

**EFFECT OF SUSPENDED PARTICLES IN A LAYER OF
KUVSHINISKI FERROFLUID THROUGH
A POROUS MEDIUM HEATED FROM BELOW**

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Abstract: The purpose of this paper is to study the effects of suspended particles, magnetization and medium permeability in a layer of Kuvshiniski ferrofluid when this layer is heated from below. In this paper, a linear stability theory and normal mode technique is used to find the dispersion relation. In case of stationary convection, it is found that both medium permeability and suspended particles have destabilizing effect on the system. Also, magnetization has a stabilizing effect on the system. Furthermore it is also found that the Principle of exchange of stabilities is satisfied for the present problem under certain conditions.

Keywords and Phrases: Thermal instability, Kuvshiniski Ferrofluid, Suspended particles, Magnetization, Porous medium.

2020 Mathematics Subject Classification: 76A10, 76D05, 76E06, 76E99, 76M25, 76S05.

1. Introduction

Chandrasekhar [4] formulated the theory of Bénard convection in viscous Newtonian fluid layers heated from below. Chandra [3] determined that in a thin air layer, convection occurs at much lower gradients than expected when the layer depth is less than 7 mm, and called this motion columnar instability. By considering dust particles as a factor in the onset of Bénard convection, Scanlon and Segel [19] found that the critical Rayleigh number was reduced solely because the pure fluid has a higher heat capacity. Considering the increasing importance of non-Newtonian fluids in modern technology and industry, it is desirable to investigate them. A study by Sharma and Aggarwal [24] examined the effects of compressibility and suspended particles on thermal convection in Walters' B' elastico-viscous fluid. By combining magnetic fields and rotation, Aggarwal and Makhija [1] show that coupled-stress fluid heated from below with suspended particles can exhibit additional properties. An investigation has been carried out by Sharma and Rana [26] into the thermosolutal instability of Walters (model B') visco-elastic rotating fluids permeated by suspended particles and with variable gravity field in porous media. Aggarwal and Verma [2] studied the effect of compressibility, rotation, and magnetic field on thermal instability of Walters' fluid permeated with suspended particles.

Rosenweig's monograph [18] provides an authoritative introduction to magnetic liquids research. The purpose of this monograph is to provide an overview of several applications of heat transfer through ferromagnetic fluids. According to Finlayson [5], convective instability of a ferromagnetic fluid occurs when the fluid layer in the presence of uniform magnetic fields is heated from below. An investigation of the effect of dust particles on thermal convection in ferromagnetic fluids saturating porous media was carried out by Sharma and Sharma [23]. Sharma [25] discussed the effect of dust particles on a rotating ferromagnetic fluid heated from below saturating a porous medium. An investigation of dust particles on ferrofluid heated and soluted from below has been carried out by Sharma et al. [21]. As well, Shandil et al. [20] studied how rotation affects a ferromagnetic fluid heated and soluted from below. Thermoconvection in liquid layers is a crucial part of geophysics, atmospheric physics, and oceanography. In addition of these, convection problems in Ferromagnetic fluid has been discussed by many authors ((Siddheswar [27], [28]), Venkatasubramaniam and Kaloni [31], Sunil et al. [29], Mahajan [11]). Also, a number of problems associated with Ferromagnetic fluid instability have been discussed by Nadian et al. ([13], [14]).

The flow of dusty visco-elastic fluid (Kuvshinski type) between two oscillating plates was studied by Kuvshinski [10]. A variety of researchers have studied

viscoelastic fluid dynamical configurations because of their importance to the polymer and electrochemical industries. A Kuvshiniski fluid flowing through a porous medium with constant suction, heat, and mass flux was studied by Varshney and Dwivedi [30]. An investigation was undertaken by Kumar and Singh [8] to determine the thermal stability of a viscoelastic Kuvshiniski fluid embedded in a porous medium containing fine dust. In a porous medium, Kumar [7] investigated the magneto-rotary stability of visco-elastic overlay fluids with two layers. Research on ferromagnetic nanofluid flow over stretching sheets using Stefan blowing has been carried out by Gowda et al. [6]. Among many studies on thermophoretic diffusion, Prasannakumara et al. [15] conducted a comprehensive study on heat and mass transfer in ferromagnetic fluid flow along a stretching cylinder. A horizontal porous plate with a multiple boundary layer flow of a casson fluid was studied by Goutham et al. [17]. Pandya and Kannoujia [16] have investigated sores and Dufour effect on thermostatically stratified MHD fluid flow through inclined porous plate. Kumari and Singh [9] have studied about thermal convection of magneto-hydrodynamic micropolar fluid flow over a porous non-linear stretching sheet with thermal radiation. Characteristics of MHD viscous incompressible fluid flow and heat transfer over a permeable sheet in porous medium has been studied by Yadav et al. [22].

To the best of our knowledge, the problem of Effect of suspended particles in a layer of Kuvshiniski Ferrofluid through a porous medium heated from below has not yet been investigated. This topic is a growing and competitive area of research and constitutes a new domain with largely unstudied potential. More attention is being paid to this area as a result of increased recognition. Recently, Nadian [12] has investigated thermoconvection in a kuvshiniski ferrofluid in presence of rotation and varying gravitational field through a porous medium. It would be very useful to have this study make a contribution to our understanding of thermal convection in a Kuvshiniski Ferromagnetic fluid in the presence of suspended particles through a porous medium. 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 suspended particles 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 gravity field

$\mathbf{g}(0, 0, -g)$. Also, let $\mathbf{q}_d(x, t)$ and $N(x, t)$ denote the velocity and number density of dust particles respectively. $K = 6\pi\mu\eta$ (η is the radius of the particle) is the Stokes drag coefficient and $\mathbf{x}(x, y, z)$. Furthermore, the Kuvshinski 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 temperature for the above model are as follows:

$$\begin{aligned} \frac{1}{\epsilon} \left(1 + \lambda \frac{\partial}{\partial t} \right) \left[\frac{\partial \mathbf{q}}{\partial t} + \frac{1}{\epsilon} (\mathbf{q} \cdot \nabla) \mathbf{q} \right] = & -\frac{1}{\rho_0} \nabla p + \mathbf{g} \left(1 + \frac{\delta \rho}{\rho_0} \right) \\ & + \left(1 + \lambda \frac{\partial}{\partial t} \right) \left(\frac{\nu}{\epsilon} \nabla^2 - \frac{\nu}{k_1} \right) \mathbf{q} + \frac{1}{\rho_0} \mathbf{M} \cdot \nabla \mathbf{H} + \left(1 + \lambda \frac{\partial}{\partial t} \right) \frac{KN}{\rho_0} (\mathbf{q}_d - \mathbf{q}) \end{aligned} \quad (1)$$

$$\nabla \cdot \mathbf{q} = 0 \quad (2)$$

$$\rho = \rho_0 [1 - (T - T_0)] \quad (3)$$

where, p , ρ , T , α , ν , κ_T and $\mathbf{q}$ denotes the pressure, density, temperature, thermal coefficient of expansion, kinematic viscosity, thermal diffusivity and velocity of the fluid respectively.

The presence of particles add an extra term of force which is proportional to the velocity difference between particles and fluid and appears in equation of motion (1). Since the force exerted by the fluid on the particles is equal and opposite to the force exerted by the particles on the fluid, so there must be an extra force term (which is equal in magnitude but opposite in sign) in equation of motion for the particles. The buoyancy force on the particles is neglected. Interparticle reactions are not considered for we assume that the distance between particles is quite large as compared with their diameter. The equations of motion and continuity for the particles, under the above approximation are,

$$mN \left[\frac{\partial \mathbf{q}_d}{\partial t} + \frac{1}{\epsilon} (\mathbf{q}_d \cdot \nabla) \mathbf{q}_d \right] = KN(\mathbf{q} - \mathbf{q}_d) \quad (4)$$

and

$$\epsilon \frac{\partial N}{\partial t} + \nabla \cdot (N \cdot \mathbf{q}_d) = 0 \quad (5)$$

where, mN is the mass of particles per unit volume.

Let c_v , c_{pt} , ρ_s , c_s be the heat capacity of the fluid at constant volume, the heat capacity of the particles, density of the solid (porous) material, and heat capacity

of the solid (porous) material respectively. Assuming that the particles and fluid are in thermal equilibrium, the equation of heat conduction gives,

$$E \frac{\partial T}{\partial t} + (\mathbf{q} \cdot \nabla)T + \frac{mNc_{pt}}{\rho_0 c_v} \left(\epsilon \frac{\partial}{\partial t} + \mathbf{q}_d \cdot \nabla \right) T = \kappa_T \nabla^2 T \quad (6)$$

where, $E = \epsilon + (1 - \epsilon) \frac{\rho_s c_s}{\rho_0 c_v}$ is a constant and $\kappa_T = \frac{\nu}{\rho_0 c_v}$.

Now, we consider magnetization to be independent of magnetic field intensity but depend upon temperature so that $M = M(T)$ only. As a first approximation, we consider that,

$$M = M_0[1 - \gamma(T - T_0)] \quad (7)$$

where, $\gamma = \frac{1}{M_0} \left(\frac{\partial M}{\partial T} \right)_H$ and M_0 is the magnetization at $T = T_0$ with T_0 being the reference temperature.

3. Basic State and Perturbation Equations

In basic state,

$$\begin{aligned} \mathbf{q} = (0, 0, 0), \mathbf{q}_d = (0, 0, 0), p = p(z), \rho = \rho(z) = \rho_0(1 + \alpha\beta z), T = T_0 - \beta z, \\ M = M_0(1 + \gamma\beta z), N = N_0 \end{aligned} \quad (8)$$

β may be either positive or negative.

The perturbed flow may be represented as,

$$\begin{aligned} \mathbf{q} = (0, 0, 0) + (u, v, w), \mathbf{q}_d = (0, 0, 0) + (l, r, s), T = T(z) + \theta, \rho = \rho(z) + \delta\rho \\ p = p(z) + \delta p, M = M(z) + \delta M \end{aligned} \quad (9)$$

where, $\mathbf{q}(u, v, w)$, $\mathbf{q}_d(l, r, s)$, θ , $\delta\rho$, δp and δM are the perturbations in velocity of fluid, velocity of suspended particles, temperature, density, pressure and magnetization respectively.

4. The Dispersion Relation

Linearizing the equations in perturbation and reading the perturbation into normal modes, we anticipate that the perturbation quantities are of the form,

$$(w, \theta) = [W(z), \Theta(z)] \cdot e^{\{i(k_x x + k_y y) + nt\}} \quad (10)$$

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 $a = kd$, $\sigma = \frac{nd^2}{\nu}$, $\tau = \frac{m}{K}$, $p_1 = \frac{\nu}{\kappa_T}$, $J = \frac{\lambda\nu}{d^2}$,

$\tau_1 = \frac{\tau\nu}{d^2}$, $O = \frac{mN_0}{\rho_0}$, $B = (1 + b)$, $P_1 = \frac{k_1}{d^2}$, $E_1 = E + b\epsilon$, $D^* = dD$ and dropping (*) for convenience, we get,

$$(1 + J\sigma)(D^2 - a^2) \left[\left\{ \frac{\sigma}{\epsilon} + \frac{1}{P_1} + \frac{O\sigma}{\epsilon(1 + \tau_1\sigma)} \right\} - \frac{1}{\epsilon}(D^2 - a^2) \right] W + \frac{\alpha a^2 d^2}{\nu} \left(g - \frac{\gamma M_0 \nabla H}{\rho_0 \alpha} \right) \Theta = 0 \quad (11)$$

$$(D^2 - a^2 - \sigma E_1 p_1) \Theta = - \left(\frac{B + \tau_1 \sigma}{1 + \tau_1 \sigma} \right) \frac{\beta d^2}{\kappa_T} W \quad (12)$$

From Equations (11) and (12), the stability governing equation is,

$$R_f a^2 \left(\frac{B + \tau_1 \sigma}{1 + \tau_1 \sigma} \right) \left(\frac{1}{D^2 - a^2 - \sigma E_1 p_1} \right) W = (1 + J\sigma)(D^2 - a^2) \left[\left\{ \frac{\sigma}{\epsilon} + \frac{1}{P_1} + \frac{O\sigma}{\epsilon(1 + \tau_1\sigma)} \right\} - \frac{1}{\epsilon}(D^2 - a^2) \right] W \quad (13)$$

where, $R_f = \frac{\alpha \beta d^4}{\nu \kappa_T} \left(g - \frac{\gamma M_0 \nabla H}{\rho_0 \alpha} \right)$ is the Rayleigh number for Ferrofluid.

The appropriate boundary conditions are,

$$W = 0, D^2 W = 0, D^4 W = 0, \Theta = 0, D^2 \Theta = 0 \text{ at } z = 0 \text{ and } z = 1. \quad (14)$$

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

$$W = W_0 \sin \pi z, \text{ where } W_0 \text{ is a constant.} \quad (15)$$

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

$$R_1 = \frac{(1 + x)}{x} (1 + J i \sigma_1 \pi^2) \left[\frac{i \sigma_1}{\epsilon} + \frac{1}{P} + \frac{O i \sigma_1}{\epsilon(1 + i \sigma_1 \pi^2 \tau_1)} + \frac{(1 + x)}{\epsilon} \right] \left(\frac{1 + i \sigma_1 \pi^2 \tau_1}{B + i \sigma_1 \pi^2 \tau_1} \right) (1 + x + E_1 i \sigma_1 p_1) \quad (16)$$

where, $x = (a^2/\pi^2)$, $i \sigma_1 = (\sigma/\pi^2)$, $R_1 = (R_f/\pi^4)$, $P = \pi^2 P_1$.

5. Analytical Discussion

(A) Stationary Convection

For stationary convection, put $\sigma_1 = 0$ in Equation (16), we get the expression for modified Rayleigh number as,

$$R_1 = \frac{(1 + x)^2}{Bx} \left[\frac{1}{P} + \frac{(1 + x)}{\epsilon} \right] \quad (17)$$

Now to see the effect of medium permeability, suspended particles and magnetization at stationary convection on the system, we have to examine $\frac{dR_1}{dP}$, $\frac{dR_1}{dB}$ and $\frac{dR}{dM_0}$ respectively. From Equation (17), we have $\frac{dR_1}{dP} < 0$, $\frac{dR_1}{dB} < 0$ and $\frac{dR}{dM_0} > 0$, which clearly shows that medium permeability and suspended particles has destabilizing effect, furthermore magnetization has stabilizing effect on the system at stationary convection.

(B) Oscillatory Convection

For oscillatory convection, multiply Equation (11) 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 (12) together with the boundary condition (14), we get,

$$(1 + J\sigma) \left\{ \frac{\sigma}{\epsilon} + \frac{1}{P_1} + \frac{O\sigma}{\epsilon(1 + \tau_1\sigma)} \right\} I_1 + \frac{1}{\epsilon}(1 + J\sigma)I_2 - \frac{\alpha a^2 \kappa_T}{\beta \nu} \left(g - \frac{\gamma M_0 \nabla H}{\rho_0 \alpha} \right) \left(\frac{1 + \tau_1 \sigma^*}{B + \tau_1 \sigma^*} \right) (I_3 + E_1 p_1 \sigma^* I_4) = 0 \quad (18)$$

where, $I_1 = \int (|DW|^2 + a^2 |W|^2) dz$, $I_2 = \int (|D^2 W|^2 + 2a^2 |DW|^2 + a^4 |W|^2) dz$, $I_3 = \int (|D\Theta|^2 + a^2 |\Theta|^2) dz$, $I_4 = \int |\Theta|^2 dz$. All these integrals are positive definite.

Now, on putting $\sigma = \sigma_r + i\sigma_i$ in Equation (18) and equating real and imaginary parts, we get,

$$\begin{aligned} \sigma_r \left[\left\{ \frac{1}{\epsilon} + \frac{J\sigma_r}{\epsilon} + \frac{J}{P_1} + \frac{OJ(\sigma_r + \tau_1 \sigma_r^2 + \sigma_i^2)}{\epsilon(B + \tau_1 \sigma_r)^2 + \epsilon \tau_1^2 \sigma_i^2} \right\} I_1 + \frac{J}{\epsilon} I_2 - \frac{\alpha a^2 \kappa_T}{\beta \nu} \right. \\ \left. \left(g_0 - \frac{\gamma M_0 \nabla H}{\rho_0 \alpha} \right) \left\{ \frac{B + \tau_1 \sigma_r(1 + B) + \tau_1^2(\sigma_r^2 + \sigma_i^2)}{(B + \tau_1 \sigma_r)^2 + \tau_1^2 \sigma_i^2} \right\} E p_1 I_4 \right] = \\ - \left[\frac{1}{P_1} + \frac{O(\sigma_r + \tau_1 \sigma_r^2 + \tau_1 \sigma_i^2)}{\epsilon(B + \tau_1 \sigma_r)^2 + \epsilon \tau_1^2 \sigma_i^2} - \frac{J\sigma_i^2}{\epsilon} - \frac{OJ\sigma_i^2}{\epsilon(B + \tau_1 \sigma_r)^2 + \epsilon \tau_1^2 \sigma_i^2} \right] I_1 - \frac{1}{\epsilon} I_2 \\ + \frac{\alpha a^2 \kappa_T}{\beta \nu} \left(g_0 - \frac{\gamma M_0 \nabla H}{\rho_0 \alpha} \right) \left\{ \frac{B + \tau_1 \sigma_r(1 + B) + \tau_1^2(\sigma_r^2 + \sigma_i^2)}{(B + \tau_1 \sigma_r)^2 + \tau_1^2 \sigma_i^2} \right\} I_3 \\ + \frac{\alpha a^2 \kappa_T}{\beta \nu} \left(g_0 - \frac{\gamma M_0 \nabla H}{\rho_0 \alpha} \right) E p_1 \tau_1 \sigma_i^2 (1 - B) I_4 \quad (19) \end{aligned}$$

and

$$\begin{aligned} \sigma_i \left[\left\{ \frac{1}{\epsilon} + \frac{O}{\epsilon(B + \tau_1 \sigma_r)^2 + \epsilon \tau_1^2 \sigma_i^2} + \frac{2J\sigma_r}{\epsilon} + \frac{2OJ\sigma_r}{\epsilon(B + \tau_1 \sigma_r)^2 + \epsilon \tau_1^2 \sigma_i^2} + \frac{J}{P_1} \right. \right. \\ \left. \left. + \frac{OJ\sigma_r^2 \tau_1}{\epsilon(B + \tau_1 \sigma_r)^2 + \epsilon \tau_1^2 \sigma_i^2} + \frac{OJ\sigma_i^2 \tau_1}{\epsilon(B + \tau_1 \sigma_r)^2 + \epsilon \tau_1^2 \sigma_i^2} \right\} I_1 + \frac{J}{\epsilon} I_2 + \frac{\alpha a^2 \kappa_T}{\beta \nu} \right. \end{aligned}$$

$$\left(g_0 - \frac{\gamma M_0 \nabla H}{\rho_0 \alpha}\right) \left\{ \frac{\tau_1 (B-1)}{(B + \tau_1 \sigma_r)^2 + \tau_1^2 \sigma_i^2} \right\} (I_3 + E p_1 \sigma_r I_4) + \frac{\alpha a^2 \kappa_T}{\beta \nu} \left(g_0 - \frac{\gamma M_0 \nabla H}{\rho_0 \alpha}\right) \left\{ \frac{B + \tau_1 \sigma_r (1+B) + \tau_1^2 (\sigma_r^2 + \sigma_i^2)}{(B + \tau_1 \sigma_r)^2 + \tau_1^2 \sigma_i^2} \right\} E p_1 I_4 = 0 \quad (20)$$

It is obvious from Equation (19) that σ_r may be positive or negative which means that system may be stable or unstable.

Also, from Equation (20), it is obvious that if $g_0 \geq \frac{\gamma M_0 \nabla H}{\rho_0 \alpha}$, then the terms in the bracket are positive definite which implies that $\sigma_i = 0$. Therefore, oscillatory modes are not allowed and the principle of exchange of stabilities is satisfied if $g_0 \geq \frac{\gamma M_0 \nabla H}{\rho_0 \alpha}$.

6. Numerical Computation

The dispersion relation (17) is analyzed numerically also. Graphs were plotted between the Rayleigh number R_1 and the medium permeability parameter P , Rayleigh number R_1 and the suspended particles parameter B , Rayleigh number R_1 and the magnetization parameter M_0 (see Figures 1-5).

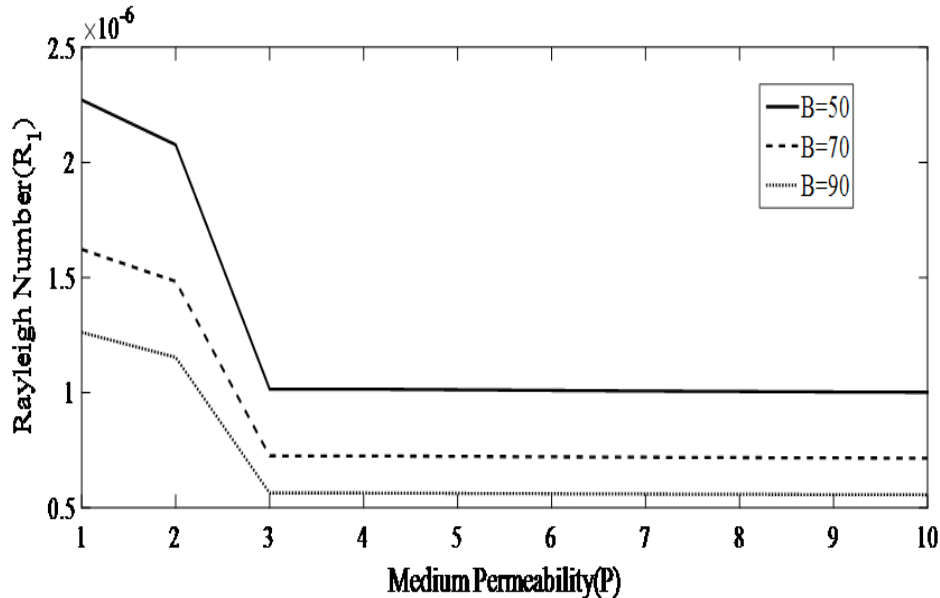
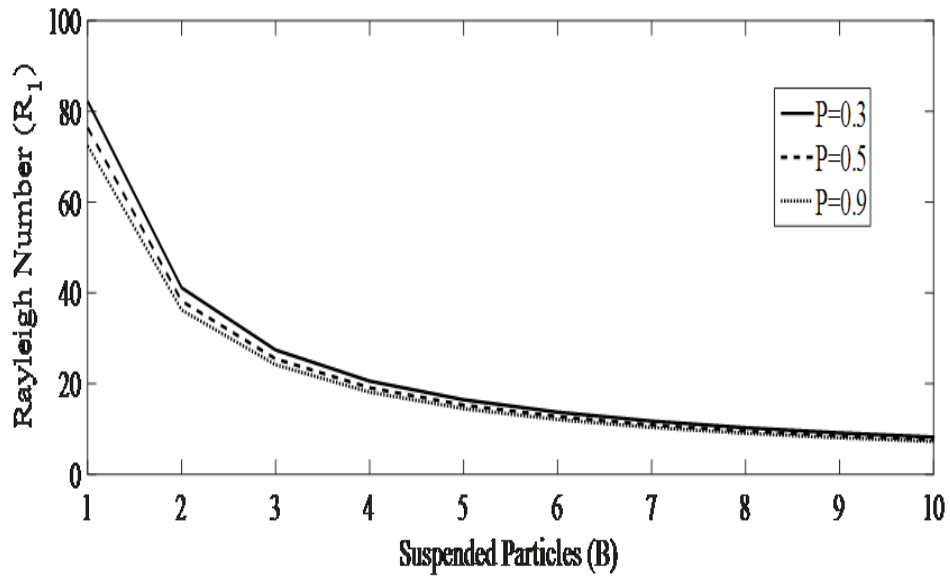
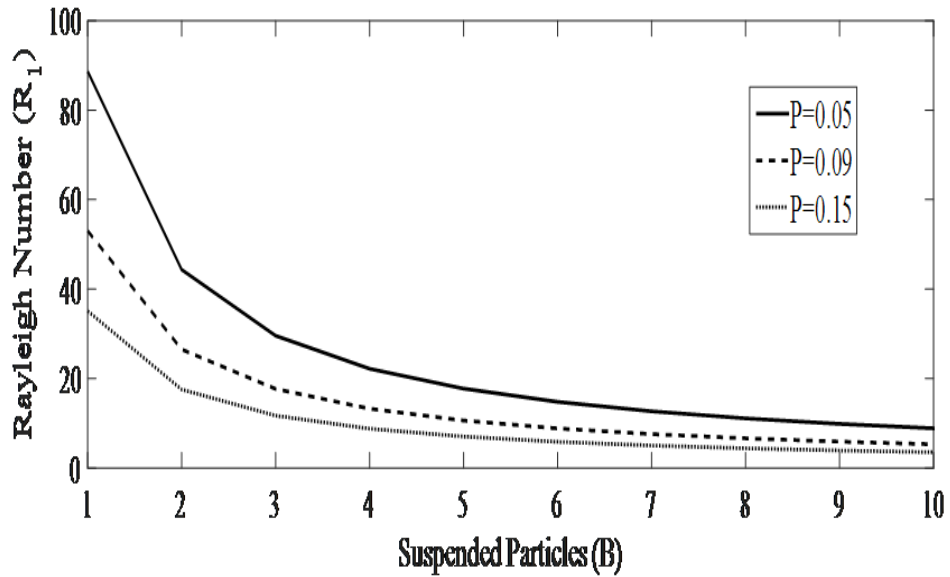
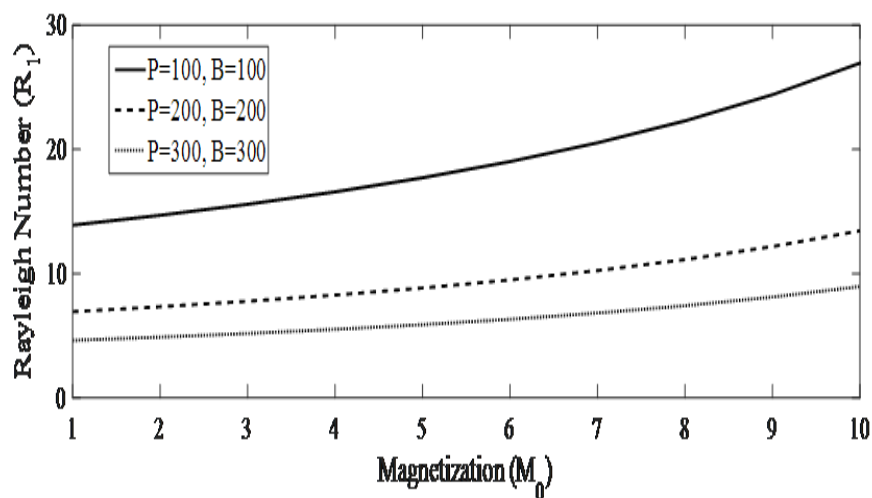
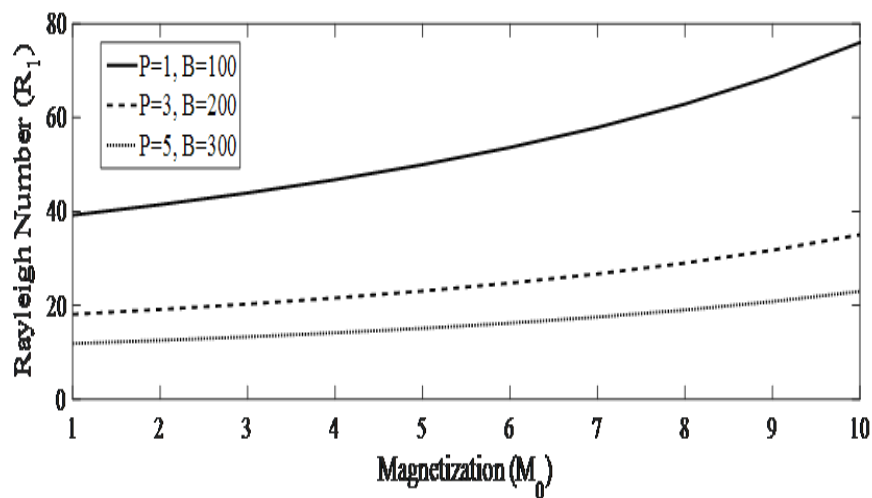


Figure 1: R_1 vs P for $\epsilon = 0.9$

Figure 2: R_1 vs B for $\epsilon = 0.1$ Figure 3: R_1 vs B for $\epsilon = 0.9$

Figure 4: R_1 vs M_0 for $\epsilon = 0.5$ Figure 5: R_1 vs M_0 for $\epsilon = 0.2$

These are some graphs plotted between critical Rayleigh number and the parameters (medium permeability, suspended particles and magnetization) for the different values of these parameters discussed as follows: Figure 1 shows the variation between critical Rayleigh number R_1 and the medium permeability parameter P for the different values of suspended particles parameter $B = 50, 70, 90$. Figure 2

and 3 show the variation between critical Rayleigh number R_1 and the suspended particle parameter B for the different values of the medium permeability parameter $P = 0.3, 0.5, 0.9$ and $P = 0.05, 0.09, 0.15$. Also, figure 4 and 5 show the variation between critical Rayleigh number R_1 and the magnetization parameter M_0 for the different values of medium permeability parameter $P = 100, 200, 300$, $B = 100, 200, 300$ (for figure 4) and $P = 1, 3, 5$, $B = 100, 200, 300$ (for figure 5).

7. Results and Discussion

This section summarizes and discusses the main findings of the work. In this paper, effect of suspended particles in a layer of Kuvshiniski Ferrofluid through a porous medium is investigated analytically and graphically using linear stability theory and normal mode technique, when this fluid layer is heated from below. 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,
 - (i) medium permeability has the destabilizing effect on the system.
 - (ii) suspended particles has the destabilizing effect on the system.
 - (iii) magnetization has a stabilizing effect on the system.
- Principle of exchange of stabilities is satisfied for the problem if $g_0 \geq \frac{\gamma M_0 \nabla H}{\rho_0 \alpha}$.
- Figure 1 shows the destabilizing effect between the critical Rayleigh number R_1 and the medium permeability parameter P for $\epsilon = 0.9$.
- Figure 2 and 3 show the destabilizing effect between the critical Rayleigh number R_1 and the suspended particle parameter B for $\epsilon = 0.1, 0.9$.
- Figure 4 and 5 show the stabilizing effect between the critical Rayleigh number R_1 and the magnetization parameter M_0 for $\epsilon = 0.5, 0.2$.

8. Conclusions

In the present study, it is examined that how suspended particles affects a Kuvshiniski Ferrofluid layer when heated from below and passes through a porous medium and found that suspended particles destabilizes the system for different values of the medium permeability parameter. Also, it is found that medium permeability and magnetization parameter destabilizes and stabilizes the system respectively. These effects on the system also show by the figures (1-5) in the numerical computation section. Furthermore, the oscillatory modes are not allowed on the system and the Principle of Exchange of stabilities is satisfied under certain conditions.

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