Journal of Mechanical Research and Application (JMRA), Vol. 10, No.4, 1399-(2020,2021), 1-25

JMRA

Journal of Mechanical Research and Application

ISSN: 2251-7383, eISSN: 2251-7391

Evaluation of water-based Fe_3O_4 ferrofluid heat transfer in the presence of external electromagnetic field: A review

Saba Yazdani[1]

1- Department of Mechanical Engineering, Isfahan University of Technology, Isfahan, Iran

(Email: yazdani.s@me.iut.ac.ir)

Received: 2021-01-20 **Accepted**: 2021-01-30

Abstract: Fe3O4 ferrofluid is an effective mean for heat transfer purposes in the presence of an external electromagnetic field that controls cluster volume and nanoparticles thermal conductivity coefficient. This paper investigates how changing the heating fluid to a special kind of magnetic nanofluid can affect efficiency enhancement. Case studies about ferrofluid (Fe3O4) are summarized in the present work and similar results have been reviewed. Besides, ferrofluid qualification of being an appropriate locator for other conveyors is surveyed. As ferrofluids are controllable in the functional magnetic field, they provide visible effects on heat transfer properties. Strictly, the effect of porous media in different geometries and magnetic fields on ferrofluid heat transfer amount is investigated and different parameters likeNusselt and Magnetic number are evaluated. The previous studies show that ferrofluids can improve heat transfer. Hence thermal efficiency is highly dependent on magnetic field strength. Heating fluid is described as laminar Fe3O4 ferrofluid flow in constant Reynolds number and temperature information has high accuracy. Heat transfer efficiency of other magnetic fluid types like Al2O3 and CuO are briefly reviewed to convince that one of the most suitable nanofluids has been studied.

Keywords: Heat transfer, Ferrofluid, Electromagnetic field, Nusselt number, Nanoparticles

1. Introduction

So far, many measures have been taken to soar the heat transfer rate. One of these measures is fluid substitution. In this way fluid having a higher heat transfer capacity is exerted [1]. Among the materials, magnetic fluids have suitable heat transfer properties. [2,3] Magnetic fluids are uniform colloidal suspensions of single-amplitude magnetic nanoparticles in the non-magnetic base fluid. [4] Despite both solid (such as metal oxides of copper, aluminum, zinc, or non-metallic materials such as carbon, in dimensions less than 100 nm) and liquid (carrier liquid), the magnetic field incapacitates colloidal suspensions accumulation manner. Among the magnetic fluids, we evaluate Fe_3O_4 ferrofluid in particular. [5] Ferrofluids were first developed as liquid fuels to counter gravity in rocket propulsion systems but were never used commercially on a large scale. [6,7] Ferrofluids are widely used for other applications including ferrofluid seals, speakers, thermal convection, optical mirrors, and microprocessors. Rosensweig instability happens as soon as ferrofluid senses magnetism. This instability is sharp peaks forming on the ferrofluid surface. For ionic ferrofluids, it is possible to amplify the electric field at the tip of these peaks. [8] Nano ferrofluids or (magnetic nanofluids) comprise superparamagnetic nanoparticles suspended in a nonmagnetic carrier liquid. These liquids are a present-day set of nanofluids due to their one of kind behavior characteristics as savvy or utilitarian liquids. [9,10] Their conductivity and viscosity can be changed beneath an outside attractive field and their characteristics rheological can be precisely controlled. These properties and particularly their capability of heat transfer upgrade make this kind of liquids a curious issue for numerous analysts.

Nomenclature

B	Magnetic heat flux
C_p	Specific heat ($Kj. Kg^{-1}. K^{-1}$)
h	Local heat transfer coefficient
k	Thermal conductivity
P	Pressure
Re	Reynolds number
Nu	Nusselt number
V	Velocity
T	Temperature
x,y,z	Directions
F	Kelvin body force
Mn	Magnetic number

Greek symbol

β	Liquid volume
ρ	Density
φ	Volume fraction
μ	Dynamic viscosity
α	Langevin equation parameter

Subscripts

SS	Stainless steel
IONP	Iron oxide nano particle

The heat transfer coefficient incensement depends on nanoparticle concentration adoption. [11,12] Wen et al [13] demonstrated that volume Concentration and Reynolds number influence heat exploitation. The reduction in thermal boundary layer thickness and the random motion due to nanoparticle addition were the essential reasons for that augmentation [14]. However, the increase in nanoparticle concentration will lead to an increase in heat transfer. As random motion intensifies, interface and collision ratio increase accordingly an increase in heat transfer is observed. [15] In the table (1) we can compare some properties which show the Fe_3O_4 qualification for heat transfer purpose.

Table 1. Thermal physical properties of Ethylene glycol & Fe_3O_4 at T=298 [16]

properties	Fe_3O_4 ferrofluid	Ethylene glycol
density (Kg/m3)	5370	1114
heat capacity (J/Kg.k)	663	2415
viscosity (Kg/m.sec)	variable	6851E-1
thermal conductivity (W/m.k)	82.6	0.258

More amount of nanoparticles, bring more uniform volume division hence, there are no irregular varieties within pressure drop. The heat transfer rate is upgraded within the nearness of the attractive field, particularly for the flouted microparticles. Besides, as the strength of the magnetic field (Ha) heightens, the top of the speed profile close to the dividers is expanded. In any case, the top of the speed profile at the center locale is diminished. [17]

The suspension is controllable by paramagnet without a mechanical excitation system. [18] The base fluid thermal properties are fundamentally different from those of the colloidal suspension [19]. For instance, the thermal conductivity of microfluid can be significantly higher than that of water or oil. Colloidal suspension systems are multi-component systems and are strongly influenced by the interaction of suspended particles. [20,21] Liquid-carrying molecules are considerably useful in thermodynamic models and for defined problems ferrofluid is one of the best candidates. [22,23]

The ferrofluid magnetic property provides a well-regulated current, thereby affecting heat transfer and other current physical properties. The nanoparticles are superficially exposed to magnetic fields, which stimulates the repulsion (esterification/ionization) between them and stabilizes the colloidal suspension. This method prevents the accumulation and deposition of nanoparticles under the action of van der Waals forces and bipolar contractions. [24]

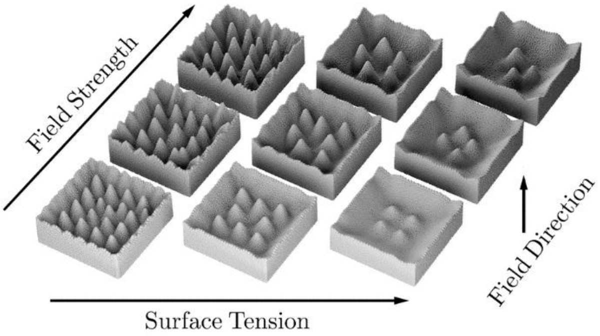


Fig 1. Ferrofluid simulations for different parameters of surface tension and magnetic field strength

Magnetic nanoparticles exhibit unique properties due to the magnetic properties of the single amplitude at roughly 25 Cº. The nanoparticles are in random directions when the paramagnet is not activated hence, the net ferrofluid magnet is zero. [25] As soon as activation, the Fe_3O_4 nanoparticles begin to align along the external magnetic field direction, resulting in a non-zero pure magnetism [26,27]. In the last decade, new applications of ferrofluid and innovative technologies based on magnetic nanoparticles have emerged. Some examples include energy harvesting, sensing, and activation of fluid micro magnets, laboratory devices on the chip, and special applications in the medical sciences, such as biomolecule sorting, magnetic drug targeting, magnetic resonance image contrast enhancement, and magnetic hyperthermia. [28,29] In order to recognize the appropriate flowing flow experiment directly specifies but it is not always cheap and fast therefore the best way is to refer to previous studies. For his reason we focus on table two to compare characteristics of 5 main ferrofluids with different volume concentration.

Table 2. Thermo-physical properties of materials. [30]

Material	^{r}ðkg=m^{3}Þ	C$_{p}$ðJ=kg:KÞ	kðW=m:KÞ	^{m}ðkg=m:sÞ
Theminol 66 (base fluid)	899.5	2122	0.107	0.00106
Fe_3O_4 (particle)	5200	670	6	e
Ferrofluid with 1 vol %	942.5	2107.48	0.110073	0.0010865
Ferrofluid with 2 vol %	985.5	2092.96	0.113206	0.001113
Ferrofluid with 4 vol %	1071.5	2063.92	0.119657	0.001166

Azizian et al [31] deliberated the heat transfer rate of slow-flowing ferrofluid, in which, ferrofluid passed through a SS tube influenced by magnetic forces. Permanent magnets are located along the tube length to control the current and cause a 40% rise in heat transfer rate for the defined magnetic gradient range (8.8 to32.5 mm). In figure 2, Bezaatpour et al [32] showed the orientation of nanoparticles affected by the magnetic sources.

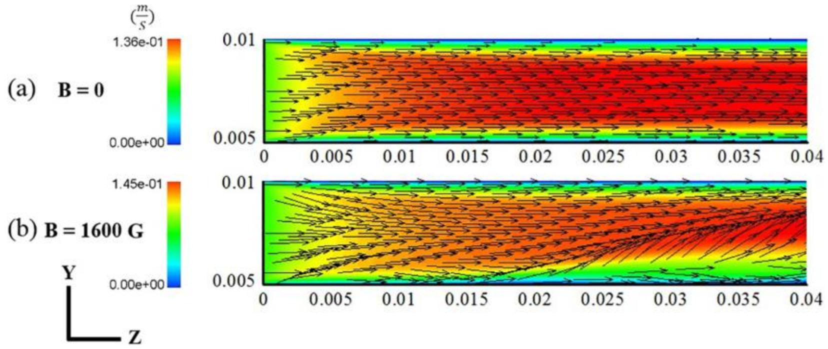


Fig 2. Velocity contours and vectors in the symmetry plane of the middle channel along the flow direction at $\varphi = 2\%$ and Re = 260 in the absence and presence of a magnetic field. [32]

The uniform magnetic fields generated by the relatively high-strength single magnetic pole had a significant impact on the local convective heat transfer coefficient (h_x). This is more common at the bipolar location due to the large local velocity of the ferrofluid around the magnets [33] and also is dependent on the ferrofluid magnetic properties. The effect of non-uniform magnetic fields on fluid flow using a mathematical model in parallel plate configuration illustrates a 13.9%, increase in heat transfer rate which depends on the frequency of the alternating magnetic forces. [34]

Laminar ferrofluid Forced convective considerably enhances by creating an external magnetic field to mix the thermal boundary layer. This mixing raises the liquid temperature at the solid boundary hence, the local Nusselt increases. Placing multipolar magnetic fields increases the thermal efficiency relative to the bipolar capsule location. However, in critical Reynolds, magnetic forces are negligible, which also disjoints the heat transfer rate. Accordingly, the use of a magnetic field does not always lead to heat transfer. On the other hand, the relation between inertial force and magnetic force can be justified by the Freud number. In the same case, Shah et al Considered numerical simulations to be effective in increasing the heat transfer of ferrofluid. [35] The main reason for concentrating on the magnetic fluid in heat exchangers is the change in displacement heat transfer coefficient and temperature gradient, which facilitates the use of the IRT technique (infrared thermography). In the IRT method, infrared waves are used to transfer heat to the material. Inertial force is caused by the interaction of the ferrofluid current with microscale particles accumulated on the container’s wall. An increase in clusters of nanoparticles' local thermal conductivity also depends on the polar directing. By replacing the ferrofluid instead of any other conveyers, the magnetic sensor to diameter ratio decreases. [36]

Following the IRT method, heat transfer of ultraviolet ferrofluid for different temperature gradients in a uniform magnetic field was examined by Xua et al. [37] In this experiment, the Latis-Boltzmann method was used to study the temperature distribution. It was found that the magnetic gradient in the direction of the ferrofluid current can reduce laminar sublayer conduction.

Goharkhah et al [38] experimented with a constant and alternating magnetic field and the ferrofluid heat transfer correlation for fluid flowing through a hot aluminum tube of 9.8 mm diameter having 2680 mm long. They estimated the 18.9% increase in heat transfer without magnetic field and roughly 31.4% increase for the constant and alternating magnetic field. Furthermore, ferrofluid heat transfer properties in a plate channel in the presence of an alternating magnetic field conveying four electromagnetic fields was calculated Ferrofluid heat transfer rate grow over 24.9% for Reynolds varying from 400 to 800 and 37.3% for Reynolds between 800 and 1200. Whereas the reduction of Reynold in regulated current contributes to the accumulation of the nanoparticles which strongly affects heat transfer rate.

Most researchers used thermocouples to measure hot surface temperatures, which provide s temperature information with low accuracy. Reynolds changes also reduce the problem data accuracy. The use of the IRT helps to increase the laboratory data accuracy to a higher spatial resolution than the use of thermocouples.

Nessab [39] and Afsar[40] evaluated a numerical study on Fe_3O_4 microfluid which was influenced by magnets separately. The results show that an increase in magnetic number (Mn), improves the heat transfer amount. which is due to the creation of rotational zones created by the magnets. Fe_3O_4 nanoparticles under the dynamic effects of the magnetic field, form an inlet vortex. The vortices grow when the magnetic field strengthens and decreases jet inlet height. This also disrupts the flow and expands the thermal boundary layers.

Remarking to the electromagnetic effect, an increase in magnetic numbers directly accretes heat transfer and pressure losses. The best-optimized results are gained at Mn = 50 and R = 1/4. Aminfar et al [41] examined the hydro-thermal behavior of a ferrofluid (4 vol% Fe_3O_4/seawater). A two-phase blend was utilized to analyze ferrofluid in the vertical position in a rectangular conduit under distinctive magnetic fields effect. Three situations have been treated for the magnetic field location to ponder the ferrofluid flow dynamic: uniform transverse field, on-uniform pivotal field (positive and negative gradient), and when both areas are connected at the same time. The results show that the negative angle pivotal field and uniform transverse field act the same and improve the Nusselt number and the grinding calculates, whereas the positive angle hub field does the inverse. It is additionally terminated that beneath the impact of both areas, expanding the concentration of the uniform transverse field comes about in diminishing the impact of non-uniform hub areas. Chakrabarty et al discussed the effect of porous medium on the ferrofluid thermal properties. Results prove that β has a direct correlation with the radial and tangential velocity components and in turn the fluid pressure. This increase for different values of β depends on the radial velocity. Ferrofluid flow with a rotating disk has practical use in many areas such as liquid seals around the spinning drive shafts in hard disks, semiconductor manufacturing, rotating machinery, lubrication, and crystal growth processes. Ferrofluid flow with rotating can also change the angular momentum and influence the rotation of the spacecraft and its magnetic resonance can be used for cancer detection and magnetic hyperthermia in cancer treatment. [42] Rea et al [43] studied convective heat transfer for Laminar flow and viscous pressure losses of two types of nanofluids with different concentrations. Results presented that heat transfer increase in both the entrance and in the fully developed regions. Duangthongsuk and Wongwises.[44] estimated the nanofluid heat transfer in the main double copper pipe heat exchanger with a turbulent regime. Results showed nanofluid heat transfer increment. Liang et al [45] studied a nanofluid two-phase blend Brownian movement and thermophoresis diffusivities. The most important point in their experiment was the noteworthy slip between solid and fluid phases.

2. Numerical study

The magnetic force density acting on ferrofluid due to the magnetic field is expressed by the Kelvin body force term (F) that:

$$F = \mu 0 (M\nabla)\, H \tag{1}$$

While M being the magnetization of the ferrofluid, μ_0 the vacuum permeability and H the magnetic field. Assuming M = χ(c)H, where χ(c) is the magnetic susceptibility at a given mass concentration of magnetic nanoparticles and magnetic field. The linear relationship for the magnetic susceptibility that:

$$\chi(c) = \chi 0(1 + \chi c\Delta c) \tag{2}$$

Where Δc = c−c_0, c_0 is a reference mass concentration, χc = 1/c0 and χ_0 is the susceptibility at reference parameters, the non-potential part of the force density becomes

$$F = A.\nabla\, [(h + \Delta H/(2H0))\, \Delta H]\ (A = constant) \tag{3}$$

with ΔH = H−H0, being a reference magnetic field, H is the unit vector. Thus, the variation of the ferroparticle concentration and magnetic field can produce magnetic convection in ferrocolloid. The diffusive dynamics of colloidal nanoparticles are very slow and relevant only on sub-millimeter length scales. In turn, the Schmidt number Sc = η(ρD) −1 (η and ρ are the viscosity and density of ferrocolloid, D the diffusivity of ferroparticles) expresses the ratio of momentum and mass diffusivities. The magnetosolutal micro convection is creeping convection. Introducing characteristic scales for the length L (equal to the radius of the cylindrical inclusion). The dynamics of ferrocolloid is described by the dimensionless Stokes equation:

$$-\nabla p + \Delta u + Rmc\,\nabla\,[(h + rH\delta H)\delta H] = 0 \tag{4}$$

and the continuity condition is:

$$\nabla \cdot u = 0 \quad Here\, rh = \Delta H/(2H0) \tag{5}$$

And the magnetosolutal Rayleigh number is:

$$Rmc = [(\mu 0\chi 0\chi C\; H0L)2(\eta D)] - 1\Delta c\Delta H \tag{6}$$

Overbars are used to denote the characteristic scales of the concentration Δc, magnetic field ΔH, and the temperature ΔT to distinguish these definitions from the deviations of the corresponding quantities from the reference values or the application of the Laplacian operator. In a non-isothermal ferrocolloid, the linearized mass flux due to diffusion and thermophoresis is:

$$J = uc - D\nabla c - c0(1 - c0)DST\nabla T \tag{7}$$

where ST is the Soret coefficient. For now, we neglect magnetophoresis contributions. Introducing the concentration scale

$$\Delta c = c0(1 - c0)\,|ST|\,\Delta T \tag{8}$$

yields the normalized concentration dynamics equation. The Lewis number L = αD−1, characterizing the ratio of thermal and mass diffusivities, is also very large in ferrofluids. Thus, the temperature dynamics are much faster than that of the concentration, and the magnetosolutal micro convection does not influence the distribution of temperature. A non-magnetic cylinder immersed in a ferrofluid with the magnetic permeability μ = 1+χ0 and exposed to the uniform magnetic field creates around itself a magnetic perturbation δH. In the dimensionless form (the radius of the cylinder is assumed as a length scale L),

$$\delta H = \cos(\theta)\, r2er + \sin(\theta)\, r2e\theta \tag{9}$$

where r and, er and eθ are the cylindrical coordinates and basis vectors. Also, the characteristic scale of the magnetic field is

$$\Delta H = |KH|H0 \; and \; KH = (\mu - 1)/(\mu + 1) \quad (10)$$

Magnetic perturbation is produced by an array of non-magnetic cylinders directly from the Maxwell equations, but the result corresponds to a superposition of 2D dipoles (3). For typical ferrofluid parameters (ST = 0.1K−1, η = 0.001Pa·s, D = 2 ×10 −11 m/s2, c0 = 0.15, the particle diameter 8nm, the particle spontaneous magnetization 5 × 105 A/m), the external field 0.1T and the imposed temperature gradient correspond to a temperature difference of 20K applied across a 1-mm thick porous membrane; the Rayleigh number in the vicinity of cylindrical inclusion with the radius 2µm reaches Rmc = 50. This is enough to cause a significant micro convective particle transfer and Zablotsky [46]and Blums [47] used this value in simulations.

3. The relation of mass flow and heat transfer rate

The main factor in the heat transfer coefficient growth is the internal particles force to the magnetic current ratio which widely involves the flowing particle mass. The magnetic force depends on them which is usually not readily available. Comparison of the base fluid with the magnetic fluid shows a considerable increase in heat transfer quality (especially for different ferrofluid). Increased local thermophysical properties of ferrofluid are one of the reasons for enhancing heat transfer in the presence of a magnetic field. As with any other magnetic suspension, each ferrofluid IONP is an independent super-magnetic particle. [48] To confirm the above theory, the ferrofluid current through a magnetic field of 500 microns × 500 micrometers in a magnetic field using the light microscope technique is depicted below.

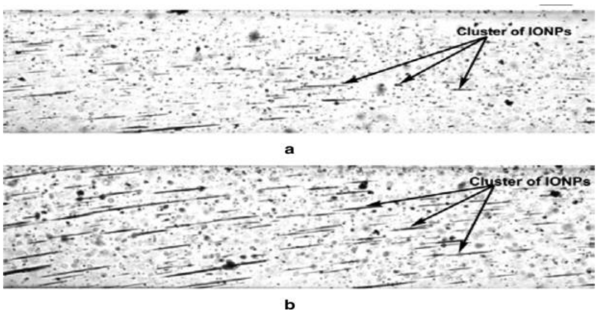


Fig 3. (a) (IONPs) in ferrofluid in the presence of a magnetic field(b)IONPs in absence of magnetic field [51]

The length of the IONP cluster, as shown in figure 3, increases with magnetic field strength. The interactions between the ferrofluid and the total IONP formed in viscous sub-layer accelerated heating. The accumulation of IONP inside the pipe is considered a local barrier to flow and changes the flow, which is transferred from one grain to another. The accumulation of IONP in the inner diameter of the steel pipe acts as local barrier to flow and in this way, the current accumulates around the pipe. In the current with lower Reynolds, large IONP clusters occur on the inner wall of the tube at any magnetic location, resulting in obstruction of the ferrofluid flow in the tube. At high velocity, a smaller accumulation of IONPs occurs in the tube wall, which does not lead to a sudden blockage inside the tube. Hence, at higher velocities, more heat is transferred from the hot surface of the pipe. [49] At a higher velocity, the ferrofluid passes from one magnet to another. The return current convergence will lead to a greater energy transfer. [50] Strek et al computed dimensionless temperature and velocity variation by time.

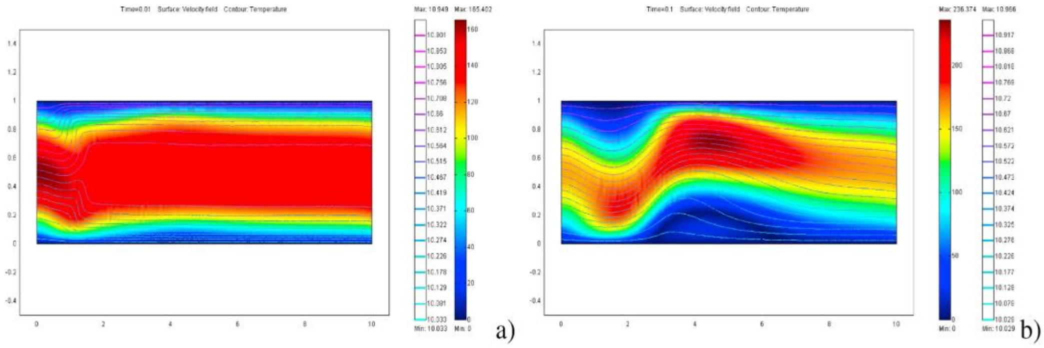


Fig 4. Time evolution of the dimensionless velocity field (surface) and the dimensionless temperature (contour) for (a) t = 0.01, (b) t = 0.1 [51]

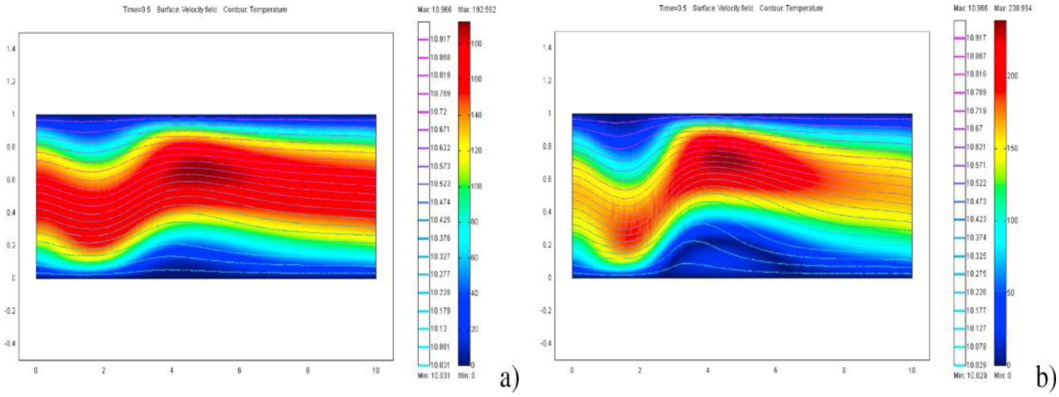


Fig 5. Comparison of the dimensionless velocity field (surface) and the dimensionless temperature (contour) for the different values of the magnetic number: (a) fluid A, (b) fluid B [51]

The assumed initial conditions for dimensionless variables are motionless fluid, zero pressure, and linear temperature variation. The time-dependent flow is considered for a dimensionless time. Tolerance Relatively is 0.05 and absolutely 0.005 for whole calculations. Two different values of the magnetic field are imposed and named Fluid A and Fluid B. Their characteristics are expressed in the table below.

Table 3. Dimensionless numbers for the four different values of the magnetic field in ferrofluid.[51]

variable	fluid A	fluid B
Hr	3819.71	5092.95
Pr	1.4	1.4
Ra	2.5701×10^{7}	2.5701×10^{7}
Ec	2.1810×10^{-12}	2.1810×10^{-12}
Re	0.7142	0.7142

It is observed that the maximum value of the velocity field magnitude in the channel under the magnetic dipole increases due to the value of the magnetic number. The velocity at the half channel and time t = 0.5 is about three times bigger than the velocity profile magnitude at the left end of the rectangular channel (inlet).[51] A numerical study has been executed on the stagnation point flow of magneto-ferrofluids attracting nonlinear thermal radiation, induced magneticfield, and non-uniform heat source effects. It is concluded from that essay that Fe_3O_4--Kerosene nanofluid effectively enhances the thickness of the velocity boundary layer when compared with Fe_3O_4-water nanofluid and also momentum. It is investigated that the magneticfield parameter tends to enhance the heat transfer rate in the presence of induced magneticfield and the non-uniform heat generation/absorption parameters help to enhance the temperature profiles. [52]

Mokhtari et al [53] analyzed the heat transfer of nanofluid of volume concentration of water-based Fe_3O_4-ferrofluid flow in tube subjected to magnetic flux. The export information is approved with numerical simulations with sensible inconsistency. Parametric thinks are performed to uncover the impact of different components such as magnetic field intensity, the concentration of nanoparticles, Reynolds number, and geometry. Agreeing to the gotten results, the average Nusselts-number of ferrofluid increments by more than 200% since it streams interior the tube with bent tapes. Moreover, the attractive field initiated by parallel wire upgrades the normal warm exchange of the whirling Ferrofluid (approximately 30%).

Sha et al [54] concluded that Nusselts-number moreover rises as the concentrations of the nanoparticles are expanded worked on an exploratory examination to analyze the impact of the attractive field on heat exchange convective of nanofluid (Fe_3O_4-water) in a turbulent stream administration. It appeared that the heat transfer coefficient expanded with the increment of the nanofluids (Fe_3O_4-water) concentration, magnetic field, and temperature intensity. The upgrade expanded beneath the gradient magnetic field than that beneath the uniform magnetic field. Without the impact of the magnetic field, the most extreme found the middle value of convective heat transfer coefficient of nanofluid (Fe_3O_4--water) is over that of Distilled Water by 5.2% at a volume concentration of 3% and the temperature of 40 °C. The greatest found the middle value of improvements of the convective heat transfer coefficient over that of within the nonattendance of the magnetic field were 4.2% and 8.1%. The test comes about concurred well with the non-dimensional investigation.

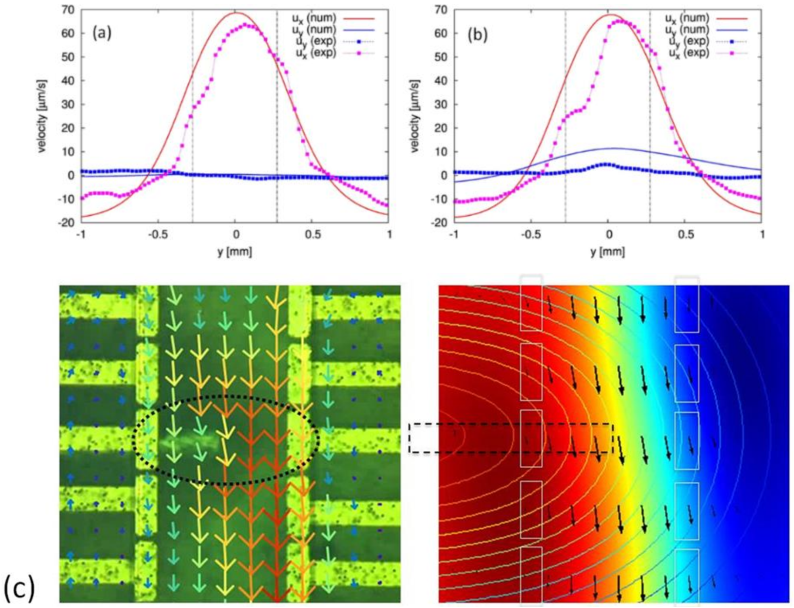


Fig 4.Combining magnetic forces for contactless manipulation of fluids in microelectrode-microfluidic systems[57]

In Figure 4-(a) and 4-b Haehnel [55] directly compared experimental and numerical velocities in x and y-direction. At x = 0, z = 320 µm versus y-coordinate (crossflow direction) the grad B-strip is ignored, velocity changes are shown in Fig 4-a (the details of the PIV data processing are described in supplementary information) and Zoomed view of the experimental (left) and numerical (right) results near the grad-strip at z = 320 µm is shown in Figure 4-c.

4. The effect of porosity and magnetic field on temperature and heat transfer rate

Among the different types of magnetic fluids, ferrofluid can improve active or passive two-phase heat transfer mostly in porous media [56, 57].The use of porous plates improves heat transfer speed. In this regard, different applications of porous media in optimizing thermal phenomena have emerged. [58,59]. Porous media are applied in pipes in two general forms: partially filled and fulfilled. Using ducts partially filled with the porous medium reduces more pressure drop compared to ducts completely filled porous medium. Heat transfer fluids namely oil, water, and ethylene glycol Which have low thermal conductivities resulting in a low heat-transfer rate in heat-transfer applications could be refined using a porous medium. [60-63] A method of modifying the heat transfer rate is adding nanoparticles to DI-water that have been extensively reported during the last years and another procedure is the simultaneous use of porous media which changes the ferrofluid regime with a certain concentration of Fe_3O_4- [64]. Nanofluids affect pure research and practical applications due to their potential in heat exchangers. [65-68] Magnetic nanowires are the same as ferrofluid in porous media surrounded by a magnetic field. The same as nanoparticles, magnetic nanowires are made of metallic nanoparticles to illustrate iron, nickel, cobalt, and their oxides in the base magnetite liquid. [69]

Mehdi et al [70] studied the magnetic nanowires Considering the main types of boundary conditions separately (constant heat flux flow and permanent wall temperature). They reported that the effect of porous thickness plate on the value of Nusselt number is not the same and there is a critical thickness. other flow characteristics are dependent. [71]

Heat transfer depends on the porosity radius and the geometry of the porous plate. [72] The three most widely used geometries in heat transfer of ferrofluids with porous plates are the geometry of the cylinder placed in the center of the tube, the porous circumference of the annular matrix inside the tube, and the porous circumference of the cylindrical matrix at a distance from the tube inlet. [73,74] The effect of porosity thickness on heat transfer rate and pressure drop is possible assuming flow for Darcy values greater than 3-10. Forchheimer's effect implies that the inertial effect is effective for Darcy values less than the range of 4-10. [75] In nanowires, the intensity of the magnetic field applied to the nanowire current, the shape of the inner tube, and the amount of Reynolds have a large effect on the heat transfer rate so that the sinusoidal shape of the inner tube increases the Nusselt value. As the magnetic field intensifies, the cold boundary layer expands toward the center of the inner tube, which in turn increases the rate of heat transfer. A numerical study of the forced heat transfer of a magnetic nanowire in a chamber with sinusoidal and movable walls was studied by Shaykhalslami [76]. The effects of Hartmann number, Reynolds amount, and nanoparticle volume percentage on hydrodynamic and thermal behavior show that the temperature gradient is a function of velocity and nanoparticle concentration. Also, the heat transfer rate increase by Reynolds number growth; However, it decreases Hartmann. [74,77]

The two-sinus tube heat exchanger was Mousavi et al case study. [78]. The results of this study demonstrate that the heat transfer rate increases with a marked increase in the Reynolds value. Heat transfer rate is directly related to the intensity of the magnetic field, while there is an optimal value for the frequency of the field. Besides, the optimum frequency increases for larger Reynolds values. The effect of magnetic field on heat transfer of the ferrofluid in a porous fin heat sink is evaluated by Bezaatpour et al [32] As shown in Figure 5 temperature contour is drowned for different magnetic field intensities.

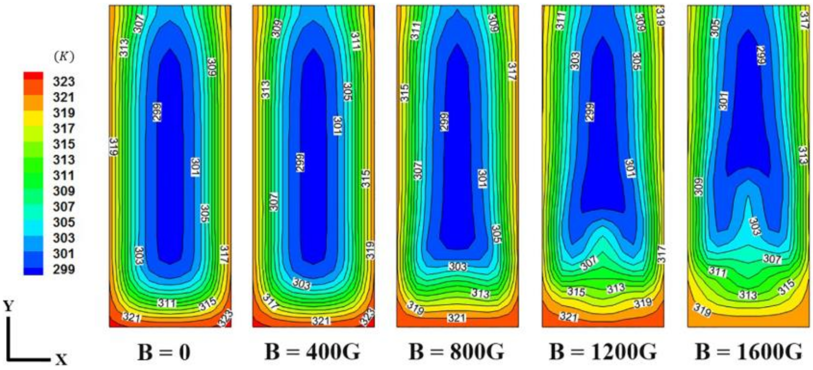


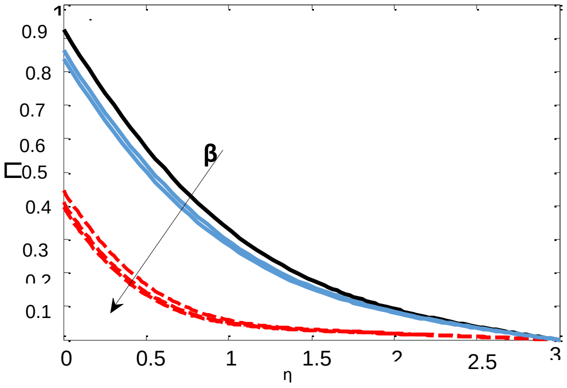
Fig 5. Effect of the magnetic field on the temperature distribution at the middle channel outlet of the solid fin heat sink for $\varphi = 2\%$ and Re = 260. [32]

Outlet temperature distribution in the middle channel controlled by the magnetic field is shown in Figure 5. The magnetic field tends to alter the bottom surface thermal boundary layer and create circulation hence this kind of convection higher the heat transfer.[32] Ghasemian et al [79] modeled Fe_3O_4-ferrofluid using two-stage mixed relations and reported 16.48% and 27.72% heat transfer increment using constant and alternating magnetic fields at f = 4 Hz in order.

Zonouzi et al [80] used a two-step method to investigate the heat transfer of a ferrofluid stream in a vertical tube. The application of a negative magnetic gradient along the tube enhances the heat transfer rate while the positive magnetic field reduces and positive magnetic gradient acts as a pump, while for an applied negative gradient, more power is needed. Zonouzi et al surveyed ferrofluid heat transfer in a vertical channel in the magnetic field generated by an electric wire using two-step modeling. They observed that direct vortices toward the wall, increase the heat transfer rate furthermore illustrated that the amount of Nusselt number can be increased up to 22%. Most of the published researches focused on heat transfer and the effects of the magnetic field with the porous medium separately [81]. Fadaei et al [82] Used a simple magnetic field to diminish the computational load. In some cases, the intended magnetic field does not satisfy the Maxwell equations, while less attention is paid to practical magnetic fields such as the solenoid[1]-induced field. Solenoid-induced magnetic fields of the limited length in the presence of a porous medium raise the heat transfer rate in various equipment for instance solar collectors and fuel cells. Therefore, it is possible to investigate the ferrofluid heat transfer in porous media applied by the solenoid.

The proposed method to increase the heat transfer speed can be used in various industrial processes. The excessive heat must be removed from chemical reactors, solar cells, and power transformers. Of course, as heaters are part of a porous environment, the pressure drop is not large, thus increasing the need for energy consumption, and this increases costs. The porous medium has less permeability than the free stream. [83] Due to the high thermal conductivity in a porous medium, its temperature is higher than in the free flow zone. As the electric current increases, the magnetic field created by the electric current amplifies the movement of the cold ferrofluid toward the porous medium. the surface of the porous medium is prepared for heat transfer; thus the heat transfer rate significantly increases. As the heat transfer rate increases, the temperature distribution becomes uniform. A backflow occurs in the solenoid region as the magnetic field intensifies. Since the thermal conductivity of a porous medium is much larger than that of a ferrofluid stream in the free flow zone, the temperature gradient in this region is smaller. The ferrofluid convection in the free flow region causes a parabolic temperature distribution. The temperature distribution in the porous region is almost linear. [84]

The imbalance of the concentration was created by thermo-phonetic separation induced by a temperature gradient. The application of the external magnetic field creates a highly inhomogeneous magnetic force distribution within the membrane, which possesses a well-defined macroscopic structure. A pressure difference appears across the membrane driving the ferrofluid flow in the temperature gradient direction. It is proved that interpretation of pore-scale simulation results of the Darcy theory framework is possible.[85]An increase in porosity parameter β affects the radial and tangential velocity components and in turn, the fluid pressure for different values of β depends on the radial velocity.



---

[1] solenoid is a type of electromagnet, the purpose of which is to generate a controlled magnetic field through a coil wound into a tightly packed helix.

Fig 6. Temperature Profiles for Different Values of the Slip Parameter (β)

Nurdin et al [86] experimentally Investigated the thermal properties enhancement (kinematic viscosity and the thermal conductivity) of nano magnetite while volume concentrations are (0.1, 0.2, 0.3, 0.4, 0.5, 0.6) % subjected to the external magnetic field in distinctive introductions (perpendicular and parallel). the nanofluid thermal conductivity increments with the magnetic field strength. The results appear that the kinematic viscosity improvement of the nanofluids also depends on the magnetic field strength. Moreover, the highest kinematic consistency upgrade (about 31.91%) is achieved at the over said exploratory conditions. Raju et al [87] studied the effect of radiation on the ferrofluids over a flat plate in presence of a non-uniform heat source and slip velocity in charge of a magnetic field. The governing partial differential equations are turned into nonlinear ordinary differential equations by using similarity transformation. They concluded that raise in inclined angle modifies the friction factor and heat transfer rate. The slip parameter enhances the momentum boundary layer thickness. In this experiment, positive values of non-uniform heat source-sink parameters refine the flow temperature profiles. In table 3 results from two experiments are compared in two different conditions. [88]

Table 4. Fe_3O_4 - water and Fe_3O_4-Kerosene properties for different volume fraction values [89]

		$M = \beta = 0$	$A\ B\ R^{*} = {}^{*} = = 0$	$M = \beta = 2$	$A\ B\ R^{*} = = = {}^{*}0$
	φ	Khan et al. (2015)	Raju et al (2019)	Khan et al. (2015)	Raju et al (2019)
Fe_3O_4-Water	0.01	0.34324	0.3432413	0.37573	0.3757321
	0.1	0.45131	0.4513102	0.38832	0.3883210
	0.2	0.59517	0.5951712	0.40242	0.4024202
Fe_3O_4-Kerosene	0.01	0.34557	0.3455732	0.37580	0.3758001
	0.1	0.47336	0.4733621	0.38896	0.3889631
	0.2	0.63950	0.6395023	0.40356	0.4035641

Hussein et al [89] numerically studied the magneto-hydrodynamic free convection flow of a nanofluid in an open enclosure utilizing the lattice Boltzmann method (LBM). Results demonstrate that supreme values of stream work are declined altogether by expanding Hartmann numbers whereas these values are raised by expanding Rayleigh numbers. Additionally, the strong volume division detailed a noteworthy impact on heat transfer and stream work, depending on the esteem of Rayleigh numbers and Hartmann. Gan et al [90] showed that ferrofluids have a thermal conductivity higher than their base watery or oil-based liquids due to the strong magnetic nanoparticle that makeup the ferrofluids. Stream heat transfer properties are improved with the ferrofluid utilization. Results show that ferrofluid convective heat transfer rate increase by expanding the strong volume concentration of magnetic particles within the investigated range (0.2–0.4%). Interestingly, increasing magnetic flux decreases heat transfer improvement. [91,92] Shah et al investigated ferrofluids for heat transfer augmentation and also studied the magnetic field effect on heat transfer amount for ferrofluid flow with Re<100. [35]

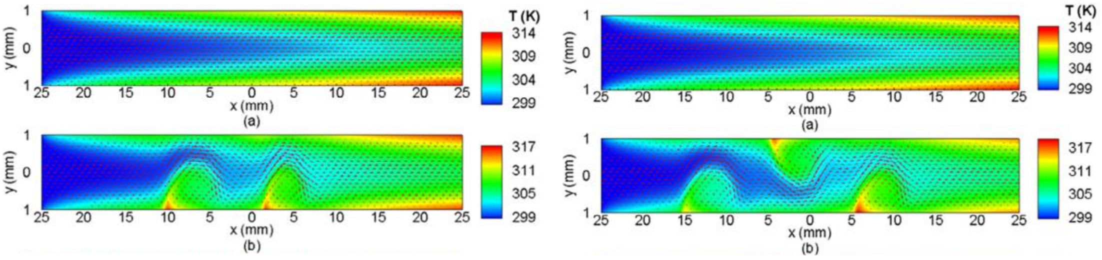


Fig 7. temperature profile for ferrofluid flow, with and without the magnetic field for three dipole cases at Re=25 and without magnetic field at (b) Re=50 [35]

External regulation of ferrofluid convection is possible in temperature-sensitive carrying fluids and porous medium ensures that stationary convection is the preferred mode consequently the measurements are easy to handle. [93,94] Zablotsky et al [95] have performed pore-scale numerical simulations of ferrofluid magnetosolutal micro convection in 1D ordered porous membranes composed of cylindrical elements.

5. Nusselt variation of ferrofluid in an external magnetic field

As the magnetic gradient increases, the Kelvin force prevails and causes the fluid to move toward the porous region. Besides, the boundary layer is disrupted due to the ferrofluid rotation in the high-intensity magnetic field. Consequently, the boundary layer is disturbed and thermal conductivity in the porous medium linearly changes with the Nusselt number. Increasing the Reynolds number in the absence of the magnetic field leads to an increase in the Nusselt number as the inertial force overcomes the larger viscosity. On the other hand, with a certain amount of Reynolds value, the use of an external magnetic field leads to an increase in the Nusselt number. [96]approve that under the influence of the magnetic field induced by a solenoid with a current intensity of 10 A, the average Nusselt number value increases up to 30%. [46] Li and Xuan [97] observed a moderate increase in Nusselt number ratio up to 60%. according to their experimental results nanofluid with 2% nanoparticles was the most appropriate fluid. Fotukian et al [98] experimentally investigated the effect of nanofluid on heat transfer rate in horizontal tube and penetrative parameters such as nanoparticles volume concentration, Reynolds number, and temperature have been considered. The results indicate that no significant increase in heat transfer coefficient enhancement accompanied with the Reynolds number and mass flow compared to the conventional fluid. The convective heat transfer of laminar flow with oxide nanoparticles under constant heat flux in the circular tube was studied experimentally by Zeinali et al [99] and Results showed that the Nusselt number increases. In this situation volume fraction increases for all Reynolds numbers.

Kayhani et al [100] investigated the convective heat transfer and nanofluid pressure drop. the y observed that at nanofluid with 2.0% nanoparticle volume fraction is about 8% of the Nusselt number. Heidary et al [101] analyzed fluid flow and heat transfer in a wavy channel, whereas a magnetic field is connected in transverse heading to the most stream. It is observed that a wavy channel is more effective than a straight one, while it can upgrade warm trade between the center stream and hot dividers. Otherwise, the utilization of magnetic-field transverse to hot dividers can upgrade heat transfer in a straight channel. They inspected in case the nearness of these two strategies at the same time value for the upgrade of warm trade or not. Figure 8 shows the average Nusselt-number variation of the hot walls of channels versus Hartmann-numbers for wave amplitude (0, 0.1, 0.2, 0.3).

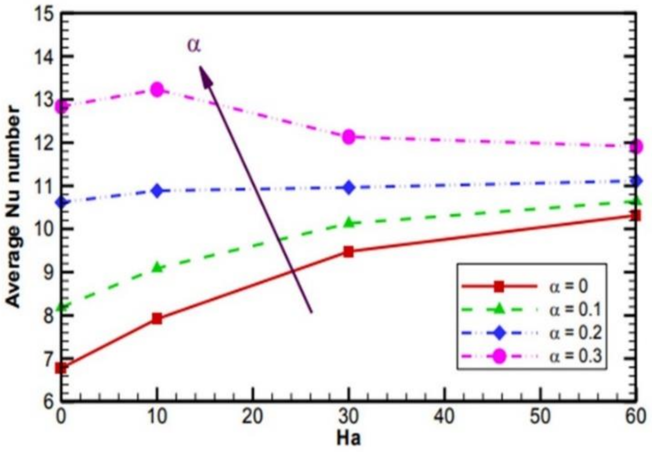


Fig 8. graph of average Nusselt number versus Hartmann numbers for various wave amplitude at Re=250 [۱۰۲]

Maouassi et al [102] outlined how commonsense application of using nanoparticles as a working liquid to fortify the efficiency of solar collector type flat plate with heat-transfer adjustment properties. A numerical study about laminar nanofluid convection, lasting and stationary, is conducted in a sun-powered level plate solar collector. The obtained results of pressure drop coefficient, Nusselt number and temperature were discussed. Finally, they concluded that warm exchange increments with expanding both nanoparticle concentration and Reynolds number. Figures 9 represents the Nusselt-number evolution as a function of Reynold number and the volume fraction.

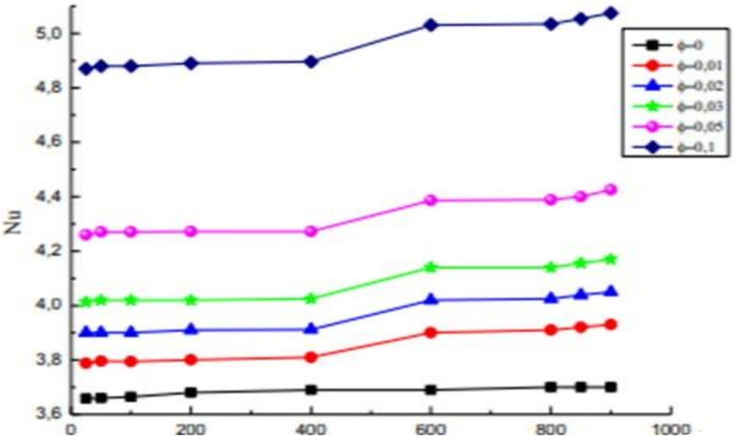


Fig 9. Nusselt variation by the increase in Reynolds number [102]

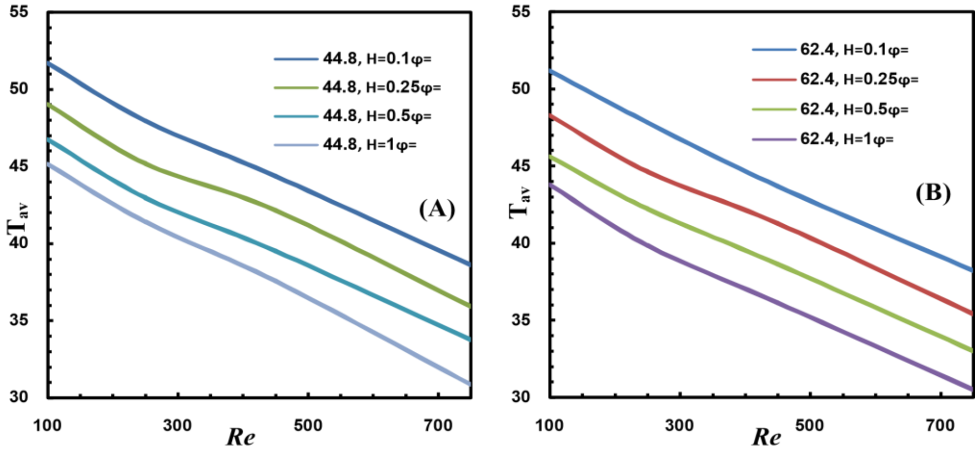


Fig 10. Variation of average wall temperature with Re for the different volume fraction of ferrofluid where (A) H=44.8, (B) H=62.4

Servati et al [103] considered the magnetohydrodynamic (MHD) properties of nanofluid in a permeable channel. They found that by expanding the nanoparticle concentration, the temperature and average speed at the channel outlet expanded drastically. Moreover, the normal Nusselt number increments marginally with the magnetic field concentrated. Nessab et al [104] investigated ferrofluid jet flow and convective heat transfer under the influence of magnetic sources numerically. They calculated local Nusselt changes for different magnetic numbers as is shown in the following.

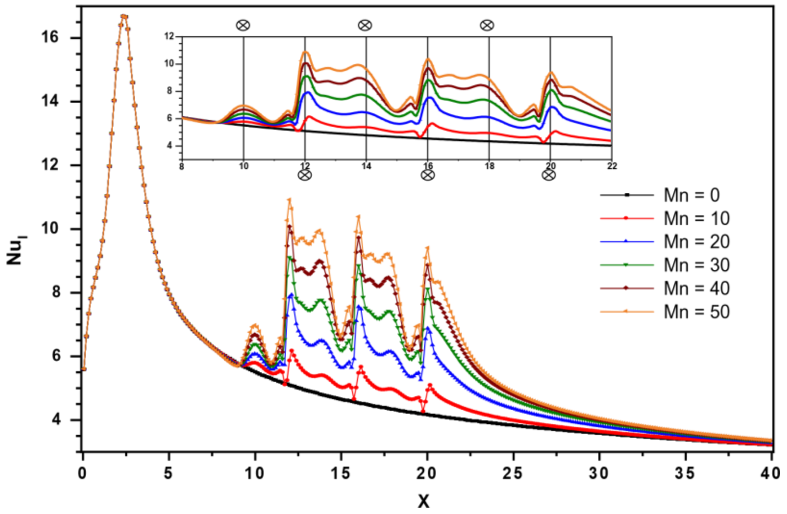


Fig 11. Local Nusselt changes for different magnetic numbers at Xi = 10 and R = 1/4 for Fe_3O_4 [104]

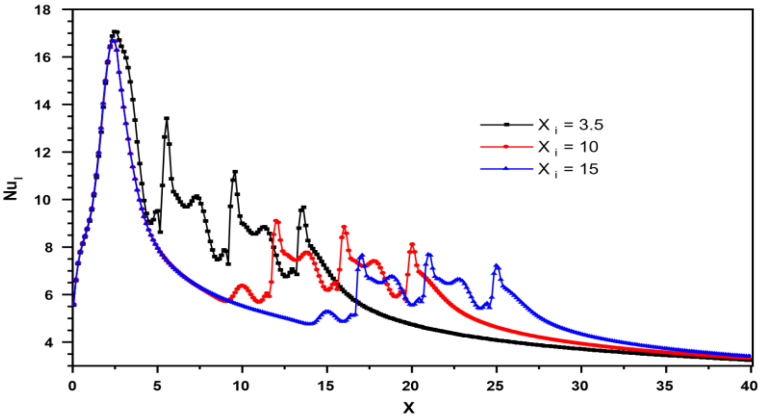


Fig 12. Local Nusselt for different Xi at Mn = 30 and R = ¼ [104]

6.Conclusion

Different types of ferrofluid have widespread utilization in various industries. They have alternative physical properties in the response to a variable intensity of magnetic fields. In the following some of the most important results are mentioned:

- The magnetic field effect can make more heat transfer efficiency. The results of numerical studies demonstrate that heat transfer rate enhances by the magnetic number increase and the opening ratio reduction but this improvement depended on magnetic field strength and flowing path geometry. For example, there are small clusters in ferrofluid which are iron oxide nanoparticles(IONPs). While an intense magnetic field affects ferrofluid in SS tube, clusters grow and decrease flow speed so heat transfer decrease but this problem will be solved in a special magnetic field strength since the increase in ferrofluid heat transfer coefficient in a magnetic field depends on the internal interaction force to the magnetic current ratio.
- The heat transfer coefficient raise (in comparison with base fluids) significantly depends on nanoparticle concentration adoption.
- Comparison of the base fluid with the magnetic fluid shows a considerable increase in heat transfer quality in convective heat transfer for appropriate magnetic field gradient and sufficient magnetic field gradient.
- Passing along, local Nusselt decrease. For different magnetic numbers, the Nusselt number has a concise increase with the Reynolds number provided that the flow regime does not change. Numerical studies show ferrofluid can optimize two-phase flow in porous media, for different base fluids (water, kerosene). Providing a suitable magnetic field affects magnetic nanoparticles.

References

[1] Wen, D., Lin, G., Vafaei, S., & Zhang, K. (2009). Review of nanofluids for heat transfer applications. *Particuology*, *7*(2), 141-150.

[2] Huang, L., Mohamed S. El-Genk, and J-M. Tournier. "Transient performance of an inclined water heat pipe with a screen wick." *ASME-PUBLICATIONS-HTD* 236 (1993): 87-87.

[3] Maxwell, James Clerk. *A Treatise on Electricity and Magnetism: pt. III. Magnetism. pt. IV. Electromagnetism*. Vol. 2. Clarendon press, 1881..

[4] Choi, S. US, and Jeffrey A. Eastman. *Enhancing thermal conductivity of fluids with nanoparticles*. No. ANL/MSD/CP-84938; CONF-951135-29. Argonne National Lab., IL (United States), 1995.

[5] Odenbach, Stefan. "Magnetoviscous effects in ferrofluids." *Appl. Rheol* 10.4 (2000): 178.

[6] Scholten, P. C. "The origin of magnetic birefringence and dichroism in magnetic fluids." *IEEE Transactions on magnetics* 16.2 (1980): 221-225.

[7] Rosensweig, Ronald E. "Magnetic fluids." *Annual review of fluid mechanics* 19.1 (1987): 437-461. [8] Saha, Kaushik, et al., eds. *Two-Phase Flow for Automotive and Power Generation Sectors*. Springer, 2019.

[9] Bossis, G., et al. "Structuration and elasticity of electrorheological fluids." *Trends in Colloid and Interface Science VI* (1992): 135-139.

[10]Chan, Daniel CF, Dmitri B. Kirpotin, and Paul A. Bunn Jr. "Synthesis and evaluation of colloidal magnetic iron oxides for the site-specific radiofrequency-induced hyperthermia of cancer." *Journal of Magnetism and Magnetic Materials* 122.1-3 (1993): 374-378.

[11] Lee, Ji-Hwan, et al. "Effective viscosities and thermal conductivities of aqueous nanofluids containing low volume concentrations of Al2O3 nanoparticles." *International Journal of Heat and Mass Transfer* 51.11-12 (2008): 2651-2656..

[12] Kang, Hyun Uk, Sung Hyun Kim, and Je Myung Oh. "Estimation of thermal conductivity of nanofluid using experimental effective particle volume." *Experimental Heat Transfer* 19.3 (2006): 181-191.

[13] Wen, Dongsheng, and Yulong Ding. "Experimental investigation into convective heat transfer of nanofluids at the entrance region under laminar flow conditions." *International journal of heat and mass transfer* 47.24 (2004): 5181-5188.

[14] Daungthongsuk, Weerapun, and Somchai Wongwises. "A critical review of convective heat transfer of nanofluids." *Renewable and sustainable energy reviews* 11.5 (2007): 797-817.

[15]Izadi, Mohsen, et al. "Nanoparticle migration and natural convection heat transfer of Cu-water nanofluid inside a porous undulant-wall enclosure using LTNE and two-phase model." *Journal of Molecular Liquids* 261 (2018): 357-372.

[16] Ali, Ahmed Hammodi, Mahdi Hatf Kadhum, and Hussein AwadKurdi Saad. "Experimental Study of Forced Convection Heat Transfer Ferrofluid in Pipe Exposed to Magnetic Field." *International J. Innovative Research in Science, Engineering and Technology* 5 (2016): 12008-12017.

[17] Khalaf, Dheyaa A., Karima E. Amori, and Firas M. Tuaimah. "EFFECT OF ELECTROMAGNETIC FIELD ON THE NATURAL CIRCULATION IN SOLAR ABSORBER TUBE."

[18]Chukhrov, A. Yu. "Convective stability of dilute colloid in the presence of magnetic diffusion in an inhomogeneous field." *Magnetohydrodynamics* 22.3 (1986): 254-258.

[19] Tawfik, Mohamed M. "Experimental studies of nanofluid thermal conductivity enhancement and applications: A review." *Renewable and Sustainable Energy Reviews* 75 (2017): 1239-1253.

[20]Erb, Randall M., et al. "Magnetic assembly of colloidal superstructures with multipole symmetry." *Nature* 457.7232 (2009): 999-1002.

[21]Cherepanov, I. N., and P. V. Krauzin. "On the thermodynamic theory of colloidal suspensions." *Physica A: Statistical Mechanics and its Applications* 540 (2020): 123247.

[22]Šustková, Hana. "Viscoelastic properties of ferrofluid-Study of normal stresses differences." (2013).

[23] Cherepanov, I. N., and P. V. Krauzin. "On the thermodynamic theory of colloidal suspensions." *Physica A: Statistical Mechanics and its Applications* 540 (2020): 123247.

[24Khan, W. A., Z. H. Khan, and Rizwan Ul Haq. "Flow and heat transfer of ferrofluids over a flat plate with uniform heat flux." *The European Physical Journal Plus* 130.4 (2015): 1-10.

[25Babu, M. Jayachandra, et al. "Nonlinear thermal radiation and induced magneticfield effects on stagnation-point flow of ferrofluids." *Journal of Advanced Physics* 5.4 (2016): 302-308.

[26] Farajollahi, B., S. Gh Etemad, and M. Hojjat. "Heat transfer of nanofluids in a shell and tube heat exchanger." *International Journal of Heat and Mass Transfer* 53.1-3 (2010): 12-17.

[27Afrand, Masoud, Davood Toghraie, and Nima Sina. "Experimental study on thermal conductivity of water-based Fe3O4 nanofluid: development of a new correlation and modeled by artificial neural network." *International Communications in Heat and Mass Transfer* 75 (2016): 262-269.

[28] Liu, Qi, et al. "A ferrofluid based energy harvester: Computational modeling, analysis, and experimental validation." *Journal of Magnetism and Magnetic Materials* 449 (2018): 105-118 .

[29] Nkurikiyimfura, Innocent, Yanmin Wang, and Zhidong Pan. "Heat transfer enhancement by magnetic nanofluids—a review." *Renewable and Sustainable Energy Reviews* 21 (2013): 548-561.

[30] Khosravi, Ali, Mohammad Malekan, and Mamdouh EH Assad. "Numerical analysis of magnetic field effects on the heat transfer enhancement in ferrofluids for a parabolic trough solar collector." *Renewable Energy* 134 (2019): 54-63.

[31] Azizian, R., et al. "Effect of magnetic field on laminar convective heat transfer of magnetite nanofluids." *International Journal of Heat and Mass Transfer* 68 (2014): 94-109.

[32] Bezaatpour, Mojtaba, and Mohammad Goharkhah. "Effect of magnetic field on the hydrodynamic and heat transfer of magnetite ferrofluid flow in a porous fin heat sink." *Journal of Magnetism and Magnetic Materials* 476 (2019): 506-515.

[33]Qasim, Muhammad, et al. "MHD boundary layer slip flow and heat transfer of ferrofluid along a stretching cylinder with prescribed heat flux." *PloS one* 9.1 (2014): e83930.

[34] Goharkhah, Mohammad, and Mehdi Ashjaee. "Effect of an alternating nonuniform magnetic field on ferrofluid flow and heat transfer in a channel." *Journal of magnetism and magnetic materials* 362 (2014): 80-89.

[35] Shah, Ram Krishna, and Sameer Khandekar. "Exploring ferrofluids for heat transfer augmentation." *Journal of Magnetism and Magnetic Materials* 475 (2019): 389-400.

[36] Hambleton, Ronald K., and H. Jane Rogers. "Detecting potentially biased test items: Comparison of IRT area and Mantel-Haenszel methods." *Applied Measurement in Education* 2.4 (1989): 313-334.

[37] Xu, Guoying, et al. "Performance evaluation of a nanofluid-based direct absorption solar collector with parabolic trough concentrator." *Nanomaterials* 5.4 (2015): 2131-2147.

[38]Goharkhah, Mohammad, Mehdi Ashjaee, and Jalil Jamali. "Experimental investigation on heat transfer and hydrodynamic behavior of magnetite nanofluid flow in a channel with recognition of the best models for transport properties." *Experimental Thermal and Fluid Science* 68 (2015): 582-592.

[39] Asfer, Mohammed, et al. "Effect of magnetic field on laminar convective heat transfer characteristics of ferrofluid flowing through a circular stainless steel tube." *International Journal of Heat and Fluid Flow* 59 (2016): 74-86.

[40] Nessab, W., et al. "Numerical investigation of ferrofluid jet flow and convective heat transfer under the influence of magnetic sources." *Applied Thermal Engineering* 150 (2019): 271-284.

[41]Aminfar, H., M. Mohammadpourfard, and F. Mohseni. "Two-phase mixture model simulation of the hydro-thermal behavior of an electrical conductive ferrofluid in the presence of magnetic fields." *Journal of Magnetism and Magnetic Materials* 324.5 (2012): 830-842.

[42] Jhumur, Nandita Chakrabarty, and Anuruddha Bhattacharjee. "Unsteady MHD mixed convection inside L-shaped enclosure in the presence of ferrofluid (Fe3O4)." *Procedia engineering* 194 (2017): 494-501.

[43] Rea, Ulzie, et al. "Laminar convective heat transfer and viscous pressure loss of alumina–water and zirconia–water nanofluids." *International Journal of Heat and Mass Transfer* 52.7-8 (2009): 2042-2048.

[44] Duangthongsuk, Weerapun, and Somchai Wongwises. "Heat transfer enhancement and pressure drop characteristics of TiO2–water nanofluid in a double-tube counter flow heat exchanger." *International Journal of Heat and Mass Transfer* 52.7-8 (2009): 2059-2067.

[45]Liang, Gangtao, and Issam Mudawar. "Review of single-phase and two-phase nanofluid heat transfer in macro-channels and micro-channels." *International Journal of Heat and Mass Transfer* 136 (2019): 324-354.

[46] Zablotsky, D., and E. Blums. "Pore-scale simulation of magnetosolutal microconvection in ferrofluid saturated porous structures." *Magnetohydrodynamics* 51.3 (2015): 249-254.

[47]Blums, Elmars, Andrejs Cebers, and Mikhail Mikhailovich Maiorov. *Magnetic fluids*. Walter de Gruyter, 2010.

[48] Malmir-Chegini, Yahya, and Nima Amanifard. "Heat transfer enhancement inside semi-insulated horizontal pipe by controlling the secondary flow of oil-based ferro-fluid in the presence of non-uniform magnetic field: A general correlation for the Nusselt number." *Applied Thermal Engineering* 159 (2019): 113839.

[49] Sheikholeslami, Mohsen, and Davood Domiri Ganji. "Ferrohydrodynamic and magnetohydrodynamic effects on ferrofluid flow and convective heat transfer." *Energy* 75 (2014): 400-410.

[50] Sharma, V., and U. Gupta. "Stability of stratified elastico-viscous Walters'(Model B') fluid in the presence of horizontal magnetic field and rotation in porous medium." *Archives of Mechanics* 58.2 (2006): 187-197.

[51] Strek, Tomasz, and Hubert Jopek. "Computer simulation of heat transfer through a ferrofluid." *Physica status solidi (b)* 244.3 (2007): 1027-1037.

[52] Babu, M. Jayachandra, et al. "Nonlinear thermal radiation and induced magneticfield effects on stagnation-point flow of ferrofluids." *Journal of Advanced Physics* 5.4 (2016): 302-308.

[53] Mokhtari, Mojtaba, et al. "Effect of non-uniform magnetic field on heat transfer of swirling ferrofluid flow inside tube with twisted tapes." *Chemical Engineering and Processing: Process Intensification* 117 (2017): 70-79.

[54] Sha, Lili, Yonglin Ju, and Hua Zhang. "The influence of the magnetic field on the convective heat transfer characteristics of Fe3O4/water nanofluids." *Applied Thermal Engineering* 126 (2017): 108-116.

[55] Veronika, Haehnel, et al. "Combining magnetic forces for contactless manipulation of fluids in microelectrode-microfluidic systems." *Scientific Reports (Nature Publisher Group)* 9.1 (2019).

[56] Poplaski, Leonard M., Steven P. Benn, and Amir Faghri. "Thermal performance of heat pipes using nanofluids." *International Journal of Heat and Mass Transfer* 107 (2017): 358-371.

[57] Kasaeian, Alibakhsh, et al. "Nanofluid flow and heat transfer in porous media: a review of the latest developments." *International Journal of Heat and Mass Transfer* 107 (2017): 778-791 .

[58] Pourfarzad, E., et al. "Experimental investigation of heat transfer and pressure drop of alumina–water nano-fluid in a porous miniature heat sink." *Experimental Heat Transfer* 31.6 (2018): 495-512.

[59] Sharma, R. C. "The effect of magnetic field dependent viscosity on thermosolutal convection in ferromagnetic fluid." *Applied mathematics and computation* 163.3 (2005): 1197-1214.

[60] Amiri, A., and Kambiz Vafai. "Analysis of dispersion effects and non-thermal equilibrium, non-Darcian, variable porosity incompressible flow through porous media." *International journal of heat and mass transfer* 37.6 (1994): 939-954.

[61] Kaviany, M. "Laminar flow through a porous channel bounded by isothermal parallel plates." *International Journal of Heat and Mass Transfer* 28.4 (1985): 851-858.

[62] Vafai, Kambiz, and Chang L. Tien. "Boundary and inertia effects on flow and heat transfer in porous media." *International Journal of Heat and Mass Transfer* 24.2 (1981): 195-203.

[63] Sharma, Divya, and R. C. Sharma. "Effect of dust particles on thermal convection in ferromagnetic fluid saturating a porous medium." *Journal of Magnetism and Magnetic Materials* 288 (2005): 183-195.

[64] Sarkar, Sandip, and Suvankar Ganguly. "Fully developed thermal transport in combined pressure and electroosmotically driven flow of nanofluid in a microchannel under the effect of a magnetic field." *Microfluidics and Nanofluidics* 18.4 (2015): 623-636.

[65] Mohamad, A. A. "Heat transfer enhancements in heat exchangers fitted with porous media Part I: constant wall temperature." *International Journal of Thermal Sciences* 42.4 (2003): 385-395.

[66] Hajipour, Mastaneh, and Asghar Molaei Dehkordi. "Mixed convection in a vertical channel containing porous and viscous fluid regions with viscous dissipation and inertial effects: a perturbation solution." *Journal of heat transfer* 133.9 (2011).

[67] Nield, Donald A., and Adrian Bejan. "Mechanics of fluid flow through a porous medium." *Convection in porous media*. Springer, Cham, 2017. 1-35.

[68] Ingham, Derek B., and Ioan Pop, eds. *Transport phenomena in porous media III*. Vol. 3. Elsevier, 2005.

[69] Behrangzade, Ali, and Mohammad Mahdi Heyhat. "The effect of using nano-silver dispersed water based nanofluid as a passive method for energy efficiency enhancement in a plate heat exchanger." *Applied Thermal Engineering* 102 (2016): 311-317.

[70] Mahdi, Raed Abed, et al. "Review of convection heat transfer and fluid flow in porous media with nanofluid." *Renewable and Sustainable Energy Reviews* 41 (2015): 715-734.

[71] Pavel, Bogdan I., and Abdulmajeed A. Mohamad. "An experimental and numerical study on heat transfer enhancement for gas heat exchangers fitted with porous media." *International Journal of Heat and Mass Transfer* 47.23 (2004): 4939-4952.

[72] Ganguly, Suvankar, et al. "Thermally developing combined electroosmotic and pressure-driven flow of nanofluids in a microchannel under the effect of magnetic field." *Chemical Engineering Science* 126 (2015): 10-21.

[73] Sarkar, Sandip, Suvankar Ganguly, and Pradip Dutta. "Thermofluidic characteristics of combined electroosmotic and pressure driven flows in narrow confinements in presence of spatially non-uniform magnetic field." *International Journal of Heat and Mass Transfer* 104 (2017): 1325-1340.

[74] Sheikholeslami, Mohsen. "CVFEM for magnetic nanofluid convective heat transfer in a porous curved enclosure." *The European Physical Journal Plus* 131.11 (2016): 1-14.

[78] Mousavi, S. Valiallah, M. Sheikholeslami, and M. Barzegar Gerdroodbary. "The Influence of magnetic field on heat transfer of magnetic nanofluid in a sinusoidal double pipe heat exchanger." *Chemical Engineering Research and Design* 113 (2016): 112-124.

[77] Aminfar, H., M. Mohammadpourfard, and S. Ahangar Zonouzi. "Numerical study of the ferrofluid flow and heat transfer through a rectangular duct in the presence of a non-uniform transverse magnetic field." *Journal of Magnetism and Magnetic materials* 327 (2013): 31-42.

[78] Amani, Mohammad, Mohammad Ameri, and Alibakhsh Kasaeian. "Investigating the convection heat transfer of Fe3O4 nanofluid in a porous metal foam tube under constant magnetic field." *Experimental Thermal and Fluid Science* 82 (2017): 439-449.

[79] Ghasemian, M., et al. "Heat transfer characteristics of Fe3O4 ferrofluid flowing in a mini channel under constant and alternating magnetic fields." *Journal of Magnetism and Magnetic Materials* 381 (2015): 158-167.

[80]Zonouzi, Sajjad Ahangar, et al. "Experimental study of the subcooled flow boiling heat transfer of magnetic nanofluid in a vertical tube under magnetic field." *Journal of Thermal Analysis and Calorimetry* (2019): 1-12.

[81] Malik, Sumit, and A. K. Nayak. "MHD convection and entropy generation of nanofluid in a porous enclosure with sinusoidal heating." *International Journal of Heat and Mass Transfer* 111 (2017): 329-345.

[82] Fadaei, Farzad, et al. "Heat transfer enhancement of Fe3O4 ferrofluids in the presence of magnetic field." *Journal of Magnetism and Magnetic Materials* 429 (2017): 314-323.

[83] Sheikholeslami, Mohsen, and D. D. Ganji. "Heated permeable stretching surface in a porous medium using Nanofluids." *Journal of Applied Fluid Mechanics* 7.3 (2014).

[84] Krauzina, Marina T., et al. "The use of ferrofluids for heat removal: Advantage or disadvantage?." *Journal of Magnetism and Magnetic Materials* 431 (2017): 241-244.

[85] Shivakumara, I. S., Chiu-On Ng, and M. Ravisha. "Ferromagnetic convection in a heterogeneous Darcy porous medium using a local thermal non-equilibrium (LTNE) model." *Transport in porous media* 90.2 (2011): 529-544.

[86] Nurdin, Irwan, Iskandar Idris Yaacob, and Mohd Rafie Johan. "Enhancement of thermal conductivity and kinematic viscosity in magnetically controllable maghemite (γ-Fe2O3) nanofluids." *Experimental Thermal and Fluid Science* 77 (2016): 265-271.

[87] Raju, C. S. K., N. Sandeep, and S. Saleem. "Effects of induced magnetic field and homogeneous–heterogeneous reactions on stagnation flow of a Casson fluid." *Engineering Science and Technology, an International Journal* 19.2 (2016): 875-887.

[88] Khan, W. A., Z. H. Khan, and Rizwan Ul Haq. "Flow and heat transfer of ferrofluids over a flat plate with uniform heat flux." *The European Physical Journal Plus* 130.4 (2015): 1-10.

[89]Hussein, Ahmed Kadhim, et al. "Lattice Boltzmann simulation of natural convection heat transfer in an open enclosure filled with Cu–water nanofluid in a presence of magnetic field." *Nuclear Engineering and Design* 268 (2014): 10-17.

[90] Gui, N. Gan Jia, et al. "Ferrofluids for heat transfer enhancement under an external magnetic field." *International Journal of Heat and Mass Transfer* 123 (2018): 110-121.

[91] Ganguly, Ranjan, Swarnendu Sen, and Ishwar K. Puri. "Heat transfer augmentation using a magnetic fluid under the influence of a line dipole." *Journal of Magnetism and Magnetic Materials* 271.1 (2004): 63-73.

[92] Straughan, Brian. *The energy method, stability, and nonlinear convection*. Vol. 91. Springer Science & Business Media, 2013.

[93] Lalas, D. P., and S. Carmi. "Thermoconvective stability of ferrofluids." *The Physics of Fluids* 14.2 (1971): 436-438.

[94] Ramanathan, A., and N. Muchikel. "Effect of temperature-dependent viscosity on ferroconvection in a porous medium." *International Journal of Applied Mechanics and Engineering* 11.1 (2006): 93-104.

[95] Zablotsky, D., and E. Blums. "Pore-scale simulation of magnetosolutal microconvection in ferrofluid saturated porous structures." *Magnetohydrodynamics* 51.3 (2015): 249-254.

[96] Garmroodi, MR Daneshvar, et al. "Natural convection of a non-Newtonian ferrofluid in a porous elliptical enclosure in the presence of a non-uniform magnetic field." *Journal of Thermal Analysis and Calorimetry* 141.5 (2020): 2127-2143.

[97] Xuan, Yimin, and Qiang Li. "Investigation on convective heat transfer and flow features of nanofluids." *J. Heat transfer* 125.1 (2003): 151-155..

[98] Fotukian, S. M., and M. Nasr Esfahany. "Experimental study of turbulent convective heat transfer and pressure drop of dilute CuO/water nanofluid inside a circular tube." *International communications in heat and mass transfer* 37.2 (2010): 214-219.

[99] Heris, S. Zeinali, S. Gh Etemad, and M. Nasr Esfahany. "Experimental investigation of oxide nanofluids laminar flow convective heat transfer." *International communications in heat and mass transfer* 33.4 (2006): 529-535.

[100] Kayhani, M. H., et al. "Experimental study of convective heat transfer and pressure drop of TiO2/water nanofluid." *International Communications in Heat and Mass Transfer* 39.3 (2012): 456-462.

[101] Heidary, Hadi, Mohammad Jafar Kermani, and Bahram Dabir. "Magnetic field effect on convective heat transfer in corrugated flow channel." *Thermal Science* 21.5 (2017): 2105-2115.

[102] Maouassi, Ammar, et al. "Numerical study of nanofluid heat transfer SiO2 through a solar flat plate collector." *International Journal of Heat and Technology* 35.3 (2017): 619-625.

[103Javaherdeh, Koroush, and Hamid Reza Ashorynejad. "Magnetic field effects on force convection flow of a nanofluid in a channel partially filled with porous media using Lattice Boltzmann Method." *Advanced Powder Technology* 25.2 (2014): 666-675.

[104] Nessab, W., et al. "Numerical investigation of ferrofluid jet flow and convective heat transfer under the influence of magnetic sources." *Applied Thermal Engineering* 150 (2019): 271-284.