South East Asian J. of Mathematics and Mathematical Sciences
Vol. 19, No. 1 (2023), pp. 433-446

DOI: 10.56827/SEAJMMS.2023.1901.33 **ISSN (Online): 2582-0850**

ISSN (Print): 0972-7752

THERMOCONVECTION IN A KUVSHINISKI FERROFLUID IN PRESENCE OF ROTATION AND VARYING GRAVITATIONAL FIELD THROUGH A POROUS MEDIUM

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(**Received:** *Jan. 24, 2022* **Accepted:** *Apr. 10, 2023* **Published:** *Apr. 30, 2023)*

Abstract: In this paper, thermoconvection in a Kuvshiniski Ferrofluid in presence of rotation and varying gravitational field through a porous medium is studied. Linear stability theory and normal mode technique are used to obtain the dispersion relationship. The effects of medium permeability, rotation and magnetization on the stationary convection of the system have been analyzed analytically and graphically and it turns out that medium permeability stabilizes as well as destabilizes the system for both $c < 0$ and $c > 0$. Also, rotation stabilizes the system for $c > 0$ and destabilizes the system for $c < 0$. Furthermore, magnetization stabilizes the system for both $c < 0$ and $c > 0$. The principle of the exchange of stabilities is fulfilled for the present problem under certain conditions.

Keywords and Phrases: Thermoconvection, Kuvshiniski Ferrofluid, Rotation, Magnetization, Porous medium.

2020 Mathematics Subject Classification: 76A10, 76D05, 76E06, 76E07, 76M25, 76S05, 76U05, 76W05.

1. Introduction

Thermoconvection in a liquid layer plays an important role in geophysics, atmospheric physics, oceanography etc. This is the area where most of the research has been carried out. We present an overview of literature that relates to work presented here. Thermal convection in different type of fluids has been studied by many authors e.g. Bénard [1], Rayleigh [14] and Jeffreys [4]. Chandrasekhar [2] provided a detailed description of the theoretical and experimental investigations of the so-called Bénard convection in Newtonian liquids. Rosensweig [17] gave a vivid introduction to magnetic liquids in his monograph. Thermal convection of Ferromagnetic fluid in the presence of magnetic field was considered by Finlayson [3]. Bénard convection in Ferromagnetic fluid has been discussed by many authors (Siddheswar [21, 22], Venkatasubramaniam and Kaloni [25], Sunil et al. [19, 20]). Some problems of Ferromagnetic fluid instability under couple-stress have been discussed by Nadian et al. [8, 9]. Also, Hall current effect on double- diffusive convection of couple-stress ferromagnetic fluid in the presence of varying gravitational field and horizontal magnetic field through a porous media has been investigated by Nadian et al. [11]. Kuvshiniski [7] studied the flow of dusty visco–elastic fluid (Kuvshiniski type) between two oscillating plates. Since visco-elastic fluids play an important role in the polymer and electrochemical industries, investigations into waves and stability in different viscoelastic fluid dynamical configurations have been carried out by various researchers. Varshney and Dwivedi [24] studied the unsteady effect on MHD free convection and the mass transfer flow of a Kuvshiniski fluid through a porous medium with constant suction, heat and mass flux. Kumar and Singh [5] investigated the thermal stability of a Kuvshiniski visco-elastic fluid with fine dust through porous medium. Kumar [6] investigated the magneto-rotatory stability of two layered fluid layers of a Kuvshiniski visco-elastic overlay fluid in a porous medium. Exploring magnetic dipole contribution on ferromagnetic nanofluid flow over a stretching sheet: An application of Stefan blowing was studied by Gowda et al. [12]. Kumar et al. [27] discussed the comparative study of ferromagnetic hybrid (manganese zinc ferrite, nickle zinc ferrite) nanofluids with velocity slip and convective conditions. A comprehensive study of thermophoretic diffusion deposition velocity effect on heat and mass transfer of ferromagnetic fluid flow along a stretching cylinder was discussed by Prasannakumara et al. [10]. An investigation on vertical porous plate in a conducting fluid with multiple boundary layer flow of casson fluid has been done by Goutham et al. [16]. Sudha et al. [18] discussed the hydrodynamic effects of secant slider bearings lubricated with second-order fluids. Unsteady flow of blood through a stenosed artery under the influence of transverse magnetic field was studied by Sujatha and Karthikeyan [23]. Exploration of multiple transfer phenomena within viscous fluid flows over a curved stretching sheet in the co-existence of gytotactic micro-organisms and tiny particles has been studied by Ragupathi et al. [13]. Fetecau et al. [26] investigated the unsteady natural convection flow due to fractional thermal transport and symmetric heat source/sink.

Also, activation energy impact in flow of AA7072-AA7075/ water-based hybrid nanofluid through a cone, wedge and plate has been discussed by Madhukesh et al. [15].

To the best of our knowledge, thermoconvection in a Kuvshiniski Ferromagnetic fluid in presence of rotation and varying gravitational field through a porous medium has not yet been investigated. This topic constitutes a new domain with largely unstudied potential. This is a growing and competitive area of research. This is still an area of active research. There has been an increased recognition that more attention needs to be paid to this area. This study would shed light on thermal convection in a Kuvshiniski Ferromagnetic fluid in presence of rotation and varying gravitational field through a porous medium, and hence would be of great interest. This work can be used as a reference for future studies. In the present paper, we have assumed that gravity is varying as $g = cg_0$, where g_0 is the value of g at the Earth's surface, which is always positive and can be positive or negative as gravity increases or decreases upwards from its value g_0. The outcome of this investigation will contribute a better understanding of the onset criterion for thermal convection in a Kuvshiniski ferrofluid soaked isotropic and homogeneous porous medium subjected to effect of rotation and magnetization, which is an often encountered phenomenon in different systems and industries.

2. Mathematical Formulation

Consider an infinite, incompressible, electrically non-conducting, and thin layer of Kuvshiniski Ferrofluid which is bounded by the planes $z = 0$ and $z = d$. The fluid layer is heated from below so that a uniform temperature gradient $\beta = \left|\frac{dT}{dz}\right|$ is maintained within the fluid. The whole system is acted upon by a uniform rotation $\mathbf{\Omega}(0, 0, \Omega)$ and variable gravity field $\mathbf{g}(0, 0, -g)$, where $g = cg_0$. Furthermore, the Kuvshiniski ferrofluid layer is assumed to be flowing through an isotropic and homogeneous porous medium of porosity ε.

The equation of conservation of momentum, continuity, density and equation of temperature for the above model are as follows:

$$\frac{1}{\varepsilon}\left(1+\lambda\frac{\partial}{\partial t}\right)\left[\frac{\partial \mathbf{q}}{\partial t}+\frac{1}{\varepsilon}(\mathbf{q}.\nabla)\mathbf{q}\right] = -\frac{1}{\rho_0}\nabla p + \mathbf{g}\left(1+\frac{\delta\rho}{\rho_0}\right)$$

$$+\left(1+\lambda\frac{\partial}{\partial t}\right)\left(\frac{\nu}{\varepsilon}\nabla^2-\frac{\nu}{k_1}\right)\mathbf{q}+\frac{1}{\rho_0}M\nabla\mathbf{H}+\frac{2}{\varepsilon}\left(1+\lambda\frac{\partial}{\partial t}\right)(\mathbf{q}\times\mathbf{\Omega}), \qquad (1)$$

$$\nabla . q = 0, \qquad (2)$$

$$\rho = \rho_0[1 - \alpha(T - T_0)], \tag{3}$$

$$E\frac{\partial T}{\partial t} + (\mathbf{q}.\nabla)T = \kappa\nabla^2 T, \tag{4}$$

where, $E = \varepsilon + (1-\varepsilon)(\rho_s c_s/\rho_0 c_\nu)$ with ρ_0, c_ν, ρ_s, c_s denote the density and heat capacity of the fluid and solid matrix respectively.
Also, we consider

$$M = M_0[1 - \gamma(T - T_0)] \quad \text{with} \quad \gamma = \frac{1}{M_0}\left(\frac{\partial M}{\partial T}\right)_H. \tag{5}$$

3. Basic State and Perturbation Equations

In undisturbed (or basic) state,
$\mathbf{q} = (0,0,0),\ p = p(z),\ \rho = \rho(z) = \rho_0(1 + \alpha\beta z),\ T = T_0 - \beta z,$
$\mathbf{\Omega} = (0,0,\Omega),\ M = M_0(1 + \gamma\beta z).$ (6)
Here, β may be either positive or negative.
The perturbed flow may be represented as,
$\mathbf{q} = (0,0,0) + (u,v,w),\ T = T(z) + \theta,\ \rho = \rho(z) + \delta\rho,$
$p = p(z) + \delta p,\ M = M(z) + \delta M,$ (7)
where, $\mathbf{q}(u,v,w)$, θ, $\delta\rho$, δp and δM are the perturbations in velocity, temperature, density, pressure and magnetization respectively.

4. Dispersion Relation

Having reviewed related work, we now present the main body of our research. Here we give a more concrete overview of the approach used in this work. This section outlines the specific method used within this research.
Linearizing the equations in perturbation and reading the perturbation into normal modes, we anticipate that the perturbation quantities are of the form,

$$(w,\theta,\zeta) = [W(z),\Theta(z),Z(z)].e^{\{i(k_x x + k_y y) + nt\}}, \tag{8}$$

where, $k = (k_x^2 + k_y^2)^{1/2}$ is the resultant wave number of the disturbance and n is the frequency of any arbitrary disturbance.

Now eliminate the physical quantities using the non-dimensional parameters $a = kd$, $\sigma = \frac{nd^2}{\nu}$, $p_1 = \frac{\nu}{\kappa}$, $J = \frac{\lambda\nu}{d^2}$, $P_1 = \frac{k_1}{d^2}$, $D^* = dD$ and dropping (*) for convenience, we obtain,

$$(D^2-a^2)\left[(1+J\sigma)\left\{\left(\frac{\sigma}{\varepsilon}+\frac{1}{P_1}\right)-\frac{1}{\varepsilon}(D^2-a^2)\right\}\right]W$$
$$+\frac{c\alpha a^2d^2}{\nu}\left(g_0-\frac{\gamma M_0\nabla H}{\rho_0\alpha c}\right)\Theta+\frac{2\Omega d^3}{\nu\varepsilon}(1+J\sigma)DZ=0, \tag{9}$$

$$\left\{\left(\frac{\sigma}{\varepsilon}+\frac{1}{P_1}\right)-\frac{1}{\varepsilon}(D^2-a^2)\right\}Z=\frac{2\Omega d}{\nu\varepsilon}DW, \tag{10}$$

$$(D^2-a^2-E\sigma p_1)\Theta=-\frac{\beta d^2}{\kappa}W. \tag{11}$$

So, from Equations (9), (10) and (11), the stability governing equation is,

$$R_f a^2 cW=(D^2-a^2)(1+J\sigma)\left\{\left(\frac{\sigma}{\varepsilon}+\frac{1}{P_1}\right)-\frac{1}{\varepsilon}(D^2-a^2)\right\}(D^2-a^2-E\sigma p_1)W$$
$$+(1+J\sigma)\frac{T_A}{\varepsilon^2}\left[\frac{(D^2-a^2-E\sigma p_1)}{\left\{\left(\frac{\sigma}{\varepsilon}+\frac{1}{P_1}\right)-\frac{1}{\varepsilon}(D^2-a^2)\right\}}\right]D^2W, \tag{12}$$

where $R_f=\dfrac{\alpha\beta d^4}{\nu\kappa}\left(g_0-\dfrac{\gamma M_0\nabla H}{\rho_0\alpha c}\right)$ is the Rayleigh number for Ferrofluid and $T_A=\left(\dfrac{2\Omega d^2}{\nu}\right)^2$ is the Modified Taylor number.

The appropriate boundary conditions are,

$$W=0,\ D^2W=0,\ D^4W=0,\ \Theta=0,\ Z=0,\ DZ=0 \text{ at } z=0 \text{ and } z=1. \tag{13}$$

So, the solution of the stability governing equation characterizing the lowest mode is,

$$W=W_0\sin\pi z,\quad \text{where}\quad W_0 \text{ is a constant.} \tag{14}$$

Now on using this solution into the stability governing equation, we get,

$$R_1=\frac{(1+x)}{cx}(1+Ji\sigma_1\pi^2)\left\{\frac{i\sigma_1}{\varepsilon}+\frac{1}{P}+\frac{(1+x)}{\varepsilon}\right\}(1+x+Ei\sigma_1p_1)$$
$$+\frac{T_{A_1}}{\varepsilon^2 cx}(1+Ji\sigma_1\pi^2)\left[\frac{(1+x+Ei\sigma_1p_1)}{\left\{\frac{i\sigma_1}{\varepsilon}+\frac{1}{P}+\frac{(1+x)}{\varepsilon}\right\}}\right], \tag{15}$$

where $x = (a^2/\pi^2)$, $i\sigma_1 = (\sigma/\pi^2)$, $R_1 = (R_f/\pi^4)$, $P = \pi^2 P_1$, $T_{A_1} = \frac{T_A}{\pi^4}$.

5. Analytical Discussion

(A) Stationary Convection

For stationary convection, put $\sigma_1 = 0$ (marginal state) in Equation (15), we get the modified Rayleigh number as,

$$R_1 = \frac{(1+x)^2}{cx}\left\{\frac{1}{P} + \frac{(1+x)}{\varepsilon}\right\} + \frac{T_{A_1}}{\varepsilon^2 cx}\left[\frac{(1+x)}{\left\{\frac{1}{P} + \frac{(1+x)}{\varepsilon}\right\}}\right] \tag{16}$$

Now to see the effect of medium permeability and rotation at stationary convection on the system, we have to examine $\frac{dR_1}{dP}$ and $\frac{dR_1}{dT_{A_1}}$ respectively.

From Equation (16), we have, $\frac{dR_1}{dP} > 0$ when $c > 0,\ T_{A_1} > \varepsilon^2(1+x)\left\{\frac{1}{P} + \frac{(1+x)}{\varepsilon}\right\}^2$ and $c < 0,\ T_{A_1} < \varepsilon^2(1+x)\left\{\frac{1}{P} + \frac{(1+x)}{\varepsilon}\right\}^2$, which clearly shows that medium permeability stabilizes the system at stationary convection.

Also, $\frac{dR_1}{dP} < 0$ when $c > 0,\ T_{A_1} < \varepsilon^2(1+x)\left\{\frac{1}{P} + \frac{(1+x)}{\varepsilon}\right\}^2$ and $c < 0,\ T_{A_1} > \varepsilon^2(1+x)\left\{\frac{1}{P} + \frac{(1+x)}{\varepsilon}\right\}^2$, which clearly shows that medium permeability destabilizes the system at stationary convection. Furthermore, in the absence of rotation, medium permeability has stabilizing effect for $c < 0$ and destabilizing effect for $c > 0$.

Also, we have $\frac{dR_1}{dT_{A_1}} > 0$ when $c > 0$ and $\frac{dR_1}{dT_{A_1}} < 0$ when $c < 0$, which clearly shows that rotation has both stabilizing and destabilizing effects on the system at stationary convection. Now to see the effect of magnetization at stationary convection on the system, we have to examine $\frac{dR}{dM_0}$.

From Equation (16), we have $\frac{dR}{dM_0} > 0$ for both $c > 0$ and $c < 0$, which clearly shows that magnetization stabilizes the system at stationary convection.

(B) Oscillatory Convection

For oscillatory convection, multiply Equation (9) by conjugate of W (i.e. W^*) and integrate over the range of z from $z = 0$ to $z = 1$ and making use of Equations (10) and (11) together with the boundary condition (13), we get,

$$(1+J\sigma)\left(\frac{\sigma}{\varepsilon} + \frac{1}{P_1}\right)I_1 + \frac{1}{\varepsilon}(1+J\sigma)I_2 - \frac{c\alpha a^2\kappa}{\beta\nu}\left(g_0 - \frac{\gamma M_0 \nabla H}{\rho_0\alpha}\right)(I_3 + Ep_1\sigma^* I_4)$$
$$+(1+J\sigma)d^2\left\{\left(\frac{\sigma^*}{\varepsilon} + \frac{1}{P_1}\right)I_5 + \frac{1}{\varepsilon}I_6\right\} = 0, \tag{17}$$

where $I_1 = \int(|DW|^2 + a^2|W|^2)dz,\ I_2 = \int(|D^2W|^2 + 2a^2|DW|^2 + a^4|W|^2)dz$, $I_3 = \int(|D\Theta|^2 + a^2|\Theta|^2)dz$, $I_4 = \int(|\Theta|^2)dz$, $I_5 = \int(|Z|^2)dz$, $I_6 = (|DZ|^2 + a^2|Z|^2)\mathrm{dz}$. All these integrals are positive definite.
Now, on putting $\sigma = i\sigma_i$ into Equation (16) and equating imaginary part, we get,

$$\sigma_i\left[\left(\frac{1}{\varepsilon}+\frac{J}{P_1}\right)I_1+\frac{1}{\varepsilon}JI_2+\frac{c\alpha a^2\kappa}{\beta\nu}\left(g_0-\frac{\gamma M_0\nabla H}{\rho_0\alpha c}\right)Ep_1I_4 \right. \\ \left. +d^2\left\{\left(\frac{J}{P_1}-\frac{1}{\varepsilon}\right)I_5+\frac{1}{\varepsilon}JI_6\right\}\right]=0. \tag{18}$$

Furthermore, in absence of rotation, if $cg_0 \geq \dfrac{\gamma M_0\nabla H}{\rho_0\alpha}$, then terms in the bracket are positive definite, which implies that . Therefore, oscillatory modes are not allowed and principle of exchange of stabilities is satisfied if $cg_0 \geq \dfrac{\gamma M_0\nabla H}{\rho_0\alpha}$.

6. Numerical Computation

The dispersion relation (16) is analyzed numerically also. Graphs were plotted between the Rayleigh number R_1 and the medium permeability parameter P, Rayleigh number R_1 and rotation parameter T_{A_1}, Rayleigh number R_1 and the magnetization parameter M_0 (see Figures 1-10).

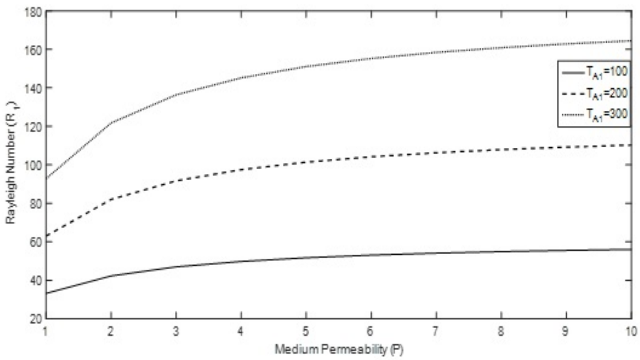

Figure 1: R_1 vs P for $c > 0$ $(c = 10000)$

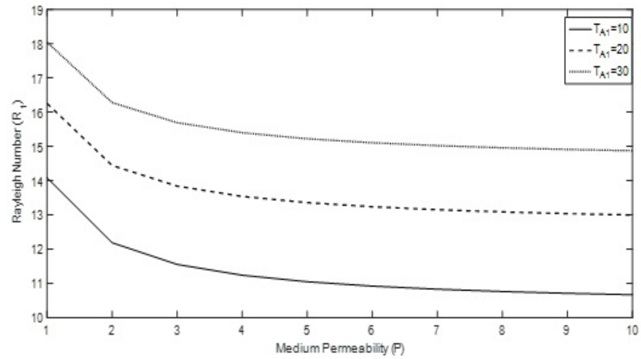

Figure 2: R_1 vs P for $c > 0$ ($c = 1$)

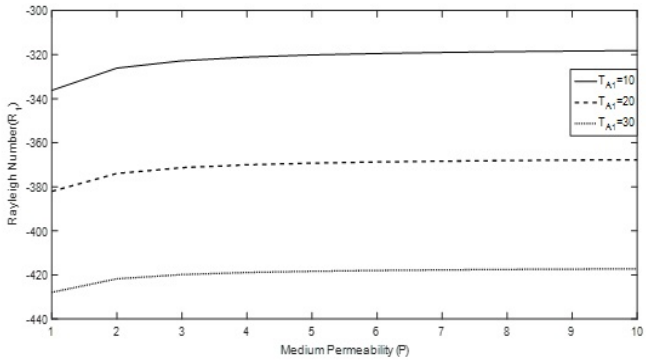

Figure 3: R_1 vs P for $c < 0$ ($c = -0.5$)

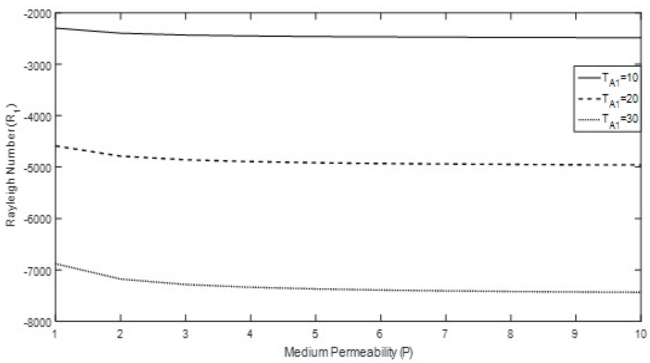

Figure 4: R_1 vs P for $c < 0$ ($c = -25$)

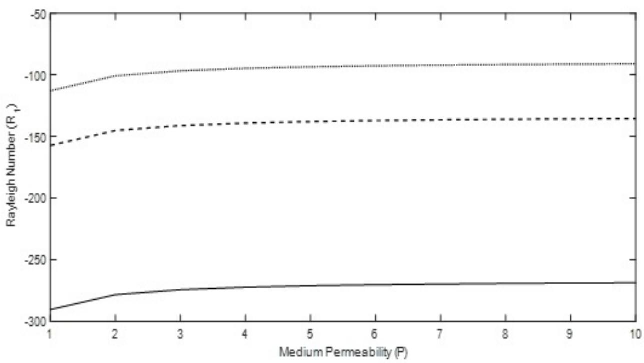

Figure 5: R_1 vs P for $c < 0$ ($c = -0.5$) (absence of rotation)

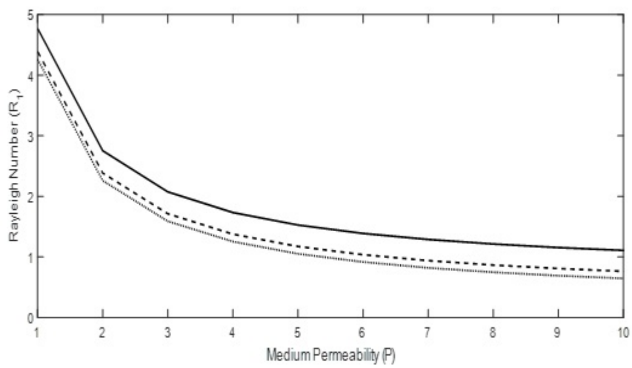

Figure 6: R_1 vs P for $c > 0$ ($c = 1$) (absence of rotation)

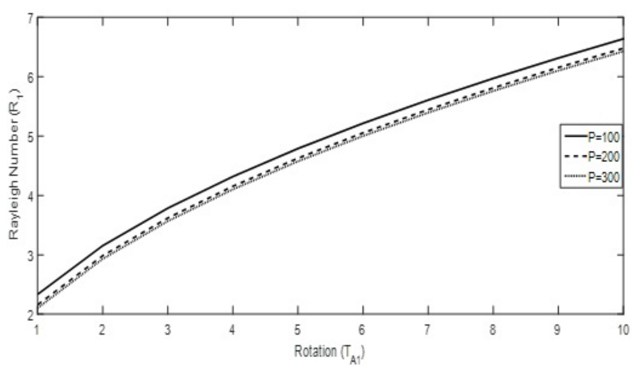

Figure 7: R_1 vs T_{A_1} for $c > 0$ ($c = 10, 20, 30$)

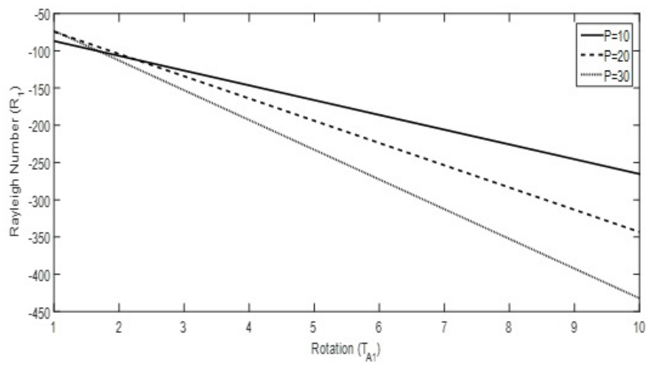

Figure 8: R_1 vs T_{A_1} for $c < 0$ $(c = -2, -3, -4)$

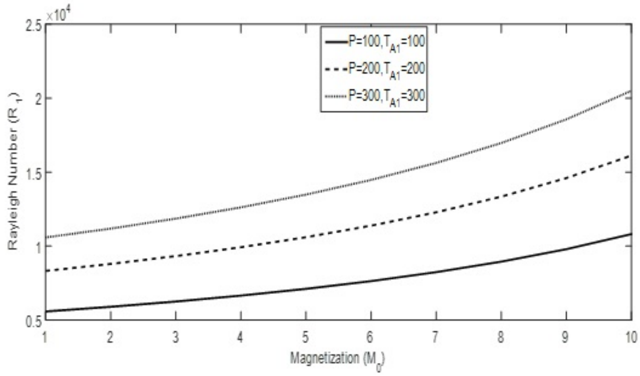

Figure 9: R_1 vs M_0 for $c > 0$ $(c = 1)$

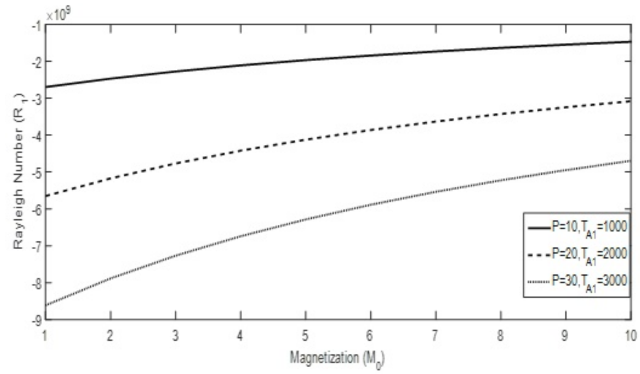

Figure 10: R_1 vs M_0 for $c < 0$ $(c = -0.5)$

These are some graphs plotted between critical Rayleigh number and the parameters (medium permeability, rotation and magnetization) for the different values of these parameters.

7. Results

This section summarizes and discusses the main findings of the work. In this paper, thermoconvection in a layer of Kuvshiniski Ferrofluid in presence of rotation and varying gravitational field through a porous medium is investigated analytically and graphically using linear stability theory and normal mode technique. One obtains the expression for the stationary Rayleigh number which characterizes the stability of the system. The main results from the analysis of this study are,

- At stationary convection, medium permeability stabilizes the system when $c > 0$, $T_{A_1} > \varepsilon^2(1+x)\left\{\frac{1}{P} + \frac{(1+x)}{\varepsilon}\right\}^2$ and $c < 0$, $T_{A_1} < \varepsilon^2(1+x)\left\{\frac{1}{P} + \frac{(1+x)}{\varepsilon}\right\}^2$. Also medium permeability destabilizes the system when $c > 0$, $T_{A_1} < \varepsilon^2(1+x)\left\{\frac{1}{P} + \frac{(1+x)}{\varepsilon}\right\}^2$ and $c < 0$, $T_{A_1} > \varepsilon^2(1+x)\left\{\frac{1}{P} + \frac{(1+x)}{\varepsilon}\right\}^2$. Furthermore, in the absence of rotation, medium permeability has stabilizing effect for $c < 0$ and destabilizing effect for $c > 0$.

- Rotation has both effects (stabilizing and destabilizing) on the system at stationary convection for both $c < 0$ and $c > 0$.

- Magnetization stabilizes the system at stationary convection for both $c < 0$ and $c > 0$.

- Principle of exchange of stabilities is satisfied for the present problem in the absence of rotation if $cg_0 \geq \dfrac{\gamma M_0 \nabla H}{\rho_0 \alpha}$.

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