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EFFECTS OF HALL CURRENT ON DARCY-FORCHHEIMER MHD MIXED CONVECTIVE FLOW OVER A VERTICAL SURFACE WITH ROTATION IN POROUS MEDIUM

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The analysis of Darcy-Forchheimer MHD flow has been a concern of consideration for research scientists and engineers. This work examines the unsteady hydrodynamic mixed convective flow of an incompressible, viscous, electrically conducting fluid as well as the transfer of heat and mass in a vertical surface with the Hall current, rotation, and Darcy-Forchheimer effect. Through similarity transformation, the dimensionless unstable governing equation is found. Then, using the Matlab method bvp4c, the similarity ordinary differential equation was solved. When the solution and those produced by Elgazery and Stanford were compared to the numerical result for a few exceptional circumstances, there was a fair degree of agreement. Graphs are used to show the temperature, concentration, and fluid velocity. In contrast, skin friction, the Sherwood number, and the Nusselt number are calculated in tabular form.

Keywords: *Hall current; Rotation; Darcy Forchheimer; Mixed convection; Bvp4c*

PACS: 44.25.+f, 44.27.+g, 33.20.Vq, 44.30.+v, 44.40.+a

1. INTRODUCTION

The study of Darcy-Forchheimer magnetohydrodynamic (MHD) flow has become significant in understanding complex fluid dynamics influenced by magnetic fields, rotation, and porous medium. MHD flow involves electrically conducting fluids interacting with magnetic fields, which is particularly relevant in engineering and environmental applications. The Hall current effect, rotation, and Darcy-Forchheimer effects play crucial roles in influencing the velocity, temperature, and concentration of such flows. This study aims to explore the dynamics of unsteady MHD mixed convective flow over a vertical surface, considering the Hall current and rotation in a porous medium, using numerical solutions. The findings can be applied to various practical scenarios, including polymer processing, metal casting, and natural convection in porous media, providing deeper insights into fluid behavior under the influence of electromagnetic forces. Sarma and Sarma (2024) [1] explored unsteady magnetohydrodynamic (MHD) bioconvection Casson fluid flow with gyrotactic microorganisms over a vertically stretched sheet. Samad and Rahman (2006) [2] studied the interaction of thermal radiation with unsteady MHD flow over a vertical porous plate in a porous medium. Mukhopadhyay and Layek (2009)[3] investigated the effects of radiation on forced convective flow and heat transfer over a porous plate within a porous medium. Later, Mukhopadhyay et al. (2012) [4] extended the study to forced convective flow and heat transfer in a Darcy-Forchheimer porous medium in the presence of radiation. Khan et al. (2022) [5] focused on MHD thin-film flow through a porous stretching sheet, considering the impact of thermal radiation and viscous dissipation. Panya et al. (2023) [6] analyzed MHD Darcy-Forchheimer slip flow in a porous medium with variable thermophysical properties. Reddy et al. (2021) [7] examined the chemical reaction impact on MHD natural convection flow through porous media around an exponentially stretching sheet, including the effects of heat sources/sinks and viscous dissipation. Sakiadis (1961)[8] initiated the study of boundary-layer behavior on continuous solid surfaces, forming the foundational equations for two-dimensional and axisymmetric flow. Crane (1970) [9] provided an analytical solution for the boundary layer equation concerning steady two-dimensional flow over a stretched surface in an incompressible fluid. Nayak et al. (2014, 2016)[10][11][12] conducted two studies focusing on the effects of chemical reactions on MHD flow of visco-elastic fluids through porous media and on steady MHD flow and heat transfer with a third-grade fluid during wire coating, considering temperature-dependent viscosity. Vafai and Tien (1982)[13] emphasized boundary and inertia effects on convective mass transfer in porous media. Hong et al. (1987)[14] investigated non-Darcian and non-uniform porosity effects on vertical plate natural convection in porous media. Jumah et al. (2001)[15] examined Darcy-Forchheimer mixed convection heat and mass transfer in fluid-saturated porous media. Chamkha (1997)[16] explored hydromagnetic natural convection from an isothermal inclined surface adjacent to a thermally stratified porous medium. Elgazery (2009)[17] assessed the effects of chemical reactions, Hall and ion-slip currents on MHD flow, considering temperature-dependent viscosity and thermal diffusivity. Kinyanjui et al. (2001)[18] looked at MHD free convection heat and mass transfer of heat-generating fluids past an impulsively started vertical porous plate with Hall current and radiation absorption. Shateyi et al. (2010)[19] examined the effects of thermal radiation, Hall currents, and Soret and Dufour effects on MHD flow over a vertical surface within porous media.

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Singh (1984)[20] analyzed Hall effects on MHD free-convection flow past an accelerated vertical porous plate. Sarma and Pandit (2015)[21] investigated thermal radiation and chemical reaction effects on steady MHD mixed convective flow over a vertical porous plate with induced magnetic fields. Sattar and Kalim (1996)[22] studied the interaction between boundary-layer flow and thermal radiation under unstable free convection past a vertical porous plate. Nandkeolyar et al. (2013) [23] provided exact solutions for unsteady MHD free convection in a heat-absorbing fluid flow over a flat plate with ramped wall temperature. Chamkha (1997)[24] again discussed MHD-free convection from a vertical plate within a thermally stratified porous medium while including Hall effects. Abo-Eldahab and Salem (2004)[25] explored Hall effects on MHD free convection flow of non-Newtonian power-law fluids over a stretching surface. Siddiqa et al. (2013)[26] investigated Hall current effects on magnetohydrodynamic natural convection flow with a strong cross-magnetic field. Seth and Singh (2016) [27] provided a solution for mixed convection hydromagnetic flow in a rotating channel considering Hall and wall conductance effects. Kumar et al. (2020) [28] studied the influence of heat sources/sinks on MHD flow between alternating conducting walls, incorporating Hall effects. Finally, Pandit and Sarma (2017) [29] explored the combined effects of Hall current and rotation on unsteady MHD natural convection flow past a vertical flat plate with ramped wall temperature and heat absorption. This structure highlights the advancements in the field of MHD flow and heat and mass transfer under various conditions, including the effects of magnetic fields, chemical reactions, Hall current, rotation, Darcy-Forchheimer effect and porous media considerations.

Motivated by the above investigations, the influences of the Hall current, soret and Dufour effect with chemical reaction and rotation on Darcy Forchheimer MHD mixed convective flow over a vertical surface are studied. The transformed dimensionless governing equations are solve by bvp4c method. The effect of various physical parameter on velocity, temperature and concentration profile are studied in details. Also the value Skin friction, Nuslet number and sherwood number for different parameters are shown in table.

2. MATHEMATICAL FORMULATION

We examine the dynamics of an unsteady flow in an electrically conducting, viscous fluid that involves mass and heat transfer. The flow passes across a vertical flat plate that is semi-infinite in length, rotated, and immersed in a homogenous porous media. Furthermore, the effect of Hall current is considered. Think of a coordinate system (x,y,z) in which the vertical plate and the x-axis are in line. with the y-axis perpendicular to it and pointing upward. Around the y-axis, the fluid and plate rotate at a constant angular velocity Ω. The front border of the plate and the z-axis line up. A homogeneous transverse magnetic field of intensity B_0 applied in the y direction causes the fluid to become saturated, as shown in Fig 1. The flow is three-dimensional because of the force that the Hall current effect creates in the z direction, which results in a cross flow velocity. Considering Hall currents,

The following is the format of generalized Ohm's law:

$$J = \frac{\sigma}{1+m^2}\left(E + (V \times B) - \frac{1}{\sigma n_e} J \times B\right)$$

The equation includes the magnetic induction vector (B), electric field intensity vector (E), electric current density vector (J), Hall current parameter (m), velocity vector (V), electrical conductivity (σ), and electron density (n_e).

The governing equation in (x,y,z)-coordinates may be expressed as follows under the standard boundary layer and Boussinesq approximations:

$$\frac{\partial u}{\partial t} + 2\Omega w + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = \nu\frac{\partial^2 u}{\partial y^2} - \frac{\sigma B_0^2}{\rho(1+m^2)}(u+mw) + g\beta_c(C - C_\infty) + g\beta_t(T - T_\infty) - \frac{\nu}{K_p}u - \frac{K^*}{\sqrt{K_p}}u^2 \quad (1)$$

$$\frac{\partial w}{\partial t} + 2\Omega u + u\frac{\partial w}{\partial x} + v\frac{\partial w}{\partial y} = \nu\frac{\partial^2 w}{\partial y^2} + \frac{\sigma B_0^2}{\rho(1+m^2)}(mu - w) - \frac{\nu}{K_p}w - \frac{K^*}{\sqrt{K_p}}w^2 \quad (2)$$

$$\frac{\partial T}{\partial t} + u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \frac{k}{\rho c_p}\frac{\partial^2 T}{\partial y^2} + \frac{D_M K_T}{c_s c_p}\frac{\partial^2 C}{\partial y^2} + \frac{\sigma B_0^2}{\rho c_p(1+m^2)}(u^2 + w^2) - \frac{1}{\rho c_p}\frac{\partial q_r}{\partial y} \quad (3)$$

$$\frac{\partial C}{\partial t} + u\frac{\partial C}{\partial x} + v\frac{\partial C}{\partial y} = D\frac{\partial^2 C}{\partial y^2} + \frac{D_M K_T}{T_m}\frac{\partial^2 T}{\partial y^2} \quad (4)$$

The boundary conditions are,

$$\begin{gathered} u(x,0) = U_s = \frac{A_0 x}{1-ct}, \;\; v(x,0) = -V_w, \;\; w(x,0) = 0, \;\; T(x,0) = T_w, \;\; C(x,0) = C_w \\ u(x,\infty) = w(x,\infty) = 0 \quad T(x,\infty) = T_\infty \quad C(x,\infty) = C_\infty \end{gathered} \quad (5)$$

Where u,v and w represent the components of fluid velocity along the x-,y-,and z-axes, respectively. The fluid temperature and concentration are represented by T and C, respectively. These variables are commonly used in physics to describe fluid properties: ν represents kinematic viscosity, μ represents dynamic viscosity, ρ represents fluid density, g represents gravitational force due to acceleration, and β_t represents the coefficient of volume expansion. β_c represents the volumetric coefficient of expansion when concentration is taken into account, while B_0 denotes the constant magnetic field. Strength is determined by the coefficient of mass diffusivity D, c_p is the specific heat at constant pressure. c_s is the Concentration susceptibility, T_m represents the average fluid temperature, K_T denotes the thermal diffusion ratio, and k is The fluid's thermal conductivity, K_p is the medium's permeability, and the Hall parameter m, are all important factors to consider.

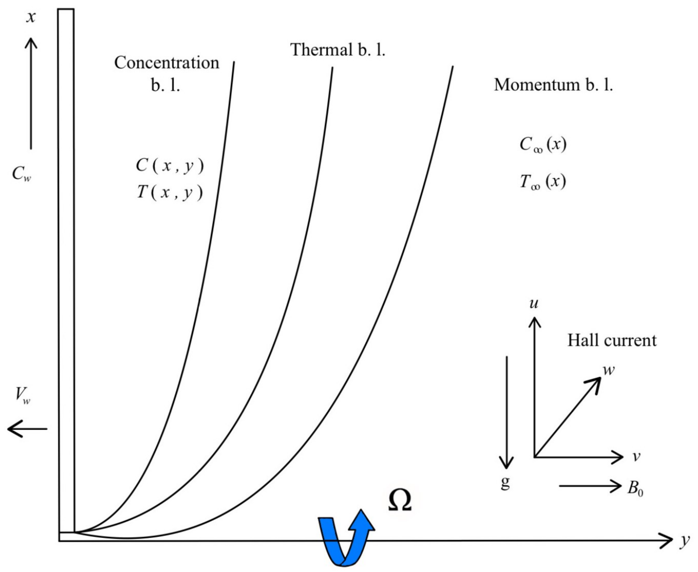

Figure 1. The coordinate system for the physical model of the problem

U_s is the surface velocity, A_0 is a constant with dimension $(time)^{-1}$, V_w, T_w and C_w are suction or injection velocity, temperature and concentration at the plate respectively. By using Rosseland approximation for thermal radiation, the radiative heat flux is modeled as,

$$q_r = -\frac{4\sigma_1}{3k_1}\frac{\partial T^4}{\partial y}$$

where k_1 is the mean absorption coefficient and σ_1 is the Stefan Boltzmann constant. Following Chamkha [16] it is assumed that T^4 can be stated as a linear function of temperature since the temperature difference within the flow are thought to be sufficiently small. This is achieved by omitting higher order terms and expanding T^4 in a Taylor series around T_∞, thus

$$T^4 \approx 4T_\infty^3 T - 3T_\infty^4$$

and thus the gradient of heat radiation term can be expressed as

$$\frac{\partial q_r}{\partial y} = -\frac{16\sigma_1 T_\infty^3}{3k_1}\frac{\partial^2 T}{\partial y^2}$$

Following [17] We nondimensionalize (1)-(4) using the following transformation,

$$\eta = \sqrt{\frac{A_0}{\nu(1-ct)}}y, \;\; u = \frac{A_0 x}{(1-ct)}f'(\eta), \;\; v = -\sqrt{\frac{A_0\nu}{(1-ct)}}f(\eta), \;\; w = \sqrt{\frac{A_0\nu}{(1-ct)}}h(\eta)$$
$$U_s = \frac{A_0 x}{(1-ct)}, \;\; \theta(\eta) = \frac{T-T_\infty}{T_w-T_\infty}, \;\; \phi(\eta) = \frac{C-C_\infty}{C_w-C_\infty} \tag{6}$$

where $f(\eta)$,$h(\eta)$,$\theta(\eta)$ and $\phi(\eta)$ are dimensional stream functions, temperature and concentration distribution function respectively.

Substituting (6) into (1)-(4) we get the following similarity equations,

$$U_n(f' + \frac{1}{2}\eta f'') + 2K^2\sqrt{Re}f'^2h + f'^2 - ff'' = f''' - \frac{M}{1+m^2}(f' + \frac{m}{\sqrt{Re}}h) + Gm\phi + Gr\theta - Spf' - Ff'^2 \quad (7)$$

$$\frac{1}{2}U_n(\eta h' + h) - 2K^2Re^{\frac{3}{2}}f'^3 + fh' = h'' + \frac{M}{1+m^2}(mf' - \frac{1}{Re}h) - Sph - F\frac{1}{Re}h^2 \quad (8)$$

$$U_n(\frac{1}{2}\eta\theta' + \theta) + \theta f' - f\theta' = (1 + \frac{4}{3N})\frac{1}{Pr}\theta'' + Du\phi'' + \frac{M}{1+m^2}Ec(f'^2 + \frac{1}{Re}h^2) \quad (9)$$

$$U_n(\frac{1}{2}\eta\phi' + \phi) + \phi f' - f\phi' = \frac{1}{Sc}\phi'' + Sr\theta'' \quad (10)$$

The transformed boundary conditions are as follows,

$$\begin{aligned} f(0) = f_w,\ \ f'(0) = 1,\ \ h(0) = 0,\ \ \theta(0) = 1,\ \ \phi(0) = 1\ \ as\ \ \eta \to 0 \\ f'(\infty) = 0,\ \ h(\infty) = 0,\ \ \theta(\infty) = 0,\ \ \phi(\infty) = 0\ \ as\ \ \eta \to \infty \end{aligned} \quad (11)$$

where the primes denote differentiation with respect to η. Where $M = \frac{\sigma B_0^2(1-ct)}{\rho A_0}$ is the magnetic parameter, $Re = \frac{xU_s}{\nu}$ is the Reynolds number, $K^2 = \frac{\nu\Omega}{u^2}$ is the Rotation parameter, $Gr = \frac{g\beta_t(T_w-T_\infty)(1-ct)}{U_sA_0}$ is the Local Grashof number, $Gm = \frac{g\beta_c(C_w-C_\infty)(1-ct)}{U_sA_0}$ is the Local modified Grashof number, $Sp = \frac{\nu(1-ct)}{A_0Kp}$ is the Permeability parameter, $Pr = \frac{\mu c_p}{k}$ is the Prandtl number, $Ec = \frac{{U_s}^2}{c_p(T_w-T_\infty)}$ is the Eckert number, $Du = \frac{D_MK_T(C_w-C_\infty)}{\nu c_s c_p(T_w-T_\infty)}$ is the Dufour number, $Sc = \frac{\nu}{D}$ is the Schmidt number, $Sr = \frac{D_MK_T(T_w-T_\infty)}{\nu T_m(C_w-C_\infty)}$ is the Soret number.

3. METHOD OF SOLUTION

A MATLAB boundary value problem solver named bvp4c was used to solve the equations (7), (8), (9), and (10) subject to boundary conditions (11). Using bvp4c, almost any BVP may be prepared for solution. The present result for the coefficient of skin friction $-f''(0)$ with different values of $k_p = \frac{1}{S_p}$ are compared with the Elgazery [17] and the Stanford [30] result. It is seen from Table 1, the obtained numerical result using bvp4c method are in an excellent agreement with those published previously. m=Gr=Gm=0, fw = -0.7, and M=1 were used to construct Table 1.

Table 1. Values of the skin friction $-f''(0)$, the present method, result of Elgazery [17] and the Stanford [30]

k_p	Elgazery [17]	Stanford Shateyi[30]	Present work
1	1.4170	1.4170	1.4171
2	1.2694	1.2694	1.2694
5	1.1739	1.1739	1.1740
10	1.1408	1.1408	1.1408
15	1.1295	1.1295	1.1294

4. RESULTS AND DISCUSSION

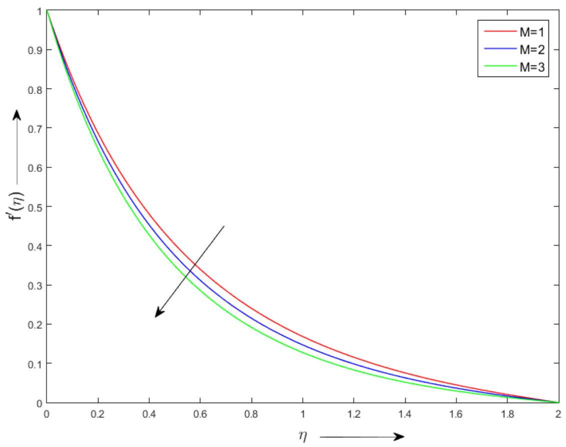

Figure 2
Variation of tangential velocity distribution with increasing Magnetic parameter M.

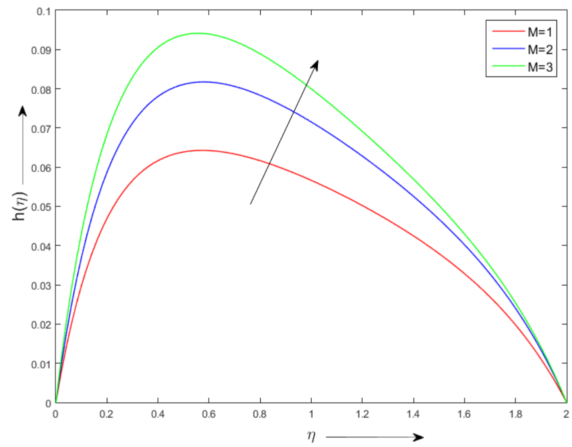

Figure 3
Variation of lateral velocity distribution with increasing Magnetic parameter M..

Figures 2 and 3 show how the magnetic parameter affects tangential and lateral velocity. The tangential velocity falls with increasing magnetic parameter. The Lorentz force causes a reduction in the tangential velocity in the direction of flow. The fluid particles slow down and decrease their sideways speed due to the magnetic field's force, which works at a right angle to the direction of flow. On the other hand, the lateral velocity rises with the magnetic parameter. The Lorentz force causes an increase in the lateral velocity perpendicular to the flow direction. The fluid particles experience lateral deflection due to the magnetic field, which raises their lateral velocity. A magnetic field produces a narrow boundary layer close to the wall, where there is a noticeable velocity gradient, which raises the lateral velocity.

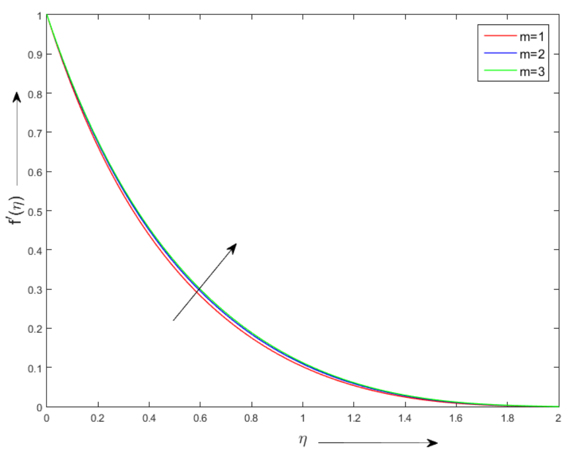

Figure 4
Variation of tangential velocity distribution with increasing Hall parameter m.

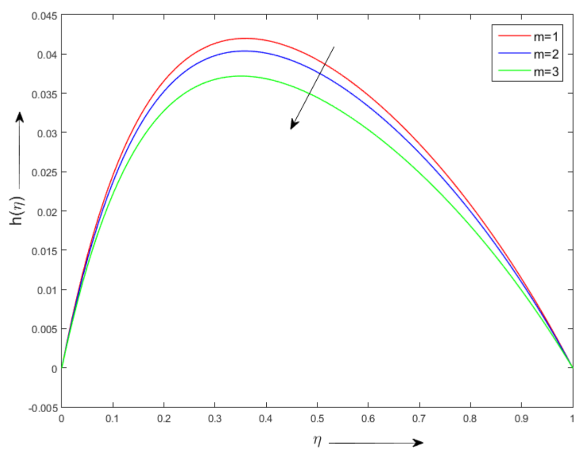

Figure 5
Variation of lateral velocity distribution with increasing Hall parameter m.

Figures 4 and 5 illustrate the effect of the Hall current parameter on tangential and lateral velocity. As the Hall current parameter increases, the tangential velocity also increases. The tangential velocity increases as a result of the force generated by Hall current, which accelerates the fluid particles in the direction of flow. On the other hand, the lateral velocity decreases as a result of the Hall current. Due to the Hall current, the fluid particle is deflected in the opposite direction, resulting in a decrease in lateral velocity.

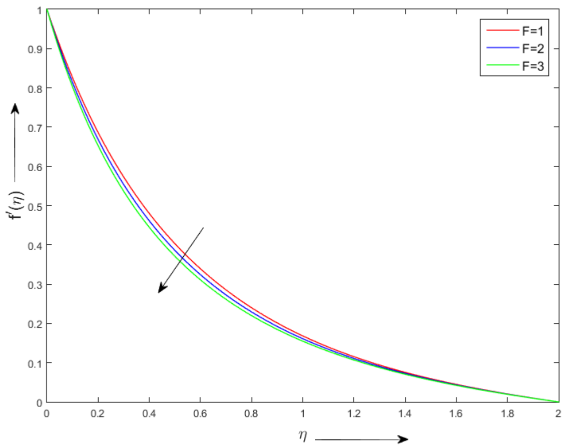

Figure 6
Variation of tangential velocity distribution with increasing Darcy-Forchheimer Parameter.

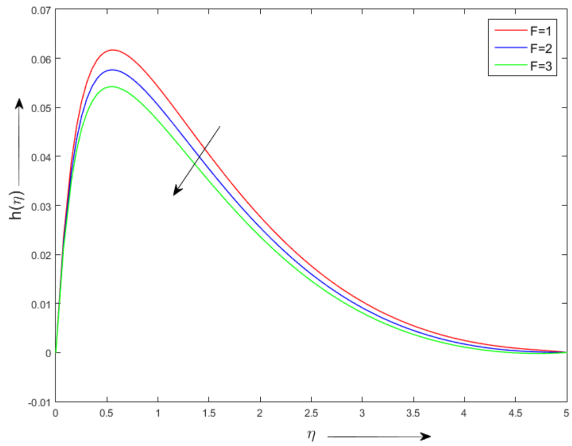

Figure 7
Variation of lateral velocity distribution with increasing Darcy-Forchheimer Parameter.

Figures 6 and 7 demonstrate the impact of the Darcy-Forchheimer number on the tangential and lateral velocity. The Darcy-Forchheimer number plays a significant role in the flow dynamics, causing greater resistance, increased viscous effects, decreased inertial effects, and overall flow stabilization. All of these factors contribute to a reduction in both tangential and lateral velocities.

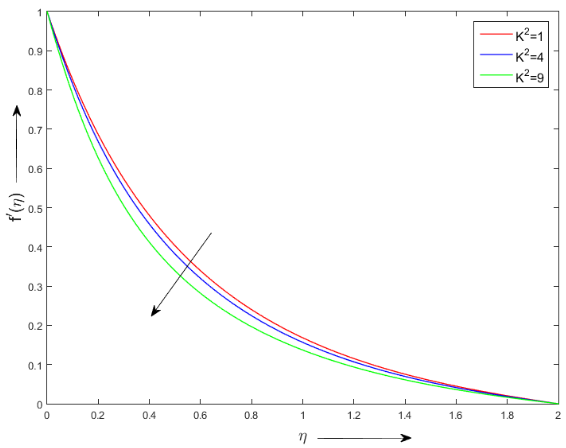

Figure 8
Variation of tangential velocity distribution with increasing Rotation parameter K^2.

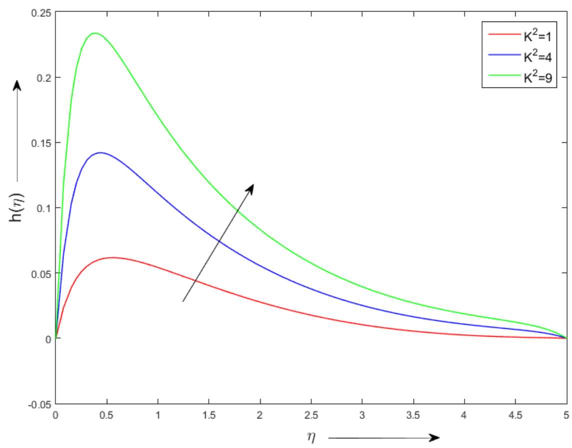

Figure 9
Variation of lateral velocity distribution with increasing Rotation parameter K^2.

Figures 8 and 9 show how the rotation parameter affects tangential and lateral velocity. From figure it is observed that tangential velocity decreases with increasing the rotation parameter whereas lateral velocity increases with increasing the rotation parameter. The coriolis force which results from rotation acts perpendicular to both the direction of motion and axis of rotation. In this fluid flow it tends to deflect the fluid particle away from the original path. As rotation parameter increase, the coriolis force become stronger, deflecting the fluid particles more towards the lateral direction. This results in increase in lateral velocity. The Coriolis force can also oppose the tangential flow, especially near the boundaries. This can lead to decrease in tangential velocities, particularly in the boundary layer region. The coriolis force can significantly affect the boundary layer leading to a thicker boundary layer and reduced tangential velocity.

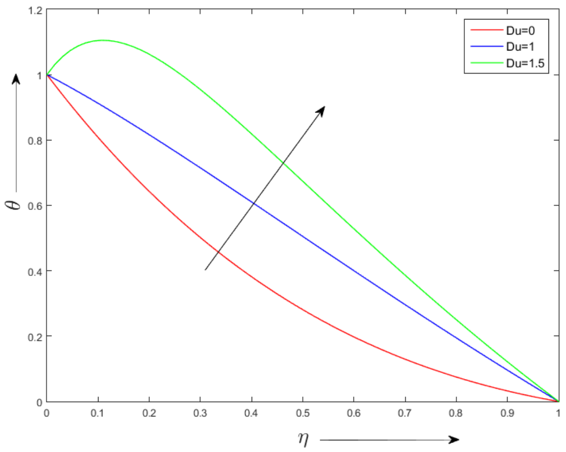

Figure 10
Variation of temperature distribution with increasing Dufour number Du.

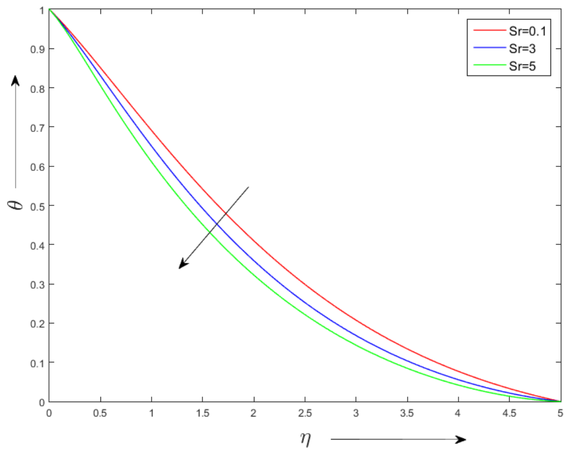

Figure 11
Variation of temperature distribution with increasing Soret number Sr.

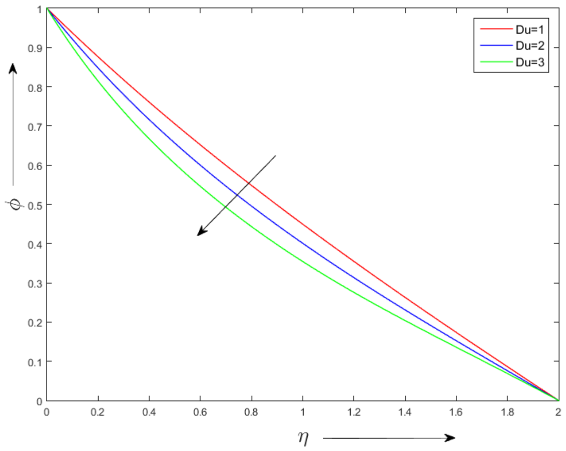

Figure 12
Variation of Concentration distribution with increasing Dufour number Du.

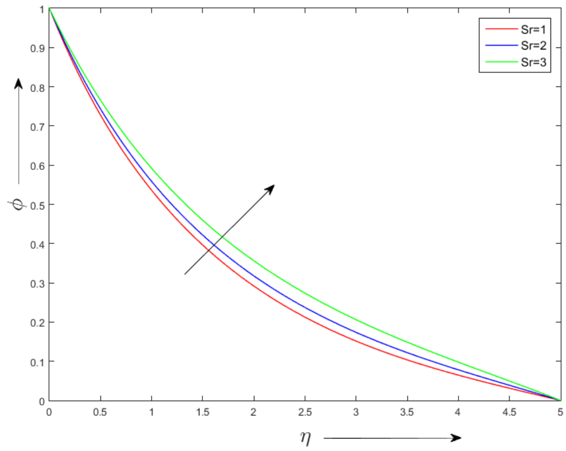

Figure 13
Variation of Concentration distribution with increasing Soret number Sr.

Figures 10 and 12 demonstrate the impact of temperature and concentration as the Dufour number increases. The Dufour effect illustrates how concentration gradients can impact heat transfer. As the Dufour number increases, the heat transfer caused by the concentration gradient becomes more significant, resulting in a rise in temperature. On the other hand, the heightened heat transfer resulting from the Dufour effect causes a reduction in concentration. The heat transfer plays a crucial role in enhancing the diffusion of species, which in turn leads to a reduction in concentration gradients.

Figures 11 and 13 demonstrate the impact of temperature and concentration as soret number rises. The soret effect illustrates the effects of temperature gradient on mass transport. As soret number grows, the mass transfer owing to temperature gradient becomes more substantial, resulting to decrease in temperature. This is because the soret effect promotes the transmission of heat from the system, cooling it down. Conversely the enhanced mass transfer owing to the soret effect leads to an increase in concentration. This is because the soret effect pushes the migration of species towards the colder zone, increasing the concentration gradients.

Table 2 illustrates the influence of M, Pr, m, F, K^2, Du, Sr on the coefficient of skin friction, sherwood number and nuslet number. From the table we observe that as M, Pr, F, K^2 increase the value of skin friction increases but it shows opposite effect with the rise in m, Du and Sr.
Also, Nuslet number rises with enlarged values of Pr and m while it shows opposite result with the increasing value of M, F, K^2, Du, Sr.

Also, it can be seen that Sherwood number rises with enlarged values of M and Du while it shows opposite result with increasing the value of Pr, m, F, K^2 and Sr.

Table 2. Variations of $-f''$,$-\theta'$, $-\phi'$ for different parameters.

M	Pr	m	F	K^2	Du	Sr	$-f''$	$-\theta'$	$-\phi'$
1							1.9434	2.0538	1.1698
2							2.0987	2.0188	1.1708
3							2.2478	1.9867	1.1714
	1						1.9466	2.1022	1.1466
	2						1.9577	2.2856	1.0587
	3						1.9651	2.4944	0.9589
		1					1.9434	2.0538	1.1698
		2					1.8567	2.0746	1.1682
		3					1.8239	2.0825	1.1678
			1				1.9434	2.0538	1.1698
			2				2.1152	2.0430	1.1646
			3				2.2754	2.0333	1.1601
				1			1.9434	2.0538	1.1698
				2			2.0694	2.0404	1.1643
				3			2.3809	2.0118	1.1528
					0.7		1.8953	1.4157	1.4775
					0.8		1.8721	1.0670	1.6446
					0.9		1.8492	0.6936	1.8229
						0.5	1.9434	2.0538	1.1698
						1	1.8591	1.3277	1.1382
						1.5	1.8271	1.0849	1.0980

5. CONCLUSION

In this work, the effect of Hall current, Darcy Forchheimer effect on an unsteady MHD mixed convective flow with rotation in porous medium is investigated. The resulting partial differential equations with boundary condition were transformed to a set of ordinary differential equation by using similarity transformation. The bvp4c method is used to obtain the numerical solution. Graphical results were obtained to illustrate the details of flow and their dependence on some physical parameter.

In conclusion, the magnetic parameter reduces tangential velocity while increasing lateral velocity due to the influence of the Lorentz force. The Hall parameter has a contrasting effect, enhancing tangential velocity while reducing lateral velocity. The Darcy-Forchheimer parameter decreases both tangential and lateral velocities, indicating increased resistance and stabilized flow in the porous medium. The rotation parameter lowers tangential velocity but boosts lateral velocity due to Coriolis force. Furthermore, an increase in the Dufour number leads to a rise in temperature and a reduction in concentration, while an increase in the Soret number decreases temperature but raises concentration. Coefficient of skin friction increases with increasing M, Pr, F, K^2 increase but decreases with increasing m, Du and Sr. With increasing Pr and m, the value of Nuslet number increases but decreases with increasing M, F, K^2, Du, Sr. Sherwood number increases with increasing M and Du but decreases with increasing Pr, m, F, K^2 and Sr. These findings highlight the significant impact of magnetic fields, rotation, and porous medium properties on fluid flow dynamics, temperature, and concentration distributions.

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ВПЛИВ СТРУМУ ХОЛЛА НА ЗМІШАНИЙ КОНВЕКТИВНИЙ ПОТІК ДАРСІ-ФОРХГЕЙМЕРА ПО ВЕРТИКАЛЬНІЙ ПОВЕРХНІ З ОБЕРТАННЯМ У ПОРИСТОМУ СЕРЕДОВИЩІ

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Аналіз МГД-потоку Дарсі-Форхгеймера був предметом занепокоєння вчених-дослідників та інженерів. У цій роботі розглядається нестаціонарний гідродинамічний змішаний конвективний потік нестисливої, в’язкої, електропровідної рідини, а також перенесення тепла та маси у вертикальній поверхні за допомогою струму Холла, обертання та ефекту Дарсі-Форхгеймера. Шляхом перетворення подібності знайдено безрозмірне нестійке керуюче рівняння. Потім за допомогою методу Matlab Bvp4c було розв’язано звичайне диференціальне рівняння подібності. Коли отримані рішення та рішення, отримані Елгазері та Стенфордом, порівняли з чисельним результатом для кількох виняткових обставин, виявилося досить значне збіг. Графіки використовуються для відображення температури, концентрації та швидкості рідини. Навпаки, тертя шкіри, число Шервуда і число Нуссельта розраховуються в табличній формі.

Ключові слова: *струм Холла; обертання; Дарсі Форххаймер; змішана конвекція; bvp4c*