

Study of the Flow Response of a Chiral Fluid Confined in a Channel in the Presence of the Transverse Magnetic Field

Nagaraju^{1*}, B.M Rajaprakash² and G.K. Suresh³

¹Department of Mechanical Engineering, Siddaganga Institute of Technology, Tumkur-561202, Karnataka, India, nagsit@gmail.com,

² Department of Mechanical Engineering, University Visvesvaraya College of Engineering, K.R. Circle-560001, Bangalore, Karnataka, India, bmruvce@yahoo.co.in

³ Department of Electronics and Communication Engineering, Adarsha Institute of Technology, Bangalore-560018, India, porfgksuresh@gmail.com

Abstract

The chiral materials are composed of the chiral molecules or inclusions which have ability to rotate electromagnetic waves or polarized light to a desired angle depending on chirality or handedness of the molecule or inclusions and the length of the medium. Fluids like sugar solution, sugar cane juice, turpentine and most of the body fluids etc are chiral. In recent years considerable attention has been given on the study of effect of chirality of molecules or inclusions on the propagation of electromagnetic waves through chiral medium, fabrication of chiral bio-interface materials, synthesis of chiral drug and chiral polymers. In this regard, present paper is intended to study the flow response of chiral fluid flowing in a vertical channel bounded by rigid permeable boundaries in the presence of applied transverse magnetic field under the influence of viscous dissipation, and convection electric current. The simplified and generalised non-linear momentum and energy equations governing the flow of a chiral fluid confined in a channel are solved for velocity and temperature for various values of dimensionless parameter analytically using the regular perturbation method with buoyancy parameter ' N ' as perturbation parameter and numerically using finite difference method with Successive Over Relaxation (SOR) technique. The results obtained are depicted graphically and found that the resistance to flow of chiral fluid decreases with increase in the transverse magnetic field and the flow reversal occurs with change in the chirality parameter γ from -1 to 1

Keywords: Chiral Fluid, Chirality, Convective Current, Magnetic Field, Vertical Channel

1. Introduction

In this era of modernization considerable interest has been evinced to the study and development of new materials such as: smart materials, nano-materials, chiral materials, biomaterials, meta-materials, composites, different types of polymers and many specialized alloys with a wide variety of properties and characteristics. Among these new materials, chiral materials are the special type of materials having optical activity and cross-coupled electromagnetic constitutive equations. The word chi-

rality refers to a three dimensional object that cannot be brought into congruence with its mirror image by any amount of translation or rotation. Chirality is exhibited in both natural and man-made objects; at micro and macro scales. In micro scale, chiral molecules have an asymmetric centre and because of this, they are able to rotate the light and electromagnetic wave to a specified angle. For instance, fluids like sugar solution, benzene, turpentine, the majority of body fluids and so on exhibit chirality. Recently there has been increasing interest in studying the interaction of electromagnetic field with chiral mate-

*Author for correspondence

rials¹. Extensive literature is available on theoretical and experimental works on the study of wave propagation in solid chiral materials. The propagation of internal electromagnetic waves in an inviscid chiral fluid in the presence of the external constraint of the transverse magnetic field was investigated and shown, that the effect of the external constraint of the magnetic field is analogous to the effect of viscosity in ordinary fluid².

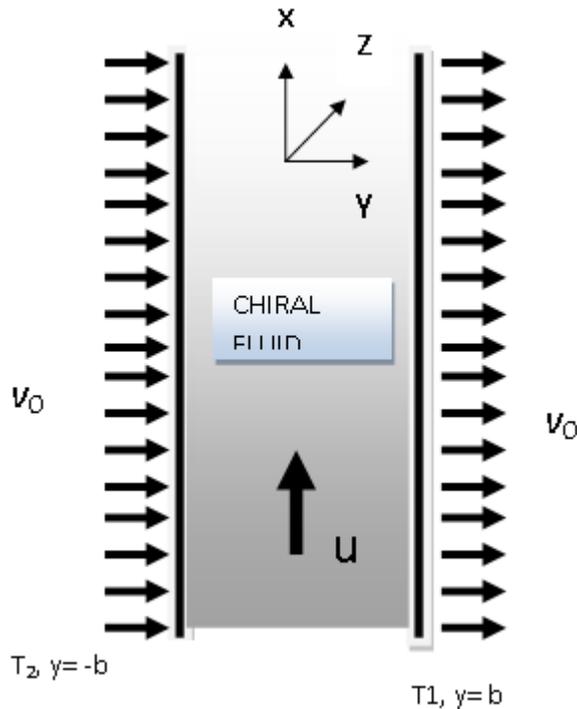


Figure 1. Schematic diagram showing the physical configuration.

The flow response of smart fluids like Magnetorheological fluids (MR fluids), Electrorheological fluids (ER fluids), Ferro-fluids and Nano-fluids confined in a channel in the presence of the external fields such as magnetic field and electric field or both has been studied in the literature using mathematical models^{4,7}. Similarly, The flow response of a poorly electrically conducting fluid confined in a vertical channel was studied in the presence of the applied electric field by solving basic governing equations of the flow both analytically and numerically^{8,9}. In literature much attention has not been given to study the flow response of a chiral fluid in a channel in the presence of the magnetic field, in spite of its importance in many practical applications. Thus, the objective of the present paper is to study the effect of the transverse mag-

netic field on the flow of a chiral fluid in a vertical channel considering only the convection electric current with an intention to study the response of chiral fluid flow under external stimuli of magnetic field and temperature difference. To achieve the above objective, mathematical formulation of the problem along with required basic equations governing the flow of a chiral fluid in the presence of the transverse magnetic field are presented in section 2. Analytical and numerical solutions of simplified and dimensionless governing equations of flow are presented in section 3 and 4 respectively, results are discussed briefly in section 5 and important conclusions are drawn in the final section.

2. Mathematical Formulation

The physical configuration considered for mathematical formulation is shown in Figure 1. It consists of a chiral fluid flow in an infinite vertical permeable channel kept at different temperatures. The temperature of the hotter is T_1 and temperature of the cooler plates is denoted by T_2 . The transverse magnetic field of uniform strength B_0 is applied in the z - direction. For mathematical formulation, a two-dimensional motion is considered with the x -axis along the vertical direction and the y -axis normal to it. Then the required basic equations for a Boussinesq incompressible chiral fluid in the absence of displacement current, induced magnetic field and no induced electric current or field are as follows:

2.1 Basic Equations of Chiral Fluid Flow

The conservation of mass $\nabla \cdot \vec{q} = 0$, (1)

Equation of state for a Boussinesq fluid

$$\rho = \rho_0 (1 - \beta_T (T - T_0)), \quad (2)$$

The modified Navier-Stokes equation, modified in the sense of addition of Lorentz force in the momentum equation is given by

$$\rho_0 \left(\frac{\partial \vec{q}}{\partial t} + (\vec{q} \cdot \nabla) \vec{q} \right) = -\nabla p + \rho_0 \vec{g} + \mu_f \nabla^2 \vec{q} + \vec{J} \times \vec{B} \quad (3)$$

Conservation of energy equation with the addition of viscous dissipation is given by

$$\rho_0 c_p \left(\frac{\partial T}{\partial t} + (\vec{q} \cdot \nabla) T \right) = K \nabla^2 T + \mu_f (\nabla \vec{q})^2 \quad (4)$$

Maxwell's equations

$$\nabla \cdot \vec{E} = \frac{\rho_e}{\epsilon}, \nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t},$$

$$\nabla \times \vec{H} = \vec{J} + \frac{\partial \vec{D}}{\partial t}, \vec{J} = \rho_e \vec{q} + \frac{\partial \vec{D}}{\partial t} \quad (5)$$

Conservation of charges

$$\frac{\partial \rho_e}{\partial t} + (\vec{q} \cdot \nabla) \rho_e + \nabla \cdot \vec{J} = 0 \quad (6)$$

and the electric charge density is assumed to be a linear function of temperature and is of the form¹⁰

$$\rho_e = \rho_{e0} [1 + \beta_c (T - T_0)] \quad (7)$$

Constitutive equations for chiral material assuming time harmonic fields for chiral fluids are

$$\vec{D} = \epsilon \vec{E} + i\gamma \vec{B} \quad \vec{B} = \mu \vec{H} - i\gamma \mu \vec{E} \quad (8a,b)$$

where γ the degree of chirality of material, $\gamma < 0$ the material is right handed, $\gamma > 0$ the material is a left-handed $\gamma = 0$ achiral material possessing the equal amount of right-handed and left-handed elements or molecules¹¹⁻¹³. The effect of magnetic field on a chiral fluid assessed by Lorentz force (electromagnetic force body force) $\vec{J} \times \vec{B}$ can be expressed as

$$\vec{J} \times \vec{B} = \rho_e \vec{q} \times \vec{B} = \rho_e (\vec{q} \times B_0) = v_0 B_0 \hat{i} - u B_0 \hat{j} \quad (9)$$

2.2 Simplification of Model using Thermo-Mechanic and Electrodynamic Assumptions

- i. A Chiral fluid is considered as incompressible Boussinesq fluid.
- ii. A fully developed unidirectional steady flow is assumed in x - direction. Therefore all the physical quantities vary with respect to y except pressure p .
- iii. The hydrostatically balanced flow is assumed in the x -direction. Therefore $-\partial p / \partial x - \rho_0 g = 0$
- iv. A uniform suction or injection velocity v_0 , is assumed at the boundaries.
- v. Electric current approximation: In chiral fluids like sugar solution, turpentine, and body fluid, etc. have low relaxation time where the convection electric current $\rho_e \vec{q}$ dominates over displacement current.

Therefore, in this present paper only convection electric current is considered whereas the displacement current is neglected.

vi. The gravity acts vertically downwards.

Then 'x' component of Equations. (3) and (4), simplified using electro thermo-mechanical approximations, are:

$$v_0 \frac{\partial u}{\partial y} = g \beta_T (T - T_0) + v \frac{\partial^2 u}{\partial y^2} + \frac{\rho_e}{\rho} v_0 B_0 \quad (10)$$

$$v_0 \frac{\partial T}{\partial y} = \kappa \frac{\partial^2 T}{\partial y^2} + \frac{v}{C_p} \left(\frac{\partial u}{\partial y} \right)^2 \quad (11)$$

2.3 Generalisation of Model using Suitable Dimensionless Quantities

To generalise the model, equations (7) ,(10) and (11) are made dimensionless, using $y^* = y/b$ for length, $u^* = (v/g\beta b^2 \Delta T)u$ for velocity,

$$\theta = (T - T_0) / \Delta T, \quad \Delta T = T_1 - T_0 \text{ for temperature,}$$

$\rho_e^* = \rho_e b^2 / \epsilon V$, for charge density and after simplification the following equations are obtained;

$$\frac{\partial^2 u^*}{\partial y^{*2}} - \text{Re} \frac{\partial u^*}{\partial y^*} + \theta + e^{\alpha y^*} W_{emt} (1 - \eta \gamma) = 0 \quad (12)$$

$$\frac{\partial^2 \theta^*}{\partial y^{*2}} - \text{Pe} \frac{\partial \theta^*}{\partial y^*} + N \left(\frac{\partial u^*}{\partial y^*} \right)^2 = 0 \quad (13)$$

$$\rho_e^* = \rho_{e0}^* (1 + \beta_c \theta^*) \quad (14)$$

where the asterisks (*) denote the dimensionless quantities, $W_{emt} = W_{em} R_c^2 / G_r$

is the electromagnetic thermal number,

$W_{em} = \epsilon_0 V \mu_m H_0 / b \rho_0 v_0$ is the electromagnetic

number, $Gr = g \beta_T \Delta T b^3 / \nu^2$ is the Grashoff

number, $N = \rho_0 g^2 \beta^2 (T_1 - T_0) b^4 / K \nu$ is the

buoyancy parameter, $R_e = v_0 b / \nu$ is the sectional

Reynolds number, and $P_e = v_0 b / \kappa$ is the Peclet

Number, $\eta = E_0/H_0$ is the wave impedance.

2.4 Solution for Electric Charge Density

A chiral fluid considered for the study is an electrically non-conducting so the contribution of Joule heating or Ohmic dissipation in energy equation (4) are negligible and hence electric charge density ρ_e depends on temperature at basic state θ_b , satisfying the condition^{2,8},

$$\frac{d\rho_e}{dy} = -\beta_c \theta_b \tag{15}$$

Boundary conditions for θ_b are given by

$$\theta_b = 1 \text{ at } y = 1, \theta_b = -1 \text{ at } y = -1 \tag{16}$$

The solution of Equation. (15) satisfying boundary conditions (16) is $\theta_b = y$. Using this solution in Equation. (14) the expression for electric charge density ρ_e is obtained as

$$\rho_e = 1 - \beta_c y \approx e^{-\alpha y} \quad (\beta_c \ll 1) \tag{17}$$

2.5 Boundary Conditions for Velocity and Temperature:

$$u = 0 \text{ at } y = \pm 1, \theta = 1 \text{ at } y = 1, \theta = -1 \text{ at } y = -1 \tag{18}$$

3. Analytical Solutions

Analytical solutions of the simplified coupled non-linear momentum and energy Equations.(12) and (13) are obtained using Regular Perturbation technique with buoyancy parameter $N (\ll 1)$ as perturbation parameter⁸. In this technique, u and θ computed in the series form given by

$$\begin{aligned} u &= u_0 + Nu_1 + N^2u_2 + \dots \\ \theta &= \theta_0 + N\theta_1 + N^2\theta_2 + \dots \end{aligned} \tag{19a,b}$$

Substituting Equations. (19a) and (19b) into Equations. (12) and (13) respectively and equating the coefficients of like powers of N to zero restricting the terms only up to the order unity because $N \ll 1$, the following boundary value problems are obtained.

Zeroth order equations:

$$\frac{\partial^2 u_0}{\partial y^2} - Re \frac{\partial u_0}{\partial y} + \theta_0 + e^{\alpha y} W_{emt} (1 - \eta\gamma) = 0, \quad \frac{\partial^2 \theta_0}{\partial y^2} - Pe \frac{\partial \theta_0}{\partial y} = 0 \tag{20a, b}$$

The corresponding boundary conditions obtained from Equations. (18) using Equations. (19a) and (19b) are:

$$u_0 = 0 \text{ at } y = \pm 1, \theta_0 = 1 \text{ at } y = 1, \theta_0 = -1 \text{ at } y = -1 \tag{21}$$

The solutions of Equations. (20a) and (20b) satisfying the boundary conditions Equation. (21), are:

$$u_0 = -a_2 e^{P_e y} + ya_3 + \frac{e^{R_e y} C_3}{R_e} + C_4, \quad \theta_0 = a_1 e^{P_e y} + C_2 \tag{22a,b}$$

First order equations are:

$$\frac{d^2 u_1}{dy^2} - Re \frac{du_1}{dy} + \theta_1 + e^{\alpha y} W_{emt} (1 - \eta\gamma) = 0,$$

$$\frac{d^2 \theta_1}{dy^2} - P_e \frac{d\theta_1}{dy} + \left(\frac{du_0}{dy} \right)^2 = 0 \tag{23a,b}$$

The corresponding boundary conditions obtained from Equations (18) using Equations (19a) and (19b) are:

$$u_1 = 0 \text{ at } y = \pm 1, \theta_1 = 0 \text{ at } y = 1, \theta_1 = 0 \text{ at } y = -1 \tag{24}$$

The solutions of Equations (23a) and (23b) satisfying the boundary conditions Equation (24), are:

$$u_1 = -a_{16} e^{2R_e y} - a_{17} e^{(P_e - R_e)y} + a_{18} e^{2P_e y} + a_{19} y + a_{20} y^2 + a_{21} e^{P_e y} - a_{22} e^{R_e (-1 + R_e y)} + \frac{e^{R_e y} C_7}{R_e} + C_8 \tag{25}$$

$$\theta_1 = -a_4 e^{2P_e y} + a_{11} e^{2R_e y} + a_{12} e^{R_e y} + a_{13} e^{(P_e + R_e)y} + a_{14} y + a_{15} e^{R_e y} (-1 + P_e y) + \frac{e^{P_e y} C_5}{P_e} + C_6 \tag{26}$$

results are depicted graphically in Figure 2 to 7 along with the numerical solution. The constants in equations (22a, b),(25) and (26) are given in the appendix.

4. Numerical Solutions

Numerical solutions of Equations (12) and (13) obtained using second order central finite difference scheme³. After applying the central difference scheme, Equations (12) and (13) using 21 mesh points with step (h) size 0.1 and solving for u_j and θ_j become:

$$L_1 = u_j = \left[u_{j-1} + u_{j+1} - \frac{R_e \Delta y}{2} (u_{j-1} - u_{j+1}) + \left(\Delta y \right)^2 \left(-\eta\gamma \right) \right] \tag{27}$$

$$L_2 = \theta_j = \frac{1}{2} \left[(\theta_{j+1} + \theta_{j-1}) - \frac{P_e \Delta y}{2} (\theta_{j+1} - \theta_{j-1}) + \frac{N}{4} (u_{j+1} - u_{j-1})^2 \right] \tag{28}$$

where suffix j represents the mesh point, j varies from 1 to 20. Equations (27) and (28) give two implicit equations in u_j and θ_j . Convergence of these solutions will be improved by applying the Successive Over Relaxation

technique (SOR). In this relaxation method the scheme for k^{th} iteration j^{th} mesh point is

$$u_j^k = \omega [u_j^k]_{L_1} + (I + \omega)u_j^{k-1} \text{ and } \theta_j^k = \omega [\theta_j^k]_{L_2} + (I + \omega)\theta_j^{k-1} \quad (29)$$

where ω is the relaxation parameter. This translates (27) and (28) respectively to

$$\dot{u}_j^k = \frac{w}{2} \left[u_j^k \theta_{j+1}^k + u_{j+1}^k \theta_j^k - \frac{R_c \Delta y}{2} (u_j^k \theta_{j+1}^k + u_{j+1}^k \theta_j^k) + u_j^k (\Delta y)^2 (I + \eta) (\Delta y)^2 (-\eta \gamma) \right] []_{L_1} \quad (30)$$

$$\dot{\theta}_j^k = \frac{w}{2} \left[\left(\theta_{j+1}^k + \theta_j^k \right) - \frac{P_r \Delta y}{2} (\theta_{j+1}^k - \theta_j^k) \right] + \frac{N}{4} (u_{j+1}^k - u_j^k)^2 + w [\theta_j^k]_{L_2} + (I + w)\theta_j^{k-1} \quad (31)$$

In Equations (30), (31) the value ω is fixed at 1.645 after checking the convergence compared with the analytical solutions. The analytical and numerical solutions of Equations (12) and (13) are computed for the different values of the dimensionless parameters which are depicted graphically from Figure 2 to 7 and important conclusions are drawn in the final section.

5. Result and Discussion

The response of a chiral fluid in a vertical channel bounded by permeable boundaries in the presence of the transverse magnetic field, velocity and temperature distributions are computed analytically and numerically and are plotted in Figures 2 to 7. In Figure 2 velocity u in x -direction is plotted against distance between the plates y for various values of W_{em} and for chirality parameter $\gamma = 0$. From figure, it is found that increase in W_{em} increases the velocity distribution. This implies that the magnetic field augments convection in a chiral fluid. Physically this is attributed to the fact that the magnetic field introduces

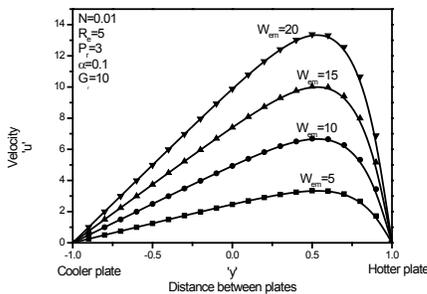


Figure 2. Depiction of effect of Electromagnetic number W_{em} (5,10,15,20) on Velocity distribution when $N=0.01$, $R_c=5$, $P_r=3$, $G_r=10$ with out considering chirality of the fluid $\gamma = 0$.

the small scale turbulence in a chiral fluid. Similarly, temperature distribution for various values of W_{em} is depicted in Figure 3. From this, it is clear that there is no significant effect W_{em} on the temperature distribution.

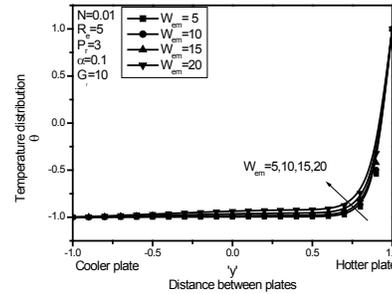


Figure 3. Depiction of effect of electromagnetic number W_{em} (5,10,15,20) on Temperature distribution when $N=0.01$, $R_c=5$, $P_r=3$, $G_r=10$, with out considering the chirality parameter $\gamma = 0$.

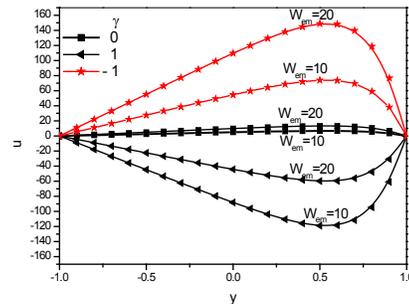


Figure 4. Depiction of effect of chirality parameter ($\gamma = 0, 1, -1$) on Velocity distribution when W_{em} (10,20), $N=0.01$, $R_c=5$, $P_r=3$, $G_r=10$, $\eta = 10$.

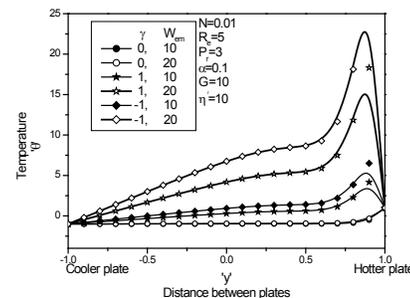


Figure 5. Depiction of effect of chirality parameter ($\gamma = 0, 1, -1$) on Temperature distribution when electromagnetic number W_{em} (10,20), $N=0.01$, $R_c=5$, $P_r=3$, $G_r=10$, $\eta = 10$.

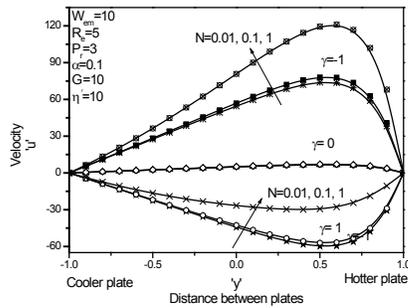


Figure 6. Depiction of Effect of chirality parameter ($\gamma=0, 1, -1$) on Velocity distribution for various values ($N=0.01, 0.1, 1.0$), when $W_{em}=10, R_e=5, P_r=3, G_r=10$.

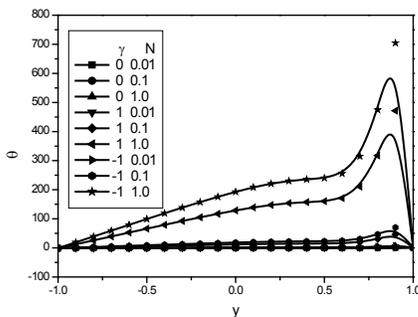


Figure 7. Depiction of effect of chirality parameter ($\gamma=0, 1, -1$) on Temperature distribution for various values of N ($N=0.01, 0.1, 1.0$), when $W_{em}=10, R_e=5, P_r=3, G_r=10, \eta=10$.

Figure 4 depicts the effect of chirality parameter γ of a chiral fluid molecules on the velocity distribution when W_{em} is 10 & 20. When $\gamma=1$ a chiral fluid is assumed to have only right-handed molecules. When $\gamma=-1$ fluid molecules has lefthandedness. When $\gamma=0$ a chiral fluid is regarded as racemic, having equal concentration of left-handed and right-handed molecules. The plot reveals that increasing in W_{em} is to accelerate the flow in the positive direction of y with higher value near the hotter plate for $\gamma=-1$ and in the negative direction of y with the lower value near the hotter plate for $\gamma=1$ and there is no much effect of W_{em} on velocity when $v=0$. The complete reversal of velocity distribution occurs with change in the value of chirality parameter γ from -1 to 1. Figure 5 depicts the effect of chirality parameter γ on temperature profile when electromagnetic number W_{em} is 10 & 20, the effect of increase in W_{em} is to increase the temperature. The increase in temperature is higher for $\gamma=-1$ than for

$\gamma=1$ and $\gamma=0$. From Figure 7 it is also clear that with an increase in W_{em} sets up meandering of thermal lines near the hotter plate at $y=1$ implying the thermal boundary layer. Therefore, this increase in the thermal distribution at $y=1$ for different values of W_{em} is due to the existence of thermal boundary at hotter plate $y=1$.

The effect of the buoyancy parameter N on velocity and temperature distribution are computed for various values of N (0.01, 0.1 & 1.0) when $W_{em}=10, R_e=5, P_r=3, G_r=10, \eta=10$ and for $\gamma=-1, 1$ & 0 and are plotted against y in Figure 6 and Figure 7. The velocity distribution increases with increase in N , since the viscous force decreases and buoyancy effect dominates with increase in the value of N . The flow reversal occurs with change in the chirality parameter γ from -1 to 1, this change may be due to the complete change in the handedness of molecules or inclusions comprising in a chiral fluid. Figure 7 shows that, with increase in the N temperature distribution increases, but increase in temperature distribution is higher for $\gamma=-1$ compared to $\gamma=1$.

6. Conclusion

The effect of the magnetic field is assessed by dimensionless parameter electromagnetic number W_{em} in Figures 2, 4 and 6. With increase in W_{em} increases velocity distribution. This result shows that, with chosen physical configuration, resistance to flow of a chiral fluid decreases with increase in the transverse magnetic field. Whereas, in case of magnetorheological fluids resistance to flow increases with an increase in magnetic field³. Thus similar to other smart fluids, a chiral fluid also responds to the transverse magnetic field by increasing in velocity distribution with increase in transverse magnetic field. Effect of chirality in a chiral fluid is addressed by chirality parameter γ . The in Figure 4 and 6 depicted results for velocity distribution for different values of γ and W_{em} . Similarly, the increase in W_{em} increases temperature distribution. This increase in temperature distribution is higher when $\gamma=-1$ compared to that when $\gamma=1$ and $\gamma=0$. The meandering of thermal lines occurs near hotter plate at $y=1$. This meandering occurred due to the presence of suction and injection velocity v_0 in positive direction.

Thus the flow/ convective instability occurred in a chiral fluid confined in a vertical channel, may be controlled effectively by using the transverse magnetic field, temperature and chirality parameter with present physi-

cal configuration. The results may be useful in the many practical applications in self-assembly of nano molecules in nano-technological and nanobiotechnological applications¹⁴, in the development of biomaterials for artificial organs and bio-interface materials based on chiral polymers, in the development of biomaterials for artificial organs and bio-interface materials based on chiral polymers¹⁵, in the development of radar absorbing materials/Radoms¹⁶, and in magnetic/electromagnetic targeted drug delivery using micro and nano fluidics, since more than half of the drug currently in use are chiral compounds,¹⁷ and so on.

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9. Appendix

$$a_1 = \frac{C_1}{P_e}, a_2 = \frac{a_1}{P_e(P_e - R_e)}, a_3 = \frac{W_{\infty}(1-\xi)}{P_e}, a_4 = (e^{-P_e} - e^{-R_e}), a_5 = \frac{R_e}{(e^{-R_e} - e^{-R_e})}, a_6 = \frac{e^{R_e}}{R_e}, a_7 = a_5 a_4 a_5 a_6, a_8 = 2a_5 a_5 a_6,$$

$$a_9 = a_2 P_e, a_{10} = -\frac{a_2^2}{2P_e^2}, a_{11} = \frac{C_1}{2P_e R_e - 4R_e^2}, a_{12} = \frac{2a_1 C_1}{(P_e - R_e) R_e}, a_{13} = \frac{2a_1 C_1}{(P_e - R_e) R_e}, a_{14} = \frac{a_1^2}{P_e}, a_{15} = \frac{2a_1 a_6}{P_e^2}, a_{16} = \frac{a_{11}}{2R_e},$$

$$a_{17} = \frac{a_{13}}{P_e(P_e + R_e)}, a_{18} = \frac{a_{10}}{4P_e^2 - 2P_e R_e}, a_{19} = \frac{a_{15} + C_1 R_e}{R_e^2}, a_{20} = \frac{(a_{15} P_e (3P_e - 2R_e) + C_1 (-P_e + R_e))}{P_e^2 (P_e - R_e)^2}, a_{21} = \frac{a_{15}}{(P_e - R_e)}, a_{23} = \frac{a_{12}}{R_e^2},$$

$$b_1 = (e^{-2P_e} - e^{-2R_e}), b_2 = (e^{2R_e} - e^{-2R_e}), b_3 = (e^{R_e} - e^{-R_e}), b_4 = (e^{P_e/R_e} - e^{-P_e/R_e}), b_5 = ((-1 + P_e) - e^{-P_e} - (-1 - P_e)),$$

$$b_6 = \left(\frac{e^{P_e}}{P_e} - \frac{e^{-P_e}}{P_e} \right), C_1 = \frac{2e^{P_e} P_e}{-1 + e^{2P_e}}, C_2 = \frac{1 + e^{2P_e}}{-1 + e^{2R_e}}, C_3 = -a_2 a_4 a_5 - 2a_5 a_6, C_4 = a_2 e^{P_e} - a_3 + a_7 + a_8,$$

$$C_5 = (-a_6 b_1 - a_1 b_2 - a_2 b_3 - a_3 b_4 - 2a_4 - a_5 b_5) / b_5, C_6 = -a_{14} + a_{16} e^{2P_e} - a_{12} e^{R_e} - a_{11} e^{2R_e} - a_{13} e^{P_e/R_e} - a_{15} e^{2R_e} (-1 + P_e) - C_1 e^{P_e} / P_e,$$

$$C_7 = \frac{e^{R_e} (m_1 - m_2)}{-1 + e^{2R_e}}, C_8 = \frac{m_1 + e^{R_e} m_2}{-1 + e^{2R_e}}, m_1 = a_{19} + a_{20} + a_{21} e^{P_e} - a_{22} e^{P_e} + a_{18} e^{2P_e} - a_{16} e^{2R_e} - a_{17} e^{P_e/R_e} - a_{23} e^{R_e} (-1 + R_e),$$

$$m_2 = -a_{19} + a_{20} + a_{21} e^{-P_e} + a_{22} e^{-P_e} + a_{18} e^{-2P_e} - a_{16} e^{2R_e} - a_{17} e^{-P_e/R_e} - a_{23} e^{R_e} (-1 + R_e),$$

10. Nomenclature

- V - kinematic viscosity
- D - mass diffusion coefficient
- ε - dielectric constant
- K - thermal diffusivity

k - thermal conductivity	V - electric potential
C_p - specific heat at constant pressure	η wave impedance
β_T - thermal expansion coefficient	b - characteristic length
β_c - coefficient of charge distribution	μ_f - viscosity of the fluid
ρ_0 - density of fluid at room temperature	ρ - density of the fluid
β^* - solutal expansion coefficient	θ - dimensionless temperature
T_0 - source temperature	- magnetic permeability
T_1 - boundary temperature	\vec{g} - gravitational field intensity
T - temperature	G_r - Grashof number
γ - chirality parameter	W_{emt} - electromagnetic thermal number
ρ_e - electric charge density	W_{em} - electromagnetic number
v_0 - suction/ injection velocity	$\vec{q} = (u, v)$ - Velocity components in x and y directions respectively
\vec{H} - magnetic induction	
\vec{B} - applied magnetic field	N - buoyancy parameter
\vec{E} - electric field	R_e - Sectional Reynolds number
\vec{D} - dielectric field	P_e - Peclet number
\vec{J} - current density	ω - relaxation parameter