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Heat transfer enhancement with actuation of magnetic nanoparticles suspended in a base fluid

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In this study, we have experimentally demonstrated that heat transfer can be substantially increased by actuating magnetic nanoparticles inside a nanofluid. In order to materialize this, we have utilized a miniature heat transfer enhancement system based on the actuation of magnetic nanoparticles dispersed in a base fluid (water). This compact system consists of a pool filled with a nanofluid containing ferromagnetic nanoparticles, a heater, and two magnetic stirrers. The ferromagnetic particles within the pool were actuated with the magnetic stirrers. Single-phase heat transfer characteristics of the system were investigated at various fixed heat fluxes and were compared to those of stationary nanofluid (without magnetic stirring). The heat transfer enhancement realized by the circulation of ferromagnetic nanoparticles dispersed in a nanofluid was studied using the experimental setup. The temperatures were recorded from the readings of thin thermocouples, which were integrated to the heater surface. The surface temperatures were monitored against the input heat flux and data were processed to compare the heat transfer results of the configuration with magnetic stirrers to the heat transfer of the configuration without the magnetic stirrers. © *2012 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4752729]

I. INTRODUCTION

Most of the micro/nanodevices tend to shrink in size while the escalation in their power densities increases every day. This trend speaks to an urgent need for heat transfer enhancement because these devices have applications in many important areas including electronics, microreactors, micropropulsion, biotechnology, fuel cells and air conditioning, as well as in new emerging areas such as heat-assisted magnetic recording (HAMR)[1,2] and the cooling mechanisms required in future thermophotovoltaic cells based on near-field radiative heat transfer principles.[3–9] In order to keep up with the miniaturization process, heat transfer and fluid flow at the micro and nanoscales have been rigorously studied in the literature to achieve higher heat removal capabilities. Such heat transfer experiments have focused mainly on three techniques: utilization of porous-layer coatings, nanofluids, and nanostructures.

Heat transfer surfaces have been treated with porous-layer coatings for the enhancement of pool boiling[10,11] and, recently, nanostructured surfaces have been utilized to achieve high heat transfer performance with enhanced heat transfer area and positive effect on heat transfer coefficients with diminishing length scale.[12,13] Moreover, nanostructures and porous layer coatings also provide additional active nucleate sites so that they promote nucleate heat transfer in boiling. Similarly, micro-machined structures have also been studied to enhance heat transfer from surfaces in pool boiling.[14,15]

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Nanofluids can be considered to be the next-generation heat transfer fluids as they offer exciting new possibilities to enhance heat transfer performance compared to pure liquids.[16] Nanofluids have been used in various studies to enhance convective heat transfer. It was observed that random movement (Brownian motion) of the nanoparticles and thermophoresis augment the energy transport process[17] significantly when there is no bulk fluid motion. Nanofluids have been usually used for the deposition of nanoparticles on pool surfaces to promote heat transfer by creating roughness and active nucleate sites.[18–24] Different from the state of art, nanofluids containing magnetic nanoparticles are utilized in this study to remove heat from excessive heat generating surfaces. Magnetic nanoparticles are actuated and utilized as heat transporters so that the system can be operated more effectively.

The actuation of nanofluids containing magnetic nanoparticles has been recently investigated in the literature.[25–30] Such fluids were used to design various pumps that do not contaminate the running fluid. Highly controllable nanofluid flows on the order of tens of microliters per second were achieved.[25–28] Motivated by the results in the above mentioned studies, the aim of this paper is to propose a magnetic nanofluid actuation for microscale thermal management applications. Pioneering experiments were conducted and surface temperatures were obtained from a miniature pool containing nanofluid actuated by magnetic stirrers. The potential for such compact pool systems in the use of microscale cooling applications was exploited, and an average heat transfer enhancement of 37.5% was obtained.

II. OVERVIEW ON NANOFLUIDS AND THEIR PREPARATION TECHNIQUES

Nanofluids are fluids with suspended nanoparticles of nanometer-size and different chemistry (metals, oxides, carbides, nitrides, or nanotubes). It is widely known that iron oxide (Fe_3O_4), the dominant magnetic material, magnetite, in magnetic fluid preparations, can be synthesized through the coprecipitation of Fe (II) and Fe (III) salts by the addition of a base.[31] Such nanofluids can be actuated by the application of a magnetic field. The actuation of these ferromagnetic nanoparticles drives its base liquid's molecules along so that a flow is generated. Motivated by this potential, a nanofluid sample was prepared, namely lauric acid bilayer (LA) coated super paramagnetic iron oxide (SPIO-LA).[32]

Nanoparticles of SPIO were coated with lauric acid to prevent aggregation of the nanoparticles and to decrease the viscosity of the nanofluid, which facilitates the motion of the nanoparticles inside the liquid. Lauric acid coating also contributes to the long term stability of the nanofluid. The sizes of the ferromagnetic nanoparticles in the sample SPIO-LA are 20–30 nm. This refers to the hydrodynamic size in water measured by dynamic light scattering (DLS) and reported as a numerical average, while the volume fraction of the prepared nanofluid is measured as 7.5%. Nanoparticle size was optimized for preventing aggregation, which is a common problem in nanofluid suspensions. Previous studies have reported that heat transfer enhancement of a nanofluid increases with the volume fraction of nanoparticles.[33] Thus, volume fraction was chosen in such a way that the nanoparticle concentration is kept at a high level while maintaining the stability of the suspension. The surface temperature was also kept below the saturation temperature in order to prevent any potential nanoparticle deposition on the heated surface, which is extensively reported in the literature.[34,35] These aqueous super paramagnetic iron oxide nanoparticles (SPIONs) are colloidally stable. They sat well-dispersed in the aqueous medium for over a year. Besides, their hydrodynamic sizes measured by DLS on the day of the synthesis and after 9 months indicate no significant change over time again indicating stability and no aggregation (Fig. 1). Their response to external magnet does not change either.

In order to prepare the nanofluid, 45 ml of distilled water was put into a 100 ml three-necked round bottom flask fitted with a mechanical stirrer and a condenser and was deoxygenated for 30 min. 2.162 g $FeCl_3.6H_2O$, 0.795 g $FeCl_2.4H_2O$ and LA were added to the flask and stirred at 400 rpm under nitrogen for about 15 min. The reaction flask was placed into an oil bath at 85 °C. After 10 min of mixing, 7 ml ammonium hydroxide was injected into the flask with vigorous stirring at 600 rpm. The reaction was allowed to continue for 30 min to produce a stable colloidal solution, then cooled to room temperature and placed atop a magnet (0.3 T) for a few hours. Any precipitate was removed with magnetic decantation. Usually, there are no precipitates. Final ferrofluid has 29 mg Fe/l.

III. EXPERIMENTAL SETUP AND PROCEDURE

The experimental setup is demonstrated in Fig. 2. The pool has an outside diameter of 31.8 mm, an inside diameter of 25.8 mm, and a height of 12 mm (Fig. 2(a)). The pool is made of aluminum for its machinability and high thermal

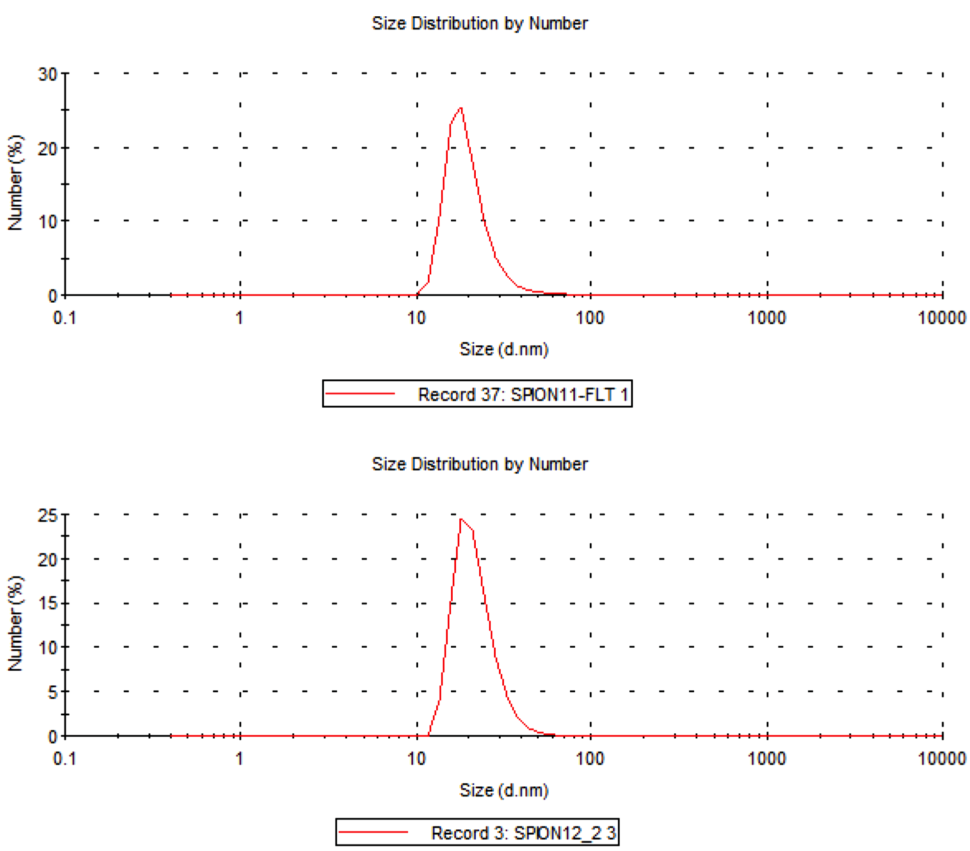

FIG. 1. (a) Nanoparticle size distribution by number after preparation and (b) after 9 months.

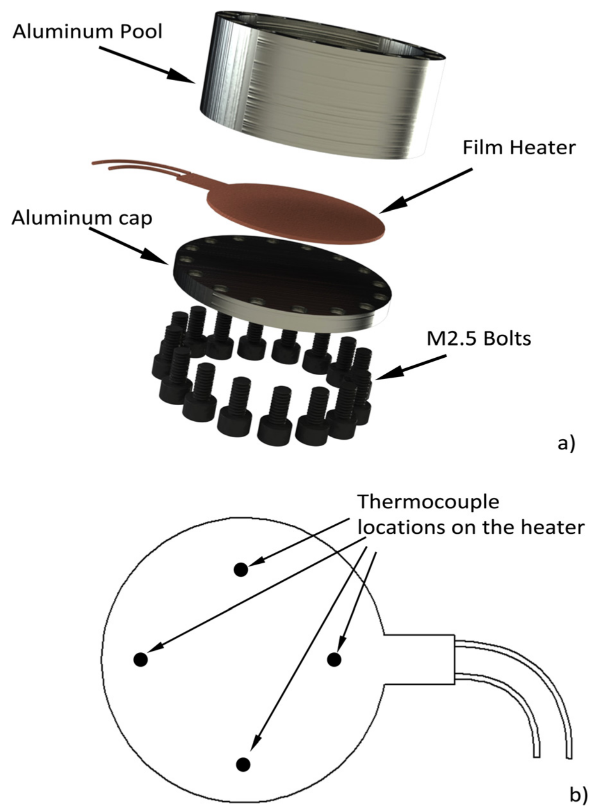

FIG. 2. (a) Pool boiling device and thermocouples (b).

conductivity. A miniature film-heater is placed underneath the pool in order to simulate unwanted heat generated by any device. The heater is treated with high quality thermal grease and sealed to the base with an aluminum cap through 16 M2.5 bolts. The whole setup is carefully insulated with glass wool sheets and placed between two magnetic stirrers (Fig. 3). The magnetic stirrers have a motor, on which two permanent magnets are placed. One of the magnetic stirrers is powered so that both magnetic stirrers rotate in unison. The magnetic stirrers generate a rotating magnetic field which is intensified in the middle of the pool. The heat generated by the miniature film-heater is delivered to the pool containing the liquid. It provides constant heat flux to the system since constant voltage is applied from the ends of the film heater. The pool is filled with nanofluid and surface temperatures are obtained along with constant heat fluxes applied to the system. Thermocouples are placed on the surface of the heater and in the bulk fluid at prescribed locations for accurate measurement of the bulk fluid and surface temperatures (Fig. 2(b)). Data are gathered through data acquisition system (NI-SCXI 1000). Data acquisition system records 100 data points per second at a 100 Hz sampling rate. These data points are then exported through data acquisition software LABVIEW for further reduction via MS Visual Studio and MATLAB software.

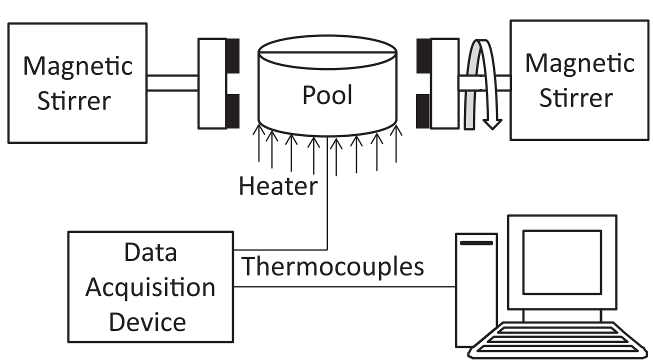

FIG. 3. Experimental setup.

After the experimental setup is prepared as explained, the rise in temperatures is obtained as a function of the input voltage and current data gathered from the readings of the power supply. The effective area of the pool surface and the power input is used to analytically calculate the constant heat flux input to the system. At certain values of the constant heat flux, steady state surface temperatures are recorded by the thermocouples until the nanofluid started to boil. For each constant heat flux, a minimum of 5000 data points have been averaged to account for possible errors. The pool is filled with the nanofluid and two separate experiments are conducted, one with the magnetic stirrers on and one with the magnetic stirrers off to emphasize on the positive effects of the magnetic stirrer. The magnetic flux densities of the two magnets attached to the motor of the magnetic stirrer are determined using a magnetometer. The magnetic flux densities were found to be 116.6 mT on the surface of the magnets and 28.4 mT in the middle of the pool. The magnetic stirrers were rotated at 30 rpm.

The power input to the system, P, is calculated from

$$P = VI, \tag{1}$$

where V is the measured voltage input and I is the measured total current passing through the system. The constant heat flux input, q'', to the system is obtained from

$$q'' = \frac{P - Q_{loss}}{A}, \tag{2}$$

where P is the power input, Q_{loss} is the thermal and electrical power loss, and A is the effective area of the pool surface. The surface temperatures are reduced by considering the thermal contact resistance from the thermocouples to the surface of the pool

$$T_s = T_{th} - qR_{tot}, \tag{3}$$

where T_{th} is the averaged thermocouple readings placed at the prescribed locations (Fig. 1(b)) and R_{tot} is the total thermal resistance from the thermocouples to the surface of the pool. Total thermal resistance from the thermocouples to the surface of the pool is calculated by addition of individual thermal resistances, R_{al} and R_{tg}, which are the thermal resistance of the aluminum block and the thermal resistance of the thermal grease, respectively. Individual thermal resistances are calculated by dividing the thickness of the material, t, by the thermal conductivity of the material, k, as follows:

$$R_{tot} = R_{al} + R_{tg} = \frac{t_{al}}{k_{al}A} + \frac{t_{tg}}{k_{tg}A}. \tag{4}$$

TABLE I. Uncertainty figures in data.

Uncertainty	Error
Thermocouple reading, T_{th}	$\pm 0.1\,°C$
Surface temperature, T_s	$\pm 0.15\,°C$
Power	1%
Area	0.5%
Heat transfer coefficient	1.4%

Heat transfer coefficient, h, is extracted from the following expression:

$$h = \frac{q''}{T_s - T_i}, \tag{5}$$

where T_i is the ambient temperature.

Moreover, an order of magnitude analysis to estimate the relative importance of possible nanoparticle transport mechanisms (thermophoresis, Brownian motion) was carried out by computing the time a nanoparticle takes to diffuse along a length equal to its diameter using the formulations provided by Buongiorno.[36] Accordingly, thermophoresis diffusion time is calculated as

$$t_T = \frac{d}{0.26\dfrac{k}{2k + k_p}\dfrac{\mu}{\rho}\dfrac{\nabla T}{T}}, \tag{6}$$

where d is the average nanoparticle diameter, k and k_p are the thermal conductivities of the fluid and the nanoparticles, respectively, μ is the viscosity and ρ is the density of the fluid, ∇T is the temperature gradient across the nanofluid, and T is the temperature of the fluid. Magnetic actuation diffusion time is found based on the flow rates in the previous studies of the authors[29] performed under similar experimental conditions and magnetic fields. Brownian motion diffusion time is expressed as

$$t_B = \frac{3\pi\mu d^3}{k_B T}, \tag{7}$$

where k_B is the Boltzmann constant.

The uncertainties of the measured values are given in Table I and are derived from the manufacturers specification sheet, while the uncertainties of the derived parameters are obtained using the propagation of uncertainty method developed by Kline and McClintock.[37]

IV. RESULTS AND DISCUSSION

The results are obtained from the experiments as explained in the previous section. Surface temperature data were plotted against heat flux values in Figure 4. It can be observed that the use of magnetically activated nanofluid increases the heat removal rate from the system. The surface temperatures have a linear trend with heat flux. The slope of the surface temperature trendline without magnetic stirrer is steeper than the slope of the surface temperature trendline with the magnetic stirrer. Thus, heat removal is promoted with the introduction of the nanofluid with ferromagnetic particles subject to the rotating magnetic field generated by the magnetic stirrers. Moreover, the nanofluid experiences more mixing, which increases convection from the surface due to applied rotating magnetic field (Fig. 5). The iron oxide nanoparticles motion near the surface and their contact with the heated surface contribute to heat transfer from the heated surface to the nanoparticles. As a result, the magnetic nanoparticles act as heat carriers, absorb more heat from the surface of the plate (Fig. 5), and release that heat to the bulk fluid which further enhances heat transfer and results in lower surface temperatures at a fixed heat flux with magnetic stirring.

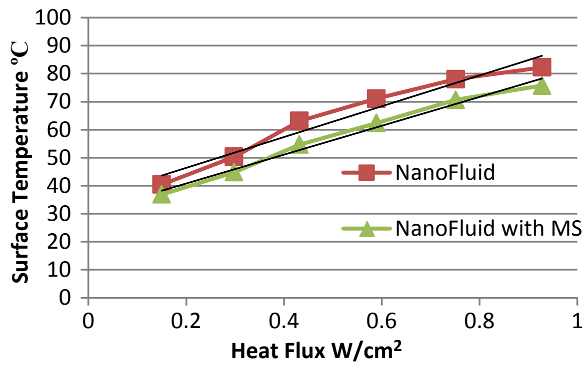

FIG. 4. Heat flux vs. surface temperature.

Heat transfer coefficients were calculated and plotted with heat flux in Figure 6. Heat transfer coefficients higher than 200 W/m^2K were realized for the nanofluid rotated with magnetic stirrers, while heat transfer coefficients could not exceed 200 W/m^2K without the effect of magnetic stirrers. To better emphasize on the enhancement due to the rotating magnetic field, the ratios of heat transfer coefficients of the configuration without magnetic stirrers to heat transfer coefficients of the configuration with magnetic stirrers were displayed for each heat flux value in Figure 7. The enhancements realized with the effect of magnetic stirrers are well above 15%. However, a decrease in the enhancement of heat transfer at elevated heat fluxes could be observed from the graph. To understand this, the overall heat transfer from the surface to the bulk fluid is considered as the additive effect of convection and magnetic stirring. Magnetic stirring enhancement is more significant at lower heat fluxes since convection contribution to the overall heat transfer is relatively less due to the increased viscosity of the fluid at lower temperatures. When the temperature of the fluid increases, the viscosity decreases,

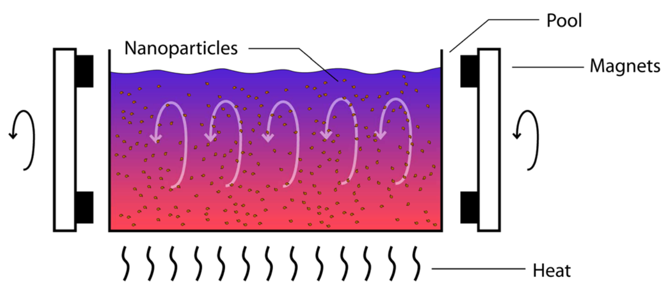

FIG. 5. Heat transfer enhancement mechanism.

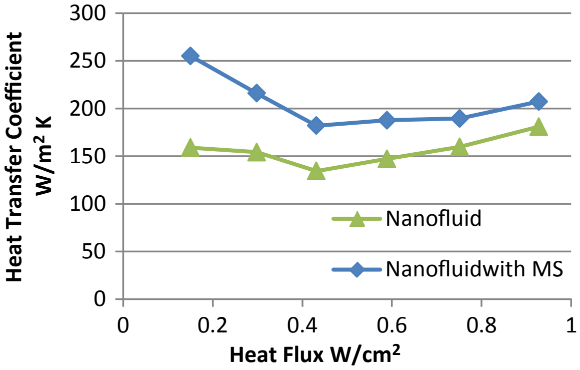

FIG. 6. Heat transfer coefficient vs. heat flux.

which contributes more to the convective heat transfer within the pool. Thus, assuming magnetic stirring mixing is less affected by the viscosity change compared to convection, the enhancement ratio decreases at higher heat fluxes. As a result, magnetic stirring is able to actuate the nanofluid within the pool even at lower temperatures and higher viscosities thereby augmenting the overall heat transfer.

Various researchers have shown that, in general, nanofluids offer better heat transfer characteristics compared to their base fluids.[16,38–40] In the absence of bulk fluid flow, it has been shown that the Brownian diffusion (the random motion of nanoparticles within the base fluid) which results from continuous collision between nanoparticles and the molecules of the base fluid and thermophoresis (diffusion of particles under the effect of a temperature gradient) greatly contribute to heat transfer enhancement in nanofluids.[36,41] In addition to these heat transfer mechanisms, the vibrating and rotating nanoparticles, due to rotating magnetic field, result in an enhanced heat removal from the surface of the pool. In the authors' previous studies,[25–28] it was shown that flow velocities greater than 1 cm/s were achievable in mini/micro scale at decent magnetic fields (~0.3 mT), which are close to those in the current study. An order of magnitude analysis to estimate the relative importance of a certain nanoparticle transport mechanism was carried out by computing the time a nanoparticle takes to diffuse along a length equal to its diameter using the formulations provided by Buongiorno.[36] Accordingly, the average nanoparticle diameter, d, the thermal conductivities of the base fluid and the nanoparticles, k and k_p, the viscosity of the nanofluid, μ, the density of the nanofluid, ρ, the temperature gradient across the nanofluid, ∇T, and the temperature of the nanofluid, T, were taken as 25 nm, 0.6 W/mK, 5 W/mK, 0.5×10^{-3} Ns/m^2, 1100 kg/m^3, 10^3 K/m, and 320 K as representative values, respectively. The results suggest that it takes 0.7 s with thermophoresis (Eq. (6)), 1.67×10^{-5} s with Brownian motion (Eq. (7)), and 1.25×10^{-6} s with the magnetic field actuation (based on the experimental results of the previous studies of the authors,[29] $v \sim 2$ cm/s) to diffuse along a length of the particle's diameter. This clearly proves the existence of additional contribution of the magnetic actuation of nanoparticles to heat transfer.

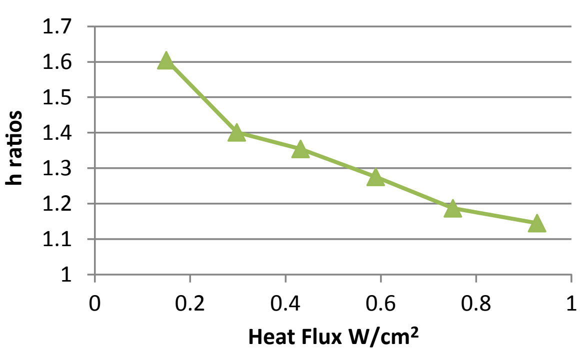

FIG. 7. Heat transfer enhancement ratio.

V. CONCLUSION

In this study, it was experimentally shown that ferromagnetic nanoparticles could be actuated inside a nanofluid with the application of rotating magnetic fields. This actuation was in the form of circulations, which were generated by active ferromagnetic particles within the liquid. The resulting flow enhanced the cooling capabilities of the system. The mechanism could be explained by the utilization of nanoparticles as heat transporters from the surface of the pool to the bulk fluid along with the circulation created within the pool by magnetic field, even at low temperatures. The results gathered from the experiments indicate the advantageous effects of magnetic nanofluid actuation (using ferromagnetic particles integrated with magnetic stirrer) on heat transfer magnification and flow circulation. An average heat transfer coefficient enhancement of 37.5% was achieved with magnetic actuation. In addition, this enhancement was achieved with 5 W of additional power consumption, which ensures that the proposed method could be further exploited to achieve higher energy efficiency. Using experimental results, further investigations, and models, nanofluids of ferromagnetic particles can be utilized in various cooling applications in the fields of electronics, microreactors, micropropulsion, biotechnology, fuel cells, air conditioning, heat assisted magnetic recording, and thermophotovoltaic cells.

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