



Penetrative ferroconvection via internal heating in a saturated porous layer with constant heat flux at the lower boundary

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ABSTRACT

A model for penetrative ferroconvection via internal heat generation in a ferrofluid saturated porous layer is explored. The Brinkman–Lapwood extended Darcy equation with fluid viscosity different from effective viscosity is used to describe the flow in the porous medium. The lower boundary of the porous layer is assumed to be rigid- paramagnetic and insulated to temperature perturbations, while at upper stress-free boundary a general convective-radiative exchange condition on perturbed temperature is imposed. The resulting eigenvalue problem is solved numerically using the Galerkin method. It is found that increasing in the dimensionless heat source strength N_s , magnetic number M_1 Darcy number Da and the non-linearity of magnetization parameter M_3 is to hasten, while increase in the ratio of viscosities A , Biot number Bi and magnetic susceptibility χ is to delay the onset of ferroconvection. Further, increase in Bi , Da^{-1} and N_s and decrease in A , M_1 and M_3 is to diminish the dimension of convection cells.

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1. Introduction

Ferrofluids are stable colloidal suspensions of magnetic nanoparticles in a carrier fluid such as water, hydrocarbon (mineral oil or kerosene), or fluorocarbon. The nanoparticles typically have sizes of about 100 Å or 10 nm and they are coated with surfactants in order to prevent the coagulation. Ferrofluids respond to an external magnetic field and this enables to control the location of the ferrofluid through the application of a magnetic field. Ferrofluids have been tailor-made and possess a wide variety of potential applications in various industries [1–5]. Mechanical engineering industries use them as fluids in vibration dampers, shock absorbers, and vacuum seals. Electrical and electronic industries use ferrofluids to improve hi-fi characteristic loud speakers as transformer coolants and also in miniaturizing inductive components. Computation industries use them as fluids in stepper motors. Therefore, studies on ferrofluids have received much attention in the scientific community over the years.

The magnetization of ferrofluids depends on the magnetic field, temperature, and density. Hence, any variations in these quantities induce a change in body force distribution in the fluid and eventually give rise to convection in ferrofluids in the presence of

a gradient of magnetic field. There have been numerous studies on thermal convection in a ferrofluid layer called ferroconvection analogous to Rayleigh–Benard convection in ordinary viscous fluids. Finlayson [6] has studied convective instability of a magnetic fluid layer heated from below in the presence of a uniform vertical magnetic field. A linear stability analysis has been carried out to predict the critical gradient of temperature corresponding to the onset of convection when both buoyancy and magnetic forces are included, by considering the bounding surfaces of the magnetic fluid layer to be either stress-free or rigid. Thermo-convective instability of ferrofluids without considering buoyancy effects has been investigated by Lalas and Carmi [7], whereas Shliomis [8] has analyzed the linear relation for magnetized perturbed quantities at the limit of instability. A similar analysis but with the fluid confined between ferromagnetic plates has been carried out by Gotoh and Yamada [9] using linear stability analysis. Schwab et al. [10] have experimentally investigated the problem of Finlayson in the case of a strong magnetic field and detected the onset of convection by plotting the Nusselt number versus the Rayleigh number. Stiles and Kagan [11] have extended the problem to allow for the dependence of effective shear viscosity on temperature and colloid concentration. The effect of the different forms of basic temperature gradients on the onset of ferroconvection driven by combined surface tension and buoyancy forces has been discussed by Shivakumara et al. [12] in order to understand the control of ferroconvection. Kaloni and Lou [13] have theoretically investigated the convective instability problem in a thin horizontal layer

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of magnetic fluid heated from below under alternating magnetic field, by considering the quasi-stationary model with internal rotation and vortex viscosity. Shivakumara and Nanjundappa [14] have analyzed the effect of various forms of nonuniform initial temperature profiles on the onset of Marangoni convection in a ferrofluid layer. The influence of magnetic field on heat and mass transport in ferrofluids has been discussed by Volker et al. [15]. Sunil and Mahajan [16] have performed nonlinear stability analysis for a magnetized ferrofluid layer heated from below in the stress-free boundaries, while Nanjundappa and Shivakumara [17] have analyzed the effects of different velocities and temperature boundary conditions on the onset of convection in a ferrofluid layer. The effect of magnetic field dependent viscosity on the onset of thermal convection in a horizontal ferrofluid layer heated from below has been studied by Nanjundappa et al. [18]. Recently, Nanjundappa et al. [19] have investigated theoretically the effect of magnetic field dependent viscosity on the onset of Benard-Marangoni ferroconvection in a horizontal ferrofluid layer.

Thermal convection of ferrofluids saturating a 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. Rosensweig et al. [20] have experimentally studied 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 Zahn and Rosensweig [21]. The thermal convection of a ferrofluid saturating a porous medium in the presence of a vertical magnetic field is studied by Vaidyanathan et al. [22] by employing the Brinkman equation with effective viscosity (Brinkman viscosity) is the same as fluid viscosity and considering that the bounding surfaces of the porous layer are shear free. Qin and Chadam [23] have carried out the nonlinear stability analysis of ferroconvection in a porous layer by including the inertial effects to accommodate high velocity. The laboratory-scale experimental results of the behavior of ferrofluids in porous media consisting of sands and sediments are presented by Borglin et al. [24]. The onset of centrifugal convection in a magnetic fluid-saturated porous medium under zero gravity condition is investigated by Saravanan and Yamaguchi [25]. The effect of dust particles on the onset of ferroconvection in a porous medium has been studied by Sunil et al. [26]. Shivakumara et al. [27] have investigated in detail the onset of ferroconvection in a ferrofluid saturated porous medium for various types of velocity and temperature boundary conditions. Nanjundappa et al. [28] have performed linear stability analysis to investigate buoyancy driven convection in a ferrofluid saturated porous medium. Recently, Shivakumara et al. [29] have studied the effect of Coriolis force on the onset of ferromagnetic convection in a rotating horizontal ferrofluid saturated porous layer in the presence of a uniform vertical magnetic field.

The practical problems cited above require a mechanism to control thermomagnetic convection. One of the mechanisms to control (suppress or augment) convection is by maintaining a nonuniform temperature gradient across the layer of ferrofluid. Such a temperature gradient may arise due to (i) uniform distribution of heat sources (ii) transient heating or cooling at a boundary, (iii) temperature modulation at the boundaries and so on. Works have been carried out in this direction but it is still in much-to-be desired state. Rudraiah and Sekhar [30] have investigated convection in a ferrofluid layer in the presence of uniform internal heat source. The effect of non-uniform basic temperature gradients on the onset of ferroconvection has been analyzed by Shivakumara and Nanjundappa [12,31,32]. Singh and Bajaj [33] have studied thermal convection of ferrofluids in the presence of uniform vertical magnetic field with boundary temperatures modulated sinusoidally about some reference

value. Idris and Hashim [34] have investigated the instability of Benard-Marangoni ferroconvection in a horizontal layer of ferrofluid under the influence of a linear feedback control and cubic temperature gradient. Recently, Nanjundappa et al. [35] have studied the effect of internal heat generation on the criterion for the onset of convection in a horizontal ferrofluid saturated porous layer in the presence of a uniform magnetic field.

The intent of the present study is to investigate ferroconvection in a ferrofluid-saturated porous layer in the presence of internal heating. The presence of internal heating deviate the basic temperature, magnetic field intensity and magnetization distributions from linear to parabolic with respect to porous layer height, which in turn play a decisive role in understanding control of ferroconvection. Besides, porous materials used in many technological applications of practical importance possess high permeability values. For example, permeabilities of compressed foams as high as $8 \times 10^{-6} \text{ m}^2$ and for a 1 mm thick foam layer the equivalent Darcy number is equal to 8 (see Nield et al. [36] and references therein). For a high porosity porous medium ($\varepsilon=0.972$), Givler and Altobelli [37] have determined experimentally that $\tilde{\mu}_f = 7.5^{+3.4}_{-2.4} \mu_f$, where $\tilde{\mu}_f$ is the effective viscosity and μ_f is the fluid viscosity. Accordingly, the flow in the porous medium is described by the Brinkman–Lapwood extended Darcy equation with fluid viscosity different from effective or Brinkman viscosity. The resulting eigenvalue problem is solved by the Galerkin technique with modified Chebyshev polynomials as trial functions. The available results in the literature are obtained as limiting cases from the present study.

To achieve the above objectives, the remainder of this paper proceeds as follows. Section 2 is devoted to the mathematical formulation of the problem. The method of solution is discussed in Section 3. In Section 4, the numerical results are discussed and some important conclusions follow in Section 5.

2. Formulation of the Problem

The system considered is an initially quiescent incompressible constant viscosity ferrofluid saturated horizontal porous layer of characteristic thickness d in the presence of a uniform applied magnetic field H_0 in the vertical direction (see Fig. 1). The horizontal extension of the porous layer is sufficiently large so that edge effects may be neglected. The boundaries are maintained at constant but different temperatures having higher temperature at the bottom T_0 and lower temperature at the top $(T_0 - \Delta T)$. In addition, a uniformly distributed overall internal heat source is present within the ferrofluid-saturated porous medium. 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. The flow in the porous medium is described by the Brinkman–Lapwood extended Darcy equation with fluid viscosity different from effective viscosity and the Oberbeck–Boussinesq approximation is assumed to be valid. Rajagopal et al. [38] have presented a frame work within which the status of the Oberbeck–Boussinesq approximation can be clearly

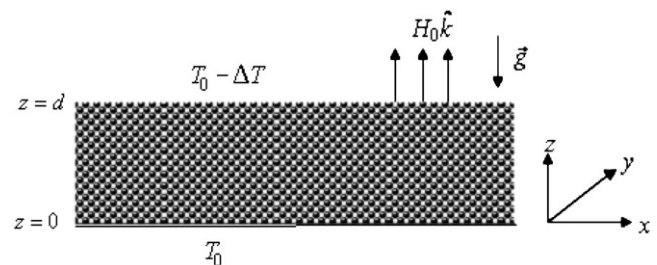


Fig. 1. Physical configuration.

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