# A Comprehensive Review of Ferromagnetic Liquid Dynamics and Nonlinear Thermal Buoyancy Effects

**[1]Dr T K Sreelakshmi**
[1]Assistant Professor , Department of Mathematics , B M S Institute of Technology and Management , Bangalore
*Corresponding Author mail id: tksreelakshmi@bmsit.in

**Abstract:** Ferromagnetic liquid is a unique class of fluids that exhibits strong magnetic properties when subjected to a magnetic field. This liquid has been extensively studied in various industrial and scientific applications due to its unique properties such as high thermal conductivity, heat capacity, and electrical conductivity. One of the key phenomena associated with this type of liquid is its nonlinear thermal buoyancy effect, which refers to the motion of the liquid due to variation in temperature caused by a non-uniform magnetic field. In recent years, there has been a growing interest in studying the nonlinear thermal buoyancy effect in ferromagnetic liquids, specifically in the context of heat transport processes.

Non-Fourier heat flux is another crucial aspect of ferromagnetic liquids that has gained considerable attention among researchers. Non-Fourier heat flux is characterized by the deviation from the linear Fourier's law of heat conduction, where the rate of heat transfer is not proportional to the temperature gradient. In ferromagnetic liquids, this phenomenon is mainly attributed to the presence of magnetic fields, which influence the heat transfer processes within the liquid. This nonlinear heat flux behavior has significant implications in a wide range of applications, including heat dissipation, cooling, and thermal insulation.

Radiated elastic surfaces are another key feature of ferromagnetic liquids that has recently emerged as a promising area of research. These surfaces are formed when a magnetic field is applied to a ferromagnetic liquid, resulting in the formation of elastic waves on the surface. These waves are created due to the interaction between the magnetic field and the elastic properties of the liquid. The formation of these surfaces has been observed to have a considerable impact on the heat transfer behavior of the liquid, where they act as efficient heat dissipators and significantly enhance the rate of heat exchange between the liquid and its surroundings.

In summary, the interplay of nonlinear thermal buoyancy, non-Fourier heat flux, and radiated elastic surfaces in ferromagnetic liquids has attracted significant attention in recent years due to its potential for a wide range of practical applications. The understanding of these phenomena has the potential to significantly improve the design and efficiency of various heat transfer processes, making ferromagnetic liquids an important area of study in materials science and engineering. Future research in this field is expected to focus on developing more comprehensive models and experimental techniques to further explore the complex thermal and magnetic interactions in ferromagnetic liquids.

**Keywords:** Ferromagnetic liquid; nonlinear thermal buoyancy; non-Fourier heat flux; radiated elastic surface.

## 1. Introduction:

Ferromagnetic liquids are complex fluids composed of magnetic nanoparticles suspended in a non-magnetic liquid medium. These materials have attracted significant attention due to their unique properties, such as tunable magnetism and thermal conductivity, as well as their potential applications in various fields including heat transfer, microfluidics, biomedical engineering, and robotics.

One of the most intriguing phenomena observed in ferromagnetic liquids is the nonlinear thermal buoyancy effect. This effect refers to the behavior of these fluids under a temperature gradient where the magnetic particles experience an attractive or repulsive force depending on their alignment with respect to the temperature gradient. This results in a net flow of fluid along the direction of the temperature gradient, which is contrary to conventional convection where hot fluid rises and cold fluid sinks.

In recent years, there has been growing interest in studying nonlinear thermal buoyancy in ferromagnetic liquids due to its potential applications for enhancing heat transfer performance and controlling flow behavior at small scales. However, there remains a need for a comprehensive review that summarizes the existing literature on this topic and provides insights into future research directions. Therefore, this paper aims to present a detailed review on keywords: ferromagnetic liquid; nonlinear thermal buoyancy; non-Fourier heat flux; radiated elastic surface.

Tuijin Jishu/Journal of Propulsion Technology
ISSN: 1001-4055
Vol. 44 No. 4 (2023)

## 2. Literature Review

1. Zubair et al. (2018), published in the Journal of Results in Physics, the authors investigate the simulation of nonlinear convective thixotropic liquid with Cattaneo–Christov heat flux. The research delves into the complex dynamics of thixotropic fluids, which exhibit time-dependent viscosity changes under shear stress. Employing the Cattaneo–Christov heat flux model, the study advances our understanding of heat transfer in these liquids. The findings, detailed in the article, contribute to the evolving field of fluid dynamics and thermal science, offering valuable insights for applications in various industrial and engineering contexts. The DOI is provided for those interested in exploring the comprehensive results of this intriguing investigation.
2. Muhammad et al. (2019), documented in "Multidiscipline Modeling in Material and Structures," explores a double-diffusion model for viscoelastic nanofluid incorporating activation energy and nonlinear thermal radiation effects. This study contributes to the understanding of nanofluid dynamics by considering both thermal and solutal diffusion simultaneously, enhancing the comprehension of intricate heat and mass transfer processes. The inclusion of activation energy and nonlinear thermal radiation adds complexity to the model, reflecting real-world scenarios. Published insights in this article are valuable for researchers and practitioners in materials science and structural engineering.
3. Naddem, Ijaz, and Ayub (2020), titled "Darcy–Forchheimer Flow under Rotating Disk and Entropy Generation with Thermal Radiation and Heat Source/Sink," published in the Journal of Thermal Analysis and Calorimetry, the authors investigate fluid dynamics in the presence of a rotating disk, incorporating Darcy–Forchheimer flow, thermal radiation, and heat source/sink effects. The research delves into the complexities of heat transfer and fluid flow phenomena, considering practical applications. The study's findings contribute to the understanding of entropy generation and thermal characteristics in such systems.
4. Lucas et al. (2020), titled "A Numerical Study on Heat Transfer of a Ferrofluid Flow in a Square Cavity under Simultaneous Gravitational and Magnetic Convection," published in Theoretical Computational Fluid Dynamics, the authors conduct a comprehensive numerical analysis. Focusing on ferrofluid dynamics, the study explores heat transfer within a square cavity under the influence of simultaneous gravitational and magnetic convection. The research contributes to the understanding of complex fluid behaviors in magnetic fields, offering insights into thermal characteristics. This work is valuable for researchers in computational fluid dynamics, providing a numerical perspective on the intricate interplay between gravity and magnetic forces in ferrofluid flows
5. Pouya, Davood, et .al (2020), explore the "Application of Rotating Circular Obstacles in Improving Ferrofluid Heat Transfer in an Enclosure Saturated with Porous Medium Subjected to a Magnetic Field." The research investigates the impact of rotating circular obstacles on enhancing heat transfer in a ferrofluid-filled enclosure within a porous medium under the influence of a magnetic field. By examining the interplay of magnetic effects and obstacle rotation, the study provides valuable insights into optimizing heat transfer in such complex systems. Researchers in thermal analysis and fluid dynamics can find this work instrumental in understanding and improving ferrofluid heat transfer mechanisms.
6. Shi and Guo's (2009) work, "Lattice Boltzmann Model for Nonlinear Convection-Diffusion Equations," published in Physical Review E, presents a lattice Boltzmann approach to simulate nonlinear convection-diffusion equations. The lattice Boltzmann method, known for its versatility, offers a numerical framework for studying complex fluid dynamics phenomena. In this study, the authors extend its application to nonlinear convection-diffusion scenarios. The research contributes to advancing numerical modeling techniques for non-linear transport processes.

## 3. Objectives:

The objectives of this review paper are:

1. To introduce readers to the concept of ferromagnetic liquids and their unique properties.
2. To provide an overview of existing mathematical formulations for describing nonlinear thermal buoyancy effects in these fluids.

3. To identify research gaps and summarize recent advancements made in understanding these phenomena.
4. To highlight the uniqueness of nonlinear thermal buoyancy in ferromagnetic liquids compared to conventional convection mechanisms.
5. To suggest future research directions that can enhance our understanding and utilization of this phenomenon.

## 4. Mathematical Formulation:

Nonlinear thermal buoyancy effects arise from complex interactions between magnetic nanoparticles suspended in a liquid medium and an external temperature gradient. These interactions can be described using various mathematical models depending on the specific properties of the ferromagnetic liquid and the phenomenon being investigated.

The simplest mathematical model involves using the Navier-Stokes equation coupled with an energy equation to describe fluid flow and heat transfer in a ferromagnetic liquid under a temperature gradient. This model considers the magnetization of particles as a constant parameter, which does not account for their variation with changes in temperature or magnetic field strength.

More advanced models incorporate additional parameters such as magnetic susceptibility, magnetization relaxation time, and magnetic field-dependent viscosity to account for the influence of temperature and magnetic fields on particle behavior. These models also include terms that account for thermal conductivity variations due to a change in particle orientation.

Another approach is to use continuum mechanics equations to analyze nonlinear thermal buoyancy effects in ferromagnetic liquids with deformable interfaces. This approach considers both fluid flow and interface deformation due to interfacial forces between various phases of these complex fluids.

## 5. Research Gap and Summary:

While several studies have been carried out on nonlinear thermal buoyancy in ferromagnetic liquids, there still remains a significant research gap that needs to be addressed. Some of these gaps include:

1. Lack of comprehensive understanding: The existing literature mainly focuses on describing different mathematical models for nonlinear thermal buoyancy without providing a complete understanding of this phenomenon.
2. Limited experimental studies: Most research has been conducted using numerical simulations rather than experimental validation which limits our understanding.
3. Influence of external factors: The influence of external factors such as geometrical configurations, fluid properties, experimental conditions, etc., on nonlinear thermal buoyancy has not been extensively studied.
4. Need for standardized terminology: There is no consensus on terminology used for describing different aspects related to nonlinear thermal buoyancy in these fluids.
5. Development of predictive models: More accurate predictive models are needed that incorporate all significant variables involved in this process.
6. Applications in microfluidics and heat transfer: While there is a potential for utilizing nonlinear thermal buoyancy in various applications, the actual implementation needs to be explored further.

The uniqueness of nonlinear thermal buoyancy in ferromagnetic liquids lies in its ability to enhance flow and heat transfer performance without any additional external forces or equipment. Unlike conventional convection, this effect does not require a temperature difference between two fluid layers, making it ideal for small-scale applications. Additionally, the availability of magnetic field gradient-induced non-Fourier heat flux and lateral forces makes these fluids suitable for direct manipulation and control using an external magnetic field.

## 6. Conclusion:

In summary, this paper provided an overview of the existing literature on nonlinear thermal buoyancy effects in ferromagnetic liquids. It highlighted the unique properties of these materials that make them attractive for various applications such as heat transfer enhancement and microfluidic manipulation. The mathematical formulations used to describe this phenomenon were also discussed along with identifying research gaps and suggesting future research directions.

Further studies are needed to develop a comprehensive understanding of nonlinear thermal buoyancy effects in these complex fluids. This can be achieved through experimental validation of existing models under different conditions while considering all significant factors that influence this phenomenon. The development of predictive models based on such experiments can greatly aid in the utilization of this effect for practical applications. Overall, it is evident that nonlinear thermal buoyancy has great potential to revolutionize various fields where precise control over fluid flow and heat transfer is needed.A detailed review on this topic will serve as a valuable resource for researchers working on ferromagnetic liquids and their applications.

**Reference**

[1] Zubair, M., Waqas, M., Hayat, T., Ayub, M., Alsaedi, A. (2018). Simulation of nonlinear convective thixotropic liquid with Cattaneo–Christov heat flux. *Journal of Results in Physics, 8,* 1023– 1027. DOI 10.1016/j.rinp.2017.12.016.

[2] Muhammad, A., Muhammad, Y. M., Misbah, I., Marei, S. A., Ali, S. A. (2019). Double–diffusion model for viscoelastic nanofluid with activation energy and nonlinear thermal radiation. *Multidiscipline Modeling in Material and Structures, 16,* 93–120. DOI 10.1108/MMMS-03-2019-0046.

[3] Nadeem, S., Ijaz, M., El-Kott, A., Ayub, M. (2020). Rosseland analysis for ferromagnetic fluid in presence of gyrotactic microorganisms and magnetic dipole. Ain Shams Engineering Journal, (in press).

[4] Naddem, S., Ijaz, M., Ayub, M. (2020). Darcy–Forchheimer flow under rotating disk and entropygeneration with thermal radiation and heat source/sink. Journal of Thermal Analysis and Calorimetry,DOI 10.1007/s10973-020-09737-1.

[5] Ijaz, M., Nadeem, S., Ayub, M. (2020). Simulation of magnetic dipole on gyrotactic ferromagnetic fluid flow with nonlinear thermal radiation. Journal of Thermal Analysis and Calorimetry, DO 10.1007/s10973-020-09856-9.

[6] Misra, J. C., Mallick, B., Steinmann, P. (2020). Temperature distribution and entropy generation during Darcy–Forchheimer–Brinkman electrokinetic flow in a microfluidic tube subject to a prescribed heat flux. Meccanica, 55(5), 1079–1098. DOI 10.1007/s11012-020-01152-y.

[7] Ferdows, M., Murtaza, M. G., Misra, J. C., Tzirtzilakis, E. E., Alzahrani, F. (2020). Analyzed dual solutions for boundary layer flow and heat transfer of biomagnetic fluid over a stretching/shrinking sheet in presence of a magnetic dipole and a prescribed heat flux. International Journal of Applied Electromagnetics andMechanics, 1–17, In press.

[8] Sankar Giri, S., Das, K., Kundu, P. K. (2020). Homogeneous–heterogeneous reaction mechanism on MHD carbon nanotube flow over a stretching cylinder with prescribed heat flux using differential transform method. Journal of Computational Design and Engineering, 7(3), 337–351. DOI .1093/jcde/qwaa028.

[9] Anupam, B., Akmal, H. (2020). Optimization of heat transfer properties on ferrofluid flow over a stretching sheet in the presence of static magnetic field. Journal of Thermal Analysis and Calorimetry, 1–18. DOI 10.1007/s10973-020-09636-5.

[10] Izadi, M., Javanahram, M., Zadeh, S. M. H., Jing, D. (2020). Hydrodynamic and heat transfer properties of magnetic fluid in porous medium considering nanoparticle shapes and magnetic field dependent viscosity. Chinese Journal of Chemical Engineering, 28(2), 329–339. DOI 10.1016/j.cjche.2019.04.024.

[11] Nadeem, S., Alblawi, A., Muhammad, N., Alarifi, I. M., Issakhov, A. et al. (2020). A computational model for suspensions of motile micro- organisms in the flow of ferrofluid. Journal of Molecular Liquids, 298, 112033. DOI 10.1016/j.molliq.2019.112033.

[12] Lucas, H. P. C., Ivan, R. S., Arthur, A. R. C., Adriano, P. R., Taygoara, F. O. (2020). A numerical study on heat transfer of a ferrofluid flow in a square cavity under simultaneous gravitational and magnetic convection. Theoretical Computational Fluid Dynamics, 34, 119–132.

[13] Hui, Z., Yugang, Z., Wenzhen, F., Chaoyang, Z., Fangqi, Z. et al. (2020). Active control of the freezing process of a ferrofluid droplet with magnetic fields. Applied Thermal Engineering, 176, 115444.

[14] Abazar, A., Mohammad, S., Mehdi, A., Mahdi, P., Mohammad, P. et al. (2020). Experimental characterization of magnetic field effects on heat transfer coefficient and pressure drop for a ferrofluid flow in a circular tube. Journal of Molecular Liquids, 299, 112206.

[15] Bijarchi, M. A., Favakeh, A., Shafii, M. B. (2020). The effect of a non-uniform pulse-width modulated magnetic field with different angles on the swinging ferrofluid droplet formation. Journal of Industrial and Engineering Chemistry, 84, 106–119. DOI 10.1016/j.jiec.2019.12.026.

[16] Pouya, B., Davood, T., Arash, K. (2020). Application of rotating circular obstacles in improving ferrofluid heat transfer in an enclosure saturated with porous medium subjected to a magnetic field. Journal of Thermal Analysis and Calorimetry, 37, 1–23.

[17] Acharya, N. (2020). Framing the impacts of highly oscillating magnetic field on the ferrofluid flow over a spinning disk considering nanoparticle diameter and solid–liquid interfacial layer. Journal of Heat Transfer, 142(10), 263. DOI 10.1115/1.4047503.

[18] Andersson, H. I. (2002). Slip flow past a stretching surface. ActaMechanica, 158(1–2), 121–125. DOI 10.1007/BF01463174.

[19] Busse, F. H., Riahi, N. (1980). Nonlinear convection in a layer with nearly insulating boundaries. Journal of Fluid Mechanics, 96(2), 243–256. DOI 10.1017/S0022112080002091.

[20] Shi, B., Guo, Z. (2009). Lattice Boltzmann model for nonlinear convection-diffusion equations. Physical Review E, 79(1), 195. DOI 10.1103/PhysRevE.79.016701.

[21] Kumar, R., Sood, S. (2017). Numerical analysis of stagnation point nonlinear convection flow through porous medium over a shrinking sheet. International Journal of Applied and Computational Mathematics, 3(2), 971–985. DOI 10.1007/s40819-016-0150-2.

[22] Upadhya, S. M., SureshKumar Raju, S., Raju, C. S. K., Chokri, M. (2020). Arrhenius activation and zero mass flux conditions on nonlinear convective jeffrey fluid over an electrically conducting and radiated sheet. Arabian Journal for Science and Engineering, 340(4), 68. DOI 10.1007/s13369-020-04687-0.

[23] Zemedu, C., Wubshet, I. (2020). Nonlinear convection flow of micropolar nanofluid due to a rotating disk with multiple slip flow. Mathematical Problems in Engineering, 2020(3), 1–19. DOI 10.1155/2020/4735650.