Numerical Analysis of Thermal Gradient & Magnetic Field using Ferrofluid Cooling

Harry Garg [1], **Sahib Singh** [2], **Vipender Singh Negi** [1], **Ashish Singh Kharola** [1],
and Arun K. Lall [2]

[1] Optical Devices & Systems
CSIR-CSIO, Chandigarh, 160030, India
harry.garg@gmail.com, vipender@live.com, ashish_kharola1988@yahoo.com

[2] Mechanical Engineering
PEC University of Technology, Chandigarh, 160012, India
s.sahib68@gmail.com, lallkarun@gmail.com

Abstract **─** Ferrofluid is a colloidal suspension of single domain magnetic particles of diameter approximately 10 nm, coated with a molecular layer of a dispersant and suspended in a liquid carrier. Ferrofluids may form the basis for next generation noiseless, vibration free passive cooling technique. The pumping ability of ferrofluid depends on temperature gradient and magnetic field orientation. The proposed work covers numerical analysis of heat transfer, magnetism and flow characteristics of ferrofluids. Thermal conductivity and viscosity of ferrofluid governs the heat transfer and flow characteristics. The variation of flow with the direction of magnetic field has been investigated in this paper.

Index Terms **─** Coupled system, ferrofluid, magnetic field, passive cooling, pyromagnetic coefficient.

I. INTRODUCTION

Ferrofluid is a temperature sensitive magnetic fluid which means that its magnetization is function of temperature. A section of Ferrofluid exposed to heat source and external magnetic field directed in a specific orientation results in non-uniform magnetic body force, such a heat transfer is called thermo-magnetic convection [1] and this resultant flow of ferrofluid can be controlled by varying ferrofluid properties, magnetic field strength and temperature distribution. Thermo-magnetic convection can be useful in situations where convective heat transfer alone is inadequate in dissipating heat effectively. Cooling using ferrofluid is a passive cooling technique and it utilizes waste heat from the system to induce the flow in the presence of a magnetic field. The synergistic effect of magnetization, temperature and gradient produces a noiseless and vibration free cooling.

The stability of the magnetic colloid depends on the thermal contribution and on the balance between attractive (Vander Waals and dipole-dipole) and repulsive (Steric and electrostatic) interactions. In order to avoid agglomeration, the magnetic particles are coated with a shell of an appropriate material called surfactant.

A prototype of a miniature automatic cooling device using ferrofluid has previously been described by Love et al. [2] & Li et al. [3]. Strek and Jopek [4] simulated ferrofluid flow in a channel between two parallel plates

Aminfar et al. [5] have investigated numerically the hydrothermal characteristics of a water based ferrofluid in vertical rectangular duct. The magnetic field is produced by a current carrying wire which is placed along the length of the duct.

The flow state in a magnetic fluid [6] heat transport device is investigated numerically. Model geometry of the device is considered when the device is placed vertically. From the results of the calculation a qualitative explanation is made for the flow state of experimental device when the magnetic field is affected.

Wrobel et al. [7] studied thermo-magnetic convective flow of paramagnetic fluid in an annular enclosure with a round rod core and a cylindrical outer wall numerically and experimentally. Their results shows that magnetizing force affects the heat transfer rate and a strong magnetic field can control the magnetic convection of paramagnetic fluid.

Kikura et al. [8] carried experimental investigations in a cubical enclosure and concentric horizontal annuli under the influence of a varying magnetic field. The permanent magnet was placed at different sides of the enclosure and the effect of magnetic field gradient on the ferrofluid heat transfer was studied.

Lajvardi et al. [9] report an experimental work on

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the convective heat transfer of ferrofluid flowing through a heated copper tube in the laminar regime in the presence of magnetic field.

Demuren & Grotjans [10] discussed simplification of flow by considering density variations in the body force term, which is a source and sink momentum in the direction of gravity. The density difference is related to the coefficient of thermal expansion and the temperature difference. This approach works very well for small density differences and has enabled simplified solution of many buoyant flow problems.

Lopez et al. [11] developed a new consistent Boussinesq type approximation. The density variations were considered in the advection term of the Navier-Stokes equations. The new approximation allows accurate treatment of situations with differential rotation or when strong vortices appear in the interior of the domain.

Although many theoretical and experimental investigations have been carried for ferrofluid flow behaviour but the investigations on how ferrofluid flow depends on the thermal conductivity and orientation of magnetic field are sparse. Besides this, the investigations were carried on novel technique to enhance the heat dissipation capacity using ferrofluid.

II. MECHANISM OF FLOW

Ferrofluid being paramagnetic obeys Curie's Law and therefore its behaviour is directly related to temperature and magnetization. The change of magnetization of ferrofluid with temperature is defined by term called pyromagnetic coefficient. Magnetization of ferrofluid decreases with increase in temperature. The temperature, at which the magnetization of the fluid is negligible, is called Curie temperature.

Figure 1 shows the flow mechanism of ferrofluid, magnetic fluid in hot region near heat source being at a higher temperature loses its magnetic properties. An external magnet is placed in the vicinity creates a magnetic field. The relatively cold ferrofluid behind experiences a greater magnetic attraction force and due to this greater attraction, cold ferrofluid pushes hot ferrofluid on the other end, thus resulting in fluid flow. This body force on fluid section near heat source is directly related to the external magnetic field, magnetic susceptibility, temperature gradient and pyromagnetic coefficient. Combining the two effects, i.e., heat and orientation of magnetic field with suitable geometry and thermo magnetic properties of ferrofluid results in flow and heat dissipation from the system.

Thus, important requirement for fluid pumping is temperature gradient and magnetization variation with temperature. Also, the flow can be controlled by varying external magnetic field and temperature gradient within the fluid. A series of experiments were conducted to study the effect of external magnetic field and temperature distribution. The results showed that fluid flow can be controlled by changing the position of the magnet.

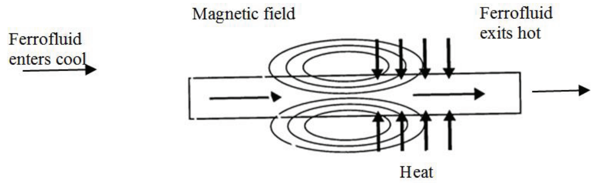

Fig. 1. Mechanism of flow.

Nomenclature

Symbol	Physical Quantity
ρ	Density (kgm^{-3})
T	Temperature (K)
u	Velocity (ms^{-1})
k	Thermal conductivity (Wm^{-1}K^{-1})
p	Pressure (N/m^{2})
v	Viscosity of the fluid (Pa.s)
M	Magnetization vector ($\mathrm{A}m^{-1}$)
B	Magnetic induction ($\mathrm{Wb}m^{-2}$)
H	Magnetic field ($\mathrm{A}m^{-1}$)
F	Kelvin body force (Nm^{-3})
μ	Permeability of medium ($\mathrm{H}m^{-1}$)
μ_0	Permeability of air or vacuum $4\pi x 10^{-7}(\mathrm{H}m^{-1})$
χ_m	Total magnetic susceptibility
χ_0	Differential magnetic susceptibility of the ferrofluid
α	Thermal expansion coefficient of the fluid (K^{-1})
T_0	Reference temperature (K)

III. GOVERNING EQUATIONS

The equations governing the ferrofluid flow under the effect of applied magnetic field are magnetostatic equation, mass conservation equation, momentum equation and the energy equation in the frame of Boussinesque approximation. The nomenclature is shown above.

A. Magnetostatic equations

Ferrofluids are non-conducting, so Maxwell's equations are for non-conducting medium and no currents are simplified to:

$$\nabla \times \mathbf{H} = 0, \tag{1}$$

$$\nabla . \boldsymbol{B} = 0. \tag{2}$$

Magnetic flux density **B** is given as:

$$\boldsymbol{B} = \mu \boldsymbol{H} = \mu_r \mu_0 \boldsymbol{H}, \tag{3}$$

$$\boldsymbol{B} = \mu_0 (1 + \chi_m) \boldsymbol{H}, \tag{4}$$

where, $\mu_r = (1 + \chi_m)$ is the relative permeability. The relationship between the magnetization vector $\boldsymbol{M}$ and magnetic field vector $\boldsymbol{H}$ can be written in the form:

$$\boldsymbol{M} = \chi_m \boldsymbol{H}, \qquad (5)$$

where, χ_m is the magnetic susceptibility of material is a dimensionless proportionality constant that indicates the degree of magnetization M of a material in response to an applied magnetic field H. The magnetic induction B, the magnetization vector M and the magnetic field vector H are related by the following relation:

$$\boldsymbol{B} = \mu_0(\boldsymbol{H} + \boldsymbol{M}). \qquad (6)$$

B. Equations governing fluid flow

The mass conservation equation is given as:

$$\frac{\partial \rho}{\partial \mathrm{t}} + \nabla.(\rho u) = 0. \qquad (7)$$

Ferrofluid are incompressible, i.e., density is constant, and the continuity equation reduces to:

$$\rho \nabla. u = 0. \qquad (8)$$

The momentum equation is given by the following equation:

$$\rho \frac{\partial \boldsymbol{u}}{\partial t} + \rho(\boldsymbol{u}.\nabla)\boldsymbol{u} = \nabla.\left[-p\boldsymbol{I} + (\mu(\nabla \boldsymbol{u} + (\nabla \boldsymbol{u})^T) - \frac{2}{3}\mu(\nabla.\boldsymbol{u})\boldsymbol{I}\right] + \boldsymbol{F}. \qquad (9)$$

Since, ferrofluid is incompressible fluid, therefore density is constant and the momentum equation reduce to:

$$\rho \frac{\partial \boldsymbol{u}}{\partial t} + \rho(\boldsymbol{u}.\nabla)\boldsymbol{u} = \nabla.(-p\boldsymbol{I} + \mu(\nabla \boldsymbol{u} + (\nabla \boldsymbol{u})^T) + \boldsymbol{F}. \qquad (10)$$

The momentum equation results from the application of Newton's second law of motion to the fluid element. The first term on the right of the Equation (10) represents net pressure force; the second term represents net effect of viscous normal and shear stress. The last term provides the body force on fluid per unit volume. In case of ferrofluids, the body force term in the momentum equation represents the Kelvin body force per unit volume and is given by the following equation:

$$\boldsymbol{F} = (\boldsymbol{M}.\nabla)\boldsymbol{B}. \qquad (11)$$

Thus, the momentum equation for ferrofluids reduces to:

$$\rho \frac{\partial \boldsymbol{u}}{\partial t} + \rho(\boldsymbol{u}.\nabla) = \nabla.(-p\boldsymbol{I} + v(\nabla \boldsymbol{u} + (\nabla \boldsymbol{u})^T) + (\boldsymbol{M}.\nabla)\boldsymbol{B}. \qquad (12)$$

Using value of **M** and **B** from (5) and (6) the body force can be written as:

$$\boldsymbol{F} = \mu_0(\chi_m \boldsymbol{H}.\boldsymbol{\nabla})(1 + \chi_m)\boldsymbol{H}, \qquad (13)$$

where χ_m is treated solely as being dependent on the temperature and is given as:

$$\chi_m = \frac{\chi_0}{1+\alpha(T-T_0)}. \qquad (14)$$

The energy equation for ferrofluids is the energy equation for an incompressible fluid and follows the modified Fourier's law as:

$$\rho c_p \left(\frac{\partial T}{\partial t} + \boldsymbol{u}.\nabla \mathrm{T}\right) = k\nabla^2 T + \mu\Phi - \mu_0 T \frac{\partial \boldsymbol{M}}{\partial T}\left((\mathbf{v}.\nabla)\mathbf{H}\right), \qquad (15)$$

where, $\mu\Phi$ is the viscous dissipation is defined as:

$$\Phi = \left(2\left(\left(\frac{\partial u_x}{\partial x}\right)^2 + \left(\frac{\partial u_y}{\partial y}\right)^2 + \left(\frac{\partial u_z}{\partial z}\right)^2\right) + \left(\frac{\partial u_y}{\partial x} + \frac{\partial u_x}{\partial y}\right)^2 + \left(\frac{\partial u_y}{\partial z} + \frac{\partial u_z}{\partial y}\right)^2 + \left(\frac{\partial u_z}{\partial x} + \frac{\partial u_x}{\partial z}\right)^2 - \frac{2}{3}(\nabla.\mathbf{u})^2\right). \qquad (16)$$

The last term in the energy Eq. (15) represents the thermal power per unit volume due to the magnetocaloric effect.

IV. DESCRIPTION OF MODEL

Figure 2 shows the basic arrangement of the experiment. The model consists of a channel, a permanent magnet and a heat source. Here, length of channel is 100 mm and width is 5 mm. The length of magnet is 25 mm and the width is 10 mm. Strength of magnet is 1 Tesla. The initial temperature of the fluid is 293.15 K. The surrounding medium is air at an initial temperature of 293.15 K. Heat is applied by considering heat source and magnet is placed near it. Fresh fluid enters the section near the magnet from the reserved storage on the left as and magnetic fluid pumping effect re-circulates it to storage to bring down temperature of fluid for next cycle of operation and thus the flow sustains in a continuous loop.

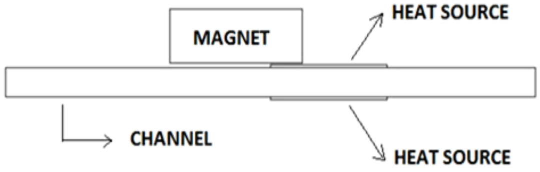

Fig. 2. 2D model of cooling system.

The various meshing parameters used in the simulation are shown in Table 1.

Table 1: Meshing parameters

Mesh Parameter	Value
Minimum element quality	0.1577
Average element quality	0.9292
Triangular elements	2776
Quadrilateral elements	268
Edge elements	325
Vertex elements	20

V. RESULTS

This model is solved using COMSOL Multiphysics by applying heat transfer, fluid flow and magnetic based physics on ferrofluids. Modifications were made in the momentum equation by adding Kelvin body force. Simulations studies are then carried to get the velocity distribution, temperature distribution and magnetization variation. The reference properties of ferrofluid used in simulation are shown in Table 2.

Table 2: Properties of Ferrofluid used in simulation

Property	Value
Density (kg/m^3)	1050.0
Viscosity (Pa-s)	0.0030
Susceptibility	0.3860
Thermal conductivity (Wm^{-1}K^{-1})	0.1500
Specific heat (Jkg^{-1}K^{-1})	1715.0
Thermal expansion coefficient (K^{-1})	0.0009
Curie temperature (K)	345.00±5

Figure 3 shows the velocity plot. The maximum velocity close to edge of magnet is 8.01 mm/s. From the velocity plot, it is observed that the velocity is high near the poles of the magnet. Streamlines are also shown in the velocity plot indicating the path followed by fluid particles. Two humps in the streamlines near the poles of the magnet indicate a stronger magnetic force at the poles.

Figure 4 shows the temperature of ferrofluid. The maximum temperature is 326 K and is near the heat source. Magnetic field lines and magnetic flux density distribution is shown in Fig. 5.

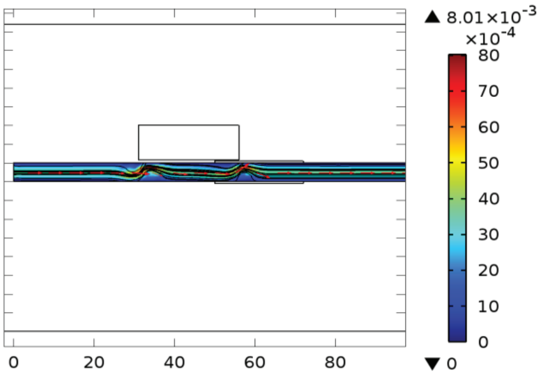

Fig. 3. Velocity profile of ferrofluid.

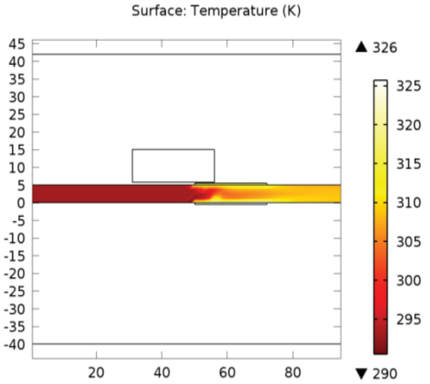

Fig. 4. Temperature of ferrofluid.

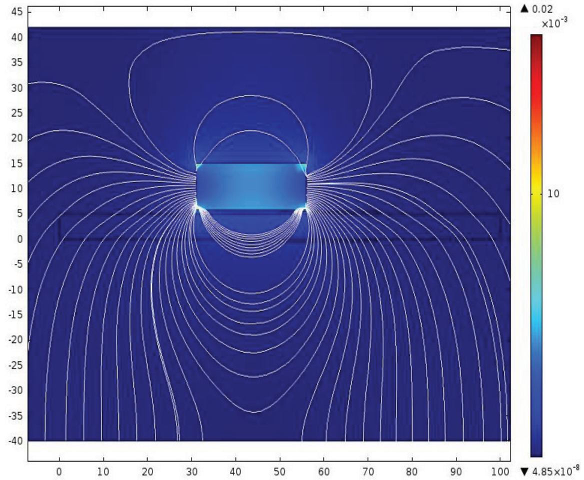

Fig. 5. Magnetic field lines.

Velocity variation along the length of the channel is shown in Fig. 6. The two peaks in the velocity profile represent the position of the poles of the magnet. It is also observed that the velocity magnitude near the two poles is different.

The smaller velocity at the right pole is because fluid in this region being at a higher temperature loses magnetization and hence experiences a lower magnetic force.

The variation of the magnetization along the length of the channel is shown in Fig. 7. Two peaks represent the region near the poles. The value of magnetization of the fluid near the right pole is less because of high temperature of the fluid in this region. The value of average velocity, resultant body force and power of fluid is given in Table 3.

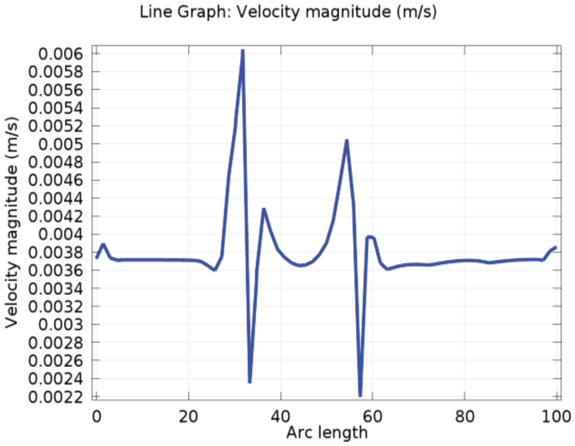

Fig. 6. Graph showing variation of velocity along length of channel.

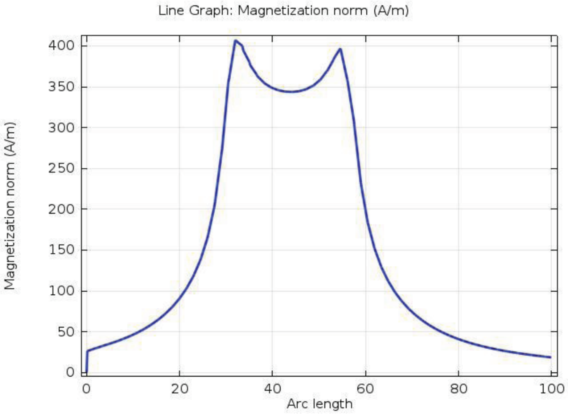

Fig. 7. Variation of magnetization of fluid along the length of channel.

Table 3: Value of output parameters

Property	Value
Average velocity	2.490 mm/s
Resultant body force	8.380 N/m^3
Power of fluid	0.34μW

A. Effect of variation in thermal conductivity of fluid

With increase in thermal conductivity of the fluid, two associated effects were observed. First effect is that with increased heat transfer rate in the ferrofluid decreases temperature gradient within the fluid, with decrease in temperature gradient the body force of ferrofluid decreases. Second effect is, by increasing the thermal conductivity, the heat carried away by the fluid from the heat source increases and this tends to increase the temperature gradient across the hot and cold junction of ferrofluid. Thus, by increasing the conductivity the temperature gradient increases across the two ends due to greater heat being carried and starts decreasing when it is conducted within the fluid.

Figure 8 shows the velocity variation with conductivity. The graphs show that at a particular value of conductivity, the velocity is maximized.

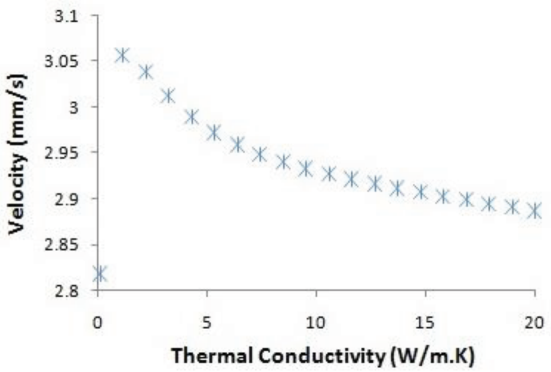

Fig. 8. Velocity variation with thermal conductivity.

B. Effect of changing the orientation of magnetic field

In numerical analysis, the effect of changing the orientation of the field is studied. Figure 9 shows magnet placed in the horizontal direction. The arrows in the diagram show distribution of the magnetic field.

Figure 10 shows the velocity distribution in the channel under the magnetic field. There is a disturbance in the flow and two curves are formed at the exit and entry of the fluid.

Figure 11 shows temperature of ferrofluid in horizontal orientation with a maximum temperature of 333 K near heat source. As can be seen from Fig.12, the velocity has decreased for vertical position.

Figure 13 shows the temperature of ferrofluid with a maximum temperature of 346 K. Table 4 compares the values of different parameters for both positions of the magnet.

Fig. 9. Direction of magnetic flux density for magnet in horizontal and vertical position.

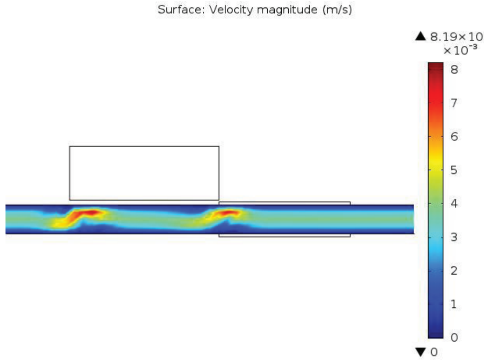

Fig. 10. Velocity of ferrofluid in horizontal position.

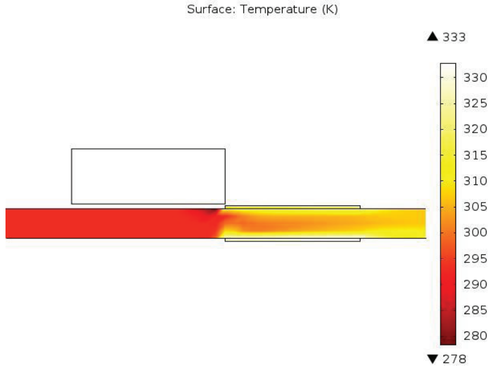

Fig. 11. Temperature of ferrofluid in horizontal position.

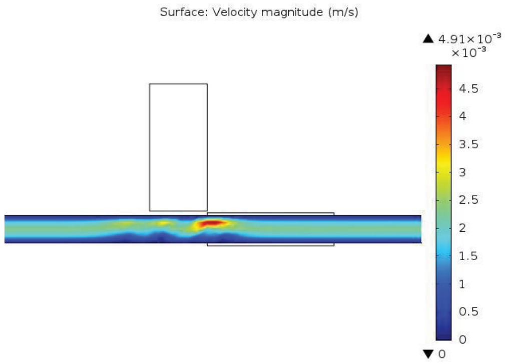

Fig. 12. Velocity of ferrofluid in vertical position.

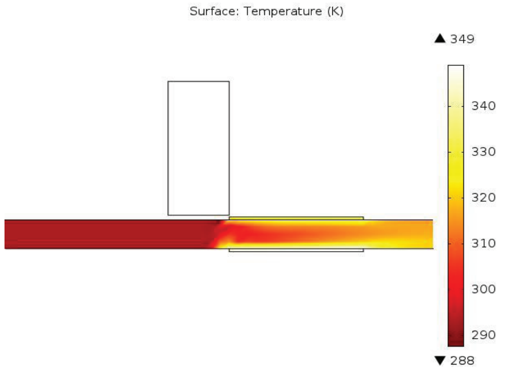

Fig. 13. Temperature of ferrofluid in vertical position.

Table 4: Comparison in different position of magnet

Physical Quantity	Magnet in Horizontal Position	Magnet in Vertical Position
Average velocity at outlet (mm/s)	2.567	1.680
Average temperature at outlet (K)	308.1	315.8
Body force (N/m^3)	8.805	4.544
Power of fluid (μW)	0.062	0.014

VI. CONCLUSION

This paper reports numerical studies on ferrofluid flow phenomena in presence of magnetic field to obtain flow, velocity distribution, temperature distribution and magnetization. Important conclusions drawn from simulation studies are:

1. Thermal conductivity of fluid influences the velocity and temperature distribution of ferrofluid. With increase in conductivity of fluid, the velocity of fluid may decrease depending on the amount of decrease in temperature gradient in the fluid.
2. The velocity of the fluid is locally high close to magnetic field and heating area.
3. Orientation of the magnetic field influences the ferrofluid flow. The velocity of ferrofluid is relatively high when the magnetic field lines are parallel to the flow direction. Since maximum number of magnetic field lines are parallel to the flow direction (interacting magnetic flux) when magnet is placed in a horizontal direction.
4. The thermal gradient has direct effect on the flow of ferrofluid under influence of magnetic field.
5. It was found that flow rate increases with increase in magnetic field and increase in temperature gradient along the flow direction.

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Harry Garg is working as Senior Scientist in CSIR-CSIO Chandigarh, India. He received doctoral degree from PEC University of Technology, Chandigarh. His research interest includes design and development of opto-mechanical systems, micro scale heat transfer using nano-coolants and ferrofluid, CFD design and development for Aerodynamics.

Sahib Singh received B.Tech. degree in Mechanical Technology, Ferozepur, and Masters in Mechanical Engineering from PEC University of Technology Chandigarh. His research interests includes engineering materials, ferrofluids and liquid cooling.

Vipender Singh Negi is working as Research Fellow in CSIR-CSIO Chandigarh, India. He has completed his bachelor degree in Mechanical Engineering from Panjab University. He is working for FEA of glass grinding and polishing; other areas of his interests are CFD, heat transfer, ferro-hydrodynamics and mechatronics.

Ashish Singh Kharola is working as Project Assistant in CSIR-CSIO Chandigarh, India. He has completed his degree in Mechanical Engineering from Kurukshetra University. He is working on ferrofluid analysis. He has also been certified in Computer Aided Tool Engineering, from Central Institute of Tool Design, Hyderabad. Other areas of his interests are heat transfer, automobile engineering, and CAE.

Arun K. Lall is working as a Professor in the Mechanical Engineering Department in PEC University of Technology, Chandigarh. He received his Doctrol degree from IIT, Kanpur. His research Interests includes FEM/FEA, enhanced heat transfer, tribology and CFD analysis.