FEA Simulation of Passive Ferrofluid Cooling Systems

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Abstract: The unique properties of ferrofluid such as the magnetization depending on temperature, excellent geometry flexibility, and non-volatility make it attractive for passive cooling systems. Here we investigate a promising passive cooling method through making advantage of these unique properties and optimize the performance of the cooling system. When a magnetic dipole or a permanent magnet is put at the hot side of a system, it will attract the cold ferrofluid to the hot place and displace the hot ferrofluid since cold ferrofluid below T_c has much stronger magnetization than that of hot ferrofluid above T_c. Then the hot ferrofluid is compelled to the cold side and transfer heat with heat sink to implement the cooling purpose. According to the direction of ferrofluid flow, two modes are analyzed: axial mode and radial mode. Then how the geometry and dynamic viscosity affect the heat transfer are investigated respectively to optimize the performance.

Keywords: Ferrofluid, Passive cooling, FEA simulation, COMSOL

1. Introduction

A ferrofluid is a liquid usually consisting of a carrier fluid like Pluronic F127 and ferromagnetic nanoparticles like the alloy of Fe, Co and Cr.[1] It exhibits strong magnetization upon applying a magnetic field under Curie temperature, T_c. For ferrofluid, the magnetization depending on temperature, excellent geometry flexibility, and non-volatility make it attractive for passive cooling system.[2] Here we investigate a promising passive cooling method through making advantage of the unique properties of ferrofluid. When a magnetic dipole or a permanent magnet is put near the hot side of a system, it will attract the cold ferrofluid to the hot place and displace the hot ferrofluid since cold ferrofluid below T_c has much stronger magnetization than that of hot ferrofluid above T_c. Then the hot ferrofluid is compelled to the cold side and transfer heat with heat sink to implement the cooling purpose. This paper includes simulation results of ferrofluid flow and heat transfer under the above mentioned condition. The magnetic field is applied by a magnetic dipole is assumed at the origin point (0,0) in *x-y* plane, and the magnetic field distribution could be calculated according to the magnetic flux formulas of a magnetic dipole. Then the magnetic force is derived based on the magnetic field distribution. All considered problems are based on two-dimensional computational simulation using standard computational software package COMSOL Multiphysics.[3] According to the direction of ferrofluid flow, two modes are analyzed in this paper: axial mode and radial mode. Then how the geometry and dynamic viscosity affect the heat transfer are investigated respectively to optimize the performance of the cooling system. The results show a promising passive cooling method using ferrofluid.

2. Governing Equations

In our simulation, a magnetic dipole is considered as the magnetic source to cause the flow of ferrofluid. We assume the magnetic dipole is located at the origin (0,0) in *x-y* plane and the magnetic moment μ is pointing in the direction of x axis to simplify the calculation of the magnetic flux density. Then the magnetic flux density produced by the magnetic dipole at any point in *x-y* plane can be expressed as:

$$B_x(x,y)=\frac{\mu_0}{4\pi}3\mu\frac{x^2-\frac{1}{3}(x^2+y^2)}{(x^2+y^2)^{\frac{5}{2}}}$$
$$B_y(x,y)=\frac{\mu_0}{4\pi}3\mu\frac{xy}{(x^2+y^2)^{\frac{5}{2}}} \quad (1)$$

where μ_0 is the permeability of free space, μ is the magnitude of magnetic dipole, and x, y are coordinates in *x-y* plane measured in meters.

The governing equations of ferrofluid flow when the magnetic field is applied are the momentum transport equations, and the mass conservation equation for incompressible fluid in Eq. (2) and (3):

$$\rho\frac{\partial \mathbf{u}}{\partial t}-\nabla\cdot[\eta(\nabla\mathbf{u}+(\nabla\mathbf{u})^{T})]+\rho(\mathbf{u}\cdot\nabla)\mathbf{u}+\nabla p=\mathbf{F} \qquad (2)$$

$$\nabla\cdot\mathbf{u}=0 \qquad (3)$$

In the above equations, ρ is the density, $\mathbf{u}$ is the velocity field, η is the dynamic viscosity, p is the pressure, $\mathbf{F}$ is a volume force field, such as magnetic force.

The magnetic term $\mathbf{F}$ represents the magnetic body force per unit volume, which results in a temperature gradient and leads to the ferrofluid flow and thus a form of heat transfer. $\mathbf{F}$ Could be written as:

$$\mathbf{F}=\nabla(\mathbf{M}\cdot\mathbf{B}) \qquad (4)$$

where $\mathbf{M}$ is the magnetization of ferrofluid and $\mathbf{B}$ is the external magnetic flux density. In our model, the magnitude of $\mathbf{M}$ is considered as a constant $M_s(T)$, which only depends on the temperature,[1] and the direction of M follows the external magnetic field $\mathbf{B}$:

$$\mathbf{M}=M_s(T)\frac{\mathbf{B}}{|\mathbf{B}|}$$
$$M_s(T)=\begin{cases}M_0\sqrt{1-\frac{T}{T_c}}(T<T_c)\\ 0(T>T_c)\end{cases} \qquad (5)$$

where T_c is the Currie temperature.

3. Methods

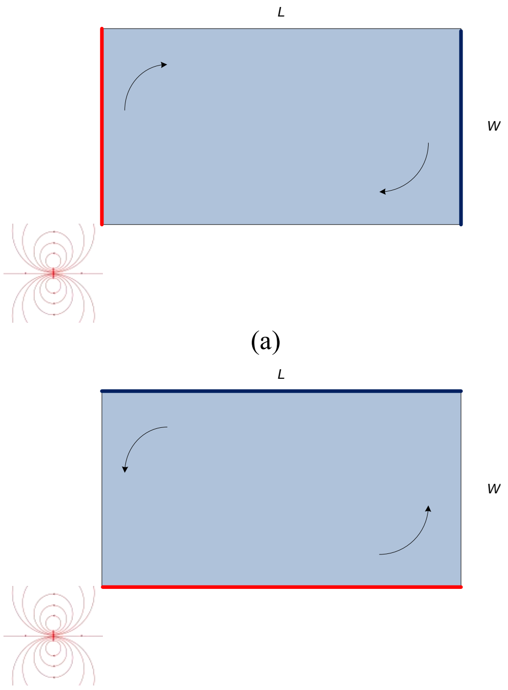


Figure 1. The illustration of (a) axial mode and (b) radial mode cooling system.

In the simulation of this paper, the magnetic dipole is located at the origin (0,0) in x-y plane and the direction is in the direction of x axis. Two modes are investigated: axial and radial. As shown in Fig. 1(a), in axial mode, the top and bottom boundaries are thermal insulation, the left boundary is set a heat flux, the right boundary is temperature fixed. Fig. 1(b) shows the radial mode, the left and right boundaries are thermal insulation, the bottom boundary is set a heat flux, the top boundary is temperature fixed. As shown in Fig. 1, the direction of the ferrofluid flow is different in axial mode and radial mode (clockwise for axial mode and anticlockwise for radial mode).

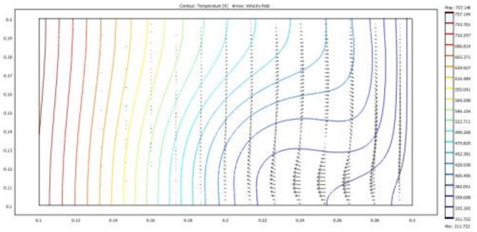
To analyze the effect of geometry, then in each mode the aspect ratio (W/L) varies from 0.5 to 1.5. Finally, η is changed from 0.1 to 1 to investigate how the dynamic viscosity impacts the flow velocity field and temperature field in ferrofluid.

The parameters of ferrofluid and the condition used in our simulation are listed in Table I.

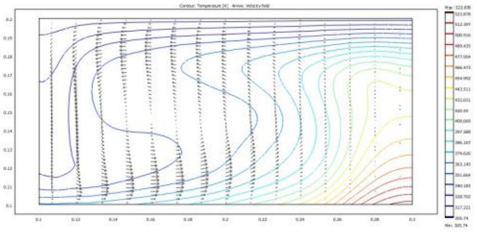
Table I. The parameters of ferrofluid and the condition used in the simulation.

Parameter	Quantity
ρ	1000 kg/m^3
η	1 Pa·s
μ	$4\pi\times10^{-7}$ m^2·A
M_0	3×10^5 A/m
T_c	350 K

4. Results and Discussion



(a)



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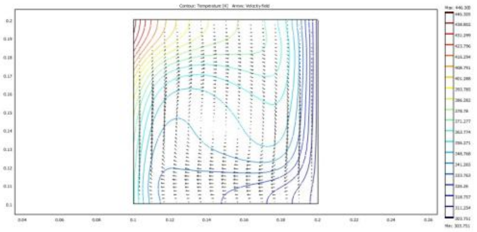

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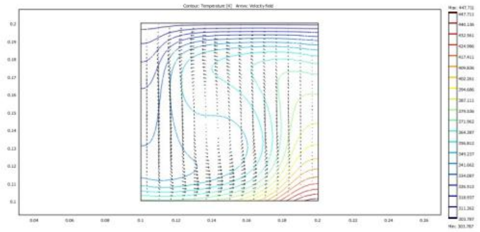
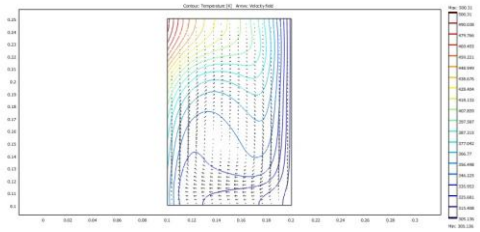
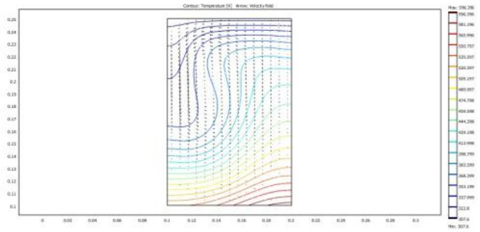


(d)



(e)



(f)

Figure 2. The temperature contour and flow velocity field of ferrofluid in axial mode and radial mode with varying aspect ratio: (a) axial mode, *W/L*=0.5, (b) radial mode, *W/L*=0.5, (c) axial mode, *W/L*=1, (d) radial mode, *W/L*=1, (e) axial mode, *W/L*=1.5, (f) radial mode, *W/L*=1.5.

Fig. 2 shows the temperature contour and flow velocity field of ferrofluid in axial mode and radial mode with varying aspect ratio under the influence of a magnetic dipole. The average temperature of the boundary with fixed hear flux is shown in Fig. 3. For axial mode, when the aspect ratio increases, the average temperature decreases since the ferrofluid has more space to flow in *y* direction and make it easier to take away heat from the boundary with fixed heat flux. In contrast, for radial mode, the average temperature increases when the aspect ratio increases, because the ferrofluid has less space to flow in *x* direction and make it more difficult to take heat away from the boundary with heat flux.

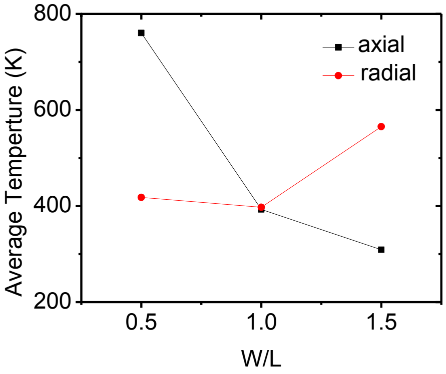


Figure 3. The average temperature of the boundary with fixed hear in axial mode and radial mode with varying aspect ratio.

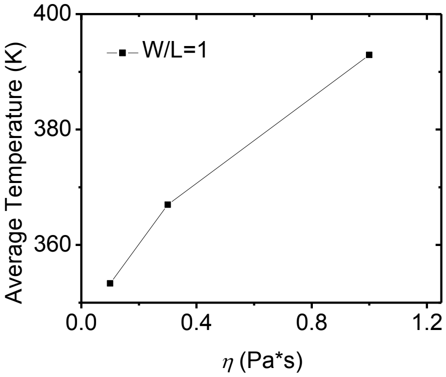


Figure 4. The average temperature of the boundary with fixed heat in axial mode with *W/L*=1.

Fig. 4 shows the effect of dynamic viscosity of ferrofluid. Since the body force per unit volume keeps the same if only the dynamic viscosity is changed, the larger the dynamic viscosity the less the flow velocity is, which leads to the higher the temperature of the boundary with heat flux.

5. Conclusions

In summary, we investigate a promising passive cooling method through making advantage of the unique properties of ferrofluid and optimize the performance by analyzing the effect of geometry and dynamic viscosity. For axial mode, high aspect ratio is necessary for better cooling performance. In contrast, low aspect ratio can improve the cooling performance. Finally, low dynamic viscosity can also enhance the performance of the cooling system remarkably. The results show a promising passive cooling system by using ferrofluid.

6. References

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2. T. Strek, Ferrofluid channel flow under the influence of magnetic dipole, *International Journal of Applied Mechanics and Engineering*, **10**, 103 (2005)
3. www.comsol.com