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Effect of uniform external magnetic-field on natural convection heat transfer in a cubical cavity filled with magnetic nano-dispersion

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ABSTRACT

Heat transfer in magnetic nano-particle dispersion can be influenced by the presence of external magnetic-field. This paper presents an experimental investigation on effect of external uniform magnetic-field on natural convection heat transfer in magnetite and iron nano-dispersion in a differentially heated cubical cavity. The experiments are conducted between the Rayleigh number range of 4.23×10^5 to 1.0×10^7. The study includes experiments and discussion on the corroborating and suppressing effects of thermo-magnetic convection induced by the external magnetic-field on the natural convection heat transfer. Additionally, this study also reports the experimental results and pertinent explanation on the directional effect of magnetic-field on the heat transfer in magnetite and iron nano-dispersion. The paper quantitatively presents the extent of heat transfer depreciation/enhancement in different orientations of the cavity in the presence of magnetic-field. The study also explores the effect of particle volume fraction in magnetic fluid on heat transfer in each case.

1. Introduction

Heat transfer by the bulk motion of fluid is termed as convection and is ubiquitous. The bulk motion of a fluid can be driven either by external sources like fan, blower or through instabilities caused by the temperature dependent fluid properties such as density (natural convection), magnetic susceptibility (thermo-magnetic convection) [1], surface tension (thermo-capillary convection) [2]. Internal convection (natural convection in enclosures) is one of the most commonly observed natural convection in heat transfer applications. To enhance heat transfer in cavities, researchers have studied this problem extensively which includes study on the effect of shape of the cavity, position of heat source and sink, inclination of the cavity and use of different working fluids [3,4] on heat transfer. In order to make natural convection heat transfer more efficient using conventional fluids like water, mineral oils, dielectrics etc., researches on enhancing the transport properties of such fluids have been a key area of interest. One such solution is – adding nano-sized particles in the fluid which improves the thermal conductivity of the fluid; such fluids are termed as “nanofluid” [5]. Additionally, the tiny size (< 100 nm) of the suspended particles enables the nanofluid to overcome the limitation of erosion and clogging encountered in fluids with micro-sized (10^{-6} m) particles [6]. Nanofluids with nano-particles of metals, ceramics, non-metals and carbon have been used in various heat transfer applications.

In addition to this, the behavior of nanofluids can be altered in the presence of external magnetic and electric fields, if suspended nano-particles possess desirable properties like high electrical conductivity (copper, graphene) and high magnetic-susceptibility (magnetite, iron). The presence of external magnetic-field can engender instabilities in heated magnetic nanofluids. This thermally induced convection in magnetic nanofluids is called thermo-magnetic convection. Magnetic nanofluids have tiny nano-meter sized particles of iron, magnetite, cobalt, nickel which have properties susceptible to the external magnetic-field, the temperature dependent magnetization of fluid induces instabilities and subsequently thermo-magnetic convection [7]. Many studies (theoretical and experimental) on the effect of uniform and non-uniform external magnetic-field on natural convection heat transfer in ferro-fluids are available [1,8–17]. Most of the studies report augmentation of heat transfer because of the cumulative effect of thermo-magnetic convection and natural convection. A few studies also discuss the depreciation of heat transfer in ferro-fluids in the presence of external magnetic-field [18]. However, there are no experimental studies showing both supplementing and suppressing effects of magnetic-field on natural convection heat transfer and study on the directional effect of magnetic-field on heat transfer in ferro-fluid is absent from the literature. In the present study,

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Nomenclature

A	area of cross section, m^2
C	specific heat capacity, J/kg K
F	force per unit volume, N/m^3
g	acceleration due to gravity, m/s^2
H	magnetic-field, A/m
h	convective heat transfer coefficient, W/m^2 K
k	thermal conductivity, W/m K
k_B	Boltzmann constant, m^2 kg/s^2 K
L	side of the cubical cavity, m
$L()$	Langevin's function
m	magnetic moment, A m^2
N	number of particles per unit volume
P	pyro-magnetic coefficient, A/m K
Nu	Nusselt number
Q	heat rate, W
Ra	Rayleigh Number
T	temperature, K
$\vec{V}$	velocity, m/s

Greek letters

α	thermal diffusivity, m^2/s
β	coefficient of thermal expansion, 1/K
μ	dynamic viscosity, kg/m s
μ_o	permeability of free space, m kg/s^2 A^2
ν	kinematic viscosity, m^2/s
ρ	density, kg/m^3
χ	magnetic susceptibility
X	X direction (direction of magnetic-field perpendicular to hot and cold side)
Y	Y direction (direction of magnetic-field parallel to hot and cold side)
Z	Z direction

Subscripts

b	buoyancy
bf	base fluid
np	nano-particle
nf	nanofluid
m	magnetic
p	particle
s	supplied

Abbreviation

Chain-cond	chain-conduction
DC	direct current
N-conv	natural convection
NMP	N-Methyl-2-Pyrrolidone
TM-conv	thermo-magnetic convection

experiments demonstrate the supplementing and suppressing effect of external uniform magnetic-field on magnetite and iron nano-dispersion. Moreover, experiments and discussion on the directional effect of uniform magnetic-field and volume fraction of nano-dispersion on heat transfer in natural convection are also presented.

2. Experiments and methodology

2.1. Description of experimental setup

The experiments are conducted in a cubical cavity of 25 mm dimension with two opposite sides maintained at a constant lower and higher temperature respectively. A schematic of the experimental setup is shown in Fig. 1. The experimental setup consists of the test cavity, the electromagnet, two Direct Current (DC) power sources, two cold baths, a data logger and a gauss meter. The lower temperature of one side in cavity is maintained by circulating water at a constant temperature, using a cold bath and the higher temperature is maintained using a nichrome wire heater, heated by a DC power supply. The critical parameters involved in the design of the test cavity includes the Rayleigh number and the permissible pole gap of the electromagnets. The cubical design of the cavity is chosen over cylindrical or any other geometry to test the effect of magnetic-field direction on the heat transfer. To measure temperature, five calibrated K-type thermocouples are installed on each cold and hot side. The ambient is maintained between 25.0 °C and 26.5 °C while carrying out experiments. The temperatures are recorded at 1 Hz for 120 s at steady state. The heat loss is calculated using an empirically constructed linear correlation by carrying out experiments with the hot side on the top and the cold side on the bottom. The experimental procedure is validated by comparing experimental results against the well-validated simulation on Ansys Fluent. A detailed description of the experimental setup, thermocouple calibration, heat loss method and validation is presented in the previous work of the authors [19].

2.2. Nanofluid preparation and characterization

The present experimental investigation is carried out with two volume fractions of magnetite (Fe_3O_4) nano-dispersion and one volume fraction of iron (Fe) nano-dispersion.

- **Magnetite (Fe_3O_4) nano-dispersion**: Concentrated (20% W/W or 4.45% V/V) magnetite nano-dispersion with water as base fluid is procured from Nanoshel limited liability company (LLC). The procured dispersion is diluted with De-ionised (DI) water to two volume fractions (0.05% V/V and 0.2% V/V) to study the effect of volume fraction.
- **Iron (Fe) nano-dispersion**: To confirm the effect observed in magnetite nano-dispersion, 0.2% V/V iron nano-dispersion suspended in N-Methyl-2-Pyrrolidone (NMP) as base fluid is used.

Images taken through Scanning electron microscope (SEM) (Fig. 2), confirmed the average size of nano-particles to be 80–100 nm for Iron nano-dispersion and 50–80 nm for magnetite (Fe_3O_4) nano-dispersion as mentioned in the specification sheet provided by Nanoshel LLC. The stability of nanofluid is measured in terms of zeta-potential, and for the given samples the zeta-potential is measured using Zetasizer Nano ZS90 which uses the principle of Dynamic Light Scattering (DLS) to measure zeta potential, measured values of zeta potential are given in Table 1.

The thermal conductivity of all the samples is measured using a KD2 Pro Thermal Property Analyzer at ambient condition (30 °C). The KD2 Pro Thermal Property Analyzer uses the transient line heat source method to estimate the thermal conductivity of the sample. The viscosity of samples is measured at three different temperatures (25–45 °C) using AntonPaar AMVn Automated Microviscometer, which calculates the viscosity using Stokes law by measuring of terminal velocity of a steel ball in a capillary. The measured viscosity has strong temperature dependence and decreases with increase in temperature, while thermal conductivity shows enhancement with the increase in volume fraction for magnetite nano-dispersion. The measured values of thermal conductivity and viscosity are shown in

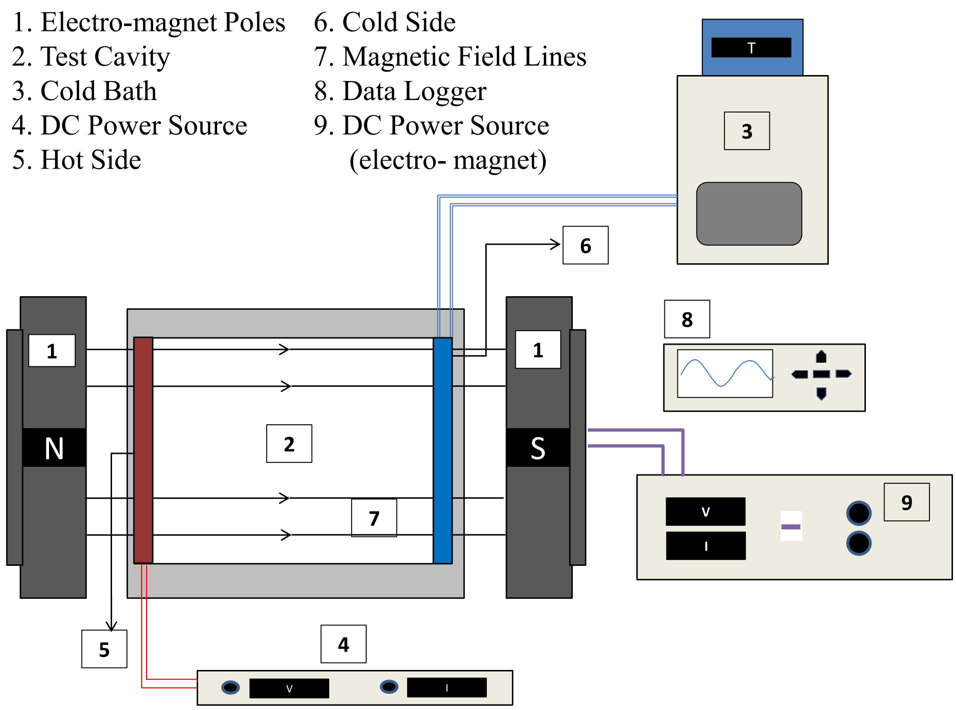
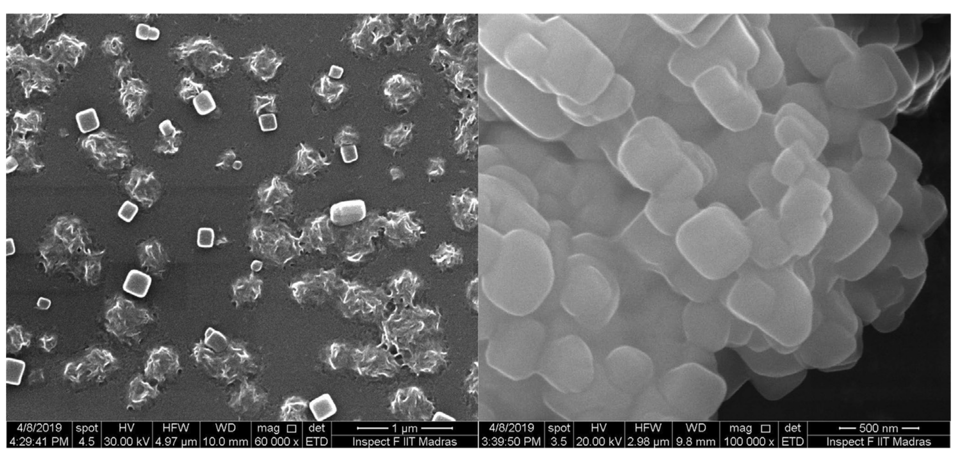


Fig. 1. Schematic of experimental setup.



(a) (b)

Fig. 2. SEM image of (a) Magnetite nano-particles, (b) Agglomeration of iron nano-particles.

Table 1
Properties.

Nano-dispersion	Zeta-potential (mV)	Size
Iron (Fe)	-21.80 ± 12.1	80–100 nm
Magnetite (Fe_3O_4)	-18.20 ± 6.47	50–80 nm

Fig. 3. Specific heat capacity, density and coefficient of thermal expansion are calculated using volume averaging correlations available in the literature [19]. Rayleigh number and Nusselt number are calculated using Eqs. (1)–(5). The calculation for uncertainty in Nusselt number is mentioned in the author's previous work [19]. The average uncertainty in calculation of Nusselt number and Rayleigh number is ±5.5% and ±3% respectively.

$$Ra = \frac{g\beta_{nf}\Delta T L^3}{\nu_{nf}\alpha_{nf}} \quad (1)$$

$$Nu = \frac{hL}{k_{nf}} \quad (2)$$

$$\text{Where,}\ \alpha_{nf} = \frac{k_{nf}}{\rho_{nf}C_{nf}} \quad (3)$$

$$\nu_{nf} = \frac{\mu_{nf}}{\rho_{nf}} \quad (4)$$

$$h = \frac{Q_s - Q_{loss}}{A\Delta T} \quad (5)$$

3. Results

The experiments are carried out in the presence of uniform external magnetic-field in two different orientations to reveal the effect of the magnetic-field and the direction of the magnetic-field on natural convection heat transfer. In the first orientation,

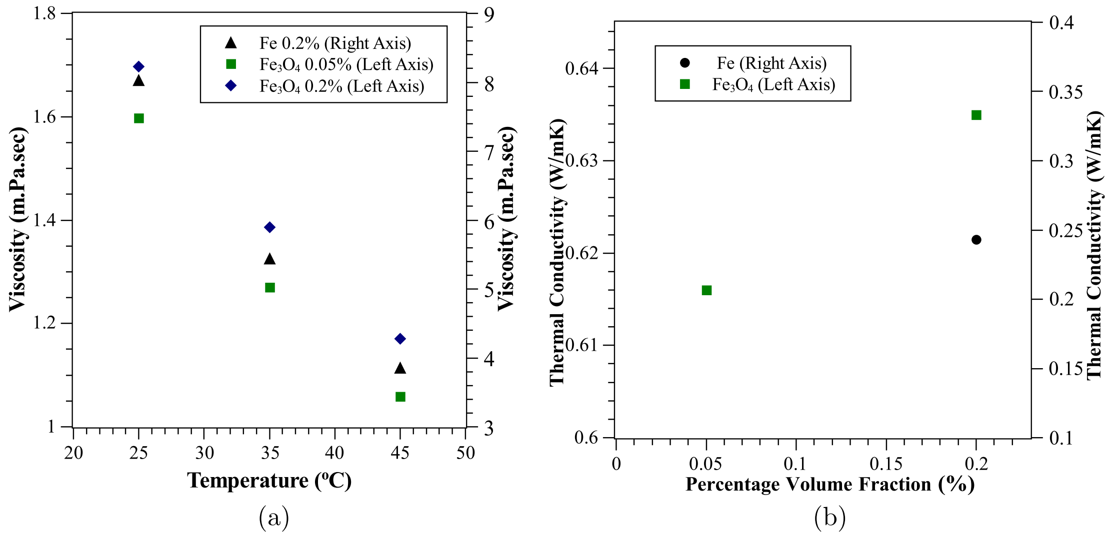


Fig. 3. (a) Dynamic Viscosity v/s Temperature , (b) Thermal Conductivity v/s Percentage volume fraction at 30 °C.

i.e. case-1 the magnetic-field lines are perpendicular to the hot and cold sides of the cavity (X-direction), while in second orientation, i.e. case-2 the magnetic-field lines are parallel to the hot and cold sides (Y-direction), as shown in the Fig. 4.

The natural convection loop for the differentially heated cavity is in anti-clockwise direction (from +Y-axis) as the fluid adjacent to hot side rises and fluid adjacent to cold side plummets thus creating a natural convection loop. Therefore, in case-1 the magnetic-field lines are parallel to the natural convection loop, whereas in case-2 the magnetic-field lines pass through the natural convection loop.

To investigate the effect of strength of the magnetic-field, experiments are conducted with 0.05% Magnetite (Fe_3O_4) nano-dispersion (base-fluid – water) in the presence of 0.3T X-direction magnetic-field 4a. The Nusselt number values are plotted as a function of Rayleigh number in Fig. 5a. It is observed that the heat transfer deteriorates by 28% (at lower Rayleigh number – 4.23×10^5) with respect to the heat transfer in the absence of magnetic-field as shown in Fig. 5a. The heat transfer deterioration is observed to decrease with an increasing Rayleigh number.

To investigate the effect of volume fraction a higher volume fraction i.e. 0.2% Magnetite (Fe_3O_4) nano-dispersion in water is used as test-fluid. With the use of 0.2% Magnetite (Fe_3O_4) nano-dispersion in 0.3T X-direction magnetic-field, the heat transfer depreciates by 30% as shown in Fig. 5b.

The effect of Y direction magnetic-field (Fig. 4b) is seen to be more potent with respect to X direction magnetic-field for both volume fractions of Magnetite (Fe_3O_4) nano-dispersion. The depreciation in Nusselt number for 0.05% magnetite (Fe_3O_4) nano-dispersion in the presence of 0.3T Y-direction magnetic field is 30% and for 0.2% is 36% as shown in the Fig. 6a and b respectively.

To confirm the effect of magnetic-field direction on heat transfer, experiments with 0.2% Iron (Fe) nano-dispersion in NMP as base-fluid are carried out with magnetic-field in X and Y direction. The depreciation in heat transfer for 0.2% Iron (Fe) nano-dispersion with magnetic-field in X-direction is found to be 21%, and for Y-direction magnetic-field the heat transfer depreciation is observed to be 25% at lower Rayleigh number as shown in Fig. 7a and b respectively.

The results for magnetite and iron nano-dispersions both confirm the directional effect of magnetic-field on the natural convection heat transfer, i.e. the Y-direction magnetic-field has a more detrimental effect on the natural convection heat-transfer than X-direction.

To investigate the effect of uniform vertical magnetic-field on heat-transfer in Rayleigh Benard convection, experiments are performed with 0.05% and 0.2% magnetite nano-dispersions with the hot side at the bottom and the cold side at the top as shown in Fig. 8.

It is observed that the presence of 0.3T vertical uniform magnetic-field has a supplementing effect on heat-transfer in Rayleigh Benard orientation, this is in contrast to the depreciation effect in other configurations discussed before. The heat-transfer augments by 11% for 0.05% magnetite nano-dispersion and 28%

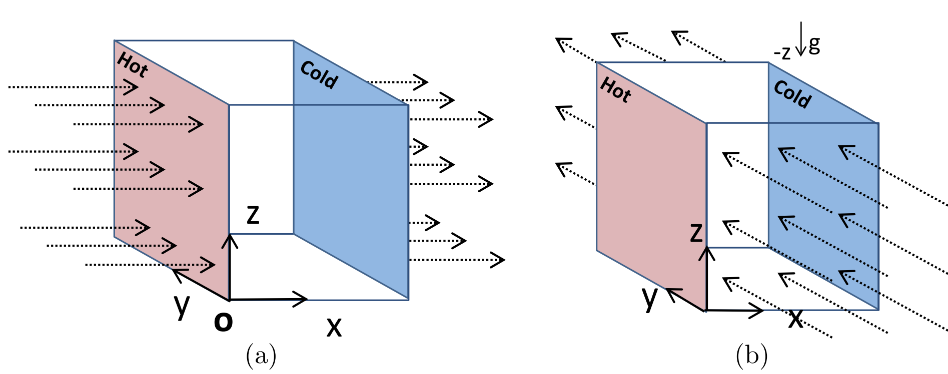


Fig. 4. Magnetic-field (a) Case 1 – perpendicular to hot side (X direction) (b) Case 2 – parallel to hot side (Y direction).

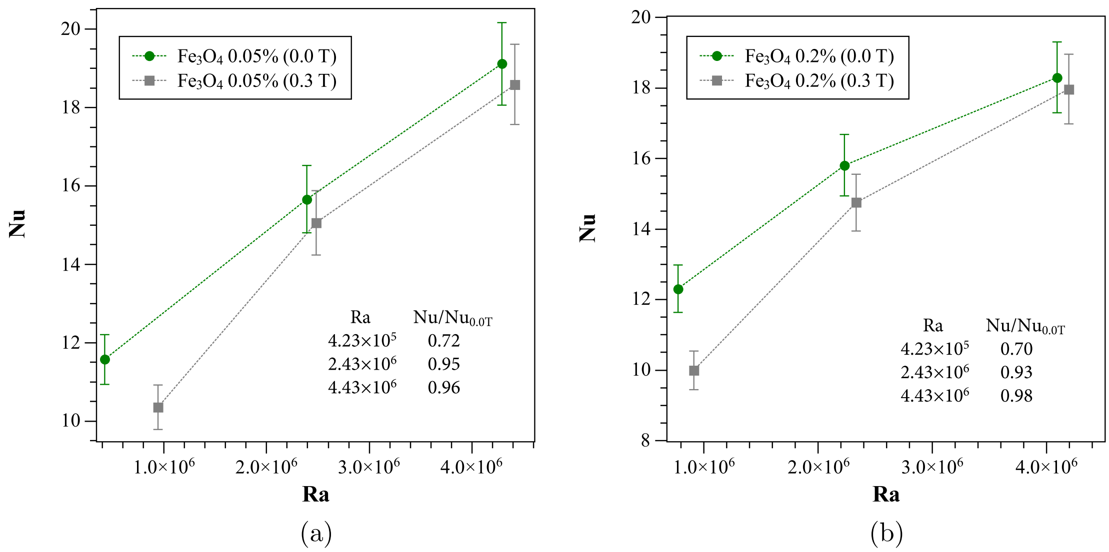


Fig. 5. Nusselt number vs Rayleigh number (a) 0.05% Magnetite (Fe_3O_4) (b) 0.2% Magnetite (Fe_3O_4) nano-dispersion in water (Magnetic-field X-direction).

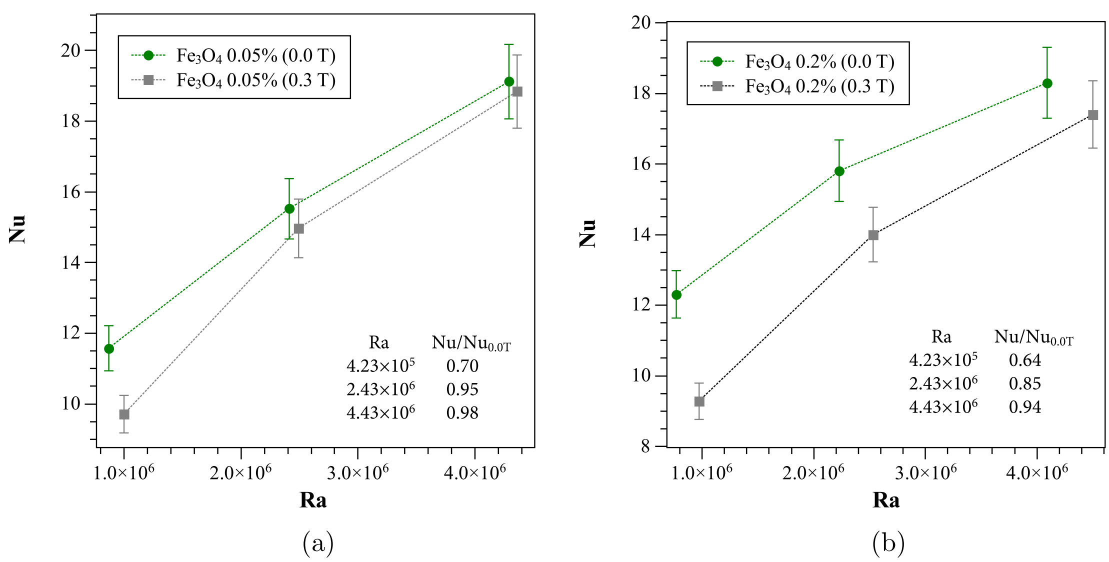


Fig. 6. Nusselt number vs Rayleigh number (a) 0.05% Magnetite (Fe_3O_4) (b) 0.2% Magnetite (Fe_3O_4) nano-dispersion in water (Magnetic-field Y-direction).

for 0.2% magnetite nano-dispersion as shown in Fig. 9a and b. The supplementing effect in Rayleigh Benard configuration with vertical magnetic-field is observed to increase with increase in Rayleigh number as shown in figures (inset) 9a and b.

The mechanism resulting in the supplementing and depreciating effects of magnetic-field on natural convection heat transfer is discussed in the subsequent section.

4. Discussion

Magnetic nano-particle dispersion experience a force similar to buoyancy force when kept in magnetic-field gradient and is termed as magnetic force or Kelvin body force [20] and is given by [21]:

$$\overrightarrow{F_m} = \mu_o M \nabla H \tag{6}$$

$$H = |\overrightarrow{H}|; M = |\overrightarrow{M}| \tag{7}$$

The magnitude of magnetic force depends upon magnetization (M) and gradient of magnetic-field (H) where, M and H are both scalar fields [1]. The magnetization per unit volume of a magnetic nano-particle dispersion is given by [22,23]:

$$\overrightarrow{M} = N\overrightarrow{m_p}L(a) \tag{8}$$

$$L(a) = coth(a) - \frac{1}{a}; a = \frac{\mu_o m_p H}{k_b T} \tag{9}$$

where $\overrightarrow{m_p}$ is the magnetic moment of a particle, N is the total number of particles per unit volume and $L(a)$ is the Langevin's function. The presence of temperature gradient (∇T) in a ferro-fluid engenders the spatial gradient of magnetization (∇M) in the fluid in the direction opposite to temperature gradient which subsequently gives rise to magnetic-field gradient within the fluid. The magnetization and magnetic-field gradient in the fluid are given by following equations [24]:

$$\nabla M = -\frac{P\nabla T}{1+\chi} \tag{10}$$

$$\nabla H = -\nabla M \tag{11}$$

$$P = \frac{\partial M}{\partial T}_{H,T}; \chi = \frac{\partial M}{\partial H}_{H,T} \tag{12}$$

where P is pyro-magnetic coefficient and χ is magnetic susceptibility. The direction of the magnetic force is same as that of the

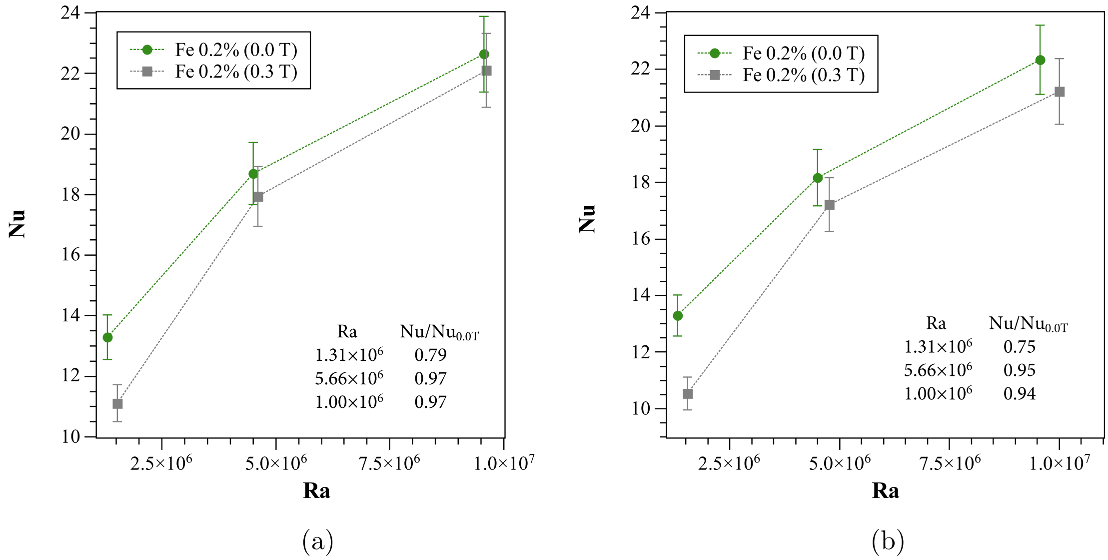


Fig. 7. Nusselt number vs Rayleigh number (a) 0.2% Iron (*Fe*) nano-dispersion in NMP (Magnetic-field X-direction) (b) 0.2% Iron (*Fe*) nano-dispersion in NMP (Magnetic-field Y-direction).

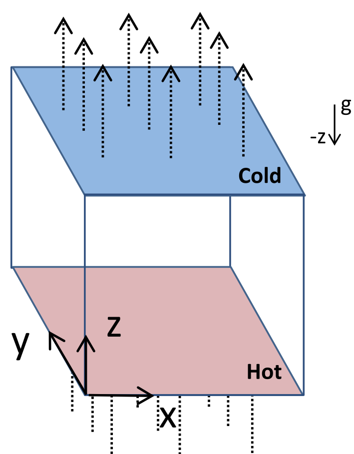


Fig. 8. Rayleigh Benard convection in presence of uniform vertical magnetic-field.

magnetic-field gradient (∇H), which is parallel to the temperature gradient (∇T). The magnetic force ($\overrightarrow{F_m}$) tries to move colder fluid (with higher magnetization) in the direction of magnetic-field gradient i.e. towards zone with higher magnetic-field. The convection created by instability induced by magnetic force is called thermo-magnetic convection. The magnetic-force is strong if the number of particles per unit volume (N) is more; therefore, the nano-dispersion with higher volume fraction experiences higher magnetic force.

The presence of natural convection inside a cubical cavity creates temperature gradients in all the three directions thus creating magnetic force in all the three directions. As the magnitude of the magnetic force depends upon the local magnetization (M – increases with decrease in temperature) and local magnetic-field gradient (∇H – increases with temperature gradients), therefore fluid in the zone with low temperature and maximum temperature gradient will experience maximum force.

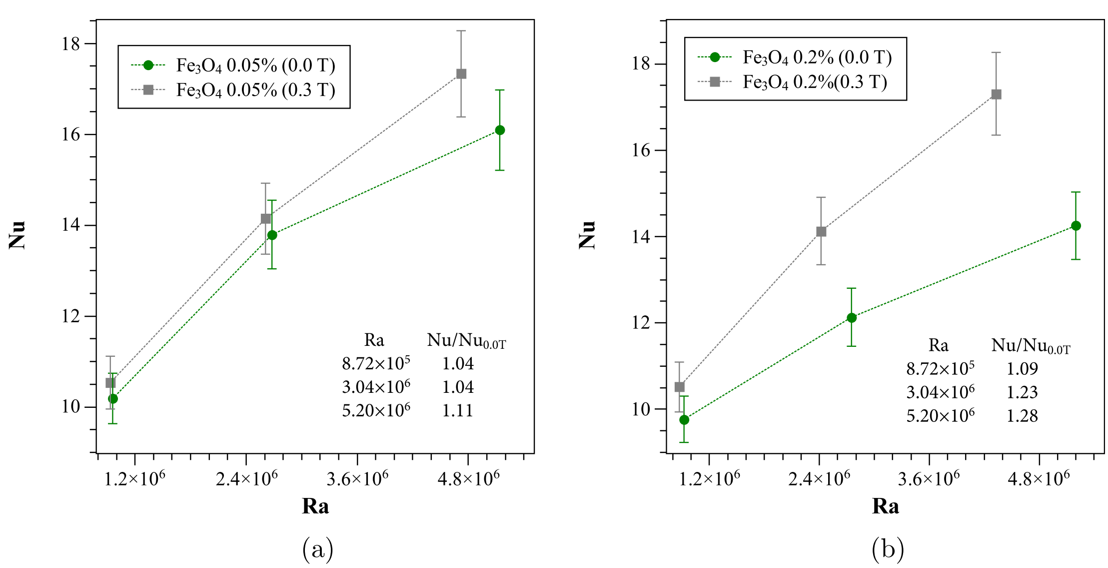


Fig. 9. (a) Nusselt number vs Rayleigh number (a) 0.05% magnetite (Fe_3O_4) (b) 0.2% magnetite (Fe_3O_4) nano-dispersion in water (Magnetic-field Z-direction) Rayleigh Benard Convection.

As the fluid experiences buoyancy force (due to temperature gradient) and magnetic force (due to temperature gradient induced magnetization gradient), thus it becomes necessary to evaluate the relative magnitude of the buoyancy force per unit volume and magnetic force per unit volume in the magnetic fluid for given experimental setup. In order to realize the mathematical calculation of forces, properties of magnetic fluid used by [1] is used (see Table 2).

For volume fraction (ϕ) = 10%

$$\overrightarrow{F_b}/\overrightarrow{F_m} = 3.05 \tag{13}$$

and for volume fraction (ϕ) = 0.2%

$$P_{0.2\%} = P/50 \tag{14}$$

$$\chi_{0.2\%} = \chi/50 \tag{15}$$

$$\overrightarrow{F_b}/\overrightarrow{F_m} = 164.01 \tag{16}$$

Table 2
Properties of magnetic fluid used by [1] at ϕ = 10.0%.

Property	Magnitude	Size
Density (ρ_{nf})	1250	kg/m^3
Coefficient of thermal expansion (β_{nf})	0.86×10^{-3}	K^{-1}
magnetic susceptibility (χ)	5	–
Pyromagnetic coefficient (P)	≈100	A/mK
Gravity(g)	9.81	m/s^2
Saturation Magnetic Field	48×10^3	A/m
Temperature difference (ΔT)	20	K
Length of cubical cavity (L)	25	mm

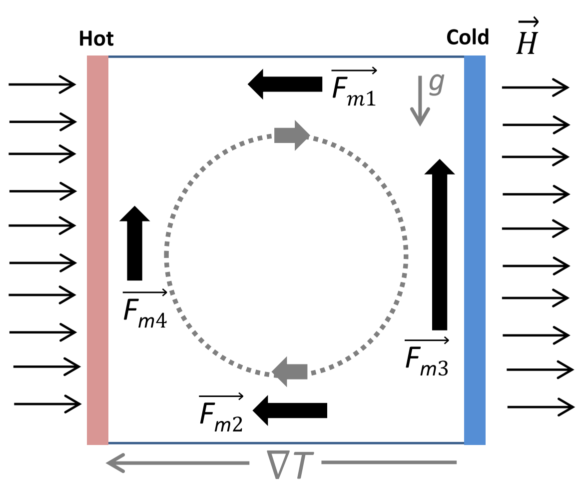


Fig. 10. Thermo-magnetic convection in the presence of natural convection (grey-natural convection, black – thermo-magnetic convection).

The calculation of ratio ($\overrightarrow{F_b}/\overrightarrow{F_m}$) for present experimental length scale shows that at volume fraction 10% the magnitude of forces are comparable (Eq. (13)). However, for volume fraction 0.2% the buoyancy force is two order larger than the magnetic force. Present experimental results evince deterioration/enhancement in heat transfer in spite of the magnetic force being two order smaller than the buoyancy force for given length scale and concentration of nano-particle dispersion.

In the present experimental study, the cubical cavity is filled with nano-dispersion and undergoing natural convection as shown in Fig. 10. The magnitude of temperature gradient is maximum near hot and cold faces, which implies that the magnetic-field gradient is maximum near cold and hot walls (Eqs. (10) and (11)). The Z-component of temperature gradient is parallel to the flow near the hot face and anti-parallel near the cold face. Therefore the direction of magnetic force is vertically up near both the faces as shown in the Fig. 10 as $\overrightarrow{F_{m4}}$ and $\overrightarrow{F_{m3}}$.

The temperature gradients near the top and bottom faces are from right to left and are very small in magnitude as the top and bottom walls are adiabatic. Moreover, the fluid near the cold face has the lowest temperature in the cavity; thus, the magnetization will be maximum near the cold face. The magnetization and magnetic-field gradient both are maximum near cold face therefore, magnetic force is maximum ($\overrightarrow{F_{m3}} > \overrightarrow{F_{m4}}, \overrightarrow{F_{m2}}, \overrightarrow{F_{m1}}$) near cold wall and vertical in direction as shown in Fig. 10 with black vertical arrow.

Theoretically, the magnetic force (Eq. (6)) depends upon the magnetization ($M = |\vec{M}|$) and magnetic-field gradient ($\nabla H; H = |\vec{H}|$) where M, H both are scalar fields. Therefore the magnetic-field direction cannot influence the thermo-magnetic convection. However, the present experimental investigation shows that the heat transfer depreciation is more for 0.3T Y-direction magnetic-field in comparison to 0.3T X-direction magnetic-field for both nano-dispersions. The directional effect of magnetic-field on heat transfer is observed due to the anisotropic nature of magnetic nano-particle dispersion in the presence of magnetic-field. In the presence of magnetic-field the nano-particles form a chain like structure in the direction of the applied magnetic-field [25] as shown in Fig. 11a

The chain formation provides an alternative less conduction resistance path to the heat which enhances the heat transfer in the direction of chain formation as shown in Fig. 11.

The net heat transfer in the presence of external magnetic field is a cumulative effect of complex thermo-magnetic convection, the

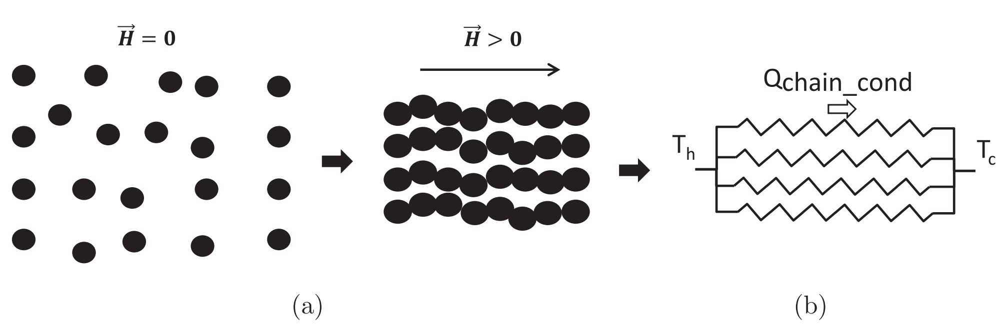


Fig. 11. (a) Chain formation in the presence of external magnetic-field (b) thermal resistance circuit representing heat conduction through chain (chain-cond).

chain formation and the natural convection can either enhance or deteriorate the heat transfer.

5. Conclusions

The present experimental study indicates that the external uniform magnetic-field can either enhance or depreciate the heat transfer depending upon the relative orientation of the heated cavity and magnetic-field lines. The natural convection heat transfer in cavity depreciates in the presence of uniform 0.3 T magnetic-field when the hot and the cold faces are vertical. In the presence of 0.3 T X-direction magnetic-field, the heat transfer in 0.05% and 0.2% magnetite nano-dispersion depreciates by 28% and 30%, respectively. The heat transfer is depreciated more in the presence of Y-direction magnetic-field in comparison to X-direction, for 0.05% and 0.2% magnetite nano-dispersion the heat transfer depreciation is 30% and 36%, respectively. The directional effect of the magnetic-field on heat transfer can be attributed to the formation of chains in the direction of the magnetic-field which provides an alternative path for heat conduction from hot side to cold side in X-direction magnetic-field. A similar effect on heat transfer is observed with the use of 0.05% and 0.2% Iron nano-dispersion. The depreciation in heat transfer diminishes with increase in Rayleigh number.

However, 0.3 T vertical (Z-direction) magnetic-field enhances the heat transfer in Rayleigh Benard orientation for both 0.05% and 0.2% magnetite nano-dispersion by 11% and 28% respectively. In the Rayleigh Benard orientation, the chain formation enhances the heat transfer. The enhancement in heat transfer increases with Rayleigh number.

The effect (depreciation and enhancement) of uniform magnetic-field on heat transfer in the presence of magnetic-field is a function of volume fraction of dispersion, i.e. the effect becomes more potent with the increase in volume fraction. The study suggests that use of magnetic nano-dispersion can be beneficial or detrimental depending upon the relative orientation of the hot, cold and magnetic-field lines.

Declaration of Competing Interest

The authors declared that there is no conflict of interest.

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