**The Influence of the Alternating Magnetic Field on the Convective Heat Transfer
Properties of Fe₃O₄-containing Nanofluids through the Neel and Brownian Mechanisms**

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Abstract

In the current investigation, magnetite nanoparticles were prepared via solvothermal technique for further application as nanofluid in heat transfer studies. Various analytical techniques were used to fully characterize the nanoparticles and/ or nanofluids. The results showed that the heat transfer properties of the examined magnetite nanofluids based on various concentrations of water and ethylene glycol were significantly enhanced under the influence of an alternating magnetic field. These findings were rationalized by the use of hyperthermia principle base on which Neel and/ or Brownian mechanisms; corresponding to internal and/ or external frictions, respectively, may lead to heat generation, and then, the increase of the mean heat transfer coefficients.

Keywords: Heat transfer coefficient; Magnetic nanofluid; Hyperthermia; Neel relaxation; Brownian relaxation.

1. Introduction

Nowadays, the efficiency and reliability of various fluids in many industries, especially, power generation, transportation, and, micro-heating systems are considerably related to their heat transport properties. Since, conventional heat transfer fluids such as water, ethylene glycol and kerosene have shown finite heat transfer characteristics, and also, the use of some apparatus such as fins and the vibration of the heated surfaces have restricted many heat transfer applications [1-2], nanofluids were found to be good candidates for the replacement with the conventional fluids.

Recently, magnetic nanofluids have attracted many attentions because of having both magnetic and fluid properties. However, a few investigations on the heat transfer properties of the magnetic fluids have been reported [3-5].

Guo et al. [6] synthesized a stable magnetic nanofluid containing γ -Fe₂O₃ nanoparticles and investigated thermal transport properties of these kinds of materials. They observed remarkable convective heat transfer coefficients in a laminar flow regime. Hong et al. [7] studied the effect of magnetic field on thermal conductivities of a water-based nanofluid containing a physical mixture of carbon nanotubes and Fe₂O₃ nanoparticles. They speculated that the formation of aligned chains of Fe₂O₃ particles under the applied magnetic field connects carbon nanotubes to each other and then, leads to the enhancement of the thermal conductivity. In another investigation, Philip et al. [8] used a nanofluid consisting of a colloidal suspension of magnetite nanoparticles with an average diameter of 6.7 nm. They could control the linear aggregation length from nano- to micro-scales under the influence of the magnetic field. Afterwards, they

measured the thermal conductivity enhancements of the nanofluid at ca. 216% by using 4.5 vol. % of nanoparticles. Ganguly and co-workers [9] also numerically studied the heat transfer properties induced by several dipoles to identify the changes of the streamlines formed between two plates. In fact, they applied a two-dimensional magnetic field to evaluate the heat transfer properties of the ferrofluid.

According to literature [10-12], single-domain magnetic nanoparticles contain global magnetic moments which are along with thermal fluctuations under the influence of an external AC magnetic field. In fact, either the external rotations (Brownian mechanism) of the magnetic nanoparticles within the carrier fluid or the internal ones of the magnetic moments with respect to the crystal lattice (Neel mechanism) are responsible for these fluctuations. These internal and external sources of friction lead to a phase lag between the applied magnetic field and the direction of the particle's magnetic moments [13]. The magnetization relaxation occurs, when the magnetic field is removed, converting this magnetic energy to the thermal energy called hyperthermia [10-12]. The internal friction of magnetic moments inside the nanocrystals originates from anisotropy energy which orients the magnetic moments in easy axes, but, the external friction is highly-dependent to the viscosity of the carrier fluid, however, both mechanisms depend on the applied particles sizes [13]. According to literature [14], Neel relaxation is more pronounced for the nanofluid with the smaller particle sizes at higher frequencies of the magnetic field, but, in the case of Brownian relaxation, having the higher particle sizes is favored.

Although a few studies have investigated the external magnetic field, none of them has been concentrated on the influence of the magnetic field on the convective heat transfer coefficients (h). Therefore, herein, we studied the effect of an external AC magnetic field on the convective

heat transfer coefficients of magnetite nanofluids with different viscosities, basing on the hyperthermia principle.

2. Experimental

All the chemicals were purchased from Merck and used as received. A solvothermal technique was applied to synthesize the Fe_3O_4 (magnetite) nanoparticles (see refs. for more details) [15-17]. Briefly, $\text{FeCl}_3 \cdot 6\text{H}_2\text{O}$ (0.454 g) was dissolved in 70 cc ethylene glycol (EG), followed by dissolving 3.6 g polyvinyl pyrrolidone. Afterwards, 2.3 g sodium acetate was added to the resulted solution under vigorous stirring. Then, the final solution was transferred to a 500 ml Teflon-lined autoclave and the reaction temperature was adjusted at 200°C . Finally, after around 16 h, the final product was filtered and dried in a vacuum oven at 90°C for 6 h.

The desired nanofluids were easily produced by a two-step method based on which the appropriate amounts of Fe_3O_4 nanoparticles were dispersed in the base fluid, followed by sonication. In the present study, 0.005 wt. % Fe_3O_4 in the base fluids of water and/ or EG was examined.

The experimental apparatus for the investigation of convective heat transfer properties is presented in Fig. 1a and b. In general, the experimental set-up consists of a test section made up of copper with an inner diameter of 8.65 mm and the tube length of 1.2 m, a pump supplied by a digital flow controller, a reservoir, a low-power sonicator, a cooling bath and 25 stators which establish the magnetic field. We inserted a switching key for all of the stators to control the field amplitude (H_0) and the configuration of the magnetic field. An electrical heating tape was used to heat up the test section during the experiment. Since, the only effect of sonication except the redispersing of nanoparticles may be attributed to the temperature increasing of the nanofluid;

we adjusted the temperature of the exit nanofluid from the reservoir by an ice-water bath, the same as the set point temperature of the inlet nanofluid to the test section.

In this research, the constant heat flux was considered to be ca. 100 W, and the test section was insulated thermally to minimize the heat loss from tube to the ambient. In addition to the inserting of two thermocouples in the middle of cross sections of tube for the inlet and outlet fluids of the test section, we soldered five thermocouples in the increments of 20 cm on the copper tube wall.

Fig. 1- a) The apparatus used in the examination of the forced convective heat transfer characteristics, b) a detailed schematic of the experimental apparatus, c) a stator for producing the magnetic field, d) the field lines produced by the stators.

To adjust the Re (Reynolds) number at around 730; i.e. laminar flow regime, we installed a digital flow controller connected to the pump. A circulating system was also used to preserve a constant temperature at the inlet part of the test section.

To calculate the convective heat transfer coefficient of the nanofluid, the measuring of the experimental heat flux (q''), the wall temperatures along the copper tube, the local bulk temperature of the fluid and the flow rate are required [18]. Then,

$$h(x) = \frac{q''}{T_s(x) - T_m(x)} \quad \text{Eq. (1)}$$

$$T_m(x) = T_{m,i} + \frac{q''P}{\dot{m}C_p} \quad \text{Eq. (2)}$$

in which, $T_m(x)$, $T_s(x)$ and $h(x)$ are locally, the bulk temperature of the fluid, the wall temperature of the tube and the heat transfer coefficient, respectively. According to literature [19-21], Equation (1) is applicable, when the flow is within the fully developed region. We observed a descending trend for the h variations of the water as the base fluid vs. the tube length, as it reached to a relatively constant value near the exit part of the tube. This observation is in a

good accordance with Li et al. [22]. According to them, for the tubes with a uniform heat flux boundary condition, thermal entrance length is dramatically reduced as a result of the superimposed natural convection. Thus, the fully developed regime is considered to be the sole concentration for most practical situations. Tahir et al. [23] also stated that the ratio of length to the diameter of 100 for the tube is sufficient for the flow to be fully developed (thermally and hydrodynamically) at the outlet. Therefore, since, in our case, $L/D=138$, the fully developed regime seems to be reasonable.

As reported in literature [21], the presence of nanoparticles affects the boundary layer development in pipe flows and then, heat transfer, but, since, in this work, the concentration of nanoparticles is very low, we observed the relatively same trend for the h variations along the tube.

Equation 2 is obtained on the basis of the energy balance with the assumption of zero heat loss through the insulation layer. To minimize the heat loss from the surface of the test section, in addition to the use of glass wool, we used several layers of insulating tapes, such that our calculations confirmed the heat loss deviation of around 10%. Furthermore, because of using the electrical heating tapes that directly located on the copper pipe, we expect a relatively uniform heat flux throughout the test section.

The uncertainties of the measurements are presented in Table 1. For instance, the uncertainty of the heat flux is equal to $\pm 3.8\%$ which means that the probable variations of the used heat flux (100 W) could be in the range of 100 ± 3.8 W. It should be taken into account that we adjusted the heat flux by the use of several ampere-meters and voltmeters to be sure about the accuracy of the measurements.

Table 1- The uncertainties during the measurements of the experimental parameters.

Variable	Uncertainty
Nanofluid inlet temperature	± 0.10 °C
Nanofluid outlet temperature	± 0.20 °C
Heat flux	± 3.80 %
Reynolds number	± 5.00 %
Convective heat transfer coefficient	± 4.10 %

In order to investigate the effect of an external magnetic field, a function generator with different modes of frequency up to MHz was applied. The used stators were able to produce a three-dimensional magnetic field perpendicular to the fluid's flow, as demonstrated in Fig. 1b and c. In Fig. 1c, we indicated a closed path for one of the field lines; however, all the lines have the same routes.

Transmission electron microscopy (TEM) images were obtained using a CM-FEG-Philips, supplied by an accelerating voltage of 120 keV to investigate the dispersion and the metal particle size of the magnetite nanoparticles. X-ray diffraction (XRD) with Cu K α radiation source (Philips PW-1840) was applied to study the crystalline phases of the catalysts. Also, to characterize the magnetic properties of the Fe₃O₄ nanoparticles, a Lake Shore (7400) vibrating sample magnetometer (VSM) was used. Since, the zeta potential has become an efficient evaluation technique for understanding the dispersion behavior of nano-particles in a liquid medium; a Malvern ZS analyzer (Malvern Instrument Inc, London, UK) was utilized.

3. Results and Discussion

3.1. TEM

Figs. 2a and b present TEM images of Fe_3O_4 nanoparticles synthesized via solvothermal method. These TEM photographs confirm that the synthesis technique leads to the formation of well-dispersed particles, mostly in the range of about 60-80 nm in accordance with the histogram implied in Fig. 2c. According to TEM images, it is found that any particle is composed of smaller particles.

Fig. 2- Transmission electron microscopy photographs of Fe_3O_4 nanoparticles (a and b) and the histogram of nanoparticles diameters of Fe_3O_4 (c).

Fig. 3 exhibits the distribution curve of zeta potential of magnetite nanoparticles. The larger absolute value of zeta potential leads to the higher particle concentration in the suspension, hence, more stable suspension is expected [24]. Studies to date have shown that the amount and the charge of nanoparticles in the nanofluid, and the interaction between the particles directly affect the stability of the suspension.

According to Fig. 3, the absolute zeta potential value of around 23 mV is found for the examined nanoparticles. This value confirms good stabilization of the nanoparticles due to the sufficient electrostatic repulsion, the same as what reported in literature [25].

To the best of our knowledge, in the presence of magnetic field, magnetic particles have various configurations in a liquid medium, depending on the nature of magnetic particles and the field

strength. According to literature [26], under a relatively strong magnetic field, small magnetic particles connect to each other as associated networks and orient toward the field direction, which in turn, more physical contacts between particles are expected. Therefore, when the nanofluid is in motion, under the influence of the magnetic field, the physical changes of the particles in configuration is more pronounced. Chang et al. [26] studied the effect of magnetic field on the nanoparticle suspension. They attributed the aggregation of nanoparticle to the activation of the surface atoms of the nanoparticles by the magnetic field. These atoms, which form a relatively large proportion of the nanoparticles, start to spin when activated. Any changes in the magnetic field strength lead to additional surface and interface effects, as a result of the change in electron energy levels. Therefore, some differences between the crystal field environment and bonding energy of the surface atoms of particles and internal atoms are occurred. Furthermore, many dangling bonds which have nonsaturated property form on the particle surface which in turn, make the particles to integrate and forms the larger clusters.

It is essential to note that under the strong magnetic field, zeta potential of nanofluid is lower than that influenced by weak magnetic field [27].

Fig. 3- The zeta potential curve of the water-based magnetite nanoparticles.

3.2. XRD

The x-ray diffraction pattern of Fe_3O_4 nanoparticles is exhibited in Fig. 4. According to this illustration, the crystallite planes of 220, 311, 400, 422, 511, 440, 620 and 622 are respectively corresponding to the Bragg angles of about 30.3° , 35.6° , 43.2° , 53.6° , 57.2° , 62.8° , 71.8° and 74.2° which obviously indicates the crystalline nature of Fe_3O_4 nanoparticles [28-30]. The average crystallite size of the magnetite nanoparticles prepared by Scherrer's equation [31] was found to be around 6 nm, which differs so much from those displayed in Fig. 2. This confirms that the Fe_3O_4 nanoparticles shown in Fig. 2 are composed of 6-nm nanoparticles, which finally form the magnetite clusters.

Fig. 4- X-ray diffraction pattern of Fe_3O_4 nanoparticles.

3.3. VSM

A field-dependent magnetization curve $M(H)$ at room temperature is displayed in Fig. 5. The saturation magnetization is found to be ca. 63.6 emu g^{-1} at room temperature, which is slightly smaller than the bulk value; i.e. 92 emu g^{-1} [15]. Since, there is negligible coercivity in the magnetization curve with no hysteresis loop; one may find that the Fe_3O_4 nanoparticles have superparamagnetic characteristics [32]. For such systems, the magnetic moments of the particles are free to rotate in response to any applied magnetic field [33]. Therefore, one may expect that the exposure of the resulting nanofluids to any external magnetic field leads to the formation of

aligned dipoles parallel to the applied field, and, then, the net magnetization in the absence of the external field is equal to zero [34-36].

According to literature [37], due to superparamagnetic nature of particles, the aggregation phenomenon is perfectly reversible. Also, the length of chains can be easily varied by changing the magnetic field strength. Also, these soft agglomerates may be easily broken up by sonication or by other means of fluid agitation [38].

Fig. 5- a) Field-dependent magnetization curve of magnetite nanoparticles at room temperature.

3.4. Heat transfer coefficient measurements

Fig. 6 implies the h variations of nanofluids with 0.005 wt. % Fe_3O_4 based on water and EG in different frequencies, while only half of the stators are connected. Fig. 5 confirms the positive effect of the higher frequencies on h enhancements. According to the figure, the h value of the water-based magnetite nanofluid is enhanced around 48%, where the field frequency varies from

50 Hz up to 1 MHz. Meanwhile, the enhancement is found to be ca. 15%, when in the same conditions, EG is inserted as the base fluid. The observed changes in the heat transfer properties indicate the considerable effect of the configuration of the magnetic field on the colloidal magnetic nanoparticles. The significant improvements of h could be explained by the hyperthermia phenomena, as stated previously. Because of the superparamagnetic characteristics of the magnetite nanoparticles, the existed magnetic moments could be oriented under the influence of the external AC magnetic field. As known, the relaxation of the magnetic moments occurs, when the AC magnetic field is removed. Therefore, higher frequencies result in more relaxation times in which the magnetic energy has more opportunity to convert to the thermal energy. Then, the presence of the AC magnetic field at higher frequencies leads to more heat generation, inferred from the internal frictions between magnetic moments; therefore, one may expect the increase of heat transfer coefficients at higher frequencies.

Fig. 6- The effect of magnetic field frequency (Maximum field amplitude=1500 A/m) on the h measurements of water- (right side) and EG-based (left side) magnetite nanofluids.

Fig. 7 illustrates the h values of the magnetite nanofluids (0.005 wt. % Fe_3O_4 nanoparticles) based on different volumetric contributions of water and EG. To achieve up to comparable results, first of all, we examined the base fluids. As shown in Fig. 7, a descending propensity of the h values is obtained, contrary to the trend of viscosity variations of the base fluids. For instance, the h values of 805 and 176 $\text{W/m}^2\cdot\text{K}$ belonged to the pure water and EG were obtained which are respectively corresponding to the viscosity values of 0.00105 and 0.01433 Kg/m.s . According to Fig. 7, due to the use of low-concentrated nanofluids, in the absence of the magnetic field, negligible enhancements of the h variations for the resulted nanofluids compared to the base fluids are expected. However, according to what implied in Fig. 7, one may observe a considerable improvement of h values in the presence of the external magnetic field (36 kA/m). In particular, in the case of nanofluids based on 25% EG+ 75% water and 50% EG+ 50% water which the enhancements are equal to ca. 118% and 97%, respectively.

In line with literature [10-14], this observation could be rationalized on the base of the hyperthermia principle. As stated before, higher field amplitudes lead to Brownian movements of the particles which are more pronounced than the rotation of magnetic moments. The main explanation for the above enhancements refers to the heat generation resulted from the external frictions of the particles. In fact, during relaxation time, as a result of the conversion of the magnetic energy to the thermal energy, heat generation occurs.

Fig. 7- The variations of viscosity and the h values of the base fluids and the effect of the magnetic field on the h variations of the magnetite nanofluids.

The effect of field amplitude on heat transfer properties of the magnetite nanofluid (0.005 wt. %) based on 25% EG+ 75% water at $f=300$ kHz is exhibited in Fig. 8. To increase the magnetic field amplitude, we decreased the number of connected stators two by two, because, as known, at the same applied voltage, the decrease of the number of resistances leads to the stronger magnetic field. The corresponding field amplitudes when decreasing the number of connected stators are presented in Table 2. According to this figure, one may find that the mean h values show a significant enhancement, when the magnetic field strength is augmented. For example, the h value is increased from 569 up to 702 W/m².K; i.e. around 23%, when H_0 is changed from 131 to 379 A/m, meanwhile, the h enhancement is found to be around 12%, followed by the augmentation of H_0 from 379 A/m up to 1260 A/m.

The enhancement may be explained by either the effect of the internal frictions as a result of the rotation of magnetic moments or the influence of the nanoparticle's external frictions as a result of the Brownian movements. As mentioned previously, these internal/ external sources of frictions lead to heat generation, when the relaxation of the magnetic moments/ nanoparticles is occurred.

Table 2- The effect of field amplitude by decreasing the connected stators on the heat transfer coefficient variations (1-25 shows that all of the stators are connected).

Connected stators	1-25	1-23	1-21	1-19	1-17	1-15	1-13	1-11	1-9	1-7	1-5	1-3	1
H_0 (A/m)	131	209	281	379	493	581	686	829	908	1022	1107	1175	1260
h (W/m ² .K)	569	598	678	702	734	739	744	763	771	779	784	786	789

Fig. 8- The effect of magnetic field amplitude on the h values of the magnetite nanofluid based on 25% EG+ 75% water ($f=300$ kHz).

3.5. Theoretical evaluations

To evaluate the approximation amounts of heat generation during relaxation, the calculation of the corresponding specific lost power (SLP) is required. The SLP values are obtained by the following theoretical equations [12, 39].

$$SLP = \frac{P}{\rho\phi} = \frac{\mu_0\chi_0 H_0^2}{2\rho\phi} \omega \frac{\omega\tau}{1 + (\omega\tau)^2} \quad \text{Eq. (2)}$$

where P assigns to the lost power, and ρ and ϕ are respectively the density and volume fraction of the magnetite nanoparticles. In Eq. (2), $\mu_0=4\pi\times 10^{-7}$ V.s.A⁻¹.m⁻¹ stands for permeability of vacuum and $\omega=2\pi f$ in which f points to the magnetic field frequency. Also, τ and H_0 denote the relaxation time and the field amplitude, correspondingly. The equilibrium susceptibility, χ_0 , is given by the following equation.

$$\chi_0 = \frac{\mu_0 M_s^2 \phi V}{k_B T} \times \left(\frac{\coth \xi - \frac{1}{\xi}}{\xi} \right) \quad \text{Eq. (3)}$$

in which ξ is defined as

$$\xi = \frac{\mu_0 M_s H_0 V}{k_B T} \quad \text{Eq. (4)}$$

The following expressions show the Neel relaxation time (Eq. (5)) and the one of the Brownian (Eq. (6)) in which τ_N and τ_B are respectively indicative of the Neel and Brownian relaxation times.

$$\tau_N = \tau_0 \exp \left[\frac{KV}{k_B T} \right], \tau_0 \sim 10^{-9} \text{ s} \quad \text{Eq. (5)}$$

In above equations, K presents the shape anisotropy constant which is $1.1 \times 10^4 \text{ J/m}^3$ for the magnetite nanoparticles, V is the particle volume based on the crystallite sizes (here, 6 nm), $k_B = 1.38 \times 10^{-23} \text{ J/K}$ and T respectively point out the Boltzmann constant and the absolute working temperature.

$$\tau_B = \frac{\pi \eta d_h^3}{2 k_B T} \quad \text{Eq. (6)}$$

in which, η is the viscosity of the carrier fluid and $d_h = 150 \text{ nm}$ stands for the hydrodynamic diameter of the particle.

Fig. 9 displays the calculated specific lost power (SLP) values generated by the magnetite nanofluids (including 0.005 wt.% Fe_3O_4 based on different mixtures of EG and water), when the field amplitude is varied. From Fig. 7, one may observe that the released SLP values are respectively more pronounced for the nanofluids based on 50% EG+ 50% water and 25% EG+ 75% water. As presented in Fig. 9, at $H_0 = 36 \text{ kA/m}$, the SLP are evaluated to be 222 and 212 W/g for the sample containing 50% EG+ 50% water and 25% EG+ 75% water, respectively, while it is decreased to 164 W/g for the nanofluid based on pure water. According to the rules governed by hyperthermia phenomena, at lower frequencies, the contribution of Brownian relaxation in the generated SLP is of great importance. Therefore, higher heat transfer coefficients for the nanofluids which generate higher SLPs, are expected, in good accordance with the results of Fig. 7.

Fig. 9- The effect of field amplitude on theoretical values of SLP for the magnetite nanofluids based on different mixtures of EG/ water ($f=50$ Hz).

In order to estimate the heat generation during relaxation times in the case of the results of Fig. 8, the theoretical calculation of SLPs is necessary. Fig. 10 shows the effect of magnetic field amplitude on SLPs at $f=300$ kHz. Based on what explained above, the generated heat is resulted from a combination of Neel and Brownian relaxations. The results of SLP at different field amplitudes are summarized in Table 1. Fig. 10 is plotted based on the presented data in Table 3. According to SLP calculations (Eq. 2), one may observe the significant effect of the magnetic field amplitude on SLP values. According to Table 1, the amounts of specific lost powers are obviously increased, when the field amplitude is augmented. However, both Neel and Brownian

mechanisms have effective contribution to supply thermal energy from the magnetic energy, as a conclusion of the use of high frequencies, the contribution of internal fluctuations in the amount of SLPs values are more significant. In general, the summation of the produced heat through various mechanisms, i.e. Neel and/ or Brownian mechanisms, leads to the enhancement of thermal properties of the applied nanofluids and then, the corresponding convective heat transfer coefficients, as shown in Fig. 8.

Table 3- The effect of field amplitude on the SLP values originated from Neel and/ or Brownian relaxations.

H_0 (A/m)	131	209	281	379	493	581	686	829	908	1022	1107	1175	1260
SLP ^a (W/g)	5.9	14.4	24.5	40.5	60.9	77.2	97.6	124.1	139.2	161.8	177.0	190.0	206.2
SLP ^b (W/g)	0.50	1.28	2.37	3.85	5.79	7.34	9.27	11.80	13.23	15.38	16.82	18.05	19.59

^aSLPs resulted from Neel relaxation mechanism

^bSLPs resulted from Brownian relaxation mechanism

Fig. 10- The effect of field amplitude on the SLP values resulted from Neel and Brownian relaxations for the magnetite nanofluid based on 25% EG+ 75% water ($f=300$ kHz).

According to the findings of the present study, however, the role of the magnetic field in the enhancement of heat transfer properties of the nanofluids are so noteworthy, but, some of its drawbacks are of great importance. As mentioned before, in the presence of magnetic field, magnetic particles begin to aggregate as larger particles. However, in the current investigation, due to superparamagnetic nature of particles, the aggregation phenomenon is perfectly reversible; then, these soft agglomerates may be broken up by simple agitation tools.

In this research, contrary to the use of strong magnetic fields, the change of field frequency seems not to apparently cause the particle agglomeration. Further investigations are required to fully investigate the effect of magnetic field and frequency on the surface charges of the nanoparticles and then, agglomeration of the particles.

4. Conclusions

Well-dispersed Fe_3O_4 nanoparticles were synthesized using a simple solvothermal method to prepare the nanofluids based on different mixtures of water and EG. According to TEM photographs, the average particles sizes were found to be around 75 nm, however, not only TEM images confirmed the formation of nanospheres by the agglomeration of smaller nanoparticles, but XRD also supported the presence of 6-nm nanocrystallites. Using VSM analysis, we found that the resulted nanocrystallites were superparamagnetic. Significant enhancements of heat transfer properties for the magnetite nanofluids were observed, when exposing an AC external magnetic field. The improved results were attributed to the heat generation resulted from the magnetic nanoparticles through Neel and/ or Brownian Mechanisms.

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