Numerical Analysis of Heat Transfer in Ferrofluid Under Constant External Magnetic Field

Jaswinder Singh Mehta, Rajesh Kumar, Harmesh Kumar, and Harry Garg

Abstract This paper reports the numerical analysis of single-phase kerosene-based ferrofluid that passes through a circular-shaped closed loop. Permanent magnet has been employed to generate the magnetic field, and fluid flows as per thermo-magnetic convection principle. A two-dimensional, incompressible, and laminar flow has been considered while performing the time-dependent heat transfer study for the ferrofluid. The governing equations such as continuity, momentum, and energy equations are solved for steady-state incompressible flow using a partial differential equation based multiphysics finite element software, COMSOL Multiphysics 5.0. Simulation results indicate that magnitude of Kelvin body force rises with time as fluid flows with increased velocity resulting in successful dissipation of heat flux.

Keywords Heat transfer · Thermo-magnetic convection · Kelvin body force · Kerosene-based ferrofluid · Velocity contour

1 Introduction

Heat transfer augmentation is of paramount concern in electronics cooling and various other industrial cooling systems. Nanofluids, as of date, are used quite frequently for various applications requiring high rate of heat dissipation, and plethora of research work [1–9] in this field signify the interest of research community to explore various nanofluids for such applications. Recently, ferrofluids have caught the researchers' eye as the fluid can be manipulated in the presence of magnetic field. Ferrofluid is a distinct class of nanofluid whose thermo-physical properties could be customized as per system requirements, and variation in its flow rate can also be

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made by changing the strength/frequency of magnetic field. The fluid is composed of magnetic particles of size usually less than 10 nm, and uniform suspension in a non-magnetic carrier fluid can be reasonably approximated [10].

The influence of asymmetrical magnetic field on heat transfer and pressure differential of water-based ferrofluid was experimentally examined. The fluid flows through uniformly heated parallel-plate channels, and the flow rate was varied between Reynolds number 20–1200. An augmentation in convective heat transfer coefficient was noticed with velocity and frequency of magnetic field while increase in volume fraction of fluid led to rise in pressure drop [11]. The effect of two kinds of magnetic arrangement on convective heat transfer coefficient of water-based ferrofluid was experimentally examined. The fluid passes through a stainless steel tube, and magnets were arranged in two different configurations along the flow direction. The authors observed higher augmentation of heat transfer coefficient for double in-line magnet arrangement as compared to single in-line arrangement at fixed flow rates. A significant enhancement in heat transfer capability of fluid was also found in the presence of magnetic field [12]. Cooling capability of thermo-magnetically pumped ferrofluid in vertical flow loop was studied. There was substantial decrease up to about 75% in size of heat sink with the use of ferrofluid. Also, high heat transfer enhancement factor was noted at higher static magnetic field strengths [13]. Flow and heat transfer characteristics of water-based ferrofluid were numerically investigated using CVFEM method. Rayleigh number, magnetic number, and particle volume fraction have direct bearing on average heat coefficient; however, with increase in Hartmann number, heat transfer coefficient was observed to decrease [14]. An experimental heat transfer analysis of a copper oscillating heat pipe filled with kerosene-based ferrofluid was performed. At a liquid filled ratio of 50%, the effect of magnetic field on temperature distribution and alteration in thermal resistance of the pipe was calculated. The authors compared the heat transfer of Fe_2O_3 nanofluid-charged oscillating heat pipe with kerosene-charged OHP and concluded that in the presence of magnetic field, substantial improvement in the former case was noticed due to reduction in its overall thermal resistance [15]. The effect of Reynolds number, location of line dipoles, and magnetic flux intensity on heat transfer characteristics of water-based ferrofluid passed through a two-dimensional duct was studied numerically using simple finite volume method. Increase in Reynolds number and magnetic field strength lead to improvement in convection heat transfer rate [16]. Convective heat transfer characteristics of water-based ferrofluid under different temperatures and magnetic field strengths varying from 100 to 200 G were analyzed experimentally. The fluid was passed through a hollow circular pipe, and convective heat transfer coefficient was observed to decrease under the effect of constant and uniform magnetic field. The intensity of magnetic field also had negative correlation with heat transfer coefficient. The authors argued that low Brownian motion along with increased viscosity might be the possible cause for reduction in heat transfer coefficient [17]. The impact of alternating magnetic field on convective heat transfer was examined, and it was deduced that heat transfer performance was enhanced with strength and frequency of the field. Non-accumulation of nanoparticles in vicinity to tube wall when the field was alternated was the primary cause behind augmentation of heat transfer coefficient [18]. The performance of a miniature automatic energy transport device was measured experimentally. A temperature-sensitive magnetic fluid was allowed to flow through the loop. Flow behavior of magnetic fluid was envisaged using particle image velocimetry technique. With increase in applied heat flux, fluid flow velocity was found to increase and performance of the device was shown to be dependent on structure of the loop [19]. Heat transfer characteristics for a ferrofluid flowing through a square-shaped duct were experimentally evaluated. Higher volume fraction resulted in increase in Nusselt number while reverse trend was noted for mass flow rates when magnetic field was applied perpendicular to the heat flux [20].

The present work reports the numerical simulation of convective heat transfer of single-phase kerosene-based ferrofluid in a circular-shaped closed loop under the influence of an external magnetic field. Governing equations were solved using COMSOL Multiphysics 5.0, an FEA-based solver. Simulation results concluded that Kelvin body force was generated inside the ferrofluid when spatial thermal gradient exist along with non-uniform magnetic field. Velocity tends to grow with the passage of time resulting in movement of ferrofluid without the need of any external pump.

2 Computational Method

2.1 Geometrical Model

Figure 1 shows the schematic of the geometry employed for numerical analysis. A circular closed loop of outer diameter 180 mm and thickness 2 mm is taken. The ferrofluid flows through the annular space having outer and inner diameter as 178 mm and 175.5, respectively. A permanent magnet of size 25 × 7 mm and intensity 1T

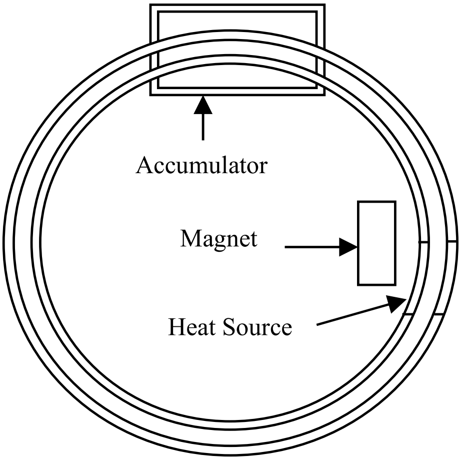


Fig. 1 Two-dimensional geometrical model

Table 1 Thermo-physical properties of ferrofluid

Sr. No.	Parameters	Value
1	Viscosity,μ	2 cP
2	Density,ρ	910 kg/m^3
3	Thermal conductivity,k	0.174 W/(m K)
4	Curie temperature of the fluid	65 °C
5	Surrounding temperature	20 °C
6	Magnetic susceptibility	0.386
7	Relative permeability	1.386

is being employed for generating external magnetic field. A constant heat flux of 2 W/cm^3 was applied. The problem undertaken was considered to be two dimensional, steady, and incompressible while flow was assumed to be non-turbulent in nature. No slip boundary conditions were assumed at the inner wall surface. The fluid was synthesized, and their thermo-physical properties were determined experimentally by the supplier and are used as such for the present study, the details of which are listed in Table 1.

2.2 Governing Equations

Since the magnetic nanoparticle size is less than 10 nm, the fluid is treated as homogenous fluid, and accordingly single-phase approach is adopted for modeling ferrofluid. The continuity, momentum, and energy equations [21] that govern the ferrofluid flow through the closed loop are as follows:

Mass continuity equation:

$$\frac{\partial \rho}{\partial t}+\nabla \cdot (\rho \vec{u})=0 \tag{1}$$

Momentum equation:

$$\rho \partial \vec{u}/\partial t + \rho \vec{u} \cdot \nabla \vec{u} = -\nabla p + \nabla \cdot (\mu(\nabla \vec{u} + \left(\nabla \vec{u})^T\right) + \vec{F} \tag{2}$$

Energy equation:

$$\rho c_p \left(\frac{\partial T}{\partial t} + \vec{u} \cdot \nabla T \right) = k \nabla^2 T \tag{3}$$

Magnetic induction:

$$\vec{B} = \mu_\circ \left(\vec{H} + \vec{M} \right) \tag{4}$$

Table 2 Grid independence study for the selected domain

Grid size	Fluid velocity (mm/s)
Normal	7.2765
Fine	7.6948
Finer	7.7257
Extra fine	7.7318
Extremely Fine	7.7311

Kelvin body force:

$$\vec{F} = \left(\vec{M} \cdot \nabla\right)\vec{B} \tag{2.5}$$

2.3 Grid Independence Test

Mesh size for the two-dimensional model was determined by conducting grid independence test. Velocity of the ferrofluid was estimated for all the grid settings used, and results are displayed in Table 2.

However, any mesh settings can be used, but physics-controlled fine mesh is being adopted for the selected domain as the best settings since no significant variations in the velocity values were observed upon increasing the mesh density further in order to access the velocity measurements accurately as shown in Fig. 2.

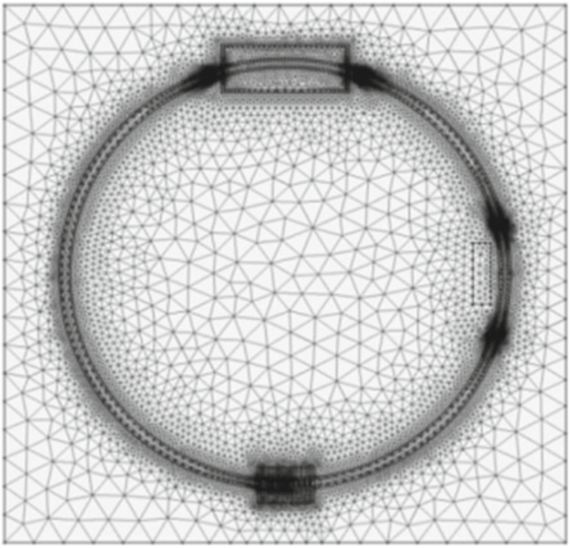


Fig. 2 Grid distribution used in the study

3 Results and Discussions

Figure 3 illustrates the temperature distribution inside the closed loop at different instant of time. As can be seen, the temperature of fluid keeps on rising up to its Curie temperature as the time progresses. A high temperature gradient exists near the heat source where permanent magnet is positioned.

The spatial thermal differential and non-uniform magnetic field were primarily the basis for generation of Kelvin body force. The Kelvin body force, thus, becomes the driving force, and fluid begins to flow due to this.

The velocity field inside the loop at different length of time is depicted in Fig. 4. There has been a spontaneous increase in velocity with time. The region of maximum velocity is found where the magnet is positioned and at the instant just when the fluid is about to enter into the heated length. The existence of higher temperature gradient and non-uniform magnetic field at that location is the principal reason for generation of Kelvin body force.

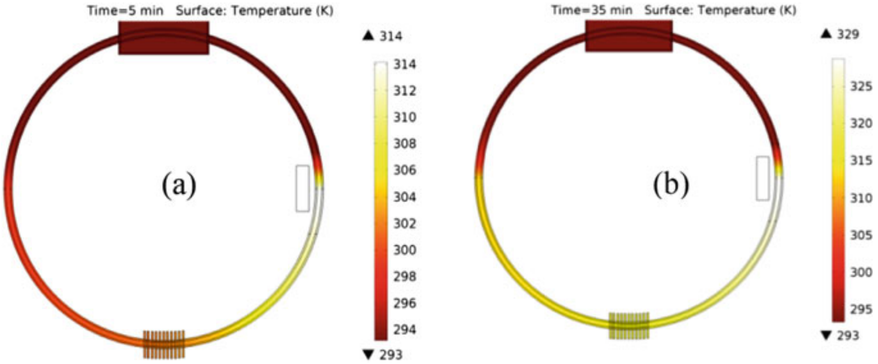


Fig. 3 Temperature distribution inside loop at different length of time **a** 5 min **b** 35 min

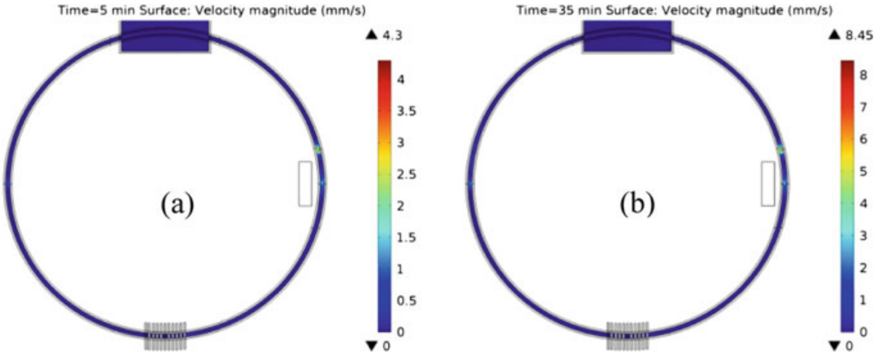


Fig. 4 Velocity contours (mm/s) inside the loop at different point of time **a** 5 min **b** 35 min

Velocity vectors showing the direction of flow of ferrofluid in the loop have been represented in Fig. 5. The fluid flows in clockwise direction under the effect of magnetic field generated by permanent magnet. Velocity profile of the ferrofluid as depicted in Fig. 6, clearly indicating the growing magnitude of velocity with time.

Fig. 5 Velocity vectors indicating fluid flow direction

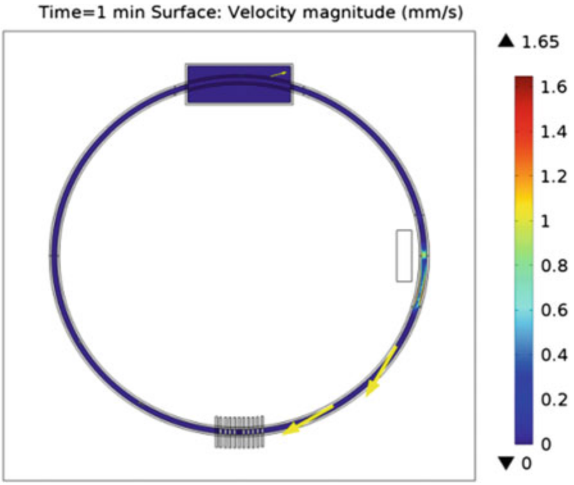
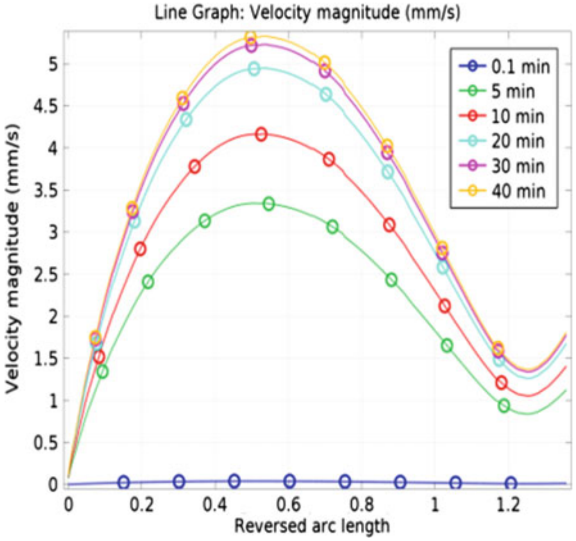


Fig. 6 Fluid velocity profile



4 Conclusions

Following conclusions could be drawn from the simulation study:

1. Temperature contours representing the variations of temperature in the loop reaffirm the movement of ferrofluid under the effect of external magnetic field. Colder fluid displaces the hot fluid as it passes through the heated length due to Kelvin body force, and as the fluid travels, it dissipates its heat to the surrounding air.
2. Velocity contours and velocity profile signify the increase in magnitude of fluid velocity with time. With the passage of time, fluid was heated in close vicinity to its Curie temperature resulting in existence of higher thermal differential, and thus, strength of Kelvin body force increases and it in turn leads to faster fluid movement that result in quick extraction of heat. This effect is very much similar to natural convection where hot, lesser dense fluid is displaced by colder, denser fluid.
3. Maximum fluid velocity of 8.45 mm/s was found at $t = 35$ min near the location where permanent magnet is positioned. The flow was also found to be continuous and laminar in nature with parabolic velocity profile.

Simulation results illustrate the heat transfer potential of ferrofluid and the distinct advantage of ferrofluid-based miniature cooling system is that system is totally passive in nature. The fluid can be tailored as per design requirement and maneuvered under the influence of magnetic field.

5 Future Recommendations

Further laboratory testing aided by numerical simulations would help to better understand the behavior of ferrofluid when subjected to magnetic field. The effect of different angles of magnet orientation and nanoparticle volume fraction on the heat transfer effectiveness of ferrofluid-based cooling system should be recommended for future studies.

References

1. Lomascolo, M., Colangelo, G., Milanese, M., & de Risi, A. (2015). Review of heat transfer in nanofluids: Conductive, convective and radiative experimental results. *Renewable and Sustainable Energy Reviews, 43*, 1182–1198.
2. Raja, M., Vijayan, R., Dinesh, K. P., & Venkatesan, M. (2016). Review on nanofluids characterization, heat transfer characteristics and applications. *Renewable and Sustainable Energy Reviews, 64,* 163–173.
3. Sheikholeslami, M., & Ganji, D. D. (2017). Nanofluid flow and heat transfer in the presence of constant magnetic field. Micro and nano technologies. In *Applications of nanofluid for heat transfer enhancement* (pp. 279–384). William Andrew Publishing.

4. Li, Q., Xuan, Y., & Wang, J. (2003). Investigation on convective heat transfer and flow features of nanofluids. *Journal of Heat Transfer, 125,* 151–155.
5. Duangthongsuk, W., & Wongwises, S. (2009). Heat transfer enhancement and pressure drop characteristics of TiO_2-water nanofluid in a double-tube counter flow heat exchanger. *International Journal of Heat and Mass Transfer, 52,* 2059–2067.
6. Colangelo, G., Favale, E., Milanese, M., de Risi, A. Laforgia D. (2017). Cooling of electronic devices: Nanofluids contribution. *Applied Thermal Enginering, 127*, 421–435.
7. Agromayor, R., Cabaleiro, D., Pardinas, A. A., Vallejo, J. P., Fernandez-Seara, J., & Lugo, L. (2016). Heat transfer performance of functionalized graphene nanoplatelet aqueous nanofluids. *Materials, 9,* 455.
8. Zhang, H., Shao, S., Xu, H., & Tian, C. (2013). Heat transfer and flow features of Al_2O_3-water nanofluids flowing through a circular microchannel-experimental results and correlations. *Applied Thermal Engineering, 61,* 86–92.
9. Heris, S. Z., Etemad, S. G., & Esfahan, M. N. (2006). Experimental investigation of oxide nanofluids in laminar flow convective heat transfer. *International Communications in Heat and Mass Transfer, 33,* 529–535.
10. Rosensweig, R. E. (1997). *Ferrohydrodynamics* (2nd ed.). New York, NY: Dover Pub. Inc.
11. Goharkhah, M., Ashjaee, M., & Shahabadi, M. (2016). Experimental investigation on convective heat transfer and hydrodynamic characteristics of magnetite nanofluid under the influence of an alternating magnetic field. *International Journal of Thermal Sciences, 99,* 113–124.
12. Asfer, M., Mehta, B., Kumar, A., Khandekar, S., & Panigrahi, P. K. (2016). Effect of magnetic field on laminar convective heat transfer characteristics of ferrofluid flowing through a circular stainless steel tube. *International Journal of Heat and Fluid Flow, 59,* 74–86.
13. Aursand, E., Gjennestad, M. A., Lervåg, K. Y., & Lund, H. (2016). Potential of enhancing a natural convection loop with a thermomagnetically pumped ferrofluid. *Journal of Magnetism and Magnetic Materials, 417*, 148–159.
14. Sheikholeslami, M., & Rashidi, M. M. (2015). Effect of space dependent magnetic field on free convection of $Fe3O_4$–water nanofluids. *Journal of the Taiwan Institute of Chemical Engineers*, 1–10.
15. Goshayeshi, H. R., Goodarzi, M., & Dahari, M. (2015). Effect of magnetic field on the heat transfer rate of kerosene/Fe_2O_3 nanofluid in a copper oscillating heat pipe. *Experimental Thermal and Fluid Science, 68,* 663–668.
16. Ghorbani, B., Ebrahimi, S., & Vijayaraghavan, K. (2018). CFD modeling and sensitivity analysis of heat transfer enhancement of a ferrofluid flow in the presence of a magnetic field. *International Journal of Heat and Mass Transfer, 127,* 544–552.
17. Sha, L., Ju, Y., Zhang, H., & Wang, J. (2017). Experimental investigation on the convective heat transfer of Fe_3O_4/water nanofluids under constant magnetic field. *Applied Thermal Engineering, 113,* 566–574.
18. Mohammad, G., Armia, S., Mehdi, A., & Mahmoud, S. (2015). Convective heat transfer characteristics of magnetite nanofluid under the influence of constant and alternating magnetic field. *Power Technology, 274,* 258–267.
19. Lian, W., Xuan, Y., & Li, Q. (2009). Characterization of miniature automatic energy transport devices based on the thermomagnetic effect. *Energy Conversion and Management, 50*(1), 35–42.
20. Cherief, W., Avenas, Y., Ferrouillat, S., Kedous-Lebouc, A., Jossic, L., & Petit, M. (2017). Parameters affecting forced convection enhancement in ferrofluid cooling systems. *Applied Thermal Engineering, 123,* 156–166.
21. Neuringer, J. L., & Rosensweig, R. E. (1964). Ferrohydrodynamics. *Physics of Fluids, 7*, 1927 (1964).