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A comprehensive review on ferrofluid convective heat transfer under the influence of external magnetic source

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Abstract— Ferrofluid is a colloidal liquid, consisting of nanoparticles of magnetic material suspended in a carrier liquid. Its important property is, though it is liquid still responds to external magnetic field and becomes highly magnetic in the presence of same. This property of ferrofluid has widened its use in many applications like energy harvesting, heat exchanger, electronic cooling, seal, lubrication and damping. In few applications like fluid transport in space, conventional convective heat transfer is inadequate due to reduced or complete absence of gravity. Also conventionally water or air is used as a working medium in convective heat transfer application. As both have lower convective heat transfer coefficient, heat transfer rate is poor with them. Thermophysical properties of ferrofluid can be controlled by varying externally applied magnetic field. Addition of ferrofluid, under the action of externally applied magnetic field, increases thermal conductivity and convective heat transfer coefficient significantly as compared to base liquid. Research work should be carried on investigating performance of ferrofluid in convective heat transfer applications, on which yet very less or no research is carried like I.C. engine cooling, electronic cooling, and heat exchanger applications in order to enhance convective heat transfer rate and thus performance of devices using ferrofluid as a working medium. This paper focuses on research work carried till now in the area of ferrofluid based convective heat transfer and area in which ferrofluid based convective heat transfer should be explored.

Keywords— Ferrofluid, Convective heat transfer, Heat Exchanger, External Magnetic Field, Thermophysical Properties

I. INTRODUCTION

Ferrofluids are colloidal liquids made of nanoscale ferromagnetic, or ferrimagnetic, particles suspended in a carrier fluid (usually an organic solvent or water). By chemical composition i.e. by volume it consists of 85% carrier Fluid, 10% surfactant, and 5% magnetic material. Its important property is, though it is liquid still responds to externally applied magnetic field and become highly magnetic in the presence of same.

Every nano particle is coated with a surfactant to restrain clustering. When exposed to strong magnetic fields, large ferromagnetic particles can be ripped out of the homogeneous colloidal mixture, forming a separate clump of magnetic dust. The magnetic attraction of nanoparticles is weak enough that the surfactant's Van der Waals force is sufficient to prevent magnetic clumping or agglomeration. The surfactants used to coat the nanoparticles include, but are not limited to: oleic acid, tetra methyl ammonium hydroxide, citric acid, soy lecithin.

In the absence of an externally applied field, ferrofluids usually do not retain magnetization and thus are often classified as "superparamagnets" rather than ferromagnets.

The difference between ferrofluids and magnetorheological fluids (MR fluids) is the size of the particles. In ferrofluid the particles are primarily nanoparticles and remain suspended by Brownian motion and generally does not settle under normal conditions. While MR fluid particles primarily consist of micrometer-scale particles which are too heavy for Brownian motion to keep them suspended, and thus will settle over time because of the inherent density difference between the particle and its carrier fluid.

In the absence of external magnetic field, magnetic dipoles of ferrofluid remains randomly oriented, but when magnetic field will be applied externally on ferrofluid, its magnetic dipole gets oriented in a same direction as that of externally applied magnetic field. It indicates that ferrofluid responds to externally applied magnetic field.

Due to this property, use of ferrofluid is widened in many applications like convective heat transfer, electronic cooling, seal, lubricant and damping. By applying external magnetic field ferrofluid’s thermophysical properties can be controlled, which will enhance the convective heat transfer rate and thus performance of equipment, using ferrofluid as a working medium. In the applications, where conventional convective heat transfer is not possible in that case thermomagnetic convective heat transfer can be adopted. Also thermomagnetic convection produces thermomagnetic pumping effect which eliminates need of mechanical pump and reduces power consumption.

Due to huge amounts of heat generation in industrial grounds, there had been always a great demand for having robust and promising cooling devices in technological fields. Currently, thermal management of electronics has become an encouraging issue for researchers since proper treatment of high operating temperature and heat flux density of these miniature devices can improve their maintenance and performance. An effective heat removal process is required, in order to maintain the chip’s temperature low enough to allow its favorable efficiency. Ferrofluid is future proposed option for electronic cooling enhancement.

II. LITERATURE REVIEW

Bozhko et al. [2004] investigated the interplay of buoyancy and thermo-magnetic convection mechanisms in a horizontal fluid layer heated from one wide side and cooled from another in the presence of external uniform transversal magnetic field. Influence of gravitational settling of magnetic particles and their aggregates on heat transfer and convection instability was studied. Experimental results showed that behavior of convective system depends on ratio of magnetic Rayleigh number and gravitational one. To control the magnetic Rayleigh number, the colloids with different concentration of magnetic phase, i.e. magnetic saturation were considered. In concentrated colloid the driving forces prevail over suppress ones, but in weak concentrated colloid the gradients of density due to gravity sedimentation of particles overwhelm convection stirring. Thermo-magnetic convection mechanism allows strengthening of heat transfer in ferrofluid three times

Jafari et al. [2008] studied heat transfer phenomena in a kerosene based ferrofluid. The flow behavior was investigated. Different temperature gradients and uniform magnetic fields were applied. Results illustrated that the transport processes in the presence of magnetic field will enhance in comparison with the field free case. In the presence of aggregation of magnetic particles heat transfer will decrease and Rayleigh rolls will not be observed. When magnetic field is perpendicular to the temperature gradient, the heat transfer will increase more compared to the case with magnetic field parallel to temperature gradient.

Li et al. [2009] investigated experimentally convective heat transfer features of the aqueous magnetic fluid flow under the influence of an external magnetic field. The convective heat transfer coefficient of the aqueous magnetic fluid flow was measured in both the uniform magnetic field and the magnetic field gradient. The effects of the external magnetic field strength and its orientation on the thermal behaviors of the magnetic fluids were analyzed. The experimental results showed that the external magnetic field is a vital factor that affects the convective heat transfer performances of the magnetic fluids and the control of heat transfer processes of a magnetic fluid flow is possible by applying an external magnetic field.

Lajvardi et al. [2010] investigated experimentally convective heat transfer of ferrofluid flowing through a heated copper tube in the laminar regime in the presence of magnetic field was investigated experimentally. Effect of various orders of magnetic field, concentration of magnetic nanoparticles and magnet position on heat transfer enhancement (heat transfer coefficient, temperature profile of ferrofluid) was investigated. Various orders of magnetic field considered were 0G, 800G, 1000G, and 1200G. Concentrations of magnetic nanoparticles were considered as, 5% & 2.5%. Coil distance was varied as 5mm and 10mm. Experimental results indicated that, order of magnetic field has remarkable effect on heat transfer enhancement. As magnetic field intensity increases, heat transfer coefficient (h) augments.

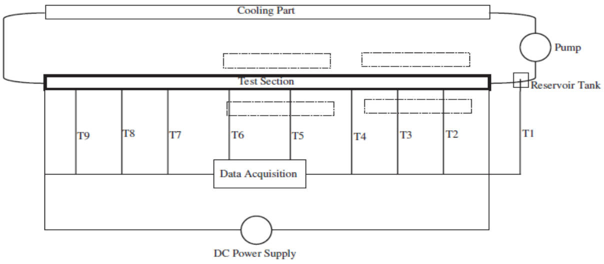

Fig.1: Schematic representation of experimental set-up [4]

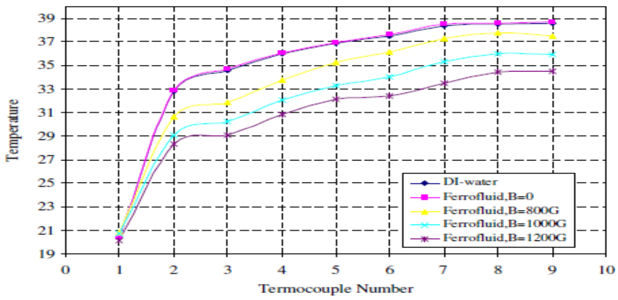

Fig. 2: Magnetic field effect on temperature profile of ferrofluid[4]

Magnetic field intensity also affects ferrofluid temperature profile. In the absence of magnetic field, temperature profile of distilled water and that of ferrofluid overlap each other through the length of test section. With increase of magnetic field intensity, ferrofluid temperature profile decreases indicating more heat is removed from copper tube. More is the magnetic field intensity, more temperature drop is achieved. When ferrofluid's concentration was reduced from 5% to 2.5%, it was observed that rate of temperature drop also decreased. Temperature of copper tube was found more at a same magnetic intensity as compared to that of 5% concentration. Effect of position of coil over ferrofluid temperature profile was found more significant when coils were placed close to each other as compared to when coils were far from each other. Increase in magnetic field intensity enhances heat transfer rate. This enhancement of heat transfer coefficient was due to change in thermo physical properties such as thermal conductivity and specific heat of ferrofluid. Application of magnetic field on ferrofluid affects its thermo physical properties.

Ashouri et al. [2010] numerically investigated magnetic convection heat transfer in a two-dimensional square cavity induced by magnetic field gradient using a semi-implicit finite volume method. The side walls of the cavity were heated with different temperatures, the top and bottom walls were isolated, and a permanent magnet was located near the bottom wall. Thermal buoyancy-induced flow was neglected due to the nongravity condition on the plane of the cavity. Conditions for the different values of non-dimensional variables in a variety of ferrofluid properties and magnetic field parameters were studied. Based on this numerical analysis, a general correlation for the overall Nusselt number on the side walls was introduced for a wide range of effective parameters. Results showed that in the absence of magnetic field, the heat transfer is caused only by conduction. In the presence of magnetic field, convective heat transfer increases.

Xuan et al. [2011] investigated thermomagnetic convection over natural convection for electronic cooling application. Experimentation was carried over two different set-up designs thermomagnetic (TM) cooler 1 and cooler 2. Experimental set up consists of heat source (chip), ferrofluid supply, cooler (blower), earth magnet. Position of magnet was different in two experimental set up to verify effect of position of magnet on thermomagnetic convection. Also effect of presence and absence of magnet and blower, heat load, was verified on thermomagnetic convection. Experimental results of thermomagnetic convection were compared with that of natural convection to investigate enhancement in heat transfer.

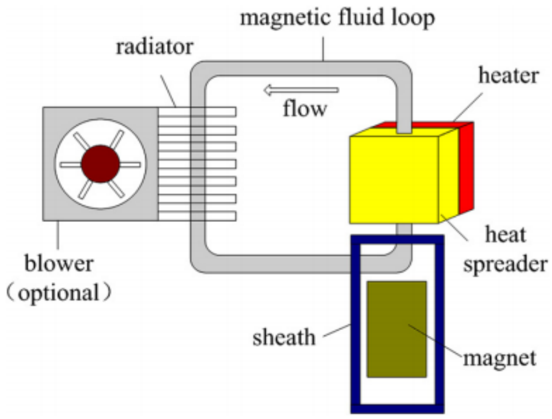

Fig. 3: Schematic layout of the thermomagnetic cooler [6]

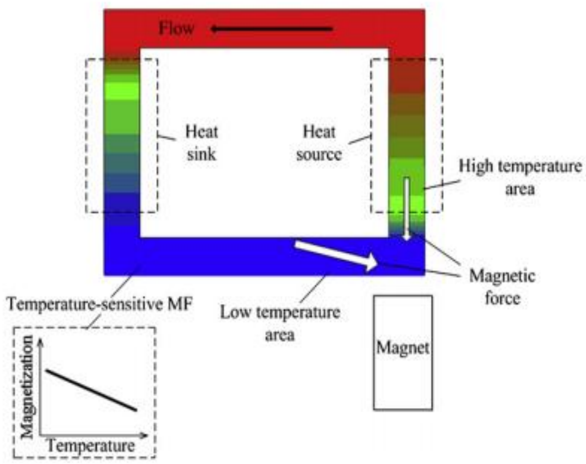

Fig. 4: Working principle of thermomagnetic convection loop[6]

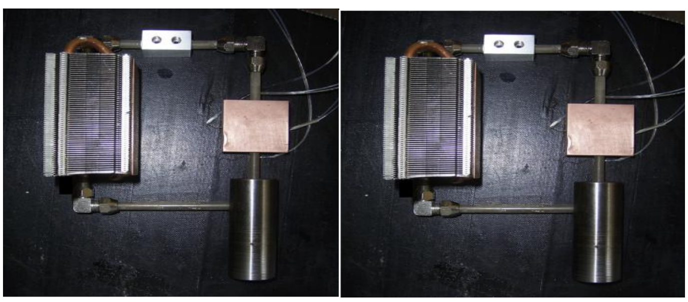

Fig. 5: Prototype of thermomagnetic cooler 1 and2 [6]

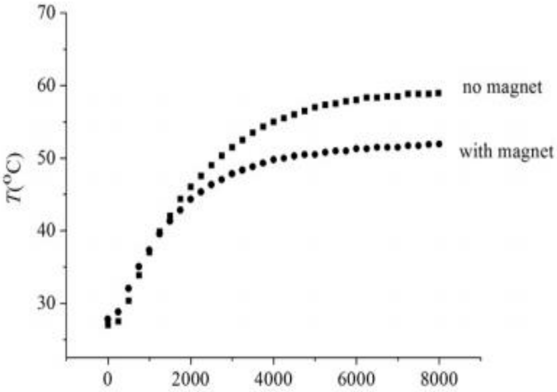

Fig.6 : Averaged surface temperature of the chip (2W heat load)[6]

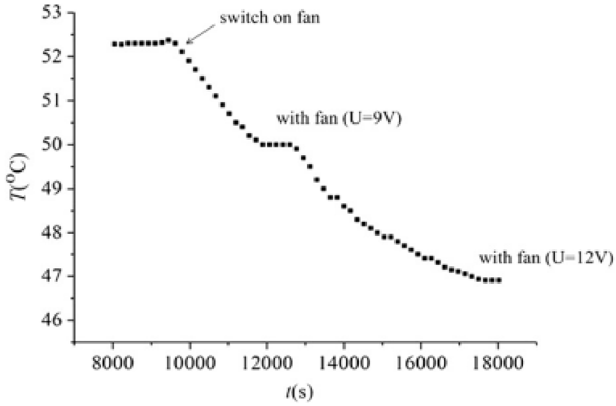

Fig.7 : Temperature drop of the chip surface after the use of fan (2 W heat load) [6]

Experimental results indicated that, there was significant drop in surface temperature (T_s) of chip (heater) in the presence of external magnet indicating enhanced heat removal by ferrofluid when it flows across the heater and hence improved heat transfer. Same results were obtained at varying heat load. When blower was switched on there was significant drop in surface temperature (T_s) of chip (heater) indicating improved heat transfer but it leads to additional power consumption and noise. Thermomagnetic convection strongly depends upon temperature difference (ΔT). At higher (ΔT), thermomagnetic convection effect is remarkably higher. Because at higher (ΔT), higher driving force is created to circulate fluid as molecules moves faster. When fluid flows across high temperature region its density decreases and velocity increases at higher rate. While when fluid flows across low temperature region its density is more and velocity decreases and thus driving force is set for fluid to flow from hot zone to cold zone. At higher temperature this process occurs at faster rate leading towards stronger driving force to circulate fluid and hence enhanced thermomagnetic convection. Hence to get higher temperature high heat load should be applied. Or at cold region temperature should be lowered down to get higher (ΔT). Even when power supply was shut off, magnetic fluid still keeps

circulating in TM cooler because there still exist (ΔT) inside magnetic field. Comparison between TMC1 and TMC2 indicated that performance of TMC1 was better than TMC2 due to position of magnet near to heater in TMC1. It was concluded that thermomagnetic effect can be used for electronic cooling work should be carried on improving its performance.

Gavili et al. [2012] carried experimental investigation on thermal conductivity of ferrofluid under the influence of magnetic field. Ferrofluid contained nanoparticles of Fe_3O_4 suspended in di-ionized water. Effect of different intensities of magnetic field on thermal conductivity of ferrofluid with respect to time span was investigated. Effect of temperature on thermal conductivity of ferrofluid was also investigated. Experimental results indicated that thermal conductivity of ferrofluid is a function of intensity of magnetic field. In the absence of magnetic field, thermal conductivity of ferrofluid is same as that of di-ionized water. It increases with the application of magnetic field. Also it increases with increase in intensity of magnetic field, reaches to maximum and after that a slight decrease is observed in thermal conductivity. Mechanism behind this is that, when magnetic field is applied, magnetic dipoles gets aligned in a same direction as that of external magnetic field's direction forming chain like structure.

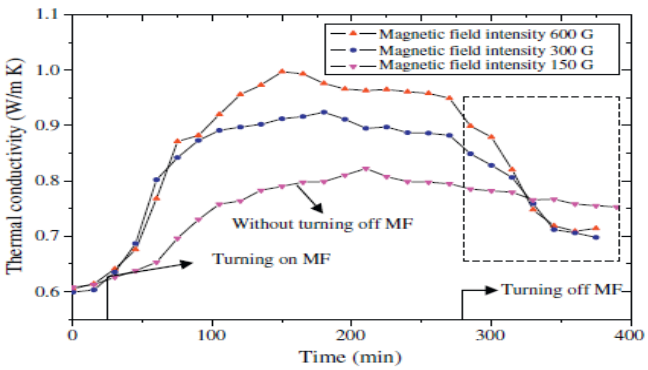

Fig. 8: Thermal Conductivity of ferrofluid versus time under three different magnetic field intensity [7]

When intensity of magnetic field increases, more number of dipoles gets aligned and magnetic moment dominates thermal energy and based on percolation theory enhancement in thermal conductivity occurs. But at higher intensity magnetic field, temperature of ferrofluid increases due to current flowing in a coil. Due to rise in a temperature, thermal energy overcome magnetic moments and breaks chin like structure decreasing the thermal conductivity of ferrofluid. This rise in temperature can be controlled by removing heat from ferrofluid using cold water. At lower intensity magnetic field, thermal conductivity reaches to its maximum value in a considerable time period and also it takes time to decrease when magnetic field is removed. But at higher intensity magnetic field thermal conductivity reaches to its maximum value in a short time period and also it decrease when magnetic field is removed very quickly. When magnetic field is applied thermal conductivity increases, but after removal of magnetic field, it never reaches to its initial value due to presence of chain like structure. To retain its starting value ultrasonification of fluid is required

Mohammadi et al. [2012] carried experimental investigation on four-turn pulsating heat pipe (PHP). Effect of working fluid, ferrofluid's volumetric concentration, heat input, magnetic field, orientation and charging ratio, on thermal performance of PHP was investigated. Experimentation revealed that thermal performance of PHP can be varied by using ferrofluid in the presence of external magnetic field. Ferrofluid enhances thermal performance of PHP, because (i) ferrofluid has greater thermal conductivity than distilled water, (ii) due to nanoparticle, surface to volume ratio increases, which in turn increases heat transfer area, (iii) sedimentation of ferrofluid in evaporator creates several active nucleate sites that enhances the boiling heat transfer. Application of magnetic field on ferrofluid reduced thermal resistance of PHP in all orientations. At higher charging ratio, better thermal performance was obtained in the presence of magnetic field. In the absence of magnetic field, thermal performance is better at lower volume fraction. While in the presence of magnetic field, thermal performance is better at a higher volume fraction. As volume fraction of ferrofluid increases, thermal resistance decreases and thermal performance increases. In horizontal orientation, in the absence of magnetic field, thermal performance is not significant due to absence of gravity. While, in the presence of magnetic field, thermal performance is better due to magnetic field exerted on ferrofluid. In vertical mode also thermal performance is better at higher charging ratio. As heat input increases thermal resistance of PHP decreases, as increase of heat input changes the flow regime from slug-plug to annular which causes the working fluid to be able to circulate more quickly.

Chaudhary et al. [2012] investigated self-pumping magnetic cooling effect so as to eliminate use of mechanical pumping to circulate working fluid as mechanical pumping has many drawbacks like more power consumption, vibrations, noise, less reliability. Experimentation was carried with polymer tube consisting of Mn-Zn ferrofluid. Effect of presence and absence of external magnetic field, magnetic field strength, heat load (i.e. load temperature), concentration of ferrofluid, temperature gradient on thermomagnetic convection and performance of cooling system was verified. Experimentation carried in the presence and absence of external magnetic field revealed that, fluid flows only when there is application of external magnetic field. To produce thermomagnetic convection effect both external magnetic field as well temperature

gradient are required. Magnetic cooling devices are self-regulating. With the application of external magnetic field, temperature at heating coil region decreases. With increase in magnetic field strength (or magnetization) temperature at heating coil region decreases. Temperature drop increases indicating enhanced convective heat transfer. With increase in particle volume concentration, temperature near heating coil region decreases. But at higher field, a high concentration nanoparticle starts to settle in magnetic field direction after some time which decreases fluid velocity and hence reduces cooling effect. Performance of cooling system strongly depends upon heat load temperature, volume concentration and magnetic field strength. Higher the heat load, i.e. higher the temperature gradient, faster is the heat transfer.

Sundar et al. [2013] carried experimental investigation on effective thermal conductivity and viscosity of magnetic Fe_3O_4/water nanofluid. Whether nanofluid behaves like a Newtonian or Non-Newtonian was investigated. Correlations were developed to estimate thermal conductivity and viscosity of nanofluid with change in temperature. It was observed that thermal conductivity and viscosity of nanofluid both are function of particle volume concentration and temperature. As volume concentration increases, thermal conductivity increases. Also as temperature increase, thermal conductivity increases. Because of Brownian motion of particles, ferrofluid offers higher thermal conductivities compared to base fluid. Its viscosity increases with increase in volume concentration while with rise in a temperature, viscosity of nanofluid decreases. Enhancement in viscosity was found better than thermal conductivity at a same temperature under same volume concentration Thermal conductivity get enhanced by 48% with 2% volume concentration at 60^{o}C. while about 2.96 times enhancement in viscosity was observed with 2% of volume concentration at 60^{o}C compared to base fluid. Experimental investigation on viscosity revealed that Fe3O4/water nanofluid exhibit Newtonian behavior. Water based nanofluid has better enhancement in thermal conductivity than kerosene based.

Krichler et al. [2013] proposed experimental procedure to calculate thermal conductivity of ferrofluid. Two methods were proposed (i) Hot wire technique (ii) Hot plate technique. In hot wire technique, line heat source is used. In hot plate technique, plane heat source is used. Hot wire technique is mainly used for liquid specimen and Hot plate technique for solid specimen. The advantage of hot wire technique is that boundary effects can be reduced easily with a large length-to-diameter ratio. Main disadvantages are that no parallel alignment of heat flux and magnetic field is possible. Hot wire technique is not suitable for anisotropic measurements. For parallel alignment of the heat flux and magnetic field t, a plane heat source is used here for the hot plate technique. The hot plate technique is characterized by an idealized linear heat flux. So both a parallel and a perpendicular arrangement of heat flux and magnetic field are possible. 4. The temperature information is obtained over a certain distance x and then by using correlation thermal conductivity is calculated. The changes in thermal conductivity measurements at various magnetic field strengths and orientations with respect to heat flux were measured. For parallel alignment, as magnetic field strength increases, thermal conductivity increases continuously. For perpendicular alignment, the thermal conductivity has an inverse relationship to the magnetic field strength.

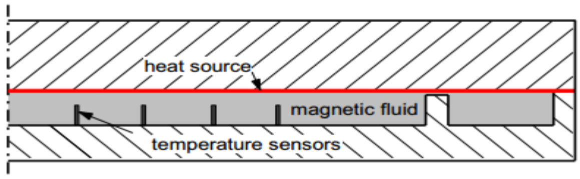

Fig. 9 : Sketch of the measuring cell: measuring volume embedded by two plates

Goharkhah et al. [2014] investigated numerically, forced convective heat transfer of water based Fe3O4 nanofluid (ferrofluid) in the presence of an alternating non-uniform magnetic field. The geometry was a two-dimensional channel which was subjected to a uniform heat flux at the top and bottom surfaces. Non-uniform magnetic field produced by eight line source dipoles was imposed on several parts of the channel. The effects of the alternating magnetic field strength and frequency on the convective heat transfer were investigated for four different Reynolds numbers (Re = 400, 600, 1200 and 2000) in the laminar flow regime. Experimental results, as compared with zero magnetic field case, showed that the heat transfer enhancement increases with the Reynolds number and reaches a maximum of 13.9% at (Re = 2000 and f = 20Hz. At a constant Reynolds number, it increases with the magnetic field intensity while an optimum value exists for the frequency. The optimum frequency increases with the Reynolds number. The heat transfer enhancement due to the magnetic field is always accompanied by a pressure drop penalty. A maximum pressure drop increase of 6% was observed at Re=2000 and f=5 Hz which shows that the pressure drop increase is not as significant as the heat transfer enhancement.

Selimefendigil et al. [2014] numerically investigated natural convection of ferrofluid in a partially heated square cavity. The heater was located to the left vertical wall and the right vertical wall was kept at constant temperature lower than that of the heater. Other walls of the square enclosure were assumed to be adiabatic. Finite element method was utilized to solve the governing equations. The influence of the Rayleigh number ($10^4 \leq Ra \leq 5\times10^5$), heater location ($0.25\ H \leq y_h \leq 0.75H$), strength of the magnetic dipole ($0 \leq \gamma \leq 2$), horizontal and vertical location of the magnetic dipole ($-2H \leq a \leq 0.5H$, $0.2H \leq b \leq 0.8H$) on the fluid flow and heat transfer characteristics were investigated. It was observed that different velocity components within the square cavity are sensitive to the magnetic dipole source strength and its position. The

length and size of the recirculation zones adjacent to the heater can be controlled with magnetic dipole strength. Averaged heat transfer increases with decreasing values of horizontal position of the magnetic dipole source. Averaged heat transfer value increases from middle towards both ends of the vertical wall when the vertical location of the dipole source is varied. When the heater location is changed, asymmetrical behavior in the averaged heat transfer plot is observed and the minimum value of the averaged heat transfer is attained when the heater is located at the mid of vertical wall. The spatial variation in the magnetization is induced through temperature gradient which acts as an inhomogeneous magnetic body force and affects the recirculation bubbles formed in the vicinity of the heater and the main cell adjacent to the right vertical wall. Velocity profiles are very sensitive to the magnetic dipole source strength. The length and size of the recirculation zones adjacent to the heater can be controlled with magnetic dipole strength. Averaged heat transfer decreases with increasing values of the magnetic dipole strength. The external magnetic field acts to decrease the local heat transfer in some locations. The minimum of averaged heat transfer along the heater was achieved when the magnetic dipole source is located at the mid of vertical wall.

Goharkhah et al. [2015] experimentally investigated the effects of constant and alternating magnetic field on the laminar forced convective heat transfer of ferrofluid in a heated tube. Results indicated that in the absence of a magnetic field, ferrofluid improves convective heat transfer as compared to DI- water. In the presence of both, constant and alternating magnetic field, as field intensity increases, convective heat transfer enhances. Convective heat transfer rate increases as ferrofluid concentration, magnetic field intensity and Reynolds number increases. As compared to constant magnetic field, better heat transfer is obtained in alternating magnetic field condition. Surface temperature of tube is found to be reduced. Effect of magnetic field is more significant at thermally developing region

Ghasemian et al. [2015] numerically studied laminar forced convection heat transfer of water based ferrofluid in a mini channel in the presence of constant and alternating magnetic fields. Two-phase mixture model was implemented and the governing equations were solved using the finite volume approach. Effects of the constant magnetic field location and intensity on the convective heat transfer were investigated. Simulation results showed that the heat transfer increases with intensity of the magnetic field and decreases as the field source is moved away from the channel surface. The heat transfer enhancement due to the magnetic field was more significant at lower Reynolds numbers. Frequency of the alternating magnetic field is a key parameter in the heat transfer enhancement. Results showed that an optimum value exists for the frequency which increases with the Reynolds number. Local vortices were formed adjacent to the magnetic field sources due to the temperature dependence of the magnetic susceptibility and resulting nonsymmetrical Kelvin body force. The vortices disrupt the thermal boundary layer and result in the augmentation of the heat transfer. This effect is more significant when the magnetic field is placed in the fully developed region. The alternating magnetic field causes the fluid particles to move up and down periodically. It disturbs the thermal boundary layer, improves the flow mixing and increases heat transfer as a result. Maximum heat transfer enhancement with a constant magnetic field is obtained as 16.48% at Mn =1.07*10^8, Re = 25. This value can be increased up to 27.72% by applying an alternating magnetic field with the same intensity.

Aursand et al. [2016] investigated use of thermomagnetically pumped ferrofluid to enhance performance of natural convection cooling system. Optimal solenoid and optimal ferrofluid was first designed for particular application and then case study was set up. Experimentation results revealed thermomagnetic driving force is significant compared to natural convection in single phase. Ferrofluid enhances heat transfer rate. Solenoid additionally enhances heat transfer rate. Heat transfer rate increases as temperature difference between heater and cooler increases. Relative improvement or enhancement factor (Qeff /Qref) increases with increase in temperature difference between heater and cooler increases. Natural convection is driven by density difference phenomena. While basic principle behind thermomagnetic pumping effect is breaking magnetization symmetry i.e. reducing magnetic force on one side and increasing it on opposite side. Thermomagnetic pumping is driven by decrease of susceptibility across the heater and increase of susceptibility across the cooler. Two mechanisms are responsible for this. First, across heater fluid's temperature increases, this decreases its susceptibility towards magnetization and across cooler fluid's temperature decreases, which increases its susceptibility towards magnetization. Due to increased susceptibility towards magnetization across cooler as compared to heater, fluid gets attracted and driven from heater to cooler without any mechanical pumping. Second, across heater fluid's density decreases and hence velocity increases and thus particle's concentration decreases by stretching the particle distribution. With increase in particle concentration, heat transfer rate increases. Using ferrofluid reduces size of heat sink. Thermomagnetic pumping effect is higher at higher ΔT.

Sheikholeslami et al. [2016] analyzed Ferrofluid convective heat transfer in a sinusoidal cold wall cavity under the effect of external magnetic field was. Fe_3O_4 - Water Nano fluid was used as a working fluid. CVFEM method was used for simulation. Impact of magnetic field on hydrothermal behavior of Nano fluid in a cavity with sinusoidal cold wall was investigated. Effect of (i) Rayleigh number, (ii) Hartman number, (iii) Amplitude of sinusoidal wall (iv) volume fraction of Fe3O4 on Nusselt number was investigated. Results indicated that magnetic field produces Lorentz force. Increase in a Lorentz force retards velocity of Nano fluid and augment thermal boundary layer thickness, which weakens eddies present in a flow. Buoyancy force decreases and conduction becomes stronger. Isotherms become parallel to each other. Heat transfer occurs mainly by conduction than convection and Nusselt number decreases. Space between cold and hot wall reduces at low buoyancy force and rate of heat transfer augments. Opposite happens when Lorentz force decreases.

Eddies becomes stronger and buoyancy force increases. Isotherms become nonparallel together. Convection becomes dominant and Nusselt number augments. Temperature gradient near right wall enhances. Addition of Fe_3O_4 nanoparticle into water enhances Nusselt number. At low Ra number, Nusselt number enhances with rise of amplitude of wall, but at high Ra number opposite happens. Impact of adding Fe_3O_4 is more sensible when buoyancy force is weak. Temperature increases with rise of Lorentz force. But it decreases with increase of buoyancy force and volume fraction of Fe_3O_4.

Goharkhah et al. [2016] experimentally investigated laminar forced convective heat transfer of ferrofluid under the effect of external magnetic field. Effect of magnetic field intensity and frequency on convective heat transfer and pressure drop was investigated at different ferrofluid concentration and flow rates. It was observed that the convective heat transfer has a direct relation with the Reynolds number and ferrofluid concentration. At a constant Reynolds number, the magnetic field intensity increases the heat transfer. There exists an optimum frequency for every single Reynolds number which increases by Reynolds number. A maximum heat transfer enhancement of 16.4% by the use of ferrofluid, in the absence of a magnetic field was observed. This value is increased up to 24.9% and 37.3% by application of constant and alternating magnetic field, respectively. Electromagnets arrangement and locations are two important parameters that affect the convective heat transfer. The optimum arrangement of the electromagnets is obtained by a numerical simulation and supporting experiments. Increase of pressure drop is an inevitable consequence of applying the external magnetic field to the ferrofluid flow. Heat transfer enhancement is shown to be greater than the increase of pressure drop under the alternating magnetic field.

Mojumder et al. [2016] numerically analyzed magneto-hydrodynamic convection in a half-moon shaped cavity filled with ferrofluid. Numerical simulation was carried out for a wide range of Rayleigh number (Ra = 10^3 ~ 10^7), Hartmann number (Ha = 0 ~ 100) and inclination angle of magnetic field (γ = 0°~ 9°) to understand the flow field, thermal field and entropy generation respectively. Cobalt-kerosene and Fe3O4-water ferrofluid were used. Galerkin weighted residual method of finite element analysis was used for numerical solution. The code validation and grid independency test have been carried out to justify the numerical accuracy. Effect of geometric position of the heater on entropy generation on a half-moon shaped cavity along with external magnetic field was thoroughly investigated.

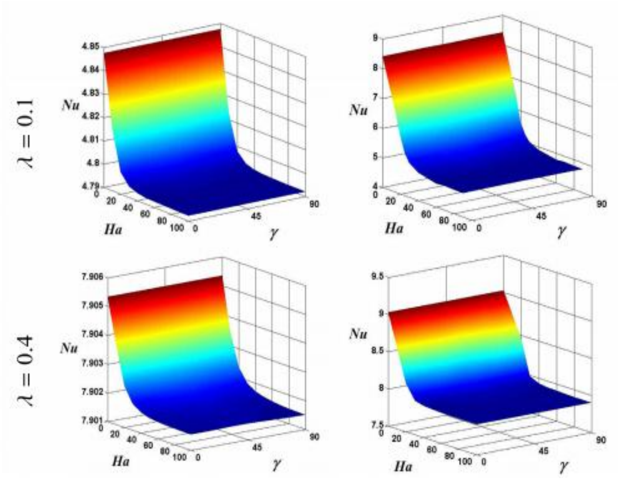

Fig. 10: Variation of average Nusselt Number with Hartmann Number for solid volume fraction of ϕ = 0.15 [19]

It was observed that increment of magnetic field reduces the heat transfer rate, whereas increment of heater distance augments the heat transfer rate significantly. λ= 0.4 shoed better heat transfer performance and entropy optimization in comparison with λ = 0.1. Value of Nu was always higher for the λ = 0.4 than λ = 0.1 for any combination of Ha, Ra and γ. At low Ra, by varying Ha and γ no significant improvement of heat transfer was found for both λ = 0.1 and 0.4. At high Ha, varying both γ and Ra showed no augmentation of heat transfer for both λ = 0.1 and 0.4. So the Ra should be kept as high as possible while Ha should be kept as low as possible at moderate inclination angle to escalate the heat transfer rate. Different other geometrical shapes (triangular shape, square shape) were considered rather than semi-circular heaters and it was found that semicircular heater maximized heat transfer rate comparing to triangular heater.

Mehrali et al. [2016] proposed ecofriendly approach to generate a graphene-based nanofluid. A novel mode of graphene oxide reduction through functionalization with polyphenol extracted from red wine was introduced. The physical and thermal properties of the generated nanofluid including chemical stability, viscosity, wettability, electrical conductivity and thermal conductivity were investigated. The convective heat transfer coefficient of the nanofluid in a laminar flow regime with uniform wall heat flux was investigated. Present study indicated that, red wine can be prosperously utilized to prepare W-rGO nanofluid. The generated graphene-based nanofluid is a formidable transporter of heat and yet ecofriendly. W-rGO can minimize the thermal boundary layer and it could increase heat removal ability from the hot surfaces. A significant thermal conductivity enhancement amounting to 45.1% was obtained for a volume fraction of 4%. W-rGO was stated as green nanofluid with high thermal conductivity, long-term colloidal stability, well fluidity and environmental friendly.

Aursand et al. [2016] proposed a one-dimensional multi-phase flow model for thermomagnetically pumped ferrofluid with heat transfer. The thermodynamic model is a combination of a simplified particle model and thermodynamic equations of state for the base fluid. The magnetization model is based on statistical mechanics, taking into account non-uniform particle size distributions. An implementation of the proposed model is validated against experiments from the

literature, and found to give good predictions for the thermomagnetic pumping performance. It was shown that the presented multi-phase flow model was capable of predicting the thermomagnetic pumping mechanism, by which the temperature-dependence of the ferrofluid magnetization led to a net pumping pressure difference. It was revealed that the predictions of thermo-magnetic pumping are highly sensitive to the temperature profile in the pipe.

Szabo et al. [2017] investigated numerically transition from natural convection to thermomagnetic convection with the consideration of situations where buoyancy and kelvin body force would be opposing each other such that magnetic effect will be dominant in some cases and in remaining cases it will be part of fluid. Magnetic fluid flow and heat transfer by natural convection and thermomagnetic convection was studied for the same in a square enclosure. Results indicated that domain of influence over flow field is largely aligned with domain of dominance of respective driving force. Due to which transition occurs from single buoyancy driven convection cell to single thermomagnetically driven cell.

Fadaei et al. [2017] investigated three-dimensional forced convection heat transfer of magnetic nanofluid in a pipe subjected to constant wall heat flux in the presence of single or double permanent magnets. Effects of magnetic field intensity, nanoparticle volume fraction, Reynolds number value and type of magnetic field source on the forced-convection heat transfer of magnetic nanofluid were investigated.

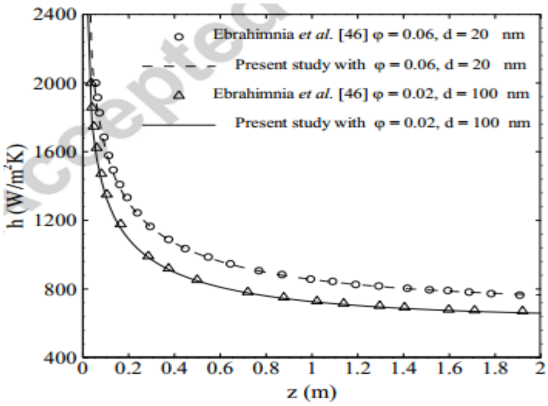

Fig. 11: Comparison of the obtained simulation results with those reported in Ref. as a function of volume fraction of nanoparticles and their diameter. [23]

Experimental results indicated that, application of magnetic field on ferrofluid, intensify fluid mixing. This improves Nusselt number value. Heat transfer rate and Nu value can be increased with an increase in the intensity of permanent magnet magnetization and electric current. Heat transfer coefficient becomes larger with an increase in the volume fraction of nanoparticles.

III. REMARK

In the presence of external magnetic field, ferrofluid becomes magnetic. Magnetic dipoles of ferrofluid are randomly oriented, in the absence of external magnetic field, while as magnetic field will be applied externally on ferrofluid, its magnetic dipoles gets oriented in a direction parallel to that of externally applied magnetic field indicating that ferrofluid responds to externally applied magnetic field. Due to this property, ferrofluid is being used in various applications such as vibration energy harvesting, damping, lubrication, seal and convective heat transfer etc.

Till now a lot of research work is carried on investigating performance of ferrofluid in damping and seal application. But very less research work is carried on investigating enhancement in convective heat transfer rate.

There are many applications of convective heat transfer, where working temperature goes up to or above 150^{o}C. In many such applications, water or air is used as a working medium i.e. to absorb heat from device and to dissipate it into surrounding. As per Newton's law of cooling convective heat transfer rate depends upon, convective heat transfer coefficient, surface area, temperature difference between operating temperature and surrounding temperature. In order to enhance convective heat transfer rate, these parameters should be increased. Water and air has lower heat transfer coefficient and thus poor heat transfer rate. If water or air will be replaced by any another fluid which is having more thermal conductivity and convective heat transfer coefficient, in that case it is possible to enhance convective heat transfer rate.

Thermophysical properties of ferrofluid can be controlled by varying externally applied magnetic field. Due to this property, ferrofluid can be effectively used in convective heat transfer applications in order to enhance convective heat transfer rate. Thermophysical properties of ferrofluid such as thermal conductivity, heat transfer coefficient and thermal diffusivity are dependent on externally applied magnetic field. Their value changes with change in intensity of externally applied magnetic field.

In the applications, when conventional convective heat transfer is not possible due to reduced or complete absence of gravity, or poor convective heat transfer rate, in that case thermomagnetic convective heat transfer can be adopted. Also thermomagnetic convection produces thermomagnetic pumping effect which eliminates need of mechanical pump and reduces power consumption.

Very less research work is carried on performance of ferrofluid in tubular heat exchanger and electronic cooling applications. No research work is carried on investigating performance of ferrofluid in I. C. engine cooling applications.

Magnetization of ferrofluid is temperature based phenomenon. But yet no research work is carried on what is the temperature limit up to which ferrofluid will retain its magnetization though temperature is increasing and beyond which ferrofluid will lose its magnetization.

Enhanced convective heat transfer in these applications leads towards improvement in the performance of devices and improved life span of devices which uses ferrofluid as a working medium.

IV. CONCLUSIONS

Thermophysical properties of ferrofluid changes as magnetic field strength changes. This property can be effectively used to enhance convective heat transfer.
Thermomagnetic pumping can lead towards reduction in necessity of mechanical pumping which will decrease power consumption
No research work is carried on investigating performance of ferrofluid in I. C. engine cooling applications
No research work is carried on developing correlation between Nusselt number and Rayleigh number in a case of natural convection and forced convection.
No research work is carried on developing optimization for ferrofluid's operating parameters. i.e. to find optimum value of nanoparticle's size, shape, volumetric concentration of nanoparticle which will give maximum heat transfer rate at a given operating temperature at which cooling is to be done..

Therefore research work should be carried on investigating performance of ferrofluid in convective heat transfer applications, its thermophysical properties under various operating conditions, its magnetization effect, developing correlation for Nusselt number and optimizing operating parameters of ferrofluid in order to enhance convective heat transfer rate.

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