Numerical Investigation and Comparison of Thermal Performance of Ferrofluid in Different Closed Loop Configurations

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Abstract. This paper describes the free convection heat transfer capability of kerosene based ferrofluid flowing through a closed loop for assessing the thermal performance. Numerical investigations were performed using COMSOL Multi Physics 5.0 for comparing the heat transfer characteristics of ferrofluid flowing through three different closed loop geometrical configurations. The heat transfer performance of rectangular, oval and circular shape closed loop was evaluated under same input test conditions. Constant magnetic field was applied and time dependent numerical study was conducted for single-phase fluid flow. The fluid moves under the effect of Kelvin Body Force and maximum velocity of 5.68 mm/s has been found for oval shaped configuration. Temperature and velocity plots have been plotted for different lengths of time and results of investigation reveal that oval shaped configuration favors better output in terms of velocity generated and heat transfer.

1. Introduction

Magnetically controlled fluids have been used for quite a long time for various applications including dynamic sealing of shafts, magnetic drug targeting, for treatment of hyperthermia and magnetic separation of cells [1]. Heat transfer is another challenging area for ferrofluids which has attracted interest of many researchers in recent years [2-8]. Over a period of last few decades, unprecedented growth has been observed in the computational power of electronic devices. Reduction in size and generation of high heat flux has been a prominent feature of their working. Smart cooling systems are thus the need of the hour which should be able to dissipate the high heat flux generated by these devices so that they can work 24×7. Ferrofluid driven heat exchangers can provide a potential solution for cooling of such miniaturized devices.

Ferrofluids are a distinct class of magnetically controllable fluid and have added advantage over magneto-rheological (MR) fluids in the sense that the fluid maintains their flowability under strong external magnetic fields while MR fluid tends to solidify when subjected to strong magnetic field. Thus, when such a fluid is subjected to temperature gradient in the presence of external magnetic field, due to non-equilibrium magnetization in the fluid, the fluid will experience a magnetic body force, called “Kelvin body force” which results in movement of fluid in the direction of higher temperature section [9]. The flow rate of the fluid, hence, could be controlled as per heating load by varying only
the intensity of magnetic field. Thus, the ferrofluid based cooling system as a whole is totally passive in nature as it does not require any mechanical means for circulation of the fluid/coolant.

The effect of non-uniform magnetic field on hydrothermal characteristics of water-based ferrofluid was studied by Shakiba and Vahedi [10]. The fluid was allowed to pass through a horizontal double-pipe heat exchanger and hydrothermal characteristics were analyzed using ANSYS Fluent. With increase in the intensity of magnetic field, increase in Nusselt number was observed. Forced convective heat transfer behavior of hybrid nanofluid containing magnetite nanoparticles and CNTs was experimentally investigated by Shahsavari et al. [11]. Fully developed fluid flows through copper tube and behaviour was studied under the influence of constant and alternating magnetic fields. Convective heat transfer coefficient was found to increase with Re in the absence of magnetic field while reverse trend was observed in the presence of magnetic field. Control volume based finite element method was applied by Sheikholeslami and Rashidi [12] to numerically investigate the flow and heat transfer characteristics of water based ferrofluid. Increase in heat transfer coefficient was reported with magnetic number, Rayleigh number and nanoparticle volume fraction. Hydrothermal behaviour of water-based ferrofluid flowing through a helical channel was numerically examined under the effect of transverse magnetic field by Aminfar et al. [13]. Augmentation in heat transfer was reported with increase in the flow rate and velocity gradient. Convective heat transfer coefficient of water based ferrofluid was experimentally evaluated under the influence of constant magnetic field by Asfar et al. [14]. Temperature measurements of fluid were done using infrared thermography technique. Augmentation in heat transfer was observed, when the ferrofluid was flowing through stainless steel tube under the effect of magnetic field. Convective heat transfer characteristics were experimentally analyzed by Cherief et al. [15] for a ferrofluid that flows through a square duct. Augmentation in heat transfer coefficient was observed with increase in volume fraction, and lower mass flow rates.

It can be observed from the reported literature that ferrofluid based cooling systems augment heat transfer. Although some research work has been done on free convection of ferrofluid, but majority of these studies have been conducted for forced circulation of fluid. An attempt has been made in this paper to numerically investigate thermal performance of kerosene based ferrofluid flowing through a closed loop due to spatially varying fluid magnetization with temperature. The fluid tends to move due to thermo-magnetic convection principle solely due to external magnetic field. A comparison of three different loop shapes i.e. rectangular, oval and circular shape have also been presented under same constant heat flux and for same volume of fluid. Numerical simulations are carried out in COMSOL MultiPhysics 5.0 on 2D closed loop and variations in flow behavior is plotted in the form of velocity and temperature plots.

2. Problem Formulation

2.1. Geometry Description

Figure 1 shows the schematic of two dimensional model used for simulation study highlighting the main components of the model. The model consists of a closed loop, a permanent magnet for applying magnetic field, accumulator that acts as a reservoir for the ferrofluid, a heat source for applying heat flux and fins for dissipating heat to the surroundings.

![Figure 1. Schematic of two dimensional model for rectangular shaped loop.](image)
The ferrofluid is assumed to flow through a copper pipe having inner diameter 2.5 mm and outer diameter 3.5 mm. A strip heater of size 28 mm × 1 mm is used as a heat source and permanent magnet has been positioned in between accumulator and heat source such that it cover half of the heated length. A constant heat flux of 2 W/cm² has been applied to the fluid as it flows through the heated length. Aluminum fins of width 1 mm and height 15 mm have been fixed on the lower loop with distance between them as 2 mm. Fins are used to increase the surface area for better heat dissipation.

Three closed loop geometries i.e. rectangular, oval and circular shapes have been considered in the problem. The loop length has been fixed in such a way that same volume of fluid should flow in all the three configurations while subjecting the fluid to same heat flux, same magnetic field intensity and initial temperature.

2.2. Governing equations

Following equations govern the flow of fluid for the problem under consideration:

Continuity Equation treating flow as incompressible:

\[ \rho (\nabla \cdot \mathbf{u}) = 0 \]  

(2.1)

Momentum Equation without viscous dissipation term:

\[ \rho \frac{\partial \mathbf{u}}{\partial t} + \rho \mathbf{u} \cdot \nabla \mathbf{u} = -\nabla p + \nabla \cdot (\mu (\nabla \mathbf{u} + (\nabla \mathbf{u})^T)) + \mathbf{F} \]  

(2.2)

Energy equation:

\[ \rho c_p \left( \frac{\partial T}{\partial t} + \mathbf{u} \cdot \nabla T \right) = k \nabla^2 T \]  

(2.3)

Magnetic Induction:

\[ \mathbf{B} = \mu (\mathbf{H} + \mathbf{M}) \]  

(2.4)

Kelvin Body Force:

\[ \mathbf{F} = (\mathbf{M} \cdot \nabla) \mathbf{B} \]  

(2.5)

The important properties of ferrofluid used for the simulation are presented in Table 1.

| Sr. No. | Parameters           | Value     |
|---------|----------------------|-----------|
| 1       | Viscosity, \( \mu \) | 2 cP      |
| 2       | Density, \( \rho \)  | 910 kg/m³ |
| 3       | Thermal conductivity, k | 0.174 W/(m-K) |
| 4       | Surrounding temperature | 293.15 K   |
| 5       | Curie temperature    | 335 K     |
| 6       | Magnetic susceptibility | 0.386     |
| 7       | Relative permeability of fluid | 1.386   |

2.3. Simulation

For modeling the system, COMSOL Multiphysics 5.0, a partial differential equation (PDEs) based multiphysics finite element package is being used. The software allow user to couple different physics like heat transfer, fluid flow etc. in the same model with ease and has large in-built library of meshing and post-processing tools. A two dimensional model was created for the flow analysis in model builder.
of COMSOL Multiphysics 5.0 and appropriate material properties were assigned to different components. No slip conditions were assumed for the flow at the pipe inner surface and physics controlled fine mesh has been used for predicting the temperature and velocity measurements accurately. Initial temperature of the ferrofluid in the loop and surrounding medium was considered as 293 K and flow was assumed to be laminar in nature.

![Figure 2. Meshing for the computational domain for rectangular shaped loop.](image)

Since the problem under consideration involve three different physics i.e. magnetic flux, heat transfer and laminar flow, thus MultiPhysics node containing different physics interfaces are used in the simulation study. Magnetic field is treated stationary, while heat transfer and laminar flow are considered as time dependent while solving the model.

3. Results and Discussions

Temperature profile generated at different length of time for rectangular, oval and circular loop shapes are presented in Figure 3-5 respectively.

![Figure 3. Fluid temperature profile (K) generated at different point of time (a) 5 min (b) 15 min (c) 35 min (d) 50 minutes for rectangular shaped closed loop.](image)
Figure 4. Fluid temperature profile (K) generated at different point of time (a) 5 min (b) 15 min (c) 35 min (d) 50 minutes for oval shaped closed loop.

Figure 5. Fluid temperature profile (K) generated at different point of time (a) 5 min (b) 15 min (c) 35 min (d) 50 minutes for circular shaped closed loop.

The temperature distribution diagrams shown in Figure 3-5 reveal that fluid is heated in close vicinity to its Curie temperature as it passes through heat source region, thus generating temperature gradient at the place where magnet is positioned. Color bar on the right side of graphic shows the temperature(K) reached in different parts of the loop; whilst values placed alongside bottom and top of the color bar shows the minimum and maximum value of temperature attained respectively in the loop at that instant of time. The temperature difference along with non-uniform magnetic field distribution is thus responsible for flow of the fluid. As the fluid flows through the loop, temperature begins to fall as heat loss by convection takes place mainly in the lower loop section. The cold fluid, thus moves towards the accumulator and is ready to perform next cycle.
Figure 6. Fluid velocity profile (mm/s) generated at different point of time (a) 5 min (b) 25 min (c) 50 minutes for rectangular shaped configuration.

Velocity profile generated at different length of time for rectangular, oval and circular loop shapes are shown in Figure 6-8 respectively.

Figure 7. Fluid velocity profile (mm/s) generated at different point of time (a) 5 min (b) 25 min (c) 50 minutes for oval shaped configuration.

Figure 8. Fluid velocity profile (mm/s) generated at different point of time (a) 5 min (b) 25 min (c) 50 min for circular shaped configuration.
Figure 9. Variation of fluid velocity at different instant of time for oval shape configuration.

Figure 10. Velocity vectors (black color arrows) representing fluid flow direction in the loop.

Velocity profiles shown in Figure 6-8 highlight the augmentation in velocity of ferrofluid with time as it flows through the loop. Lesser velocity is generated in the beginning, as temperature difference in the loop was less. However, as the time progress, fluid was heated in close vicinity to the Curie temperature near the section where magnet was positioned. Thus, higher temperature gradient near the location of magnet along with non-uniform magnetic field led to generation of Kelvin body force that act as driving force.

The variation of velocity shown in Figure 7 for oval shaped configuration is also represented in the form of line graph in Figure 9 across a cross-section when fluid is about to enter heated length. At fluid-pipe interface, velocity of ferrofluid is zero and it reaches its maximum value as centre line of the pipe is being approached.

4. Conclusion

Following conclusions could be drawn from the numerical study conducted on different loop geometries:

(a) Temperature plots for different loop configurations confirm the movement of ferrofluid in the loop. Higher temperature gradient near the heat source entrance section leads to generation of Kelvin body force. The non-uniform magnetic field distribution along with spatial temperature variation is thus responsible for the movement of the fluid in the loop. Higher force experienced by the cold fluid on the left side of the heat source section near the site where magnet is positioned displaces the hot fluid in the heated section; thus establishing flow of fluid. Higher temperature drop is visible for oval shaped configuration at different lengths of time in comparison to other two loop shapes.

(b) Steady/equilibrium state was established after t= 35 minutes in oval and rectangular shaped loop while fluid took even lower time to reach equilibrium state in circular loop.

(c) Maximum velocity of 5.68 mm/s was generated at t = 35 minutes for oval shaped loop just when the fluid is about to pass through heat source section. Corresponding value for rectangular and circular shaped loop at same time was found to be 2.45 mm/s and 3.58 mm/s respectively. Thermal performance of oval shaped loop is, thus, better in comparison to other two loop profiles as higher force was generated in the loop resulting in higher fluid velocity. The fluid is thus capable of completing the cycle in lesser time, extracting more heat, thus maintaining safe working temperature.
(d) A line graph as shown in Figure 9 represents the variation in the velocity across the cross section at time $t = 5$ min, 25 min and 50 min, when the fluid is just about to enter heated length for oval shaped loop. Velocity of fluid is zero at the fluid pipe interface due to no slip conditions and it tends to increase towards the centerline of the pipe.

(e) Velocity vectors in Figure 10 shows the direction of fluid flow. Under the influence of Kelvin body force, fluid starts to move in clockwise direction, extracting heat from the heat source and during its passage dissipate thermal energy to the surroundings. Thus low temperature fluid is always available at the end of every cycle in the accumulator region.

The numerical study conducted in this paper signifies the heat transfer capability of ferrofluid as a coolant. The system as a whole is passive in nature, as it does not require any external device such as pump for circulation of the fluid. Oval shaped loop proved to perform better in terms of velocity generated and maintaining lower source temperatures.

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