ISSN 2393-9850
GEM — Georgian Educational Mine
Interdisciplinary International Peer-Reviewed Research Journal
St. George's College Aruvithura, Kerala, India

Volume 3, Issue 1, 2023
Pages 76–83
gem.sgcaruvithura.ac.in

ORIGINAL RESEARCH ARTICLE

Convection in Ferrofluids

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Received: 1 October 2023 · **Revised:** 23 November 2023 · **Accepted:** 15 December 2023 · **Published:** 18 December 2023

Keywords: Convection; Ferrofluids; Thermal Instability

Abstract

Convective heat transfer in ferrofluids has attracted significant attention due to its wide range of applications in engineering, materials processing, biomedical systems, and thermal management. The onset of convection in magnetic fluids is governed by complex interactions among buoyancy, magnetic forces, surface tension, porous media characteristics, and fluid rheology. Extensive studies have been carried out on Rayleigh–Bénard and Marangoni convection in Newtonian fluids. Convective instability in ferrofluids plays a vital role in many engineering and industrial applications involving heat transfer and magnetic field interactions. This study focuses on the scope of the onset of convection in ferromagnetic fluids. The outcomes of this work are expected to provide deeper insight into the heat transfer characteristics of ferrofluids and contribute to the design and optimization of systems involving magnetic fluids in industrial and technological applications.

1. INTRODUCTION

Thermo-mechanical interactions in fluids make possible the onset of convection induced by externally applied temperature gradients. Rayleigh–Bénard convection is the instability of a fluid layer which is confined between two thermally conducting plates heated from below to produce a fixed temperature difference. Since liquids typically have a positive thermal expansion coefficient, the hot liquid at the bottom expands and produces an unstable density gradient in the fluid layer. If the density gradient is sufficiently strong, the hot fluid will rise, causing a convective flow which results in enhanced transport of heat between the two plates.

There are two processes which oppose this amplification. First, viscous damping in the fluid directly opposes the fluid flow. In addition, the dissipative effect of thermal diffusion will suppress the temperature fluctuation. Convection occurs if the amplifying effect exceeds the viscous damping and the dissipative effect of thermal diffusion. If the temperature difference is very large, then the fluid rises very quickly, and a turbulent flow may be created.

Experiments in the early stage were carried out with fluid heated from below and the top surface open to the atmosphere. Thus, the top surface is free to move and deform. It was later (around 1960) realized that this could lead to another instability mechanism (Bénard–Marangoni convection) due to a gradient in surface tension. This mechanism coexists with Rayleigh's mechanism but dominates in a thin layer. Most of the findings reported by Bénard were actually due to this second instability mechanism. The instability driven by surface tension decreases as the layer becomes thicker.

In the case of Rayleigh–Bénard convection, only buoyancy is responsible for the appearance of convection cells. In the case of a free liquid surface in contact with air, surface tension effects will play a role besides buoyancy. It is known that liquids flow from places of lower surface tension to places of higher surface tension. This is called the Marangoni effect. Marangoni convection plays an important role in Bénard convection in shallow fluid layers, in chemical engineering as well as in crystal growth and other materials processing technologies. Convective instability analyses are useful for predicting the critical temperature gradient above which motion occurs.

The investigation of heat transfer in ferrofluids is of practical importance. Their commercial applications include ink jet printing, sealing, pumping, semiconductor and computer industries, and medicine and high-speed noiseless printing [Rosensweig, 1997, Fertman, 1990]. Ferromagnetic fluids are formed by suspending submicron sized particles of magnetite in a carrier medium such as kerosene, heptane or water. To prevent the particles from agglomerating in the presence of a magnetic field they are surrounded by a surfactant such as oleic acid. The combination of the short-range repulsion due to the surfactant and the thermal agitation yields a material which behaves as a continuum and can experience forces due to magnetic polarization. The fluids are usually good insulators and forces due to interaction of magnetic fields with currents of free charge, such as found in magnetohydrodynamics, are negligible. The presence of a ferromagnetic fluid can distort an external magnetic field if magnetic interaction (dipole–dipole) takes place, but this is negligible for small particle concentrations. Experience also suggests that hysteresis is unlikely in these fluids with the exception of rapidly changing external magnetic fields. In many heat transfer problems involving ferromagnetic fluids, it has been found that these fluids may have enhanced or diminished heat transfer when compared to classical Newtonian fluids.

Although the problem of Rayleigh–Bénard convection has been extensively investigated for Newtonian fluids, fairly little attention has been devoted to studying thermal convection of non-Newtonian fluids. With the growing importance of non-Newtonian fluids with suspended particles in modern technology and industries, the investigations of such fluids are desirable. The study of such fluids has applications in a number of processes that occur in industry, such as the extrusion of polymer fluids, solidification of liquid crystals, cooling of a metallic plate in a bath, exotic lubrication, and colloidal and suspension solutions. In the category of non-Newtonian fluids, couple-stress fluids have distinct features, such as polar effects. The theory of polar fluids and related theories are models for fluids whose microstructure is mechanically significant. The constitutive equations for couple-stress fluids were given by Stokes [1966], and the theory proposed by Stokes is the simplest one for microfluids, which accounts for polar effects such as the presence of couple stress and body couple.

The study of convection in a fluid saturated porous medium is of considerable interest due to its applications to chemical engineering, geothermal activities, oil recovery techniques and biological processes. Over the past couple of decades, a great deal of effort has been invested in studying natural convection in a fluid-saturated porous medium with and without uniformly distributed heat sources, keeping in mind the applications to nuclear reactor safety and geothermal reservoir engineering.

Interest in natural convection in fluids with internal heat sources has been stimulated by the demands of nuclear power engineering [Bol'shov et al., 2001]. When an exothermic reaction takes place in a fluid-saturated porous medium, the heat generated by the reaction changes the fluid density and free convection may occur. The induced natural convection, in turn, affects the rate of heat release by the reaction. The complex interaction between these two processes is the major cause of many of the instabilities observed in chemically reacting systems. This reaction-driven convection is also responsible for the delay of spontaneous ignition in coal piles, stored chemicals, grain, and biological and waste dumps. Chemically driven convective instability in a porous medium is of practical importance because reactions of these types are common in various electrochemical processes and in the oxidation of fine solids [Frank-Kamenetskii, 1969].

The propagation of thermal waves is sometimes referred to as the second sound effect. The classical energy equation allows for an infinite speed for the propagation of heat, which is physically unacceptable. The energy equation to be considered in the proposed research work is effectively a damped wave equation and is therefore hyperbolic rather than parabolic. On the other hand, breaking of the top–bottom symmetry is quite generic in experimental situations. When the fluid viscosity varies with temperature, the top and bottom structures are different. We refer to this as a non-Boussinesq effect [Wu and Libchaber, 1991]. Several mathematical models have been proposed for the variable viscosity. To sum up, the foregoing aspects shed light on the internally and externally controlling convection in a ferromagnetic fluid.

2. LITERATURE REVIEW

The problem of convection in a ferromagnetic fluid is different from magnetoconvection even though the influence of the magnetic field exists in both problems. In the case of magnetoconvection, the fluid is electrically conducting and we see the influence of a body force, known as the Lorentz force. Magnetic fluids are not electrically conducting and hence the Lorentz force does not appear. As a result of the magnetization of the micron-sized suspended ferrite particles, a pondermotive force, analogous to the Lorentz force, appears and gives rise to a dynamically different situation than the type that occurs in the magnetoconvection problem. The problems of Rayleigh–Bénard and Marangoni convection in couple stress magnetic fluids are of great importance because they are representative of a variety of industrial application situations.

Finlayson [1970] made a detailed study of convective instability in a ferromagnetic fluid. He predicted the critical temperature gradient for the onset of convection when only the magnetic mechanism is important as well as when both the magnetic and buoyancy mechanisms are operative. The magnetic mechanism is shown to predominate over the buoyancy mechanism in fluid layers which are about 1 mm thick. For fluid layers contained between two free boundaries, which are constrained flat, the exact solution has been obtained for some parameter values and oscillatory stability is ruled out. For rigid boundaries, an approximate solution for stationary instability using a higher order Galerkin method is obtained.

Gupta and Gupta [1979] investigated thermal instability in a layer of ferromagnetic fluid subject to Coriolis force and permeated by a vertical magnetic field. It is substantiated that overstability cannot occur if the Prandtl number is greater than unity.

Siddheshwar [1993] investigated the Rayleigh–Bénard instability problem of a Newtonian ferromagnetic fluid with second sound. It is shown that oscillatory convection is possible for heating from above. He further showed that the critical eigenvalue for stationary convection, when heated from below, is significantly influenced by second sound effects. Venkatasubramanian and Kaloni [1994] studied the effects of rotation on the thermoconvective instability in a horizontal layer of ferrofluid heated from below in the presence of a uniform vertical magnetic field.

Malashetty et al. [1994] analyzed the onset of convective instability in a horizontal inert porous layer with zero-order exothermic chemical reaction. They used a Galerkin method to calculate critical values. They found that, in the presence of chemical reaction, the fluid in a porous medium is more prone to instability when compared to a fluid in which chemical reaction is absent. Sharma and Sharma [2004] studied the onset of convection in a couple-stress fluid-saturated porous layer in the presence of rotation and a magnetic field. Siddheshwar and Pranesh [2004] analytically studied linear and nonlinear convection in a couple-stress fluid layer.

Reviews of extensive research on both Rayleigh–Bénard and Marangoni convective instability have been documented in the works of Normand et al. [1977], Davis [1987] and Bodenschatz et al. [2000]. Illuminating and detailed information on convective instability in porous media is available in the books of Ingham and Pop [1998], Nield and Bejan [2006] and Vafai [2000, 2005].

Sunil et al. [2005] dealt with the theoretical investigation of the combined effect of magnetic field dependent (MFD) viscosity and rotation on ferroconvection saturating a porous medium in the presence of dust particles subjected to a transverse uniform magnetic field. The cases of stationary convection and oscillatory modes have been discussed. An attempt is also made to obtain the sufficient conditions for the non-existence of overstability. The effect of thermal and gravity modulation on the onset of Rayleigh–Bénard convection in a couple-stress fluid layer was studied by Malashetty and Basavaraja [2005]. Malashetty et al. [2006] studied the Soret effect on double-diffusive convection in a couple-stress liquid using both linear and nonlinear analyses. Ramanathan and Muchikel [2006] investigated the effect of temperature dependent viscosity on ferroconvection in a sparsely distributed porous medium using the Brinkman model. It is found that the stationary mode of instability is preferred to the oscillatory mode and that variable-viscosity has a destabilizing effect on the onset of ferroconvection. Malashetty et al. [2009] investigated the local thermal non-equilibrium effect on the onset of convection in a couple-stress fluid-saturated porous layer.

Sunil and Mahajan [2009] performed a nonlinear energy stability analysis for a rotating magnetized ferrofluid layer heated from below in the stress-free boundary case. It is shown that with the increase of the magnetic parameter, the sub-critical instability region between the two theories decreases quickly, while with the increase of the Taylor number, the sub-critical region expands a little for small values and expands significantly for large values. Malashetty et al. [2010] studied the onset of double-diffusive convection in a couple-stress fluid-saturated horizontal porous layer using linear and weak nonlinear stability analyses. It is found that the couple-stress parameter and the solute Rayleigh number have a stabilizing effect on stationary, oscillatory and finite-amplitude convection. The Vadasz number advances the onset of oscillatory convection.

Vanishree and Siddheshwar [2010] performed a linear stability analysis for mono-diffusive convection in an anisotropic rotating porous medium with temperature-dependent viscosity. The effect of the Taylor–Vadasz number and the other parameters of the problem are considered for stationary convection in the absence or presence of rotation. Oscillatory convection seems highly improbable. Thomas and Maruthamanikandan [2013] examined the stability of a horizontal porous layer of a ferromagnetic fluid heated from below when the fluid layer is subject to a time-periodic body force. It is found that subcritical instability is possible for low frequency g-jitter and that the magnetic and g-jitter mechanisms work against each other for small and moderate values of frequency of modulation. The effect of the Vadasz number is shown to reinforce the influence of gravity modulation for small and moderate values of frequency.

Assuming an exothermic chemical reaction of order zero and a horizontal inert porous layer, Mubeen Taj et al. [2013] and Akbar et al. [2015] extended the problem with couple-stress and Maxwell viscoelastic fluids respectively. They found that the nonlinear temperature distribution of the basic state resulting from chemical reaction is responsible, to a great extent, for the instability due to chemical reaction. Sekhar et al. [2017] investigated a linear stability analysis of thermal convection in variable viscosity Newtonian ferromagnetic fluid considering all possible boundary combinations. The effect of viscosity variation on non-Darcy ferroconvection was studied by Mathew and Maruthamanikandan [2018] and Maruthamanikandan et al. [2018]. Both temperature and field dependent viscosities have been incorporated into the governing equations.

Lawanya et al. [2019] made a discussion on the effects of heat and mass transfer on oscillatory flow under the influence of couple stress fluid in a wavy channel in the presence of chemical reaction.

The effects of thermal radiation, buoyancy, chemical reaction parameter and heat source parameter on the couple stress fluid are taken into account. Neha Aanam A et al. [2021] investigated linear and nonlinear stability of a ferrofluid with temperature and magnetic field dependent viscosity subjected to gravity modulation. They have found that the thermorheological effect and the magnetization effect work in unison to destabilize the system, while the magnetorheological effect and the effect of vertical oscillations stabilize the system.

Meghana et al. [2021] examined the effects of sinusoidal and non-sinusoidal forms of gravity modulation on convection in a ferromagnetic liquid with couple stress using linear and nonlinear stability analyses. It is shown that the couple stress parameter stabilizes the system and decreases the heat transfer. Advancement of onset due to nanoparticle presence, and thereby enhanced heat transfer, is discussed.

3. NEED FOR STUDY

Convective instability in ferrofluids is an important area of research because it determines the conditions under which a stationary magnetic fluid becomes unstable and develops convective motion under the combined influence of temperature gradients, magnetic fields, surface tension, and buoyancy. Understanding this phenomenon is essential for both theoretical studies and practical engineering applications. The major reasons for studying convective instability in ferrofluids are as follows.

Convective instability in ferrofluids has emerged as a significant area of research due to its fundamental importance in understanding heat and mass transport in magnetically responsive fluids and its wide range of engineering and technological applications. Ferrofluids, which consist of stable suspensions of magnetic nanoparticles dispersed in a carrier liquid, exhibit unique thermophysical properties that can be actively controlled using external magnetic fields. This distinctive feature provides an additional degree of freedom for regulating fluid motion and heat transfer, making ferrofluids superior to conventional heat transfer fluids in many thermal management applications. The onset of convection plays a crucial role in determining the efficiency of heat transport, as convective motion substantially enhances thermal energy transfer in systems such as electronic cooling devices, heat exchangers, nuclear reactors, and renewable energy systems. Unlike ordinary fluids, the flow behavior of ferrofluids can be manipulated through magnetic forces, enabling the initiation, suppression, or control of convective motion without the need for mechanical actuators. Such magnetic control has opened new possibilities for the development of compact, energy-efficient, and intelligent thermal management technologies.

The investigation of convective instability is equally important in biomedical engineering, where ferrofluids are extensively employed in magnetic drug delivery, magnetic hyperthermia for cancer treatment, and magnetic resonance imaging. A comprehensive understanding of convection enables precise control of nanoparticle transport and temperature distribution, thereby improving treatment efficiency and safety. In materials science, convection significantly influences crystal growth, solidification, and other manufacturing processes, where uncontrolled fluid motion may lead to structural defects and degradation of material quality. Furthermore, in microgravity environments, where buoyancy-driven convection is considerably weakened, magnetic body forces provide an effective alternative mechanism for inducing and controlling fluid motion, making ferrofluids highly attractive for spacecraft thermal management and space-based manufacturing processes. Industrial applications such as magnetic seals, dampers, bearings, loudspeakers, rotating shaft seals, and lubrication systems also benefit from a detailed understanding of ferrofluid convection, leading to improved operational stability and performance.

From a theoretical perspective, convective instability in ferrofluids represents a complex multiphysics phenomenon involving the interaction of buoyancy forces, magnetic body forces, surface tension gradients, porous media effects, fluid viscosity, rotation, nanoparticle concentration, and thermomagnetic coupling. Stability analysis provides the critical conditions governing the onset of convection, including the critical Rayleigh number, magnetic Rayleigh number, and Marangoni number, thereby offering valuable guidelines for the design and optimization of engineering systems in which convection must either be enhanced or suppressed. Moreover, the study of ferrofluid convection contributes significantly to the broader understanding of nonlinear fluid dynamics, pattern formation, bifurcation, and transition to complex flow regimes under coupled thermal and magnetic effects.

In recent years, research on ferrofluid convection has expanded considerably to incorporate more realistic physical models involving Rayleigh–Bénard and Marangoni convection, porous media, non-Newtonian ferrofluids, nanofluids, local thermal non-equilibrium, variable gravity, rotation, viscoelastic effects, and fractional-order constitutive models. These developments are motivated by the increasing demand for advanced thermal management systems, high-performance energy technologies, biomedical devices, and smart materials. Consequently, the study of convective instability in ferrofluids continues to be an active and interdisciplinary research area, providing both fundamental insights into magneto-thermofluid dynamics and practical solutions for the design of next-generation thermal and engineering systems.

4. CONCLUSION

Convective instability in ferrofluids remains one of the most fascinating and rapidly evolving areas of magneto-thermofluid research due to the complex interaction between thermal gradients, magnetic forces, fluid rheology, porous media, and surface tension effects. This review highlights the significant theoretical developments achieved over the past several decades in understanding the onset of Rayleigh–Bénard and Marangoni convection in ferrofluids under various physical conditions, including rotation, variable viscosity, second sound, chemical reactions, porous media, and non-Newtonian fluid behavior. The studies reviewed demonstrate that external magnetic fields provide an effective means of controlling convective motion, enabling either enhancement or suppression of heat transfer according to application requirements.

The literature further reveals that the onset of convection is strongly influenced by several governing parameters such as the Rayleigh number, magnetic Rayleigh number, Marangoni number, Taylor number, Vadasz number, viscosity variations, and nanoparticle interactions. The incorporation of increasingly realistic physical models has considerably improved the understanding of ferrofluid stability and has expanded its potential applications in thermal management, electronic cooling, energy systems, biomedical engineering, crystal growth, microfluidics, and space technologies.

Despite substantial progress, several important challenges remain. Future research should focus on coupled multiphysics models incorporating nanoparticle dynamics, non-equilibrium thermodynamics, fractional-order constitutive relations, machine learning-assisted stability prediction, and experimental validation under realistic operating conditions. The integration of numerical simulations with experimental investigations will further enhance the understanding of ferrofluid convection and facilitate the development of smart, energy-efficient thermal systems.

Overall, the study of convective instability in ferrofluids continues to offer rich opportunities for both fundamental scientific investigation and technological innovation. A deeper understanding of the underlying instability mechanisms will contribute significantly to the design and optimization of next-generation magnetic fluid-based thermal management and engineering systems.

REFERENCES

Syeda Khudeja Akbar, Achala L. Nargund, and S. Maruthamanikandan. Thermal instability of chemically reacting Maxwell fluid in a horizontal porous layer with constant heat flux lower boundary. *International Journal of Engineering Research and Applications*, 5:168–177, 2015.

E. Bodenschatz, W. Pesch, and G. Ahlers. Recent developments in Rayleigh–Bénard convection. *Annual Review of Fluid Mechanics*, 32:709–778, 2000.

L. A. Bol'shov, P. S. Kondratenko, and V. F. Strizhov. Natural convection in heat generating fluids. *Soviet Physics Uspekhi*, 44:999–1016, 2001.

S. H. Davis. Thermocapillary instabilities. *Annual Review of Fluid Mechanics*, 19:403–435, 1987.

V. Fertman. *Magnetic Fluids Guidebook: Properties and Applications*. Hemisphere Publishing Corporation, New York, 1990.

B. A. Finlayson. Convective instability of ferromagnetic fluids. *Journal of Fluid Mechanics*, 40: 753–767, 1970.

D. A. Frank-Kamenetskii. *Diffusion and Heat Exchange in Chemical Kinetics*. Plenum, New York, 1969.

M. D. Gupta and A. S. Gupta. Convective instability of a layer of a ferromagnetic fluid rotating about a vertical axis. 17:271–277, 1979.

D. P. Ingham and I. Pop. *Transport Phenomena in Porous Media*. Pergamon, Oxford, 1998.

T. Lawanya, M. Vidhya, A. Govindarajan, and E. P. Siva. Effect of chemical reaction and heat source on oscillatory flow of couple stress fluid in wavy channel. *AIP Conference Proceedings*, 2112: 020158, 2019.

M. S. Malashetty and D. Basavaraja. Effect of thermal/gravity modulation on the onset of Rayleigh–Bénard convection in a couple stress fluid. *International Journal of Transport Phenomena*, 7:31–44, 2005.

M. S. Malashetty, P. Cheng, and B. H. Chao. Convective instability in a horizontal porous layer with a chemically reacting fluid. *International Journal of Heat and Mass Transfer*, 37:2901–2908, 1994.

M. S. Malashetty, S. N. Gaikwad, and M. Swamy. An analytical study of linear and non-linear double diffusive convection with Soret effect in couple-stress liquids. *International Journal of Thermal Sciences*, 45:897–907, 2006.

M. S. Malashetty, Kulkarni, and Sridhar. The onset of convection in a couple-stress fluid-saturated porous layer using a thermal non-equilibrium model. *Physics Letters A*, 373:781–790, 2009.

M. S. Malashetty, Dulal Pal, and Premila Kollur. Double-diffusive convection in a Darcy porous medium saturated with a couple-stress fluid. *Fluid Dynamics Research*, 42:021, 2010.

S. Maruthamanikandan, Nisha Mary Thomas, and Soya Mathew. Thermorheological and magnetorheological effects on Marangoni-ferroconvection with internal heat generation. *Journal of Physics: Conference Series*, 1139:012024, 2018.

Soya Mathew and S. Maruthamanikandan. Darcy–Brinkman ferroconvection with temperature dependent viscosity. *Journal of Physics: Conference Series*, 1139:012023, 2018.

J. Meghana, S. Pranesh, and P. G. Siddheshwar. Individual effects of sinusoidal and non-sinusoidal gravity modulation on Rayleigh–Bénard convection in a ferromagnetic liquid and in a nanoliquid with couple stress. *The European Physical Journal Special Topics*, 230:1415–1425, 2021.

Mubeen Taj, S. Maruthamanikandan, and S. Khudeja. Effect of chemical reaction on convective instability in a horizontal porous layer saturated with a couple-stress fluid. *International Journal of Engineering Research and Applications*, 3:1742–1748, 2013.

Neha Aanam A, P. G. Siddeshwar, Smita S. Nagouda, and S. Pranesh. Thermoconvective instability in a vertically oscillating horizontal ferrofluid layer with variable viscosity. *Heat Transfer*, 49: 4543–4564, 2021.

Donald A. Nield and Adrian Bejan. *Convection in Porous Media*. Springer, New York, 2006.

C. Normand, Y. Pomeau, and M. G. Velarde. Convective instability: A physicist's approach. *Reviews of Modern Physics*, 49:581–624, 1977.

A. Ramanathan and N. Muchikel. Effect of temperature dependent viscosity on ferroconvection in a porous medium. *International Journal of Applied Mechanics and Engineering*, 11:93–104, 2006.

R. E. Rosensweig. *Ferrohydrodynamics*. Dover Publications, New York, 1997.

G. N. Sekhar, G. Jayalatha, and R. Prakash. Thermal convection in variable viscosity ferromagnetic liquids with heat source. *International Journal of Applied and Computational Mathematics*, 3(4): 3539–3559, 2017.

R. C. Sharma and M. Sharma. Effect of suspended particles on couple-stress fluid heated from below in the presence of rotation and magnetic field. *International Journal of Pure and Applied Mathematics*, 35:973–989, 2004.

P. G. Siddheshwar. Rayleigh–Bénard convection in a magnetic fluid with second sound. In *Proceedings of the Japan Society of Magnetic Fluids, Sendai, Japan*, pages 32–36, 1993.

P. G. Siddheshwar and S. Pranesh. An analytical study of linear and non-linear convection in Boussinesq–Stokes suspensions. *International Journal of Non-Linear Mechanics*, 39:165–172, 2004.

V. K. Stokes. Couple stresses in fluids. pages 1709–1715, 1966.

Sunil and A. Mahajan. A nonlinear stability analysis for rotating ferrofluid heated from below. *Applied Mathematics and Computation*, 204:299–310, 2009.

Sunil, A. Sharma, R. G. Shandil, and U. Gupta. Effect of magnetic field dependent viscosity and rotation on ferroconvection saturating a porous medium in the presence of dust particles. *International Communications in Heat and Mass Transfer*, 32:1387–1399, 2005.

Nisha Mary Thomas and S. Maruthamanikandan. Effect of gravity modulation on the onset of ferroconvection in a densely packed porous layer. *IOSR Journal of Applied Physics*, 3(3):30–40, 2013.

K. Vafai. *Handbook of Porous Media*. Marcel Dekker, 2000.

K. Vafai. *Handbook of Porous Media*. Taylor & Francis, New York, 2005.

R. K. Vanishree and P. G. Siddheshwar. Effect of rotation on thermal convection in an anisotropic porous medium with temperature-dependent viscosity. *Transport in Porous Media*, 81:73–87, 2010.

S. Venkatasubramanian and P. N. Kaloni. Effects of rotation on the thermoconvective instability of a horizontal layer of ferrofluids. 32:237–256, 1994.

X. Z. Wu and A. Libchaber. Non-Boussinesq effects in free thermal convection. 43:2833–2839, 1991.