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Numerical Approach for a Sutter by Fluid Impinging to a Non-Fourier Flux and a Nonlinear Radiation with a Binary Chemical Reaction

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Abstract— Present effort is executed to read the thermal and mass transfer of Sutterby fluid by discussing sparkling characteristics of nonlinear thermal radiation and binary chemical reaction. Flow field equations for stretched surface are attained by incorporating a non-uniform heat source/sink, viscous dissipation and second order convective slip condition. The motive is to scrutinize the thermal transmission by means of a rephrased form of the Fourier law coined as Non-Fourier flux model. The formulation of physical problem convolutes a system of nonlinear partial differential expressions. To transfigure these consequent equations into non-dimensional form an appropriate scaling group of variables are used and solved numerically by RK4S method- bvp4c set of instructions in Matlab. Graphical depiction is offered for the flow manner of convoluted physical parameters of interest. In addition, the quantities which are likely to excavate the physical tendency in the environs of the stretching sheet are calculated.

Keywords: *Sutterby fluid, non-linear thermal radiation, binary chemical reaction, viscous dissipation, non-uniform heat source and sink*

I. INTRODUCTION

Many investigators and scientists have experimented on the transporting abilities of fluids. Fluid rheology is the best way to recognize the dynamical transport mechanism of fluids. In some walks of discipline transport processes and have linearity between the shear stress and shear stain. But in certain industrial and technological projects (melting of Polymers, some lubricating oils and other suspensions, mud drilling etc.) have thorny transport process. This was addressed by Navier. Hence a non-empirical strain-stress demonstrated by the above mentioned materials. Such type of fluids well-known as Non-Newtonian fluids involves a nonlinear proportionality between stress and strain. These fluids has various applications: in electronic cooling devices, medicine, for reducing friction, changing angular momentum, for heat transmission etc. To describe the physical nature, these fluids are mainly classified into three types: pseudoplastic, dilatant and thixotropic. Newly, numerous fluid patterns are recommended which express the dual nature of dilatant and pseudoplastic materials. One of the model branded as Sutterby fluid model [1, 2] has received much public interest due to its special compacted structure. This model shows the properties of shear thickening liquids or dilatent (for example: wet beach sand, starch in water) when $m > 0$, the rheological trends of pseudoplastic liquids or shear thinning (for example: paint, starch, paper pulp) when $m < 0$, and behaves like Newtonian fluid (water, light oil, kerosene) when $m=0$, m is power law index. A good amount of literature survey on this model is available in Refs. [3 - 6]

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The mechanism of heat transfer plays a crucial role in management of heat in electronic devices, magnetic drug therapy, conduction of heat in tissues, reducing heat in nuclear reactors, etc which is demonstrated by conventional Fourier law of heat conduction [7]. Fourier law describes the flow temperature in a parabolic equation and got a negative feature which discloses a small interruption throughout the medium. The Fourier law describes the flow temperature in a parabolic equation. Cattaneo [8] was one who productively modified the law proposed by Fourier, by attaching the heat relaxation period which let the movement of heat by the employment of transmission of heat energy with unchanging speed. The Cattaneo law was renovated by Christov [9] with time derivative by Oldryod upper convected derivative in turn to achieve the substance-invariant formulation which is familiar as 'The Cattaneo-Christov heat flux model'. Problems with incompressible flow having C-CHFM were studied by Tibulle and Zampoli [10]. Reddy and Suneetha [11] provided a model with C-CHFM over a moving surface.

Electromagnetic radiation is the core reason for transmitting heat radiation subjected to structure, hotness and deportment of the material that ooze or soak up heat, and doesn't needed any means to prorogation. But in industry with a tiny difference in temperature inside the fluid is bothersome. For this reason scientists included an additional term nonlinear radiation besides radiation. This additional term states the discrimination in temperatures of wall and working fluid. To give an aeriel survey a few citations were given in [12-14].

In heat transfer analysis heat generation or absorption plays a major role in amendable the heat transfer in the boundary layer. Temperature assimilations is noticed inside the boundary layer by applying heat source/sink, consequently effects the deposition rate of the particles in the system such as nuclear reactors, electronic chips and semiconductor wafers etc. The temperature distribution can be modified by producing heat in the fluid, as a result the particle deposition rate is affected. A like studies have different applications in nuclear reactors, electronic chips, semi-conductor wafers and in modelling of biomedical instruments. At present we consider source/sink of heat which is not uniform. Some related articles has been described in Refs [15- 17].

Viscous dissipation play like an energy source and also changes the temperature distributions and affects the heat transfer rates. The upshot of viscous dissipation depends on whether the sheet is being cooled or heated. Such effects are important in geophysical flows and also in the large range process, for instance., on bigger planets, working class of gas in large space and in certain industrial operations and are usually characterized by the Eckert number. Gebhart [18] was first who revealed the significance of dissipation in convection. The process in which a part of kinetic energy converts into thermal energy by the viscosity of the fluid in motion which is an irreversible process known as viscous dissipation. Reddy et al. [19] conducted a study on the magneto hydrodynamic flow of blood over a porous inclined plate with dissipation. Hayat et al. [20] discussed that for higher Eckert number the internal energy of system enhances and thus temperature increases and show an opposite response to Prandtl number.

Mechanical chemistry, engineering sciences, processed food are the areas where mass transfer takes place and carry out a chemical reaction with activation energy. Few reactions occur naturally when some elements and compounds come close to each other, have nil activation energy whereas some occur only by adding a definite amount of energy. For example, while striking a match stick, activation energy is needed (in the form of friction to produce heat) so that the chemicals on the match get ignited. Svante Arrhenius was the first person who proposed the term Activation energy in 1889. He narrates it as the minimum amount of energy required to commence the reaction. It is helpful in water emulsions, oil reservoir and geothermal engineering. Differences in concentration of species results in mass transfer. In 1990 Bestman disclosed binary chemical reaction in a fluid flow. An equation which describes the relationship between the activation energy and the rate of the reaction is known as the Arrhenius equation.

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A two-step chemical reaction in deposition processes of both liquid and vapour is termed as a binary chemical reaction. A few chemical deposition uses are varnish of metallic objects, manufacturing of diodes etc., given by Shafique et al. [21]. In chemical reactions the activation energy take part a major role. Pedersen and Elliott [22] investigated that the reaction appears on the surface of the substrate in chemical deposition process. Some recent developments on this topic are revealed in Refs. [23-27].

In sight of practical uses in diverging applied fields of science, and to make an effort in the system with thermal and species transference by incorporating the non-Fourier approach for the rheology of dissipative flow of radiating Sutterby fluid model with the addition of non-uniform heat source /sink and binary chemical reaction on a stretching surface. Existing literature witness that, in past no work has been noticed in this direction, so an attempt is made to investigate it by make use of shooting technique in MATLAB emblematic software is functioned. The present 2D examination is applicable in some of the engineering processes and industrial fluid mechanics.

II. MATHEMATICAL FORMULATION

Let us consider a 2 dimensional flow of Sutterby fluid past a stretching sheet with non-uniform heat source/sink, nonlinear thermal radiation and binary chemical reaction. The mechanism of heat transfer is deliberated with the Cattaneo - Christov heat fluxtheory. The surface concur with the plane $y=0$ and the flow is limited to $y>0$. The flow is generated by the simultaneous efforts of two equal and opposite forces along the x -axis as shown in the Fig.1. Keeping the origin fixed, the surface is then stretched with a velocity $U_w(x)=\varepsilon_1 x$, the free stream velocity $U_\infty(x)=\varepsilon_2 x$ where $\varepsilon_1>0, \varepsilon_2>0$, the stretching rate and x along the stretching sheet, changing linearly with some distance as of the slit. The ambient fluid temperature is T_∞ and concentration is C_∞.

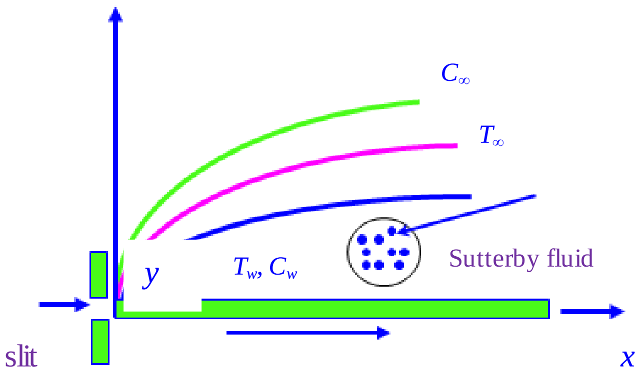

Figure.1 Physical model of the flow.

The governing equations expressing conservation of mass, momentum, energy and species are given as follows:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \qquad (1)$$

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=\frac{\mu_0}{\rho}\frac{\partial}{\partial y}\left[\frac{\partial u}{\partial y}+\frac{mB^2}{3}\left(\frac{\partial u}{\partial y}\right)^2\right]+g\delta\left(T-T_w\right)+g\delta^*\left(C-C_w\right) \qquad (2)$$

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}+\lambda_0\left(u\frac{\partial u}{\partial x}\frac{\partial T}{\partial x}+v\frac{\partial v}{\partial y}\frac{\partial T}{\partial y}+u\frac{\partial v}{\partial x}\frac{\partial T}{\partial y}+v\frac{\partial u}{\partial y}\frac{\partial T}{\partial x}+u^2\frac{\partial^2 T}{\partial x^2}+v^2\frac{\partial^2 T}{\partial y^2}+2uv\frac{\partial^2 T}{\partial x\partial y}\right)=\alpha\frac{\partial^2 T}{\partial y^2}-\frac{1}{\upsilon}\frac{\partial q_r}{\partial y}+\frac{\upsilon}{c_p}\left(\frac{\partial u}{\partial y}\right)^2+q''' \qquad (3)$$

$$u\frac{\partial C}{\partial x}+v\frac{\partial C}{\partial y}=D\frac{\partial^2 C}{\partial y^2}-k_r^2\left(\frac{T}{T_\infty}\right)^s\left(C-C_\infty\right)e^{-\frac{E_a}{kT}}, \qquad (4)$$

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The non-uniform source/sink of heat q''' is modelled as

$$q''' = \frac{kU_w}{x\nu}\left[A^*\left(T_w - T_\infty\right)f' + B^*\left(T - T_\infty\right)\right].$$

In Eq. (4), the term $k_r^2\left(\frac{T}{T_\infty}\right)^s e^{-\frac{E_a}{kT}}$ designates the modified Arrhenius equation in which E_a signifies the activation energy, k_r^2 stand the reaction rate, s be the fixed rate constants, $-1 < s < 1$ and Boltzmann constant $k = 8.61\times10^{-5}\,eV/K.$

By the Rosseland approximation the net radiation heat flux $q_r\,[Wm^{-2}]$ is symbolized by

$$q_r = -\left(\frac{4}{(3K^*)}\right) grad(e_b) \tag{5}$$

where $K^*[m^{-1}]$ be the Rosseland mean spectral absorption coefficient, $e_b\,[Wm^{-2}]$ be the blackbody emission power, T be the absolute temperature, $e_b = \sigma^* T^4$ be the Stefan-Boltzmann radiation law and $\sigma^* = 5.6697 \times 10^{-8} W m^{-2} K^{-4}$ be the Stefan-Boltzmann constant.

The term T^4 can be defind as a linear function of temperature itself. Therefore, T^4 can be extended as Taylor series in terms of T_∞ and approximated by neglecting terms with higher order.

$$T^4 = T_\infty^4\left\{1 + \left(\theta_w - 1\right)\theta\right\}^4 \tag{6}$$

where $\theta_w = \frac{T_w}{T_\infty},\ \theta_w > 1$ be the wall temperature ratio parameter.

Where u and v denote the velocity components along the x and y directions, respectively. $\upsilon = \mu_0/\rho$ is the kinematic viscosity, μ_0 is the viscosity of the fluid, λ_0 is the fluid relaxation time, B is the material constant, δ is the coefficient of thermal expansion, δ^* is the coefficient of thermal expansion with concentration, T is the temperature of fluid, C is the concentration of fluid, ρ is the density of the fluid, c_p is the heat capacity of the fluid, k_r^2 is the chemical reaction rate coefficient and $\alpha = k/\rho c_p$ is thermal diffusivity, where k is the thermal conductivity. Moreover, the slip velocity at the sheet, is assumed to be in the form $u_{slip} = a\frac{\partial u}{\partial y} + b\frac{\partial^2 u}{\partial y^2}$ where $a > 0$ and $b < 0$ are velocity slip quantities.

The boundary conditions in the present problem are

$$\left.\begin{array}{l} u = U_w(x) + a\frac{\partial u}{\partial y} + b\frac{\partial^2 u}{\partial y^2},\ v = 0, \\ -k\frac{\partial T}{\partial y} = h_f\left(T_w - T\right),\ C = C_w \end{array}\right\},\ \text{at}\quad y = 0 \tag{7}$$

$$u \to 0,\ T \to T_\infty,\ C \to C_\infty,\ \text{as}\quad y \to \infty \tag{8}$$

By using these transformations, we have

$$\begin{array}{l} \eta = \sqrt{\frac{\varepsilon_1}{v}}\,y,\ \psi = \sqrt{v\varepsilon_1}\,x\,f(\eta),\ \theta(\eta) = \frac{T - T_\infty}{T_w - T_\infty}, \\ \varphi(\eta) = \frac{C - C_\infty}{C_w - C_\infty} \end{array} \tag{9}$$

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In which ψ is the stream function, equations (2) - (4) can be reduced to a system of two coupled ordinary differential equations as follows:

$$f'''(\eta)-f'^2(\eta)+f(\eta)f''(\eta)+\frac{m}{2}Re\,De\,f''^2(\eta)f'''(\eta)+Gr\theta+Gc\phi=0 \tag{10}$$

$$\frac{1}{Pr}\begin{pmatrix}\theta''(\eta)\left[1++\frac{4}{3}Rd\left[(\theta_w-1)\theta+1\right]^3\right]\\+4Rd\left[(\theta_w-1)\theta+1\right]^2(\theta_w-1)\theta'^2\end{pmatrix}+f(\eta)\theta'(\eta)-\gamma\left(f(\eta)f'(\eta)\theta'(\eta)+f^2(\eta)\theta''(\eta)\right)+Ecf''+A^*f'+B^*\theta=0 \tag{11}$$

$$\frac{1}{Sc}\varphi''(\eta)+f(\eta)\varphi'(\eta)-\sigma\phi\left[\theta(\theta_w-1)+1\right]^S e^{-\frac{E}{\theta(\theta_w-1)+1}}=0 \tag{12}$$

Where the prime denotes the derivative with respect to η. The Prandtl number is given as $\Pr=\upsilon/\alpha$, where α is thermal diffusivity. $De=B^2\varepsilon_1{}^2$ is the Deborah number, $Re=\frac{xU_w(x)}{\upsilon}$ is the Reynolds number, $\gamma=\lambda_0\varepsilon_1$ is the non -dimensional thermal relaxation time, where ε_1 is a positive constant, λ_0 is fluid relaxation time, *Gr* is Grashof number, *Gc* is solutal Grashof number, λ is a first order velocity,
β is a second order velocity

$$Sc=\frac{\upsilon}{D},\ \sigma=\frac{k_r^2}{c},\ E=\frac{E_a}{kT_\infty},\ Rd=\frac{4\sigma^*T_\infty^{*3}}{kk_1},\ Ec=\frac{U_w^2}{C_p\left(T_w-T_\infty\right)},$$
$$Gr=\frac{g\delta x\left(T_w-T_\infty\right)}{U_w{}^2},Gc=\frac{g\delta^*x\left(C_w-C_\infty\right)}{U_w{}^2},\lambda=a\sqrt{\varepsilon_1/\upsilon},$$
$$\beta=b\,\varepsilon_1/\upsilon,Bi=\left(\frac{h_f}{k}\right)\sqrt{\upsilon/c},\ \Pr=\frac{\mu C_p}{k}$$

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

$$f(\eta)=0\ ,\ f'(\eta)=1+\lambda f''(0)+\beta f'''(0),\quad \theta'(\eta)=-Bi\left(1-\theta(\eta)\right),\ \varphi(\eta)=1 \quad \text{at } \eta=0 \tag{13}$$

$$f'(\eta)\to 0,\theta(\eta)\to 0,\ \varphi(\eta)\to 0,\text{as}\,\eta\to\infty \tag{14}$$

The physical quantities of interest are the skin friction coefficient C_f, local Nusselt number *Nu* and local Sherwood number *Sh*, which are defined as

$$C_f=\frac{\tau_w}{\rho u_w^2},\ Nu=\frac{xq_w}{k(T_w-T_\infty)},\ Sh=\frac{xq_m}{D(C_w-C_\infty)}, \tag{15}$$

Where surface shear stress τ_w, the surface heat flux q_w and the surface mass flux q_m are given by

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$$\tau_w = \mu\left(\frac{\partial u}{\partial y}\right)_{y=0}, \quad q_w = -xk\left(\frac{\partial T}{\partial y}\right)_{y=0} + \left(q_r\right)_{y=0}, \quad q_m = -D\left(\frac{\partial C}{\partial y}\right)_{y=0} \tag{16}$$

With μ being dynamic viscosity, k and D being thermal and mass conductivity's. Using similarity transformations (9), we obtain

$$\sqrt{Re_x}\,C_f = -\left[f''(0) + \frac{m}{6} De\, Re\left(f''(0)\right)^3\right],$$
$$\frac{Nu}{\sqrt{Re_x}} = -\left\{1 + \frac{4}{3} Rd\left[(\theta_w - 1)\theta(0) + 1\right]^3\right\}\theta'(0), \tag{17}$$
$$\frac{Sh}{\sqrt{Re_x}} = -\phi'(0).$$

Where $Re_x = \frac{U_w x}{\upsilon}$ is local Reynolds number.

III. VALIDATION OF THE NUMERICAL PROCEDURE

For the purpose of authentication, results were compared with previously reported results in the literature. The comparison of our analytical results is made with the existing literature for the particular values of flow parameters. These comparisons are displayed in Table 1. The comparison was satisfactory and found in good agreement with existing results with minimal errors.

	$-\theta'(0)$			
Pr	Malik et al. [28]	Khan and Pop [29]	Siri et al. [30]	Present results
0.7	0.45392	0.4539	0.453930	0.453457
2.0	0.91135	0.9113	0.911345	0.911342
7.0	1.89543	1.8954	1.895489	1.895423
20.0	3.35395	3.3539	3.353905	3.353924

Table 1 Comparison of local Nusselt number $-\theta'(0)$ for different values of Pr $\left(m = De = Re = \gamma = \theta_w = Ec = Rd = E = \sigma = Bi = Sc = A^* = B^* = 0\right)$.

IV. COMPUTATIONS AND DISCUSSION

The transformed momentum equation (10), energy equation (11) and species equation (12) subjected to the boundary conditions of equation (13) and (14) were numerically solved by means of the R-K fourth order method. The computations for the RK method were performed by using MATLAB. Numerical computations have been shown for various values of the parameters involved, namely m, Re, De, Pr, Rd, Ec, A^*, B^*, σ, θ_w, E, λ, β, Bi and Sc that describe the characteristics of flow, heat and mass transfer and the results are presented in the form of graphs and tables. In figs the following data is generally utilized, (unless stated otherwise): $Pr = 0.7$, $m = 0.5$, $De = Re = 0.3$, $Rd = 0.3$, $Ec = 0.02$, $A^* = 0.05$, $B^* = 0.05$, $\sigma = 3.0$, $\theta_w = 1.1$, $E = 1.0$, $\lambda = 0.5$, $\beta = -1.0$, $Bi = 0.5$ and $Sc = 0.66$.

The impact of the power law indexparameter m on velocity is displayed in Fig.2. Velocity enhances as m enhances is noticed from figure 2. Also velocity improves more for shear thickening fluids than Newtonian and shear thickening fluids.

The velocity profile is visualized in figure 3 for shear thinning and shear thickening fluids with various values of Reynolds number. The fluid velocity boost up for high Re for $m > 0$ and a reverse trend is observed for $m < 0$, as the viscous force diminishes and consequently a reduction in the fluid flow is noticed in figures 3a and 3b.

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The fluidity of materials are measured by the Deborah number *De* under the specific flow forms. The Deborah number has relatively an opposite effect on the velocity of the fluid for positive and negative *m*. The fluid flow accelerates with a hike in *De* (see Fig. 4a) and a reverse trend is noted in Fig. 4b. Higher *De* shows an enhancement in the elastic effects, which improves the fluid flow for dilatant fluids, while an opposite tendency is viewed for Pseudoplastic fluid.

Figure 5 disclosed that a growth in Pr gradually shrinks the thermal profile and for that reason thermal boundary layer thickness reduces. $Pr > 1$ represents the polymeric non-Newtonian fluids. Elevated values of Pr are related with a drop in thermal diffusivity. Moreover, Prandtl number is in reverse to thermal conductivity. A declinement in thermal conductivity is noticed for higher Pr which concludes a strong decrease in temperatures.

In accordance with Fig. 6 the temperature profile increases with greater values of thermal radiation which results a increase in the thermal boundary layer thickness. For the reason that, a shrinkage in the mean absorption coefficient is spotted for growth in Rd. Thus, the rate of heat transfer by radiation to the fluid rises. In reality, the temperature of the fluid grows as the working fluid is heated in the process of radiation.

As regards figure 7 describes the thermal variation for assorted values of Eckert number. Thus temperature raises with *Ec*. Physically, for greater *Ec* the internal energy of system enhances and thus temperature raises. Also Eckert number is defined as the ratio between enthalpy difference and kinetic energy.

As Schmidt number enlarges the magnitudes of the concentration contracts is figured out in figure 8. The Schmidt number is a fraction of the momentum to the mass transport by diffusivity. The values of Sc = 0.24 (hydrogen), 0.62 (water vapour), 0.78 (ammonia at 25°C) and 2.62 (propyl benzene).

Fig.9 portrays the concentration magnitudes for different values of σ. An increase in σ, results in thinner concentration profiles. From this

$\sigma\left(1+(\theta_w-1)\theta\right)^S\, e^{\left[\frac{-E}{1+(\theta_w-1)\theta}\right]}$, we say that, an increment is noted as σ or s increases. A useful destructive reaction grows, as a result, concentration profile rises.

Fig.10 visualizes the concentration sketch counter to the activation energy *E*. A declining nature in the Arrhenius function is observed with inclining activation energy, which tends to betterment in the productive chemical reaction producing a thick concentration. With the occurrence of extreme activation energy at low temperature indicates a lesser action rate which decrease the chemical action. Therefore, species of solute boostup.

The deviation of *De* and *Re* on skin friction coefficient is plotted in figure 11. It is observed that skin friction coefficient increases with an increase in Deborah number and Reynolds number.

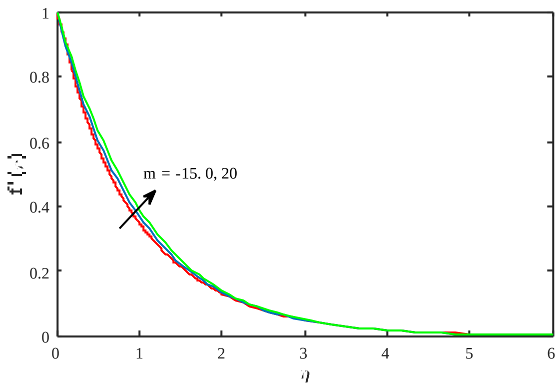

Fig. 2: Velocity distribution $f'(\eta)$ for different *m*.

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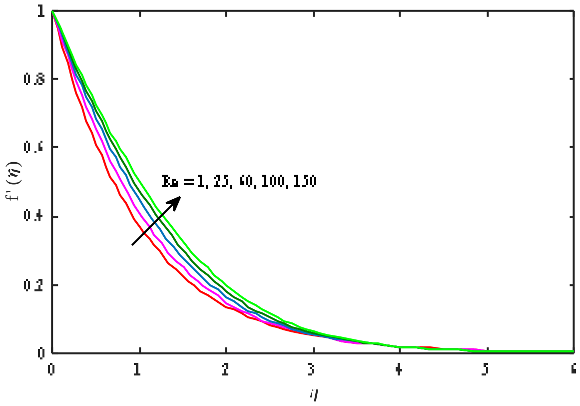

Fig. 3a: Velocity distribution $f'(\eta)$ for different *Re* for

$m > 0$.

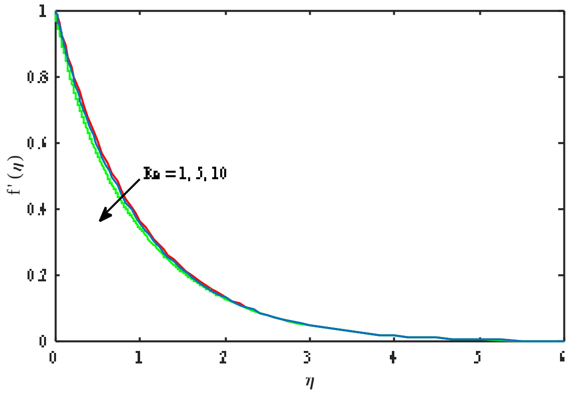

Fig. 3b: Velocity distribution $f'(\eta)$ for different *Re* for

$m < 0$.

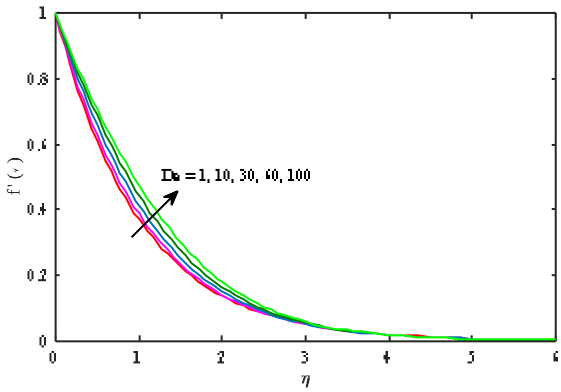

Fig. 4a: Velocity distribution $f'(\eta)$ for different *De* for

$m > 0$

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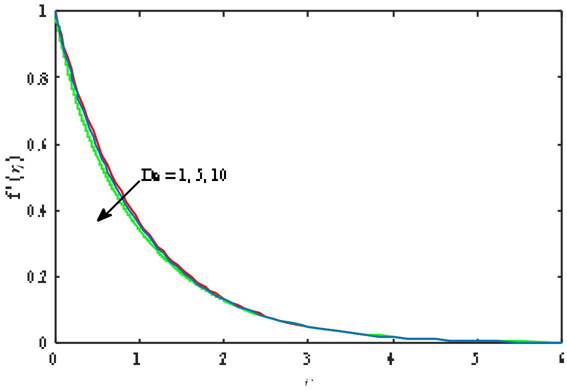

Fig. 4b: Velocity distribution $f'(\eta)$ for different *De* for $m < 0$.

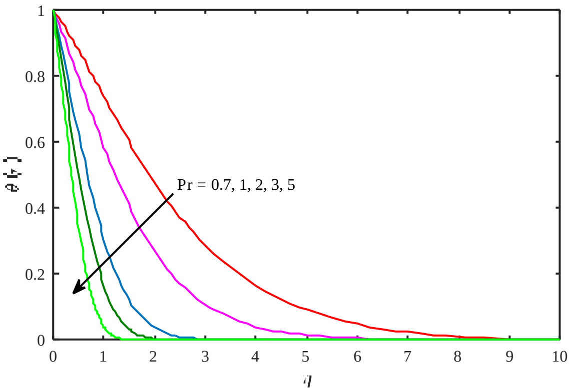

Fig. 5: Temperature distribution $\theta(\eta)$ for different *Pr*.

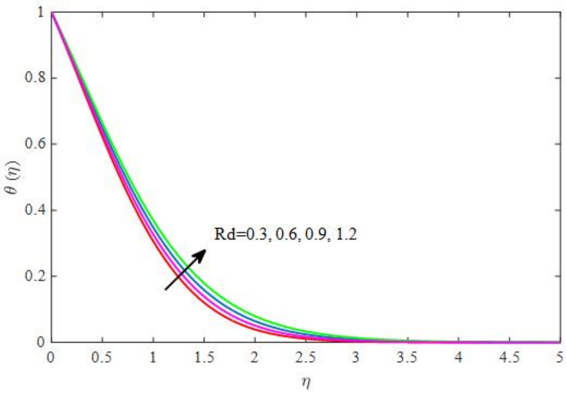

Fig. 6: Temperature distribution $\theta(\eta)$ for different *Rd*

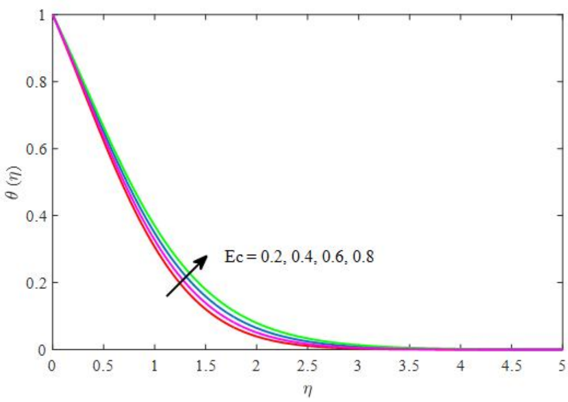

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Fig. 7: Temperature distribution $\theta(\eta)$ for different Ec.

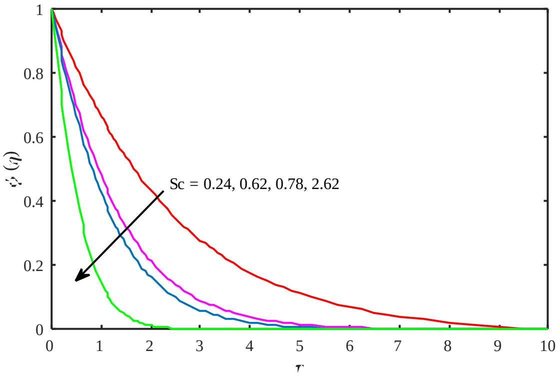

Fig. 8: Concentration distribution $\phi(\eta)$ for different Sc.

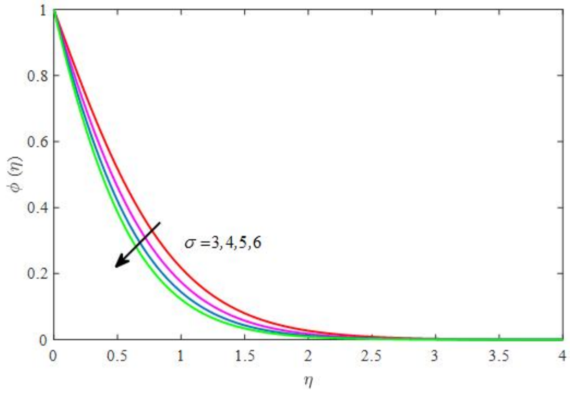

Fig. 9: Concentration distribution $\phi(\eta)$ for different σ.

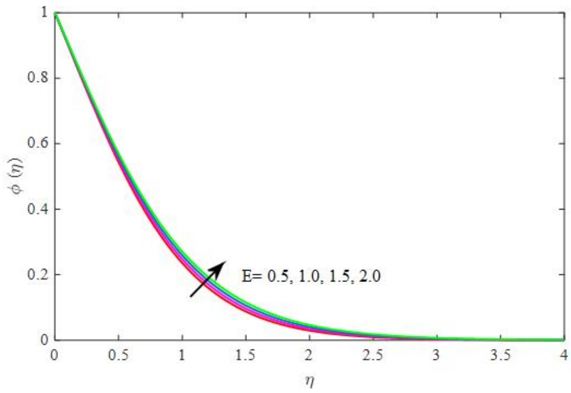

Fig. 10: Concentration distribution $\phi(\eta)$ for different E.

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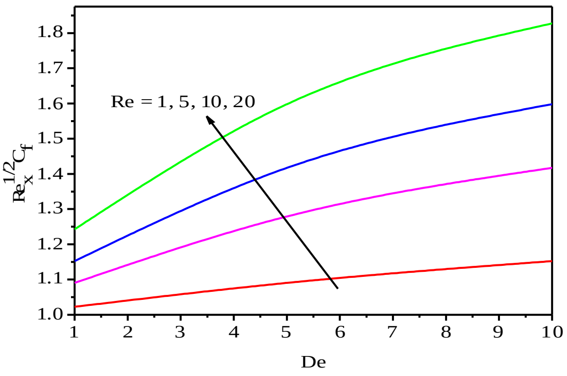

Fig. 11: Skin friction coefficient $\mathrm{Re}_x^{1/2} C_f$ for different *De* and *Re*.

V. CONCLUDING REMARKS OF PRESENT EXPLORATION

From the contemporary investigations, the main interpretations were as follows:

- The velocity field increases while the temperature and concentration profiles decrease, as the *Re* and *De* increase for shear thickening fluids.
- Thermal boundary layer thickness decreases by increasing the *Pr*.
- Thermal boundary layer thickness decreases by increasing the *Pr*.
- Temperature is an increasing function of *Ec*.
- A rise in concentration with the rise in Activation energy.
- For higher Sc lower the concentration.
- For m > 0, the values of skin friction decreases for large *Re* while a reverse trend for m < 0.

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