Effect of Cubic Temperature Profiles on Ferroconvection in a Brinkman Porous Medium

C. E. Nanjundappa¹, I. S. Shivakumara² and R. Arunkumar ³†

¹ Department of Mathematics, Dr. Ambedkar Institute of Technology, Bangalore -560 056, India
² UGC-Centre for Advanced Studies in Fluid Mechanics, Department of Mathematics, Bangalore University, Bangalore – 560 001, India
³ Department of Mathematics, Sai Vidya Institute of Technology, Bangalore- 560 064, India

†Corresponding Author Email: rakrrce@gmail.com
(Received December 23, 2014; accepted July 29, 2015)

ABSTRACT

The effect of cubic temperature profiles on the onset ferroconvection in a Brinkman porous medium in presence of a uniform vertical magnetic field is studied. The lower and upper boundaries are taken to be rigid-isothermal and ferromagnetic. The Rayleigh-Ritz method with Chebyshev polynomials of the second kind as trial functions is employed to extract the critical stability parameters numerically. The results indicate that the stability of ferroconvection is significantly affected by cubic temperature profiles and the mechanism for suppressing or augmenting the same is discussed in detail. It is observed that the effect of Darcy number $Da$, magnetic number $M$, and nonlinearity of the fluid magnetization parameter $M_3$ is to hasten, while an increase in the ratio of viscosity parameter $\lambda$ and Biot number $Bi$ is to delay the onset of ferroconvection in a Brinkman porous medium. Further, increase in $Bi$, $M_1$, $M_3$ and decrease in $\lambda$, $Da$ is to decrease the size of the convection cells.

Keywords: Ferrofluid; Cubic temperature profiles; Ferro convection in Brinkman porous medium; Rayleigh- Ritz technique.

NOMENCLATURE

<table>
<thead>
<tr>
<th>Variable</th>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall horizontal wave number</td>
<td>$a$</td>
<td></td>
</tr>
<tr>
<td>Magnetic induction field</td>
<td>$B$</td>
<td></td>
</tr>
<tr>
<td>Biot number</td>
<td>$Bi$</td>
<td></td>
</tr>
<tr>
<td>Specific heat at constant volume and magnetic field</td>
<td>$C_{v,H}$</td>
<td></td>
</tr>
<tr>
<td>Magnetic field intensity</td>
<td>$H$</td>
<td></td>
</tr>
<tr>
<td>Darcy number</td>
<td>$Da$</td>
<td></td>
</tr>
<tr>
<td>Heat transfer coefficient</td>
<td>$h_t$</td>
<td></td>
</tr>
<tr>
<td>Permeability of the porous medium</td>
<td>$k$</td>
<td></td>
</tr>
<tr>
<td>Pyromagnetic coefficient</td>
<td>$K$</td>
<td></td>
</tr>
<tr>
<td>Magnetization</td>
<td>$M$</td>
<td></td>
</tr>
<tr>
<td>Constant mean value of magnetization</td>
<td>$M_0$</td>
<td></td>
</tr>
<tr>
<td>Magnetic number</td>
<td>$M_1$</td>
<td></td>
</tr>
<tr>
<td>Magnetic parameter</td>
<td>$M_2$</td>
<td></td>
</tr>
<tr>
<td>Nonlinearity of magnetization parameter</td>
<td>$M_3$</td>
<td></td>
</tr>
<tr>
<td>Pressure</td>
<td>$p$</td>
<td></td>
</tr>
<tr>
<td>Velocity vector</td>
<td>$\vec{q}$</td>
<td></td>
</tr>
<tr>
<td>Magnetic vector</td>
<td>$\vec{R}_m$</td>
<td></td>
</tr>
<tr>
<td>Magnetic Rayleigh number</td>
<td>$R_m$</td>
<td></td>
</tr>
<tr>
<td>Thermal Rayleigh number</td>
<td>$R_t$</td>
<td></td>
</tr>
<tr>
<td>Temperature</td>
<td>$T$</td>
<td></td>
</tr>
<tr>
<td>Basic temperature</td>
<td>$T_b$</td>
<td></td>
</tr>
<tr>
<td>Average temperature</td>
<td>$\bar{T}$</td>
<td></td>
</tr>
<tr>
<td>Amplitude of vertical perturbed velocity</td>
<td>$W$</td>
<td></td>
</tr>
<tr>
<td>Thermal expansion coefficient</td>
<td>$\alpha_t$</td>
<td></td>
</tr>
<tr>
<td>Magnetic susceptibility</td>
<td>$\chi$</td>
<td></td>
</tr>
<tr>
<td>Porosity of the porous medium</td>
<td>$\varepsilon$</td>
<td></td>
</tr>
<tr>
<td>Del operator</td>
<td>$\nabla$</td>
<td></td>
</tr>
<tr>
<td>Laplacian operator</td>
<td>$\nabla^2$</td>
<td></td>
</tr>
<tr>
<td>Horizontal Laplacian operator</td>
<td>$\nabla^2_h$</td>
<td></td>
</tr>
<tr>
<td>Thermal diffusivity</td>
<td>$\kappa$</td>
<td></td>
</tr>
<tr>
<td>Ratio of viscosities</td>
<td>$\lambda$</td>
<td></td>
</tr>
</tbody>
</table>
\[ \mu \quad \text{dynamic viscosity} \]
\[ \mu_0 \quad \text{free space magnetic permeability of vacuum} \]
\[ \phi \quad \text{perturbed magnetic potential} \]
\[ \Phi \quad \text{amplitude of perturbed magnetic potential} \]
\[ \rho \quad \text{density} \]
\[ \rho_0 \quad \text{reference density at } T_0 \]
\[ \theta \quad \text{amplitude of perturbed temperature} \]
\[ \omega \quad \text{growth rate} \]

1. INTRODUCTION

Ferrofluids are stable colloidal suspensions of magnetic nano-particles suspended in a carrier liquid with low electrical conductivity. In the absence of an external magnetic field the magnetic moments of the particles are randomly orientated and there is no net macroscopic magnetization. In an external magnetic field, however, the magnetic moments of particles easily orient and a large (induced) magnetization prevails. There are two additional features in ferrofluids not found in ordinary fluids, the Kelvin force and the body couple (Rosensweig 1985). In addition, in an external magnetic field, a ferrofluid exhibits additional rheological properties such as a field-dependent viscosity, special adhesion properties, and a non-Newtonian behavior, among others (Odenbach 2003). The theory of thermal convective instability in a ferrofluid layer began with Finlayson (1970) and extensively continued over the years (Stiles and Kagan 1990, Ganguly et al. 2004, Nanjundappa et al. 2008, Shivakumara et al. 2012, Nanjundappa et al. 2015).

Thermal convection of ferrofluids saturating a layer of porous medium has also attracted considerable attention in the literature owing to its importance in controlled emplacement of liquids or treatment of chemicals and emplacement of geophysically imageable liquids into particular zones for subsequent imaging etc. Rosensweig et al. (1978) have studied experimentally the penetration of ferrofluids in the Hele-Shaw cell. The stability of the magnetic fluid penetration through a porous medium in high uniform magnetic field oblique to the interface is studied by Zhan and Rosensweig (1980). The thermal convection of ferrofluid saturating a porous medium in the presence of a vertical magnetic field is studied by Vaidyanathan et al. (1991) by employing the Brinkman equation. Qin and Chadam (1995) have carried out the non-linear stability analysis of ferroconvection in a porous layer by including the inertial effects to accommodate high velocity. The experimental results of the behavior of ferrofluids in porous media consisting of sands and sediments are presented in detail by Borglin et al. (2000). Sunil and Mahajan (2008) have used generalized energy method to study nonlinear convection in a magnetized ferrofluid saturated porous layer heated uniformly from below for the stress-free boundaries case. Shivakumara et al. (2009) have investigated theoretically the onset of convection in a layer of ferrofluid saturated porous medium for various types of velocity and temperature boundary conditions. Sunil et al. (2011) have investigated the effect of rotation in a magnetized ferrofluid with internal angular momentum, heated and soluted from below subject to transverse uniform magnetic field. Nanjundappa et al. (2012) have explored a model for penetrative ferroconvection via internal heat generation in a ferrofluid saturated porous layer using the Brinkman-Lapwood extended Darcy equation with fluid viscosity different from effective viscosity to describe the flow of porous medium. Nanjundappa et al. (2013) have investigated the effect of penetrative ferroconvection via internal heat generation in a ferrofluid anisotropic porous layer theoretically using a Brinkman extended-Darcy equation with fluid viscosity different from effective viscosity. Nanjundappa et al. (2014) have studied effect of cubic temperature profiles and MFD viscosity on Benard-Marangoni ferroconvection with convective surface boundary conditions. Recently, Ram et al. (2014) have studied the effect of viscous dissipation and variable viscosity on rotationally symmetric ferrofluid flow in porous medium subjected to applied vertical magnetic field.

The objective of the present paper is to make clear the effects of cubic temperature profiles on the onset of ferroconvection in a Brinkman porous medium in the presence of a uniform vertical magnetic field. In investigating the problem, the lower and upper boundaries are taken to be rigid-isothermal and ferromagnetic. The study helps in understanding control of ferroconvection by cubic temperature profiles in a Brinkman porous medium, which is useful in many heat transfer related problems. The resulting eigenvalue problem is solved numerically by employing the Rayleigh Ritz method with Chebyshev polynomials of the second kind as trial functions.

2. MATHEMATICAL FORMULATION

The system considered is an initially quiescent magnetic fluid saturated horizontal porous layer of characteristic thickness \( d \) in the presence of an applied magnetic field \( H_0 \) in the vertical direction. The physical configuration is as shown in Fig. 1. The horizontal extension of the porous layer is sufficiently large so that edge effects may be neglected. A Cartesian co-ordinate system \( (x, y, z) \) is used with the origin at the bottom of
the porous layer and \( z \)-axis is directed vertically upward. Gravity acts in the negative \( z \)-direction, \( \vec{g} = -g \hat{k} \), where \( \hat{k} \) is the unit vector in the \( z \)-direction.

\[ H_b(z) = \left[ H_0 - \frac{K \beta z}{1 + \chi} \right] \hat{k} \]
\[ \vec{M}_b(z) = \left[ M_0 + \frac{K \beta z}{1 + \chi} \right] \hat{k} \]

To study the stability of the system, we perturb all the variables in the form
\[
[q, p, T, \vec{H}, \vec{M}] = [q', p_b(z) + p', \bar{T}_b(z) + T', \bar{H}_b(z) + \vec{H}', \bar{M}_b(z) + \vec{M}']
\]

where, \( q', p', T', \vec{H}' \) and \( \vec{M}' \) are perturbed variables and are assumed to be small.

Substituting Eq. (9) into momentum Eq. (2), linearizing, eliminating the pressure term by operating curl twice, the \( z \)-component of the resulting equation is:
\[ \rho_0 \frac{\partial}{\partial t} + \frac{\mu}{k} \mu_k T f(z) \frac{\partial}{\partial z} \left( \frac{\partial^2 \varphi}{\partial z^2} \right) - \rho_0 k f(z) \frac{\partial}{\partial z} \left( \frac{\partial^2 \varphi}{\partial z^2} \right) = k \nabla^2 T \]

As before, substituting Eq. (9) into energy Eq. (3), linearizing, we obtain (after neglecting primes)
\[ \left( \rho_0 C_v \frac{\partial T}{\partial t} - \rho_0 k T f(z) \frac{\partial}{\partial z} \left( \frac{\partial^2 \varphi}{\partial z^2} \right) \right) \left( \frac{\partial}{\partial z} \left( \frac{\partial^2 \varphi}{\partial z^2} \right) \right) = k \nabla^2 T \]

where,
\[ (\rho_0 C_v) = \rho_0 C_v + \epsilon \mu_0 H_0 K + (1 - \epsilon) (\rho_0 C_v) \]
and \( (\rho_0 C_v) = \rho_0 C_v + \epsilon \mu_0 H_0 K \).

Equations (4a, b), after substituting Eq. (9), may be written as (after dropping the primes)
\[ \left( 1 + \frac{M_0}{H_0} \right) \nabla^2 \varphi + (1 + \chi) \frac{\partial^2 \varphi}{\partial z^2} - K \frac{\partial^2 \varphi}{\partial z^2} = 0 \]

Since there are no physical mechanisms to introduce oscillatory motions, the principle of exchange of stability is assumed to be valid and hence the normal mode expansion of the dependent variables are taken in the form
\[ \{ w, T, \varphi \} = \{ W(z), \Theta(z), \Phi(z) \} \exp(i(\ell x + m y)) \]

where, \( \ell \) and \( m \) are wave numbers in the \( x \) and \( y \) directions, respectively.

Substituting Eq. (13) into Eqs. (10)-(12) and non-dimensionalizing the variables by setting
\[
(x^*, y^*, z^*) = \left( \frac{x}{d}, \frac{y}{d}, \frac{z}{d} \right), \quad f(z) = \frac{1}{\beta} f(z),
\]
\[
W^* = \frac{vA}{v}, \quad \Theta^* = \frac{\kappa}{\beta v} \Theta, \quad \Phi^* = \frac{(1 + \chi^2) k^2}{\beta v \beta v} \Phi
\]

where, \( v = \eta_0 / \rho_0 \) is the kinematic viscosity,
\[ \kappa = k/\left(\rho C_\ell\right)_2 \] is the thermal diffusivity and \( A = \left(\rho C_\ell\right)_1/\left(\rho C_\ell\right)_2 \) is the ratio of heat capacities, we obtain (after ignoring the asterisks)

\[
\left[\lambda(D^2 - a^2) - Da^{-1}\right]\left[D^2 - a^2\right]W = a^2 W = a^2 R_i \Theta - a^2 R_m f(z) [D \Phi - \Theta] = 0.
\]  

(15)

\[
(D^2 - a^2) \Theta = -(1 - M_2) W f(z) \]

(16)

\[
(D^2 - a^2 M_3) \Phi - D \Theta = 0.
\]  

(17)

In the above equations, \( D \) is the differential operator, \( a \) the overall horizontal wave number, \( R_i \) the thermal Rayleigh number, \( R_m \) the magnetic Rayleigh number, \( Da^{-1} \) the inverse Darcy number, \( \lambda \) the non-dimensional viscosity ratio parameter, \( M_3 \) the measure of nonlinearity of fluid magnetization parameter. The typical value of \( M_3 \) for magnetic fluids with different carrier liquids turns out to be of the order of \( 10^{-6} \) and hence its effect is neglected as compared to unity. The non-dimensional basic temperature gradient \( f(z) \) is given by

\[ f(z) = a_1^* + 2 a_2^*(z - 1) + 3 a_3^*(z - 1)^2. \]  

(18)

Three types of basic temperature gradients are considered for discussion as mentioned below.

<table>
<thead>
<tr>
<th>Reference steady-state temperature gradients</th>
<th>( f(z) )</th>
<th>( a_1^* )</th>
<th>( a_2^* )</th>
<th>( a_3^* )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linear</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Cubic 1</td>
<td>3(z - 1)^2</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Cubic 2</td>
<td>0.66 + 1.02(z - 1)^2</td>
<td>0.66</td>
<td>0</td>
<td>0.34</td>
</tr>
</tbody>
</table>

Equations (15)-(17) are solved using the following boundary conditions:

\[ W = DW = \Theta = \Phi = 0 \quad \text{at} \quad z = 0 \]

\[ W = DW = D\Theta + Bi \Theta = \Phi = 0 \quad \text{at} \quad z = 1 \]  

(19a, b)

where, \( Bi \) is the Biot number. The case \( Bi = 0 \) and \( Bi \to \infty \) respectively correspond to constant heat flux and isothermal conditions at the upper boundary.

3. METHOD OF SOLUTION

Equations (15)-(17) together with the corresponding boundary conditions constitute an eigenvalue problem with thermal Rayleigh number \( R_i \) as an eigenvalue. The resulting eigenvalue problem is solved numerically using the Rayleigh Ritz method. In this method, the test (weighted) functions are the same as the base (trial) functions. Accordingly, \( W \), \( \Theta \) and \( \Phi \) are written as

\[ W = \sum_{i=1}^n A_i W_i(z), \]

\[ \Theta(z) = \sum_{i=1}^n C_i \Theta_i(z), \]

\[ \Phi(z) = \sum_{i=1}^n D_i \Phi_i(z) \]

where, the trial functions \( W_i(z), \Theta_i(z) \) and \( \Phi_i(z) \) will be generally chosen in such a way that they satisfy the respective boundary conditions, and \( A_i, C_i \) and \( D_i \) are constants.

We select the trial functions as

\[ W_i = (z^4 - 2z^3 + z^2) T_{i-1}^*, \quad \Theta_i = z(1 - z^2) T_{i-1}^*, \]

\[ \Phi_i = (z^2 - z) T_{i-1}^*. \]  

(21)

where, \( T_{i-1}^* \)'s are the Chebyshev polynomials of the second kind. Substituting Eq.(20) into Eqs.(15)-(17), multiplying the resulting momentum Eq. (15) by \( W_j(z) \), energy Eq. (16) by \( \Theta_j(z) \) and magnetic potential Eq. (17) by \( \Phi_j(z) \), performing the integration by parts with respect to \( z \) between \( z = 0 \) and \( z = 1 \) and using the boundary conditions (19a, b), we obtain a system of linear homogeneous algebraic equations in \( A_i, C_i \) and \( D_i \). A nontrivial solution to the system requires the characteristic determinant of the coefficient matrix must vanish and this leads to a relation in the form

\[ f(R_i, \lambda, Da^{-1}, Bi, M_1, M_3, a_1^*, a_2^*, a_3^*, a) = 0 \]  

(22)

The critical values of \( R_i \) are found as a function of wave number \( a \) for various values of physical parameters.

4 RESULTS AND DISCUSSIONS

The linear stability analysis is carried out to investigate the effect of different forms of basic temperature profiles on the onset of ferroconvection in a ferrofluid Brinkmann porous layer. The bounding surfaces of the ferrofluid layer are considered to be rigid ferromagnetic and the resulting eigenvalue problem is solved numerically by employing the Galerkin technique. The results presented here are for \( i = j = 6 \) the order at which the convergence is achieved, in general.

Figure 2(a) represents the variation of critical thermal Rayleigh number \( R_i \) as a function of \( Da^{-1} \) for various values of ratio of viscosity parameter \( \lambda \). It is observed that an increase in \( \lambda \) is to delay the onset of ferroconvection. This is because increase in the value of \( \lambda \) is related to increase in viscous effect which has the tendency to retard the fluid flow and hence higher heating is required for the onset of ferroconvection.
In other words, higher value of \( \lambda \) is more effective in suppression of ferroconvection in a ferrofluid saturated porous medium. It is seen that \( R_{nc} \) increases with increasing \( Da^{-1} \) and hence its effect is to delay the onset of ferroconvection. For a fixed thickness of the porous layer, increase in \( Da^{-1} \) leads to decrease in the permeability of the porous medium which in turn retards the flow of ferrofluid. Therefore, higher heating and hence higher value of thermal Rayleigh number is required for the onset of ferroconvection in a porous medium. Moreover, \( (R_{nc})_{\text{linear}} < (R_{nc})_{\text{cubic2}} < (R_{nc})_{\text{cubic1}} \) suggesting cubic 1 basic temperature profile is more stabilizing than cubic 2 temperature profile and the linear temperature profile is the least stable. Thus, it is possible to control ferroconvection in a Brinkmann porous medium effectively by the choice of different forms of basic temperature profiles. The variation in critical wave number \( \lambda_c \) as a function of \( Da^{-1} \) is elucidated in Fig. 2(b) for different forms of basic temperature profile with different values of \( \lambda \). It may be noted that the critical wave number \( \lambda_c \) increases with increasing \( Da^{-1} \). Moreover, an increase in the value of \( \lambda \) is to decrease \( \lambda_c \) and hence its effect is to reduce the size of convection cells and also it is observed that \( (\lambda_c)_{\text{linear}} < (\lambda_c)_{\text{cubic2}} < (\lambda_c)_{\text{cubic1}} \).

Figure 3(a) shows the plot of \( R_{nc} \) as the function of \( Da^{-1} \) for different values of \( \lambda \), \( M_1 \) and \( M_3 \) with three different forms of basic temperature profiles. From the figure it is evident that an increase in the value of \( Bi \) is to increase \( R_{nc} \) and thus its effect is to delay the onset of ferroconvection in a porous medium. This may be attributed to the fact that with increasing \( Bi \), the thermal disturbances can easily dissipate into the ambient surrounding due to a better convective heat transfer coefficient at the top surface and hence higher heating is required to make the system unstable. Fig. 3(b) represents the variation of \( \lambda_c \) as a function of \( Da^{-1} \) for different values of \( Bi \) and we note that as \( Da^{-1} \) increases the critical wave number and hence its effect is to contract the size of convection cells.

Figure 4(a) reveals that critical thermal Rayleigh number \( R_{nc} \) as a function of \( Da^{-1} \) for different values of \( M_1 \) with different forms of basic temperature profile. Physically, increase in \( M_1 \) leads to either increase in destabilizing magnetic force or decrease in stabilizing viscous force on the system and hence it has a destabilizing effect on the system. A closer inspection of the figure further reveals that the magnetic force is to reinforce together with buoyancy force and to hasten the onset of ferroconvection when compared to their effect in isolation. Besides, it may be noted that the difference in the critical thermal Rayleigh numbers among different values of \( M_1 \) diminishes as the value of \( M_1 \) increases.

The variation in \( \lambda_c \) as a function of \( Da^{-1} \) is elucidated in Fig. 4(b) for different forms of basic temperature profile with different values of \( M_1 \). It may be noted that the critical wave number \( \lambda_c \) increases with increasing \( Da^{-1} \). Moreover, an increase in the value of magnetic parameter \( M_1 \) is to increase the value of critical wave number \( \lambda_c \) and thus its effect is to increase the dimension of convection cells.

Figure 5 shows the locus of critical thermal Rayleigh number \( R_{nc} \) and magnetic Rayleigh number \( R_{nc} \) for different values of non-linearity of fluid magnetization, denoted through the parameter \( M_1 \), on the onset of ferroconvection in a Brinkman porous medium. In the figure, the regions above and below the curves, correspond respectively to unstable and stable ones.
It is observed that there is a strong coupling between \( R_{nc} \) and \( R_{mc} \) such that an increase in the one decreases the other. Thus, when the buoyancy force is predominant, the magnetic force becomes negligible and vice-versa. The stability curves are slightly convex and in the absence of buoyancy forces \( (R_{nc} = 0) \), the instability sets in at higher values of \( R_{mc} \) indicating the system is more stable when the magnetic forces alone are present. Fig. 5 demonstrated that an increase in \( M_{3} \) is to decrease \( R_{nc} \) and \( R_{mc} \) and thus it has a destabilizing effect on the system. This may be due to the fact that the application of magnetic field makes the ferrofluid to acquire larger magnetization which in turn interacts with the imposed magnetic field and releases more energy to drive the flow faster. Hence, the system becomes unstable with a smaller temperature gradient as the value of \( M_{3} \) increases. Alternatively, a higher value of \( M_{3} \) would arise either due to a larger pyromagnetic coefficient or larger temperature gradient. Both these factors are conducive for generating a larger gradient in the Kelvin body force field, possibly promoting the instability. The variation of \( a_{c} \) as a function of \( Da^{-1} \) is shown in Fig. 6 for different values of \( M_{3} \). From the figure, we note that increasing \( M_{3} \) and \( Da^{-1} \) is to increase \( a_{c} \) and hence to decrease the dimension of convection cells.
5. CONCLUSIONS

The linear stability theory is used to investigate the effect of different forms of basic temperature profile on onset of ferroconvection in a Brinkman porous medium. The lower and upper boundaries is taken to be rigid-ferromagnetic and insulated to temperature perturbations. The Galerkin technique is used to find the eigenvalues as this technique is found to be more convenient to tackle different forms of basic temperature profiles.

From the foregoing study, it is observed that

(i) The cubic 1 basic temperature profile delays, while linear profile hastens the onset of ferroconvection. That is

\( (R_{tc})_{\text{linear}} < (R_{tc})_{\text{cubic 2}} < (R_{tc})_{\text{cubic 1}} \)

(ii) The critical thermal Rayleigh number \( R_{tc} \) increases with an increase in the value of ratio of viscosity parameter \( \lambda \), Biot number \( Bi \) and thus their effect is to delay the onset of ferroconvection.

(iii) The effect of increase in the value of Darcy number \( Da^{-1} \), magnetic number \( M_1 \) and non-linearity of the fluid magnetization parameter \( M_3 \) is to reinforce together and to hasten the onset of ferroconvection.

(iv) The magnetic and buoyancy forces are complementary with each other and the system is more stabilizing when the magnetic forces alone are present.

(v) The effect of increasing \( Bi, Da^{-1}, M_1 \) and \( M_3 \) as well as decrease in \( \lambda \) is to increase the critical wave number \( \alpha_c \) and hence their effect is to narrow the convection cells.

(vi) The critical wave numbers \( \alpha_c \) for cubic 1 basic temperature profile are higher than those of cubic 2 basic temperature profile and linear temperature profiles. That is,

\( (\alpha_c)_{\text{linear}} < (\alpha_c)_{\text{cubic 2}} < (\alpha_c)_{\text{cubic 1}} \)

(vii) It is possible to either augment or suppress ferroconvection in a porous medium by tuning the physical parameters of the system.

REFERENCES


via internal heating in a Saturated Porous Layer with constant heat flux at the lower boundary. *Journal of Magn and Magn Mater.* 324, 1670-1678.


