dynamics scenarios. These studies reveal that the Soret effect, which drives species migration in response to temperature gradients, and the Dufour effect, which induces thermal gradients due to concentration differences, significantly influence boundary layer behavior. When combined with thermal radiation, which alters heat transfer rates by adding radiative heat flux components, and chemical reactions, which affect species concentration and energy release or absorption, the resulting fluid dynamics become highly intricate. Advanced numerical simulations and experiments have shown that these factors collectively impact heat and mass transfer efficiencies, temperature

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distributions, and reaction rates in diverse applications such as chemical reactors, heat exchangers and atmospheric studies. The impact of these Dufour and Soret effects is the primary focus of the current study.

Many researchers have explored heat and mass transfer processes through various geometries, highlighting the complexity and significance of these phenomena. Tewfik and Yang [1] conducted experimental investigations into thermodynamic convectional fluid flow with Helium suction, confirming the critical roles of Dufour and Soret effects in transpiration-cooled boundary layer flows. Goddard and Acrivos [2] analyzed forced convectional flow involving chemical reactions, laying foundational insights into the interactions of mass transfer and reaction kinetics.

Further contributions include Hydromagnetic flow over a stretching sheet with heat transfer was discussed by Chakrabarthiand Gupta [3]. Similarly, Chen and Strobel [4] analyzed laminar boundary layer flow over a horizontal flat plate with the combined influence of buoyancy forces from thermal and species diffusion. Grubka and Bobba [5] focused on Variable surface temperature over a stretching continuous surface on the other hand, Noor Afzal [6] explored a Constant surface temperature over a stretching surface with chemical processing equipment. Influence of Soret and Dufour effects on boundary layer fluid flow with temperature-dependent viscosity was investigated by Kafoussias and Williams [7].

These studies collectively underscore the multifaceted nature of heat and mass transfer in various systems, offering valuable insights into the intricate interplay of fluid dynamics, thermal properties, and chemical reactions.

Fluid flow over a accelerating porous surface with internal heat generation was analysed by Acharya et al. [8]. Atul Kumar Singh [9] analysed the Magnetohydrodynamics incompressible, viscous fluid flow over a infinite vertical plate with suction, internal heat generation and thermal diffusion.

Anjalidevi and Thiyagarajan [10] was discussed Nonlinear MHD electrically conducting viscous fluid past a stretching sheet with power-law velocity. Regarding the influence of Dufour and Soret on vertical surface with convective heat and mass transfer with various other influences was analysed, so as to include magnetic field by Postelnicu in [11], variable suction by Alam and Rahman in [12] and chemical reaction by Postelnicu in [13].

Natural and forced convectional boundary layer flows with thermal-diffusion and diffusion-thermo effects was analysed by Abreu et al. [14]. This investigation in saturated porous medium has been analysed by Lakshmi Narayana and Murthy [15] using the similarity solution technique.

Many authors like Abd El-Azizand Mohamed [16], Anwar Beg et al. [17], Abdel-Rahman [18] investigated the combined influence of Dufour and Soret Parameters on electrically conducting gray fluid over a continuous stretching porous sheet. Chien-Hsin Chen [19] further expanded this field by examining the influence of viscous dissipation and Joule heating on magnetohydrodynamic gray fluid flow past a stretching permeable surface, incorporating free convectional heat transfer into the analysis. Anjalidevi and Kayalvizhi [20, 21] analyzed the thermal boundary layer flow with the influence of radiation, MHD gray fluid past a non-isothermal, permeable stretching sheet. In this investigation with partial slip MHD flow was studied by Abdul Hakeem et al., [22].

The investigation by Ching Yang Cheng [23, 24], Sharma et al. [25], and Chandra Sekhar Bella et al. [26] have highlighted the significant impacts of influence of Soret and Dufour parameters on convection flow in porous media. These effects relate to the thermal and concentration gradients in the fluid, influencing both fluid flow and heat and mass transfer characteristics. Recent research has expanded on these findings by examining the implications of magnetohydrodynamics in the context of Hiemenz flow, particularly regarding mass transfer over a stretching surface. The investigation from Gandluru Sreedevi et al. [27], Shalini Jain and Rakesh Choudhary [28], and Seema Tinkar et al. [29] have provided insights into how MHD interactions can alter the behavior of fluid flow and thermal fields. Their investigations consider various physical phenomena.

More Recently, Verma and Sharma [30] examined the influence of Soret and Dufour effects on MHD flow past a stretching surface, focusing on heat and mass transfer. Temjennaro Jamir and Hemanta Konwar [31] investigated a numerical analysis of unsteady MHD mixed convective flow over a curved stretching surface, incorporating Dufour and Soret effects, chemical reactions, and Joule heating, along with thermal and velocity slip effects; however, it did not account for viscous dissipation and radiation effects.

The main aim of this present work is to analyze nonlinear MHD gray fluid flow past a stretching porous horizontal sheet, incorporating the effects of chemical reactions, dissipation, radiation, internal heat generation, and, alongside the Soret and Dufour effects. This comprehensive study aims to enhance understanding of these complex interactions in practical applications.

Formulation of the problem

The present problem is based on the following assumptions:

1. The study involves a 2-D steady Magnetohydrodynamic (MHD) flow of a laminar, incompressible, gray viscous electrically conducting fluid.
2. The fluid properties are assumed to be constant.
3. A uniform transverse magnetic field is applied normal to a linear stretching permeable sheet.
4. Internal heat generation, chemical processes, radiative heat transmission, viscous and Joule heating dissipation, thermal diffusion (Soret), and diffusion-thermo (Dufour) effects are among the influences taken into account.
5. Non scattering medium occurs at a temperatureT_∞.
6. A chemical reaction takes place in the fluid characterized by an effective mass diffusivity $D$and a uniform chemical reaction rate k_1.
7. The magnetic Reynolds number is sufficiently small, allowing us to neglect the induced magnetic field relative to the applied uniform magnetic field B = (0, B_0, 0), which acts normal to the plate.
8. The flow direction is established along the x-axis, with the velocity component u. The y-axis is oriented perpendicular to the plate, and the velocity component in this direction is denoted as v.
9. In the energy equation, $\frac{\partial q_r}{\partial x}$ is negligible compared with $\frac{\partial q_r}{\partial y}$.

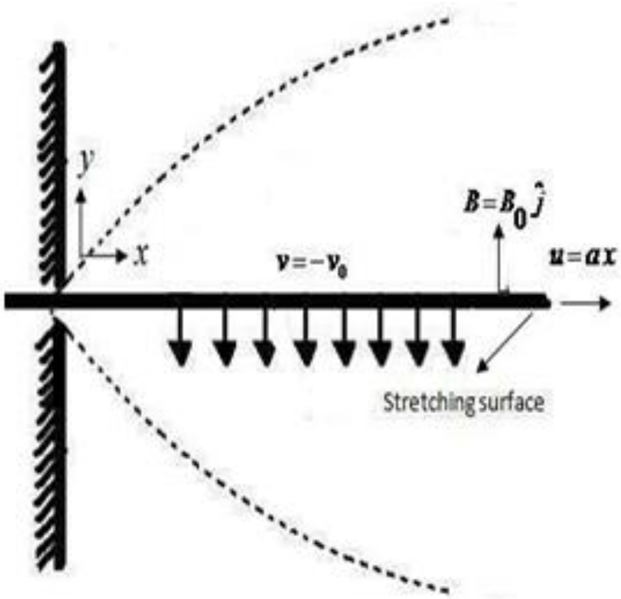

Fig.1:- Schematic representation.

Under these assumptions, the governing boundary layer equations could be written as following:

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

$$u\frac{\partial u}{\partial x}+\mathrm{v}\frac{\partial v}{\partial y}=\vartheta\,\frac{\partial^2 u}{\partial y^2}-\frac{\sigma B_0^2 u}{\rho} \tag{2}$$

$$u\,\frac{\partial T}{\partial x}+\,v\,\frac{\partial T}{\partial y}=\frac{K}{\rho\,C_p}\frac{\partial^2 T}{\partial y^2}-\frac{1}{\rho\,C_p}\frac{\partial q_r}{\partial y}+\frac{Q_0}{\rho\,C_p}(T-T_\infty)+\frac{\mu}{\rho\,C_p}\left(\frac{\partial u}{\partial y}\right)^2+\frac{j^2}{\rho\,C_p\sigma}+\frac{D_m K_T}{c_s c_p}\left(\frac{\partial^2 C}{\partial y^2}\right) \tag{3}$$

$$u\,\frac{\partial C}{\partial x}+\,v\,\frac{\partial C}{\partial y}=D_m\frac{\partial^2 C}{\partial y^2}-k_1 C+\frac{D_m K_T}{T_m}\frac{\partial^2 T}{\partial y^2} \tag{4}$$

and $q_r = \frac{-4\sigma^*}{3\alpha^*}\left(\frac{\partial T^4}{\partial y}\right)$ (5)

Table 1:- Terminology

Symbol	Abbreviation
T	Temperature
C	Concentration
ρ	Density
μ	Coefficient of Viscosity
c_p	Specific Heat at Constant Pressure
K	Thermal Conductivity of the Medium
j	Current Density
ϑ	Kinematic Viscosity
σ	Electrical Conductivity of the Fluid
B_0	Magnetic Field
D_m	Mass Diffusivity
k_1	Rate of Chemical Reaction
Q_0	Volumetric Rate of Heat Generation
K_T	Thermal - Diffusion Ratio
c_s	Concentration Susceptibility
T_m	Fluid Mean Temperature
q_r	Radiative Heat Flux
σ^*	Stefan – BoltzmanConstant
α^*	Rosseland Mean Approximation Coefficient.

Assuming that the temperature difference within the flow is sufficiently small. Expand Taylor series about T_∞, We obtain,

$$T^4 \cong 4T_\infty^3\, T - 3T_\infty^4 \tag{6}$$

In the view of equations (5) and (6), the energy equation (3) becomes

$$u\ \frac{\partial T}{\partial x} + v\ \frac{\partial T}{\partial y} = \frac{K}{\rho C_p}\frac{\partial^2 T}{\partial y^2} + \frac{16\,\sigma^* T_\infty^3}{3\rho C_p \alpha^*}\frac{\partial^2 T}{\partial y^2} + \frac{Q_0(T-T_\infty)}{\rho C_p} + \frac{\mu}{\rho C_p}\left(\frac{\partial u}{\partial y}\right)^2 + \frac{\sigma B_0^2 u^2}{\rho C_p} + \frac{D_m K_T}{c_s C_p}\frac{\partial^2 C}{\partial y^2} \tag{7}$$

The boundary conditions for the above problem are as follows

$$\begin{aligned} &u = U_w = ax, \quad T = T_w(x) = T_\infty + A_0 x^r && \text{at} \quad y = 0 \\ &v = -v_0, \quad C = C_w(x) = C_\infty + A_1 x^{r_0} && \text{at} \quad y = 0 \\ &u \to 0, \quad T \to T_\infty \quad C \to C_\infty \text{as} && \quad y = \infty \end{aligned} \tag{8}$$

To facilitate the analysis, we choose a stream function $\psi(x, y)$ such that

$$u = \frac{\partial \psi}{\partial y} \qquad \text{and} \qquad v = -\frac{\partial \psi}{\partial x}$$

which satisfies the continuity equation.

By introducing the relative parameters are

$$\psi = \sqrt{a\vartheta}\ \ x\ f(\eta), \qquad \eta = \sqrt{\frac{a}{\vartheta}}\,y$$

$$u = axf'(\eta), \qquad v = -\sqrt{a\vartheta}\ f(\eta)$$

$$\theta(\eta) = \frac{T-T_\infty}{T_W - T_\infty}, \qquad \varphi(\eta) = \frac{C-C_\infty}{C_W - C_\infty}$$

The above similarity transformations transform the equations (2), (7) and (4) into a set of ODE's which are expressed as,

$$f''' + ff'' - f'^2 - M^2 f' = 0 \tag{9}$$

$$\theta'' + \beta f\theta' - r\,\beta f'\theta + S_h\beta\theta + D_f\beta\varphi'' = -\,Ec\beta[f''^2 + M^2 f'^2] \tag{10}$$

$$\varphi'' + Sc\,f\varphi' - Sc\,(r_0 f' + \beta_1)\,\varphi + S_r S_c\,\theta''(\eta) = 0 \tag{11}$$

together with boundary conditions

$$f(0) = S, \quad f'(0) = 1\,, \quad f'(\infty) = 0 \tag{12}$$

$$\theta(0) = \varphi(0) = 1, \quad \theta(\infty) = \varphi(\infty) = 0 \tag{13}$$

Where $\beta = \frac{3\,Pr\,R_d}{3R_d+4}$

Table 2:-Parameter Definitions and Descriptions

Parameter	**Description**
$R_d = \frac{K\alpha^*}{4\sigma^* T_\infty^3}$	Radiation Parameter
$Pr = \frac{\mu C_p}{K}$	Prandtl Number
$M^2 = \frac{\sigma B_0^2}{\rho a}$	Magnetic Interaction Parameter
$S_h = \frac{Q_0}{a\rho C_p}$	Heat Source Parameter
$Ec = \frac{a^2x^2}{C_p(T_w - T_\infty)}$	Eckert Number
$S = \left({v_0}/{\sqrt{\vartheta a}}\right)(v_0 > 0)$	Suction Parameter
$\beta_1 = \frac{k_1}{a}$	Chemical ReactionP arameter
$Sc = \frac{\vartheta}{D}$	Schmidt Number
$D_f = \frac{D_m K_T}{\vartheta\, c_s c_p}$	Dufour Number
$S_f = \frac{D_m K_T}{\vartheta T_m}$	SoretNumber

Solution Of The Problem

Exact Solution of Momentum Equation

Equation (9) with boundary conditions (12) admit a solution of the form [Chakrabarthi and Gupta [3]]

$$f(\eta) = A + Be^{-\alpha\eta}$$

where $A = S + \frac{1}{\alpha}$, $B = \frac{-1}{\alpha}$ and $\alpha = \frac{S+\sqrt{S^2+4(1+M^2)}}{2}$

Hence the exact solution is $f(\eta) = S + \frac{1}{\alpha}(1 - e^{-\alpha\eta})$

The velocity components are

$$u = axe^{-\alpha\eta} \qquad v = -\sqrt{av}[S + \tfrac{1}{\alpha}(1 - e^{-\alpha\eta})] \tag{14}$$

Skin Friction

$\tau^* = \mu \left(\frac{\partial u}{\partial y}\right)_{y=0}$ is shear stress at the wall.

$C_f = f''(0) = -\alpha$ is the co-efficient of skin friction. (15)

Numerical Solution for Temperature & Concentration

Equations (10) and (11) with the boundary conditions (13) are non-linear ODE's that form the nonlinear BVP. Numerical solution is obtained by reducing the nonlinear BVP into IVP using RK shooting method along with Nachtsheim-Swigert Iteration Scheme for satisfaction of boundary conditions. For various values of physical parameters S, M^2, R_d, S_h, Ec, Pr, β_1, S_r, D_f and Sc numerical results are obtained.

Result And Discussion:-

In the present investigation, various physical parameters were analyzed, and the results were visually represented. The numerical computations conducted considered scenarios without Dufour and Soret effects and excluded mass transfer. The results for the nondimensional rate of heat transfer were compared with those from Kayalvizhi [33]. This comparison is illustrated in Tables 3.

Table 3:- Comparison of Present Results with Kayalvizhi [33] at $r = 2$ under without mass transfer and excluding Soret and Dufour Effects

S	R_d	Pr	Ec	S_h	M^2	$-\theta'(0)$ Kayalvizhi [33] (AnalyticalSolution)	$-\theta'(0)$ Present Result (NumericalSolution)
3	3	0.71	0.01	0.1	9	1.64981	1.649808
4						2.11278	2.112783
5						2.58115	2.581145
3	3	0.71	0.01	0.1	9	1.64981	1.64980
	4					1.78515	1.785149
	10^9					2.36581	2.365814
3	3	0.71	0.01	0.1	9	1.64981	1.649808
		1.0				2.30832	2.308319
		7				15.0662	15.066230
3	3	0.71	0	0.1	9	1.66633	1.666326
			0.05			1.58374	1.583738
			0.1			1.50115	1.501152
3	3	0.71	0.01	0	9	1.68010	1.680103
				0.15		1.63418	1.634182
				0.2		1.61821	1.618210
3	3	0.71	0.01	0.1	0	1.73257	1.732573
					6	1.64981	1.649808
					16	1.61913	1.619134

The transverse velocity for various values of $M^2$is depicted in Fig.1. The horizontal velocity for various values magnetic field is illustrated in Fig.2. It is discerned that fluid velocity decreases as the magnetic field increases.

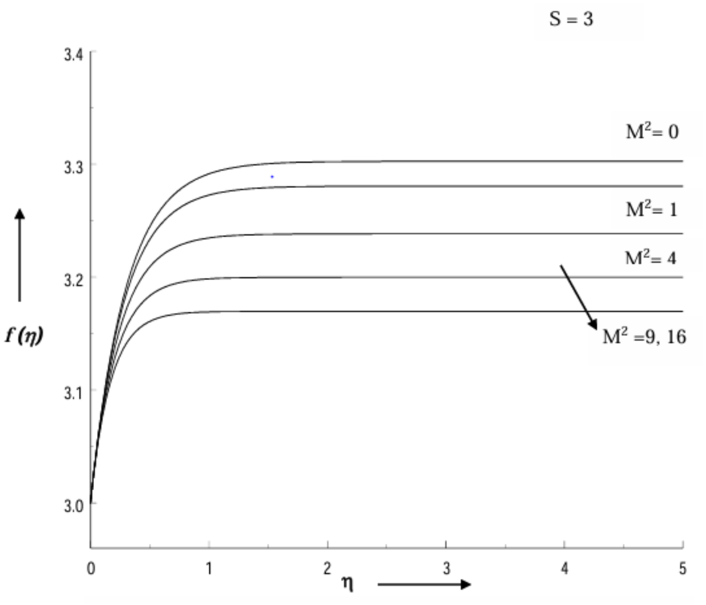

Fig.1:- Influence of M^2over $f(\eta)$

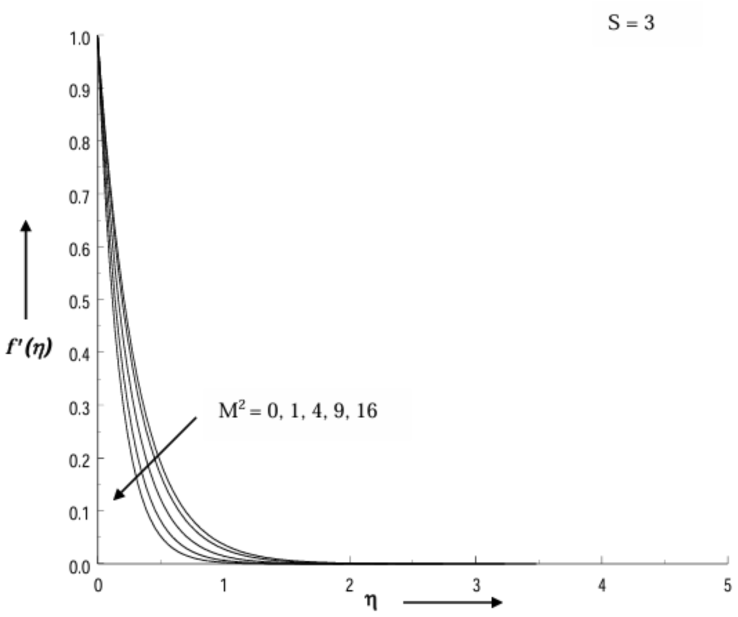

Fig. 2:- Effect of M^2over $f'(\eta)$

Fig.3 depicts the effect of M^2on $C_f$against porosity. The magnetic field has the effect of reducing the skin friction coefficient.

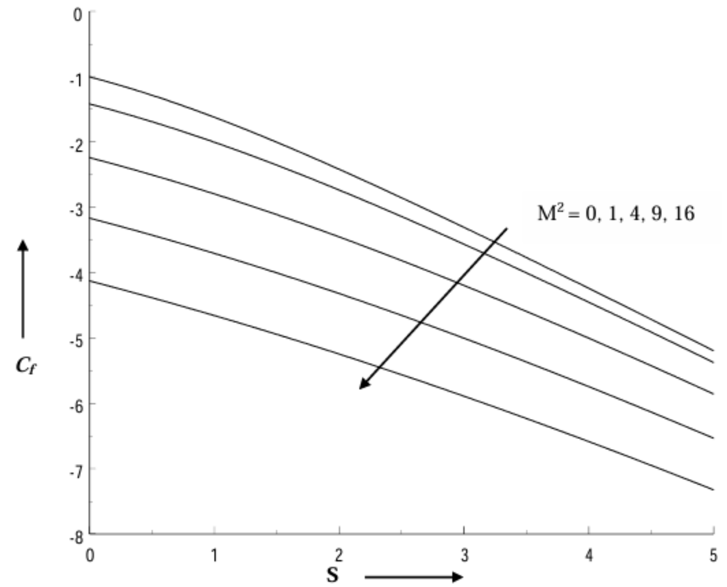

Fig. 3:- Skin Friction for various M^2

Fig.4 displays the graph of temperature distribution for variousR_d. It is revealed that an increase in R_d results in a decrease in $\theta(\eta)$which implies that radiation reduces the thermal boundary layer thickness. Since R_d directly proportional to K and T_∞, the Rosselend mean absorption coefficient α^*. As α^* inversely proportional to $\frac{\partial q_r}{\partial y}$, this demonstrates that the rate of heat transfer increases. Therefore, temperature increases.

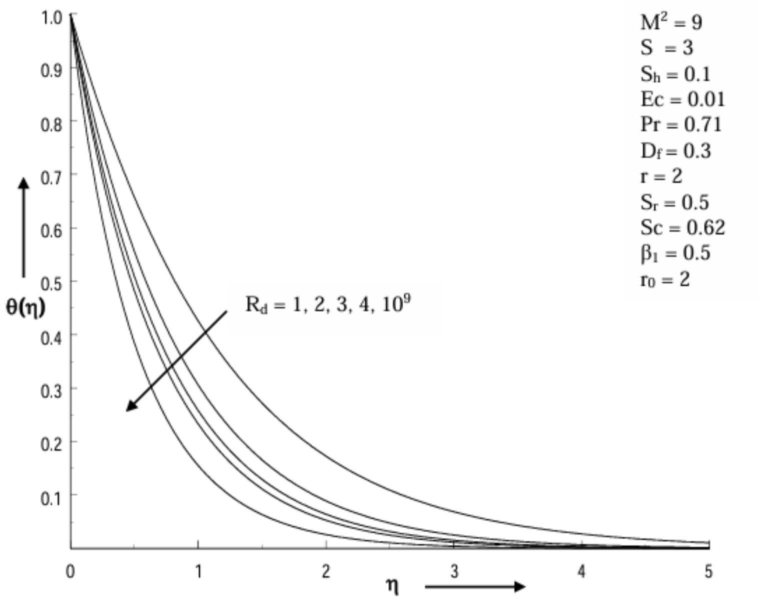

Fig. 4:- Effect of R_d on $\theta(\eta)$

$\theta(\eta)$ for various values of Pr is shown in Fig.5. Clearly, it is concluded that the effect of Pr is to reduce thermal boundary layer thickness and the temperature.

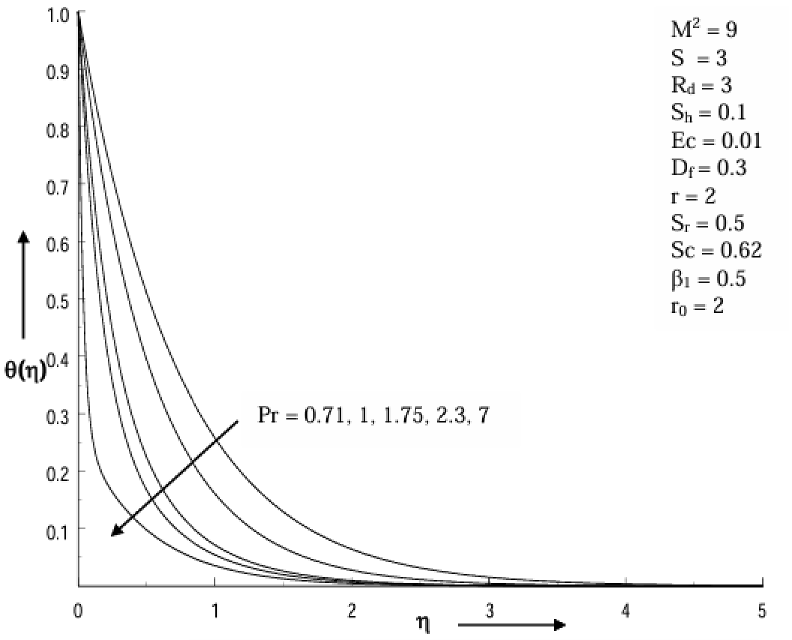

Fig. 5:- Effect ofPr on temperature.

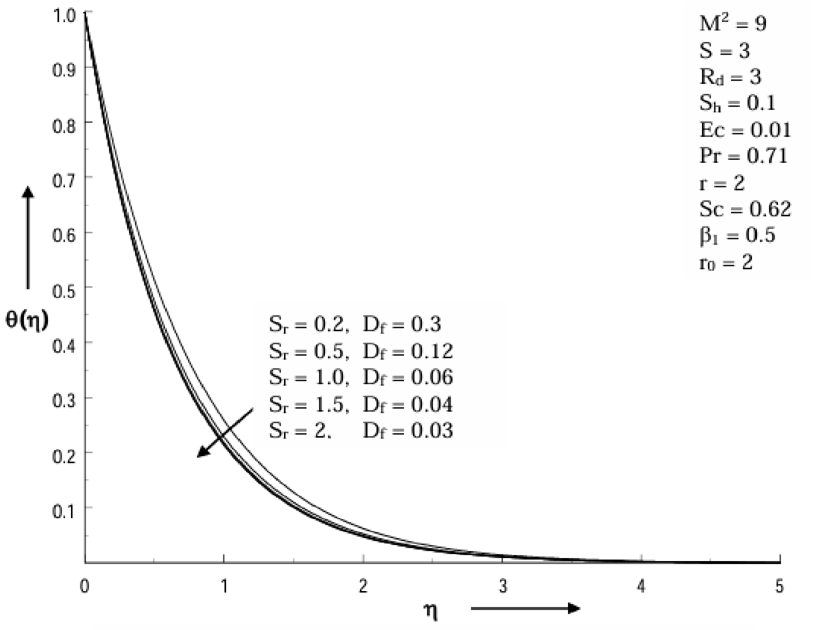

Fig. 6:- Effect of S_r and D_f on temperature.

Fig. 6 presents the thermal-diffusion and diffusion-thermo effects on temperature distribution. The product $S_r\, D_f$ is kept constant by selecting different values of D_f and S_r. A simultaneous increase in D_f and decrease in S_r result in a rise in temperature across the boundary layer.

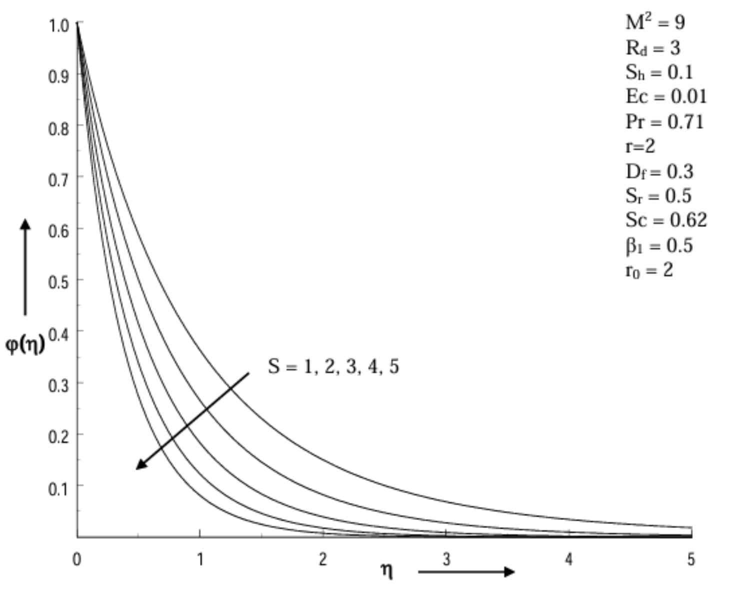

Fig.7:- Concentration distribution for various$S$

$\varphi(\eta)$for different values of suction parameter S is shown through Fig.7. Porosity reduces the species concentration which is physically true. Concentration reaches its maximum value only near the wall.

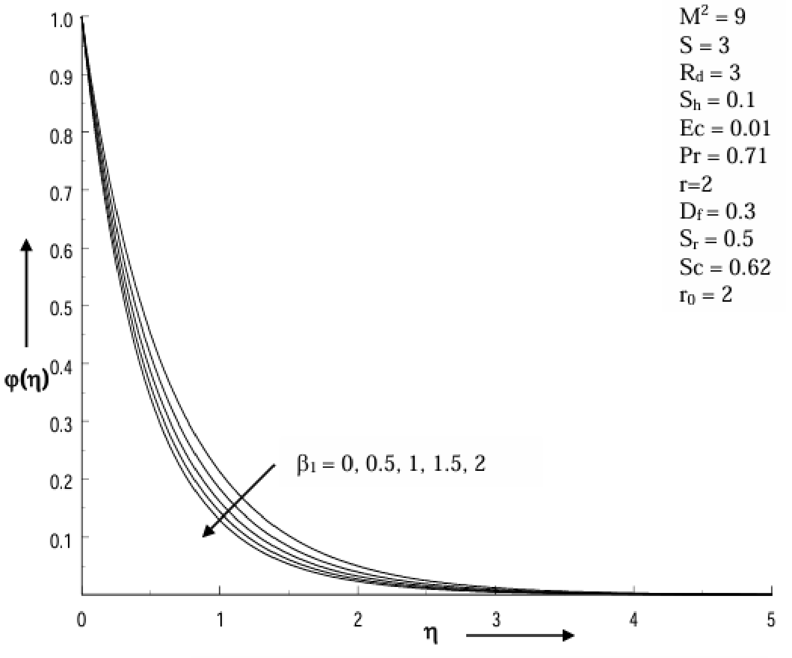

Fig.8:- Concentration distribution for various β_1

The influence of chemical reaction on the species concentration is clearly portrayed in Fig.8. It is noticed that for increasing values of β_1, the concentration decreases. ie., The concentration boundary layer becomes thin as chemical reaction increases.

Fig.9 depicts $\varphi(\eta)$ for different values of Sc. It is inferred that the influence of Sc decreases the concentration. ie., Schmidt number reduces the boundary layer thickness.

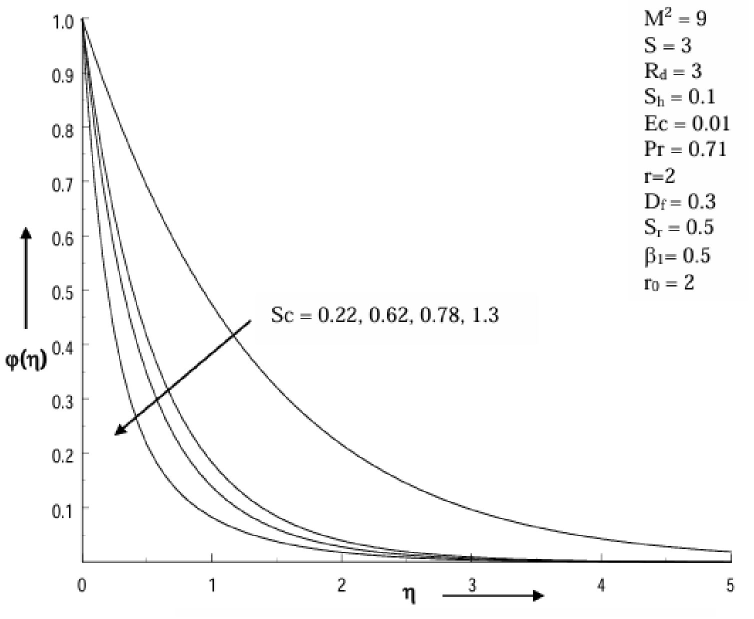

Fig.9:- Concentration distribution for various Sc.

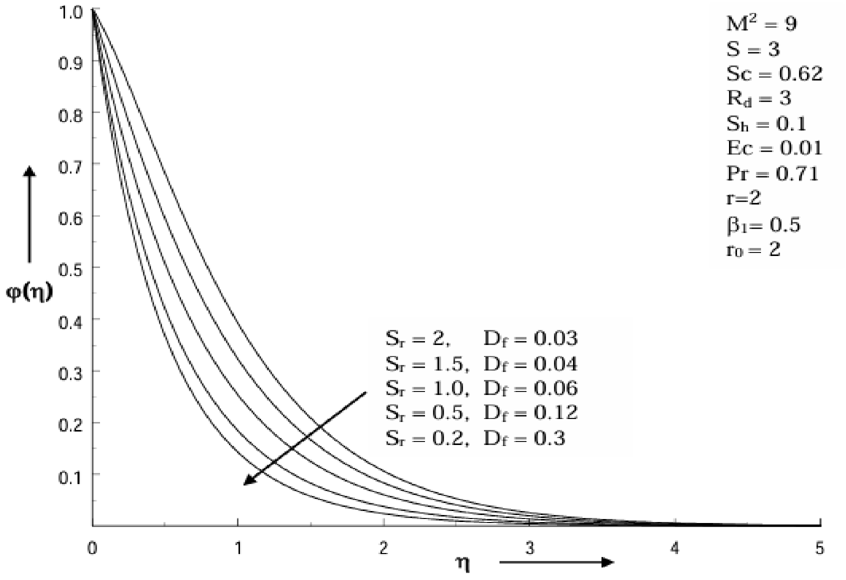

Fig.10:- Concentration distribution for various S_r and D_f

The influence of S_r and D_f on the concentration distribution are shown in Fig.10. It is observed that the influence of thermal-diffusion (Soret) enhances the temperature whereas influence diffusion-thermo (Dufour) is to suppress it.

Conclusion:-

Generally, Influence of Physical parameters affects the fluid flow, temperature and concentration. In the absence of dissipation effects, internal heat generation, thermal diffusion effect and when there is no mass transfer, the results are same as that of Ouaf [32]. In the absence of thermal-diffusion (Soret) and diffusion-thermo (Dufour) effects and when there is no mass transfer, the results are similar to that of analytical results presented in Kayalvizhi [33] which justify our numerical results.

From the results and discussions, the following conclusions are arrived.

1. The non-dimensional horizontal velocity, skin friction coefficient, and dimensionless transverse velocity are all reduced by the magnetic field.
2. Influence of porosity accelerate the transverse velocity whereas decelerate the horizontal velocity and skin friction coefficient.
3. Influence of magnetic field, Eckert number and heat source parameter enhances the temperature, however, the influence of porosity, radiation, Prandtl number and wall temperature parameter over temperature is to reduce it.
4. The suction parameter, Schmidt number, chemical reaction parameter, and wall concentration parameter reduce the concentration in magnitude, while the magnetic field increases it.
5. Influence of thermal-diffusion enhances the temperature whereas influence diffusion-thermo is to suppress it.

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