Gravity modulation effect on ferromagnetic convection in a Darcy-Brinkman layer of porous medium

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Abstract. The influence of a time-dependent body force on the threshold of convective instability in a magnetic fluid filled horizontal porous layer is investigated. The gravity modulation effect is treated by employing a perturbation method. The correction Rayleigh number is computed as a function of the modulation frequency, porous and magnetic parameters. It is expounded that, for small and reasonable values of the modulation frequency, gravity modulation and magnetic mechanism have opposing influence on the stability. The study further explicates that, when the gravity modulation frequency increases beyond all bounds, manifestation of the disappearance of the magnetic and porous medium effects on the stability is highly likely.

1. Introduction
Ferromagnetic fluids can come in handy for heat transfer related applications since they could be disciplined by an externally acting magnetic field. Owing to the idea that heat transfer could be critically enriched by virtue of ferroconvection, quite a few fascinating applications of magnetic fluids such as cooling with motors, loudspeakers and transmission lines have manifested (Bashtovoy et al [1]). Motivated by the fact that the magnetic force drastically modifies the critical values associated with the ferroconvective instability, several researchers attacked the ferroconvective instability problem with diverse range of constraints (Finlayson [2], Gupta and Gupta [3], Gotoh and Yamada [4], Stiles and Kagan [5], Abraham [6], Maruthamanikandan [7], Soya Mathew et al [8], Vishnu Ganeshet al [9] and Vataniet al [10]).

Taking advantage of the sophisticated phenomenon of vibrations resulting from magnetic field, boundary temperatures, rotation of the fluid layer and the like, several researchers studied the thermovibrational instability in both magnetic and non-magnetic fluid layers with a variety of modulation mechanisms in order to control the characteristics of heat transfer (Anisset al [11], Singh and Bajaj [12], Govender [13], Bhuvaneswari et al [14] and Sivasankaran et al [15]).

On the other hand, thermal convection induced by modulated gravitational forces has received much attention in recent time. The time dependent body force due to gravity has implications for space related experiments and crystal growth. It was reported by Wadihet al [16] that this fluctuating gravity can have a significant bearing on the convection mechanism. Govender [17] showed that porous medium convection is postponed with increasing frequency of vibrations due to a time varying gravitational field. Saravanan and Purusothaman [18] performed an investigation on gravity modulation effect in a porous medium which is considered anisotropic and showed that the synchronous instability mode is greatly affected by the non-Darcian effects. Malashetty and Begum
[19] analyzed porous medium convection problem of a Maxwell fluid undergoing thermal and gravity modulations. Nisha Mary and Maruthamanikandan [20] analysed the gravity modulation effect on the threshold of ferromagnetic convection in a porous medium of Darcian type and clarified that subcritical instability might exist provided the gravity modulation frequency is small enough. More recently, Maria Thomas and Sangeetha George [21] have examined the effect of second sound and volumetric heat source on the threshold of thermal instability in a couple-stress fluid undergoing gravity modulation effect. In this paper we would like to address the problem of ferroconvective instability induced by gravity modulation when the ferrofluid filled porous layer is of Darcy-Brinkman type.

Figure 1. Schematic of the problem.

2. Mathematical Formulation
We consider a magnetic fluid filled porous layer situated between two infinite horizontal surfaces \( z = 0 \) and \( z = h \) under the influence of a vertically acting uniform magnetic field \( H_0 \) and a gravity force varying with time \( \ddot{g} = (0, 0, -g(t)) \), where \( g(t) = g_0 \left( 1 + \varepsilon \cos \omega t \right) \), \( g_0 \) the mean gravity, \( \varepsilon \) the small amplitude, \( \omega \) the frequency and \( t \) the time. Let \( \Delta T \) be the gradient in temperature which is uniformly maintained between the upper and lower boundaries (see figure 1). The Boussinesq approximation is adopted to deal with the density variation and the local thermal equilibrium condition pertaining to the solid and fluid matrix is assumed.

The governing equations of the problem under consideration are (Finlayson [2], Malashetty and Padmavathi [22])

\[
\nabla \cdot \mathbf{q} = 0, \quad (1)
\]

\[
\rho_R \left[ \frac{1}{\varepsilon_p} \frac{\partial \mathbf{q}}{\partial t} + \frac{1}{\varepsilon_p} (\mathbf{q} \cdot \nabla) \mathbf{q} \right] = -\nabla p - \rho g_0 \left( 1 + \varepsilon \cos \omega t \right) \hat{k} - \frac{\mu_k}{k} \mathbf{q} + \mathbf{P} \mathbf{j} \nabla \dot{\mathbf{q}} + \nabla \cdot \left( \dot{H} \right), \quad (2)
\]

\[
\varepsilon_p C_l \left[ \frac{\partial T}{\partial t} + (\mathbf{q} \cdot \nabla) T \right] + (1 - \varepsilon_p) \left( \rho_R C_l \frac{\partial T}{\partial t} + \mu_o T \left( \frac{\partial \mathbf{q}}{\partial t} \right) \nabla \cdot \mathbf{H} \right) = K_1 \nabla^2 T, \quad (3)
\]

\[
\rho = \rho_R \left[ 1 - \alpha (T - T_R) \right], \quad (4)
\]

\[
\dot{M} = \frac{\dot{H}}{H} M (H, T), \quad (5)
\]

\[
M = M_0 + \chi (H - H_o) - K_m (T - T_R), \quad (6)
\]
where $\vec{q} = (u, v, w)$ is the velocity of fluid, $\rho$ the density, $\rho_R$ a reference density, $\varepsilon_p$ the porosity, $p$ the pressure, $\vec{H}$ the magnetic field, $\mu_f$ the dynamic viscosity, $k$ permeability of the porous medium, $\bar{\mu}_f$ is the effective viscosity, $\mu_o$ the magnetic permeability, $T$ the temperature, $\vec{M}$ the magnetization, $\vec{B}$ the magnetic induction, $K_1$ the thermal conductivity, $\alpha$ the coefficient of thermal expansion, $T_R$ a reference temperature and $C$ the specific heat. Here the subscript $s$ represents the solid and $C_V = \rho R C_{V,H} = \mu_o \vec{H} \left( \frac{\partial M}{\partial T} \right)_{V,H}$, where $C_{V,H}$ is the specific heat at constant volume and constant magnetic field, $\chi$ is the magnetic susceptibility and $K_m$ is the pyromagnetic coefficient. The surface temperatures are $T_R + \frac{\Delta T}{2}$ at $z = 0$ and $T_R - \frac{\Delta T}{2}$ at $z = h$.

The relevant Maxwell equations are

$$\nabla \cdot \vec{B} = 0, \quad \nabla \times \vec{H} = 0, \quad \vec{B} = \mu_0 \left( \vec{H} + \vec{M} \right). \quad \text{(7)}$$

2.1 Basic State

The quiescent basic state is represented by

$$\begin{align*}
\vec{q} &= \vec{q}_H = (0,0,0), \quad \rho = \rho_H(z), \quad p = p_H(z) \\
T &= T_H(z,t), \quad \vec{H} = \vec{H}_H, \quad \vec{M} = \vec{M}_H, \quad \vec{B} = \vec{B}_H.
\end{align*} \quad \text{(8)}$$

The temperature, pressure, magnetic field, magnetic induction and magnetization of the basic state satisfy the following equations

$$\begin{align*}
\vec{q} &= \vec{q}_H = (0,0,0), \quad \rho = \rho_H(z), \quad p = p_H(z) \\
T &= T_H(z,t), \quad \vec{H} = \vec{H}_H, \quad \vec{M} = \vec{M}_H, \quad \vec{B} = \vec{B}_H.
\end{align*}$$

$$\rho_H = \rho_R \left[ 1 - \alpha \Delta T \left( \frac{1}{2} - \frac{z}{h} \right) \right], \quad H_H = H_{0} + K_m \Delta T \left( \frac{1}{2} - \frac{z}{h} \right), \quad B_H = \mu_0 (M_{0} + H_{0}).$$

In what follows we examine the stability of the system by means of the linear stability analysis.

3. Linear Stability Analysis

Infinitesimal perturbations are used to perturb the basic state so that

$$\begin{align*}
\vec{q} &= \vec{q}_H + \vec{q}', \quad p = p_H + p', \quad \rho = \rho_H + \rho', \quad T = T_H + T' \\
\vec{H} &= \vec{H}_H + \vec{H}', \quad \vec{M} = \vec{M}_H + \vec{M}'.
\end{align*} \quad \text{(10)}$$

where primes indicate the infinitesimal disturbances. Use of equation (10) into equations (1) – (7) and making use of the solution pertaining to the basic state, one obtains

$$\nabla \cdot \vec{q}' = 0, \quad \text{(11)}$$

$$\rho' = -\alpha \rho R T', \quad \text{(12)}$$

In what follows we examine the stability of the system by means of the linear stability analysis.
\[
\frac{\rho R}{\varepsilon p} \frac{\partial \vec{q}}{\partial t} = -\nabla p' - \rho' \bar{\rho}_o \left( 1 + e \cos \bar{\omega} t \right) \hat{k} - \frac{\mu_f}{k} q' + \bar{R}_f v^2 q' + \mu_o \left( M_o + H_o \right) \frac{\partial \vec{H}'}{\partial z} \tag{13}
\]

\[
- \frac{\mu_o K_m}{(1 + \chi)} \left( \frac{\Delta T}{h} \right) \left[ (1 + \chi) H'_3 - K_m T' \right] \hat{k},
\]

\[
C_2 \frac{\partial T'}{\partial t} - \varepsilon_p C_1 \left( \frac{\Delta T}{h} \right) w' - \mu_o K_m T R \frac{\partial}{\partial t} \left( \frac{\partial \phi'}{\partial \bar{z}} \right) + \frac{\mu_o K_m T R}{(1 + \chi)} \left( \frac{\Delta T}{h} \right) w' = K_1 \nabla^2 T', \tag{14}
\]

\[
\left[ 1 + \frac{M_o}{H_o} \right] \nabla^2 \phi' + \frac{\mu_o K_m T R}{(1 + \chi)} \frac{\partial T'}{\partial \bar{z}} - K_m \frac{\partial T'}{\partial \bar{z}} = 0. \tag{15}
\]

where \( C_2 = \varepsilon_p C_1 + \left( 1 - \varepsilon_p \right) \left( \rho_o C \right) \), \( \vec{q}' = (u', v', w') \), \( \vec{H}' = \nabla \phi' \) with \( \phi' \) being the magnetic potential.

Eliminating the pressure term \( p' \) and using the transformations \( \left( x, y, \bar{z} \right) = \left( \frac{x}{h}, \frac{y}{h}, \frac{z}{h} \right) \),

\[
w' = \frac{C_1 h}{K_1} w', \quad T' = \frac{T'}{\Delta T}, \quad \phi' = \frac{(1 + \chi) \phi}{K_m \Delta T h},
\]

one obtains (after ignoring the asterisks)

\[
\left( \frac{1}{Pr} \frac{\partial}{\partial t} + D_a^2 - \Lambda \nabla^2 \right) \nabla^2 w = \left[ R \left( 1 + e \cos \omega t \right) + RM_1 \right] \nabla^2 T - RM_1 \frac{\partial}{\partial \bar{z}} \left( \nabla^2 \phi \right) \tag{16},
\]

\[
\lambda_p \frac{\partial T}{\partial t} - w - M_2 \frac{\partial}{\partial \bar{z}} \left( \frac{\partial \phi}{\partial \bar{z}} \right) + M_2 w = \nabla^2 T. \tag{17}
\]

\[
\left( \frac{\partial^2}{\partial \bar{y}^2} + M_3 \nabla^2 \right) \phi = \frac{\partial T}{\partial \bar{z}}. \tag{18}
\]

where \( \lambda_p = \frac{C_2}{C_1}, \phi \) is the dimensionless frequency of modulation given by \( \bar{\omega} = \frac{C_1 h^2}{K_1} \omega \),

\[
\nabla^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} \text{ and } \nabla^2 = \frac{\partial^2}{\partial \bar{y}^2} + \frac{\partial^2}{\partial \bar{z}^2}. \] The dimensionless parameters are \( Pr = \frac{\gamma}{\kappa} \), the Prandtl number, \( R = \frac{\alpha \bar{g}_o \Delta T h^3}{\gamma \kappa} \), the Darcy-Rayleigh number, \( M_1 = \frac{\mu_o K_m \Delta T}{(1 + \chi) \alpha \bar{g}_o \rho R h} \), the buoyancy magnetization parameter, \( M_2 = \frac{\mu_o K_m T R}{(1 + \chi) C_2} \), the magnetization parameter, \( M_3 = \frac{M_o + H_o}{H_o (1 + \chi)} \), the non-buoyancy magnetization parameter, the porous parameter \( D_a = \frac{h}{\sqrt{k}} \), and \( \Lambda = \frac{\bar{R}_f}{m_f} \), the Brinkman number with \( \kappa = \frac{K_1}{C_1} \) and \( \gamma = \frac{\mu_f}{\rho R} \).

Since the typical values of \( M_2 \) are negligibly small (Finlayson [2]), we neglect \( M_2 \) and proceed further. The appropriate boundary conditions are (Nisha Mary and Maruthamanikandan [20] and Malashetty and Padmavathi [22]).
\[ w = \frac{\partial^2 w}{\partial z^2} = T = \frac{\partial \phi}{\partial z} = 0 \text{ at } z = 0, 1. \quad (19) \]

It is convenient to express the equations in terms of \( w \) alone. Upon combining equations (16) – (18), one obtains the following equation

\[ \left( \frac{1}{Pr} \frac{\partial}{\partial t} + D_\alpha^2 - \Lambda \nabla^2 \right) \left( \frac{\partial^2}{\partial z^2} + M_3 \nabla_1^2 \right) \nabla^2 w = R \left( 1 + \varepsilon f \right) \left( \frac{\partial^2}{\partial z^2} + M_3 \nabla_1^2 \right) \nabla_1^2 w + R M_3 \nabla_1^4 w, \]

where \( f(t) = \cos \omega t \). The boundary conditions accordingly take the form (Chandrasekhar [23])

\[ w = \frac{\partial^2 w}{\partial z^2} = \frac{\partial^4 w}{\partial z^4} = \frac{\partial^6 w}{\partial z^6} = 0 \text{ at } z = 0, 1. \quad (21) \]

4. Method of Solution

Solution of equation (20) is based on the perturbation method and the same is taken to be

\[ (w, R) = (w_o, R_o) + \varepsilon (w_1, R_1) + \varepsilon^2 (w_2, R_2) + \cdots \quad (22) \]

where \( R_o \) is the Darcy-Rayleigh number for the problem at hand without modulation effect. The expression for \( R_o \) turns out to be

\[ R_o = \frac{D_\alpha^2 + \Lambda \left( \alpha^2 + \pi^2 \right) \left( \pi^2 + M_3 \alpha^2 \right) \left( \pi^2 + \alpha^2 \right)^2}{\alpha^2 \left[ \pi^2 + M_3 \left( 1 + M_4 \right) \alpha^2 \right]} \quad (23) \]

where \( \alpha^2 = l^2 + m^2 \) being overall horizontal wavenumber \( l \) and \( m \) being wavenumbers in \( x \) and \( y \) directions respectively. Following the analysis of Malashetty and Padmavathi [22], one obtains the following expression for \( R_2 \)

\[ R_2 = K_3 \sum_{n=1}^{\infty} \left( n^2 \pi^2 + M_3 \alpha^2 \right) \frac{C_n}{D_n} \quad (24) \]

where

\[ K_3 = \frac{R_o^2 \alpha^2 \left( \pi^2 + M_3 \alpha^2 \right)}{2 \left[ \pi^2 + M_3 \left( 1 + M_4 \right) \alpha^2 \right]} \]

\[ C_n = \frac{\lambda \rho}{Pr} \omega^2 \left( n^2 \pi^2 + \alpha^2 \right) \left( n^2 \pi^2 + M_3 \alpha^2 \right) - D_\alpha^2 \left( n^2 \pi^2 + \alpha^2 \right)^2 \left( n^2 \pi^2 + M_3 \alpha^2 \right) - \Lambda \left( n^2 \pi^2 + \alpha^2 \right)^3 \left( n^2 \pi^2 + M_3 \alpha^2 \right) + R_o \alpha^2 \left[ n^2 \pi^2 + M_3 \left( 1 + M_4 \right) \alpha^2 \right]. \]

\[ D_n = A_1^2 + A_2^2 \]

with
\[ A_1 = \frac{\lambda \rho}{Pr} \omega^2 \left( n^2 \pi^2 + \alpha^2 \right) \left( n^2 \pi^2 + M_3 \alpha^2 \right) - D_\alpha^2 \left( n^2 \pi^2 + \alpha^2 \right)^2 \left( n^2 \pi^2 + M_3 \alpha^2 \right) \]

\[ - \Lambda \left( n^2 \pi^2 + \alpha^2 \right)^3 \left( n^2 \pi^2 + M_3 \alpha^2 \right) + R_0 a^2 \left[ n^2 \pi^2 + M_3 \left( 1 + M_1 \right) \alpha^2 \right]. \]

and

\[ A_2 = \frac{\omega}{Pr} \left( n^2 \pi^2 + \alpha^2 \right)^2 \left( n^2 \pi^2 + M_3 \alpha^2 \right) + \omega D_\alpha^2 \lambda \rho \left( n^2 \pi^2 + \alpha^2 \right) \left( n^2 \pi^2 + M_3 \alpha^2 \right) \]

\[ + \omega \Lambda \lambda \rho \left( n^2 \pi^2 + \alpha^2 \right)^2 \left( n^2 \pi^2 + M_3 \alpha^2 \right). \]

The Rayleigh number \( R \) at its critical value is calculated up to \( O(\varepsilon^2) \) by computing \( R_0 \) and \( R_2 \) at \( \alpha_0 = \alpha_c \), where \( \alpha_c \) is the value at which \( R_0 \) is minimum. Supercritical instability occurs provided \( R_{2c} \) is positive. On the other hand, subcritical instability is said to occur when \( R_{2c} \) turns out to be negative.

5. Results and Discussion
The effect of gravity field varying with time on ferromagnetic porous medium convection has been examined analytically. Considering small amplitude of modulation and employing the regular perturbation method, the correction Darcy-Rayleigh number \( R_{2c} \) is established to be dependent on the modulation frequency \( \omega \), magnetic parameters \( M_1 \) and \( M_3 \), Prandtl number \( Pr \), porous parameter \( D_\alpha \) and Brinkman number \( \Lambda \).

![Figure 2](image)

Figure 2. \( R_{2c} \) variation with respect to \( \omega \) and \( M_1 \).

Variation of \( R_{2c} \) with modulation frequency \( \omega \) is exhibited in figures 2 – 6. It is seen that when \( \omega \) is small enough, \( R_{2c} \) happens to be negative implying the destabilising effect of modulated gravity field. However, when \( \omega \) is moderate as well as large enough, the opposite effect is observed as \( R_{2c} \) is
positive. It is therefore made plain that subcritical instability is possible as long as $\omega$ is small enough and supercritical instability exists otherwise.

![Graph](image)

**Figure 3.** $R_{2c}$ variation with respect to $\omega$ and $M_3$.

The influence of buoyancy magnetization parameter $M_1$ on the stability is presented in figure 2. The parameter $M_1$ is the ratio of forces due to magnetization to gravitational force. Clearly $R_{2c}$ increases with an increase in $M_1$ provided that $\omega$ is small.

![Graph](image)

**Figure 4.** $R_{2c}$ variation with respect to $\omega$ and $Pr$.

However, the trend reverses provided $\omega$ is moderate and large. Also, the magnetic mechanism diminishes the influence of gravity modulation. Further, the negligible influence of $M_1$ on stability could be perceived when $M_1$ is sufficiently large.
Figure 5. $R_{2c}$ variation with respect to $\omega$ and $D_a$.

Figure 3 depicts the deviation of $M_3$ with respect to $R_{2c}$. The magnetic parameter $M_3$ takes care of the departure of linearity in the magnetic equation of state. The results concerning figure 3 are qualitatively similar to that of figure 2. It therefore follows that the contribution of $M_3$ is to lessen the effect of gravity modulation.

Figure 6. $R_{2c}$ variation with respect to $\omega$ and $A$.

Figures 4–6 portray the deviations in $Pr$, $D_a$ and $A$ respectively over the critical correction Darcy-Rayleigh number. It is tacit that $R_{2c}$ decreases when the values of $Pr$, $D_a$ and $A$ are increased thus implying the augmenting convective effect of all the three parameters on ferromagnetic convection.
However, the reverse effect of the Brinkman number $\Lambda$ on stability is noticed provided $\omega$ is considerably large. Equivalently $\Lambda$ has a stabilizing effect when $\omega$ is large enough.

6. Conclusions
Gravity modulation effect on ferromagnetic porous medium convection is studied using the method of regular perturbation. The investigation has led to the following conclusions:

- Subcritical instability manifests by virtue of gravity modulation for low frequency.
- Gravity modulation and the magnetic mechanism have mutually antagonistic effect on the system provided the gravity modulation frequency is small as well as moderate.
- Prandtl number augments the amplifying effect of gravity modulation irrespective of the range of frequency.
- Effects of magnetic force, porous medium and gravity modulation disappear when the frequency of the time-periodic body force is considerably large.

In conclusion, the threshold of ferromagnetic porous medium convection could be hastened or delayed through gravity modulation by tuning the frequency of gravitational modulation. Hence the gravity modulation and porous mechanisms could be exploited to straighten out issues arising in situations involving convective instability of ferromagnetic fluids.

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