Formulating the behavior of thermal radiation and magnetic dipole effects on Darcy-Forchheimer grasped ferro-fluid flow
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Abstract:
In existing article a boundary layer analysis has been carried out to examine the Darcy-Forchheimer flow of Carreau ferrofluid through a sensor duct between two parallel plates. The top plate is assumed to be squeezed whereas the lower plate is at rest. Inspection has been accomplished in the occupancy of thermal radiation and magnetic dipole. Thermal conductivity is also considered which is determined by temperature. After incorporating these speculations, dimensional equations supervising the flow and heat transfer distinctions are transfigured into dimensionless system of differential equations by implementing similarity transformations. The result of squeezed flow index \( b \), ferrohydrodynamic interaction \( \beta \), Porous medium permeability parameter \( S_1 \), local inertia coefficient \( S_2 \), Eckert number \( \lambda \), Prandtl number \( \Pr \), curie temperature \( g \) and Weissenberg number \( W_e \) on velocity and temperature curves are observed. The numerical solution for boundary layer momentum and energy equations are obtained. The present analysis demonstrates that velocity profile significantly drops owing to rise in Weissenberg number.

Keywords:
Magnetic dipole; Ferrofluid; Darcy-Forchheimer flow; Carreau fluid; Thermal radiation effects; Sensor surface.

1 Introduction
Researchers [1-10] have shown a lot of interest towards the study of non-Newtonian fluids due to its extended applications in different fields. In mining industry non-Newtonian behavior is also used where mud and slurries are frequently managed and in applications like biomedical and lubrication flows. Therefore the reflection of non-Newtonian fluid flow fact is of significance to industry. A substantial amount of work has been extinct in the realm of non-Newtonian fluids and further sufficient work is required in a variation of non-Newtonian fluid models. Because of considerable clarity of the power-law model it has been investigated by many researchers for the sake to examine non-Newtonian impacts. But Power-law model has its restrictions. Due to obstacles of Power-law model, notably for very high and for very low shear rates, we examine another viscosity model namely Carreau fluid model. Carreau fluid is generalize Newtonian fluid type in which viscosity determines by the shear rate. Carreau fluid model is helpful in explaining the fluid flow behaviors in the high shear rate division.

Ferrofluids have various technological applications like dynamic sealing, damping, heat dissipation, doping of materials in various gadgets while in biomedical field these found applications in magnetic targeting of drugs, contrast amplification for magnetic resonance imaging,
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hyperthermia and magnetic partition of cells. In the future investigation the predictable applications of ferrofluids in biomedical field will be that the experiments performed on small animals is moving very hurriedly to apply on humans. For curing of cancer, in peculiarly, is requiring rapid growth than has been attained by conventional medicine, the ferrofluids for targeting of drug or chemotherapy or hyperthermia or integration of this technique with conventional radiotherapy, will definitely be the topic of extreme research in coming years. On the other hand, formation of ferrofluids will consider keenly over biocompatible coatings, comprises affinities to various living cells. At basic level of research, the advancement in computer technology, producing very rapid, powerful and inexpensive computers, by this line envisaging qualities and properties of ferrofluids, to be checked in laboratories. In appropriate carrier liquids colloidal suspensions consisting nano scale ferromagnetic particles demonstrate a liquid system with intense magnetic dipoles which can be forcefully effected by magnetic fields. In 1964, Papell [11] introduced a stable suspension of this type at NASA. The particles have diameter of about 10nm. It has astonishing applications owing to its importance in shock absorbers, lithographic patterning, purification of molten metals, leak-proof seals, coolers of nuclear reactors, microfluidic valves and pumps, microfluidic actuators and MEMS (Micro Electric Mechanical System) and many others. Zeeshan et al. [12] examined the consequences of iron nanoparticles shape in a ferrofluid flow by considering extremely oscillating magnetic field across a stretchable rotating disk. Ellahi et al. [13] discussed Maxwell ferrofluid flow over a stretching sheet in existence of magnetic dipole with soret and suction impacts. Sheikholeslami et al. [14,15] have done a considerable work on ferrofluid flows in the occupancy of a magnetic field. Taseer et al. [16] explored Darcy-Forchheimer Maxwell nanofluid flow soaking a non-Darcian porous medium. Hayat et al. [17] observed the flow of a Jeffrey nanofluid across a nonlinear stretching surface under passive and active controls of nanoparticles. Hayat et al. [18] analyzed heat generation/absorption impacts on MHD Oldroyd-B nanofluid flow caused by a stretching surface. Hayat et al. [19] investigated three-dimensional MHD flow of nanofluid across a nonlinear stretching surface. Hayat et al. [20] explored three dimensional MHD flow of a viscoelastic nanofluid in the existence of nonlinear thermal radiation. Ellahi et al. [21] examined shape effects of both spherical and nonspherical nanoparticles in mixed convection flow of a nanofluid across a vertical stretching sheet.

There are several applications in industrial and environmental systems which involve the convection flow through porous media. These applications are generally involved in fossil fuels beds, production of crude oil, heat exchanger layout, ground water systems, catalytic reactors, movement of water in reservoirs, geothermal energy schemes, nuclear water disposal and many others. Non-Darcian porous media is a revamped form of classical Darcy model which includes boundary and inertia characteristics. The Darcian law is preferable for weaker porosity conditions and smaller velocities and for high velocities this law is incapable. Forchheimer [22] included a velocity squared term in momentum equation to examine inertia effects, which is known as Forchheimer term. Zeeshan et al. [23] observed the flow of non-Darcy \( Fe_3O_4 \)-water nanofluid through an invariant porous medium in which nanofluid viscosity is supposed to be depend over an external magnetic field. Hayat et al. [24] analyzed homogeneous-heterogeneous reactions over Darcy-Forchheimer flow owing to a curved stretching surface. Cattaneo-Christove heat flux phenomenon is also taken into account. Hayat et al. [25] discussed Darcy-Forchheimer flow of a third grade fluid with generalized versions of Fourier’s and Fick’s laws. Substantial work related to Darcy-Forchheimer flow have done by Tasawar Hayat as described in Refs. [26-28].

The main theme of the present investigation is to explore Darcy-Forchheimer squeezed
flow of Carreau ferrofluid over a sensor surface in the appearance of thermal radiation and magnetic dipole effects. The first section represents introductory section. Mathematical modeling of the flow problem is representing in second section. Third section demonstrates numerical solution of the problem with the help of shooting technique. Comprehensive discussion about the consequences of different physical substantial parameters on velocity and temperature accounts is given in section four. Fifth section depicts concluding remarks of the present investigation.

2 Mathematical Model

We consider Carreau ferrofluid flow through a sensor surface between two parallel plates. Magnetic dipole is located over a sensor plate at a distance \( \alpha \) for magnetization of fluid. Fig. 1 depicts the closed squeezed duct with length \( h(t) \) suspected to be appreciably larger than the boundary layer thickness. Furthermore it is imagined that the squeezing free stream is presumed to be happened from the tip to the plane. Besides, It is deduced that the top plate is squashed while lower plate is at rest and a sensor surface is placed among them.

![Physical model of the sensor surface.](image)

By using boundary layer approximation the dimensional equations for the flow problem will be of the form

\[
\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0,
\]

\[
u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + \frac{\partial u}{\partial t} = -\frac{1}{\rho} \frac{\partial p}{\partial x} + v[1 + \frac{3(n-1)}{2}(\frac{\partial u}{\partial y})^2] \frac{\partial^2 u}{\partial y^2} + \frac{\partial H M \lambda_o}{\rho} \frac{\partial^2 u}{\partial y^2} + \frac{\partial H M k_1}{\rho} u - \frac{\nu}{k_1} u - u^2 F,
\]

where \( u \) and \( v \) are elements of velocity field, \( t \) represents time, \( p \) indicates pressure of the fluid, \( \lambda_o \) indicates magnetic permeability, \( H \) denotes the magnetic field, \( \nu \) is the kinematic viscosity, \( M \) illustrates Magnetization, \( \mu \) is the viscosity of the fluid, \( \rho \) represents density, \( F \) expresses Forchheimer constant, \( n \) and \( \Gamma \) are Carreau fluid parameters.

Sensor duct is positioned in a locally free stream therefore the flow is accelerated by exterior free stream velocity \( U(x, t) \). So, we have

\[
U \frac{\partial U}{\partial x} = \frac{1}{\rho} \frac{\partial p}{\partial x} + \frac{\mu}{\rho k_1} U + U^2 F
\]
\[ U \frac{\partial U}{\partial x} + \frac{\partial U}{\partial t} + \frac{\mu}{\rho k_1} U + U^2 F = -\frac{1}{\rho} \left( \frac{\partial p}{\partial x} \right), \]  

(4)

in the last two expressions \( U \) indicates free stream velocity. Eradicating the pressure gradient we have

\[
u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + \frac{\partial u}{\partial t} = (U - u) \frac{v}{k_1} + (U^2 - u^2) F + \frac{\partial U}{\partial t} + U \frac{\partial U}{\partial x} + v(1 + 3(n - 1)) \Gamma^2 (\frac{\partial u}{\partial y})^2 (\frac{\partial^2 u}{\partial y^2}) + \frac{\partial H M \lambda_o}{\partial x} \rho. \]  

(5)

### 2.1 Energy equation

Energy equation for the flow problem will take the form

\[
(v \frac{\partial T}{\partial y} + \frac{\partial T}{\partial t} + u \frac{\partial T}{\partial x}) = \alpha(T) \frac{\partial^2 T}{\partial y^2} - \frac{1}{\rho C_p} \frac{\partial q_r}{\partial y} - \frac{1}{\rho C_p} \frac{\partial M}{\partial T} \lambda_o T (v \frac{\partial H}{\partial y} + u \frac{\partial H}{\partial x}),
\]  

(6)

where \( T \) is the fluid temperature, \( C_p \) represents the specific heat, \( \alpha(T) \) illustrates variable thermal conductivity where \( \alpha = \alpha_\infty (1 + \epsilon \theta_1 + \epsilon_2 \theta_2^2) \) and \( q_r \) is the integrand of radiative heat flux \( q \). Now by using Rosseeand approximation [29] :

\[ q_r = -\frac{4}{3} \frac{\sigma^*}{m^*} \frac{\partial T^4}{\partial y}, \]

(7)

here \( m^* \) represents the mean absorption coefficient and \( \sigma^* \) demonstrates the Stefan-Boltzmann constant.

If the temperature distinctions within the flow are abundantly small then it can be linearized by extending \( T^4 \) into Taylor series about \( T_\infty \) and by ignoring higher order terms it is of the form

\[ T^4 \approx 4T_\infty^3 T - 3T_\infty^4. \]

(8)

putting the value of \( \frac{\partial q_r}{\partial y} \) we have

\[
(v \frac{\partial T}{\partial y} + \frac{\partial T}{\partial t} + u \frac{\partial T}{\partial x}) = \alpha(T) \frac{\partial^2 T}{\partial y^2} - \frac{16 \sigma^* T_\infty^3}{3m^*} \frac{\partial^2 T}{\partial y^2} - \frac{1}{\rho C_p} \frac{\partial M}{\partial T} \lambda_o T (v \frac{\partial H}{\partial y} + u \frac{\partial H}{\partial x}),
\]

(9)

with appropriate set of boundary conditions

\[
v(x, 0, t) = v_0(t), u(x, 0, t) = 0, -\frac{\partial T(x, 0, t)}{\partial y} = q(x),
\]

\[
T(x, \infty, t) = T_\infty, u(x, \infty, t) = U(x, t).
\]

(10)

Here \( q(x) \) illustrates wall heat flux.
2.2 Magnetic Dipole

Illustration of magnetic scalar potential is

$$\Phi = \left( \frac{x}{x^2 + (y + a)^2} \right) \frac{\gamma}{2\pi}.$$  \hspace{1cm} (11)

The elements of magnetic scalar potential are

$$H_x = -\frac{\partial \Phi}{\partial x} = \left\{ \frac{x^2 - (y + a)^2}{(x^2 + (y + a)^2)^2} \right\} \frac{\gamma}{2\pi},$$  \hspace{1cm} (12)

$$H_y = -\frac{\partial \Phi}{\partial y} = \left\{ \frac{2x(y + a)}{(x^2 + (y + a)^2)^2} \right\} \frac{\gamma}{2\pi}.$$  \hspace{1cm} (13)

Amplitude of magnetic field $H$ is

$$H = \{ \left( \frac{\partial \Phi}{\partial x} \right)^2 + \left( \frac{\partial \Phi}{\partial y} \right)^2 \}^{1/2}.$$  \hspace{1cm} (14)

$$\frac{\partial H}{\partial x} = -\left( \frac{2x}{(y + a)^4} \right) \frac{\gamma}{2\pi},$$  \hspace{1cm} (15)

$$\frac{\partial H}{\partial y} = \left( \frac{-2}{(y + a)^3} + \frac{4x^2}{(y + a)^5} \right) \frac{\gamma}{2\pi}.$$  \hspace{1cm} (16)

Change in Magnetization ($M$) regarding temperature is given by

$$M = K^*(T_{\infty} - T),$$  \hspace{1cm} (17)

where $K^*$ illustrates pyromagnetic coefficient, $T_{\infty}$ demonstrates ambient temperature, $\gamma$ denotes strength of magnetic field.

2.3 Transformations

Suitable transformations are

$$\eta = y \sqrt{\frac{c}{v}}, \quad \xi = \sqrt{\frac{c}{v}}x, \quad u = cx f'(\eta), \quad v = -f(\eta)\sqrt{cv}, \quad U = cx, \quad \psi = x\sqrt{cv} f(\eta),$$

$$\theta(\eta) = \frac{T - T_{\infty}}{T_w - T_{\infty}} = \theta_1(\eta) + \xi^2 \theta_2(\eta), \quad c = \frac{1}{(s + bt)}, \quad \psi = x\sqrt{cv} f(\eta).$$  \hspace{1cm} (18)

Here $q(x) = q_o x$, $f_o = \sqrt{v}$, $v_o(t) = v\sqrt{c}$ and $T_w - T_{\infty} = q_o x \sqrt{\frac{c}{v}}$.

Therefore, transformed equations are

$$f^{'''} + \frac{3(n - 1)}{2} W_{v}^2(f'')^2 f''' + \left( \frac{b_1}{2} + f \right) f'' + b(f' - 1) - (f')^2 + S_1(1 - f')$$

$$= 0,$$  \hspace{1cm} (19)
\[(1 + \varepsilon\theta_1 + R)\theta_1'' - \text{Pr} \theta_1'\left(\frac{b}{2} + f'\right) + \text{Pr} \theta_1'\left(\frac{b}{2} + f\right) + 2\lambda\beta^* (\theta_1 - g) \frac{f}{(\eta + \delta)^3} = 0, \quad (20)\]

\[(1 + \varepsilon\theta_1 + R)\theta_2'' + \varepsilon_2\theta_1' + \frac{1}{2} \text{Pr} b\theta_2' + \frac{1}{2} \text{Pr} b\eta\theta_2' - 3 \text{Pr} f'\theta_2 + \text{Pr} f\theta_2' + \frac{2\lambda\beta^* \theta_2 f}{(\eta + \delta)^3}\]

\[-2\lambda\beta^*(\theta_1 - g)\left[\frac{f'}{(\eta + \delta)^4} + \frac{2f}{(\eta + \delta)^5}\right] = 0, \quad (21)\]

corresponding transformed conditions are

\[f'(0) = 0, \quad f(0) = -f_0, \quad f'(\infty) \to 1, \quad \theta_1'(0) = -1, \quad \theta_2'(0) = 0, \quad \theta_1|_{\eta \to \infty} \to 0, \quad \theta_2|_{\eta \to \infty} \to 0, \quad (22)\]

where

\[W_e^2 = \frac{c^3 x^2 \Gamma^2}{v}, \quad \beta^* = \frac{\gamma \rho \lambda_o}{2\pi \mu^2 k^* (q_o x \sqrt{\frac{v}{c}})}, \quad g = \frac{T_{\infty}}{q_o x \sqrt{\frac{v}{c}}}, \quad \delta = a \sqrt{\frac{cp}{\mu}}, \quad (23)\]

\[\xi = x \sqrt{\frac{c}{v}}, \quad S_1 = \frac{v}{k_1 c}, \quad \text{Pr} = \frac{v}{\alpha_{\infty}}, \quad S_2 = F x, \quad \lambda = \frac{c\mu^2}{\rho \alpha_{\infty} (q_o x \sqrt{\frac{v}{c}})} \quad R = \frac{16 \sigma^* T_{\infty}^3}{3 \alpha_{\infty} m^*} \quad (23)\]

Here \(W_e\) illustrates Weissenberg number, \(\beta^*\) depicts ferrohydrodynamic interaction, \(g\) denotes the curie temperature, \(\delta\) exhibits the velocity slip parameter, \(S_1\) represents the porous medium permeability parameter, \(\text{Pr}\) indicates the Prandtl number, \(S_2\) illustrates the local inertia coefficient where \(F\) is Forchheimer number, \(\lambda\) depicts the Eckert number and \(R\) represents the thermal radiation parameter.

### 2.4 Nusselt number and skin-friction expressions

By utilizing boundary approximations wall shear stress and heat flux at the sensor duct is of the form

\[\tau_w = \mu_o \left[ \frac{\partial u}{\partial y} + \frac{n - 1}{2} \Gamma^2 \left( \frac{\partial u}{\partial y} \right)^3 \right], \quad (24)\]

\[q_w = k(1 + R)[(\theta'_1(0) + \xi^2 \theta'_2(0))]. \quad (25)\]

Nusselt number and skin friction expressions in non-dimensional form are explicated as

\[Nu_x = -(1 + R)[(\theta'_1(0) + \xi^2 \theta'_2(0))] \sqrt{Re_x}, \quad (26)\]

\[\sqrt{Re_x C_{f_x}} = \frac{f'' \left( \frac{n - 1}{2} \right)}{W_e^2} \left( f'' \right)^3, \quad \text{Re}_x = x \sqrt{\frac{v}{c}}. \quad (26)\]
3 Solution of the problem

Shooting algorithm is employed on eqs. (12-14) for the sake of numerical solution. Suppose

\[ r_1 = f, \quad r_2 = f', \quad r_3 = f'', \quad r_4 = \theta_1, \quad r_5 = \theta_1', \quad r_6 = \theta_2, \quad r_7 = \theta_2'. \]  

(27)

So, the corresponding equations take the form

\[ r_1' = r_2, \quad r_2' = r_3, \]  

(28)

\[ r_3' = \frac{1}{1 \pm \frac{3(n-1)}{2} We^2 r_3^2} [(r_2)^2 - b(r_2 - 1) - 1 - r_3(r_1 + \frac{b\eta}{2}) - S_1(1 - r_2) - S_2(1 - (r_2)^2) + \frac{2\beta^* r_4}{(\eta + \delta)^2}], \]  

(29)

\[ r_4' = r_5, \]  

(30)

\[ r_5' = \frac{1}{1 + \epsilon r_4 + R} \left[ \Pr(r_1 + \frac{b}{2})r_5 + \Pr(r_2 + \frac{b}{2})r_4 - 2\lambda\beta^*(r_4 - g) \frac{r_1}{(\eta + \delta)^3} \right], \]  

(31)

\[ r_6' = r_7, \]  

(32)

\[ r_7' = \frac{1}{1 + \epsilon r_4 + R} \left[ -\epsilon r_6 r_5' - \frac{1}{2} \Pr br_6 - \frac{1}{2} \Pr b\eta r_7 + 3 \Pr r_2 r_6 - \Pr r_1 r_7 - \frac{2\beta^* r_1 r_6}{(\eta + \delta)^3} \right. \]

\[ \left. + 2\lambda\beta^*(r_4 - g) \left[ \frac{r_2}{(\eta + \delta)^4} + \frac{2r_1}{(\eta + \delta)^5} \right] \right]. \]  

(33)

with initial conditions:

\[ r_2(0) = 0, \quad r_1(0) = -f_0, \quad r_2(\infty) \to 1, \]  

\[ r_5(0) = -1, \quad r_7(0) = 0, \quad r_4 \mid_{\eta \to \infty} \to 0, \quad r_6 \mid_{\eta \to \infty} \to 0. \]  

(34)

4 Graphical Results and Discussions

Behavior of velocity and temperature curves \( \theta_1(\eta) \) and \( \theta_2(\eta) \) according to different substantial physical parameters are discussed comprehensively. Fig. 1. demonstrates the geometry of the flow phenomena. Fig. 2 explicates the impact of porous medium permeability parameter \( S_1 \) on velocity curve. It demonstrates increasing performance for \( S_1 = 0.01, 1.5, 3.1, 5.1 \). Behavior of velocity profile for escalating values of squeezed flow index \( b \) is depicted in Fig. 3. It reveals growing manner for \( b = 0.1, 0.6, 1.2, 1.8 \). Fig. 4 indicates the increasing performance of velocity curve for \( \delta = 1.1, 1.17, 1.29, 2.9 \). Velocity profile according to increasing values of \( n \) is explicoted in Fig. 5. Velocity curve illustrates decline manner for \( n = 1.0, 1.2, 1.9, 4.5 \). Fig. 6 determines the impact of local inertia coefficient \( S_2 \) on velocity account. Velocity account shows intensifying performance for \( S_2 = 0.1, 1.2, 2.2, 3.5 \). Fig. 7 exhibits the consequences of Weissenberg number \( W_e \) on velocity profile. Velocity curve determines decreasing behavior for \( W_e = 0.1, 0.3, 0.5, 0.8 \). Velocity field for contrary values of ferrohydrodynamic interaction
parameter is expressed in Fig. 8. It manifests decline reaction for $\beta^* = 1.1, 2.7, 3.5, 4.1$. Temperature curve $\theta_1(\eta)$ according to individual values of squeezed flow index $b$ is depicted in Fig. 9. Temperature field $\theta_1(\eta)$ reveals dwindle response for $b = 0.1, 0.2, 0.3, 0.4$. Fig. 10 shows the effects of curie temperature $g$ on temperature account $\theta_1(\eta)$. It illustrates rising response for $g = 0.01, 1.5, 2.5, 3.1$. Fig. 11 displays the reaction of small parameter $\epsilon$ on temperature curve $\theta_1(\eta)$. Temperature profile $\theta_1(\eta)$ verifies growing reaction for $\epsilon = 0.1, 0.9, 2.1, 3.5$. Fig. 12 manifests diminishing response of temperature field $\theta_1(\eta)$ for $\delta = 1.1, 1.15, 1.25, 1.5$. Fig. 13 signifies the reaction of temperature account $\theta_1(\eta)$ according to escalating values of $\lambda$. Temperature curve $\theta_1(\eta)$ manifests reducing manner for $\lambda = 0.01, 1.2, 2.3, 3.1$. Fig. 14 expresses the impact of $Pr$ on temperature field $\theta_1(\eta)$. It reveals depletion for $Pr = 7.1, 8.5, 10.7, 13.1$. Temperature field $\theta_1(\eta)$ according to different values of $R$ is explicated in Fig. 15. Temperature profile manifests increasing performance for $R = 0.1, 0.5, 1.0, 1.5$. Ferrohydrodynamic interaction parameter $\beta^*$ on temperature field $\theta_1(\eta)$ is manifested in Fig. 16. Temperature curve $\theta_1(\eta)$ reveals decline reaction for $\beta^* = 0.01, 1.2, 2.0, 2.8$. Fig. 17 indicates the impact of squeezed flow index $b$ on temperature curve $\theta_2(\eta)$. It determines expanding behavior for $b = 0.1, 0.3, 0.5, 0.7$. Fig. 18 indicates the escalating reaction of temperature curve $\theta_2(\eta)$ for $g = 1.1, 1.3, 1.5, 1.7$. Fig. 19 demonstrates the performance of temperature account $\theta_2(\eta)$ for distinct values of small parameter $\epsilon$. Temperature account $\theta_2(\eta)$ determines accumulating response for $\epsilon = 0.1, 0.8, 1.6, 2.4$. Fig. 20 illustrates the behavior of temperature profile $\theta_2(\eta)$ for divergent values of $\delta$. Temperature curve manifests reducing reaction for $\delta = 1.1, 1.15, 1.2, 1.26$. Fig. 21 expresses the increasing manner of temperature profile $\theta_2(\eta)$ for $\lambda = 0.11, 0.12, 0.13, 0.14$. Temperature account $\theta_2(\eta)$ for individual values of $Pr$ is demonstrated in Fig. 22. Temperature curve $\theta_2(\eta)$ expresses dwindle performance for $Pr = 7.1, 8.1, 9.6, 11.4$. Fig. 23 displays the effects of $R$ on temperature field $\theta_2(\eta)$. It exhibits reducing response of temperature profile $\theta_2(\eta)$ for $R = 0.1, 0.4, 0.9, 1.5$. Fig. 24 depicts the increasing reaction of temperature account $\theta_2(\eta)$ for $\beta^* = 0.5, 0.6, 0.7, 0.8$. Fig. 25 exhibits skin friction curve performance according to escalating values of $n$ and $b$. Fig. 26 illustrates increasing manner of skin friction curve for escalating values of $b$ and $W_e$. Figs. 27-29 manifest the response of three dimensional curve for $b = 3, 5, 7$. Figs. 30-32 indicate the reaction of stream lines performance for $b = 3, 5, 7$. Table 1 expresses increasing values of skin friction coefficient according to parameters $b, n$ and $W_e$. Table 2 depicts skin friction coefficient values for $b, W_e$ and $n$. 

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Fig. 2. Response of velocity curve for divergent values of $S_1$.

Fig. 3. Behavior of velocity curve for divergent values of $b$. 
Fig. 4. Behavior of velocity curve for divergent values of $\delta$.

Fig. 5. Behavior of velocity curve for divergent values of $n$. 
Fig. 6. Behavior of velocity curve for divergent values of $S_2$.

Fig. 7. Behavior of velocity curve for divergent values of $W_e$. 

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Fig. 8. Response of velocity curve for divergent values of $\beta^*$. 

Fig. 9. Performance of temperature curve $\theta_1(\eta)$ for contrary values of $b$. 
Fig. 10. Performance of temperature curve $\theta_1(\eta)$ for contrary values of $g$.

Fig. 11. Performance of temperature curve $\theta_1(\eta)$ for contrary values of $\epsilon$. 

\[ \epsilon = 20.4, \beta = 6.1, \delta = 0.001, \delta = 1.1, \lambda = 7.1 \]

\[ g = 0.1, R = 0.005, \beta = 7.1, \beta = 0.04, b = 0.2, \delta = 1.3, \lambda = 4.1 \]
Fig. 12. Performance of temperature curve $\theta_1(\eta)$ for contrary values of $\delta$.

Fig. 13. Performance of temperature curve $\theta_1(\eta)$ for contrary values of $\lambda$. 
Fig. 14. Performance of temperature curve $\theta_1(\eta)$ for contrary values of $Pr$.

Fig. 15. Performance of temperature curve $\theta_1(\eta)$ for contrary values of $R$. 
Fig. 16. Performance of temperature curve \( \theta_1(\eta) \) for contrary values of \( \beta^* \).

Fig. 17. Performance of temperature field \( \theta_2(\eta) \) for escalating values of \( b \).
Fig. 18. Performance of temperature field $\theta_2(\eta)$ for escalating values of $g$.

Fig. 19. Performance of temperature field $\theta_2(\eta)$ for escalating values of $\epsilon$. 
Fig. 20. Performance of temperature field $\theta_2(\eta)$ for escalating values of $\delta$.

Fig. 21. Performance of temperature field $\theta_2(\eta)$ for escalating values of $\lambda$. 
Fig. 22. Performance of temperature field $\theta_2(\eta)$ for escalating values of $Pr$.

Fig. 23. Performance of temperature field $\theta_2(\eta)$ for escalating values of $R$. 
Fig. 24. Performance of temperature field $\theta_2(\eta)$ for escalating values of $\beta^*$. 

Fig. 25. Behavior of skin friction curve for contrary values of $n$ and $b$. 
Fig. 26. Skin friction curve for individual values of $b$ and $W_e$.

Fig. 27. Three-dimensional demonstration for $b = 3$. 

\[ b = 3 \]
Fig. 28. Three dimensional demonstration for $b = 5$.

Fig. 29. Three dimensional demonstration for $b = 7$.
Fig. 30. Stream lines demonstration for $b = 3$.

Fig. 31. Stream lines demonstration for $b = 5$. 
Fig. 32. Stream lines demonstration for $b = 7$.

Table 1. Values of skin friction coefficient according to $b$, $W_e$ and $n$.

<table>
<thead>
<tr>
<th>$b$</th>
<th>$W_e$</th>
<th>$n$</th>
<th>$C_{f_x} R_{e_x}^{1/2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>1.2</td>
<td>1.1</td>
<td>2.077131</td>
</tr>
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<td>2.098540</td>
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<td>2.117344</td>
</tr>
<tr>
<td>0.1</td>
<td>1.6</td>
<td></td>
<td>2.160822</td>
</tr>
</tbody>
</table>

Table 2. Values of skin friction coefficient according to $b$, $n$ and $W_e$.

<table>
<thead>
<tr>
<th>$b$</th>
<th>$n$</th>
<th>$W_e$</th>
<th>$C_{f_x} R_{e_x}^{1/2}$</th>
</tr>
</thead>
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<td>0.1</td>
<td>1.33</td>
<td>7.1</td>
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</tr>
<tr>
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<td>1.35</td>
<td></td>
<td>10.928646</td>
</tr>
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5 Closing Remarks

In this paper Darcy’s flow of Carreau ferro magnetic fluid using a sensor surface was investigated numerically in residence of magnetic dipole and thermal radiation effects. Some
important findings from the computed results are elaborated below:

1. Velocity curve decayed for escalating values of \( n, W_e \) and \( \beta^* \) on the other hand it enhances for expanding values of \( b, S_1, \delta, \) and \( S_2. \)

2. For increasing values of \( \epsilon \) and \( R \) temperature curve \( \theta_1(\eta) \) rises whereas for growing values of \( b, g, \delta, \lambda, \) Pr and \( \beta^* \) temperature curve \( \theta_1(\eta) \) drops.

3. Temperature profile \( \theta_2(\eta) \) increase for extended values of \( b, g, \epsilon, \lambda \) and \( \beta^*. \)

4. Skin friction curve explicates increasing response for \( b \) and \( n \) as well as for \( b \) and \( W_e. \)

**References**


