CFD Investigation of Gravitational Sedimentation Effect on Heat Transfer of a Nano-Ferrofluid

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ABSTRACT: *In the present attempt, flow behavior and thermal convection of one type of nanofluids in a disc geometry was investigated using Computational Fluid Dynamics (CFD). Influence of gravity induced sedimentation also has been studied. The commercial software, Fluent 6.2, has been employed to solve the governing equations. A user defined function was added to apply a uniform external magnetic field. Obtained results showed that the critical value for Rayleigh number is near 1708, so simulations are in good agreement with the theoretical value for critical Rayleigh number. In addition, it was found that gravity causes separation of phases and sedimentation of nanoparticles, besides, increase in natural convection due to presence of gravity, leads to heat transfer enhancement. In addition, results indicate that, thermal forces are able to disrupt agglomerates when ratio of thermal energy to dipole-dipole contact energy becomes more than unity.*

KEY WORDS: *CFD Simulation, Thermal convection, Heat transfer, Gravitational sedimentation, Nano-ferrofluid.*

INTRODUCTION

Nanofluids are produced by adding only a small amount of nanoparticles or nanotubes into a fluid [1]. It has been shown that in the presence of nanoparticles the heat transfer of the base fluid increases. Although with increasing the nanoparticles concentration pressure drop enhances, by moderating the volume fraction of nanoparticles we can shortening the pressure drop and maximizing the heat transfer [2]. Another factor for having better heat transfer is to use convenient nanoparticles [3]. Nano-ferrofluids are one type of nanofluids which are suspension of magnetic nanoparticles in a carrier liquid such as water or kerosene [4]. In the presence of an external magnetic field, a ferrofluid is magnetized as the particles align with the magnetic field [5]. Therefore, they have a wide range of potential application in biomedicine and technology. The advantage of the ferrofluids is that the fluid flow and heat transfer can be controlled by an external magnetic field.

As *Keblinski et al.* [6] illustrated that various factors affect the heat transfer capability of nanofluids such as: Brownian motion of nanoparticles; molecular-level layering of the liquid at the nanoparticle surface; nature of heat transfer in nanoparticles; and the effects of nanoparticles’ clustering. In nano-ferrofluids transfer of particles in the presence of temperature gradients and magnetic fields [7], and settling of particles and their aggregates [8] lead to heterogeneity of the fluid. High surface energy of a nanofluid causes the coagulation

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of nanoparticles; therefore, dispersion of nanoparticles in the base fluid is not easy. Therefore, it is important to control the coagulation of nanoparticles and it necessitates investigation of dispersion and stability of nanoparticles in order to exploit their potential benefits and applications [9]. The colloidal instability is one of the biggest problems that makes commercial use of nanofluids difficult. Aggregated nanoparticles instigate sedimentation which lead to non-homogenous dispersion of particles. Sedimentation phenomena affect the distribution of particles concentration in the flow and based on observation of *Sarimeseli & Kelbaliyev* [10], it leads to formation of non-symmetric layer of sedimented particles on the wall of a horizontal channel. In the midst of a sedimenting suspension, regions with particle's density higher than the average will constantly be formed and destroyed [11].

Several numerical and experimental studies have been carried out to investigate effectiveness of nano-ferrofluids on the heat transfer enhancement. *Finlayson* [12] was the first who studied thermomagnetic convection instability in the presence of homogeneous vertical magnetic field. *Aminfar et al.* [13-14] investigated the effect of magnetic field gradient on a magnetic fluid flowing in a vertical pipe. Their results illustrate that with negative gradient of magnetic field, Nu number increases. While the positive magnetic field gradient has an inverse effect. *Lajvardi et al.* [15] observed that in the absence of magnetic field, dispersion of Fe_3O_4 in water has no effect on heat transfer; therefore, magnetic field has a significant effect on heat transfer enhancement of nano-ferrofluids. Experimental study on force convection of ferrofluid through a copper tube demonstrates that the magnetic field had more effect on heat transfer enhancement at low Reynolds number [16]. In numerical studies, nano-ferrofluids usually are treated as a two-phase mixture of magnetic nanoparticles in a carrier phase; in this method, governing equations over the meshed control volume, is solved for each phase separately [17]. However, in small volume fraction of magnetic particles they can be assumed as a single phase [18]. CFD is a virtual modeling technique with powerful visualization capabilities. Engineers can evaluate the performance of different phenomenon using the computer with lower cost and time [19]. Numerical study of hydro-thermo properties of Fe_3O_4/water nano-ferrofluid flow through a rectangular duct indicated that applying a magnetic field prevents sedimentation of nanoparticles and increases the heat transfer [20].

As sedimentation of nanoparticles may affect the heat transfer behavior of nano-ferrofluids and stability of such fluids is an important property, the main objective of this work was to study the effect of gravitational sedimentation and aggregation on heat transfer of a kerosene based nano-ferrofluid using CFD technique.

THEORITICAL SECTION

Mathematical formulation

In the literature two approaches, single phase model and mixture method, have been applied to investigate the heat transfer characteristics of nanofluids. The first approach assumes that the continuum assumption is still valid for fluids with suspended nano size particles. The other approach uses a two-phase model for description of both the fluid and solid phases [21]. In this work in order to compare the effect of single phase approximation and mixture model on prediction of nano-ferrofluids' behavior, both methods were studied.

Single phase approximation

In this study, the nano-ferrofluid is assumed incompressible, and the conservation equations of mass, momentum and energy are as follow [18]:

$$\nabla . u = 0, \tag{1}$$

$$\rho_0 \left(\frac{\partial u}{\partial t} + u . \nabla u \right) = \tag{2}$$

$$-\nabla p + \rho(T) g + \mu \nabla^2 u + \mu_0 (M . \nabla) H + \frac{\mu_0}{2} \nabla \times (M \times H)$$

$$\left[\rho c_{V,H} - \mu_0 H . \left(\frac{\partial M}{\partial T} \right)_{V,H} \right] \left(\frac{\partial T}{\partial t} + u . \nabla T \right) + \tag{3}$$

$$\mu_0 T \left(\frac{\partial M}{\partial T} \right)_{V,H} . \frac{\partial H}{\partial t} = k \nabla^2 T + \mu \Phi$$

Properties of the magnetic fluid except density are assumed constant. The last term in Eq. (2) represents dissipative which is often neglected for stationary fields. Also the last term on the left hand side of Eq. (3) vanishes when stationary fields are applied and due to small velocities the viscous dissipation, $\mu\Phi$, may also be neglected [16]. By applying the Boussinesq approximation,

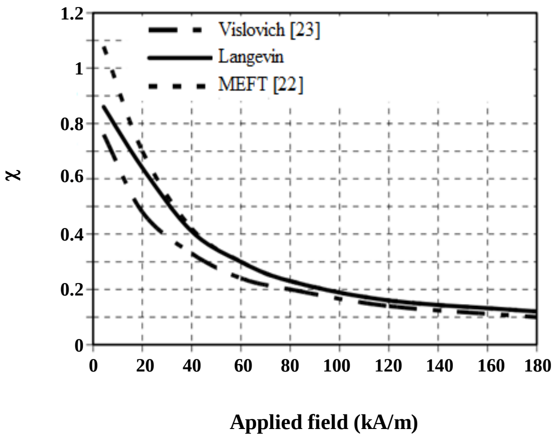

Fig. 1: Susceptibility of nano-ferrofluids versus applied magnetic field calculated using three different theories.

$\rho(T)=\rho_0\left[1-\beta(T-T_0)\right]$, for density variation in the buoyancy term and $M(T,H)=\chi H_0-\beta_m M_0(T-T_0)$ for magnetization, momentum and energy equations can be written as:

$$\rho_0\left(\frac{\partial u}{\partial t}+u.\nabla u\right)=-\nabla p+\rho_0\beta\left(T-T_0\right)g+ \tag{4}$$

$$\mu\nabla^2 u+\mu_0\beta_m M_0\left(T-T_0\right)\nabla H$$

$$\left(\frac{\partial T}{\partial t}+u.\nabla T\right)=\frac{k}{\rho c_{V,H}}\nabla^2 T \tag{5}$$

Subscript 0 represents initial conditions. The temperature dependence of β_m is:

$$\beta_m=-\frac{1}{M}\left(\frac{\partial M}{\partial T}\right) \tag{6}$$

Far from the Curie temperature and for strong fields the pyromagnetic coefficient of magnetic fluids is equal to thermal expansion coefficient [16].

Fig. 1 illustrates three different methods to calculate susceptibility. Deviation between different theories for prediction of χ is the largest at weak field strength. In order to find susceptibility in single-phase approximation and mixture model, the Modified variant of the Effective Field Theory (MEFT) [22] and Langevin theory were used, subsequently. Vislovich [23] is an approximate method, and this theory did not use in this study.

Mixture phase approximation

Mathematical formulation of two-phase mixture model is as follow [24]:

$$\frac{\partial}{\partial t}\left(\rho_m\right)+\nabla.\left(\rho_m u_m\right)=0 \tag{7}$$

$$\frac{\partial}{\partial t}\left(\rho_m u_m\right)+\nabla.\left(\rho_m u_m u_m\right)=-\nabla P_m+\mu_m\nabla^2 u_m- \tag{8}$$

$$\nabla.\left(\alpha_p\rho_p u_{MP}u_{MP}+\alpha_c\rho_c u_{Mc}u_{Mc}\right)+$$

$$\rho_m g+\alpha_p\frac{m}{V_p}L(\xi)\nabla H$$

$$\frac{\partial}{\partial t}\left(\rho_m c_{v,m}T\right)+\nabla.\left(\left(\alpha_p\rho_p u_P c_{p,p}+\alpha_c\rho_c u_c c_{p,c}\right)T\right) \tag{9}$$

$$=\nabla.\left(k_m\nabla T\right)$$

Subscripts m, p and c refer to mixture, magnetic particles and carrier fluid, respectively and $u_{im}=u_i-u_m$. The volume fraction equation for magnetic phase can be obtained:

$$\frac{\partial}{\partial t}\left(\alpha_p\rho_p\right)+\nabla.\left(\alpha_p\rho_p\left(u_m-u_{dr,p}\right)\right)=0 \tag{10}$$

The slip velocity is defined as:

$$u_s=u_p-u_c=\frac{m_p L(\xi)}{3\pi\mu_c d_p}\nabla H+\frac{d_p^2\left(\rho_p-\rho_c\right)}{18\pi\mu_c}g \tag{11}$$

Magnetic field calculation

Because of small conductivity of ferrofluids the Maxwell's equations can be defined as follow [25]:

$$\nabla.B=0 \tag{12}$$

$$\nabla\times H=0 \tag{13}$$

The magnetization vector, M, and the magntic field vector are related by the constitutive relation:

$$B=\mu_0(M+H) \tag{14}$$

Where μ_o is the magnetic permeability in vacuum. Magnetic scalar potentioal, $\varnothing_m$, is defined as:

$$H=-\nabla\phi_m \tag{15}$$

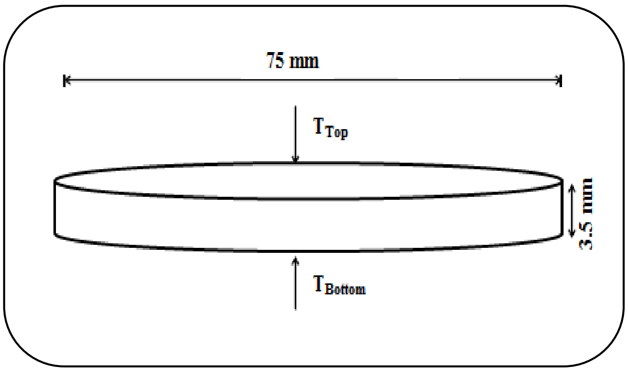

Fig. 2: Schematic of the geometry used in this study.

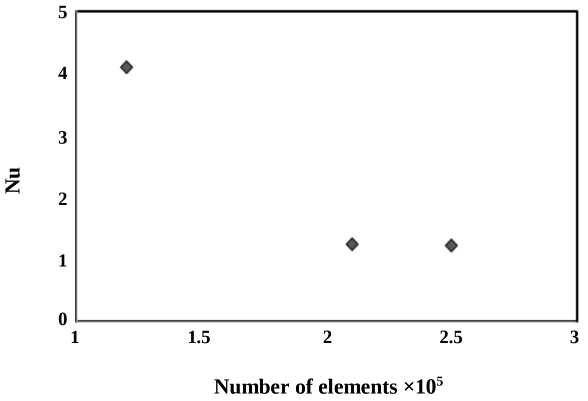

Fig. 3: Results of the grid independency check.

Using the maxwell's equations, the flux function for magnetic scalar potentioal, ø$_m$, can be written as:

$$\nabla.\left[\left(1+\frac{\partial M}{\partial H}\nabla\phi_m\right)\right]= \tag{16}$$

$$\nabla.\left[\left(\frac{\partial M}{\partial T}\left(T-T_0\right)+\frac{\partial M}{\partial \alpha_p}\left(\alpha_p-\alpha_{p0}\right)\right)\right]$$

Subscript 0 represent initial conditions. Within simulations $\frac{\partial M}{\partial H}=\chi$, $\frac{\partial M}{\partial T}=-\beta_m M_0$ and $\frac{\partial M}{\partial \alpha_p}$ are assumed to be constant and using Langevin equation they can be defined [25].

Numerical method

The geometry that is used in this study is a disc with a height and diameter 3.5 mm and 75 mm, respectively (Fig. 2). Commercial software, Gambit 2.2, was used to create the geometry and generate the grid.

In order to check that results are not grid dependent, a grid independency check has been conducted at temperature difference $\Delta T_{critical}$ = 25 K, nanoparticles diameter d = 5.5 nm and magnetic field M_s = 48 kA/m. As Fig. 3 shows, three different grids have been chosen and Nusselt number was considered to compare grids. Finally, the grid with 2.4×10^4 nodes and 2.1×10^5 mesh volume was used for all simulations.

Governing equations were solved using a commercial software, Fluent, and a User Defined Function (UDF) was added to apply a uniform external magnetic field parallel to the temperature gradient. By using UDF, it is possible to apply various features to the Fluent software. This work is done by introducing a C++ code included the factors that user wants. For instance user can apply various boundary conditions and magnetic fields by implementing a special code [25].

Constant temperature boundary conditions were applied for both bottom and top of the disc, and the sidewall was insulated. The solver specifications involve the presto for pressure and second-order upwind for momentum and energy in both single and mixture models. In addition, first-order upwind was used for the volume fraction in mixture model. Under-relaxation factors, which are significant parameters affecting the convergence of the numerical scheme, were set to 0.5 for the pressure, 0.7 for the momentum, and 0.5 for the volume fraction. Using mentioned values for the under-relaxation factors, a reasonable rate of convergence was achieved.

RESULTS AND DISCUSSION

A kerosene-based magnetic fluid with magnetization 48 kA/m, particle magnetic moment 2.5×10^{-19} Am^2, vacuum permeability $4\pi\times10^{-7}$ H/m and thermal expansion coefficient 0.0086 1/K was used in this study. Other properties are listed in Table 1.

The thermo convective motion of a nano-ferrofluid is investigated for different conditions of gravitational and magnetic Rayleigh numbers. Ra_g and Ra_m are dimensionless parameters which provide a measure of the thermal efficiency of the investigated heating system. Fig. 4 illustrates Nusselt number versus gravitational Rayleigh number in the absence of magnetic field and using single phase approximation. This figure corresponds to pure thermal convection and only temperature difference between top and bottom of

Table 1: Properties of the studied nono-ferrofluid (c and p illustrate continuous phase and nanoparticles, respectively.

Model					
Single		Mixture			
Property	Value	Property (c)	Value (c)	Property (p)	Value (p)
Thermal conductivity	0.22 W/mK	Thermal conductivity	0.149 W/mK	Thermal conductivity	1 W/mK
Dynamic viscosity	0.008 kg/ms	Dynamic viscosity	0.0024 kg/ms	Dynamic viscosity	0.03 kg/ms
Heat capacity at constant pressure	3259 J/kgK	Heat capacity at constant pressure	2090 J/kgK	Heat capacity at constant pressure	4000 J/kgK
Density	1250 kg/m^3	Density	1248-1.56×T kg/m^3	Density	5400 kg/m^3

the domain has been varied. In this case warm flow due to buoyancy forces goes up and cold flow comes down. In addition magnetic particles are transferring toward decreasing temperatures. Ra_g can be defined as:

$$Ra_g = \frac{g.\beta.\Delta T.\, l^3}{\upsilon.\, \alpha}, \tag{17}$$

Where l, υ, and α represent length of the disc, kinematic viscosity, and thermal diffusivity, respectively. As Fig. 4 depicts, the critical value for Rayleigh number is near 1708, so simulation results are in good agreement with theoretical value for critical Rayleigh number.

In order to study the influence of magnetic field on convection a series of simulations has been made for different magnetic Rayleigh numbers. Ra_m is a good criterion to characterize convection defined as follow:

$$Ra_m = \frac{\mu_0.\beta_0.M_0.\Delta T.l^3.\Delta H}{\rho.\, \upsilon.\, \alpha} \tag{18}$$

The presence of sufficiently strong magnetic field changes the structure of the flow. In Fig. 5 the Nusselt number as a function of magnetic Rayleigh number, Ra_m, using single phase approximation has been presented. Comparison of Figs. 4 and 5 shows that the heat transfer in the case of thermomagnetic convection is more efficient than in the case of pure natural convection. In addition, it was obtained that the critical magnetic Rayleigh number for the onset of convection is dramatically reduced as compared to the pure-fluid reference value or the field free system.

Fig. 6 represents the effect of gravity on heat transfer of the nano-ferrofluid using both single and two phase methods. As this figure shows for both methods in the presence of gravity because of natural convection the heat transfer will enhance. Simulations for the mixture model were performed at particles diameter 10 nm and solid volume fraction 0.1. There are few experimental data to validate the single phase approximation and two phase method. As the particle–liquid interaction and the movement between the particle and liquids play important roles in affecting the convective heat transfer performance of nanofluids, it seems that mixture method can better predict the behavior of such fluids. But some researchers deal with the nanofluids as single-phase fluid because it is much simpler and computationally more efficient.

Convection patterns of the magnetic fluid at ΔT=38 K, H=120 kA/m, and using single phase model at different times are shown in Fig. 7. Disordered convection rolls spontaneously appear and disappear. Similar behaviors have been observed experimentally [22]. Number of Rayleigh rolls depends on different parameters such as temperature difference and magnetic field strength and its direction. Any variation of these quantities can induce a change in behavior of the nanofluid.

The temperature oscillations recorded corresponded to Fig. 7 are presented in Fig. 8. As it is visible, temperature signals contains high and low frequency oscillations. As *Tynjälä* [18] showed using wavelet analysis, temperature signals are more evident.

In order to better illustration of gravity effect on heat transfer of the nano-ferrofluid, temperature contours in the presence and absence of gravity have been presented in Fig. 9. As this figure illustrates in the presence of gravity, the system is more non-uniform and sedimentation can occur.

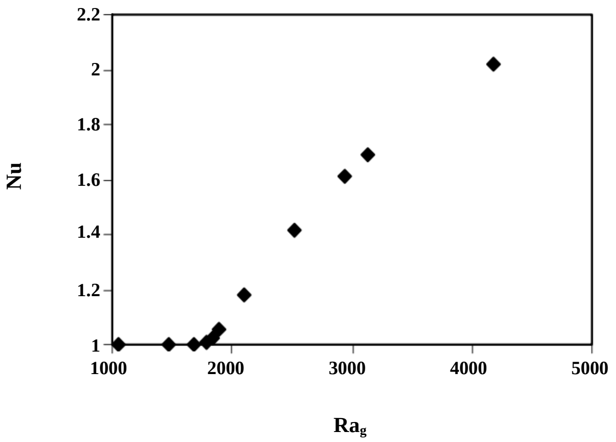

Fig. 4: Nusselt number versus gravitational Rayleigh number.

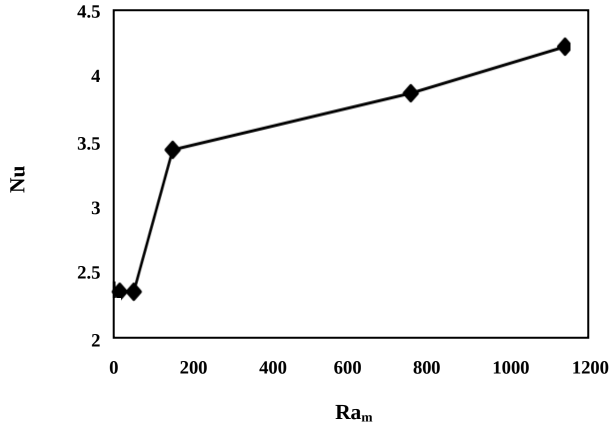

Fig. 5: Nusselt number versus magnetic Rayleigh number.

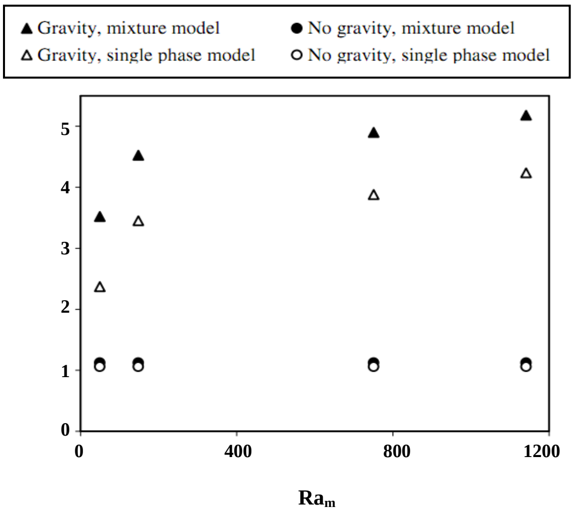

Fig. 6: Effect of gravity on Nusselt number using mixture and single phase methods.

Gravitation induces phase separation; therefore, it causes particle sedimentation within the nanofluid. In other words, there is an interaction between gravity and suspension-driven sedimentation. Sedimentation can damage the stability of the system, and then lead to oscillatory convection. This phenomenon will stop as phase equilibrium is approached. For nano-ferrofluids the following ratio can describe the relative influence of gravity to magnetism [15];

$$\frac{\text{Gravitational energy}}{\text{Magnetic energy}} = \frac{\Delta\rho g l}{\mu_0 M H} \qquad (19)$$

If the above ratio is sufficiently smaller than 1, therefore the gravity is less of a threat to sedimentation.

The presence of gravity sedimentation of particles causes the nano-ferrofluid to be more heterogeneous. Fig. 10 shows separation of phases because of gravity using the mixture model at ΔT=38K, and H=20 kA/m not only the nanoparticles move around, but also significantly large bodies of fluid around nanoparticles interact with each other, which leads to a strong micro convection.

Convection pattern and change of temperature on a plane at z=0.00175m when $T_{top}>T_{Bottom}$ and using single method are shown in Figs. 11 (a) and (b). Comparison of Fig. 11 with Figs. 7 and 8 illustrate that in the presence of buoyancy forces because of formation of rolls and circulation of the fluid in the system transport phenomena will improve. Similar treatment has been observed using mixture model [11].

CONCLUSIONS

Hydrodynamics behavior and thermomagnetic convection in a nano-ferrofluid has been studied using computational fluid dynamics. Results show that the critical value for Rayleigh number is near 1708, so simulation results are in good agreement with theoretical value for critical Rayleigh number. It was found that the heat transfer in the presence of thermomagnetic convection is more efficient than in the case of pure natural convection. In addition, it was obtained that for both mathematical models in the presence of gravity because of natural convection heat transfer will enhance.

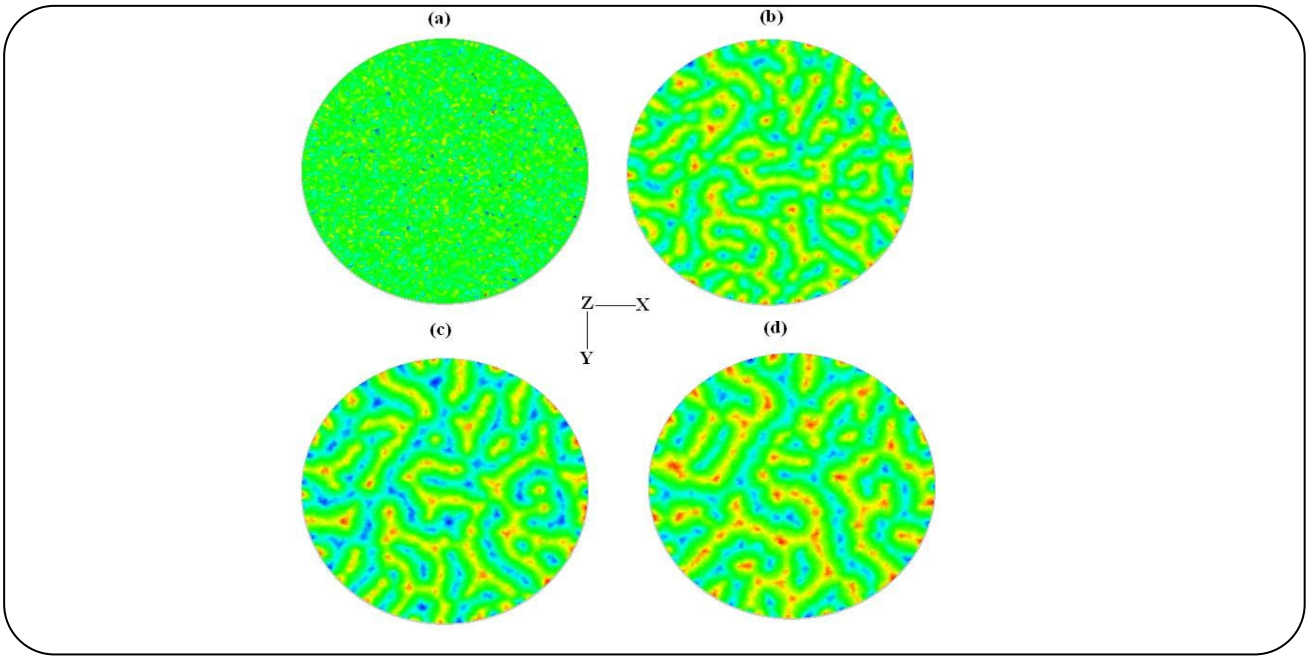

Fig. 7: Convection pattern in the nano-ferrofluid at different times on a plane at z=0.00175 m. (a) 1s, (b) 50 s, (c) 100 s, and (d) 200 s.

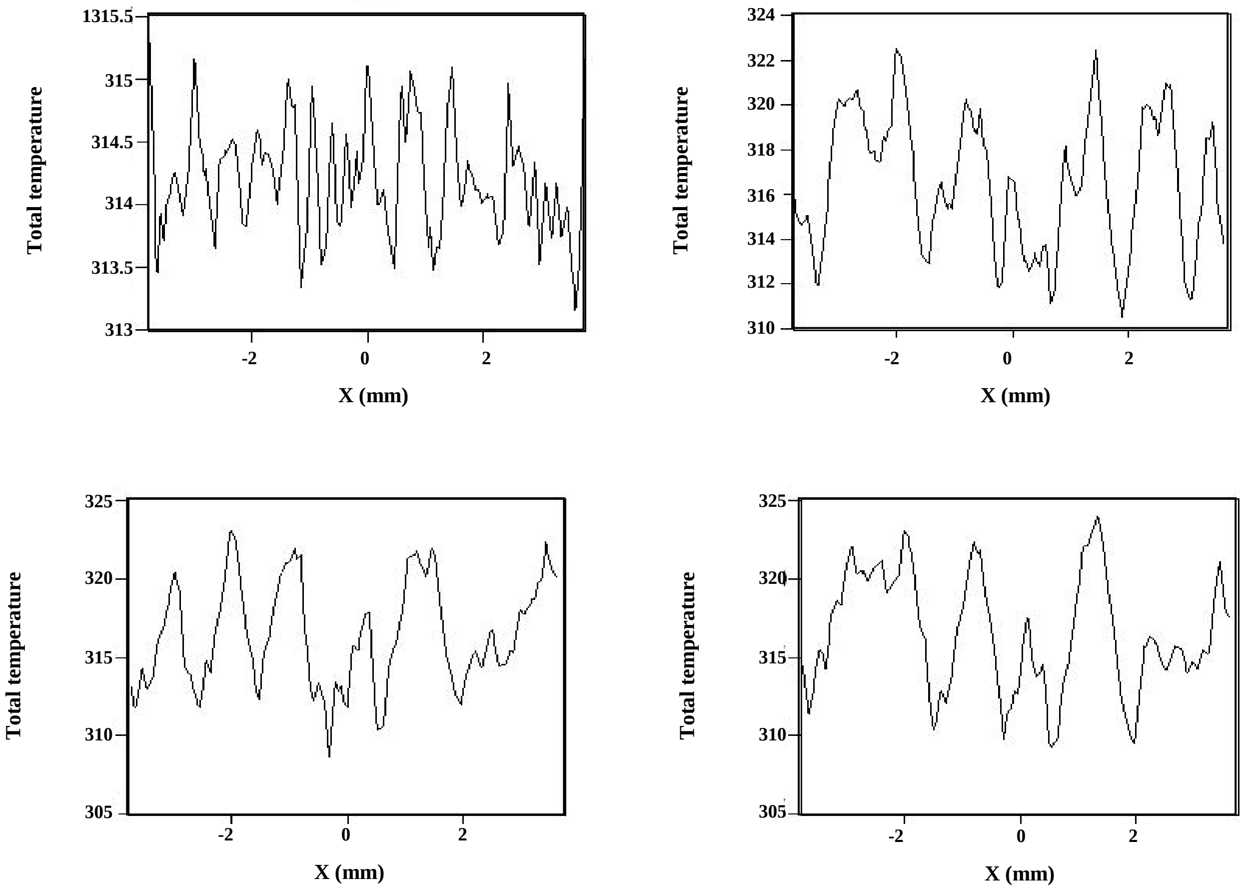

Fig. 8: Temperature oscillation of the nano-ferrofluid at different times on a plane at z=0.00175 m. (a) 1s, (b) 50 s, (c) 100 s, and (d) 200 s.

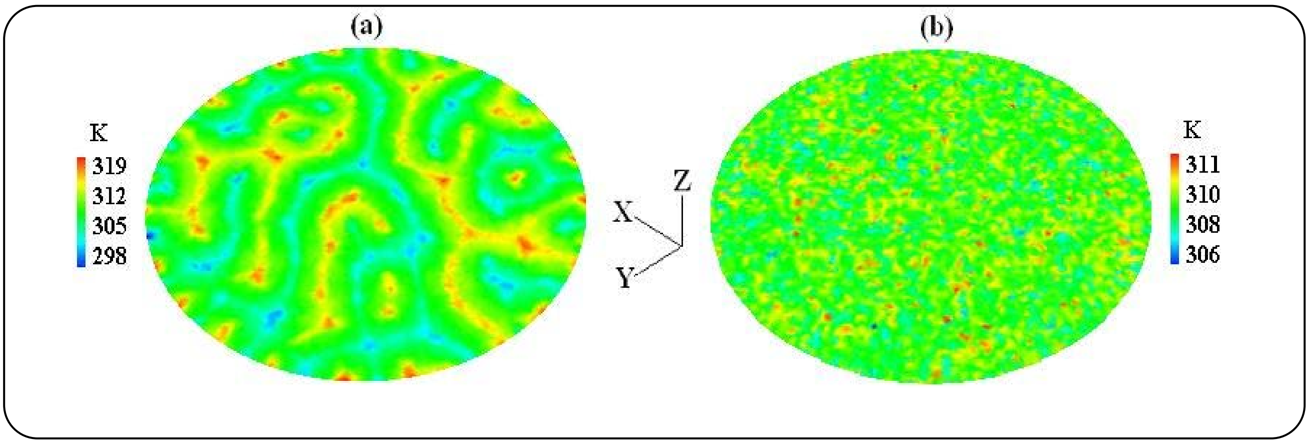

Fig. 9: Temperature contours at z=0.00175 m in the (a) presence and (b) absence of gravity.

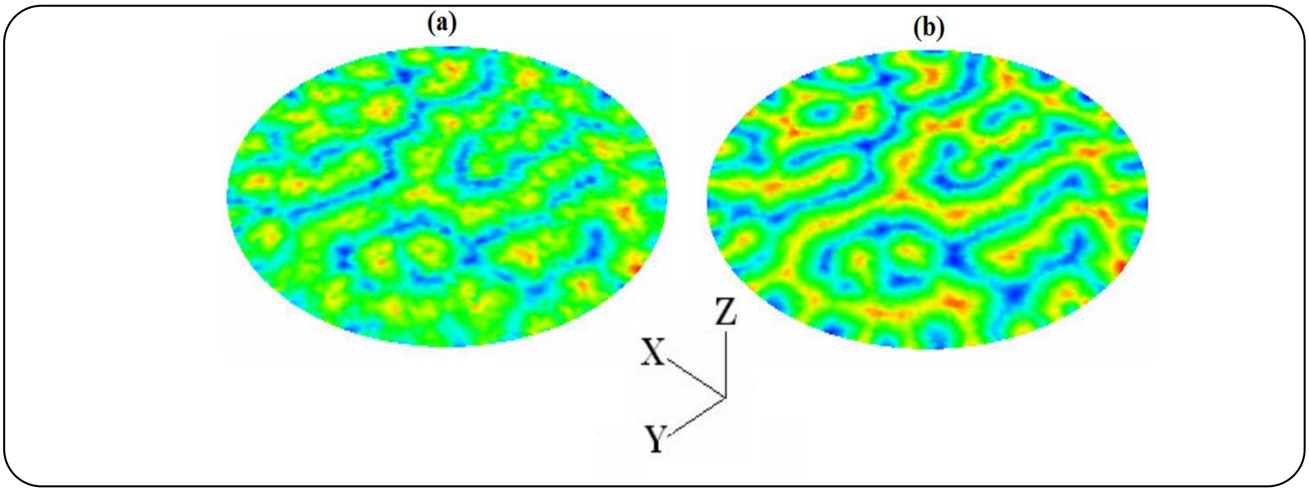

Fig. 10: Solid volume fraction of dispersed phase (magnetic particles) on a z-plane after 100 s. (a) z=0 and (b) z=0.00175 m. Red and blue colors refer to the maximum and minimum values, respectively. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

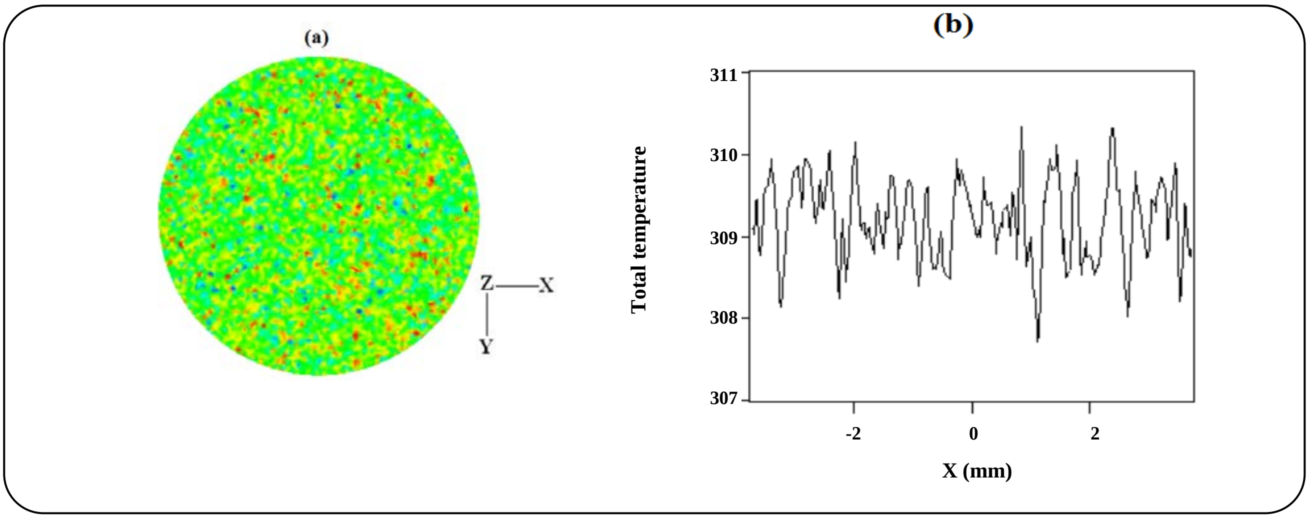

Fig. 11: Convection pattern and temperature oscillation of the nano-ferrofluid on a plane at z= 0.00175m after 200s and in the absence of natural convection.

Nomenclature

ρ	Density
u	Velocity vector
T	Temperature
μ	Dynamic viscosity
M	Magnetization vector
$c_{V,H}$	Heat capacity in constant volume
β	Thermal expansion coefficient
χ	Susceptibility
u_{im}	Diffusion velocity
d_p	Magnetic particle diameter
B	Magnttic induction
α_p	Volume fraction of magnetic particles
Ra_g	Gravitational Rayleigh numbers
t	Time
P	Pressure
g	Gravity
μ_0	Magnetic permeability in vacuum
H	Magnetic field vector
k	Thermal conductivity
β_m	Pyromagnetic coefficient
ξ	Langevin parameter
u_s	Slip velocity
$u_{dr,p}$	Drift velocity
ϕ_m	Magnetic scalar potentioal
Ra_m	Magnetic Rayleigh numbers

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