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Review Articles

Engineering applications of ferrofluids: A review

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ABSTRACT

Ferrofluids are stable colloidal suspensions of nanometric sized ferromagnetic, or their oxide particles, in conventional basefluids like water, oil, etc. The property of ferromagnetism is changed to superparamagnetism by size reduction of the particles to nanometer level. It opens the possibility to tune the thermophysical properties of ferrofluids by the application of an external magnetic field. Ferrofluids were invented by Steve Papell of NASA in 1963 with the intention to make a suitable liquid rocket fuel which could be attracted by an external magnetic field towards the inlet of a pump in a zero-gravity environment. Subsequently, intense research has led to diverse applications of these fluids, from computer hard discs, clean room robots to dynamic loudspeakers, exploiting their unique operational behavior. Ferrofluid lubrication and film bearing have emerged as better alternatives to conventional systems. Contemporary times have also witnessed a plethora of bio-medical applications of ferrofluids, ranging from location-specific drug delivery, treatment of tumor cells, cell separation, tagging, and in diagnostic systems like Magnetic Resonance and Particle Imaging, to name a few. New vistas have opened in the context of thermal management of miniaturized systems. Ferrofluids, with enhanced thermal conductivity, and possibility of external control and manipulation of heat transfer coefficient, can potentially compete with other standard heat transfer solutions. In this background, this article attempts a comprehensive review of the gamut of existing and emerging applications of ferrofluids. Relevant insights of the underlying physics and transport mechanisms, which are harnessed in these applications, is also delineated.

1. Introduction

Ferrofluids or magnetic nanofluids are stable colloidal suspensions of ultrafine single domain superparamagnetic nanoparticles (mainly iron and its oxides such as magnetite (Fe_3O_4) or maghemite (γ-Fe_2O_3)), in either polar or non-polar basefluids, viz. water, ethylene glycol (EG), transformer oil, engine oil, etc. It is noted here that ferrofluids are different from the conventional magneto-rheological fluids (MRF), which are used in brakes and clutches; the latter are formed by micrometre sized particles dispersed in oil. The viscosity of MRF increases enormously by the application of a magnetic field. These may behave like a quasi-solid under very high externally applied magnetic fields. However, a ferrofluid remains in its 'fluid' state even under the application of strong magnetic fields ($\sim$ 10 kG) [1].

Control and manipulation of properties and behavior of ferrofluids by the application of external magnetic field is a promising area for advanced applications since early-1960s, when these materials were initially synthesized [2]. Ferrofluids are widely used in magnetic sealing, dynamic loudspeakers, computer hardware, electronic packaging, aerospace, and bioengineering [1]. Some other applications of ferrofluids are in microfluidic pumps and valves, microfluidic actuators and devices, accelerometers and inclinometers in sensor applications, separation processes, catalytic reaction supports, pneumatic and hydraulic micro-actuators, to name a few [3]. Ferrofluids also have optical applications, like dichroism and birefringence based on magneto-optic effect [3]. Magnetic nanoparticles in body fluids (blood, lymph fluid, etc.) can also be used for drug delivery at the specific affected site and induce hyperthermia, providing new cancer treatment techniques [4].

Several thermophysical properties of the conventional basefluids can be altered by the right choice of the solid phase material. For example, the effective thermal conductivity of the mixture can be enhanced, viscosity and surface tension can be altered, and eventually momentum/thermal/mass diffusivity of the non-magnetic nanofluids can be potentially tailored. These nanofluids have been extensively explored, for several applications, the primary among them being for applications involving enhancement of heat transfer [5–15]. If the solid-phase

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material possesses additional features, such as magnetic properties, then the functionality of the magnetic nanofluids or ferrofluids can be further exploited.

Many nanoparticles (e.g., Cu, Al_2O_3, TiO_2, etc.) have higher thermal conductivity than the basefluids, in general. Hence, it was initially thought that the origin of thermal conductivity enhancement in nanofluids was due to the higher thermal conductivity of the nanoparticles. However, magnetic materials (like Fe_3O_4) have relatively lower thermal conductivity; accordingly, researchers in thermal sciences did not give much attention to ferrofluids till it was revealed that the thermal conductivity of the solid particles may have only little impact in the overall increment of the thermal conductivity of the suspension [16]. Moreover, the effective thermal conductivity of ferrofluids can be potentially controlled by the application of magnetic field. This in turn, increased the intensity of further research in this area. Recent studies indicate that heat transfer enhancement using a ferrofluid under an applied magnetic field is more advantageous compared to the conventional non-magnetic nanofluids. The thermo-magnetic convection gets intensified as compared to classical convection [17]. Moreover, the size and cost of components of the heat transfer device can be reduced by the application of ferrofluids [18].

Several review articles are available till date on the synthesis and characterization of ferrofluids. However, very few comprehensive review articles exist in open literature on the diverse engineering/industrial applications of ferrofluids, and associating it with specific underlying physics, which is behind each application [1,3,19,20]. In this article, an attempt has been made to fill this gap. Here, we have presented a detailed overview of some existing and emerging applications of ferrofluids in various industrial sectors, from inception to the present times, focusing especially on the machine element designing, bio-medical, and thermal engineering domains. As noted, the mechanisms and underlying physics exploited in each ferrofluid application is also delineated. Hence, this review article is believed to serve as a comprehensive platform for early-stage researchers in this art, and for potential industrial application engineers.

2. Physics of ferrofluids

The thermophysical properties of ferrofluids depend on the basefluid properties, dispersed magnetic phase, aggregation stability of the nanoparticles, and the strength and orientation of the externally applied magnetic field [21]). The nanoparticles in the ferrofluids are superparamagnetic at room temperature, though their micro-sized particles are ferromagnetic in nature [22]. The width of the hysteresis loop diminishes significantly for superparamagnetic materials as compared to ferromagnetic materials and resemble that of a paramagnetic material; but the saturation magnetization value (M_S) remains high, as shown in Fig. 1 (a). With the increase of magnetic field intensity, nanoparticles orient towards the field until magnetic saturation (M_S) is reached. In contrast to the ferromagnetic materials, the magnetic ordering of superparamagnetic materials is broken when the field is removed; the induced magnetism is lost with zero remnant magnetisation. The size of magnetic nanoparticles in ferrofluids is mostly of the order of ~ 10 nm. These particles can act as individual magnetic monodomains and have

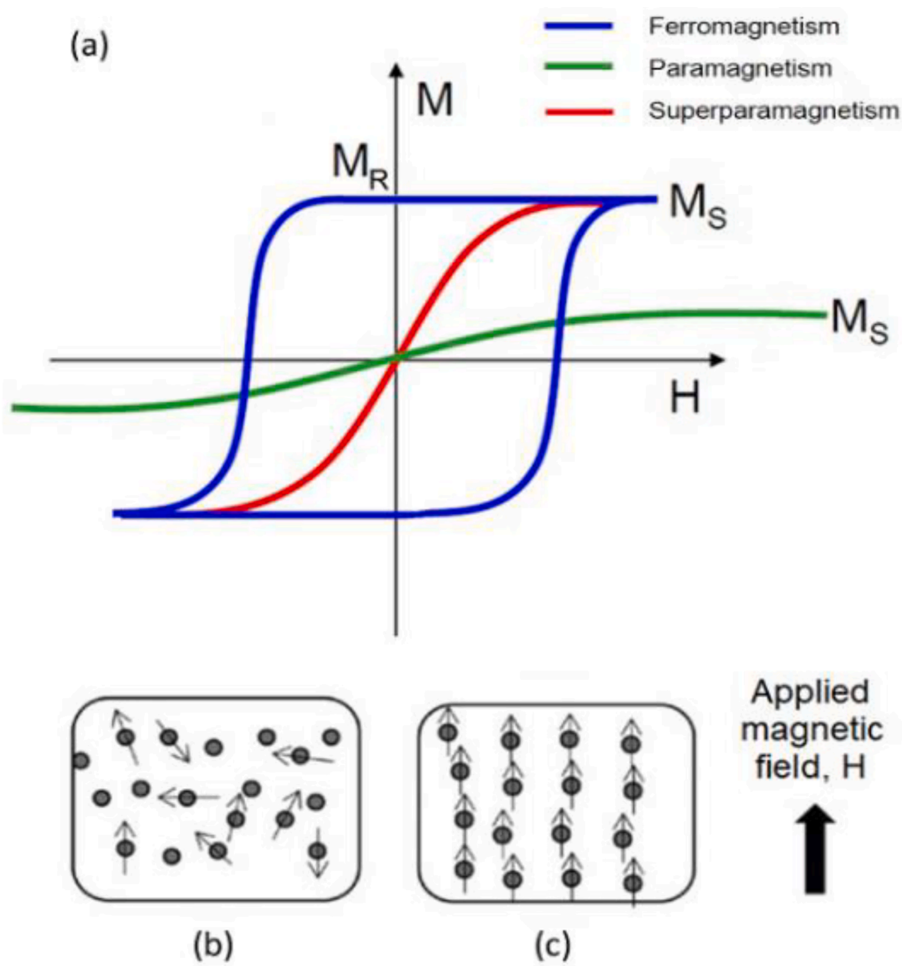

Fig. 1. (a) The magnetization (M) vs. magnetic field intensity (H) of a ferromagnetic, paramagnetic, and superparamagnetic material. Schematic representation of magnetic nanoparticles (b) random orientation in absence of field, (c) chain-like structure in a magnetic field H [17].

non-zero magnetic moment of the order 10^4 μ_B, where μ_B is Bohr magneton [23].

There exists an interaction between the magnetic dipoles and the interaction potential energy U_d, which is given as [17],

$$U(ij)_d = \frac{3(m_i.r_{ij})(m_j.r_{ij})}{r_{ij}^5} - \frac{(m_i.m_j)}{r_{ij}^3} \quad (1)$$

where, m_i and $m_j$are the magnetic moments of the ith and jth particles, respectively, which are separated by a distance r_{ij}. When no field is applied, the thermal energy exceeds the magnetic dipole interaction energy i.e., $k_BT > U(ij)_d$. Hence, the magnetic nanoparticles remain suspended randomly in the basefluid due to the Brownian motion and the ferrofluid has no net magnetization (Fig. 1 (b)). With the application of external magnetic field, the dipole interaction energy increases, overcoming the thermal energy, as a result of which the particles start orienting along the direction of the field [17] and form chain like structures (Fig. 1 (c)), until saturation magnetization (M_s) is reached. This effect strongly contributes towards enhancement of thermal conductivity of ferrofluids (elaborated in detail later in section 6.1). With rise of temperature, again the thermal energy predominates, and magnetic saturation decreases. This results in the breaking of the chain like structures leading to a decrease in the thermal conductivity of the ferrofluid.

The ferrofluid magnetization relaxes to a new magnitude and direction with the change in applied magnetic field. There are two different types of relaxation mechanisms of the magnetic moments in ferrofluids, namely Brownian relaxation and Neél relaxation [3]. In the absence of a magnetic field, the particles rotate due to the collisions among molecules, which causes Brownian relaxation characterized by the relaxation time $\tau_B = 3V_h\eta/k_BT$ [24], where V_h is the hydrodynamic particle volume, η the base fluid viscosity, k_B the Boltzmann constant, and T the absolute temperature. Neél relaxation occurs when the magnetic moments rotate within the particle with the relaxation time $\tau_N = \frac{1}{f_0}\exp(\frac{KV}{k_BT})$, where f_0 is the Larmor frequency and K is the anisotropy constant of the particle material, and V is the magnetic core volume of the particle. For example, the value of K at room temperature is $\sim 15 \times 10^3$ J/m^3 and $\sim 180 \times 10^3$ J/m^3 for magnetite and cobalt ferrite nanoparticles, respectively [3]. The value of τ_N for magnetite nanoparticles increases from 4×10^{-9} s to 7×10^{-5} s when the nanoparticle diameter changes from 10 nm to 20 nm ([1]). The resultant relaxation time is given as: $\frac{1}{\tau} = \frac{1}{\tau_B} + \frac{1}{\tau_N}$.

A phenomenological shift from Newtonian to non-Newtonian behavior is another trend which is observed in ferrofluids, with the application of magnetic field. Its viscosity gets enhanced and the yield stress becomes a prominent function of the applied magnetic field [21]. The field dependent viscosity of ferrofluids is given as follows [17]:

$$\frac{\Delta\eta}{\eta} = \frac{3}{2}\varnothing\frac{\frac{1}{2}\alpha L(\alpha)}{1+\frac{1}{2}\alpha L(\alpha)}sin^2\beta \quad (2)$$

where, η is fluid viscosity, $\varnothing$ is nanoparticles volume fraction, $L(\alpha) = coth\alpha - \alpha^{-1}$ is the Langevin's function.

The lubrication property of ferrofluid gets enhanced due to the shift towards non-Newtonian behavior under external magnetic fields [25]. As a result, both the 'zero pressure-gradient angle' and load capacity increase, whereas the friction parameter decreases. The Brownian and Néel relaxation together produce rotational viscosity that supports a higher load capacity [21]. Another mechanism is the interplay among magnetic force, gravity, and surface tension in ferrofluids that can lead to the different types of air/fluid interface instabilities. One famous example of such a pattern formation is the Rosensweig instability or the normal field instability of a ferrofluid layer with an air interface [26]. Ferrofluids, in presence of a magnetic field, also undergo interfacial instabilities when separated from a non-magnetic medium by an elastic membrane [27].

It may be noted that magnetic nanoparticles tend to get attracted due to the van der Waals forces and the magnetic interactions. Accordingly, a suitable surfactant must be chosen such that it forms a layer around the magnetic nanoparticles, via formation of a bond of a functional group, to avoid *in-situ* nanoparticle agglomeration and allow the particles to remain suspended in the basefluid. Then the nanoparticles can move almost freely, and equilibrium magnetization of the fluid can be precisely explained by the Langevin function as agglomeration is avoided [24].

3. Broad classification of ferrofluid applications

The research on ferrofluids or magnetic nanofluids requires multidisciplinary strategies. Chemists focus on the synthesis process of nanoparticles as well as stability of suspensions. Physicists investigate the physical properties, both experimentally and theoretically. Engineers make use of the underlying physics for various applications via translational research, to design and create commercial products, exploiting their unique and singular properties and responses to external stimuli. Biologists and physicians study their bio-medical characteristics and apply them in medicine and clinical research. Thus, ferrofluids can have a wide range of technological applications. The broad classifications of ferrofluid applications are shown in Fig. 2. These are mainly: (i) machine element design applications, (ii) bio-medical applications, and (iii) thermal engineering applications.

The next section on machine element design applications will deal with ferrofluids as the magnetic sealants, inertial and viscous dampers, bearing components, and lubricants. The ferrofluids can be held at a particular position with the application of magnetic field, and thus can act as good sealants. The viscosity of ferrofluids gets manipulated by the external magnetic field and hence, these can have better/controllable lubrication properties. The advantages of ferrofluids for site-specific drug delivery for hyperthermia and ferrofluids as a contrast agent or tracer in diagnostics techniques like Magnetic Resonance Imaging (MRI) and Magnetic Particle Imaging (MPI) respectively will be discussed in the section on bio-medical applications. We will also highlight the emerging potential applications of ferrofluids in thermal engineering, which are based on the enhancement of ferrofluid thermal conductivity on one hand, and convective and boiling heat transfer coefficients on the other.

4. Machine element design applications

In this section, we will elaborate the application of ferrofluids in design and operation of machine elements. The focus of discussion will be on ferrofluids acting as: (i) different types of magnetic seals like feedthroughs, tandem seals, and exclusion seals, (ii) inertial and viscous dampers, (iii) bearing components, and (iv) lubricants.

4.1. Magnetic sealing

A mechanical seal is a device that helps to join parts of a system together by preventing leakage (e.g., in pumps and mixers) and maintaining required internal fluid pressure. The successful operation of a seal depends on adhesion property of sealants and compression property of gaskets. Ferrofluid seals are contactless seals and so the 'torque friction' is comparatively much lower than mechanical contact seals [28]. Here, torque friction arises only due to the internal friction of the fluid itself [29]. Ferrofluid seals are reliable and durable. Sealing performance depends strongly on the magnetic, thermophysical, and flow properties of the ferrofluids [30]. These operate successfully in wide range of parameters like temperature, differential pressure, speed, applied loads and operating environment, etc., both under static and dynamic conditions [31].

The schematic of the magnetic sealing structure is shown in Fig. 3 (a). Ferrofluid, when introduced into the gaps, forms discrete liquid rings, and can be held at the sealing stage by applying an external

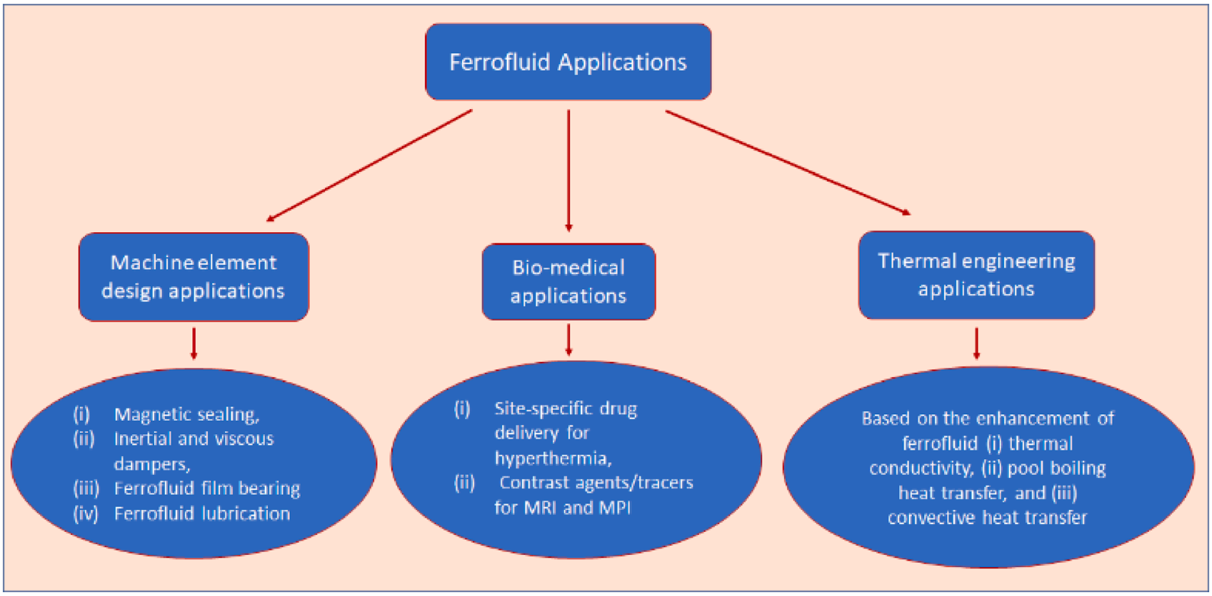

Fig. 2. Several application areas of ferrofluids.

magnetic field and thus it can support a pressure difference without any leakage. When the shaft rotates, the ferrofluid seals operate without any wear and tear because the mechanical moving parts do not touch each other. The sealing pressure of the ferrofluid is inversely proportional to the rotational speed of the shaft [32]. The ferrofluid does not move along the axis while the sealing is functional, wherein the pressure difference is balanced by the magnetic surface tension, which in turn strongly depends on the direction of external magnetic field, and varies inversely with fluid temperature [33]. Such sealings are widely used in various industries viz., chemical, biochemical, pharmaceutical, refining, etc.

Magnetic sealing offers a cost-effective and environmentally friendly solution compared to the mechanical sealing [34]. Ferrofluid feedthroughs are successfully applied in the radio frequency sputtering unit [35]. Ferrofluids are also being used as the feedthroughs in high power electrical switches (Fig. 3 (b)), and for vacuum sealing applications (Fig. 3 (c)) for example, in crystal growth equipment. This type of specialized feedthrough has also been designed for applications in boron-gadolinium mixers. Ferrofluid seal and mechanical seal when combined (known as tandem seals) together offer several advantages over usual multiple mechanical seal arrangements. Such a dual ferrofluid + mechanical seal was proposed by Potencz et al. [36] for agitators of chemical reactors. Later, Borbáth et al. [30,31] developed tandem seals for liquefied gas pumps Fig. 3 (d) and compressors, as well as for vacuum deposition equipment.

Another application of ferrofluids for magnetic sealing is the exclusion seals. These are manufactured to protect sensitive environments and critical machinery components. Exclusion seals are used in various industries such as textiles, machine tools, and computer hardware [19]. The schematic of a ferrofluidic exclusion seal is shown in Fig. 3 (e). Robots are widely used in various applications in contemporary times. They are becoming more and more predominant and essential in several critical applications, e.g., semiconductor fabrication, which needs ultraclean environments. A seal (Fig. 3 (f)) is essential on all robot joints, rotating around to prevent contaminants, like oils, greases, particles, from entering the clean room. For clean room robots, the requirements are low rotational speed and ambient temperature condition. Ferrofluidic exclusion seals are perfect for such applications.

Ferrofluid seals have been used successfully in sealing vacuum and gases. However, when it comes to liquid sealing, ferrofluid seals tend to fail [37,38]. The interface between the sealed liquid, and the ferrofluid contained in the seal, becomes unstable as the ferrofluid emulsifies with the liquid, resulting in severe degradation of the sealing capacity. It may be noted that ferrofluids lose their magnetic property in contact with water [39]. Moreover, shearing forces exist between interface of the sealed liquid and the ferrofluid, which is detrimental to the life of the seal [40]. Some modifications are urgently demanded so that ferrofluid seals become potential and promising in several marine applications like sealing of propeller shafts of boats [41], and medical applications like blood in rotary blood pumps [42]. A novel ferrofluid rotary seal was designed by van der Wal et al. [43] very recently, wherein the ferrofluid gets replenished in the sealing ring maintaining the sealing capacity. This type of technique is successful in improving the service life of the ferrofluid rotary seals.

4.2. *Inertial and viscous damper*

Nowadays, ferrofluid is used in most of the high-power loudspeakers. The most important requirement of loudspeaker operation is that a strong magnetic field (~ 0.8–1.8 T) must exist in a small air gap [44]. The performance of the loudspeaker improves significantly when this gap is filled with a ferrofluid [45]. The schematic of the application of ferrofluid in a loudspeaker is shown in Fig. 4 (a). The four advantages of using ferrofluids in different kinds of loudspeakers are: (i) voice coil cooling, (ii) voice coil centering, (iii) reduction of power compression, and (iv) damping [46]. The ferrofluid, with appropriate thermal conductivity and viscosity, helps to dissipate the excess heat from the coil, and simultaneously damps the unnecessary resonances which would produce an unpleasant noise. The comparison in the frequency response curve, with and without, a ferrofluid is shown in Fig. 4 (b). At present, several commercial sound systems, such as full range speakers, tweeters, mid-range units, small woofers, etc. use ferrofluids. In large woofers (i.e., 25 and 35 cm), the generated internal pressure is relieved through venting using a ferrofluid splash [47]. Sony is one of the leading companies in the audio industry, using ferrofluid technology, since 2012. Besides professional installations in movie theaters, concert halls, and recording studios, this company is also using ferrofluids for slim speakers in various high end television models and sound systems.

Ferrofluids are also used as inertial and viscous dampers in motors, as in stepper motors. When a stepper motor operates at its natural frequency, it may undergo excess settling time, vibration, and acoustic noise. Hence, there is a damper arrangement, which has a non-magnetic casing attached to the motor shaft. An inertial mass inside the housing

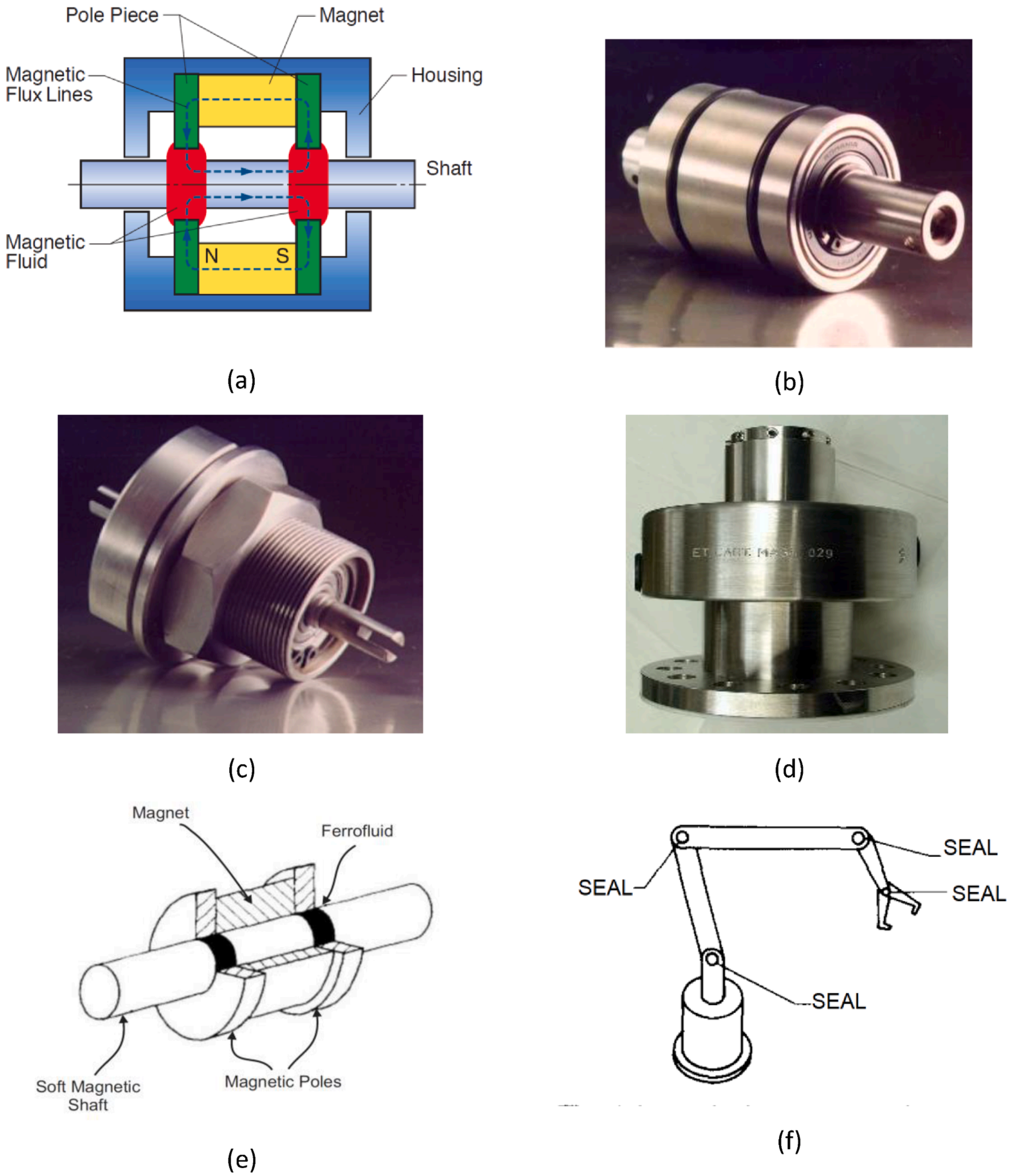

Fig. 3. (a) Schematic of a magnetic seal (b) Ferrofluid feedthrough for high power electric switches, (c) Ferrofluid vacuum feedthrough for crystal growth equipment, (d) Mechanical-ferrofluid combined seal for liquefied gas pump [30]. (e) Ferrofluidic exclusion seal [19], (f) Schematic of hermetic ferrofluid exclusion seals used in clean room robots [19].

levitates on the ferrofluid. This eliminates the requirement of any bearing to support the mass [48]. Moreover, the viscous shearing of the ferrofluid film removes any unwanted oscillations emanating from the system. Another use of ferrofluids as inertia damper is in microprocessor controlled digital devices that convert electrical signals into precise mechanical motion. It is also applied in optical character readers which read a typed or printed page electro-optically and translate it into computer language for word processing [49]. The laser head in a CD or DVD player also has a ferrofluid drop acting as the damper [50].

4.3. *Ferrofluid film bearing*

In general, there are three types of bearings to achieve high rotational accuracies. These are precision ball bearings, air bearings, and oil film bearings [51]. Precision ball bearings have limited accuracy due to 'mechanical imperfections', which result in the higher 'nonrepeatable runout' (~ 0.25 μm) [19]. Although, the nonrepeatable runout for an air bearing is much lower (~ 0.05 μm), it is expensive, less stiff, and should be maintained regularly. The nonrepeatable runout of an oil film hydrodynamic bearing, on the other hand is very less. However, this type of bearing requires oil which needs to be circulated by an auxiliary pump. Sometimes seals are also required to retain the oil. Hence, there are problems of space restrictions, oil leakage and contamination. This has limited the widespread use of oil film bearing technology.

A low volatile oil-based ferrofluid when used in hydrodynamic bearing can overcome the above-mentioned problems. The ferrofluid is

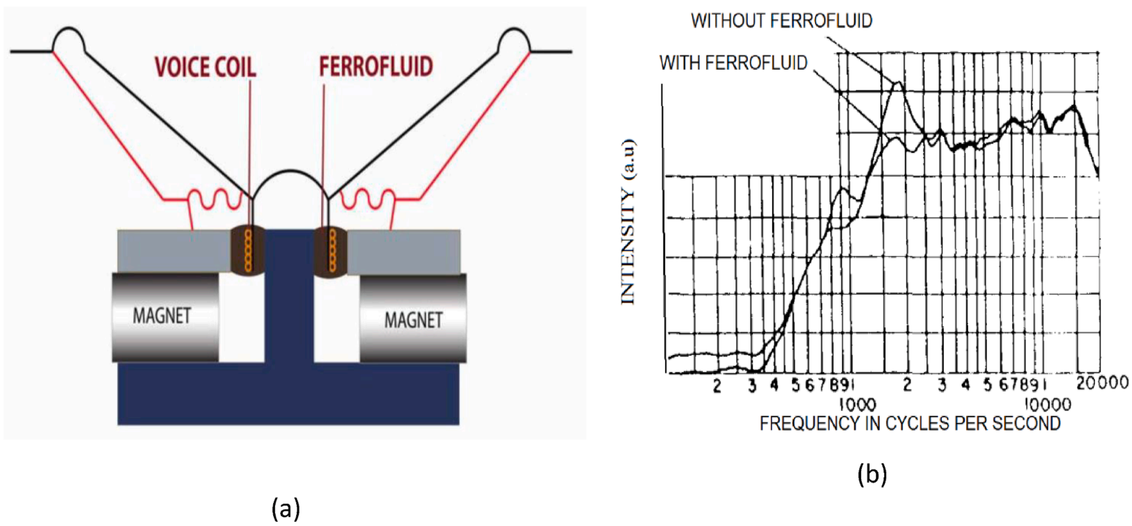

Fig. 4. (a) Schematic of ferrofluid application in a loudspeaker [46], (b) Comparison in the frequency response curve with and without a ferrofluid [19].

used both as a working liquid within the bearing, and as a seal. It is passed with a high pressure into a narrow passage by the rotating shaft [52]. This fluid film creates a pressure which holds the shaft in place and provides stiffness ($\sim 2 \times 10^7$N/m) to the bearing. The ferrofluid inside the bearing can withstand a high shear of $\sim 10^6$ s^{-1} [19]. Odenbach and Thurm [53] studied the magneto-viscous effect and observed shear thinning of ferrofluid film with the applied magnetic field (Fig. 5). The probable reason thought was due to the breaking of the magnetic microstructures (particle–particle interaction in presence of magnetic field) by the shear. With the increase of viscous shear of the fluid, less power is consumed, which depends inversely on temperature, as shown in the inset of Fig. 5.

Ferrofluid bearings can be mainly of two types: (i) pressure bearings, (ii) pocket bearings [54]. Ferrofluid pressure bearings hold load by virtue of the pressure developed inside the ferrofluid. Pocket bearings function depending on both, the pressurized air pocket encapsulated by the ferrofluid seal, and the pressure inside the seal itself. Boots et al. [55] found that the range of operation using a ferrofluid pocket bearing depends only on the quantity of ferrofluid used and magnetic field applied. Ferrofluid bearings have been proved to be very useful for high precision systems. The friction posed by these bearings is free of 'stick-slip' and thus increases the precision [56,57]. Huang et al. [58] investigated ferrofluids lubricated thrust bearings. Eight cylindrical NdFeB magnets,

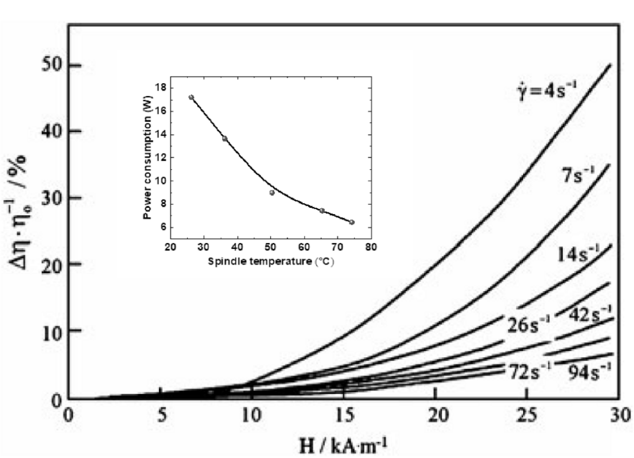

Fig. 5. The percentage change of viscosity (η) with magnetic field at various shear strain rate ($\dot{\gamma}$) [53]. The inset shows the power consumption as a function of temperature for a 8″ ferrofluid film bearing spindle [19].

of size 4.0 mm × 4.0 mm were distributed uniformly on a cylinder surface to produce the magnetic field. The images of the cylindrical surface, before and after covering with ferrofluids, are shown in Fig. 6. The 'static loading capacity' and frictional properties of bearings can be improved with ferrofluids subjected to an external magnetic field [58].

Shah and Bhat [59] observed that the load capacity improved while the frictional forces decreased with the increasing ferrofluid film thickness (in turn, ferrofluid viscosity), while they were studying the slider bearing operation using a ferrofluid. Wang et al. [60] analyzed, both theoretically and experimentally, the lubrication of oil-film bearing using ferrofluids. A solenoid was designed to produce the magnetic field. The impact of temperature and pressure of the oil-film, and magnetic intensity on ferrofluid viscosity was discussed in details [60]. It was seen that the load capacity of bearing can be increased by controlling the viscosity of the ferrofluid. Huang and Wang [21] pointed out that the ferrofluid lubricated bearings have potential applications for space microgravity environment also.

4.4. Ferrofluid lubrication

Ferrofluids can be used for lubrication purposes too. The advantage of using ferrofluids instead of the conventional oil, is that it can be held at the proper place by an external magnetic field, simultaneously maintaining its flow property [61]. Thus, the environmental pollution caused due to the leakage of lubricants can be prevented by the application of magnetic field [62]. In addition, the load capacity will get enhanced as the viscosity of the ferrofluid lubricant will increase under the application of an external magnetic field [63]. Moreover, the rubbing surfaces are not affected by any wear because the magnetic nanoparticles used in the lubricants are much smaller than their surface roughness [64].

Wang et al. [65] and Huang et al. [66] studied the lubrication properties of ferrofluids containing $Mn_{0.78}Zn_{0.22}Fe_2O_4$ and Fe_3O_4 nanoparticles, respectively. It was clearly depicted that the ferrofluids have much better friction reduction and wear resisting capabilities than the base oil. Both groups observed that the maximum load capacity using ferrofluids increased substantially compared to the oil lubricant. Miyake and Takahashi [67] investigated the friction and wear characteristics of cylindrical shaped permanent magnets using a ferrofluid for lubrication. It was concluded that friction and wear can be reduced by using ferrofluids for low velocity condition [67]. On the contrary, hydrodynamic lubrication reduces friction in the high velocity conditions [21]. The experimental results of Huang et al. [68] also showed that ferrofluids under the action of external magnetic field have better

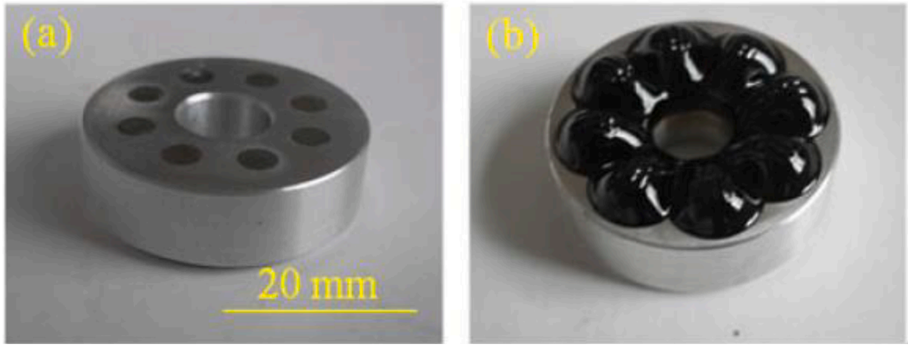

Fig. 6. Cylindrical surface with eight NdFeB magnets (a) without ferrofluid, (b) covered with ferrofluids [58].

friction-reduction characteristics than the basefluid. The friction lifetime can also be significantly improved with lubrication with the ferrofluids. Shen et al. [69] developed some magnetically arrayed structures to decrease the size of the bulk magnet for studying ferrofluid lubrication characteristics. Firstly, they fabricated micro dimple patterns on a disk surface and then electrodeposited films of permanent magnet into the dimples. It is clearly seen from Fig. 7 that an ordered pattern is formed due to the magnetic interaction between the magnetic arrayed films and the ferrofluid, when the magnetic surfaces are covered with the ferrofluid.

The tribological performances of the magnetic film arrayed surfaces using ferrofluids were investigated for different speed-load conditions [70–72]. These test results showed that the magnetic surfaces displayed reduced friction at higher sliding speed as compared to a normal surface. The tribological characteristics of magnetically arrayed structures improved when lubricated with a ferrofluid [70]. A magnetic film is deposited on the dimple shaped structure and is then covered by a ferrofluid, as shown in Fig. 8 (a). Huang et al. [73] measured the static contact angle on the normal and magnetic film and concluded that the contact angle increased with the increasing thickness of the film (as shown in Fig. 8 (b)) due to the increase in magnetic pressure in fluid film per unit volume. Shahrivar and De Vicente [74] studied the frictional properties of Newtonian fluids and ferrofluids in ‘compliant point contacts’. It was seen that friction reduced when the magnetic field distribution was displaced in the direction of the flow towards the contact inlet [74].

In this section we reviewed the various applications of ferrofluids as magnetic seals, inertial and viscous dampers, bearing components, and lubricants in designing machine elements. These ferrofluids can also be guided to the proper site with the application of a suitable external magnetic field and these fluids can also absorb electromagnetic energy and convert it to heat energy [1]. Hence, ferrofluids can be harnessed in another class of important application, i.e., the bio-medical field, which will be discussed in the subsequent section.

5. Bio-medical applications of ferrofluids

In this section, we will elaborate the application of ferrofluids in bio-medical applications. The two main potential areas are: (i) site-specific drug delivery for hyperthermia, and (ii) contrast agents/tracers for diagnosis via MRI and MPI.

5.1. Site-specific drug delivery for hyperthermia

Magnetic nanoparticles in body fluids (bio-fluids) are now used in delivering drugs to the site of concern for hyperthermia therapy. Firstly, the drug, along with an appropriate ferrofluid is injected into the artery of the patient. Subsequently, these are guided to the proper location of a tumor or target cells using powerful external electromagnets. These particles, due to their small size, can reach to the areas that are not accessible to larger entities. In general, the Interstitial Fluid Pressure (IFP) increases for most tumors due to abnormalities in blood vessel, fibrosis and interstitial matrix contraction [75] and this can obstruct the intravenous drug delivery. However, the ferrofluid flow to the tumor site is not affected by the IFP as magnetic nanofluids follow the magnetic gradient path.

The magnetic field is then increased to excite the particles strongly when they concentrate near the appropriate site. The magnetic nanoparticles absorb the electromagnetic energy from the external magnetic field and subsequently, a large amount of heat is generated which helps in raising the internal temperature of the affected lesion. This effectively kills only the targeted cells, leaving the surrounding healthy tissues with little or no damage [1]. The amount of drug necessary in this type of treatment is comparatively much smaller as compared to the amount necessary to disperse in the body throughout. When the magnetic field is switched off, the drug will disperse in the body, but there will be practically no side effects, as the total amount is exceedingly minuscule.

Halbreich et al. [76] conducted different experiments with the aim of using specifically targeted ferrofluids, both for *in vitro* cellular mechanisms such as apoptosis, membrane constitution, etc., and *in vivo* for diagnostic (e.g., MRI) and therapeutic (magneto-cytolysis) applications, depending on the magnetic properties of the particles. For successfully

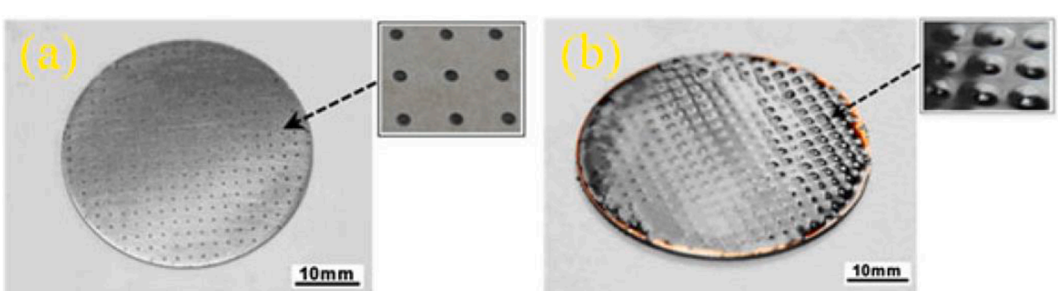

Fig. 7. Disk with magnetic arrayed film (a) without ferrofluid, (b) covered with ferrofluid [69].

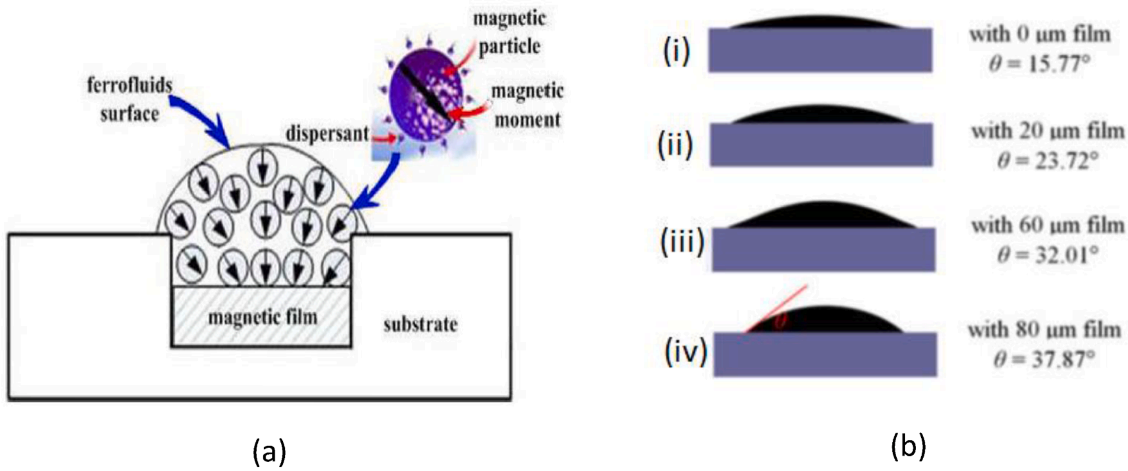

Fig. 8. (a) Schematic of the CoNiMnP magnetic film in a dimple and covered by a ferrofluid [70], (b) The contact angles on the normal and magnetic arrayed surfaces [73].

implementing the magnetic fluid hyperthermia technique and minimize the dosage for use in clinical settings, heating rates of ferrofluids must be increased. In this context, Weimuller et al. [77] achieved significantly higher heating rates with iron oxide nanoparticles when the size of the nanoparticles was optimized and polydispersity of the ferrofluid was decreased. Rahisuddin et al. [78] have overviewed the use of ferrofluids in many novel approaches such as, cell separation, immunoassay, drug and gene delivery, minimally invasive surgery, hyperthermia, magnetic targeted drug delivery.

Kandasamy et al. [79] synthesized novel Multifunctional Magnetic-Polymeric Nanoparticles (MMPNs) based ferrofluids and tested various combinations thereof. They observed that Superparamagnetic Iron Oxide Nanoparticles (SPIONs) and dual-drugs co-loaded with Poly Lactic-co-Glycolic Acid (PLGA) nanoparticles enhanced the therapeutic efficacy in liver cancer cells when treated with combined therapies of thermotherapy and chemotherapy. Accordingly, it was concluded that MMPNs based ferrofluids are potential therapeutic candidates for multi-modal *in vitro* cancer treatment using combined thermotherapy and chemotherapy.

There has been very little progress till now in the diagnosis of patients with brain cancer. The challenge remains at the delivery of drugs across the Blood-Brain Barrier (BBB) and reaching the brain tumors, including glioblastoma, the deadliest of them [80]. Some new and innovative therapeutic strategies and novel drug delivery materials are needed. The accumulation of magnetic nanoparticles can be reduced by various detoxification and antioxidant mechanisms in any part of the body outside the brain. However, if the SPIONs cross the BBB and accumulate inside the brain, then these cannot be easily cleared. The maximum limit of iron oxide nanoparticles that cells can metabolize may be exceeded, and this in turn might lead to neurodegeneration and impede normal brain functioning in the long run. Therefore, developing innovative methods and less toxic carriers for specifically targeting across the BBB remained a critical issue [81]. Shi et al. [82] established an *in vitro* model of the BBB using murine brain endothelioma cells. Their results laid the foundation for manipulating the magnetic nanoparticle to cross the BBB by selecting an appropriate bioactive coating (natural proteins). Collagen coated ferrofluids pass through the BBB, and when coated with glycine and glutamic acid, they also avoid penetration across the BBB.

The chemotherapy for bone cancer has become largely ineffective as bone is a hard-vascular tissue and it is difficult to discern tumours (osteosarcoma) from the healthy tissue into which these are interspersed in. Wu et al. [83] synthesized a surfactant-free, water based ferrofluid. The basis was the idea of the earthicle, i.e., a particle meant to copy the stratified structure of the Earth. The ferrofluid contained SPIONs coated with silicate *meso*-layers and carbon shells, having an average size of ~ 13 nm. This double coating on the magnetic cores improved the colloidal stability and enhanced the target efficacy of cancer cells. This special type of ferrofluid was successful in reducing the life of both, osteosarcoma, and glioblastoma cells *in vitro*, while affecting the primary cell lines minimally. The schematic representation of crossing the BBB by the drug coated newly synthesized composite nanoparticles (SPION/SiO_2/C) and attaching on the glioblastoma cells is shown in Fig. 9. Both, *in vitro* and *in vivo* models of the BBB demonstrate that the nanoparticles can cross the barrier and get attached to the brain tissue. Thus, this composite ferrofluids exhibit high potential

for successfully treating different types of cancer and may act as an alternative to traditional chemotherapy techniques.

5.2. Contrast agents/tracers for diagnostics

5.2.1. Magnetic Resonance imaging (MRI)

MRI is one of the most powerful techniques used for diagnosis of several medical diseases in the recent years. It is based on the principle of Nuclear Magnetic Resonance (NMR). A large constant magnetic field (B0) is applied to the sample as shown in Fig. 10. As a result, all the nuclear spins get aligned along the direction of the applied field. Subsequently, another small varying magnetic field, in the form of radio frequency pulse, is applied perpendicular to the constant field. This makes the aligned nuclear spin to flip in the transverse plane; after that, the pulse is switched off. The nuclei emit a signal, and the net magnetization begins to relax, returning to the longitudinal plane. The amplitude of this signal decreases with time, and from this temporal data, the 'spin–spin relaxation time' can be calculated, which depends on the ambient [19].

Magnetic nanoparticles have been used as effective contrast agents for MRI. Paramagnetic contrast agents, like Gadolinium and Manganese, are being used since long. Recently, it is discovered that super-paramagnetic iron oxide nanoparticles also substantially influence the MRI contrast. The SPIONs can be functionalized specifically to target the tumor cells ([1,84,85], and size-tailored to accumulate in specific organs or soft tissues [86,87]. Hence, the contrast of MRI is significantly enhanced by SPIONs, in comparison to paramagnetic contrast agents, and diseases can be detected at an earlier stage [88]. Biocompatible dextran coated iron oxides are selectively absorbed by the reticuloendothelial system [1]. The relaxation time of the tumor cells is not modified by the contrast agent, as they do not consist of the effective reticuloendothelial system of healthy cells. Thus, one can easily distinguish the tumor cells from the surrounding healthy cells. Pankhurst et al. [89] have overviewed several situations where the MRI diagnosis

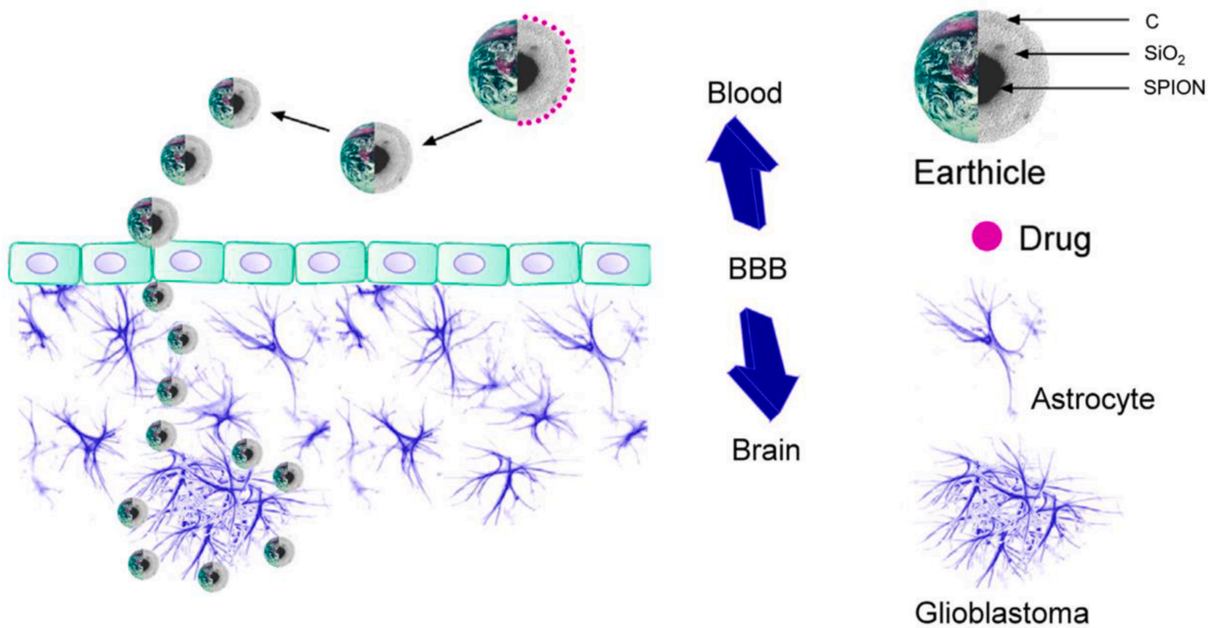

Fig. 9. A schematic representation of crossing the BBB by the drug coated newly synthesized composite nanoparticles (SPION/SiO_2/C) and attaching on the glioblastoma cells (Adapted from [83]).

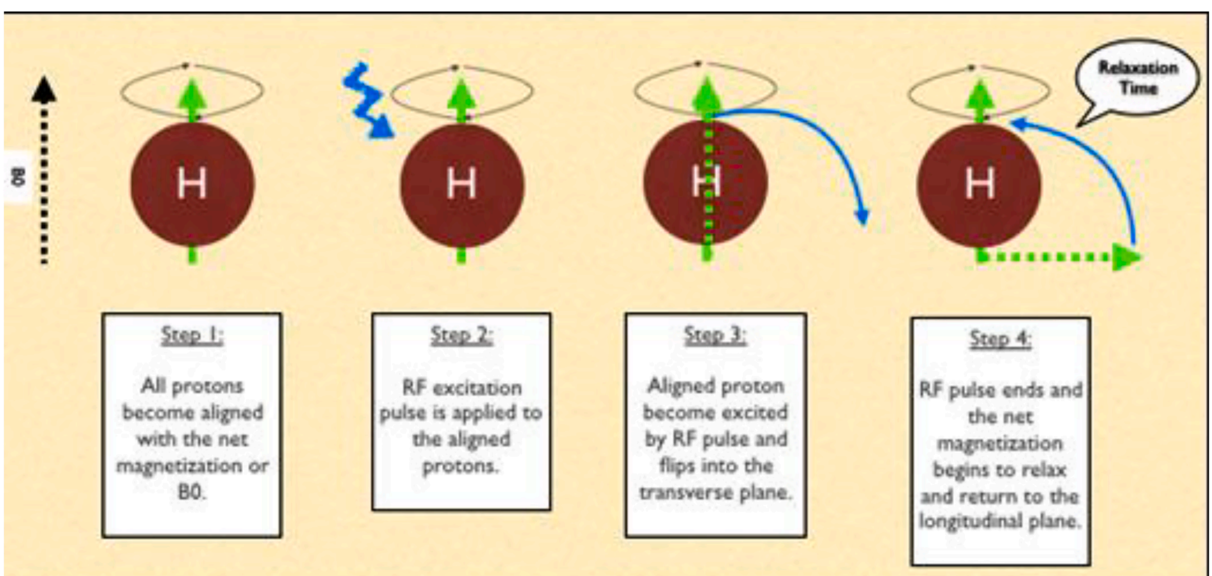

Fig. 10. Schematic of the working principle of MRI.

technique is successfully applied using ferrofluid contrast agent.

Paramagnetic Gadolinium ions are cytotoxic and retain in liver, spleen, and bone [90]. Moreover, patients suffering from severe kidney and liver diseases are affected with nephrogenic systemic fibrosis due to Gadolinium. Manganese is also highly toxic if subjected to overdoses. Moreover, the brain is vulnerable to manganese exposure and may lead to Parkinson disease [91]. The SPIONs contrast agents on the other hand are cleared naturally by the body through the mononuclear phagocyte cells present in the reticuloendothelial system [92]. They are broken down in the liver, stored as iron and used to produce hemoglobin. However, some cases are observed where moderate-to-severe allergic reactions occurred as a side effect of SPIONs injections [93–95].

5.2.2. *Magnetic particle imaging (MPI)*

MPI is an emerging non-invasive tomographic technique that is based on detecting the superparamagnetic nanoparticle tracers directly. It relies on the nonlinear magnetization response of magnetic nanoparticles to generate a tomographic image [96]. Human body is diamagnetic, so it demonstrates zero MPI signal, as there is nothing that will create magnetic interference in imaging [97], meaning that MPI images have almost perfect contrast, with near zero background noise. This new imaging method is characterized by both high spatial sub-millimeter (~ 0.4 mm) resolution and high sensitivity. The range of imaging is milliseconds to seconds. No ionizing radiation is used while imaging, and hence, a signal can be produced at any depth in the body [97]. MPI does not use any nuclear medicine and so the risky radiation exposure to population is significantly reduced. Therefore, it can be used for sentinel lymph node imaging [98,99], which generally uses blue dye and/or radioactive material at the tumor site. Harmful element like iodine is also not used here. MPI can act as a more efficient candidate compared to today's standard angiography techniques like X-ray and CT iodinated angiography, and it can be effectively used to diagnose patients with chronic kidney disease as well [97].

Besides angiographic applications, MPI can be used for detecting tagged cells *in vivo*. Here, cells are labeled with iron oxide nanoparticles [100]. The 'magnetic tags' are non-toxic, do not alter cell function and remain stable for weeks *in vivo*. The tracer is stable while tagged to a cell and can be detected successfully even after three months [101]. MPI has numerous applications in the field of oncology research also. The tracers can get accumulated within solid tumors due to the enhanced permeability and retention effect [102]. This has been successfully used to detect tumor sites within rats [103]. MPI can also be used in stem cell therapy [104].

Recently, Wu et al. [105] have reviewed the principles of MPI, current applications, promising neuroimaging applications, and practical considerations. The retention and localization of signals was monitored in the brain of a stroke affected mouse. The SPION-labeled macrophages in the brain are shown in Fig. 11. It can be clearly seen that accumulation of iron labeled cells is highest for 48 h and decreasing thereafter, but still detectable even after 96 h of post injection.

Gleich and Weizenecker [96] established and reported the first MPI system in 2005 and since then, the technology has advanced. The first *in vivo* 3D real-time MPI scans were presented by Weizenecker et al. [106] revealing details of heart beating of a mouse. The earliest image processing technique for MPI was harmonic-space MPI [96,106]. Goodwill et al. [97] have developed another type of theoretical framework for MPI analysis called x-space MPI. This type of MPI can be utilized to optimize the size and magnetic properties of the SPION tracers. The iron oxide nanoparticles used in MPI in general have diameters in the range of 10–20 nm, enabling millimeter-scale resolution in small animals. The x-space MPI theory predicts that larger nanoparticles can enable up to 250 μm imaging resolution [97].

Researchers have used MRI technique using SPIONs to track inflammation [107,108]. However, SPIONs in MRI cause a decrease in signal intensity as they have high magnetic susceptibility. This could often lead to confusion with signal-voids originating from bone, air bubbles, susceptibility blowouts, and imaging artifacts (Wu, [20]. MPI does not view tissues directly, in contrast to MRI, but develops a 3-dimensional image of injected nanoparticles. Hence, using MPI, SPIONs can be more effectively detected with a higher signal-to-noise ratio than MRI. Very high electric fields are induced in the human body by rapid change of the applied magnetic fields to the kilohertz frequency range. This causes Peripheral Nerve Stimulation (PNS), which is one of the limiting factors on the use of high gradient fields for fast imaging (like echo-planar imaging) with the latest MRI gradient technology [109]. Application of MPI in humans is similarly constrained due to PNS [109].

The real-time and successful use of ferrofluids containing SPIONs in the treatment of bone and brain cancer in humans still needs to be further explored. Till now, all such related studies are tested and validated on small animals like rats, guineapig, etc. Presently, further work is ongoing to improvise the imager design, tracer design, and imaging protocols for successfully developing the human-sized scanner. Therefore, the use of SPIONs in MRI as well as MPI for humans has significant potential in the future. Having reviewed the use of magnetic nanofluids in the field of bio-medical engineering, we will now explore another exciting and potentially high impact application in thermal engineering.

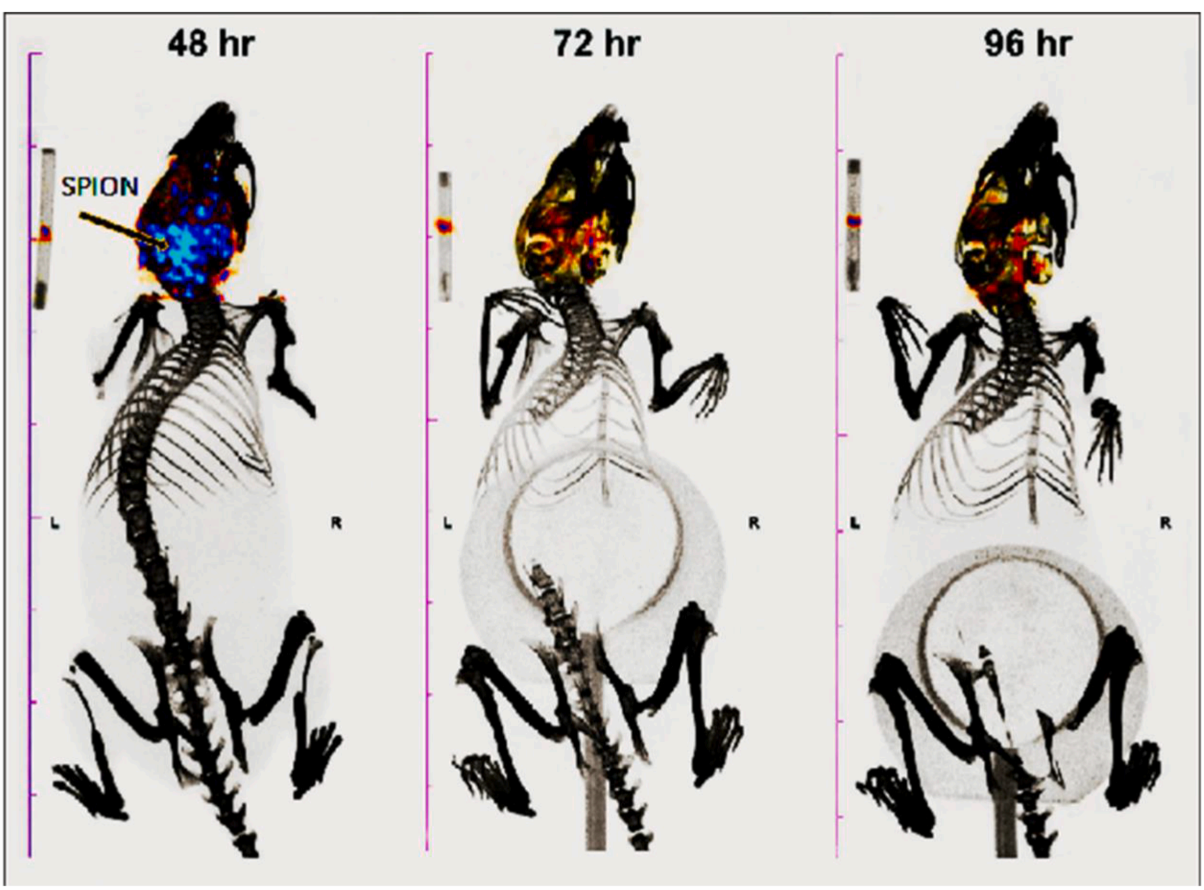

Fig. 11. SPION-labeled macrophages in the brain of a stroke affected mouse after 48, 72, and 96 h of post-injection (Adapted from [105]) .

6. Ferrofluid applications in thermal engineering

In the recent past, researchers have explored several applications of ferrofluids in thermal science and engineering. Some of the potential properties which are under scrutiny are enhanced thermal conductivity, augmentation of pool boiling heat transfer, improved convective heat transfer coefficient, both under single-phase and two-phase heat transfer, and manipulation, as well as control of two-phase flow parameters due to the presence of the magnetic nanoparticles.

6.1. Enhancement of thermal conductivity of ferrofluids

Zhu et al. [110] measured the thermal conductivity (k) of Fe_3O_4-water ferrofluids. A non-linear increase of the ferrofluid thermal conductivity was reported, which they attributed to the nanoparticle alignment and clustering. The thermal conductivity of the prepared ferrofluids with other oxide based nanofluids (e.g., Al_2O_3, CuO, and TiO_2) was also compared. It was observed that the thermal conductivity of the ferrofluid is higher than that of nanofluids at the same volume concentrations of different oxide nanoparticles, although bulk Fe_3O_4 has lower thermal conductivity than the others.

Philip et al. [111,112] have studied the thermal conductivity of a stable colloidal suspension of oleic acid coated Fe_3O_4 nanoparticles (6.7 nm) dispersed in kerosene oil. An enhancement of 23% of thermal conductivity at 7.8 vol% of Fe_3O_4 nanoparticles loading at 25 °C was obtained. The effect of external magnetic field (parallel to the temperature gradient) on the thermal conductivity of the prepared ferrofluids was also investigated. They achieved a maximum enhancement of 300% for 6.3 vol% of magnetite nanoparticles when an external magnetic field of 82 G was applied. Fig. 12 (a) shows the change in thermal conductivity of 6.3 vol% Fe_3O_4 nanoparticles concentration as a function of the applied magnetic field. Maximum enhancement occurred when the value of magnetic field matched the value of saturation magnetization of the ferrofluid. Beyond this value, thermal conductivity decreased with increase in magnetic field for all the studied ferrofluids. This thermal conductivity enhancement was attributed to the formation of chain-like structures acting as highly conductive paths for heat flow under the external magnetic field when the 'dipolar interaction energy' exceeds the 'thermal energy' (as shown in Fig. 12 (b)).

It may be noted that on changing the direction of magnetic field, from parallel to perpendicular to the heat flow, the values of thermal conductivity remained unchanged, irrespective of the strength of magnetic field and volume concentration of the particles [111]. On the contrary, Krichler and Odenbach [113] observed that the direction of the applied magnetic field has a strong effect on the thermal conductivity of ferrofluids. For parallel field, thermal conductivity increased continuously with increasing magnetic field strength, whereas, for perpendicular field, thermal conductivity decreased as shown in Fig. 13 (a). Thus, dependence of thermal conductivity of ferrofluids on the direction of magnetic field remains an area of active research till date.

Shima et al. [114] have studied the temperature-dependent thermal conductivity and viscosity of aqueous and non-aqueous stable ferrofluids with Fe_3O_4 ($\sim$ 8 nm) as the dispersed nanoparticles. The plot of thermal conductivity with temperature showed opposite trends in aqueous and non-aqueous nanofluids (Fig. 13 (b)). Moreover, it was observed that the temperature dependence of thermal conductivity in ferrofluids simply tracks that of the basefluids. Altan and Bucak [115] performed experiments to study the effect of Fe_3O_4 nanoparticles on the thermal conductivity of different basefluids like hexane, heptane, and light mineral oil. It was found that thermal conductivities of the nonpolar solvents increased linearly with the concentration of magnetic nanoparticles.

Gavili et al. [116] experimentally studied the thermal conductivity of 5 vol% Fe_3O_4-water ferrofluid under an external magnetic field using Helmholtz coils. The schematic of their experimental setup is shown in Fig. 14 (a). A maximum enhancement in the thermal conductivity of over 200% at 25 °C, under an applied magnetic field of 1000 G, was observed. It was seen that the maximum value of thermal conductivity increased nonlinearly with increasing magnetic field intensities (Fig. 14 (b)). It is worth mentioning that at all intensities of applied magnetic field, the thermal conductivity of the ferrofluid first increased and then decreased as a function of time. The rate of increase and decrease of thermal conductivity with time was different at various intensities of magnetic field. They also performed experiments to study the effect of

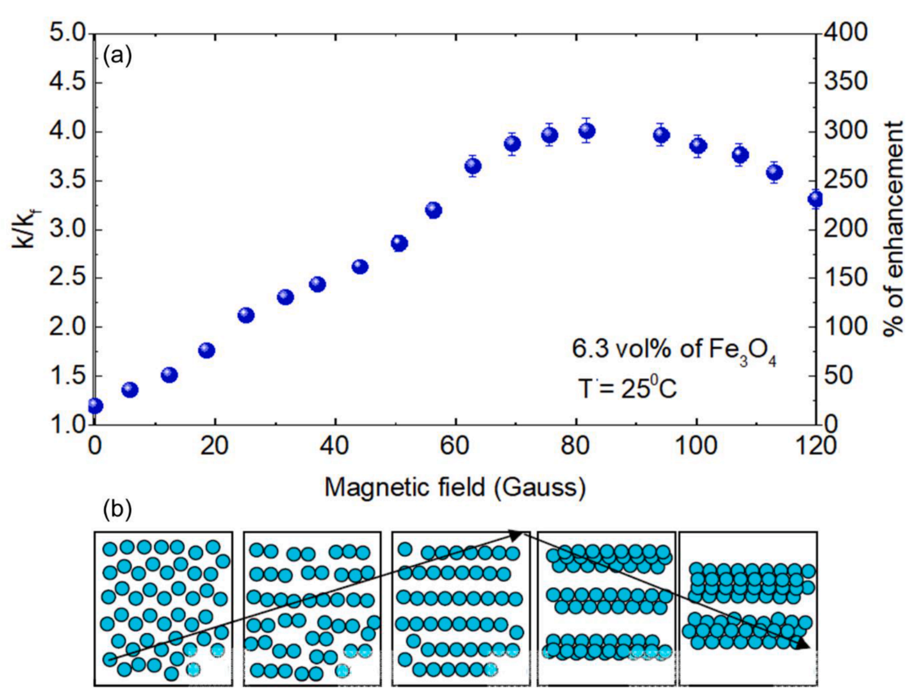

Fig. 12. (a) Variation of thermal conductivity ratio (k/k_f) and its percentage enhancement as a function of applied magnetic field (Replotted from [111], (b) Schematic representation of the chain-like structures formed within the fluid at different magnetic fields (Adapted from [112]. The arrow depicts the increasing and decreasing trend of thermal conductivity with increasing magnetic field.

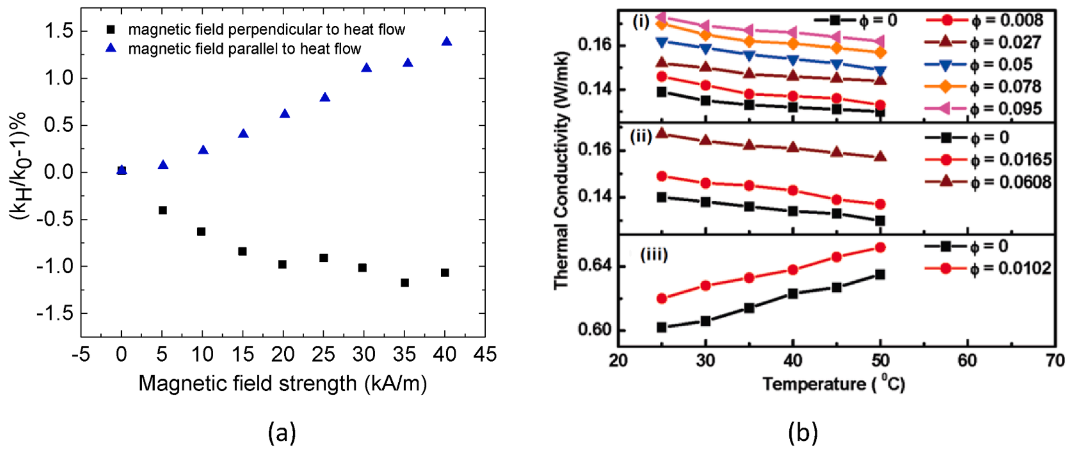

Fig. 13. (a) Relative change of thermal conductivity (k_H/k_0) as a function of magnetic field strength (Replotted from [113], (b) The variation of thermal conductivity with temperature for (i) kerosene, (ii) hexadecane, and (iii) water-based iron oxide ferrofluids of average particle size 8 nm, respectively (.
Adapted from [114]

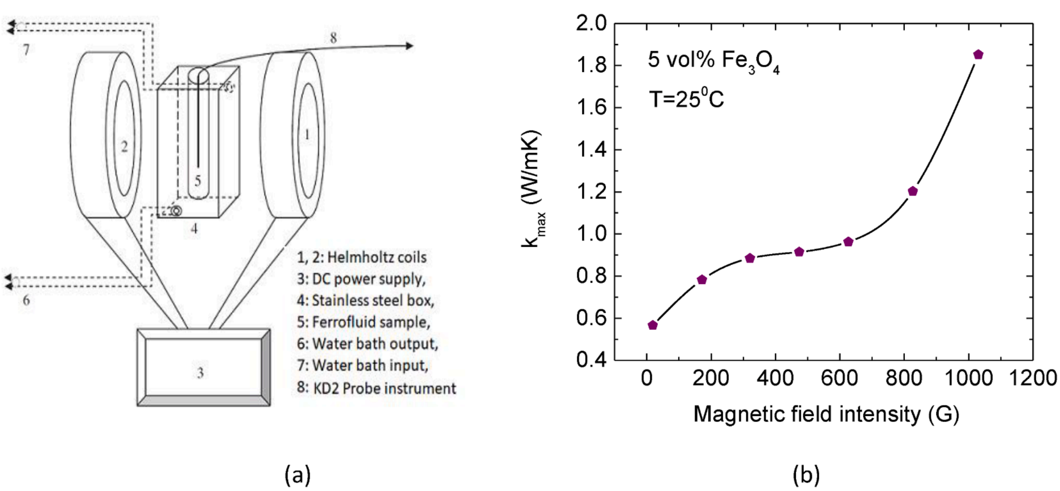

Fig. 14. (a) Schematic diagram of the thermal conductivity measurement setup [116], (b) Maximum thermal conductivity (k_{max}) value of the ferrofluid as a function of magnetic field intensity at 25 °C (Replotted from [116].

Table 1
Thermal conductivity enhancement of ferrofluids from the reported literatures.

Research groups	Ferrofluids used	Maximum loading of nanoparticles	Particle size	Parameters studied	Magnetic field intensity	M00aximum thermal conductivity enhancement
Abareshi et al. [121]	Fe_3O_4-water	3 vol%	8–10 nm	Vol. conc. of nanoparticles and Temperature	No field	11.5% at 40 °C
Pastoriza-Gallego et al. [122]	(i) ɣ Fe_2O_3-EG (ii) Fe_3O_4-EG	6.6 vol% 6.9 vol%	20–30 nm ~ 15 nm	Vol. conc. of nanoparticles and Temperature	No field	~ 15% at 50 °C ~ 11% at 50 °C
Sundar et al. [123]	Fe_3O_4-water/EG mixture	2 vol%	13 nm	Vol. conc. of nanoparticles and Temperature	No field	46% at 60 °C
Sundar et al. [124]	Water based Fe_3O_4-MWCNT hybrid ferrofluid	0.3 vol%	Not specified	Vol. conc. of nanoparticles and Temperature	No field	28.46% at 60 °C
Shahsavar et al. [125]	Water based Fe_3O_4-CNT hybrid ferrofluid	0.9 vol% Fe_3O_4 and 1.35 vol% CNT	Not specified	Vol. conc. of nanoparticles, Temperature, and Magnetic field	Permanent Magnet using plates	151%
Dzhuraev and Safarov [126]	Iron-Transformer oil	75 wt%	Not specified	Vol. conc. of nanoparticles, Temperature, Pressure, and Magnetic field	1.594 mT to 3.866 mT	71.2% at 3.866 mT
Haiza et al. [127]	Fe_3O_4-water	1 vol%	Not specified	Vol. conc. of nanoparticles and Temperature	No field	49.4% at 60 °C
Goharkhah et al. [128]	Fe_3O_4-water	2 vol%	30 nm	Vol. conc. of nanoparticles, Flow velocity, and Magnetic field	0.04–0.08 T	32.3% at Reynolds number 400 and magnetic field 0.08 T

temperature on thermal conductivity of the ferrofluid under an external magnetic field. It was observed that thermal conductivity decreased drastically with increase in temperature, and this was attributed to the reduction of magnetization with the increasing temperature from the standpoint of statistical mechanics of paramagnetic material. Župan and Renjo [117] studied thermal conductivity and viscosity of magnetite-water ferrofluids without using any surfactant at different temperatures both in presence and absence of an external magnetic field. The maximum observed increase in thermal conductivity was 37% at 20 °C with a loading of 1 g/l of magnetite nanoparticles.

The review articles by Philip and Shima [118], Alsaady et al. [119] and more recently by Gui et al. [120] give an overview of the present status on the thermal conductivity studies of ferrofluids. Table 1 summarizes the recent research (2010–2019) on thermal conductivity enhancement of ferrofluids in presence/absence of external magnetic field.

6.2. Pool boiling heat transfer of ferrofluids

The phenomenon of boiling is used for effective heat removal in a variety of phase-change heat exchangers like boilers and evaporators characterized by ultra-high heat flux in a compact volume. In the process of pool boiling, the heating surface is immersed in a large pool of stationary liquid. The nucleate boiling regime, before the occurrence of the critical heat flux (CHF) phenomenon, is an efficient heat transfer zone. The CHF is defined as the maximum heat flux up to which a boiling surface can sustain nucleate boiling. At CHF, there is a sudden overshoot of wall temperature (under constant heat flux boundary condition) due to vapor blanketing and associated instability, which may lead to catastrophic damage of the heated wall, depending on the operating temperature. Above the CHF, the regime becomes film boiling, which is unsuitable for efficient heat transfer. Therefore, by augmentation of the CHF, the safety margin of the thermal system can be enhanced. It is also advantageous to design compact and efficient cooling systems required for electronic devices, nuclear and chemical reactors, air conditioning, food processing and power generation [129].

The number of studies addressing pool boiling of ferrofluids is comparatively less. Bashtovoi et al. [130] investigated Boiling Heat Transfer (BHT) of ferrofluids from a surface of medium-carbon steel specimen kept vertical. A constant magnetic field was applied to both, normal and tangential directions of the sample's axis. It was observed that the orientation of magnetic field has intense effect on the BHT. Takahashi et al. [131] investigated the nucleate pool boiling heat transfer of a ferrofluid on a horizontal surface under a vertical linear magnetic field. An increment of heat transfer with increasing field or for low concentration of nanoparticles was obtained.

Xu and Peng [132] theoretically suggested that BHT can be enhanced on the application of magnetic field. It was suggested that the magnetic particles help in the formation of nucleation sites by adsorption of high-energy fluid molecules. The 'detachment diameter and frequency' of the vapour bubbles decreased and increased respectively, to enhance the BHT when subjected to an optimum external magnetic field. Aminfar et al. [133] experimentally investigated subcooled flow boiling using Fe_3O_4-water ferrofluids in a vertical annulus, both in absence and presence of a magnetic field. The CHF increased up to 33% on using ferrofluid of 0.1 vol% of nanoparticle loading. An enhancement of 56% in CHF was obtained over pure water when magnetic field was applied.

Khoshmehr et al. [134] applied a constant magnetic field and obtained a 50% enhancement in BHT for a ferrofluid compared to pure water. Shojaeian et al. [135] investigated the effect of magnetic actuation on the surface morphology of the heated surface. The surface roughness increased due to the formation of thick and porous film on the surface by the application of magnetic actuation. This in turn enhanced the pool boiling heat transfer by 29%. Abdollahi et al. [136] studied the effect of a magnetic field on pool boiling heat transfer of Fe_3O_4-water ferrofluids from a flat plate. It was observed that positive and negative magnetic field gradients decreased and increased the BHT, respectively as shown in Fig. 15. They also observed that Boiling Heat Transfer Coefficient (BHTC) increased by 43%, as a function of nanoparticle loading up to 0.1 vol%, and then decreased by further increasing the particle loading to 0.4 vol%. A similar trend was observed by Kole and Dey [129] for ZnO-ethylene glycol nanofluids.

More recently, Vatani et al. [137] performed experiments on transient boiling heat transfer using an electrically heated microwire in Fe_3O_4-water ferrofluids. It was seen that below the boiling point of water, the heat transfer enhanced with ferrofluids. However, above the boiling point, a substantial decrease in heat transfer was observed due to deposition of particles on the wire. Particle deposition rate on the wire and thickness of the coating layer increased by increasing the current, time and concentration of nanoparticle loading. Abad et al. [138] performed experiments to visualize the pool boiling heat transfer of Fe_3O_4-water ferrofluids. An enhancement in BHTC was observed up to 50 ppm loading of Fe_3O_4 nanoparticles, and then it decreased for 500 ppm concentration. Visualization showed that at higher nanoparticle concentration of 500 ppm, the bubbles rolled over horizontally rather than rising upwards in the vessel and thus, the decrement of heat transfer

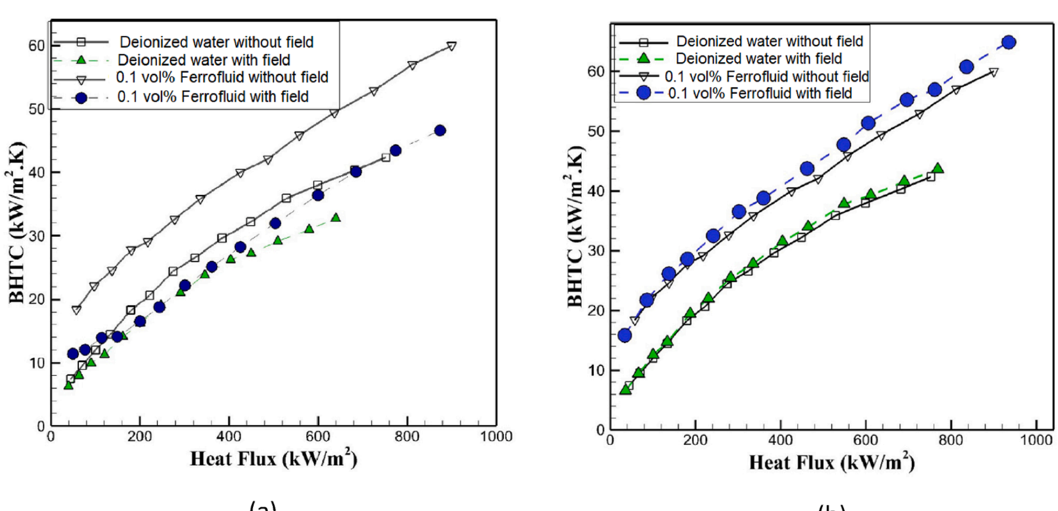

Fig. 15. The BHTC as a function of heat flux for 0.1 vol% ferrofluid and basefluid in presence of a (a) positive and (b) negative magnetic field gradient (. Adapted from [136]

occurred. The effect of a constant magnetic field on the heat transfer of ferrofluids was also studied. It was seen that with the application of magnetic field, the BHTC deteriorated at higher heat fluxes. This may happen due to the growth in thickness of the ferrofluid layer and the blocking of the nucleation sites by the application of the external magnetic field.

6.3. Convective heat transfer of ferrofluids

6.3.1. (a) Single-phase (ferrofluid) convection

The pumping power must be increased by a factor of about ten to nearly double the heat transfer while using a conventional fluid to dissipate the heat in a heat exchanger. In contrast, using a suitable fluid, having thrice the thermal conductivity of the conventional fluid, the rate of heat transfer can be nearly doubled without any such increase in the pumping power, provided the viscosity of the fluid does not substantially increase [139]. Ferrofluids, having much higher thermal conductivity than the normal base fluids, can act as potential candidates for heat exchangers [110–117]; Philip and Shima 2012; [119,120]. Moreover, the thermophysical properties of the ferrofluids can be tuned by applying an external magnetic field. Additionally, there is no need of any mechanical pump to circulate the ferrofluids, as these can be driven by the magnetic field produced by any permanent or electromagnet (Singh [140,141]. This phenomenon is known as thermo-magnetic convection, the schematic of which is shown in Fig. 16.

Bozhko and Putin [142] investigated the buoyancy and thermo-magnetic convection mechanisms, when a horizontal ferrofluid layer was heated and cooled simultaneously from the two ends, in presence of an external uniform transverse magnetic field. Three times augmentation of heat transfer in ferrofluid due to the thermo-magnetic convection was obtained. Lajvardi et al. [143] investigated the effects of different intensity of magnetic field (0 T, 0.08 T, 0.1 T, and 0.12 T), concentration of magnetic nanoparticles, and magnet position on convective heat transfer of ferrofluid flowing inside a hot copper tube in the laminar regime. Increasing magnetic field intensity enhanced the ensuing heat transfer coefficient. Motozawa et al. [144] observed a maximum 20% heat transfer enhancement of a ferrofluid in a rectangular duct under a constant magnetic field.

Xuan and Lian [145] compared the thermo-magnetic convection over natural convection for electronic cooling application. A significant drop in surface temperature of the chip (heater) occurred when the ferrofluid flowed across the heater in the presence of external magnet, indicating enhanced heat transfer. Ghofrani et al. [146] obtained an increase of 27.6% of heat transfer of a ferrofluid, flowing in a circular copper tube, under an alternating magnetic field (0.02 T) and a Reynolds number of 80. Azizian et al. [147] studied the effect of a magnetic field on laminar convective heat transfer of a ferrofluid filled in a stainless-steel tube and obtained a maximum enhancement of 300% in the local heat transfer coefficient at a constant magnetic field.

Yarahmadi et al. [148] investigated the laminar forced convective heat transfer of a Fe_3O_4-water ferrofluids in a tube at constant and oscillating magnetic fields. In comparison with the non-magnetic field, the local convective heat transfer coefficient enhanced by 19.8% at 5 vol % loading of Fe_3O_4 nanoparticles at a Reynolds number of 465 and a magnetic field with the frequency 50 Hz. Aursand et al. [149] observed that thermo-magnetically pumped ferrofluid enhanced the performance of natural convection cooling system by enhancing the heat transfer rate. Goharkhah et al. [150] studied the laminar forced convective heat transfer of Fe_3O_4-water ferrofluid in a uniformly heated parallel plate channel at different magnetic field intensities. An increase in convective heat transfer by 24.9% and 37.3%, under constant and alternating magnetic fields, respectively, compared to no-magnetic field was obtained.

Asfer et al. [151] reported the role of magnetic field on the convective heat transfer of Fe_3O_4-water ferrofluids flowing through a circular stainless-steel (SS) tube at constant heat flux conditions using infrared thermography technique. The schematic of their experimental arrangement is shown in Fig. 17 (a). Cylindrical permanent magnets were arranged in two different configurations, viz., single-inline (magnets at one side of the SS tube), and double-inline (magnets at both the sides of the SS tube), as shown in Fig. 17 (b) and (c), respectively. It was noted (as shown in Fig. 17 (d) and (e)) that the Nusselt number was higher as compared to no-magnetic field for the single-inline arrangement of magnets above a critical ferrofluid flow rate of 30 ml/min. Moreover, Nusselt number increased with the increasing magnetic field gradient for double-inline arrangement of magnets, compared to that of single-inline at a constant ferrofluid flow rate through the tube. Fadaei et al. [152] investigated three-dimensional forced convection heat transfer of ferrofluid in a pipe subjected to constant wall heat flux in the presence of single or double permanent magnets. Heat transfer rate and Nusselt number were found to increase with an increase in the intensity of magnet and electric current. Heat transfer coefficient also enhanced with an increase of nanoparticles loading.

Wang et al. [153] conducted several experiments on the convective heat transfer of ferrofluids inside a pipe for different numbers and position of block permanent magnets. It was noted that a continuous increase in the magnetic flux density (i.e., increasing the numbers of magnets) can enhance the heat transfer significantly. Heat transfer enhancements of 26.5% and 54.5% at Reynolds number 391 and 805, respectively was observed by the ferrofluid using two permanent

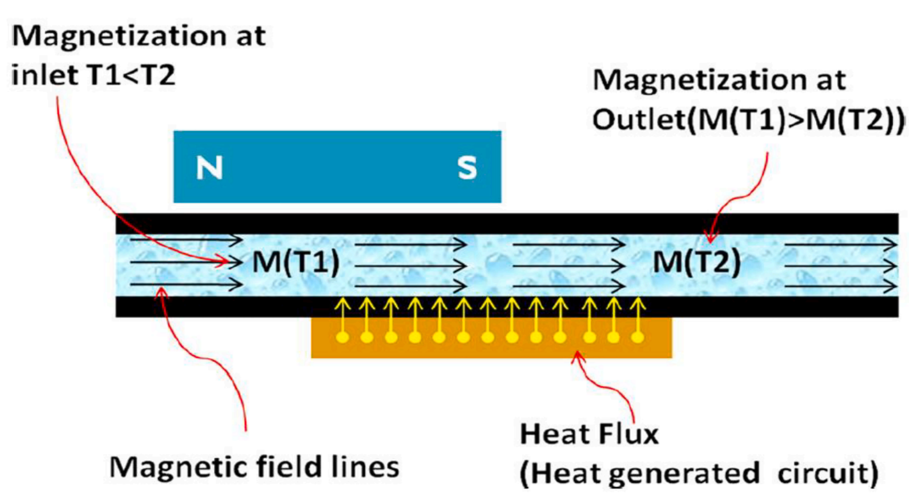

Fig. 16. Principle of thermo-magnetic convection (Singh [140]

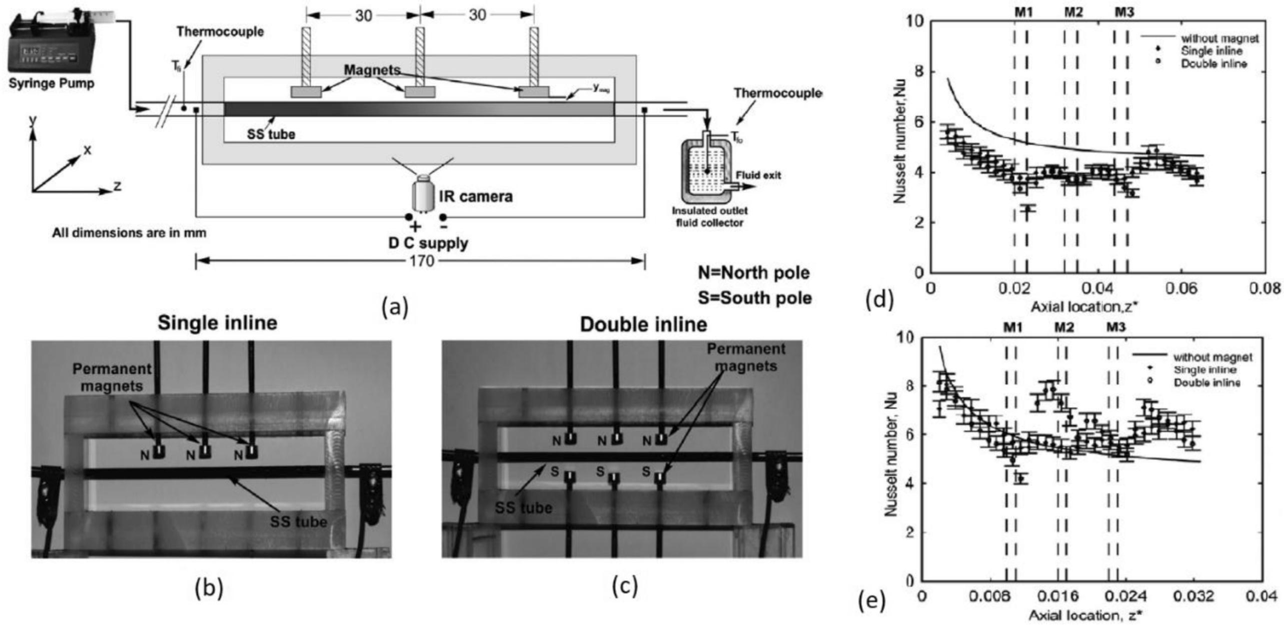

Fig. 17. (a) Schematic of the experimental set, (b) single-inline, (c) double-inline arrangement of magnets, Nusselt number (*Nu*) as a function of dimensionless distance (z^*) of the ferrofluid for single-inline and double-inline arrangements of magnets at flow rates: (d) $Q = 20$ ml/min and, (e) $Q = 40$ ml/min up [151].

magnets. When ten such magnets were used at Reynolds number 805, then a heat transfer enhancement of 261% was obtained with the ferrofluid compared to the no-magnet case.

Some investigations on the convective heat transfer focused on the type of ferrofluid materials. Zablotsky et al. [154] investigated, both experimentally and numerically, the thermo-magnetic convection in a rectangular convection cell filled with Mn–Zn ferrofluid. When the magnets were close to the warm or cold end, convective heat transfer was maximized. Chaudhary et al. [155] studied the 'self-pumping magnetic cooling effect' of Mn-Zn ferrofluids without the use of any mechanical pump. It was observed that the fluid flowed when external magnetic field was applied. The magnetic field thus acted as a pump. Shahsavar et al. [156] reported that forced convective heat transfer of a hybrid (Fe_3O_4 nanoparticles and carbon nanotubes) ferrofluid showed better enhancement under a constant magnetic field compared to an alternating magnetic field. Shyam et al. [157] investigated the convective heat transfer of iron-water ferrofluids flow of Reynolds number 66 in a heated SS tube, under the influence of constant and alternating magnetic field by using infrared thermography. The schematic of their experimental set up is shown in Fig. 18 (a). An electromagnet of C shape (Fig. 18 (b)) was used to provide the magnetic field. Copper wire was wounded around the mild steel core while fabricating the electromagnet. It was ensured that the magnetic lines passed through the SS tube (2 mm outer diameter), when it was placed in between the two

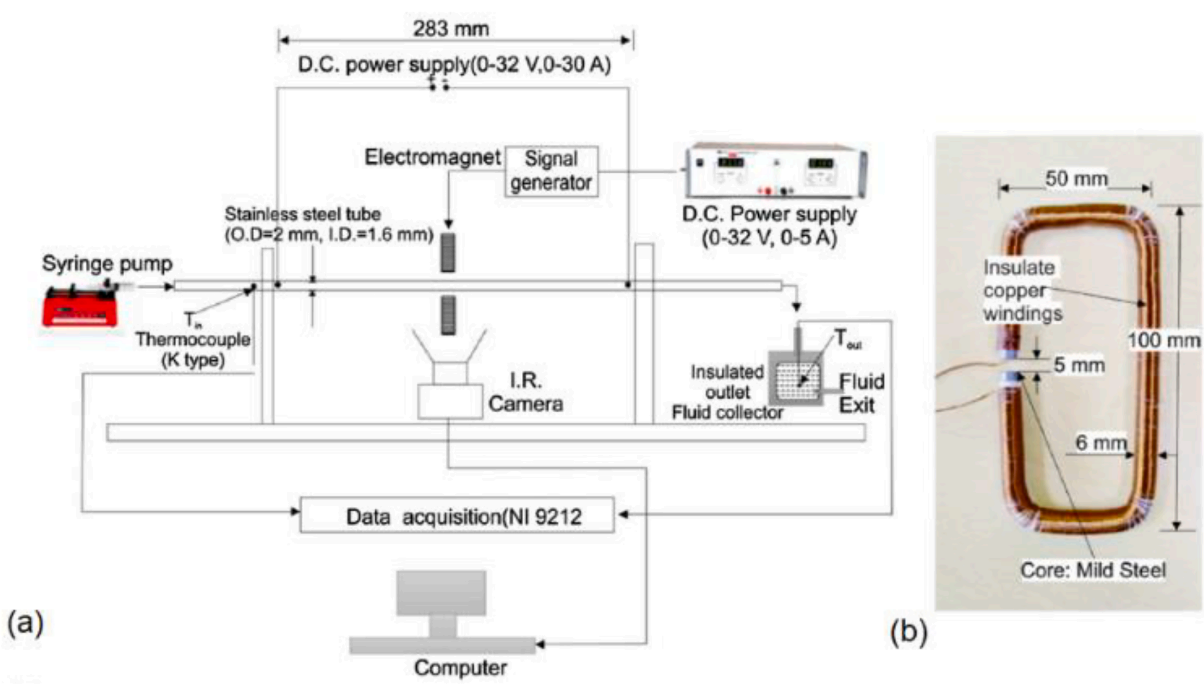

Fig. 18. (a) Schematic of the experimental setup; (b) Fabricated electromagnet used [157].

poles of the electromagnet situated 5 mm apart. A heat transfer enhancement of 23% was obtained by the application of constant magnetic field as compared to no-magnetic field case. At an alternating magnetic field with frequency 0.1 Hz, the heat transfer enhanced by ~ 39%.

A recent review article by Buschmann [158] in 2020, compiled the experimental results of both laminar and turbulent flow of ferrofluids in straight circular tubes in presence or absence of an external magnetic field. Three main physical mechanisms (as shown in Fig. 19) responsible for heat transfer enhancement were explained, i.e., (i) formation of 'chain-like aggregates', (ii) secondary motion, and (iii) 'pinning of nanoparticles' at the inner wall of the pipe. Besides the experimental works, several numerical studies are emerging [159–163] on convective heat transfer of ferrofluids, which are summarized in Table 2. These numerical studies are generally based on solving the strongly coupled mass, momentum, and energy balance equations along with the Maxwell equations that incorporates the magnetic field physics.

6.3.2. (b) Two-phase (air-ferrofluid) convection

It is evident from the literature that there are relatively few studies available on two-phase (gas–liquid) flows involving ferrofluids. Most of the available studies are on liquid–liquid two phase [164–168]. Gas-liquid two phase Taylor bubble flows can be used effectively in many important applications like mini/micro two-phase heat and mass exchangers and reactors, microfluidics and lab-on-chip (LoC) devices [169], pulsating heat pipes [170,171] to name a few.

Shah and Khandekar [172] have performed novel and seminal experimental studies on the formation, control, and manipulation of the air-ferrofluid two phase Taylor bubble flow in a T-junction square mini-channel of 2 mm × 2 mm cross-section. Fe_3O_4-water ferrofluids were used. Magnetic field was produced using two different permanent magnets Magnet #1 (strength 4.20 × 10^4N/m^3) and Magnet #2 (strength 5.10 × 10^4N/m^3). The concentrations of nanoparticles loading, position of the magnet from the T-junction (both upstream and downstream), and the flow rates of the ferrofluid were varied keeping the air flow rate constant. It was observed that the size of bubbles was smaller with a higher frequency of formation in presence of a magnet compared to without any magnet. The effect of magnetic field on the bubble formation of air-ferrofluid Taylor bubble flow is shown in Fig. 20. However, keeping the magnetic field constant, the size of bubbles was not affected much with the increasing ferrofluid flow rate. Thus, the flow transport mechanism of air-ferrofluid could be manipulated by the three factors, viz., (i) externally applied magnetic field strength, (ii) flow Reynolds number (i.e., the flow rate of the ferrofluid), and (iii) local magnetic pressure barrier induced for different concentrations of ferrofluid used.

Thus, it is noted that ferrofluids have enhanced thermophysical properties and heat transfer characteristics in presence of an external magnetic field. Therefore, future studies on ferrofluids must be focused to find potential application in industries. The testing, validation, and commercialization of heat transfer applications of ferrofluids is still at an early stage and need more attention in future.

7. Summary and conclusions

Ferrofluids exhibit unique thermophysical properties which have

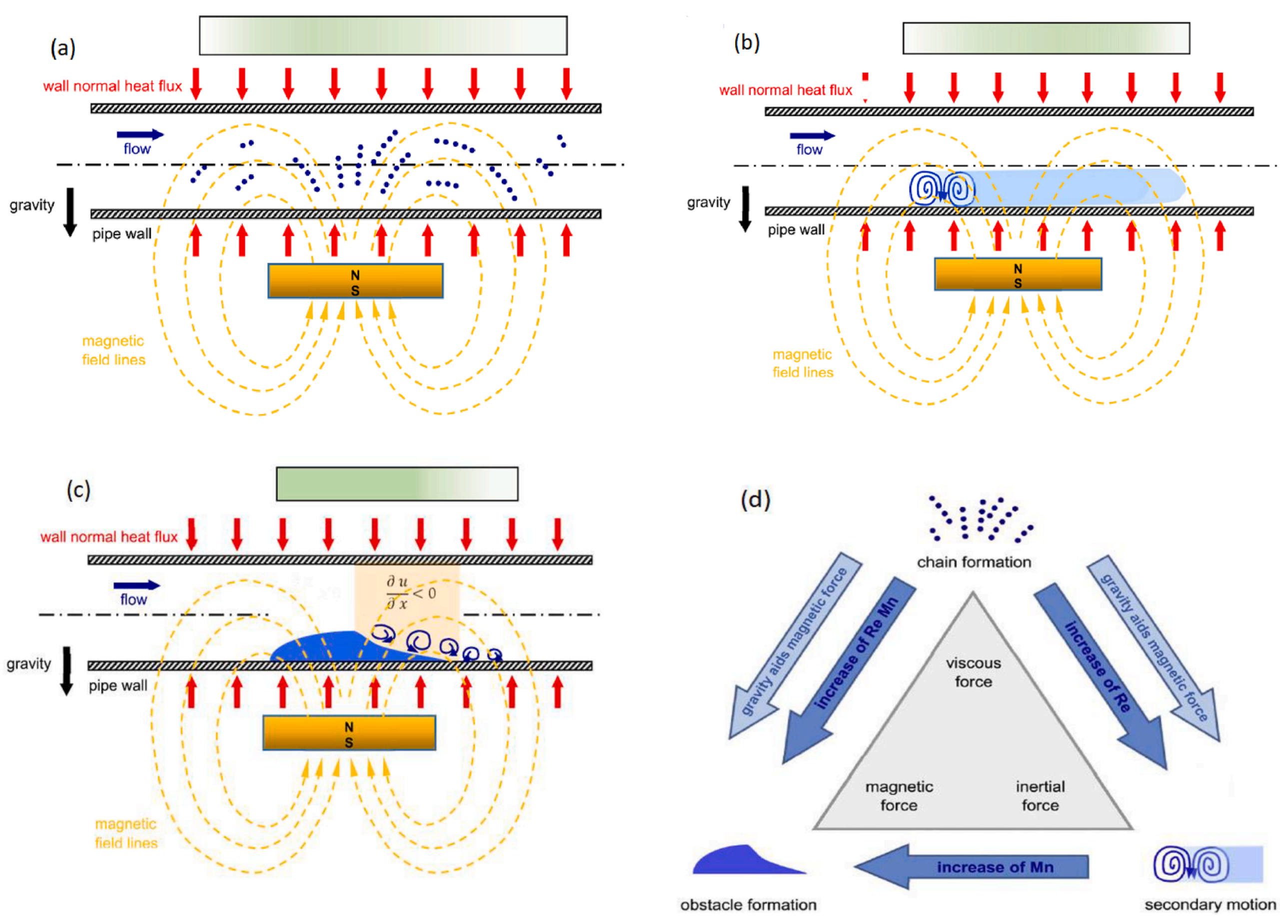

Fig. 19. The schematic of the physical mechanisms responsible for enhanced heat transfer (a) formation of chains, (b) secondary motion, (c) pinning of nanoparticles at the inner side of the tube, (d) The interplay among the gravitational, inertial, viscous, and magnetic forces responsible for enhanced convective heat transfer (. Adapted from [158]

Table 2
Convective heat transfer of ferrofluids (Numerical simulation works).

Research groups	Ferrofluids used	Numerical method used	Parameters studied	Magnetic field	Maximum heat transfer enhancement
Bahiraei and Hangi [159]	Water based Mn-Zn ferrite ferrofluids	Two-phase Euler–Lagrange method and Multilayer perceptron neural network analysis	Vol. conc. and size of nanoparticles, Reynolds number, and constant magnetic field	1.01–2.99 T	17% at a particle loading of 5 vol%, Reynolds no. 10, 000 and particle size of 30 nm
Ghasemian et al. [160]	Fe_3O_4-water	Finite volume two-phase mixture model with control volume method.	Reynolds number and magnetic field	Constant magnetic field intensities Mn = 0, 6.02 × 10^7, 1.07 × 10^8, and 1.67 × 10^8, Alternating magnetic field with frequency 0 to 10 Hz	16.48% at Mn = 1.07 × 10^8 and 27.72% at a frequency of 4 Hz
Sheikholeslami et al. [161]	Fe_3O_4-water	Control Volume based Finite Element Method	Reynolds number, nanoparticle volume fraction parameter, magnetic number, and Hartmann number	Magnetic number (from Ferro-hydrodynamics) = 0, 2, 6 and 10	Heat transfer enhances with the Reynolds number and the magnetic number, while it decreases with the Hartmann number
Gibanov et al. [162]	Fe_3O_4-water	Computational Fluid Dynamics using finite difference method of the second order accuracy	Hartmann number, magnetic field inclination angle, Darcy number, porous layer thickness, and nanoparticles volume conc.	Inclination angle 0–180^0	Heat transfer modifies with the increase of magnetic field inclination angle and porous layer height
Shah and Khandekar [163]	Fe_3O_4-water	Commercial software Comsol Multiphysics® based on finite element formulation	Reynolds number, nanoparticle volume fraction parameter, and magnetic field position and intensity	Non-uniform magnetic field	Heat transfer can be enhanced significantly by applying external magnetic field compared to no magnetic field case, at a certain value of Reynolds number and particle vol. fraction

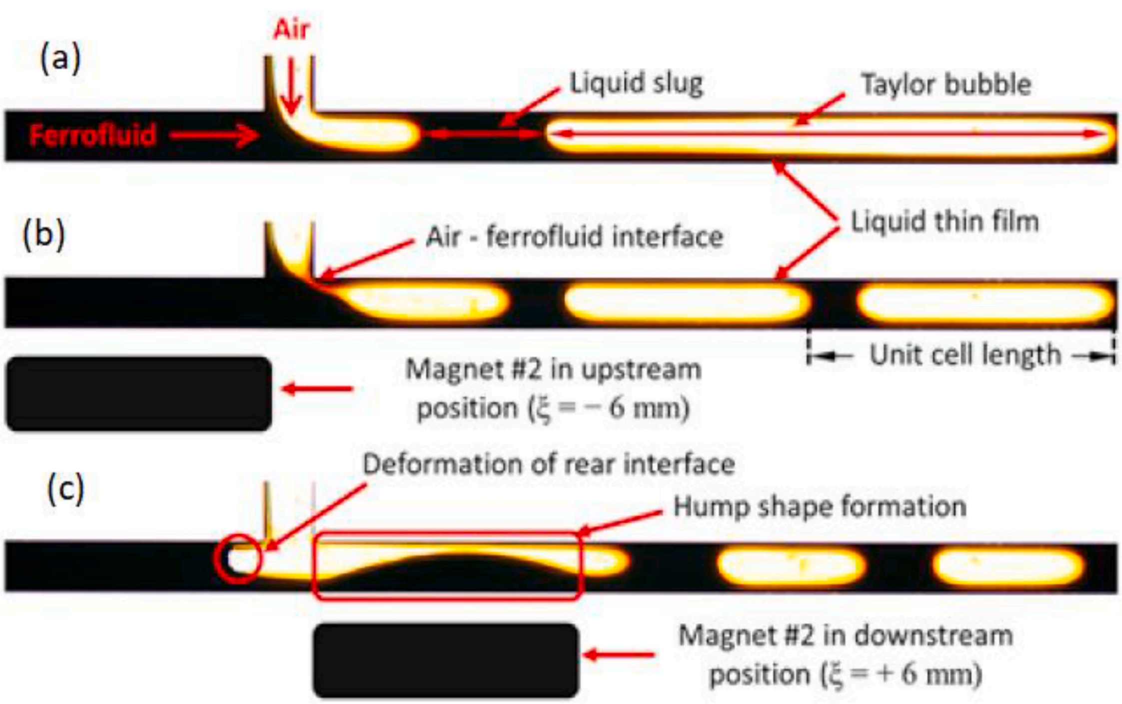

Fig. 20. Taylor bubble formation with air- 0.25 vol% ferrofluid when ratio of ferrofluid and air flow rate is 0.25 (a) No-magnet case, Magnet #2 placed in (b) upstream (c) downstream w.r.t to the T-junction [172].

been harnessed in several applications in the past, and new potential areas where such fluids can be employed are fast evolving. Due to the suspension of magnetic particles in the base fluids, and the fact that the suspended particles are in nanometric sizes, provides a distinctive platform for interesting physics that can be exploited for niche applications. The advent of modern manufacturing techniques for fabricating bulk nanoparticles, and improved understanding of nanofluid suspensions, has given the required impetus to researchers to explore new avenues of engineering applications of ferrofluids. This review article, summarizing not only the wide spectrum of applications of ferrofluids, but also delineating the underlying physics behind the specific application, is catering to this renewed interest of the community. Contemporary times has witnessed a surge in applications of ferrofluids ranging from machine-element design to bio-medical engineering, and to more recent wave of explorations in thermal aspects of ferrofluids. Since coupling of inertial, viscous, surface, and magnetic forces are involved, the problem of understanding the transport phenomena of ferrofluids involves an interactive multi-physics approach. Here, numerical modeling and experimentation, both play a complementary role in the design and development of ferrofluid based systems.

The control and manipulation of the effective viscosity, thin film dynamics and damping characteristics of ferrofluids is utilized in applications such as seals being used in high-power electrical switches, vacuum deposition systems, hard discs in computers, clean room robots, loudspeakers, and stepper motors, to name a few. In many instances, the superior quality of ferrofluids as regards bearing high shear rates, lubrication mechanics, and leakage control is used in mechanical and acoustic systems. The energy absorption characteristics of ferrofluids, when interacting with an externally applied electro-magnetic field, leads to several application in localized medical procedures involving thermal interactive treatment, such as in treating some types of cancers, tumors, and internal lesions. Superparamagnetic iron oxide nanoparticles in biocompatible fluids can be effectively used as agents or tracers in clinical diagnosis techniques like MRI and MPI. Realistic use of ferrofluids in human beings for site specific drug delivery and hyperthermia remains a challenge as nanoparticles with exact favorable biocompatible coatings still needs to be optimized.

Ferrofluids are also potential candidates to act as efficient thermal management agents in the electronics/power industries. Evidence about the ability of ferrofluids to provide high local heat transfer coefficients is fast emerging. The thermal conductivity of ferrofluids increases with the application of external magnetic field. With the application of external magnetic field, the boiling heat transfer may increase or decrease depending on several factors. In fact, there are only few studies which have dealt with these aspects of two-phase heat transfer of ferrofluids, as compared to investigations on convective heat transfer without phase-change. While most studies have reported an enhancement in convective heat transfer with an increase of the applied magnetic field, parametric effects of particle size, shape, and volumetric concentration of the nanoparticles have not yet been fully investigated or explained. There are several potential applications of ferrofluids in the domain of multiphase fluid manipulation (fluid involving gas, liquid, and solid magnetic nanoparticles, such as in Taylor bubble flows of ferrofluids) and phase-change heat transfer (including pool boiling and evaporation) with ferrofluids which require careful scrutiny.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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