Khairul, M. A.; Alam, M; Doroodchi, Elham; Azizian, Reza; Moghtaderi, Behdad; 'Advanced applications of tunable ferrofluids in energy systems and energy harvesters: a critical review.' Published in *Energy Conversion and Management* Vol. 149, p. 660-674 (2017)

Available from: http://dx.doi.org/10.1016/j.enconman.2017.07.064

Advanced applications of tunable ferrofluids in energy systems and energy harvesters: a critical review

M.A. Khairul[1], Elham Doroodchi[2], Reza Azizian[3], Behdad Moghtaderi[1,]*

[1]Priority Research Centre for Frontier Energy Technologies and Utilisation, Chemical Engineering, Faculty of Engineering and Built Environment, The University of Newcastle, Callaghan, NSW 2308, Australia.

[2]Center for Advanced Particle Processing, Chemical Engineering, Faculty of Engineering and Built Environment, The University of Newcastle, Callaghan, NSW 2308, Australia.

[3]Advanced Thermal Solution Inc., 89-27 Access Road, Norwood 02062, MA, USA.

Abstract

Ferrofluids or Magnetic nanofluids (MNFs) are the suspensions of magnetic nanoparticles and non-magnetic base fluid. The heat transfer performance of a magnetic nano-suspension is influenced by the strength and orientation of an applied magnetic field. The main attraction of these types of nanofluids is that they not only enhance the fluids' thermophysical properties but also possess both magnetic characteristics like the other magnetic materials and flow ability similar to any other fluids. Such an exclusive feature enables to control heat transfer, fluid flow and movement of the nanoparticles by using the external magnetic fields. This review paper summarises the recent investigations of magnetic nanofluids with the aim of identifying the effects of major parameters on the performance of heat transfer. In addition, this study also acknowledged the novel application of ferrofluids in the electromagnetic energy harvesters, and its challenges as well as the potentiality in the future research.

[*] Corresponding author: Tel: +61 2 4033-9062, Fax: +61 2 4033-9095
Email: Behdad.Moghtaderi@newcastle.edu.au (Attn: Professor Behdad Moghtaderi)

Keywords: Magnetic nanofluid; ferrofluid; electromagnetic energy harvester; stability; heat transfer enhancement; electromechanical systems (MEMS)

Contents

Abstract 1
Contents 2
Nomenclature 2
1. Introduction 3
2. Preparation and characterisation of magnetic nanofluids 6
3. Stability of magnetic nanofluids 10
4. Mechanism of heat transfer enhancement using magnetic nanofluids 14
4.1 Brownian motion 15
4.2 Liquid layering on the nanoparticle-liquid interface 16
4.3 Effects of nanoparticles clustering 17
5. An overview of thermal properties of magnetic nanofluids 18
5.1 Effects of nanoparticle size 20
5.2 Effects of magnetic field 21
5.3 Effects of chain-like structures of the magnetic nanoparticle 24
6. Convective heat transfer and pressure drop characteristics of magnetic nanofluids 25
7. Ferrofluid based energy harvester 32
8. Conclusion and recommendations for future work 38
Acknowledgments 40
References 40

Nomenclature

A	constant	Re	Reynolds number
C_p	specific heat capacity ($J/kg\ K$)	T	temperature (K)

d	sample size (*m*)	V	velocity (*m/s*)
$\vec{f}$	vector sum of the gravitational body force (*N/m³*)	Greek symbols	
g	gravitational acceleration (m/s^2)	φ	particles volume fraction
g^*	effective acceleration (m/s^2)	ρ	density (kg/m^3)
Gr	total potential energy (*J*)	$\Delta\rho$	density difference (kg/m^3)
h	liquid height (*m*)	μ	viscosity ($N\,s/m^2$)
H	magnetic field (*A/m*)	μ_0	vacuum permeability (*H/m*)
k_B	Boltzmann constant (*J/K*)	β	relative coefficient
K	thermal conductivity (*W/m. K*)	γ	system dependent coefficient
M_0	Magnetisation (*A/m*)	Subscripts	
Pr	Prandtl number	f	base fluid
ΔP	pressure drop (*Pa*)	L	liquid
R	radius of the container (*m*)	m	magnetic
R'	radius of the spherical particle (*m*)	p	particle
Ra	Rayleigh number	T	thermal

1. Introduction

Currently, cooling is one of the most important scientific challenges in production related industries, such as transportation, manufacturing and microelectronics. Technological advancements have led to increased thermal loads and thus, improvements to cooling systems have become a necessity. Maximising the surface area of heat exchanger systems is the conventional approach to enhance heat dissipation. However, this method needs an unwanted rise in the size of thermal management systems, thus, there is an urgency for novel coolants with enhanced performance [1]. One such coolant is the innovative concept of ‘nanofluids’, which are a mixture of metallic/nonmetallic nanoparticles in a base fluid. The term nanofluid was originally introduced by Choi at Argonne National Laboratory [2]. A substantial improvement in liquid thermal conductivity, specific heat and viscosity are the unique features of nanofluids. The relatively large overall surface area of nanoparticles not only improves heat transfer capabilities but also increases the stability of the suspension by alleviating particle settling phenomenon. There are also several potential benefits from nano-suspension testing, specifically: better long-standing stability compared to the millimetre or even micrometre sized particle suspensions and lower erosion and pressure drop, especially in micro-channels [3]. Nanofluids are very potential fluids for heat transfer application [4-7].

A unique class of nano-suspensions named magnetic nanofluids demonstrate both fluid and magnetic properties. Magnetic nanofluids have drawn considerable attention due to the possibility of tuning their heat transfer and flow properties through the application of an external magnetic field [8, 9]. The nanoparticles can be either ferromagnetic materials, such as cobalt or iron, or ferrimagnetic materials such as magnetite. Magnetite nanoparticles are not susceptible to oxidation and therefore are a far better alternative to iron or cobalt nanoparticles which tend to lose their magnetic characteristics over time because of oxidation [10]. Magnetite-based nanofluids with particle sizes less than 10 nm, known as ferrofluids, were initially introduced by Stephen Pappell in the 1960s (at NASA) as an advanced method for controlling fluid in space [11]. He concluded that magnetite nanofluids have a wide range of applications from lubricating rotary shafts to biomedicine. These types of nanofluids have improved thermal properties (such as heat capacity, thermal conductivity, viscosity etc.), as well as magnetic properties, both of those tunable characteristics help to control the heat transfer and the movement of the particle by applying the magnetic fields. As a result, they are believed to be one of the promising fluids in different engineering fields such as bioengineering, thermal engineering, electronics, and energy harvests [12, 13].

However, when subjected to an external magnetic field, the thermal conductivity of magnetite nanofluid can be raised to levels much higher than any other nanofluid. In one such example, Philip et al. [14] have shown remarkable enhancements in thermal conductivity of up to 300%

for a magnetite based nanofluid. This high rise in thermal conductivity is associated with the effective heat conduction through the chain-like structures induced in the magnetite nanofluid. The advantage of using a magnetically polarisable nanofluid, such as magnetite nanofluid, is that the size, shape and form of aggregates can be precisely controlled by the external magnetic field. More importantly, unlike other nanofluids, the aggregation observed in magnetite nanofluids is perfectly reversible due to the super-paramagnetic nature of particles [15]. This tunable nature offers great opportunities for resolving the inherent problems associated with conventional nanofluids, such as lower heat transfer capacity, clogging and blockage of the flow passage. The ferrofluid with magnetic fields in the application of heat transfer is considered as the compound heat transfer method [16]. The magnetic nanofluids offer the following advantages compared to the nonmagnetic nanofluids [17];

(a) the temperature gradient and non-uniform magnetic field are induced by using a magnetic field, which may initiate a flow in the fluid. Such phenomenon is called thermomagnetic convection [18] and it is readily handled;

(b) the thermomagnetic convection is higher compare to the gravitational convection;

(c) the possibility of changing thermal properties of ferrofluids by applying external magnets/solenoids [19, 20]

Furthermore, a ferrofluid is a suspension of solid-liquid, made-up from nano-sized permanent magnetic dipoles [21]. The magnetic nanofluids are potential fluids for vibrational energy harvesting application due to their fluidity and magnetic properties in which they act as a soft ferromagnetic substance [22, 23]. Energy harvesting is an alteration of the environmental energy to the electrical energy at a small scale and was originally introduced in 1966 [24]. The energy sources for energy harvesters are freely available in the environment. Examples of energy sources include vibration, wind energy, wave energy, and thermal temperature gradients. Nowadays energy harvesting has become a hot topic for research because of its exceptional advantages. The cost of the battery supply, in particular, the maintenance cost to replace the discharged batteries, make the energy harvesters a very attractive option. The conventional energy harvesting techniques only capable to generate a few micro-watts, whereas vibration energy harvesters demonstrate high performance in less vibration by replacing the solid magnets with ferrofluid.

Recently magnetite nanofluids have come to the attention of the research community after showing high enhancement in heat transfer by applying external magnetic field as well as their usage in the electromagnetic energy harvesters to generate more power with a small vibration with compare to the traditional harvesters. The objective of this paper is to concentrate on the recent investigations of magnetic nanofluids in the application of heat transfer and energy harvesting. It is anticipated that this review paper will help to provide a clear idea about the current status of ferrofluid, and also specify the recommendations for the future study.

2. Preparation and characterisation of magnetic nanofluids

The magnetic nanofluids are prepared by dispersing of super-paramagnetic nanoparticles into a non-magnetic base fluid such as water, hydrocarbon oil and so on [25]. Generally, the preparation of ferrofluids consist of two steps: (a) the magnetic nanoparticles preparation, (b) the dispersion of the synthesised magnetic nanoparticles in different polar/non-polar carrier liquids. In the first step, the nano-sized magnetic particles can be produced by various processes such as ball milling [26], sonochemically synthesised [27], sol-gel method [28, 29], reverse micelle technique [30], and thermal decomposition [31]. Moreover, the metal oxide magnetic nanoparticles are synthesised by micro-emulsion, chemical co-precipitation and phase transfer methods [25, 29, 32-34]. In the second step, the magnetic nanoparticles are coated by various methods such as co-precipitation [29], core-shell [35], and then dispersed in the base fluids.

Currently some researches have completed experiments to synthesise metal and metal oxide magnetic nanoparticles with a specific size distribution [32]. Metallic nanoparticles were prepared using different techniques such as the thermal decomposition of metal carbonyl complexes, the simple reduction of metal salts, thermolysis of metal-polymer complexes, submerged arc nanoparticle synthesis system, and gas phase reduction of metal complexes [32, 36]. Among the metal oxide nanoparticles, Fe_3O_4, γ-Fe_2O_3 and spinel type ferrites (MFe_2O_4, with M= Mn, Co, Zn, Ni, etc.) are most commonly used nanoparticles because of their chemical stability. The most efficient method for the ferrite nanoparticles and subsequent magnetic fluid preparation is chemical precipitation [37]. The preparation of magnetic nanofluids consist the following steps;

- co-precipitation ($\approx$80 ºC) of magnetite from aqueous solutions of Fe^{3+} and Fe^{2+} ions in solutions of sodium hydroxide (NaOH), ammonium hydroxide (NH_4OH) or potassium hydroxide (KOH) [38]; and ammonium hydroxide has better crystallinity, smaller size and higher magnetic saturation among them [39]
- subdomain magnetite particles
- steric stabilisation (chemisorption of lauric acid, myristic acid or oleic acid; 80–82 ºC)
- phase separation, and magnetic decantation as well as repeated washing
- mono-layer covered magnetite nanoparticles + free surfactant
- extraction of mono-layer covered magnetite nanoparticles (acetone addition; flocculation)

Cobalt ferrite and Fe_2O_3 nanoparticles were prepared using NaOH instead of NH_4OH.

Finally, the dispersion of lauric acid, myristic acid or oleic acid mono-layer coated synthesised magnetic nanoparticle in non-polar carriers (such as kerosene, toluene, cyclohexane, transformer oil, etc) are demonstrated as follows;

- the dispersion process of nanoparticles in non-polar carriers carried out at the temperature of 120-130 ºC [40]
- magnetic decantation/filtration; and repeated flocculation and redispersion of magnetic nanoparticles for the elimination of free surfactant called advanced purification process

whereas, the dispersion method of magnetic nanofluids in organic polar carriers such as alcohol, diester, ketone, amine, different mixtures of mineral and synthetic oils involves;

- primary magnetic fluid on light hydrocarbon carrier
- repeated flocculation and redispersion of magnetic nanoparticles to eliminate the free surfactant known as advanced purification
- mono-layer stabilised magnetic nanoparticles
- dispersion in a polar solvent (stabilisation with a secondary surfactant, e.g. dodecylbenzenesulphonic acid, physically adsorbed to the first layer)

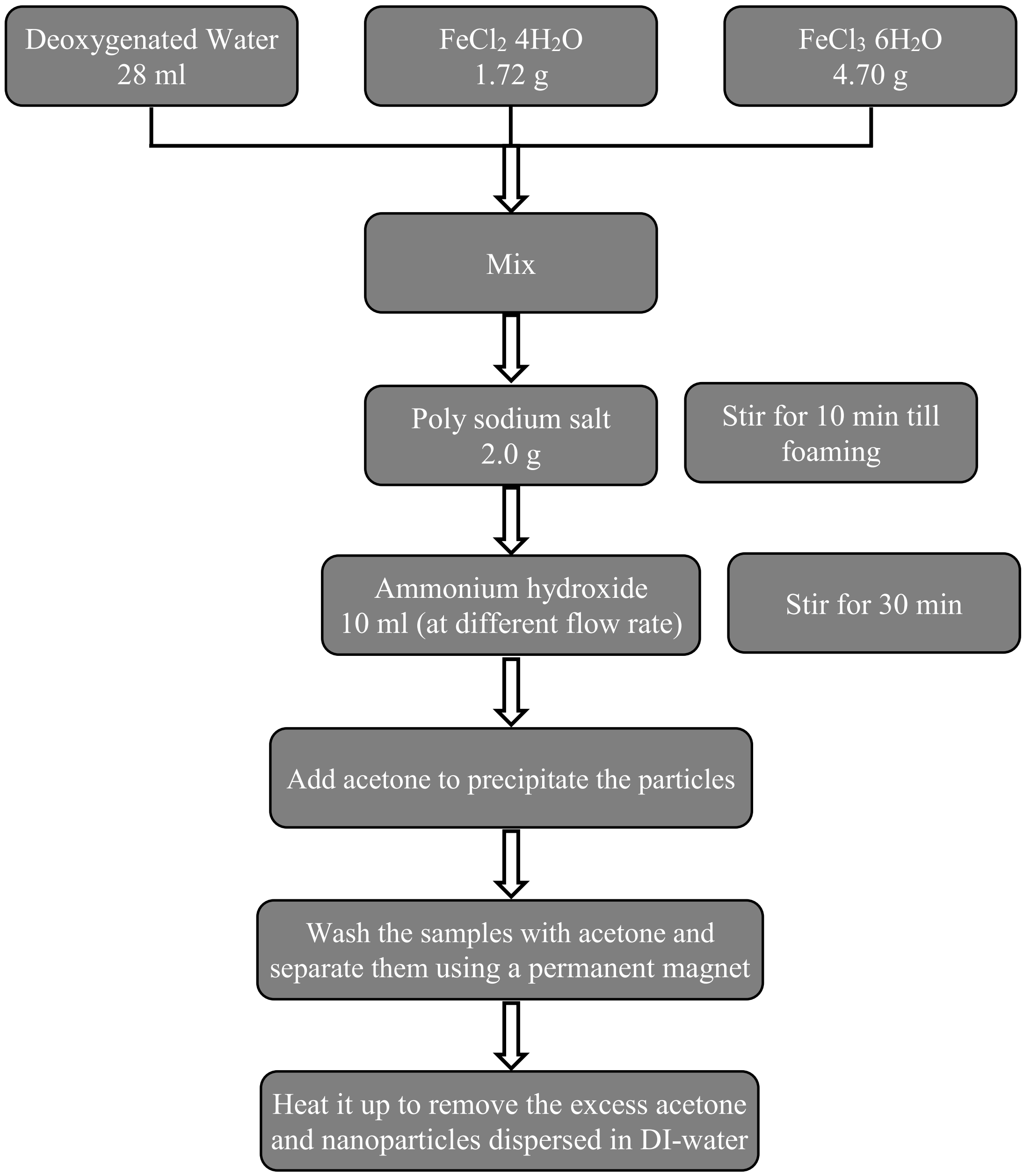


Fig. 1. Methodology of ferrofluids production [34]

The details of the multi-step procedures applied to prepare the magnetite nanofluids at the University of Newcastle described in Fig. 1 [34], which were refined and optimised for the synthesis of magnetic fluids for various applications, such as vibration based energy harvesters and as a highly efficient heat transfer fluids. The magnetic nanoparticles and nanofluids are characterised using different techniques and methods, as shown in Table 1.

Table 1. Physicochemical characterisation of magnetic nanoparticles

Characteri-sation	Method and technique	Measured parameter
Geometry	Transmission Electron Microscopy (HRTEM) and Field Emission Scanning Electron Microscopy (FESEM) [41-43]	Size and the shape of magnetic particles
	Dynamic Light Scattering (DLS), Quasielastic Light Scattering (QELS) [43, 44] X-ray Diffraction and Mössbauer Spectroscopy [45]	Mean particle size and size distributions
Structure	X-ray diffraction, thermal analysis, and Mössbauer and infrared spectroscopy [44]	Nanoparticle structure
	Thermogravimetric and differential thermogravimetric analysis (TGA), Differential Scanning Calorimetry (DSC), Fourier Transform Infrared spectroscopy (FTIR) and Statistic Secondary Ion Mass Spectra (SSIMS) [45-47]	The structures of composite particles made of iron oxide and organic molecules The nature of the interactions between the iron oxide core and the associated molecular structures within the composite
	Atomic Force Microscopy (AFM) and Chemical Force Microscopy (CFM) [48]	The morphological changes occurring on the surface of iron oxide nanoparticles upon exposure to a coating material
Colloidal Stability	Dynamic Light Scattering (DLS) [49, 50]	The colloidal stability is based on the hydrodynamic particle size
	Turbidity measurements [51, 52]	Stability of magnetic nanoparticles by measuring the aggregation kinetics

3. Stability of magnetic nanofluids

A nanofluids' stability relies on a number of aspects [53]: a) nanofluids are multiphase dispersion systems with high surface energies and hence, are thermodynamically unstable, b) nanoparticles dispersed in the nanofluids have strong Brownian motions. The nanoparticles' movement can offset their sedimentation due to gravity, c) the dispersed nanoparticles in the fluids may settle out with time because of nanoparticle aggregation, which is initiated by van der Waals forces, d) no chemical reactions among the suspended nanoparticles nor between the base fluid and nanoparticles are expected. Consequently, aggregation and sedimentation are the two critical phenomena relating to the stability of a nanofluid.

The sedimentation of the particle in the magnetic nanofluid may occur due to the effects of magnetic field, gravitational field and/or magnetic field gradient, because of the external magnetic field is directly associated with the size distribution of magnetic nanoparticles [54]. The sedimentation of the particle has a significant impact on the stability of magnetic nanofluids. The stability against the particle sedimentation can assure when the thermal energy of the nanoparticles goes higher than the gravitational and magnetic energies, accordingly. The maximum size of the nanoparticle was calculated by using the Odenbach [54] formulas; $d < (6k_B T / \mu_0 M_0 \pi H)^{1/3}$ in the presence of magnetic field and $d < (k_B T / \Delta\rho g h \pi)^{1/3}$ under the gravitational field, where $k_B, T, \mu_0, M_0, H, \Delta\rho, g$ and d denote the Boltzmann constant, temperature, vacuum permeability, the spontaneous magnetisation of the magnetic material, magnetic field, density difference between nanoparticle and the base fluid, gravitational acceleration, and size of the sample, respectively. In principle, the particle aggregation rises the active diameter, hence a destabilisation of the suspension occurs due to the sedimentation. In this case, the maximum diameter (d) of the particle was estimated as, $d < (144 k_B T / \mu_0 {M_0}^2)^{1/3}$ corresponding to the maximum interaction of energy [54].

The use of super-paramagnetic particles in magnetic nano-suspension is not necessarily definitive of the stability of magnetic nanofluids [55]. Magnetic nanoparticles in a base fluid will not be stable because of the existence of London-van der Waals and magnetic forces, contributing to the irreversible aggregation of nanoparticles. Thus, magnetic nanofluids introduce the repulsive forces between the magnetic nanoparticles to repel the dipole-dipole magnetic interactions and London-van der Waals force. The repulsive force between the nanoparticles can be attained by using a polymer surfactant as a coating around the particles, which could produce an entropic repulsion, and/or by introducing a coulombian repulsion from the variation of the nanoparticle surface [55, 56]. Generally, the dispersion process of the magnetic nanofluids is carried out by ultrasonic homogenization method in the presence of a surfactant.

Finely divided iron is very sensitive in the presence of water or humid air and oxidising agents. Therefore, protection of magnetic nanoparticles is the prior requirement to obtain chemically and physically stable colloidal systems, and such protection may be attained by surface coating around the nanoparticle as shown in Fig. 2 [57]. A couple of methods have been suggested to attain stable nanofluids, such as chemical or physical treatment. These treatments may involve the modification of the dispersed nanoparticle surface, the addition of an extra surfactant, or enforcing strong forces on the agglomerated nanoparticles. The active surface agent was applied for the modification of hydrophobic materials, thus allow dispersion in an aqueous solution [58]. The chemical treatment changes the suspension stability through the resultant surface potential, as well as surface charge states [59]. Otherwise, sedimentation, aggregation, and clogging may occur and hamper the thermal properties of the nanofluids. It is well known that the theory of aggregation and clustering is one of the primary causes of stability and unexpected increase of nanosuspensions thermal conductivity [60]. Philip et al. [14] and Evans et al. [60] showed that the greater aspect ratio structure of the fractal-like aggregates is a fundamental factor that allowed for enhanced heat flow over large distances.

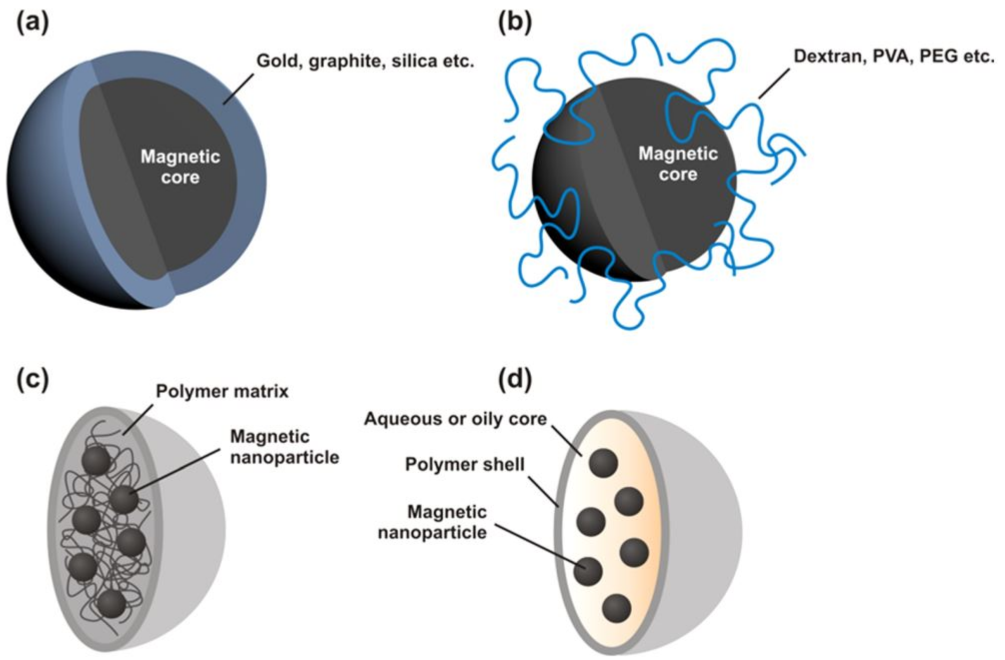


Fig. 2. Schematic representation of the stabilisation of magnetic nanoparticles by surface coating (a) inorganic material, (b) organic material, (c) encapsulation into nanospheres, (d) nanocapsules [57]

Normally, nanoparticles need to fulfill the two principles in order to gain a high-quality suspension, the diffusion principle as well as the zeta potential principle [61]. The stability of a colloidal suspension is highly influenced by its zeta potential value or surface charge [62]. It is well known that the dividing line between stable and unstable suspensions is generally around ±30 mV and nanoparticles with a zeta potential more negative or positive than ±30 mV accordingly are considered physically stable [53, 63]. In addition, zeta potential of a colloidal suspension is highly dependent on the pH value of the solution [7].

In a stationary state, a nanoparticles' sedimentation velocity in a nano-suspension complies with Stokes Law [64]:

$$V = \frac{2R'^2}{9\mu}(\rho_p - \rho_L)g \qquad (1)$$

where V is the sedimentation velocity of nanoparticles, R' is the radius of spherical particle, μ is the viscosity of the liquid medium, ρ_p and ρ_L are the density of particle and the liquid medium, respectively and g is the acceleration of gravity. Eq. (1) exposes a balance of the viscous drag, buoyancy force and gravity, those are actively influencing the dispersed nanoparticles. The following actions might be helpful to reduce the sedimentation speed of nanoparticles in nano-suspension, and henceforward to produce an improvement in nanofluids stability: (a) reducing nanoparticles size/radius, (b) increasing the viscosity of the fluid medium and (c) minimising the difference between nanoparticle and base fluid density. It is obvious that the reduction in particle size should significantly reduce the nanoparticles sedimentation speed, as a result enhance the nanofluids' stability, since V is proportional to the square of R. According to the colloid chemistry theory, when the nanoparticle size reduces to a critical size, there is no sedimentation due to the Brownian motion of the particle [65]. However, nanoparticles have the possibility to aggregate due to its higher surface energy. Therefore, the preparation of a stable nanofluid is associated with using the smaller nanoparticles to prevent the aggregation process concurrently [65].

4. Mechanism of heat transfer enhancement using magnetic nanofluids

Numerous methods have been identified on the mechanism of the heat transfer enhancement in the different studies. The thermal properties especially the thermal conductivity of magnetic nanofluids was the main focus of some investigations, but the mechanisms to justify the experimental data in the presence and absence of external magnetic field are still desirable. The Brownian motion [66-69], liquid layering on the particle-liquid interface, and the effects of nanoparticles clustering is the much debated among all of the proposed heat transfer mechanisms [14, 69].

4.1 Brownian motion

Brownian motion can be expressed as a random motion induces from the collision of the base fluid molecules, consequently particle experiences a random walk motion [70, 71]. This parameter has a significant impact on the heat transfer and flow features of nanosuspensions [72]. Generally, nanofluids containing smaller particles are offering more improvement of heat transfer with compare to the bigger particles [73]. The Brownian motion can enhance the heat transfer in two different ways, firstly, the motion of the nanoparticles help to transport the heat (diffusion of nanoparticles) through direct contribution and the indirect contribution because of the micro-convection is acting on the surrounding of the individual nanoparticles [71, 74]. Some authors [68, 75] were recommended that the thermal conductivity is controlled by Brownian motion at nano and micro levels. The thermal conductivity and particle motion rise with the increment of temperature [68]. Besides, the motion of nanoparticles due to the Brownian motion was noticeably slow in heat transfer, because a particle needs to travel massive distances to achieve a perfect place and this distance may be a shorter one. Consequently, the random motion could not be a significant phenomenon in heat transfer.

Current analyses refused the hypothesis of Brownian motion, reporting that the enhancement of thermal conductivity of magnetic nanofluids can be described from the theory of particle clustering [14, 20]. Philip et al. [20] presented that the micro-convection model overvalued the thermal conductivity, thus the micro-convection of the fluid medium around randomly moving nanoparticles did not have any effect on nanofluids thermal conductivity. The diffusion of magnetic nanoparticles exhibits a vital role at low nanoparticle volume concentrations ($\varphi < 2$), which can be described by the effective medium (Maxwell) theory instead of the mechanism related to the Brownian motion induced hydrodynamics. The improvement in thermal conductivity of magnetic nanofluids at the high-volume fraction ($\varphi > 2$) was associated with the presence of dimmers or trimmers in the field. These experimental results had a reasonable agreement with the Maxwell-Gannet model, especially at a greater nanoparticle volume concentrations [20]. Tsai et al. [76] examined the effect of viscosity on the thermal conductivity of magnetic nanofluids. They concluded that the experimental value of the nanofluids thermal conductivity progressively matches the value of thermal conductivity predicted by using the Maxwell equation. In addition, diffusion of magnetic nanoparticles could be one of the potential reasons for thermal conductivity improvement.

4.2 Liquid layering on the nanoparticle-liquid interface

Previous studies clearly showed that the liquid molecules may form layers around the nanoparticle due to the strong force of the nanoparticle and the atomic structure of liquid layer is more arranged compared with the bulk liquid. Since phonon transfers in crystalline solid is very effective, such ordered layer in the liquid shows higher thermal conductivity and as a result, the thermal conductivity of nanofluids was enhanced [77]. Keblinski et al. [78] suggested that the resultant higher effective volume of the particle-layered-liquid structure can improve the value of thermal conductivity (refer to Fig. 3). Yu et al. [79] explained the existence of liquid molecules near to a solid surface. Ren et al. [80] confirmed the thermal conductivity increment with this liquid layer, maximum 165% enhancement in thermal conductivity was found for 3 nm liquid layer compared to 1 nm. Yu et al. [81] also clarified the significance of the solid-liquid interfacial layers in the enhancement of nanoparticle (<10 nm) thermal conductivity.

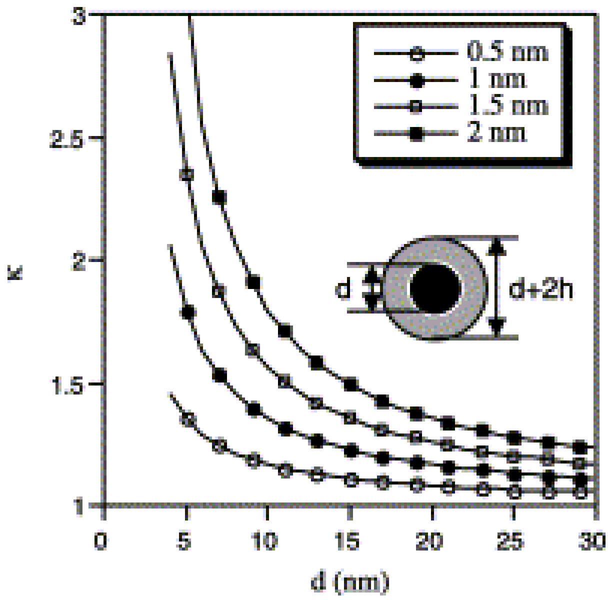


Fig. 3. Thermal conductivity improvement due to the formation of highly conductive liquid structure at liquid/particle interface for various layer thickness (h) as a function of particle diameter (d) [78]

4.3 Effects of nanoparticles clustering

Aggregation of nanoparticles is considered as one of the main mechanisms of heat transfer enhancement using nanofluids, and nowadays it receives a wide interest of research community [71, 82, 83]. The particle clusters may involve the fastest heat transport along the long distance, because of the high heat conductivity of the solid particle compare to the base fluid [84, 85].

Bishop et al. [86] showed that the magnetic nanofluids have the magnetic interaction to introduce a self-assembled aggregation even though in the absence of an external magnetic field. The structures of aggregations of magnetic nanoparticles control the heat conduction in the fluid. Without the application of the external magnetic field, the nanoparticles distribution in the nanofluid is disordered and the thermal conductivity is isotropic [16]. Magnetic nanoparticle tries to align its magnetic moments toward the direction of the local magnetic field because of the external magnetic field or the neighbouring nanoparticles [54, 87]. This allows magnetic nanoparticles to form micron-sized, one-dimensional chains, rings, two-dimensional aggregates or even three-dimensional super lattices. The mechanisms of the aggregate formation, manipulation of nanofluids and distribution morphology in the presence of external magnetic fields are required to understand the thermal conduction mechanism of magnetic nanofluids.

5. An overview of thermal properties of magnetic nanofluids

Investigations on magnetic nanofluids without the application of external magnet exhibit that thermophysical properties of nanofluids are affected by different factors such as nanoparticle size, types and intensities of magnetic fields, nanoparticle volume concentration, base fluid properties, temperature, the chemical composition of the nanoparticle, the coating around the nanoparticles etc. The properties of magnetic nanofluids and their effects on the volume fraction of nanoparticle and temperature have been discussed in most of the studies. Syam Sundar et al. [88] studied the viscosity and effective thermal conductivity of Fe_3O_4/water nanofluids and showed that the nanofluid demonstrates Newtonian behavior, and the thermal conductivity increases with the rise of nanoparticle volume fraction as well as temperature. Pastoriza-Gallego et al. [89] concluded that a linear improvement of the thermal conductivity with rising the particle volume concentration and the nanofluids was nearly temperature independent. Magnetic nanofluids were prepared by dispersing magnetite nanoparticle in the water using a surfactant called tetramethyl ammonium hydroxide, and the highest thermal conductivity enhancement was found 11.5% with 3% volume concentration of nanoparticle at 40 ºC [90]. Many studies have been focused on the thermal conductivity of nanofluids and proposed various correlations to calculate its value, Table 2 shows the frequently used models for the determination of the thermal conductivity of magnetic nanofluids.

Table 2. Summary of most common thermal conductivity models of magnetic nanofluids

Model	**Expression**	**Description**
Maxwell-Gannet model [91]	$\dfrac{K_p + 2K_f + 2\varphi(K_p - K_f)}{K_p + 2K_f - \varphi(K_p - K_f)}$	Spherical particles with low volume fraction φ
Modified Maxwell-Gannet model [92]	$\dfrac{K_i}{K_f} = \dfrac{K_p + 2K_f + 2\varphi_i(K_p - K_f)}{K_p + 2K_f - \varphi_i(K_p - K_f)}$	Spherical particles with volume fraction φ_i; $i = x, y, z$
Microconvection model [93]	$\left(1 + A\,\mathrm{Re}^{\gamma}\,\mathrm{Pr}^{0.003}\,\varphi\right)\left[\dfrac{K_p + 2K_f + 2\varphi(K_p - K_f)}{K_p + 2K_f - \varphi(K_p - K_f)}\right]$	A is constant, *Re* and *Pr* represents Reynolds and Prandlt numbers, correspondingly, and γ denotes system dependent coefficient
Bruggeman model [94]	$\dfrac{K}{K_f} = \dfrac{1}{4}\left[(3\varphi - 1)\dfrac{K_p}{K_f} + (2 - 3\varphi)\right] + \dfrac{K_f}{4}\sqrt{\Delta}$ $with\ \Delta = (3\varphi - 1)^2\left(\dfrac{K_p}{K_f}\right)^2 + 2(2 + 9\varphi - 9\varphi^2)\left(\dfrac{K_p}{K_f}\right)$	Spherical-sized particles with high volume fraction of the particle
Jeffrey model [95]	$\dfrac{K}{K_f} = 1 + 3\varphi + \varphi^2\left[3\kappa^2 + \dfrac{3\kappa^3}{4} + \dfrac{9\kappa^3}{16}\left(\dfrac{\alpha + 2}{2\alpha + 3}\right) + \dfrac{3\kappa^4}{64} + \cdots\right]$ $with\ \kappa = \dfrac{\alpha - 1}{\alpha + 2}\ and\ \alpha = \dfrac{K_p}{K_f}$	High order terms represent pair interaction of randomly dispersed particles
Rayleigh model [96]	$\dfrac{K}{K_f} = K_f + 3\varphi\dfrac{K_p K_f}{2K_f + K_p\varphi[1 + 3.939\varphi^2(K_p K_f)/4K_f + 3K_p]K_p K_f}$	Suspensions of spherical particles with a regular particle distribution
Murshed model [97]	$K = \left\{K_f\dfrac{Q_p\omega(K_p - \omega K_f)(2\gamma_1^3 - \gamma^3 + 1)(K_p + 2\omega K_f)\gamma_1^3[Q_p\gamma^3(\omega - 1) + 1]}{\gamma_1^3(K_p + 2\omega K_f) - (K_p - \omega K_f)Q_p(\gamma_1^3 - \gamma^3 + 1)}\right\}$ $+\left\{Q_p^6\gamma^6 K_f\left[3\Lambda^2 + \dfrac{3\Lambda^2}{4} + \dfrac{9\Lambda^3}{16}\left(\dfrac{K_{cp} + 2K_f}{2K_{cp} + 3K_f}\right) + \dfrac{3\Lambda^4}{2^6}\right]\right\}$ $+\left\{\dfrac{1}{2}\rho_{cp}C_{p-cp}d_s\left[\sqrt{\dfrac{3\kappa_B T(1 - 1.5\gamma^3 Q_p)}{2\pi_{cp}\gamma^3 r_p^3}} + \dfrac{G_T}{6\pi r_p d_s}\right]\right\}$ $with\ \gamma = 1 + \dfrac{t}{r_p},\ \gamma_1 = 1 + \dfrac{t}{2r_p},\ \Lambda = \dfrac{K_{cp} - K_f}{K_{cp} + 2K_f},$ $K_{Cp} = K_{lr}\dfrac{2(K_p - K_{lr}) + \gamma^3(K_p + 2K_{lr})}{(K_{lr} - K_p) + \gamma^3(2K_{lr} + K_p)},$	Murshed model considers the effects of nanolayer, size and movements of the particle, and surface chemistry of nanoparticles. C_{p-p} and C_{p-f} represent the specific heat capacity at constant pressure for nanoparticles and

	ρ_{cp} *and* C_{p-cp} *are density and specific heat of complex particle, respectively, and they are given by* $\rho_{cp} = \frac{1}{\gamma^3}\rho_p + \left(1 - \frac{1}{\gamma^3}\right) \left\{\frac{3\rho_p}{pb^3}(2t^2 + 2br_p t + b^2 r_p^2) - \frac{3\rho_f}{pb^3}[(2 + 2b + b^2) + br_p(br_p + 2bt + t)]\right\}$ $C_{p-cp} = \frac{1}{\gamma^3}C_{p-p} + \left(1 - \frac{1}{\gamma^3}\right) \left\{\frac{3C_{p-p}}{pb'^3}(2t^2 + 2b'r_p t + b'^2 r_p^2) - \frac{3C_{p-f}}{pb'^3}[(2 + 2b' + b'^2) + b'r_p(b'r_p + 2b't + t)]\right\}$ *where* $p = 3r_p^2 + 3r_p t + t^2;\ b = \ln\left(\frac{\rho_p}{\rho_f}\right);\ b' = \ln\left(\frac{C_{p-p}}{C_{p-f}}\right)$	base fluid, respectively. *Gr* denotes the total potential energy between two interacting nanoparticles.

5.1 Effects of nanoparticle size

A number of researchers have been investigated the effect of magnetic nanoparticle cluster and size on the thermal properties of nanofluids. Zhu et al. [98] stated that the clustering, as well as nanoparticle alignment was one of the main reasons for the irregular improvement of thermal conductivity. They conclude that the Fe_3O_4 nanofluid with 4% volume fraction of nanoparticle shows 38% enhancement in thermal conductivity. Jiang and Wang [99] synthesized a magnetic nanofluid by one step phase transfer, showed that the particle coating on the surface of the nanoparticle was an important parameter in the cluster formation. They concluded that the thermal conductivity of magnetic nanofluid can be influenced by using a stabiliser, hence it controls the structure of the aggregates. Besides, the thermal conductivity decreases in case of well-dispersed composites. There is no recognisable standard for the superlative mix of combining methods. The techniques are (a) the surfactant or activator addition, (b) pH control (surface chemical effect), and (c) ultrasonic vibration [100]. According to the literature, three effective techniques are applied to achieve suspension stability against nanoparticles sedimentation. Some researchers used all of these tactics to achieve better stability [101-103] but others applied just one [104] or two techniques [105-107] with satisfaction. Wang et al. [108] experimentally examined the effect of nanoparticle size (4~ 44 nm) on the thermal conductivities and exhibited that the magnetic nanofluids showed greater thermal conductivities with compare to the heat transfer oils, and the enhancement of thermal conductivity was found with reducing the size of the nanoparticle. The improvement in thermal conductivity has showed up to 26.4% at 4 vol% of Fe_3O_4 nanofluids with 4 nm size of the particle. Additionally, the values of viscosity for all nanofluids were significantly lower than that of the carrier fluid. Hong et al. [109] investigated the effect of nanoparticles clustering for a glycol based magnetic nanofluids in the absence of magnetic field, and it was found that thermal conductivity decreased with sonication time. Thus, the size of the clusters formed by the nanoparticles had a major influence on the thermal conductivity. The non-linearity was attributed to the rapid clustering of nanoparticles in the condensed nanofluids. Moreover, the carrier fluid effect on the ferrofluids properties was demonstrated in some analyses. Chen et al. [110] suggested that the aggregation of nanoparticles was one of the main reasons for the enhancement in viscosity of nanofluids beyond the classical Einestien equation. They proposed their model by adding an aggregation effect to the Krieger and Dougherty [111] model, finding good agreement between their experimental data and the proposed model.

5.2 Effects of magnetic field

Applying a magnetic field can affect the thermophysical properties of magnetic nanofluids, as a result, some researchers were analysed the properties of magnetic nanofluids in the presence of magnetic field. The effect of external magnetic fields and its directions and strengths on the thermophysical properties of nanofluids have also been assessed. Results revealed that the thermophysical properties of magnetic nanofluids are easily changeable by varying the strength and direction of the magnetic field. Krichler and Odenbach [112] used an advanced measuring device (a hot plate technique with a non-stationary mode) for measuring the thermal conductivity of ferrofluid by changing the direction and strength of the magnetic fields. The thermal conductivity improved with the increment of the magnetic field strength for parallel alignment of the magnetic field and heat flux. On the other hand, the relation between the thermal conductivity and magnetic field strength was totally opposite in the case of perpendicular alignment. Therefore, the strength, parameters, and orientation of the external magnetic field can also affect the properties of magnetic nanofluids because of the structure formation of the magnetic particles in the magnetic nanofluid depends on the types of magnetic fields. Azizian et al. [84] used electromagnets and solenoids to apply the parallel and perpendicular magnetic fields to the temperature gradient, accordingly (as shown in Fig. 4); and illustrated the influence of nanoparticle aggregation on the thermal conductivity of nanofluids. They concluded that the maximum enhancement of thermal conductivity of Fe_3O_4/water nanofluid is 167% under external magnetic field configuration.

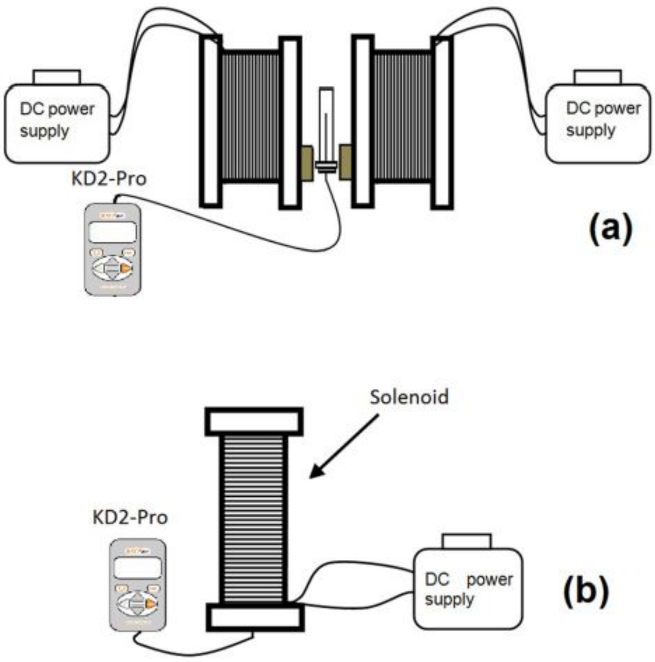


Fig. 4. Schematic diagram of (a) electromagnet and (b) solenoid

Li et al. [113] shows the enhancement in relative viscosity of aqueous Fe and Fe_3O_4 nanofluids by applying the magnetic field, as shown in Fig. 5. The higher viscosity of the magnetite nanofluid under an externally applied uniform magnetic field caused a reduction in fluid velocity.

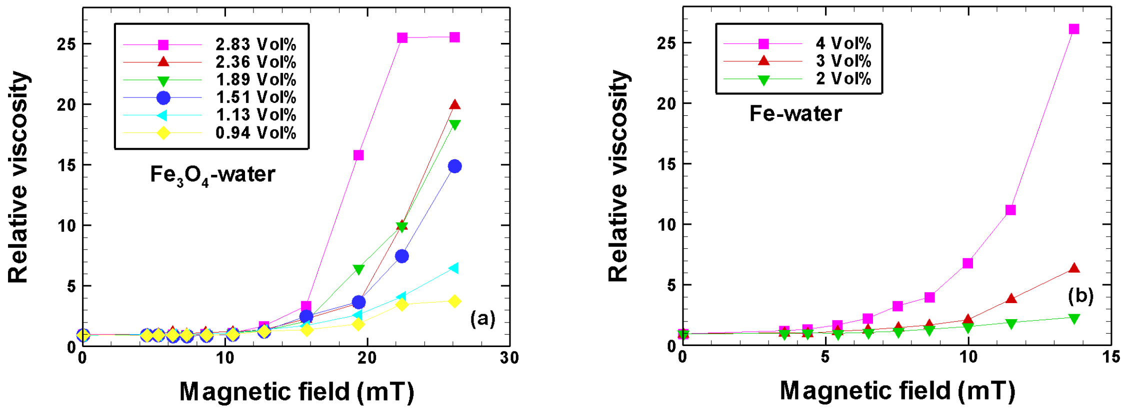


Fig. 5. Relative viscosity as a function of perpendicular external magnetic field strength (a) Fe_3O_4/water, (b) Fe/water [113]

Shima and Philip [114] examined the effect of magnetic field on the thermal properties of magnetic nanofluids and showed that the thermal properties can be easily adjusted from very low to high values by changing the strength and orientation of the magnetic field. Baby and Ramaprabhu [115] investigated the effect of the application of magnets on the thermal conductivity of the magnetic nanofluid. It was confirmed that a small augmentation in thermal conductivity in the absence of magnetic field, whereas a significant rise in the thermal conductivity was noticed in the presence of magnetic field. They specified that the aligned nature of Fe_2O_3/MWNT toward the direction of the magnetic field may one of the possible reasons for the improvement of thermal conductivity under the application of magnetic field. Parekh and Lee [116] concluded that the enhancement in thermal conductivity of Mn-Zn and magnetic nanofluids exhibit 45% and 17%, respectively without the existence of the magnetic field. However, the magnetite nanofluid demonstrated a further development in thermal conductivity in the presence of a transverse magnetic field, although no variation was detected for Mn-Zn ferrite. Gavili et al. [8] showed that the enhancement of thermal conductivity was not significant in the absence of magnetic field. However, a maximum 200% improvement in thermal conductivity of ferrofluid was observed under the effect of the magnetic field. Mehrali et al. [117] investigated the thermophysical and magnetic properties of hybrid graphene/Fe_3O_4 ferro-nanofluid in the presence of a magnetic field, and thermal conductivity has shown an development of 11%. Chiu et al. [118] analysed the influence of magnetic field and temperature on the specific heat of a water based magnetic nanofluid. The specific heat did not depend on the temperature under the lower magnetic field strength, but it decreased noticeably with the rise of temperature in the presence of higher magnetic field strength. This may be due to the reduction in the degrees of freedom of the ferrite nanoparticle in the magnetic nanofluid under the higher magnetic field strength.

5.3 Effects of chain-like structures of the magnetic nanoparticle

Studies have been carried out on the thermophysical properties of magnetic nanofluids, and their structural changes with the application of the external magnets, such as chain-like structures formation, have been suggested as one of the efficient factors to enhance the heat transfer. Nkurikiyimfura et al. [93] studied the influence of chain-like aggregation of magnetic nanoparticle on the thermal conductivity of magnetic nanosuspensions in the presence of the magnetic fields. They concluded that a significant enhancement of thermal conductivity with the existence of the magnetic field parallel to the temperature gradient because of the development of chain-like magnetic nanoparticle aggregates. Fu & Gao [91] introduced the two-step homogenisation method for studying the anisotropic thermal conductivity of magnetic nanofluids by considering the effect of physical anisotropy as well as the magnetic field. The result showed that the aspect ratio of the chain-like aggregates of magnetic nanoparticle exposed a vital role in the improvement of anisotropic thermal conductivity. Philip et al. [20] found the highest thermal conductivity enhancement about 300% and 216% under the influence of external magnetic fields for Fe_3O_4-kerosene and Fe_3O_4-hexadecane nanofluids, accordingly. Such a large improvement was found due to the formation of chain-like structures of magnetic nanoparticles. Parekh and Lee [119] also reported approximate 30% of thermal conductivity increment at 4.7% of volume concentration of magnetite nanofluids in the presence of a magnetic field and this may happen due to the continuous development of three-dimensional zipper-like structures of nanoparticle inside the magnetic fluid.

Furthermore, the nanoparticle size, magnetic field as well as chain-like structure of magnetic nanoparticle are the important parameters to change the thermal properties of magnetic nanofluids in particle application. It is very important to consider the viscosity and thermal conductivity of magnetic nanofluids at the same time. Because, Prasher et al. [120] have shown that if the increase in viscosity becomes more than four times that of a comparable increase in thermal conductivity of nanofluid, then the use of nanofluid is not economically viable. Venerus et al. [121] also ran a benchmark study on the viscosity behaviour of ten different nanofluids. They concluded that all of the nanofluids used in their study clearly failed the qualifications of practical nanofluids as proposed by Prasher et al. [120].

6. Convective heat transfer and pressure drop characteristics of magnetic nanofluids

Nanofluids are dilute suspensions of functionalised nanoparticles and their objective is to enhance the heat transfer performance of coolants/fluids, and nowadays has evolved into a promising nanotechnological area [122, 123]. Although thermal conductivity of magnetic nanofluids in the absence and presence of magnetic field has been the subject of many past studies, relatively little effort has been focused on the convective heat transfer of magnetic nanofluids. It has been proven that the thermal conductivity of magnetic nanofluids increases under applied magnetic field parallel to the temperature gradient. If this is the case, enhancement in heat transfer coefficient is expected. A review of studies related to the convective heat transfer of magnetic nanofluid in the absence and presence of an external magnetic field is provided in this section.

One of the main attractions of magnetic nanofluids application is the induction of a body force due to the application of magnetic fields which allows the magnetic nanofluids to control the fluid motion. The thermogravitation phenomenon may define as the natural movement of the fluid because of the buoyancy force, where the reasons for the fluid motion are the presence of temperature gradient and density difference. Moreover, these types of magnetic nanofluids are temperature sensitive, and its magnetisation reduces with the rise of temperature. The temperature gradient involves a non-equilibrium state in the magnetisation of the fluid under the magnetic field. As a result, a net magnetic driving force induces, which may initiate a flow in the fluid. Such phenomenon is called thermomagnetic convection.

When the approximation of equilibrium magnetisation with the magnetic susceptibility is only depend on the local external magnetic field as well as the density then the gravitational and magnetic forces are potential. The Kelvin body force produces a static pressure field in the fluid flow, which is symmetric about the external magnetic field creating an irrotational force field. This type of symmetric field does not change the velocity profile and the convection inside the fluid could not rise [124]. The non-potentiality in the bulk forces is coming into the scenario if a fluid experiences a non-uniformity of the magnetisation and density because of their dependence on the volume fraction of nanoparticle or temperature [125]. Afterwards, the condition is fulfilled for non-isothermal systems with an asymmetric temperature distribution about the applied magnetic field. The resultant Kelvin body force induces a field force, which contributes to the self-organised adjective motion of the magnetic nanofluid across isotherms. The condition for the free convection to develop is estimated by the following Eq. (2) [125]:

$$\vec{\nabla} \times \vec{f} = \vec{\nabla} T \times \left[\beta_T \rho_o \vec{g} \pm \mu_o \beta_m \frac{\chi_o(H)}{2} \nabla H^2 \right] \neq 0 \tag{2}$$

where $\vec{f}$ represents the vector sum of the gravitational body force and Kelvin body force; β_T denotes the relative volumetric expansion coefficient, the $\pm$ sign means the anti-parallel and parallel alignment of the magnetic field gradient with respect to the gravitational force and β_m is the relative pyromagnetic coefficient of the fluid.

The intensity of the heat transfer is calculated by the Rayleigh number *Ra*, which is the combination of thermogravitational and thermomagnetic parts as follows;

$$Ra = Ra_T + Ra_m = \frac{\rho c_p l^4}{\eta K} \frac{dT}{dz} \left(\beta_T \rho g + \mu_o \beta_m M \frac{dH}{dz} \right) \tag{3}$$

where Ra_T and Ra_m represent the thermal and magnetic Rayleigh number, accordingly. The efficiency of a device by applying the magnetic nanofluid gives the magnetic field, the temperature distributions fields as well as the tunable thermal properties of ferrofluid and the pyromagnetic coefficient. The pyromagnetic coefficient of a magnetic nanofluid is expressed as follows [17];

$$\beta = \beta_T M + \left(\frac{\partial M}{\partial m} \right) \left| \frac{dm}{dT} \right| + \left| \frac{\partial M}{\partial T} \right| \tag{4}$$

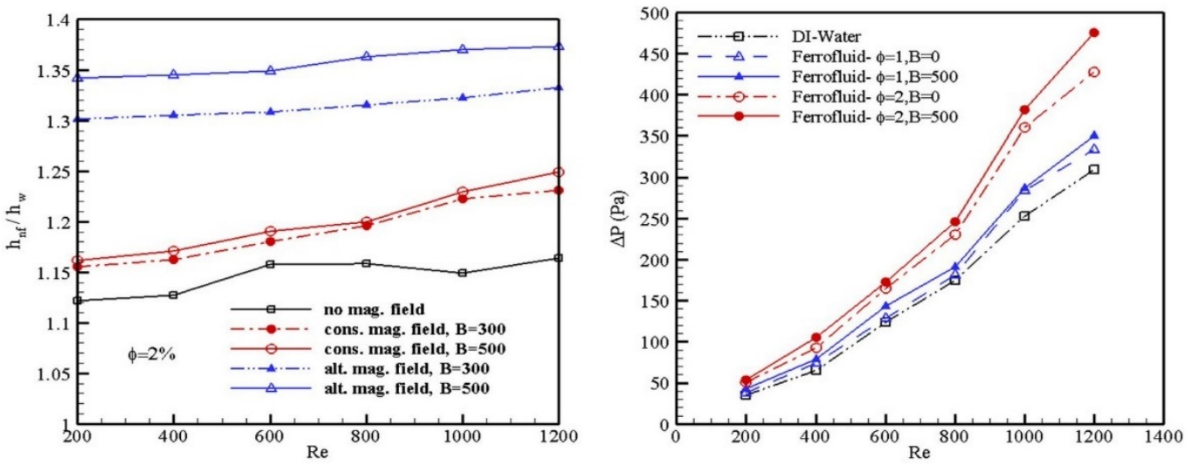
where, thermal expansion coefficient, $\beta_T = -\frac{1}{\rho}\frac{d\rho}{dT}$, and ρ denote the density of magnetic nanofluid. Almost all of the studies have been discussed the influence of temperature on the magnetic nanofluids, which involves the dependency of magnetisation on the fluid temperature, thus the existence of thermomagnetic phenomenon [18, 126, 127]. It is considered that the thermal properties of ferrofluids are independent as well as constant under the external magnetic field [18]. Though some of the inquiries have been concluded that the external magnetic fields can influence the thermal properties of ferrofluids, thus has a significant impact on heat transfer performance of nanofluids. The magnetic nanofluid varies the value of viscosity under the application of magnetic field, known as the magneto-viscous effect. Recently, some of the studies considered the effects of thermal properties on the enhancement of heat transfer as well as pressure drop of magnetic nanofluids in the absence and presence of the external magnetic field, shown in Table 3.

Table 3. Recent development on magnetic nanofluid as a heat transfer fluid

Author	**Types of magnetic field**	**Result**
Mehrali et al. [117]	Constant magnetic field	The local convective heat transfer coefficient increased up to 4% The thermal efficiency index was only 1 in the absence of the magnetic field and it was increased between 1.1 and 1.7 after applying a magnetic field. In addition, the total entropy generation rate was reduced up to 41% compared to distilled water
Goharkhah et al. [128]	Oscillating and constant magnetic field	The heat transfer coefficients were enhanced by 37.3% and 24.9% under alternating and constant magnetic field, accordingly. The rise in pressure drop under the alternating magnetic field was not significant compared to heat transfer enhancement

Goharkhah et al. [129]	Constant and alternating magnetic field	The average convective heat transfer grows up to 18.9% and 31.4% by application of constant and alternating magnetic field
Yarahmadi et al. [130]	Constant magnetic field with different magnetic field arrangements	The local convective heat transfer coefficient enhanced by 19.8% with Re = 465 and the concentration of 5%
Azizian et al. [131]	Constant magnetic field with different arrangements of magnets	The local heat transfer coefficient of magnetite nanofluids enhanced noticeably up to 300%, whereas, only 7.5% increment in the pressure drop under applied magnetic field
Ghofrani et al. [132]	Alternating magnetic field	A maximum of 27.6% enhancement in the convection heat transfer was observed
Sundar et al. [133]	Without magnetic field	The heat transfer coefficient and friction factor were improved 30.96% and 10.01%, respectively
Lajvardi et al. [134]	Constant magnetic field	The use of magnetic particles dispersed in distilled water cannot improve the convective heat transfer in the absence of magnetic field

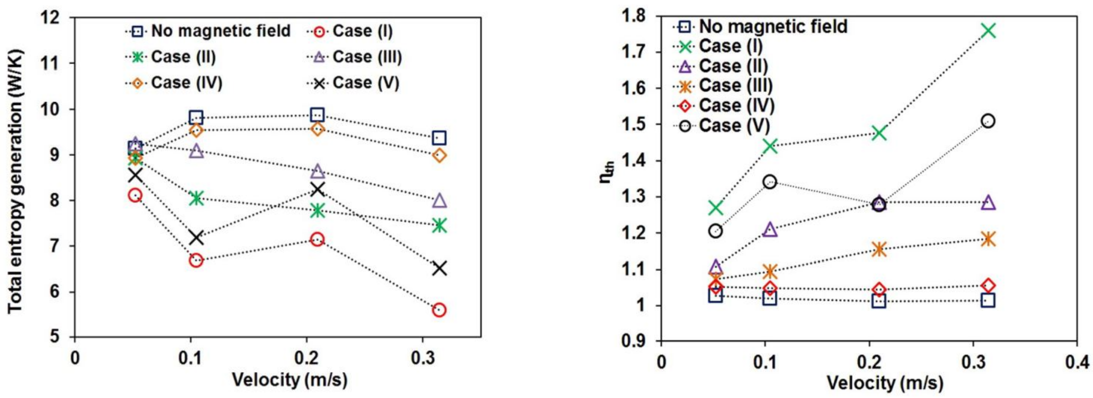
Goharkhah et al. [128] studied the convective heat transfer and hydrodynamic features of magnetite nanofluid under the influence of magnetic fields. The improvement of heat transfer in the presence of the alternating magnetic field was compared with the heat transfer at the constant magnetic field as well as in the absence of magnetic field configurations in Fig. 6a. In the absence of magnetic field, a maximum 16.4% enhancement was found in magnetite nanofluid compare to DI-water, although, it was enhanced up to 37.3% and 24.8% in the presence of alternating and constant magnetic fields, correspondingly. Fig. 6b shows the influence of magnetic field on the pressure drop of the magnetic nanofluid at different nanoparticle volume concentrations. The pressure drop rises with the increase of ferrofluid volume concentration and magnetic field because of the increase in fluid viscosity as well as the tendency of chain alignment of magnetic particle in base fluid [128].



(a) (b)

Fig. 6. The Fe_3O_4/water nanofluid under different magnetic field (a) heat transfer enhancement versus Reynolds number, (b) pressure drop versus Reynolds number [128]

Mehrali et al. [117] analysed the hybrid graphene/Fe_3O_4 ferro-nanofluid flow under the influence of a magnetic field. Fig. 7a shows that the total entropy generation reduces as the rise of fluid velocities and the effect of frictional entropy generations were low (the maximum value of frictional entropy generations were <1 in all cases). The effect of magnetic field arrangements on the thermal efficiency index is also shown in Fig. 7b. The maximum thermal efficiency index was only 1 in the absence of the magnetic field. After applying a magnetic field, this amount increased between 1.1 and 1.7. Therefore, use of hybrid magnetic nanofluids could be beneficial for improvement of heat transfer coefficient under the effect of magnetic fields.



(a) (b)

Fig. 7. The rGO-Fe_3O_4 nanofluid for different arrangements of magnetic bars (a) total entropy generation rate versus velocity, (b) thermal efficiency versus velocity [117]

Li and Xuan [135] studied the heat transfer coefficient of magnetic nanofluids under the application of the external magnetic field in the laminar flow regime. The maximum Nusselt number enhancement of 40.6% under the application of an external magnetic field compared to the result in the absence of an external magnetic field.

From the above literature review, it is expected that the thermomagnetic convection and magneto-viscous effect should be assessed together and not separately in the future studies. Therefore, this may allow to understand the mechanism of the occurrence of thermomagnetic convection. Moreover, the uniform magnetic fields have been studied in the most of the current literature. Although the application of uniform magnetic field is essential and beneficial to get a clear idea about the mechanism of thermomagnetic convection, using electromagnets and Helmholtz coils to provide uniform magnetic fields looks uneconomical because of the consumption of the electrical energy. Thus, the phenomenon of thermomagnetic convection can utilise in a more economical and practical way by applying the magnetic fields using the permanent magnets. Such magnetic fields are more accessible as well as energy efficient. In addition, the pressure drop induced during coolant flow is a significant parameter to determine the efficiency of nanosuspensions. Different researchers have concluded that nanofluids have a higher pressure drop than base fluids and as a result a notable rise in pumping power [136]. Hence, the heat transfer enhancement and pressure drop should be evaluated at the same circumstances to characterise the magnetic nanofluids.

7. Ferrofluid based energy harvester

Over the current years, interest has raised in the development of micro-electromechanical systems (MEMS) and miniaturised system. In this approach, there has been great effort to decrease the energy consumption of these devices from being in the order mW to the order μW [137]. Applications such as sensors in buildings, medical implants, wireless sensors networks, sensors used in military applications, monitoring of the environment, sensors that may provide different information about the maintenance requirements of various industrial equipment and sensors for structural monitoring are just a few of the many examples [137, 138]. Currently, batteries are used to supply the power to such systems, but some limitations of this are their: limited lifetime, large size, difficulty in replacement and containing dangerous and hazardous substances. An energy harvester can be utilised to improve the capability and lifespan of these devices by swapping the usage of the batteries [139, 140]. Energy harvesting devices can use to get vital information on structural and operational conditions by engaging them in remote areas [141]. Hence, an energy harvester can be used to charge or replace the existing battery and enhance the lifetime of the system [137, 142, 143].

Energy harvesting devices are classified based on the form of energy they use to scavenge power. For example, piezoelectric harvesters scavenge mechanical energy and change it into electrical energy. Primarily there are four types of ambient energy available in the environment: thermal energy (temperature variations), radiant energy (RF, sun, infrared), mechanical energy (deformations, vibrations) and chemical energy (biochemistry, chemistry). These sources are characterised by different power densities as shown in Fig. 8 [144]. Fig. 8 demonstrates that the accessible power ranges from 10 μW to 100 μW and is a good order of magnitude for a 1cm^2 or a 1cm^3 energy harvester. Apparently, 10-100 μW is a small amount of power; yet it can be adequate for various types of applications, in particular, wireless sensor networks.

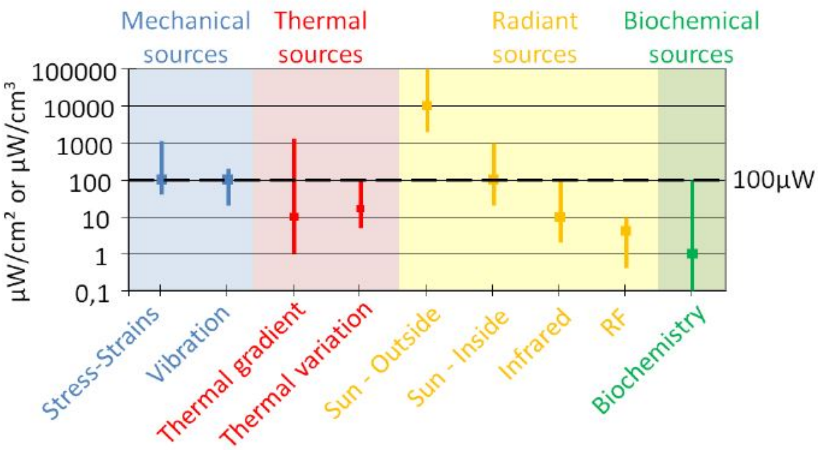


Fig. 8. Power densities of ambient sources before conversion [144]

The mechanical vibrations are the most dominant and attractive ambient energy source because of its abundance [145, 146]. Unlike solar cells, a vibration energy harvester can supply the power during the day as well as the night, whether light is present or not. Here, the focus is on the vibration which can convert into electric power. Some vibration sources are available in the environment including electric motor rotation, wind energy, vehicle motion, wave energy, seismic vibrations and human movement all of which vary widely in both amplitude and frequency. Vibrational energy is found in most of the built environment [147]. The sources of vibration vary with the variation of dominant frequency and amplitude [148]. Roundy et al. [149] completed a number of measures of vibration sources [149] and concluded that the amplitude and frequency of the vibration sources differs from 12 ms^{-2} to 0.2 ms^{-2} at 200 Hz

and 100 *Hz*, respectively. Most of the sources were measured to a fundamental frequency in the range of 50-200 *Hz*. Table 4 shows a market survey of mechanical vibration based energy harvesting products [150].

Table 4. Market survey of vibration based energy harvesting products [150]

Product	**Max. harvested power (mW)**	**Frequency (Hz)**
Volture Piezo Energy Harvester-PEH20W (Mide)	20	50-150
PMG27 Microgenerator (Perpetuum)	4	17.2
VEH-APA400M-MD (Cedrat)	95	110
VEH360 (Ferro Solutions)	10.8	60
Energy Harvesting Shoe (Scientific Research Institute)	800 mW of power/shoe at a place of 2 steps/sec	

An inertial mass is responsible for initiating the movement due to the vibration of a device. This movement can be transformed into the electrical energy by applying three types of mechanisms: electromagnetic (inductive), piezoelectric and electrostatic (capacitive) [151]. Electrostatic and piezoelectric energy harvesters have several shortcomings. Electrostatic generators require an additional power source to charge the capacitor with an initial voltage in order to initiate the alteration process. Another disadvantage is the difficulty of manufacturing these converters because capacitor electrodes must not come into contact with each other. Piezoelectric energy harvesters are not efficient with microelectronics and are more compatible for moderately high vibrational frequencies. Among the other vibrational energy harvesting techniques, an electromagnetic energy harvester is able to drive low impedance load with a high current level [139]. Moreover, vibration energy harvesters are usually assembled on resonant structures with rigid suspensions such as membranes [152], cantilevers [153] or springs [154]. Their construction processes are complicated because of the low resonant frequency and it is difficult to fabricate with microfabrication process. Furthermore, a rigid suspension may tend to failure or breakage in the presence of strong vibration and in the long-run. Hence, an energy harvester with sturdy suspension structure and low resonant frequency is highly desired.

The basic principles of electromagnetic energy harvesters were introduced almost two hundred years ago. The Lorentz force caused by a magnetic field on moving charged carriers is initially introduced by Hans Christian Ørsted in 1920 [155, 156]. Michael Faraday [155, 157] invented the electric motor, and describe the transformation of mechanical to electrical energy and vice versa [158]. The mechanism of the energy harvester depends on the variation of the flux linkage in the coil of the energy harvester because of the natural vibration. According to the Faraday's law of induction, a voltage is found and partly energy is supplied to the connected load and some loss of energy due to the resistance of the coil. Using a permanent magnet is one efficient way to induce an electromagnetic induction for energy harvesting [139]. Since the late 1990s, many researchers [159-161] have acknowledged the different approaches used to generate power from electromagnetic resources. The electromagnetic generator is an enclosed system and has the advantage of being protected from the outside environment. In addition, it is reliable and may reduce the mechanical damping because there is no mechanical contact between the parts as well as the separate voltage source does not necessary [162].

Sazonov et al. [163] have described a self-powered wireless system that utilises the vibrations of a bridge induced by passing traffic. The vibrations are converted into the electrical energy by using the electromagnetic generator, which can produce power up to 12.5 mW with a vibrational frequency of 3.1 Hz. Sterken et al. [164] studied on the electrostatic micro generator and concluded that this system was compatible up to the power of 50 μw for 0.1 cm^2 surface area. Dallago et al. [165] have introduced an active electronic interface for an energy harvester containing an electromagnetic transducer. This transducer can deliver a voltage of 3.25 V at resonance frequency of 10.4 *Hz*. Furthermore, electromagnetic materials are large in size and are complex to integrate with MEMs [166]. Bayrashev et al. [167] and Staley & Flatau [168] focused on energy harvesting from magnetostrictive materials because these types of materials were employed to build sensors and actuators as they were capable of altering magnetic energy into kinetic energy. The magnetostrictive materials are flexible, suitable for the high frequency of vibration as well as overcome the drawbacks of the other vibration sources. Wang & Yuan [166] described magnetostrictive materials which were used to harvest energy and supply power to the wireless sensors in a health monitoring application. El-Hami et al. [143] described a vibration based electromechanical energy harvester that contained a pair of magnets and cantilever beam.

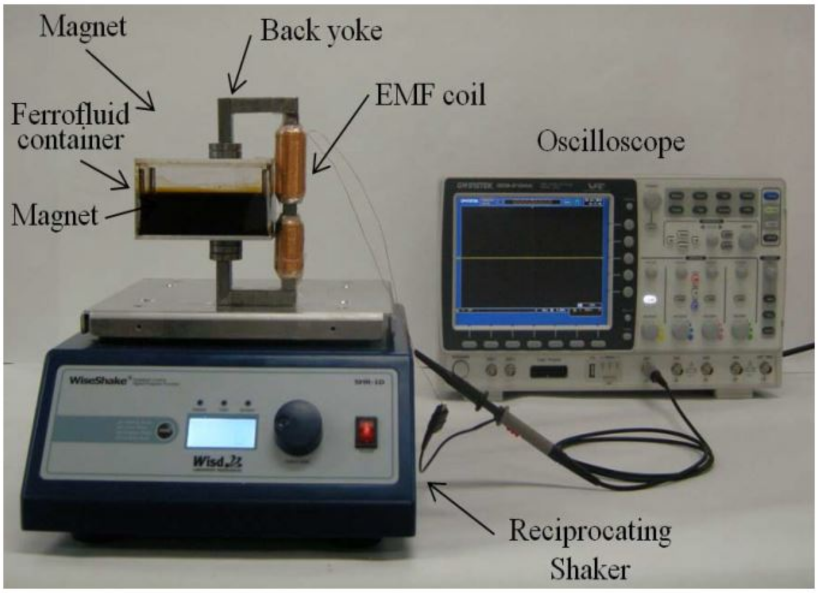


Fig. 9. Experimental setup for measuring induced electromotive force of electromagnetic energy harvester [146]

Nowadays, electromagnetic generator utilises the sloshing of ferrofluid columns to harvest vibration energy. A ferrofluid is strongly magnetised under the influence of a magnetic field.

Ferrofluid is a stable suspension with a mixture of magnetic nanoparticles in a conventional carrier fluid such as water or oil. Generally, the nanoparticles are ferri- or ferromagnetic particles with the diameter of <10 nm and coated with a surfactant layer of 1-2 nm. The difference between magnetorheological fluid and ferrofluid is the size of the particles. Bibo et al. [21] studied the use of ferrofluids in an electromagnetic micro-power generator and determined the influence of the ferrofluid quantity, magnetic field strength and acceleration level on the output voltage of the harvester. They concluded that the harvester output voltage increased with an increase in acceleration level, but the height of the fluid column had a small effect on the output voltage. Oh et al. [146] analysed the effect of ferrofluid sloshing movement on energy harvester to generate an electromotive force (EMF), and the experimental set-up used in this study is shown in Fig. 9. The influence of ferrofluid volume and different strength of permanent magnets on the characteristics of induced electromagnetic force were also examined. Results showed that, output power (μW) increased with an increase in vibration speed (*RPM*) and a decrease in magnetic flux densities (*mT*). Alazmi et al. [169] investigated the sloshing motion of ferrofluids, and concluded that the sloshing motion of the magnetised nanofluids creates a time dependent magnetic flux, which can generate an EMF in a coil. Seol et al. [170] studied the ferrofluid based triboelectric-electromagnetic hybrid generator for vibration energy harvesting. The result showed that the hybrid energy harvester was advantageous for harvesting subtle and irregular vibrations in the extremely low threshold amplitude and a wide operating frequency range. Wang et al. [171, 172] examined ferrofluid liquid springs for vibration energy harvesting. The results showed that the ferrofluid liquid spring can attain relatively low resonant frequency when engaging small volume of liquid. It is also compatible in the presence of high input acceleration. The modal frequencies of the fluid column are determined by the following equation [21, 173]:

$$f_{mn} = \frac{1}{2\pi}\sqrt{\frac{g^* k_{mn}}{R}\left(1 + \frac{\sigma k_{mn}^2}{\rho g^* R^2}\right)\tanh\left(\frac{k_{mn} h}{R}\right)} \quad (5)$$

where, the effective acceleration, $g^* = g - \frac{\chi}{\rho \mu_o}\frac{dB(z)}{dz}B(z)\Big|_{z=h}$, and g represents the gravitational acceleration, m & n are the different oscillation nodes, h is the liquid height, R is the radius of the container, μ_o is the magnetic permeability of vacuum. From Eq. (5), it is clear that the ferrofluids properties (like density and surface tension) have an important impact on the modal frequencies as well as the electromagnetic force, accordingly.

A large number of studies have been done on conventional electromagnetic energy harvester, where solid magnets were used to generate electromotive force. Dissimilar to the solid magnets, ferrofluids can easily change its shape and injected into hard to access locations due to its fluidity. Moreover, ferrofluid based energy harvester can also respond at infinite closely spaced modal frequencies which may enhance the performance of energy harvester under the influence of non-stationary and random excitations. Therefore, a broad study is needed on ferrofluid based electromagnetic energy harvester in the future to overcome the difficulties in the current energy harvesters as discussed earlier.

8. Conclusion and recommendations for future work

This paper involved the recent development on magnetic nanofluids for energy systems and energy harvesters. Recent studies have discussed the thermomagnetic convection and thermomagnetic effects. Few investigations have been done on the other features of heat transfer such as the improvement and control of thermal properties of ferrofluid under the external magnetic field. The use of magnetic nanofluids in heat transfer, as well as electromagnetic energy harvester applications, appear promising. Several studies have been investigated the outstanding thermal properties of nanofluids, and showed that the nanofluids exhibit significantly higher thermal conductivities and convective heat transfer properties in comparison to conventional heat transfer fluids (e.g. ethylene glycol, water, and mineral oils, etc.), although some doubts have been raised recently about these exaggerated claims. The overall effectiveness of nanofluids in heat transfer applications can be best evaluated if the enhancements in both thermal conductivity and viscosity are considered at the same time. In comparison, relatively little work has been done on the factors affecting nanofluid stability, specifically the effect of zeta potential and particle size distribution on nanofluid viscosity and thermal conductivity. Stability is an important concern in nanofluids research as attaining the desired stability of nano-suspensions remains a big challenge.

The development of magnetic nanofluids as a heat transfer fluid is still challengeable by many aspects ranging from the production and characterisation of nanofluids to the practical applications through the understanding of the mechanisms responsible for the observed heat transfer improvement. Future investigations should emphasise the preparation of ferrofluids and influence of different parameters on the size of the final synthesised nanoparticles. Another important aspect is the control of particle morphology during the preparation of the nanoparticles, because the cluster formation may be affected by the particle morphology. The control of the particle morphology and particle size may enable to prepare a unique ferrofluid with desired thermal properties as well as long-term stability, and further on the development of devices using magnetic nanofluid for practical applications.

The ferrofluid based electromagnetic energy harvesters implement ferrofluids, which can easily change shape and respond to very small vibrations. The further research will be needed to examine the science underpinning the behaviour of tunable magnetic nanofluids with a view towards creating a step-change improvement in the performance of electromagnetic energy harvesters. Most of the researches have been done on conventional electromagnetic energy harvester using solid magnets, and very few studies have been performed on ferrofluid based energy harvesters. The effect of fluid quantity, the shape, and size of the fluid container, magnetic field induction, vibration speed on EMF and power output of ferrofluid based energy harvester have been studied. But, the consequence of changing the physicochemical properties (such as pH, the weight concentration of nanoparticles, the size of nanoparticles etc.) of ferrofluids on the output power of the energy harvester will need to be examined and analysed. Then, the feasibility of the proposed method will need to be determined and the characteristics of electromagnetic force should be explained through the use of the experimental result.

Acknowledgments

The authors gratefully acknowledge the financial support provided by the University of Newcastle (Australia), Granite Power Pty Ltd and the Australian Research Council through the ARC-Linkage grant LP100200871, for the present study.

References

[1] E. Sadeghinezhad, M. Mehrali, R. Saidur, M. Mehrali, S. Tahan Latibari, A.R. Akhiani, et al. A comprehensive review on graphene nanofluids: Recent research, development and applications. Energy Conversion and Management. 111 (2016) 466-87.

[2] S. Choi. Enhancing thermal conductivity of fluids with nanoparticles. ASME-Publications-Fed. 231 (1995) 99-106.

[3] M. Khairul, K. Shah, E. Doroodchi, B. Moghtaderi. Application of nanofluids to enhance heat transfer in renewable energy systems. 3rd ASEAN Australian Engineering Congress (AAEC 2015) : Australian Engineering Congress on Innovative Technologies for Sustainable

Development and Renewable Energy. Barton, ACT: Engineers Australia, Singapore 2015. pp. 49-54.

[4] M. Jourabian, M. Farhadi. Melting of nanoparticles-enhanced phase change material (NEPCM) in vertical semicircle enclosure: numerical study. Journal of Mechanical Science and Technology. 29 (2015) 3819-30.

[5] M.A. Khairul, E. Doroodchi, R. Azizian, B. Moghtaderi. The influence of different flow regimes on heat transfer performance and exergy loss of Al2O3/DI-water and CuO/DI-water nanofluids. Applied Thermal Engineering. 122 (2017) 566-78.

[6] M. Jourabian, M. Farhadi, K. Sedighi. On the expedited melting of phase change material (PCM) through dispersion of nanoparticles in the thermal storage unit. Computers & Mathematics with Applications. 67 (2014) 1358-72.

[7] M.A. Khairul, K. Shah, E. Doroodchi, R. Azizian, B. Moghtaderi. Effects of surfactant on stability and thermo-physical properties of metal oxide nanofluids. International Journal of Heat and Mass Transfer. 98 (2016) 778-87.

[8] A. Gavili, F. Zabihi, T.D. Isfahani, J. Sabbaghzadeh. The thermal conductivity of water base ferrofluids under magnetic field. Experimental Thermal and Fluid Science. 41 (2012) 94-8.

[9] M. Bahiraei, M. Hangi. Investigating the efficacy of magnetic nanofluid as a coolant in double-pipe heat exchanger in the presence of magnetic field. Energy Conversion and Management. 76 (2013) 1125-33.

[10] G.D. Moeser. Colloidal magnetic fluids as extractants for chemical processing applications. Massachusetts Institute of Technology2003.

[11] R. Azizian. A fundamental study on heat transfer characteristics of magnetite nanofluids. The University of Newcastle, Australia Australia 2013.

[12] A. Miaskowski, B. Sawicki. Magnetic Fluid Hyperthermia Modeling Based on Phantom Measurements and Realistic Breast Model. Biomedical Engineering, IEEE Transactions on. 60 (2013) 1806-13.

[13] Y.-W. Lee, T.-L. Chang. Novel perturbations between magnetic nanofluid and the thermal fluidic system at heat dissipation. Microelectronic Engineering. 111 (2013) 58-63.

[14] J. Philip, P.D. Shima, B. Raj. Enhancement of thermal conductivity in magnetite based nanofluid due to chainlike structures. Applied Physics Letters. 91 (2007) 203108.

[15] J. Philip, J. Laskar, B. Raj. Magnetic field induced extinction of light in a suspension of Fe_3O_4 nanoparticles. Applied Physics Letters. 92 (2008) 221911--3.

[16] I. Nkurikiyimfura, Y. Wang, Z. Pan. Heat transfer enhancement by magnetic nanofluids—A review. Renewable and Sustainable Energy Reviews. 21 (2013) 548-61.

[17] A. Kuzubov, O. Ivanova. Magnetic liquids for heat exchange. Journal de Physique III. 4 (1994) 1-6.

[18] M. Bahiraei, M. Hangi. Flow and heat transfer characteristics of magnetic nanofluids: A review. Journal of Magnetism and Magnetic Materials. 374 (2015) 125-38.

[19] S. Odenbach, S. Thurm. Magnetoviscous effects in ferrofluids. Springer2002.

[20] J. Philip, P. Shima, B. Raj. Evidence for enhanced thermal conduction through percolating structures in nanofluids. Nanotechnology. 19 (2008) 305706.

[21] A. Bibo, R. Masana, A. King, G. Li, M. Daqaq. Electromagnetic ferrofluid-based energy harvester. Physics Letters A. 376 (2012) 2163-6.

[22] S.M. Elborai. Ferrofluid surface and volume flows in uniform rotating magnetic fields. Massachusetts Institute of Technology2006.

[23] X. He. Ferrohydrodynamic flows in uniform and non-uniform rotating magnetic fields. Massachusetts Institute of Technology2006.

[24] W. Bertsch, J. Azzi, J. Davidson. Delayed light studies on photosynthetic energy conversion. I. Identification of the oxygen-evolving photoreaction as the delayed light emitter in mutants of Scenedesmus obliquus. Biochimica et Biophysica Acta (BBA)-Bioenergetics. 143 (1967) 129-43.

[25] L. Vékás, D. Bica, M.V. Avdeev. Magnetic nanoparticles and concentrated magnetic nanofluids: Synthesis, properties and some applications. China Particuology. 5 (2007) 43-9.

[26] H. Yin, H.P. Too, G.M. Chow. The effects of particle size and surface coating on the cytotoxicity of nickel ferrite. Biomaterials. 26 (2005) 5818-26.

[27] J. Lai, K.V.P.M. Shafi, A. Ulman, K. Loos, N.-L. Yang, M.-H. Cui, et al. Mixed Iron−Manganese Oxide Nanoparticles. The Journal of Physical Chemistry B. 108 (2004) 14876-83.

[28] Y. Lu, Y. Yin, B.T. Mayers, Y. Xia. Modifying the Surface Properties of Superparamagnetic Iron Oxide Nanoparticles through A Sol−Gel Approach. Nano Letters. 2 (2002) 183-6.

[29] A.S. Teja, P.-Y. Koh. Synthesis, properties, and applications of magnetic iron oxide nanoparticles. Progress in Crystal Growth and Characterization of Materials. 55 (2009) 22-45.

[30] A. Kale, S. Gubbala, R.D.K. Misra. Magnetic behavior of nanocrystalline nickel ferrite synthesized by the reverse micelle technique. Journal of Magnetism and Magnetic Materials. 277 (2004) 350-8.

[31] J.K. Oh, J.M. Park. Iron oxide-based superparamagnetic polymeric nanomaterials: Design, preparation, and biomedical application. Progress in Polymer Science. 36 (2011) 168-89.

[32] V.L. Kolesnichenko. Synthesis of Nanoparticulate Magnetic Materials. Magnetic Nanoparticles. (2009) 1837.

[33] D.S. Mathew, R.-S. Juang. An overview of the structure and magnetism of spinel ferrite nanoparticles and their synthesis in microemulsions. Chemical Engineering Journal. 129 (2007) 51-65.

[34] M.A. Khairul, E. Doroodchi, R. Azizian, B. Moghtaderi. Experimental Study on Fundamental Mechanisms of Ferro-Fluidics for an Electromagnetic Energy Harvester. Industrial & Engineering Chemistry Research. 55 (2016) 12491-501.

[35] U. Tamer, Y. Gündoğdu, İ.H. Boyacı, K. Pekmez. Synthesis of magnetic core–shell Fe_3O_4–Au nanoparticle for biomolecule immobilization and detection. Journal of Nanoparticle Research. 12 (2010) 1187-96.

[36] C.-H. Lo, T.-T. Tsung, L.-C. Chen. Ni nano-magnetic fluid prepared by submerged arc nano synthesis system (SANSS). JSME International Journal Series B. 48 (2005) 750-5.

[37] S.W. Charles. The Preparation of Magnetic Fluids. in: S. Odenbach, (Ed.). Ferrofluids: Magnetically Controllable Fluids and Their Applications. Springer Berlin Heidelberg, Berlin, Heidelberg, 2002. pp. 3-18.

[38] M. Mascolo, Y. Pei, T. Ring. Room Temperature Co-Precipitation Synthesis of Magnetite Nanoparticles in a Large pH Window with Different Bases. Materials. 6 (2013) 5549.

[39] R.Y. Hong, J.H. Li, H.Z. Li, J. Ding, Y. Zheng, D.G. Wei. Synthesis of Fe_3O_4 nanoparticles without inert gas protection used as precursors of magnetic fluids. Journal of Magnetism and Magnetic Materials. 320 (2008) 1605-14.

[40] L. Vékás, D. Bica, O. Marinica. Magnetic nanofluids stabilized with various chain length surfactants. Romanian Reports in Physics. 58 (2006) 257-67.

[41] J.L. Arias, M. López-Viota, M.A. Ruiz, J. López-Viota, A.V. Delgado. Development of carbonyl iron/ethylcellulose core/shell nanoparticles for biomedical applications. International Journal of Pharmaceutics. 339 (2007) 237-45.

[42] C. de Mello Donegá, P. Liljeroth, D. Vanmaekelbergh. Physicochemical Evaluation of the Hot-Injection Method, a Synthesis Route for Monodisperse Nanocrystals. Small. 1 (2005) 1152-62.

[43] J.L. Arias, L.H. Reddy, P. Couvreur. Magnetoresponsive Squalenoyl Gemcitabine Composite Nanoparticles for Cancer Active Targeting. Langmuir. 24 (2008) 7512-9.

[44] M. Di Marco, C. Sadun, M. Port, I. Guilbert, P. Couvreur, C. Dubernet. Physicochemical characterization of ultrasmall superparamagnetic iron oxide particles (USPIO) for biomedical application as MRI contrast agents. International journal of nanomedicine. 2 (2007) 609.

[45] C.W. Jung. Surface properties of superparamagnetic iron oxide MR contrast agents: ferumoxides, ferumoxtran, ferumoxsil. Magnetic resonance imaging. 13 (1995) 675-91.

[46] M. Carmen Bautista, O. Bomati-Miguel, M. del Puerto Morales, C.J. Serna, S. Veintemillas-Verdaguer. Surface characterisation of dextran-coated iron oxide nanoparticles prepared by laser pyrolysis and coprecipitation. Journal of Magnetism and Magnetic Materials. 293 (2005) 20-7.

[47] C. Yee, G. Kataby, A. Ulman, T. Prozorov, H. White, A. King, et al. Self-Assembled Monolayers of Alkanesulfonic and -phosphonic Acids on Amorphous Iron Oxide Nanoparticles. Langmuir. 15 (1999) 7111-5.

[48] D.I. Kreller, G. Gibson, W. Novak, G.W. Van Loon, J.H. Horton. Competitive adsorption of phosphate and carboxylate with natural organic matter on hydrous iron oxides as investigated by chemical force microscopy. Colloids and Surfaces A: Physicochemical and Engineering Aspects. 212 (2003) 249-64.

[49] H. Holthoff, S.U. Egelhaaf, M. Borkovec, P. Schurtenberger, H. Sticher. Coagulation Rate Measurements of Colloidal Particles by Simultaneous Static and Dynamic Light Scattering. Langmuir. 12 (1996) 5541-9.

[50] M. Schudel, S.H. Behrens, H. Holthoff, R. Kretzschmar, M. Borkovec. Absolute Aggregation Rate Constants of Hematite Particles in Aqueous Suspensions: A Comparison of Two Different Surface Morphologies. Journal of Colloid and Interface Science. 196 (1997) 241-53.

[51] J.L. Ortega-Vinuesa, A. Martín-Rodríguez, R. Hidalgo-Álvarez. Colloidal Stability of Polymer Colloids with Different Interfacial Properties: Mechanisms. Journal of Colloid and Interface Science. 184 (1996) 259-67.

[52] J.L. Viota, J. de Vicente, J.D.G. Durán, A.V. Delgado. Stabilization of magnetorheological suspensions by polyacrylic acid polymers. Journal of Colloid and Interface Science. 284 (2005) 527-41.

[53] Z. Haddad, C. Abid, H.F. Oztop, A. Mataoui. A review on how the researchers prepare their nanofluids. International Journal of Thermal Sciences. 76 (2014) 168-89.

[54] S. Odenbach, S. Thurm. Magnetoviscous Effects in Ferrofluids. in: S. Odenbach, (Ed.). Ferrofluids: Magnetically Controllable Fluids and Their Applications. Springer Berlin Heidelberg, Berlin, Heidelberg, 2002. pp. 185-201.

[55] S. Odenbach. Recent progress in magnetic fluid research. Journal of physics: condensed matter. 16 (2004) R1135.

[56] S.W. Charles. The preparation of magnetic fluids. Ferrofluids. Springer2002. pp. 3-18.

[57] L.H. Reddy, J.L. Arias, J. Nicolas, P. Couvreur. Magnetic Nanoparticles: Design and Characterization, Toxicity and Biocompatibility, Pharmaceutical and Biomedical Applications. Chemical Reviews. 112 (2012) 5818-78.

[58] X.F. Li, D.S. Zhu, X.J. Wang, N. Wang, J.W. Gao, H. Li. Thermal conductivity enhancement dependent pH and chemical surfactant for Cu-H_2O nanofluids. Thermochimica Acta. 469 (2008) 98-103.

[59] D. Lee, J.-W. Kim, B.G. Kim. A New Parameter to Control Heat Transport in Nanofluids: Surface Charge State of the Particle in Suspension. The Journal of Physical Chemistry B. 110 (2006) 4323-8.

[60] W. Evans, R. Prasher, J. Fish, P. Meakin, P. Phelan, P. Keblinski. Effect of aggregation and interfacial thermal resistance on thermal conductivity of nanocomposites and colloidal nanofluids. International Journal of Heat and Mass Transfer. 51 (2008) 1431-8.

[61] H. Chang, Y. Wu, X. Chen, M. Kao. Fabrication of Cu Based Nanofluid with Superior Dispersion 2006.

[62] S.K. Verma, A.K. Tiwari, D.S. Chauhan. Experimental evaluation of flat plate solar collector using nanofluids. Energy Conversion and Management. 134 (2017) 103-15.

[63] W.S. Sarsam, A. Amiri, S.N. Kazi, A. Badarudin. Stability and thermophysical properties of non-covalently functionalized graphene nanoplatelets nanofluids. Energy Conversion and Management. 116 (2016) 101-11.

[64] P.C. Hiemenz, R. Rajagopalan. Principles of Colloid and Surface Chemistry, revised and expanded. CRC press1997.

[65] D. Wu, H. Zhu, L. Wang, L. Liu. Critical issues in nanofluids preparation, characterization and thermal conductivity. Current Nanoscience. 5 (2009) 103-12.

[66] C.H. Chon, K.D. Kihm. Thermal Conductivity Enhancement of Nanofluids by Brownian Motion. Journal of Heat Transfer. 127 (2005) 810-.

[67] S. Krishnamurthy, P. Bhattacharya, P.E. Phelan, R.S. Prasher. Enhanced Mass Transport in Nanofluids. Nano Letters. 6 (2006) 419-23.

[68] R. Prasher, P. Bhattacharya, P.E. Phelan. Thermal Conductivity of Nanoscale Colloidal Solutions (Nanofluids). Physical Review Letters. 94 (2005) 025901.

[69] J.A. Eastman, S. Phillpot, S. Choi, P. Keblinski. Thermal transport in nanofluids. Annual Review of Materials Research. 34 (2004) 219-46.

[70] E.C. Nsofor. Recent Patents on Nanofluids (Nanoparticles in Liquids) Heat Transfer. Recent Patents on Mechanical Engineering. 1 (2008) 190-7.

[71] J. Eapen, R. Rusconi, R. Piazza, S. Yip. The Classical Nature of Thermal Conduction in Nanofluids. Journal of Heat Transfer. 132 (2010) 102402--14.

[72] V. Singh, M. Gupta. Heat transfer augmentation in a tube using nanofluids under constant heat flux boundary condition: A review. Energy Conversion and Management. 123 (2016) 290-307.

[73] X.-Q. Wang, A.S. Mujumdar. Heat transfer characteristics of nanofluids: a review. International Journal of Thermal Sciences. 46 (2007) 1-19.

[74] S. Özerinç, S. Kakaç, A.G. Yazıcıoğlu. Enhanced thermal conductivity of nanofluids: a state-of-the-art review. Microfluidics and Nanofluidics. 8 (2010) 145-70.

[75] S.P. Jang, S.U.S. Choi. Role of Brownian motion in the enhanced thermal conductivity of nanofluids. Applied Physics Letters. 84 (2004) 4316-8.

[76] T.-H. Tsai, L.-S. Kuo, P.-H. Chen, C.-T. Yang. Effect of viscosity of base fluid on thermal conductivity of nanofluids. Applied Physics Letters. 93 (2008) 233121.

[77] L. Li, Y. Zhang, H. Ma, M. Yang. Molecular dynamics simulation of effect of liquid layering around the nanoparticle on the enhanced thermal conductivity of nanofluids. Journal of Nanoparticle Research. 12 (2010) 811-21.

[78] P. Keblinski, S.R. Phillpot, S.U.S. Choi, J.A. Eastman. Mechanisms of heat flow in suspensions of nano-sized particles (nanofluids). International Journal of Heat and Mass Transfer. 45 (2002) 855-63.

[79] C.J. Yu, A.G. Richter, A. Datta, M.K. Durbin, P. Dutta. Observation of Molecular Layering in Thin Liquid Films Using X-Ray Reflectivity. Physical Review Letters. 82 (1999) 2326-9.

[80] R. Yajie, X. Huaqing, C. An. Effective thermal conductivity of nanofluids containing spherical nanoparticles. Journal of Physics D: Applied Physics. 38 (2005) 3958.

[81] W. Yu, S.U.S. Choi. The role of interfacial layers in the enhanced thermal conductivity of nanofluids: A renovated Hamilton–Crosser model. Journal of Nanoparticle Research. 6 (2004) 355-61.

[82] P. Keblinski, R. Prasher, J. Eapen. Thermal conductance of nanofluids: is the controversy over? Journal of Nanoparticle Research. 10 (2008) 1089-97.

[83] L. Wang, J. Fan. Toward nanofluids of ultra-high thermal conductivity. Nanoscale Research Letters. 6 (2011) 153.

[84] R. Azizian, E. Doroodchi, B. Moghtaderi. Influence of Controlled Aggregation on Thermal Conductivity of Nanofluids. Journal of Heat Transfer. 138 (2016) 021301.

[85] R. Prasher, W. Evans, P. Meakin, J. Fish, P. Phelan, P. Keblinski. Effect of aggregation on thermal conduction in colloidal nanofluids. Applied Physics Letters. 89 (2006) 143119.

[86] K.J.M. Bishop, C.E. Wilmer, S. Soh, B.A. Grzybowski. Nanoscale Forces and Their Uses in Self-Assembly. Small. 5 (2009) 1600-30.

[87] V.S. Mendelev, A.O. Ivanov. Ferrofluid aggregation in chains under the influence of a magnetic field. Physical Review E. 70 (2004) 051502.

[88] L. Syam Sundar, M.K. Singh, A.C.M. Sousa. Investigation of thermal conductivity and viscosity of Fe_3O_4 nanofluid for heat transfer applications. International Communications in Heat and Mass Transfer. 44 (2013) 7-14.

[89] M.J. Pastoriza-Gallego, L. Lugo, J.L. Legido, M.M. Piñeiro. Enhancement of thermal conductivity and volumetric behavior of FexOy nanofluids. Journal of Applied Physics. 110 (2011) 014309.

[90] M. Abareshi, E.K. Goharshadi, S. Mojtaba Zebarjad, H. Khandan Fadafan, A. Youssefi. Fabrication, characterization and measurement of thermal conductivity of Fe_3O_4 nanofluids. Journal of Magnetism and Magnetic Materials. 322 (2010) 3895-901.

[91] H. Fu, L. Gao. Theory for anisotropic thermal conductivity of magnetic nanofluids. Physics Letters A. 375 (2011) 3588-92.

[92] X. Fang, Y. Xuan, Q. Li. Anisotropic thermal conductivity of magnetic fluids. Progress in Natural Science. 19 (2009) 205-11.

[93] I. Nkurikiyimfura, Y. Wang, Z. Pan. Effect of chain-like magnetite nanoparticle aggregates on thermal conductivity of magnetic nanofluid in magnetic field. Experimental Thermal and Fluid Science. 44 (2013) 607-12.

[94] B. Finlayson. Convective instability of ferromagnetic fluids. Journal of Fluid Mechanics. 40 (1970) 753-67.

[95] H. Yamaguchi. Engineering fluid mechanics. Springer Science & Business Media2008.

[96] R.E. Rosensweig. Magnetic fluids. Annual review of fluid mechanics. 19 (1987) 437-61.

[97] R. Ganguly, S. Sen, I.K. Puri. Heat transfer augmentation using a magnetic fluid under the influence of a line dipole. Journal of Magnetism and Magnetic Materials. 271 (2004) 63-73.

[98] H. Zhu, C. Zhang, S. Liu, Y. Tang, Y. Yin. Effects of nanoparticle clustering and alignment on thermal conductivities of Fe3O4 aqueous nanofluids. Applied Physics Letters. 89 (2006) 023123.

[99] W. Jiang, L. Wang. Monodisperse magnetite nanofluids: Synthesis, aggregation, and thermal conductivity. Journal of Applied Physics. 108 (2010) 114311.

[100] A. Ghadimi, R. Saidur, H.S.C. Metselaar. A review of nanofluid stability properties and characterization in stationary conditions. International Journal of Heat and Mass Transfer. 54 (2011) 4051-68.

[101] X.-j. Wang, D.-s. Zhu, S. yang. Investigation of pH and SDBS on enhancement of thermal conductivity in nanofluids. Chemical Physics Letters. 470 (2009) 107-11.

[102] D. Zhu, X. Li, N. Wang, X. Wang, J. Gao, H. Li. Dispersion behavior and thermal conductivity characteristics of Al2O3–H2O nanofluids. Current Applied Physics. 9 (2009) 131-9.

[103] M.N. Pantzali, A.G. Kanaris, K.D. Antoniadis, A.A. Mouza, S.V. Paras. Effect of nanofluids on the performance of a miniature plate heat exchanger with modulated surface. International Journal of Heat and Fluid Flow. 30 (2009) 691-9.

[104] M. Chandrasekar, S. Suresh, A. Chandra Bose. Experimental investigations and theoretical determination of thermal conductivity and viscosity of Al_2O_3/water nanofluid. Experimental Thermal and Fluid Science. 34 (2010) 210-6.

[105] X. Wei, T. Kong, H. Zhu, L. Wang. CuS/Cu2S nanofluids: Synthesis and thermal conductivity. International Journal of Heat and Mass Transfer. 53 (2010) 1841-3.

[106] M.E. Meibodi, M. Vafaie-Sefti, A.M. Rashidi, A. Amrollahi, M. Tabasi, H.S. Kalal. The role of different parameters on the stability and thermal conductivity of carbon nanotube/water nanofluids. International Communications in Heat and Mass Transfer. 37 (2010) 319-23.

[107] M.J. Assael, I.N. Metaxa, J. Arvanitidis, D. Christofilos, C. Lioutas. Thermal Conductivity Enhancement in Aqueous Suspensions of Carbon Multi-Walled and Double-Walled Nanotubes in the Presence of Two Different Dispersants. International Journal of Thermophysics. 26 (2005) 647-64.

[108] B. Wang, B. Wang, P. Wei, X. Wang, W. Lou. Controlled synthesis and size-dependent thermal conductivity of Fe_3O_4 magnetic nanofluids. Dalton Transactions. 41 (2012) 896-9.

[109] K.S. Hong, T.-K. Hong, H.-S. Yang. Thermal conductivity of Fe nanofluids depending on the cluster size of nanoparticles. Applied Physics Letters. 88 (2006) 031901.

[110] H. Chen, Y. Ding, Y. He, C. Tan. Rheological behaviour of ethylene glycol based titania nanofluids. Chemical Physics Letters. 444 (2007) 333-7.

[111] I.M. Krieger, T.J. Dougherty. A mechanism for non-Newtonian flow in suspensions of rigid spheres. Transactions of The Society of Rheology (1957-1977). 3 (1959) 137-52.

[112] M. Krichler, S. Odenbach. Thermal conductivity measurements on ferrofluids with special reference to measuring arrangement. Journal of Magnetism and Magnetic Materials. 326 (2013) 85-90.

[113] Q. Li, Y. Xuan, J. Wang. Experimental investigations on transport properties of magnetic fluids. Experimental Thermal and Fluid Science. 30 (2005) 109-16.

[114] P.D. Shima, J. Philip. Tuning of Thermal Conductivity and Rheology of Nanofluids Using an External Stimulus. The Journal of Physical Chemistry C. 115 (2011) 20097-104.

[115] T.T. Baby, S. Ramaprabhu. Magnetic Nanoparticles Decorated Multiwalled Carbon Nanotubes Dispersed Nanofluids. AIP Conference Proceedings. 1349 (2011) 965-6.

[116] K. Parekh, H.S. Lee. Experimental investigation of thermal conductivity of magnetic nanofluids. AIP Conference Proceedings. 1447 (2012) 385-6.

[117] M. Mehrali, E. Sadeghinezhad, A.R. Akhiani, S. Tahan Latibari, H.S.C. Metselaar, A.S. Kherbeet, et al. Heat transfer and entropy generation analysis of hybrid graphene/Fe_3O_4 ferro-nanofluid flow under the influence of a magnetic field. Powder Technology. 308 (2017) 149-57.

[118] Y.P. Chiu, Y.F. Chen, S.Y. Yang, J.C. Chen, H.E. Horng, H.C. Yang, et al. Specific heat of magnetic fluids under a modulated magnetic field. Journal of Applied Physics. 93 (2003) 2079-81.

[119] K. Parekh, H.S. Lee. Magnetic field induced enhancement in thermal conductivity of magnetite nanofluid. Journal of Applied Physics. 107 (2010) 09A310.

[120] R. Prasher, D. Song, J. Wang, P. Phelan. Measurements of nanofluid viscosity and its implications for thermal applications. Applied Physics Letters. 89 (2006) -.

[121] D. Venerus, J. Buongiorno, R. Christianson, J. Townsend, I.C. Bang, G. Chen, et al. Viscosity measurements on colloidal dispersions (nanofluids) for heat transfer applications. Applied rheology. 20 (2010).

[122] M. Jourabian, M. Farhadi, A.A. Rabienataj Darzi. Outward melting of ice enhanced by Cu nanoparticles inside cylindrical horizontal annulus: Lattice Boltzmann approach. Applied Mathematical Modelling. 37 (2013) 8813-25.

[123] M. Jourabian, M. Farhadi, K. Sedighi, A.A.R. Darzi, Y. Vazifeshenas. Melting of NEPCM within a Cylindrical Tube: Numerical Study Using the Lattice Boltzmann Method. Numerical Heat Transfer, Part A: Applications. 61 (2012) 929-48.

[124] R. Ganguly, I.K. Puri. Field-Assisted Self-Assembly of Superparamagnetic Nanoparticles for Biomedical, MEMS and BioMEMS Applications. in: A. Hassan, G. Erik van der, (Eds.), Advances in Applied Mechanics. Elsevier2007. pp. 293-335.

[125] E. Blums, A. Mezulis, G. Kronkalns. Magnetoconvective heat transfer from a cylinder under the influence of a nonuniform magnetic field. Journal of Physics: Condensed Matter. 20 (2008) 204128.

[126] H. Yamaguchi, X.-D. Niu, X.-R. Zhang, K. Yoshikawa. Experimental and numerical investigation of natural convection of magnetic fluids in a cubic cavity. Journal of Magnetism and Magnetic Materials. 321 (2009) 3665-70.

[127] C. Nanjundappa, I. Shivakumara, K. Srikumar. Effect of MFD Viscosity on the Onset of Ferromagnetic Fluid Layer Heated from Below and Cooled from Above with Constant Heat Flux. Measurement Science Review2009. p. 75.

[128] M. Goharkhah, M. Ashjaee, M. Shahabadi. Experimental investigation on convective heat transfer and hydrodynamic characteristics of magnetite nanofluid under the influence of an alternating magnetic field. International Journal of Thermal Sciences. 99 (2016) 113-24.

[129] M. Goharkhah, A. Salarian, M. Ashjaee, M. Shahabadi. Convective heat transfer characteristics of magnetite nanofluid under the influence of constant and alternating magnetic field. Powder Technology. 274 (2015) 258-67.

[130] M. Yarahmadi, H. Moazami Goudarzi, M.B. Shafii. Experimental investigation into laminar forced convective heat transfer of ferrofluids under constant and oscillating magnetic field with different magnetic field arrangements and oscillation modes. Experimental Thermal and Fluid Science. 68 (2015) 601-11.

[131] R. Azizian, E. Doroodchi, T. McKrell, J. Buongiorno, L.W. Hu, B. Moghtaderi. Effect of magnetic field on laminar convective heat transfer of magnetite nanofluids. International Journal of Heat and Mass Transfer. 68 (2014) 94-109.

[132] A. Ghofrani, M.H. Dibaei, A. Hakim Sima, M.B. Shafii. Experimental investigation on laminar forced convection heat transfer of ferrofluids under an alternating magnetic field. Experimental Thermal and Fluid Science. 49 (2013) 193-200.

[133] L. Syam Sundar, M.T. Naik, K.V. Sharma, M.K. Singh, T.C. Siva Reddy. Experimental investigation of forced convection heat transfer and friction factor in a tube with Fe_3O_4 magnetic nanofluid. Experimental Thermal and Fluid Science. 37 (2012) 65-71.

[134] M. Lajvardi, J. Moghimi-Rad, I. Hadi, A. Gavili, T. Dallali Isfahani, F. Zabihi, et al. Experimental investigation for enhanced ferrofluid heat transfer under magnetic field effect. Journal of Magnetism and Magnetic Materials. 322 (2010) 3508-13.

[135] Q. Li, Y. Xuan. Experimental investigation on heat transfer characteristics of magnetic fluid flow around a fine wire under the influence of an external magnetic field. Experimental Thermal and Fluid Science. 33 (2009) 591-6.

[136] M. Pantzali, A. Mouza, S. Paras. Investigating the efficacy of nanofluids as coolants in plate heat exchangers (PHE). Chemical Engineering Science. 64 (2009) 3290-300.

[137] I. Sari, T. Balkan, H. Kulah. An electromagnetic micro power generator for wideband environmental vibrations. Sensors and Actuators A: Physical. 145–146 (2008) 405-13.

[138] P. Glynne-Jones, M.J. Tudor, S.P. Beeby, N.M. White. An electromagnetic, vibration-powered generator for intelligent sensor systems. Sensors and Actuators A: Physical. 110 (2004) 344-9.

[139] S.P. Beeby, M. Tudor, N. White. Energy harvesting vibration sources for microsystems applications. Measurement science and technology. 17 (2006) 175-95.

[140] A. Kansal, M.B. Srivastava. Distributed Energy Harvesting for Energy Neutral Sensor Networks. 2005.

[141] G. Park, T. Rosing, M.D. Todd, C.R. Farrar, W. Hodgkiss. Energy harvesting for structural health monitoring sensor networks. Journal of Infrastructure Systems. 14 (2008) 64-79.

[142] D. Zhu, S. Roberts, M.J. Tudor, S.P. Beeby. Design and experimental characterization of a tunable vibration-based electromagnetic micro-generator. Sensors and Actuators A: Physical. 158 (2010) 284-93.

[143] M. El-hami, P. Glynne-Jones, N.M. White, M. Hill, S. Beeby, E. James, et al. Design and fabrication of a new vibration-based electromechanical power generator. Sensors and Actuators A: Physical. 92 (2001) 335-42.

[144] S. Boisseau, G. Despesse, B.A. Seddik. Electrostatic conversion for vibration energy harvesting. arXiv preprint arXiv:12105191. (2012).

[145] A. Munaz, B.-C. Lee, G.-S. Chung. A study of an electromagnetic energy harvester using multi-pole magnet. Sensors and Actuators A: Physical. 201 (2013) 134-40.

[146] D.W. Oh, D.Y. Sohn, D.G. Byun, Y.S. Kim. Analysis of electromotive force characteristics and device implementation for ferrofluid based energy harvesting system. Electrical Machines and Systems (ICEMS), 2014 17th International Conference on. IEEE2014. pp. 2033-8.

[147] S. Roundy, P. Wright, J. Rabaey. Energy scavenging for wireless sensor networks: with special focus on vibrations. Norwell, Massachusetts: Kluwer Academic Publishers. (2004).

[148] S. Roundy. On the effectiveness of vibration-based energy harvesting. Journal of intelligent material systems and structures. 16 (2005) 809-23.

[149] S. Roundy, P.K. Wright, J. Rabaey. A study of low level vibrations as a power source for wireless sensor nodes. Computer communications. 26 (2003) 1131-44.

[150] R. Moghe, Y. Yang, F. Lambert, D. Divan. A scoping study of electric and magnetic field energy harvesting for wireless sensor networks in power system applications. Energy Conversion Congress and Exposition, 2009 ECCE 2009 IEEE. IEEE2009. pp. 3550-7.

[151] S. Chalasani, J.M. Conrad. A survey of energy harvesting sources for embedded systems. Southeastcon, 2008 IEEE. IEEE2008. pp. 442-7.

[152] Q. Zhang, S. Chen, L. Baumgartel, A. Lin, E. Kim. Microelectromagnetic energy harvester with integrated magnets. Solid-State Sensors, Actuators and Microsystems Conference (TRANSDUCERS), 2011 16th International. IEEE2011. pp. 1657-60.

[153] H. Liu, C.J. Tay, C. Quan, T. Kobayashi, C. Lee. Piezoelectric MEMS energy harvester for low-frequency vibrations with wideband operation range and steadily increased output power. Microelectromechanical Systems, Journal of. 20 (2011) 1131-42.

[154] Q. Zhang, E.S. Kim. Energy harvesters with high electromagnetic conversion efficiency through magnet and coil arrays. Micro Electro Mechanical Systems (MEMS), 2013 IEEE 26th International Conference on. IEEE2013. pp. 110-3.

[155] M. Faraday. On some new electro-magnetical motions, and on the theory of magnetism. Quarterly Journal of Science. 12 (1821) 74-96.

[156] D.S. Cardwell. On Michael Faraday, henry wilde, and the dynamo. Annals of science. 49 (1992) 479-87.

[157] M. Faraday. Historical sketch of electro-magnetism. Annals of Philosophy. 2 (1821) 195-200.

[158] M. Faraday. Experimental researches in electricity. Philosophical transactions of the Royal Society of London. 122 (1832) 125-62.

[159] S. Beeby, M. Tudor, E. Koukharenko, N. White, T. O'Donnell, C. Saha, et al. Micromachined silicon generator for harvesting power from vibrations. The 4th International Workshop on Micro and Nanotechnology for Power Generation and Energy Conversion Applications (PowerMEMS 2004), Kyoto, Japan, 2004. pp. 104-7.

[160] H. Wen-Sheh, T. Kung-Ei, C. Ming-Cheng, H. Ruey-Shing. Design and Fabrication of a Vibrational Micro-Generator for Wearable MEMS. Institute of Electrical and Electronics Engineers2003. pp. Portugga-l.

[161] M. Umeda, K. Nakamura, S. Ueha. Energy storage characteristics of a piezo-generator using impact induced vibration. Japanese journal of applied physics. 36 (1997) 3146.

[162] S.J. Roundy. Energy scavenging for wireless sensor nodes with a focus on vibration to electricity conversion. Mechanical Engineering. University of California, Berkeley2003.

[163] E. Sazonov, H. Li, D. Curry, P. Pillay. Self-powered sensors for monitoring of highway bridges. Sensors Journal, IEEE. 9 (2009) 1422-9.

[164] T. Sterken, P. Fiorini, K. Baert, R. Puers, G. Borghs. An electret-based electrostatic/spl mu/-generator. TRANSDUCERS, Solid-State Sensors, Actuators and Microsystems, 12th International Conference on, 2003. IEEE2003. pp. 1291-4.

[165] E. Dallago, A. Danioni, M. Marchesi, V. Nucita, G. Venchi. A self-powered electronic interface for electromagnetic energy harvester. Power Electronics, IEEE Transactions on. 26 (2011) 3174-82.

[166] L. Wang, F.G. Yuan. Energy harvesting by magnetostrictive material (MsM) for powering wireless sensors in SHM. The 14th International Symposium on: Smart Structures and Materials & Nondestructive Evaluation and Health Monitoring. International Society for Optics and Photonics2007. pp. 652941--11.

[167] A. Bayrashev, W.P. Robbins, B. Ziaie. Low frequency wireless powering of microsystems using piezoelectric–magnetostrictive laminate composites. Sensors and Actuators A: Physical. 114 (2004) 244-9.

[168] M.E. Staley, A.B. Flatau. Characterization of energy harvesting potential of Terfenol-D and Galfenol. Smart Structures and Materials. International Society for Optics and Photonics2005. pp. 630-40.

[169] S. Alazmi, Y. Xu, M.F. Daqaqa. Harvesting energy from the sloshing motion of ferrofluids in an externally excited container: Analytical modeling and experimental validation. Physics of Fluids. 28 (2016) 077101.

[170] M.-L. Seol, S.-B. Jeon, J.-W. Han, Y.-K. Choi. Ferrofluid-based triboelectric-electromagnetic hybrid generator for sensitive and sustainable vibration energy harvesting. Nano Energy. 31 (2017) 233-8.

[171] Y. Wang, Q. Zhang, L. Zhao, E.S. Kim. Ferrofluid liquid spring for vibration energy harvesting. Micro Electro Mechanical Systems (MEMS), 2015 28th IEEE International Conference on. IEEE2015. pp. 122-5.

[172] Y. Wang, Q. Zhang, L. Zhao, Y. Tang, A. Shkel, E.S. Kim. Vibration energy harvester with low resonant frequency based on flexible coil and liquid spring. Applied Physics Letters. 109 (2016) 203901.

[173] H.F. Bauer, W. Eidel. Free oscillations and response of a viscous liquid in a rigid circular cylindrical tank. Aerospace Science and Technology. 3 (1999) 495-512.