Morphological effects on natural convection heat transfer of magnesium ferrite ferrofluid

Ajith Kongassery[a], Archana Sumohan Pillai[b], Muthu Vijayan Enoch[b], Li-Zhi Zhang[c], Brusly Solomon[a*], Mohsen Sharifpur[d,e**], Josua Meyer[f], Deepak Tudu[a]

[a*]Micro and Nano Heat Transfer Lab, Centre for Research in Material Science and Thermal Management, Department of Mechanical Engineering, Karunya Institute of Technology and Sciences, Coimbatore, India

[b]Centre for NanoScience and Genomics, Karunya Institute of Technology and Sciences, Coimbatore, India

[c]Key Laboratory of Enhanced Heat Transfer and Energy Conservation of Education Ministry, School of Chemistry and Chemical Engineering, South China University of Technology, Guangzhou, 510640, China

[d]Department of Mechanical and Aeronautical Engineering, University of Pretoria, Pretoria 0002, South Africa

[e]Department of Medical Research, China Medical University Hospital, China Medical University, Taichung, Taiwan

[f]Department of Mechanical and Mechatronic Engineering, Stellenbosch University, Stellenbosch Central, Stellenbosch, South Africa

*Corresponding author

E-mail address: * abruslysolomon@gmail.com; brusly@karunya.edu

**Mohsen.Sharifpur@up.ac.za

Tel.: +91-8220023860

Abstract

This investigation intends to analyze the influence of nanoparticles morphology on the magnetic flux dependent thermophysical properties and magnetohydrodynamic free convection heat transfer performance of water-based magnesium ferrite ferrofluid under various volume fractions. The thermophysical parameters of the ferrofluid suspended with cube shaped particles are examined at 25 °C using KD2 pro thermal analyser, Ostwald viscometer and specific gravity bottle under magnetic flux. The free convection heat transfer is obtained using heat pipes assisted cubical enclosure. Without the influence of magnetic flux, the thermal conductivity of the ferrofluid was improved by a maximum of 12.75% at a volume fraction of 0.15%. At the same time, the maximum viscosity and density were raised by 32.92% and 6.11% at a volume fraction of 0.20% in comparison with water. Under the influence of 350 Gauss, thermal conductivity, and viscosity of ferrofluid enhanced by 21.81% and 37.41% while the density decreased by 4.91%. It was revealed that the addition of cube-shaped magnesium ferrite particles in ferrofluid improved the thermo-physical properties. The optimum concentration for maximum heat transfer is reduced to 0.025% with the use of cube shaped particles compared to other types of nanoparticles reported in previous studies.

Introduction

Recent studies found that the effectiveness of free convection heat transfer in various heat transfer systems can be improved by using passive approaches. Nanofluids (NFs) are blends of conventional coolants and nanoscale particles (NPs)[1]. The application of this NF is one of the passive techniques for natural convection heat transfer enhancement[2–6]. The thermal and physical properties of NFs are an intriguing topic to be researched to identify their usage in heat transfer systems. Carbon nanotubes, multi-walled carbon nanotubes, metal NPs, metal oxide NPs, gold NPs, etc. are the conventional NPs used for the augmentation of heat transfer properties of traditional cooling fluids[7]. The results of numerous studies conducted to analyze the thermal and physical properties of NFs conclude that these parameters are enhanced to a higher percentage than that of the base fluid (BF), and these studies also concluded that there are many influential parameters such as type of NPs, the quantity of NPs in the BF, and NF temperature, which will alter the thermal and physical features of NFs. Additionally, some studies reported that the structure of the NPs influences the thermal and physical characteristics of the resulting NF[8].

Xie et al.[9] analysed the influence of Silicon Carbide NPs structure on thermal conductivity of aqueous Silicon Carbide NF. This study reported that thermal conductivity of aqueous Silicon Carbide NF with cylindrical shape NPs is enhanced by 22.9% and this enhancement is more than the same NF with spherical type NPs (15.8% enhancement) at a volume fraction (VF) of 4%. The findings also reported that improved thermal conductivity of NF with cylindrical NPs can be related to their higher aspect ratio than spherical NPs. Singh et al.[10] analyzed the effects of various structures of Silicon carbide NPs on the thermal conductivity of aqueous Silicon Carbide NF. The results of this study reported that NF with platelet NPs has the highest progress in thermal conductivity related to other structures. Timofeeva et al.[11] examined the thermal and physical characteristics of aqueous Al_2O_3 NF containing different structures of NPs. This study reported that the highest thermal conductivity was found for NF consisting of cylindrical NPs and minimum viscosity was found for NF consisting of spherical NPs. Jeong et al.[12] found that aqueous Zinc Oxide NF with rectangular-structure NPs exhibited maximum thermal conductivity and viscosity than those with spherical ones at 5% VF. Yu et al.[13] examined the thermal conductivity of Carbon NF comprising various morphologies of Carbon NPs and liquid Paraffin as BF. The findings of this study indicated that maximum thermal conductivity enhancement and viscosity rise were exhibited by NF with Graphene nanoplatelets. Fang et al.[14] examined the thermal conductivity augmentation of Silver: EG NF through the use of NPs with different shapes such as sphere, flake, and wire. The results indicated that NF with nanowires enhanced the thermal conductivity by 15.6% with respect to BF. Meanwhile, Silver NF with sphere and flake-shaped NPs enhanced by around 5% in comparison with BF. They found that with the impact of the high aspect ratio of nanowires the viscosity of the NF significantly elevated.

Kim et al.[15] examined thermal properties of aqueous Bohemite: Al_2O_3 NF having NPs with dissimilar morphology such as brick, blade, and platelets. And this study reported that thermal conductivity of NF with brick shaped NPs at VF 7% enhanced maximum by 28% compared to water. At the same instant NF with blade and platelet, NPs exhibited thermal conductivity improvement of 16% and 23% respectively compared to water. Maheshwary et al.[16] assessed the significance of NPs morphology on thermophysical properties of aqueous Titanium Oxide NF prepared by cylindrical, spherical, and cube shaped NPs. The outcome of this study reported that Titanium Oxide NF with cylindrical morphology exhibited maximum thermal conductivity compared to NF with spherical and cube shaped NPs. And the minimum increase in viscosity of the Titanium Oxide NF was observed for NF with spherical morphology. Zhang et al.[17] analysed the thermal conductivity of aqueous Silver NF suspended with nanowires and sphere-shaped silver NPs. The NF with silver nanowires exhibited the highest thermal conductivity improvement of 13.42% related to NF with sphere-shaped silver NPs at 0.46% VF. From this kind of study, it can be concluded that the NF with different shapes of the same NPs exhibit different viscosity and thermal conductivity. These findings also reported that NF with high aspect ratio NPs has a higher viscosity and thermal conductivity than NF with low aspect ratio NPs. These kinds of studies discusses the effect of NPs shape on the thermophysical properties of NF, followed by this it is important to study the influence of NPs shape on natural convection heat transfer characteristics of NF as well. Paul et al.[18] investigated free convection heat transfer using ionic liquid-based Al_2O_3 NF consisting of different shapes (whisker and sphere) at different weight percentages ranging from 0.5wt% to 2.5wt% in a rectangular enclosure. The results concluded that the free convection heat transfer coefficient of nano-enhanced ionic liquid was decreased concerning that of the BF. And more deterioration was observed for NF with spherical NPs compared to NF with whisker shape NPs. Alkanhal et al.[19] studied the magnetohydrodynamic free convection in a wavy shaped cavity using aqueous Alumina NF with different shapes of NPs (cylindrical, spherical, brick, and platelet). The results concluded that NFs with platelet shape showed more natural convection heat transfer enhancement than NFs with cylindrical, spherical, and brick shape NPs. Dogonchi et al.[20] investigated the effect of different structures of Copper oxide NPs (platelet, spherical and cylindrical) on the free convection heat transfer performance of Copper Oxide filled partially heated rhombus cavity and achieved maximum heat transfer by using NF with platelet-shaped NPs. Rahimi et al.[21] studied the effects of the shape of NPs on the heat transfer efficiency of a multi-channel cavity containing Copper Oxide–water NF. This study concluded that the most effective heat transfer was obtained for NF with platelet-shaped NPs.

Gholinia et al.[22] analyzed the impact of dissimilar shapes of Copper Oxide NPs on the heat transfer enhancement of Copper Oxide/EG: H_2O NF in an enclosure. This study concluded that the NF with cylindrical NPs exhibited the maximum heat transfer enhancement related to NF with the tetrahedron and spherical shaped NPs.

From the review, it is understood that the experimental studies analysing the effect of morphology on thermo-physical properties and natural convection heat transfer characteristics of ferrofluid (FF) under the influence of magnetic flux is very limited. Therefore, the study of magnetic flux-dependent thermophysical properties of FF with different shapes of magnesium ferrite ($MgFe_2O_4$) NPs is essential. The goal of this work is to study and compare the thermal and physical properties of $MgFe_2O_4$ FF with cube shaped NPs in the presence of the magnetic flux to those of disk shaped NPs. Furthermore, this study also aims to compare the magnetohydrodynamic natural convection heat transfer characteristics of FF with cube and disk shaped NPs.

Materials and Methods

Nanoparticles synthesis and preparation of ferrofluid

Cube shape $MgFe_2O_4$ Nps were synthesised by hydrothermal method[23–25]. By using a magnetic stirrer Fe $(NO_3)_3(H_2O)_9$ and $Mg(NO_3)_2 \cdot 6\ H_2O$ were combined in DIW. Following this stirring, 4 gm of surfactant (SDS) was suspended in the mixture. After this, the prepared solution was mixed with the blend of Ethyl acetate and Triethylamine. The prepared solution was heated in an oven at 150°C over 18 hours in a hydrothermal autoclave. The precipitate obtained was rinsed, filtered and dehydrated for 3 hours in a vacuum at 70 ºC. After this procedure, NPs were collected when the sample dried. The SEM and TEM images of the $MgFe_2O_4$ NPs as shown in Figure.1(a) and (b) indicates particles are cubical with an average particle dimension of 149.95 nm. The magnetic properties of cube-shaped NPs were examined by vibrating sample magnetometry analysis, and the analysis results represented in Figure.1(c) specifies that synthesized NPs are ferromagnetic particles with saturation magnetization of 19.973 emu/gram, the coercivity of 387.93 Oe, and retentivity of 5.989 emu/gram. By using the Hielscher UP400S probe sonicator, the synthesized NPs were suspended in DIW to get stabilized $MgFe_2O_4$ FF.

Thermophysical property analysis of magnesium ferrite ferrofluid

Thermal conductivity of $MgFe_2O_4$ FF was tested by KD2 Pro thermal analyzer (Figure.2(a)). The glass tube occupied with FF was placed between two electromagnets, and when linked to the DC power system, these electromagnets generated magnetic flux. As shown in Figure.2(b), an Ostwald viscometer was used to assess the viscosity of $MgFe_2O_4$ FF with and without the impact of magnetic flux at 25°C. And this viscometer was positioned in the middle of two electromagnets to apply the magnetic flux. The density of $MgFe_2O_4$ FF was determined using a specific gravity bottle [17].

Magnetohydrodynamic natural convection studies

The experimental testing facility used for natural convection heat transfer study under magnetic flux is shown in Figure 2(c). The experimental setup contains of a cubical cavity (length=width=height=100 mm) with a heat pipe attached on two sides, a data logger and computer, a constant temperature bath, pressure measurement, and flow monitoring devices. The two sides of the cavity are covered with two flat heat pipes and all other sides including the bottom are covered with Teflon. Two copper heat pipes are placed at a distance of 100 mm and the other sides of the enclosure are covered with Teflon. One of the heat pipes is cooled using a constant temperature bath (cold) and another heat pipe is attached with a heater to maintain a higher temperature. There are 5 thermocouples are positioned in the fluid from the hot side towards the cold side to measure the fluid's temperature distribution. There are 5 thermocouples each is welded on both heat transfer surfaces of heat pipes (hot and cold sides) to measure the temperature. Two thermocouples are used to measure the inlet and outlet of cooling water supplied to the cold side heat pipe's condenser. Finally, the entire cavity arrangement is covered with the glass wool 4 cm thick and kept inside the box filled with polyurethane foam. After that, the cubical cavity was filled with 1000 ml of $MgFe_2O_4$ FF. The heat is supplied to the heat pipe to maintain a temperature difference between the cavity of 10, 15, 20, and 25 °C respectively, while the low temperature is maintained on the other side of the cavity by supplying cooling water to the condenser. Temperatures at all the proposed points are monitored and recorded for about 40 mins once the system reached a steady state.

Solution methodology

To find out the heat transfer performance of the cavity filled with $MgFe_2O_4$ FF having cube shaped NPs in terms of its average heat transfer coefficient (h_{avg}) and average Nusselt number (Nu), the following equations are utilized.

$$Q_{in} = V * I \quad (1)$$

$$Q_{out} = m_w * C_{p(w)} * \Delta T_w \quad (2)$$

$$h_{hot} = \frac{Q_{in}}{A(T_h - T_f)} \quad (3)$$

$$h_{cold} = \frac{Q_{out}}{A(T_f - T_c)} \quad (4)$$

$$h_{avg} = \frac{h_{hot} + h_{cold}}{2} \quad (5)$$

$$Nu_{avg} = \frac{h_{avg} * L_c}{k_{wf}} \quad (6)$$

$$Ra = \frac{g\beta_{wf}[T_h - T_c]\rho_{wf}{}^2(C_{pwf})(L_c{}^3)}{(\mu_{wf})(k_{wf})} \quad (7)$$

Uncertainty Analysis

Eqn. (8) is used to determine the uncertainty in thermal and physical properties of $MgFe_2O_4$ FF. The estimated uncertainty for thermal conductivity, viscosity and density is presented in Table 1.

$$\text{Uncertainty} = \sqrt{\sum_1^n \frac{((xi - X)^2}{n(n-1)}} \quad (8)$$

Eqs. (11) to (15) utilised to determine the uncertainty in heat input to the cavity, heat output from the cavity, heat transfer coefficient at the hot and cold side of the cavity and average Nu. and the estimated uncertainties were 3.24% (Heat input), 8.75% (Heat output), 4.83% (h_{hot}), 8.62% (h_{cold}) and 6.18% (Nu_{avg}).

$$\delta Q_{in} = \sqrt{\left(\frac{\Delta V_{in}}{V_{in}}\right)^2 + \left(\frac{\Delta I_{in}}{I_{in}}\right)^2} \quad (9)$$

$$\delta Q_{out} = \sqrt{\left(\frac{\partial Q_{out}}{\partial m_w}\delta m_w\right)^2 + \left(\frac{\partial Q_{out}}{\partial C_{p_w}}\delta C_{p_w}\right)^2 + \left(\frac{\partial Q_{out}}{\partial \Delta T_w}\delta \Delta T_w\right)^2} \quad (10)$$

$$\delta h_{hot} = \sqrt{\left(\frac{\partial h_h}{\partial Q_{in}}\delta Q_{in}\right)^2 + \left(\frac{\partial h_h}{\partial A}\delta A\right)^2 + \left(\frac{\partial h_h}{\partial T_h}\delta T_{hot}\right)^2 + \left(\frac{\partial h_h}{\partial T_f}\delta T_{fluid}\right)^2} \quad (11)$$

$$\delta h_{cold} = \sqrt{\left(\frac{\partial h_c}{\partial Q_{out}}\delta Q_{out}\right)^2 + \left(\frac{\partial h_c}{\partial A}\delta A\right)^2 + \left(\frac{\partial c}{\partial T_f}\delta T_{fluid}\right)^2 + \left(\frac{\partial h_c}{\partial T_c}\delta T_{cold}\right)^2} \quad (12)$$

$$\delta Nu = \sqrt{\left(\frac{\partial Nu}{\partial h}\delta h_{avg}\right)^2 + \left(\frac{\partial Nu}{\partial L}\delta L\right)^2 + \left(\frac{\partial Nu}{\partial k_{nf}}\delta k_{nf}\right)^2} \quad (13)$$

Result and discussions

Morphology effect of $MgFe_2O_4$ nanoparticles on thermophysical properties

Figure 3(a) illustrates the variation of thermal conductivity of $MgFe_2O_4$ FF having cube shaped NPs at 0 and 350 Gauss magnetic flux. At 0 Gauss the thermal conductivity of FF with cube particles increases as the VF raises from 0.01% to 0.15%. Thermal conductivity of BF at 25°C is measured as 0.596 W/mK and it is increased by 6.04% at 0.01% VF. By augmenting the VF to

0.15%, thermal conductivity again enhanced to 12.75% concerning that of BF. Whereas by rising the VF from 0.15% to 0.20%, the thermal conductivity of FF was reduced by 1.19%, but it is higher than that of BF by 11.40 %. Prior studies have been undertaken to determine the thermal conductivity of disk shaped $MgFe_2O_4$ NPs, it showed a maximum thermal conductivity augmentation of 10.06 % at a VF of 0.20 % to BF [23] and it is lower than that of the same FF with cube structure NPs. The thermal conductivity of FF improves with increasing magnetic flux strength from 0 to 350 Gauss. And maximum improvement of 21.82% was noticed by the application of magnetic flux 350 Gauss for FF with cube shaped NPs at a VF of 0.15%. It was pointed out that magnetic flux influenced thermal conductivity of $MgFe_2O_4$ FF having cube shaped NPs is greater than those of disk shape NPs (13.92% at 0.20% and 350 Gauss). The viscosity of $MgFe_2O_4$ FF with cube structure NPs at various VFs and comparison of results with those of FF having disk NPs are represented in Figure 3(b). From this analysis, it is clear that the viscosity of FF consisting of cube shaped NPs is more dominant than the same FF with disk shaped NPs. The viscosity of BF deionized water is enhanced with the addition of $MgFe_2O_4$ NPs. The results indicated that the viscosity of FF augmented more at the highest VFs. The maximum viscosity improvement of 32.92% is observed for a 0.20% VF of the FF having cube shaped NPs. It is noted that the viscosity of $MgFe_2O_4$ FF with disk shaped NPs increased by 25.51% at a VF of 0.20%[23]. This shows that FF with cube shaped NPs possesses higher viscosity than a fluid with disk shaped NPs at the same experimental condition. At 350 Gauss magnetic flux, the viscosity of FF with the cube and disk shaped NPs are augmented. The viscosity of FF (0.20%) with cube shaped NPs improved from 32.92% to 37.41% and for FF with disk shaped NP it enhanced from 25.51% to 28.31% at 350 Gauss. Variation in the density of FF with cube and disk shaped NPs with and without the application of magnetic flux is represented in Figure 3(c). The density of FF with the addition of cube shaped NPs raised from 0.75% to 6.11% for the respective VFs from 0.01% to 0.20%. In the absence of magnetic flux, FF with cube shaped NPs at VF 0.20% exhibits more percentage of enhancement (6.11%) than FF with disk shaped NPs (5.33%). By the application of magnetic flux 350 Gauss, the density of FF with cube and disk shaped NPs reduced, and the maximum percentage of reduction is observed at VF 0.20% of FF.

In the absence of applied magnetic flux, when cube shaped magnetic NPs with a high aspect ratio are suspended in the BF, the brownian motion of dispersed particles inside the BF increases. As a result, the interaction between the NPs and fluid molecules improves, thus thermal energy transaction between the particles and fluid raises. As a result, the thermal conductivity of FF increases. By raising the cube shape NPs concentration in the BF, the brownian motion of NPs in the BF also increases and results in high thermal conductivity [26] However, the higher concentration of particles in the BF leads to the agglomeration of NPs in the BF and it deteriorates the brownian motion of particles at higher concentration and results in the reduction of thermal conductivity of FF. This may be the reason for diminishing of thermal conductivity of FF having cube shaped particles at 0.20% VF. At the same time, the viscosity and density of the FF having cube shaped particles increases with respect to the rise in VF due to the high agglomeration of NPs. Due to the high aspect ratio of cube shaped NPs compared to disk shaped NPs the chain-like aggregation of cube shape particles are higher than disk shape particles in the BF [27]. This results in the enhanced thermophysical properties for FF having cube shaped particles. With the influence of magnetic flux, the cube shaped NPs will align in the chain-like form in the BF in a direction parallel to the direction of magnetic flux and this leads to the formation of large chain-like clusters of NPs. This chain-like formation of magnetic NPs act as a heat transfer path, thus thermal conductivity of the FF increases along with viscosity augmentation [28].

Morphology effect on magnetohydrodynamic natural convection of ferrofluid

The effect of morphology on the free convection heat transfer performance of $MgFe_2O_4$ FF in the cubical cavity is analyzed by determining the h_{avg} and *Nu* of the FF filled cavity. Here the h_{avg} is calculated as the average of the heat transfer coefficient at hot and cold side of the cavity. Figure 4(a) shows the variation of the h_{avg} of the cavity with an increase in wall temperature difference between the hot and cold side of the cavity for different working fluids filled in the cavity without the application of magnetic flux. The h_{avg} of the cavity filled with FF consisting of cube shaped NPs at various VFs 0.01%, 0.025% and 0.05% is higher than that of BF. And more improvement in h_{avg} (27.20%) is observed at VF 0.025% of FF with cube shaped particles at wall temperature difference 25ºC compared to that of the BF. However, with the increasing VF of FF from 0.025% to 0.05%, the h_{avg} of the cavity was reduced to 11.99%. Furthermore, the h_{avg} of the cavity filled with FF consisting of disk shaped NPs showed an optimum VF for a higher h_{avg} as 0.05% by an enhancement of 23.50%. At this instant FF having cube shaped NPs indicated a higher h_{avg} at a lower VF (0.025%) compared to FF with disk shaped (0.05%) NPs. Figure 4(b) shows the effect of magnetic flux on the h_{avg} of the magnetic fluid-filled cavity. With the application of magnetic flux ranging from 0 to 350 Gauss, the h_{avg} of the cavity filled with FF consisting cube shaped particles at VF 0.025% was enhanced from 27.20% to 37.95% at a wall temperature difference of 25ºC compared to BF. At the same experimental condition, the h_{avg} of the cavity filled with FF consisting of disk shaped NPs shows an enhancement of 36.01% at VF 0.05% and magnetic flux 350 Gauss.

Figure 5(a) shows the influence of varying Rayleigh number (*Ra*) on the *Nu* of the FF -filled cavity in the absence of magnetic flux. The *Nu* of the FF -filled cavity is raised by increasing the *Ra* for all VFs of FF with cube shaped NPs. The maximum *Nu* obtained at 0.025% VF of FF consisting of cube shaped NPs at *Ra* 8.74×10^9 (34.84% higher than BF water). The increase in

VF from 0.025% to 0.05% of FF consisting of cube shaped NPs reduced the *Nu* by 7.92%. It is also observed that FF filled cavity with cube shape NPs at 0.025% exhibited more *Nu* (1.09% higher) than FF with disk shape NPs at VF 0.05%. Figure 5(b) shows the comparison of *Nu* of FF consisting cube and disk shaped NPs filled cavity in the presence of magnetic flux 350 Gauss. At 350 Gauss magnetic flux *Nu* inside the cavity field with FF with disk shaped NPs at VF, 0.05% enhanced by 41.76% compared to that of the BF. At the same instance, the *Nu* for a cavity filled with FF consisting of cube shaped NPs was enhanced by 44.57% compared to the BF. This result shows that FF with cube shaped NPs exhibits more natural convection heat transfer enhancement than disk shaped NPs. The aspect ratio of cube-shaped NPs is higher than that of disk-shaped NPs, this greatly enhances the natural convection heat transfer performance of $MgFe_2O_4$ FF with cube shaped particles. Table 2 presents the natural convection heat transfer performance of various NFs in different type of enclosures. And these results reported that optimum VF for enhanced natural convection heat transfer performance was obtained at certain VF s in the range of 0.05% to 0.10%. At the same time this study confirms that better heat transfer performance of FF can be obtained at lower VF s such 0.025% by the use of low density $MgFe_2O_4$ FF having cube shaped NPs. Thus, this study suggests that the application of low density FF with high aspect ratio NPs could improve the natural convection heat transfer performance at lower VFs.

Conclusion

The effect of $MgFe_2O_4$ NPs morphology on the magnetic flux dependent thermophysical properties of FF at temperature 25^{o}C is measured and the natural convection heat transfer is also measured using a heat pipe assisted cavity. The conclusions arrived from this experimental analysis

- In the absence of magnetic flux, thermal conductivity of $MgFe_2O_4$ FF having cube shaped particles enhanced by 12.75% at a VF of 0.15%. At the same time, the maximum viscosity and density were raised by 32.92% and 6.11% at a VF of 0.20% in comparison with water.
- Thermal conductivity of $MgFe_2O_4$ FF containing cube structure NPs at a VF of 0.15 % was increased from 12.75 to 21.82 % when 350 Gauss magnetic flux was applied. By comparing these results to those obtained with FF containing disk-shaped NPs, it is revealed that $MgFe_2O_4$ magnetic fluid containing cube-shaped NPs has better thermal conductivity.
- The viscosity of FF containing cube and disk shaped NPs increased while the density decreased when subjected to magnetic flux
- FF having cube shaped NPs indicated a higher h_{avg} of 27.20% at a lower VF of 0.025% compared to FF with disk shaped NPs (23.50% enhancement at a VF of 0.05%).

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Disclosure Statement

We wish to confirm that the present manuscript titled "Morphological effects on natural convection heat transfer of magnesium ferrite ferrofluid" authored by Ajith, Archana Sumohan Pillai, Muthu Vijayan Enoch, Li-Zhi Zhang, Brusly Solomona, Mohsen Sharifpur, Josua Meyer, Deepak Tudu is a new research work carried out at our institution. We wish to confirm that there is no conflict of interest among the co-authors. And the Authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Nomenclature

A	Area of the cavity, m^2
BF	Base fluid
C_p	Specific heat, J/kg °C
g	Acceleration due to gravity, m^2/s
FF	Ferrofluid
h	Heat transfer coefficient, W/ m^2 °C
I	Current, A
L_c	Characteristic length of cavity, m
m	Mass flow rate, kg/ second
$MgFe_2O_4$	Magnesium Ferrite
NF	Nanofluid
NPs	Nanoparticles
Nu	Nusselt number
Pr	Prandtl number
Q	Heat transfer, W
Ra	Rayleigh number
SDS	Sodium Dodecyl Sulfate
T	Temperature, °C
V	Voltage, v
VF	Volume fraction

Greek Symbols

ρ	density (kg/m^3)
Δ	difference

μ	dynamic viscosity (Cp)
∂	partial derivative
β	thermal expansion coefficient, 1/K
k	thermal conductivity, W/m ºC
Φ	volume fraction (%)

Subscripts

avg	average
bf	base fluid
cold	cold side
hc	hot and cold side
hot	hot side
in	input
nf	nanofluid
np	nanoparticles
out	output
w	water
wf	working fluid

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Table 1Uncertainty in measurement of thermophysical properties

Thermophysical properties	**Average Uncertainty**
Thermal conductivity	0.0755%
Viscosity	2.64%
Density	1.98%

Table 2 Natural convection heat transfer enhancement of various nanofluid at different volume fractions

Authors	**Type of nanofluid**	**Nanoparticles Shape**	**Optimum Volume fraction**	**Percentage of Improvement**
Brusly Solomon et al. [2]	Al_2O_3 + Ethylene glycol	Spherical	0.05%	10%
Sharifpur et al.[3]	TiO_2 + Water	Spherical	0.05%	8.2%
Garbadeen et al.[29]	MWCNT + Water	Cylindrical Nanotubes	0.10%	45%
Ghodsinezhad et al.[30]	Al_2O_3 + Water	Spherical	0.10%	15%
Giwa et al.[31]	Al_2O_3: MWCNT (60:40 wt%) + Water	Spherical & Cylindrical	0.10%	20.5%
Hu et al.[32]	Al_2O_3 + Water	Not specified	1wt%	7%
Ilyas et al.[33]	Al_2O_3 + Thermal oil	Not specified	0.5wt%	2.72%
Joubert et al.[34]	Fe2O3 + Water	Spherical	0.10%	5.63%
Lei et al.[35]	Fe_3O_4: CNT + Water	Not specified	2:1	15%
Giwa et al.[36]	Fe_2O_3:Al_2O_3 + Water	Spherical	0.10%	10.81%
Giwa et al.[37]	Fe_2O_3: MWCNT + Water	Spherical & Tubular	0.05%	11.21%

LIST OF FIGURES

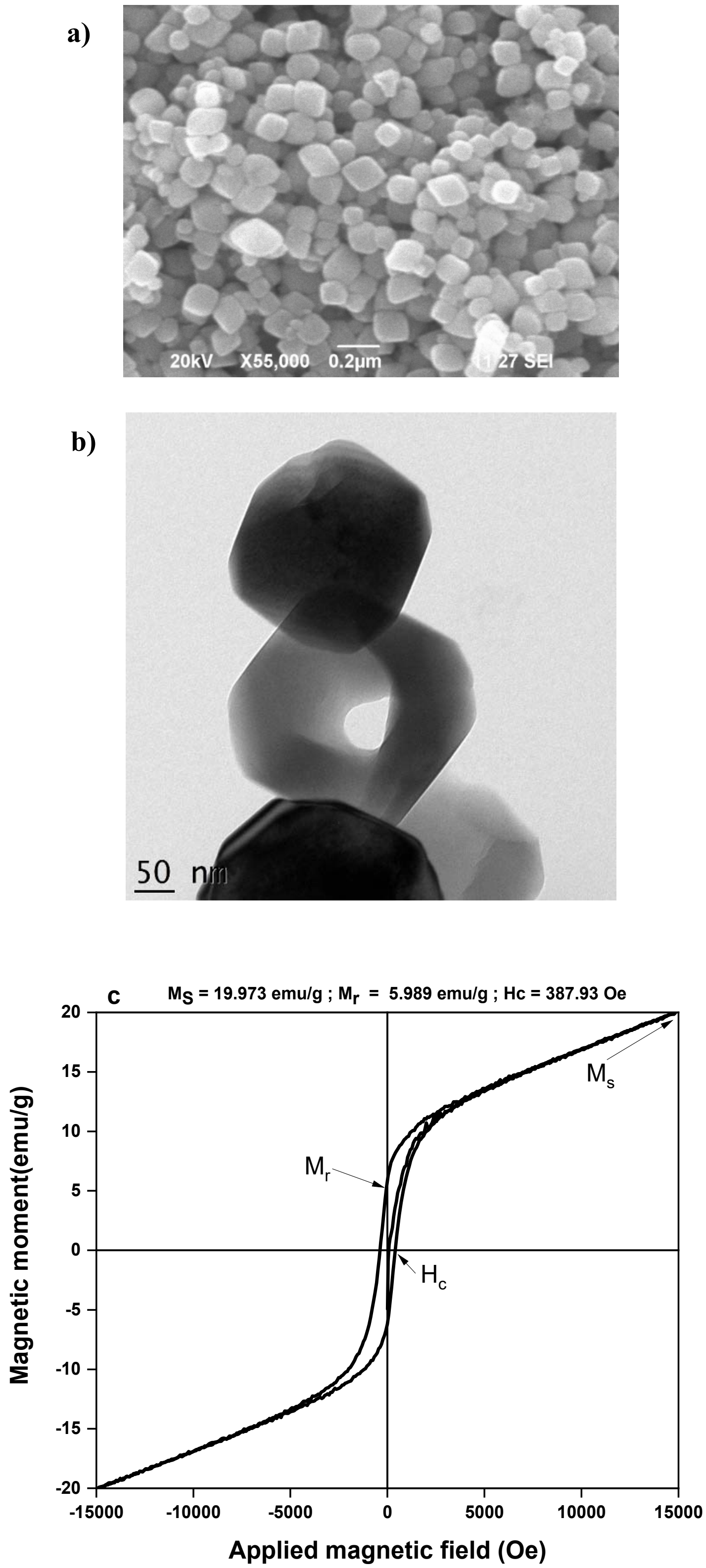


Figure 1 Particle characterization using a) SEM; b) TEM and c) magnetic hysteresis of Cube shape magnesium ferrite nanoparticles

a)
b)
c)

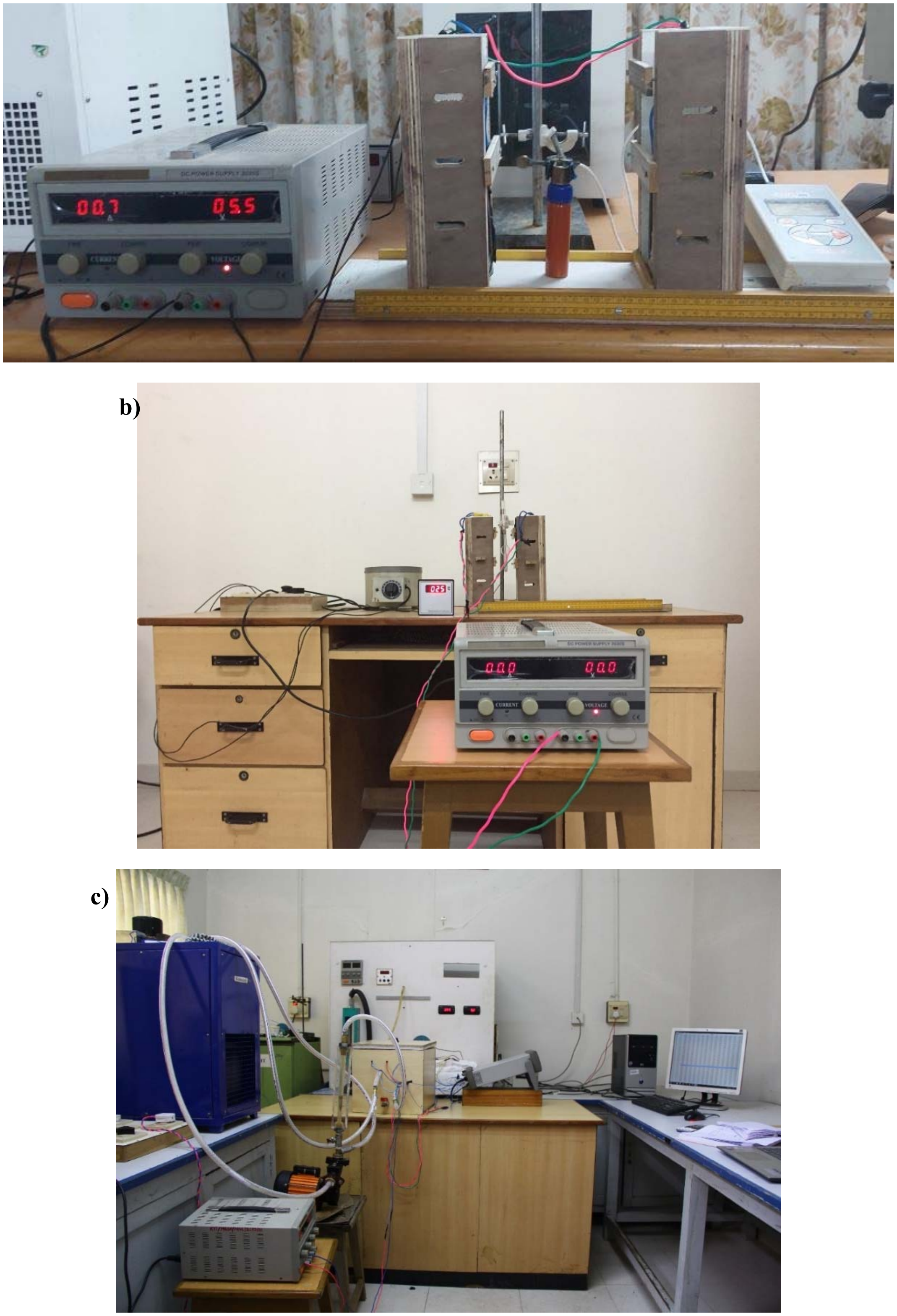
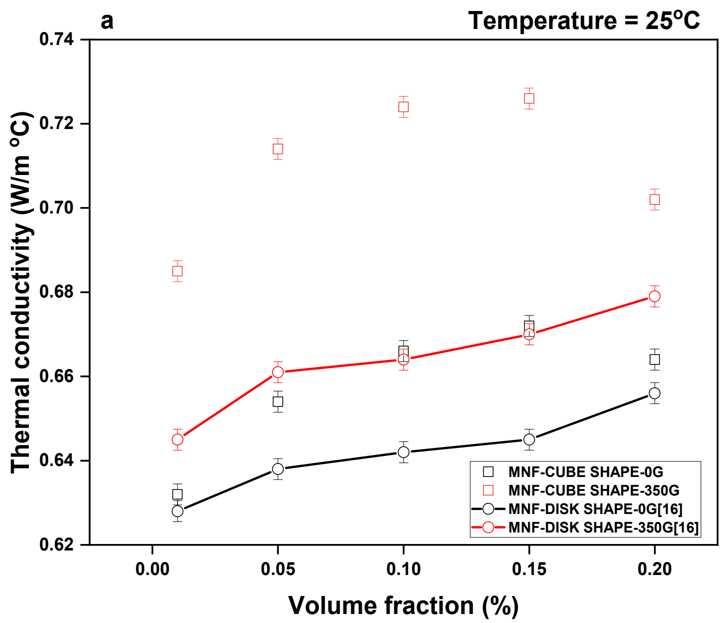
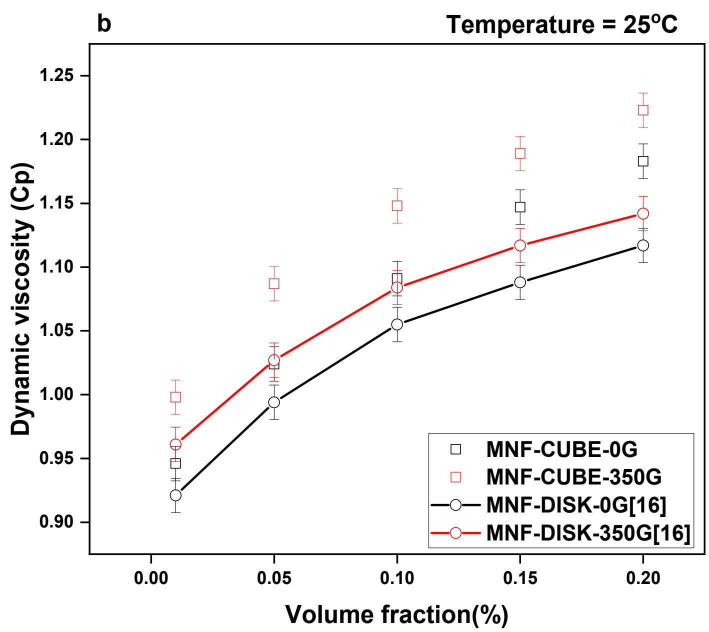


Figure 2 Experimental setup for a) Thermal conductivity; b) Viscosity; c) Magnetohydrodynamic natural convection analysis of magnesium ferrite ferrofluid with cube shape nanoparticles


a
Temperature = 25°C
Thermal conductivity (W/m °C)
Volume fraction (%)
0.74
0.72
0.70
0.68
0.66
0.64
0.62
0.00
0.05
0.10
0.15
0.20
MNF-CUBE SHAPE-0G
MNF-CUBE SHAPE-350G
MNF-DISK SHAPE-0G[16]
MNF-DISK SHAPE-350G[16]


b
Temperature = 25°C
Dynamic viscosity (Cp)
Volume fraction(%)
1.25
1.20
1.15
1.10
1.05
1.00
0.95
0.90
0.00
0.05
0.10
0.15
0.20
MNF-CUBE-0G
MNF-CUBE-350G
MNF-DISK-0G[16]
MNF-DISK-350G[16]

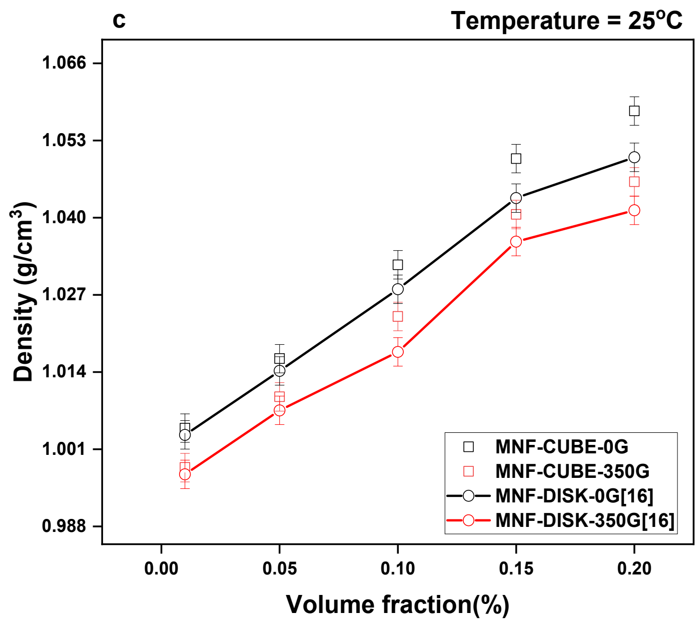


Figure 3 Effect of particle morphology on a) Thermal conductivity; b) Viscosity; and c) Density of magnesium ferrite ferrofluid

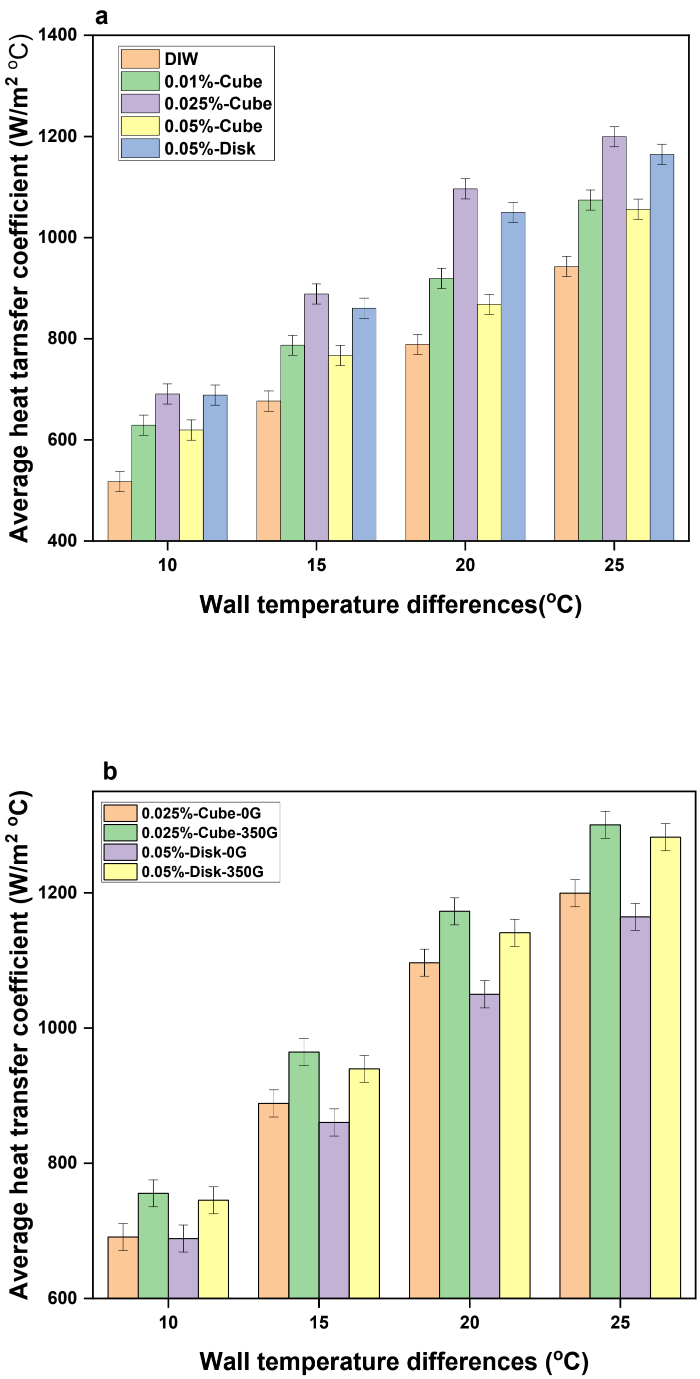
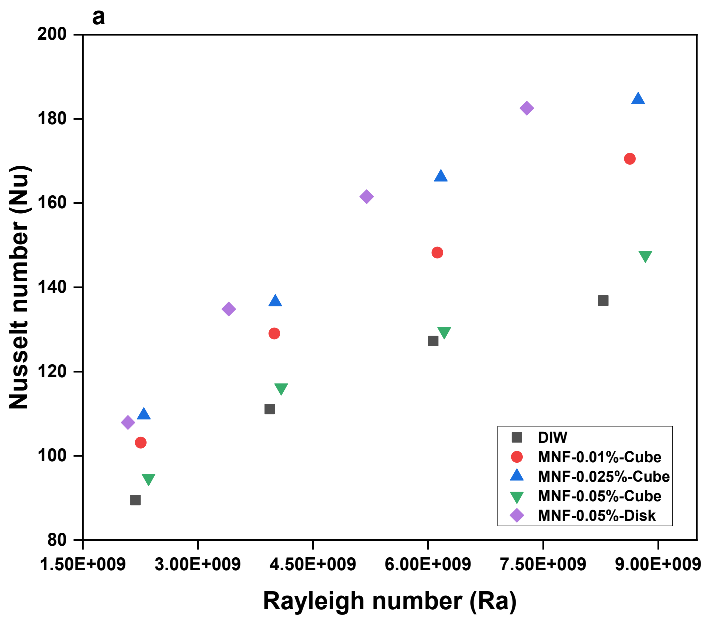


Figure 4 Effect of surface morphology on average heat transfer coefficient of ferrofluid in the a) absence; and b) presence of magnetic field



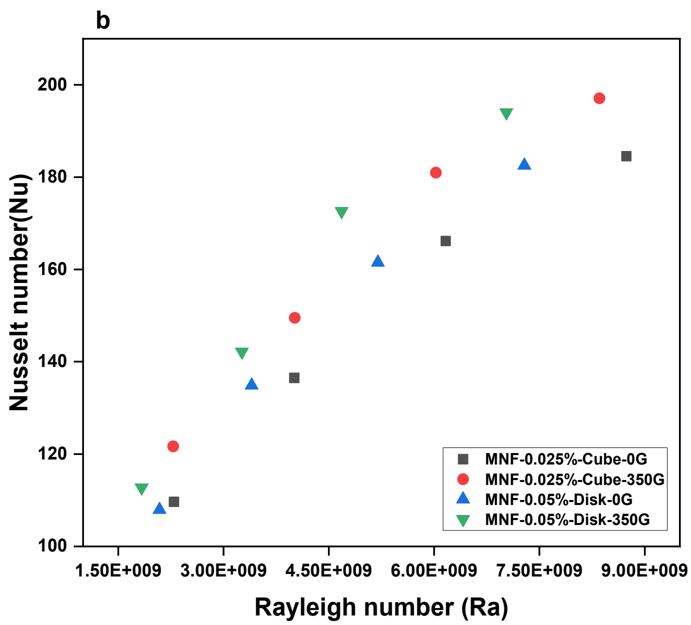


Figure 5 Effect of surface morphology on variation of Nusselt number in the a) absence; b) presence of magnetic field

Mr. Ajith received his B. Tech in Mechanical Engineering from Calicut University and his Masters in Thermal systems from Calicut University. Currently, He is Full-time research scholar in the Department of Mechanical Engineering in Karunya Institute of Technology and Sciences. He has authored/co-authored 3 refereed International Journals. He has also presented 3 papers in reputed International Conferences. His areas of interest include Heat transfer, Renewable Energy, and Computational Fluid Dynamics.

Ms. Archana Sumohan Pillai is currently an Assistant professor and a doctoral candidate pursuing her degree (since July 2019) in the field of nanoscience from Karunya University. Her research is focused on developing NIR-absorbing magnetic nanocarriers for anti-cancer drug delivery. She pursued her M.Sc. (Int) in Nanoscience & technology from Karunya University.

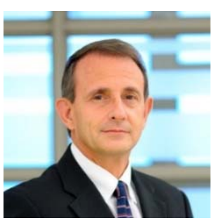
Dr. Enoch had his initial schooling in Margoschis Higher Secondary School and undergraduate education in Nazareth Margoschis College. He graduated with M.Sc. Organic Chemistry and M.Phil. from Annamalai University, Chidambaram. Dr. Enoch worked with Prof. M. Swaminathan in Annamalai University and earned doctorate in the year 2005. In addition, he earned M.Tech. Nanotechnology from Anna University of Technology, Coimbatore. For his postdoctoral research, Dr. Enoch worked with Prof. Yves Mely, University of Louis Pasteur, France. Dr. Enoch is a veteran in teaching with 14 years of experience. He has instructed students of B.E/B.Tech, B.Sc. Chemistry, M.Sc. Chemistry, M.Sc. Organic Chemistry, M.Sc. Nanoscience & Technology, and M.Tech. Nanotechnology. He extended an active contribution to the design of the M.Sc. programme in Nanoscience & Technology and its programme structure, and curriculum and syllabi. Dr. Enoch has published more than 110 articles in reputed scientific journals mostly as either the first or corresponding author.

Li-Zhi Zhang has worked with Functional materials and Heat and Mass Transfer, with Built Environmental technologies since 1992. His research interests include: membrane technologies; Development of novel functional materials for built environment; self-cleaning surfaces. He has been the principal investigators for numerous fundings like NSFC (Natural Science Foundation of

China, key projects, distinguished young scholar project); National Key projects of Science & Technology; Key projects of provincial and municipal governments, etc. Li-Zhi Zhang has published more than 150 SCI papers in international journals. Among them, ESI Highly-cited paper 1; Cover article 1; Featured article 1. He has authored 5 books in advanced humidity control and heat and mass transfer. His book titled "Conjugate Heat and Mass Transfer in Heat Mass Exchanger Ducts" was published by Academic Press, Elsevier, in 2013. He has been cited more than 5000 times on SCI, and his current ISI H-index is 46.

Dr. Brusly Solomon is currently an Associate Professor (since July 2018) in the Department of Mechanical Engineering at Karunya Institute of Technology and Sciences (KITS), Coimbatore. He joined as Research Associate in the Dean Research office of the KITS in the year 2006. He received his doctorate in the Department of Mechanical Engineering from Karunya Institute of Technology and Sciences, Coimbatore in 2014. His research focused on the development of phase change cooling devices such as heat pipes and thermosyphons and vapor chambers with nanofluids and various wick materials. He pursued his Post-doctoral research in the Thermo fluids Research Laboratory of Department of Mechanical and Aeronautical Engineering, University of Pretoria. He is recipient of Govt. of India, Young Scientist Award 2015 by Science and Engineering Research board, Young Achievers Award 2015 by Karunya Institute of Technology and Sciences, UP postdoctoral fellowship 2015 by University of Pretoria.

Mohsen Sharifpur is a Professor in the Department of Mechanical and Aeronautical Engineering at the University of Pretoria and is responsible for the Nanofluids Research Laboratory. He received his B.Eng. (Mechanical Engineering) degree from Shiraz University in Iran. He completed his M.Eng. degree in Nuclear Engineering and Ph.D. in Mechanical Engineering (Thermal Fluid). He is the author and coauthor of more than 120 articles and conference papers. His research interests include convective multiphase flow, thermal fluid behavior of nanofluids, convection in porous media, computational fluid dynamics and fluid dynamics from nano-scale to the Universe scale. He is rated as a C2 scientist by National Research Foundation (NRF) of South Africa. He has also recognized as a Professional Engineer (Pr. Eng) by Engineering Council of South Africa.



Prof Josua Meyer, was in April 2022 appointed as a professor at Stellenbosch University. Before this appointment he was a professor at the University of Pretoria. During his professor term he was the Head of Mechanical and Aeronautical Engineering (1 900 students) for 20 years, and Chair of the School of Engineering (7 000 students) for 17 years. His research has a broad focus on the thermal sciences, but with a narrower focus on heat exchangers. His heat exchanger work focuses on fundamental work in internal forced convection, the transitional flow regime, nanofluids, boiling, and condensation. On an applications level his work focuses on thermalsolar, wind- and nuclear energy. He has grown this research group to approximately 30 full-time graduate students and 10 staff members. During this time he also established various labs with state-of-the-art instrumentation and designed and constructed (with his group members) more than 12 unique experimental set-ups. He has received 11 different national teaching awards from three different universities, as well as an international award.

Mr. Deepak Tudu is a Mechanical Engineering graduate. He received his B-Tech degree in the department of Mechanical Engineering from Karunya Institute of Technology and Sciences, Coimbatore in 2020.