STM JOURNALS

Nano Trends:
A Journal of Nanotechnology and Its Applications

ISSN: 0973-418X
Volume 25, Issue 2, 2023
DOI (Journal): 10.37591/NTs

http://techjournals.stmjournals.in/index.php/NTs/index

Research NTs

Smart Fluids: Magnetorheological Fluids Ferrofluids, and Nanofluids—Prospects for Medical and Technological Applications

Gizachew Diga Milki[1,*]

Abstract

The physiochemical and biomedical applications of smart fluids, typically ferrofluid, magnetorheological fluids, and nanofluids are studied. It is predicted that these fluids are impacted by the three most important rheology parameters, namely strain, magnetic field, and temperature. The magnetoresistive contribution is treated in terms of drug force in order to determine the coefficient of viscosity. The research presents that the viscosity of studied fluids will increase in proportion to applied magnetic field. The variables accounting for the resulting coefficient of viscosity are fluid density, drag force, shear strain, and magnetic field. On the other hand, the action of controlled fields on bee honey, blood, yolk, and lava lake shows that they behave as magnetorheological fluids. By computing the coefficient of viscosity and strain, it is possible to determine the dispersion relation. This relation reveals that the angular frequency is a function of mass, electric charge, magnetic field, and position. From the crystal dynamics, the dispersion relations for magnetorheological fluids/ferrofluids is determined and compared with dispersions relation of solids (phonons), plasma, and spin excitations (magnons). On the basis of the calculated dispersion relations, the biomedical and technological applications of smart fluids are predicted. This paper is aimed at investigating some of the new features and applications of these fluids in electromechanical systems, medicine, and nanotechnology.

Keywords: Dispersion relation, ferrofluid, magnetorheological fluids, nanofluids, smart fluids, rheology, viscosity

INTRODUCTIONS

Several types of smart materials have been identified. Smart fluids, multiferroics, and nanoparticles are part of a family of smart materials. Smart fluid is intelligent fluid where its rheology (viscosity) can be changed by electric, magnetic field, and strain. In this research, smart fluids are given greater attention. This is because their rheology (viscosity) is greatly influenced by magnetic field, strain, temperature, and viscosity.

Smart fluids include ferrofluids, magnetorheological fluids (MRFs), and nanofluids. MRF fluid is a rheological fluid which changes its properties as a function of magnetic field. Their electrical equivalent is called electrorheological materials. According to the research of Ismail et al. [1], MRFs are named in response to the type of the stimulus they interact. MRF is a smart fluid whose property is controlled by external stimuli (magnetic field). Assessment of nature fluids indicates that blood, honey, yolk, and mafic lava can be categorized as MRFs fluids. This is due to the fact that their viscosity and velocity can be controlled by magnetic field, heat, and pressure. Blood, yolk, honey, and

***Author for Correspondence**
Gizachew Diga Milki
E-mail: phygidg@gmail.com

[1]Professor, Department of Physics, College of Natural Sciences, Jimma University, Jimma, Ethiopia

Received Date: November 05, 2023
Accepted Date: November 30, 2023
Published Date: December 12, 2023

Citation: Gizachew Diga Milki. Smart Fluids: Magnetorheological Fluids Ferrofluids, and Nanofluids—Prospects for Medical and Technological Applications. Nano Trends: A Journal of Nanotechnology and Its Applications. 2023; 25(2): 47–57p.

lava fluids are naturally occurring fluids that are subjected to high viscosity. The first three fluids are representatives of bio-colloids and lava exists during the volcano eruption. The dynamic viscosities of these liquids are typically several orders of magnitude higher than dynamic viscosities of gases. As Phule [2] verified, MRFs are applicable in automotive, aerospace, and other technologies. As Vékás [3] realized, magnetically ordered nanochannels can be formed from magneto rheological fluids, which can act as “on-off “switches or “permeability valve”.

A typical body fluid called hemoglobin is an MRF in the sense that its rheology is viscosity. Hemoglobin has four protein molecules called chain globulin (Figure 1). Each chain globulin contains a central structure referred to as hemi. As Lecomte [4] stated, guanidinium chloride is usually preferred to maintain hemi in the Fe (III) version of heme in solution and in the monomeric state.

MRFs are equated with sensitive devices like actuators. Actuators are devices that can deform in response to applied stimuli. Like actuators, MRFs respond to external stimulus. Like MRFs, the sensitivity of actuator is affected by electric potential, current, magnetic field, light, pressure, and temperature. As Bayaniahangar et al. [6] discussed, soft actuators are a special class of actuators made of soft materials, which have been of great interest in micro fluidic systems.

At ferromagnetic state, MRF can form a semisolid state (Figure 2). Thus, it shares partly the properties of semiconducting solids like Si, ZnO, Fe_2O_3, and GaMnAs. It also enables MRF suitable fluid in optoelectronics, molecular electronics, bioelectronics, and micro fluidics. They are used for solid tumor detection and treatment. The magneto rheological fluids have potential applications in cyclotron and rotor. Dietterich et al. [7] verified a potential application of lava in remote sensing channelized flow parameters and applied in near-real-time to flows.

Ferrofluids are colloid liquids from ferromagnetic nanoparticles and nanocomposite. A ferrofluid is a colloidal suspension of single-domain magnetic particles, with dimensions of nearly 10 nm. It has a stable strong ferromagnetic ordering. Ferrofluids can be formed by mixing iron oxide with vegetable oil. As Scherer Figueiredo Neto [8] demonstrated, external magnetic field increase the viscosity of MRF forms solid state, however, ferrofluid keeps its fluidity even if subjected to magnetic field.

Magnetic nanoparticles (ferrofluids) are both biocompatible and biomarkers (Figure 3). Ferrofluids are also found in human lung, brain tissues, and lymphatic systems. Rajagopalan et al. [9] had illustrated ferrofluid are emerging as materials for actuating thermal overload relay due to their tunable Curie temperature. They are widely used in microelectromechanical (MEMS) systems, nano electromechanical (NEMs) systems, and microfluidics. Ferrofluid are used in loudspeakers, laser heads of CD and DVD players, and in the inks used in paper currency.

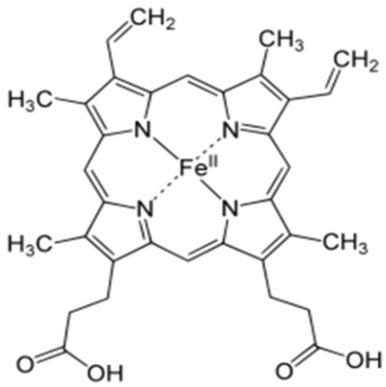


Figure 1. Molecular structure of Hemi, Ref. Winslow S Caughey et al. 1975 [5].

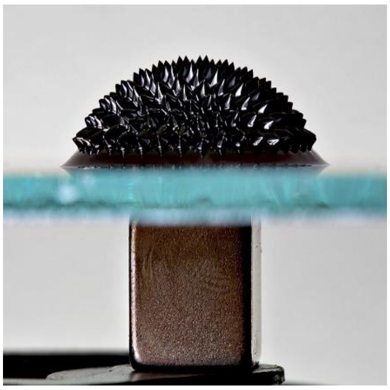


Figure 2. Ferroelectric fluids under glass.

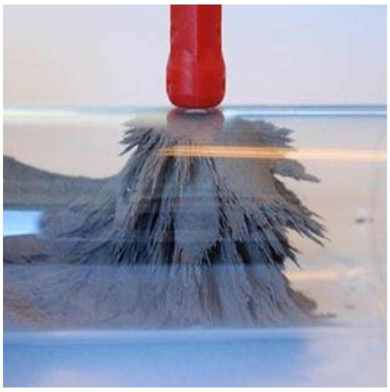


Figure 3. Attraction of ferrofluids by magnets.

Nanofluids are fluids which are engineered colloidal suspensions of nanoparticles in base fluids. They are dilute liquid suspensions of nanoparticles with dimensions of 1 to 100 nm. Nanofluids and ferrofluids are similar to some extent. Ferrofluids are magnetic nanofluids which are prepared from magnetic nanoparticles, magnetic oxide nanoparticles, and magnetic nanofilms. Like ferrofluids, nanofluids possess enhanced thermophysical properties such as thermal conductivity, thermal diffusivity, and temperature gradient. Moreover, Usman et al. [10] demonstrated the heat absorption behavior, the Darcy effect, the thermal radiation, and viscosity dissipation of magnetohydrodynamic hybrid nanofluids flow. Lone et al. [11] had notified the use of nanofluids in modern heating and cooling systems. Moreover, they are used for solar panels, fuel generation, hybrid-powered vehicles, cancer treatment, drug delivery, and medicine.

PHYSICAL PROPERTIES OF SMART FLUIDS

Smart materials exhibit different properties that are influenced by the rheological conditions. The physio chemical properties are noticed during interactions with stimulus like magnetic field, lights, temperature, and pressure. A typical MRF such as blood contains iron in the hemi which exists in two forms ferrous (Fe^{2+}) and ferric (Fe^{3+}). Hemoglobin, which is the host of hemi, exists in the form of ferro-hemoglobin or ferric-hemoglobin. In ferrous form, iron combines with oxygen and is substituted with rare and transition metal elements giving rise to its magnetic properties. Hence, hemoglobin controls the magnetic behavior of blood. As illustrated by Furlani [12], white blood cells (WBCs) behave as diamagnetic micro particles, while red blood cells (RBCs) exhibit diamagnetic or paramagnetic behavior depending on the oxygenation of their hemoglobin.

MRFs in lava lakes consist of MgO and Fe_3O_4 nanoparticles. The existence of these compounds determined the magnetic properties of lava lakes. Liquid lava emerges on the surface of earth resembling as ferrofluid. It contains silicates and iron oxide exhibiting paramagnetic if no external magnetic field is applied. In the presence of external magnetic field, it can be tuned to either ferromagnetic phase or antiferromagnetic. Mafic lava usually exhibits ferromagnetism at a Curie temperature. However, it shifts to paramagnetic up on heating. Thus, the physiochemical properties of mafic lava are impacted greatly by magnetic field and heat.

The density of MRF/ferrofluid is three times the density of water. This property enables ferrofluids, MRFs, and nanofluids in mass flow measurement techniques. Mass flow measurements depend on the vibration of the tube where calibration depends on the changes in the rigidity of the flow tubes. On the other hand, MRFs/ferrofluids are characterized by high viscosity since they possess Reynolds number greater than 2300. Most ferrofluids, MRFs, and nanofluids undergo a turbulent flow. However, with sufficient supply of heat or electric energy, they can be guided to maintain streamline flow between layers of fluids.

The classical MRFs focused upon in this research, namely blood, honey, mafic lava, and yolk, exhibit both electrical conductivity and possess semiconducting properties. These fluids are categorized under classical fluid since their dynamics can be treated by Newtonian mechanics. As Shi et al. [13] demonstrated, the permeability of ferrofluid synthesized using glycine, glutamic acid, glycine, glutamic acid and collagen can be controlled by blood–brain barrier model. Ayari et al. [14] showed that Tunisian honey’s electric conductivity lies in the range 0.19 ± 0.01 to 0.7 ± 0.02 mS/cm. As Darvish et al. [15] demonstrated, the ohmic heating of egg at voltage gradient of 30 V/m in the temperature range of 19℃ to 60℃ shows that electrical conductivities increased linearly with temperature. Electric conductivity and electrochemical impulse of yolk is caused by the existence of electrical charge carriers in living life. They also exhibit high electron mobility.

METHODS OF STUDY

Different methods are used to prepare smart fluids, typically ferrofluids, MRFs, and nanofluids. However, the discussion here focuses on the natural occurring fluids. Here the theoretical methods and separation techniques are given attention. The relations among the rheology of smart fluids particularly, dispersions, magnetic field, resistance, and viscosity are determined using theorems. The data on the relations between stimuli of smart fluids studied are simulated by Origin 8. Origin 8 is a powerful drawing, simulating and extrapolating software which is sometimes released free on websites. Origin lab comprises of Origin, 6, 8, 10, 11, 12, and up to 50.

Preparation and Separation Methods

Different methods have been employed to prepare and separate MRFs. As Philip [16] discussed, magnetic nanofluids (ferrofluid) can be prepared by grinding micron-sized magnetite in a ball mill for weeks. It is then subsequently stabilized with oleic acid for applications of pH sensors and in biomedicine. As Kamble et al. [17] described, highly sensitive and intelligent MRF can be prepared by mixing iron oxide nanoparticles with oil by adding fine lithium grease in order to reduce the sedimentation.

Blood can be easily collected from humans and kept in tissue cultures thus can be studied, and honey and yolk is easily bought from the local shopkeepers. However, lava lake is rare and needs a great deal of energy expenditure. However, it can be collected from the depressions where volcanoes are known to erupt. The diagram below illustrates the mechanism of separating smart fluids.

Kim et al. [18] demonstrated that nanoparticles aggregations can be prevented by polymeric starch network as a coating agent. Ferrofluid of Fe_2O_3 and ZnO can be prepared from blood, lava, and yolk by hydrolysis and thermogravimetric process (Figure 4). To achieve the ferrofluid behavior: (1) heating the ferromagnetic materials until its melting temperature will produce superparamgnetic fluid and (2) mixing magnetic nanoparticles with oil can produce ferrofluid. Hong et al. [19] and Lotfizadeh Dehkordi et al. 2013 [20] found that increasing sonication times reduce particle clustering during the synthesis of iron (Fe)/ethylene glycol nanofluids and TiO_2 water nanofluids.

Theoretical Methods

The derivation is based on the magnetoelastic property of fluids. The assumption made is that (1) MRFs acts as elastic materials and their physical properties are expressed in terms of strain. (2) The applied magnetic field is responsible for the rheology of the fluids.

$$\eta = \frac{-1}{6}\left[\Pi q\vec{B}sin\theta + \frac{\rho r}{\vec{v}}\omega^2 x\right] \tag{1}$$

where $\Pi = \frac{\pi x}{r}$ is shear strain and r is the radius of artery, θ is the angle between the direction of blood flow and magnetic field.

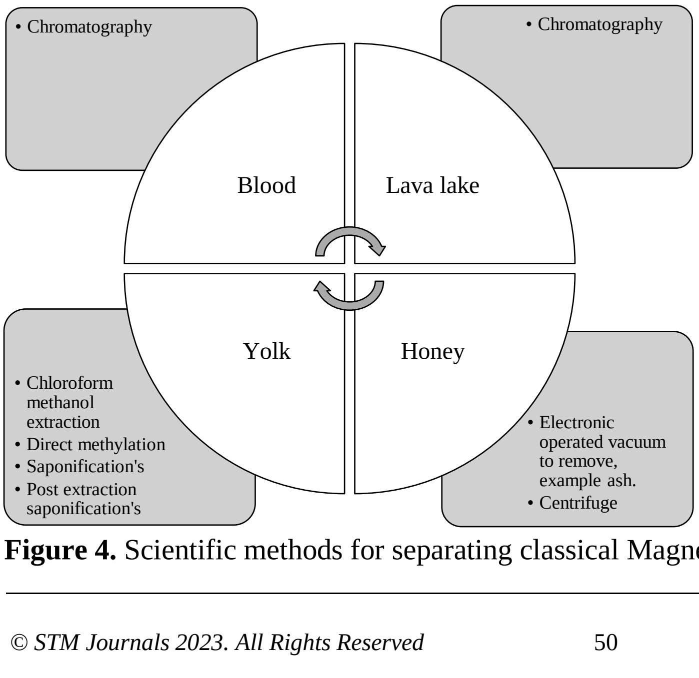


Figure 4. Scientific methods for separating classical Magnetorheological fluids.

The relation between $\vec{B}$ and the resistance of the fluid is

$$\vec{B}_{eff} = \frac{12.45}{\alpha\mu}\left(\frac{R-R_0}{R_o}\right) \tag{2}$$

The smart fluids act as elastic crystals obeying the dispersion relations

$$\omega = \left[-\left(\frac{6\eta+\Pi qBsin\theta}{xM}\right)\vec{v}\right]^{\frac{1}{2}} \tag{3}$$

Where η is the coefficient of viscosity, q is the magnitude of electric charge, B is magnetic field strength, M is mass of the fluid arising from its density, r is the radius, x is displacement, $\underset{V}{\rightarrow}$ is the speed of the fluid, and θ is the contact angle. Equations 1 to 3 virtually describe most physiochemical properties such as mechanical, thermal, electrical and magnetic properties of smart fluids. Unlike frequency of solids (phonons) frequency of smart fluids is a function of viscosity, electric charges, and magnetic fields. In order to express the in standard form, the wave vector K is defined in terms of coefficient of viscosity, electric charge, magnetic field, and strain.

$$K = \left(\frac{6\eta+\Pi qBsin\theta}{xM}\right) \tag{4}$$

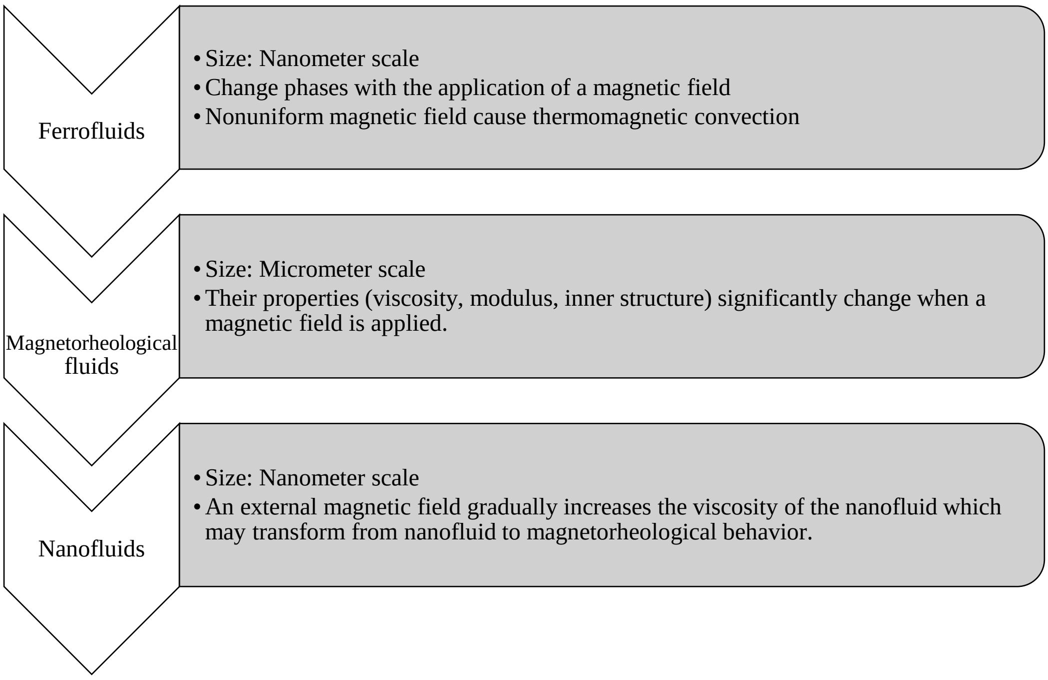
Thus, the frequency is reduced to the simplest form as

$$\omega = V_g^{\frac{1}{2}}\sqrt{k} \text{ for smart fluids.} \tag{5}$$

Where, V_g is the group velocity and K is the wave vector. Generally, the frequency of MRF/ferrofluid is compared with frequency of phonons due to crystals of solid vibrations and frequency of plasma.

DISCUSSION

The stream of particles flowing against fluid is subjected to drag force and electrostatic repulsion between identical electrons. In order to develop the phenomena of fluid transport, we start from equation of motion. The flow is characterized by recirculation, vortex shedding, turbulence, and helical flow. As described by Wang and Gordaninej [21], the viscosity of an MRF depends on density, electric charges, the magnitude and direction of the magnetic field, and the shear rate (Figure 5).



- Size: Nanometer scale
- Change phases with the application of a magnetic field
- Nonuniform magnetic field cause thermomagnetic convection

- Size: Micrometer scale
- Their properties (viscosity, modulus, inner structure) significantly change when a magnetic field is applied.

- Size: Nanometer scale
- An external magnetic field gradually increases the viscosity of the nanofluid which may transform from nanofluid to magnetorheological behavior.

Figure 5. Rheological response of smart fluids to heat and magnetic field.

These fluids are regarded as MRFs since their viscosity and velocity can be altered by external magnetic fields, thermal energy, and strain energy. The coefficient of viscosity of these fluids greatly increases as the magnetic field increase. As Choi [22] verified, the sedimentation of MRF can be improved by covering nanoparticles with dimer acid.

Magnetomechanical Property and Elasticity

One distinguishing feature of MRF is that increasing magnetic field causes a greatest increase in viscosity as in the equation. The increased viscosity will reduce high amplitude oscillations; Thus, this saves buildings from cracking and collapse.

$$\eta = -Cx(x+1) \tag{6}$$

where, x is the flow distance.

The coefficient of viscosity is a quadratic function of the flow displacement. As the flow distance increases, the coefficient of viscosity increases abruptly. As shown in Figure 6, the viscosity of normal fluids decrease linearly as the flow distance increase. However, for the case of MRFs, the viscosity decreases as a polynomial function of flow distance.

Flow Distances

As in Figure 6(b), the coefficient of viscosity is constant for laminar flow. This due to the fact that in laminar flow a smooth flow is established due to the absence of disruption between parallel layers. As shown in the Figure 7, green colors represent turbulent fluid flow. However, for turbulent flow the coefficient of viscosity decreases as the flow distances increases. The turbulence is caused by theapplication of magnetic field, which makes disruptions between parallel layers of MRFs.

Figure 7 presents different relations between the varying magnetic field and radius of cross sections for a fluid flow in pipes/tunes. Again, at the center points, the speed of the fluid is fastest due to the contribution of the solenoidal like magnetic field of the circular cross-sections.

Magnetic Field Effect

The effects of magnetic field are significantly demonstrated on MRF, particularly blood. The red blood cell contains hemoglobin which consists of four hemis, which contains iron connected with neighboring nitrogen by covalent bonds. The iron in the hemi exists in two forms ferrous Fe^{2+} and ferry Fe^{3+}. In ferrous form, iron interacts with bloods hemoglobin which controls the magnetic behavior of blood. As Taylor et al. [23] discussed, blood flow in arteries is a complex 3D phenomenon and can be modeled and computed with software system.

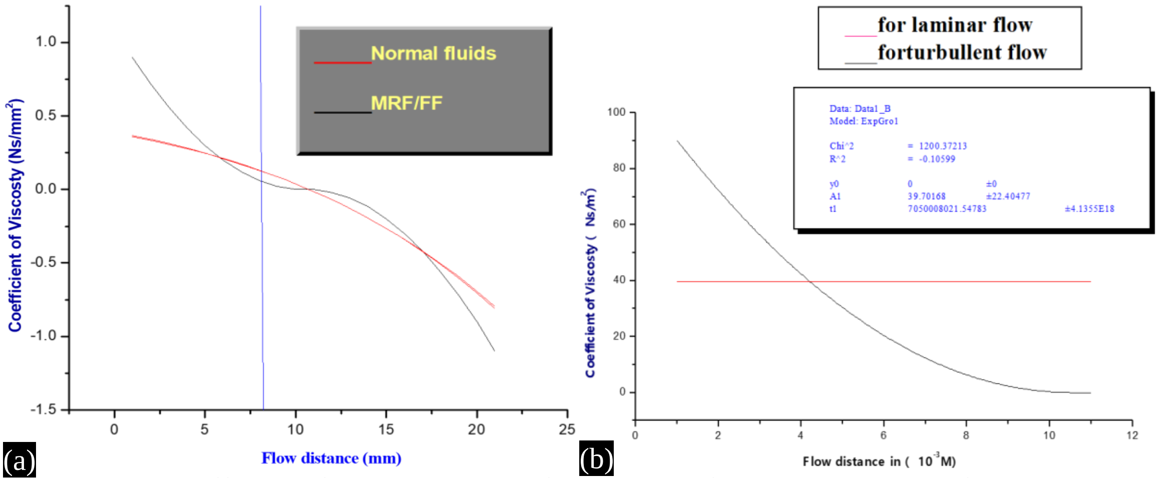


Figure 6. (a) Coefficient of Viscosity Versus flow distance for normal and smart fluids
(b) Coefficient of viscosity versus flow distance for laminar flow and turbulent flow.

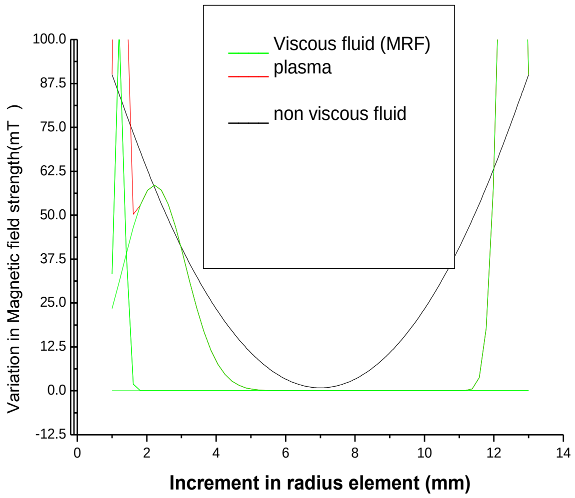


Figure 7. Variation of applied magnetic field as a function of radius element for MRFs.

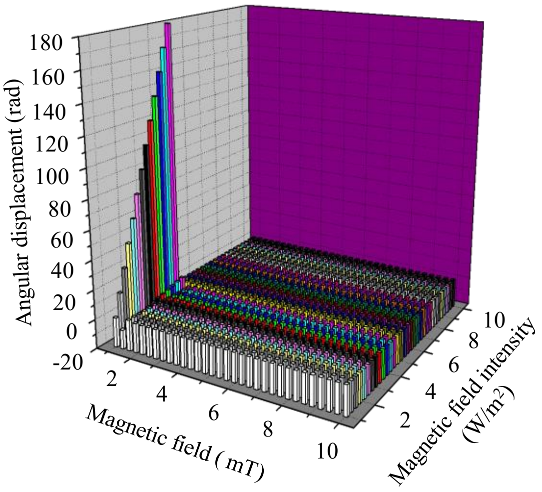


Figure 8. The relations between magnetic field, magnetic field intensity, and angular displacement.

When a magnetic field is applied along the flow direction, the fluid motions are enhanced. When it is applied in a direction that is opposite to the direction of flow, the velocity is retarded and it exhibits a high resistance, referred to as magneto resistance. When the field is applied in a direction that is perpendicular to direction of fluid flow, the fluid velocity is retarded and tends to come at rest.

The effect of an external field is (1) changing the direction of flow and velocity, (2) virtually its wavelength since fluids changes their color virtually depending on color of the containers and an external agent exposed to it, (3) changing magnitude of rheology or the stimuli where they are exposed, for example, light, temperature, pressure, or viscosity.

For instance, a magnetic field is used as an external stimulus. The magnetic field is preferred due to its ability to control both electrical parameters such as potential, magneto resistance, and temperature. Other parameters such as deviations in angles are taken into consideration. When the angular displacement is equivalent to 0° (Figure 8), the resulting band is white light equivalent to laser light. On the contrary, as the direction of applied field and the displacement of fluid are 90°, the resulting band is dark band. However, when the direction of applied field and the displacement of fluid are 180°, the band intensity is altered. The band intensities are a series of bright and dark bands, which are formed when the MRF/ferrofluid is exposed to external magnetic fields.

As shown in Figure 9(a), the resistance increases linearly with field. However, in order to produce giant magnetoresistance (GMR), fields greater than 120 T are needed. As shown in Figure 9(a) the effective magnetic field is directly proportional to the resistance. As the magnetic field changes by factor of 20, the magnetoresistance changes by twofold. Therefore, every change in 10 T of magnetic field will produce a resistance of 1 Mohm. Therefore, MRFs have greatest potential for storing energies like thermal, photovoltaic, and solar energy.

As stated in the Figure 9(b), the frequency of MRFs resemble that of frequency of plasma. This is the consequence of three important conditions:

1. When an extremely high magnetic field is applied in order to monitor MRF, they are capable of changing into a state which is intermediate between solids and liquids (plasma).
2. Upon heating, plasma state will produce a state change from plasma to fluids.
3. Both frequency of MRF and plasma have some sort of relations on electric properties, the first is dependent on electrical charge and the latter is dependent on dielectric media.

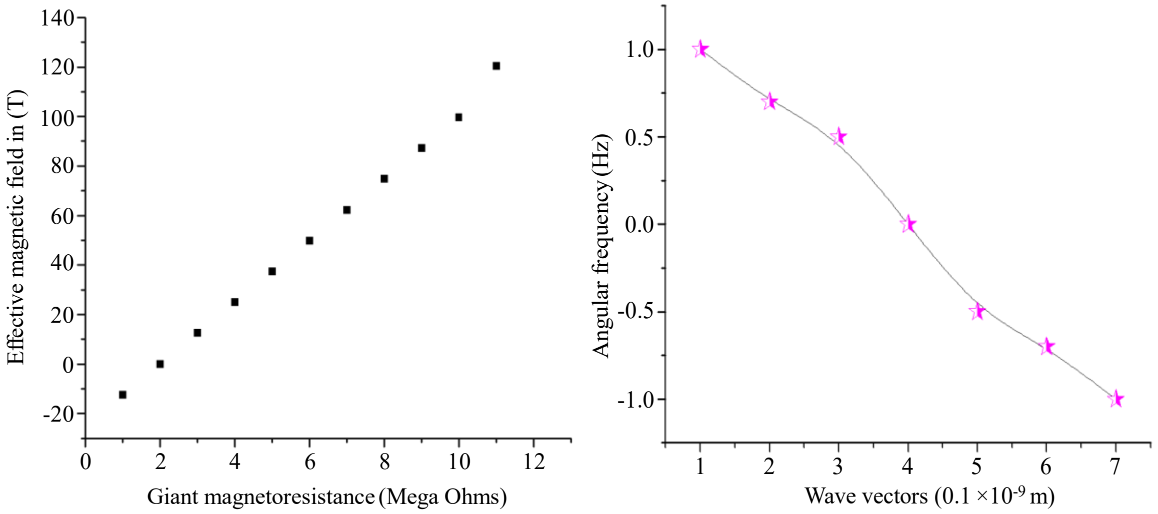


Figure 9. (a) Relations between applied field and resistance of fluids (b) Frequency and wave vector.

Table 1. The relation between Phonon frequency and wave vector for smart fluids, plasma, solids, and spins waves.

S.N.	Frequency	Type of Crystal	Reference	Ref.
1	$\omega \approx k^{\frac{1}{2}}$	Magnetorheological fluid (Ferrofluid)	This research	Present work
2	$\omega_p = \left(\frac{4\pi n}{\varepsilon(\infty)m}\right)^{\frac{1}{2}}$	Plasma	Kittel C. 2005	[24]
3	$\omega \approx K$	Phonons	Kittel C. 2005 and Neil Mermin, 1976.	[24, 25]
4	$\omega_m \approx k^2$	Magnons	Kittel C. 2005 and Neil. Mermin, 1976.	[24, 25]

However, one is not advised to apply them for storing electric energy since electric discharge process might occur. Table 1 summarizes the relation between the frequency of crystal vibrations and wave vector of different states of matter (solid, fluids, and plasma) for the long wavelength limits: If the wavelength of crystal vibration is very long compared to the lattice parameter, that is, in the first Brillouin (FBZ) region, k << $\frac{1}{a}$ or λ >> ɑ corresponds to the continuum approximations and $\frac{-\pi}{a} \leq k \leq \frac{\pi}{a}$.

The frequency of the smart fluids is directly proportional to the square root of the wave vector, *K*. It is also directly proportional to the square root of the group velocity, V_g. Although these materials resemble the same, their frequencies are different from one to another. This is due to the difference in density, ground state energy, and responses of external rheology such as magnetic field, temperature, and phase.

PROSPECTS AND APPLICATIONS OF SMART FLUIDS

Medical Application

As Arab Hassani et al. [26] discussed, smart materials offer a significant role in sensing and actuation applications in healthcare due to their responsive stress, light, temperature, moisture, pH, and electric and magnetic fields. Magnetic nanofluids (ferrofluids) are both biocompatible and biodegradable. These ferrofluid are used for biomarkers, contrast agents, cell labels, and increase cell viability. As Socoliuc et al. [27] revealed, biocompatible ferrofluid or bio ferrofluid are proven for applications in biotechnology and nanomedicine. Hypertension can be reduced by demagnetizing blood using smart fluids, which reduces blood pressure. Hadjivassiliou et al. [28] revealed that intensive blood pressure was lowered from 140 mm Hg to 120 mm Hg by demagnetization. To this end, blood’s iron content is reduced by demagnetizing with smart fluids and heating. This can maintain a standard body pressure by the law of thermodynamics. Nanostructures, mainly silicon dioxide, coming out of the lava can be a rheological additive.

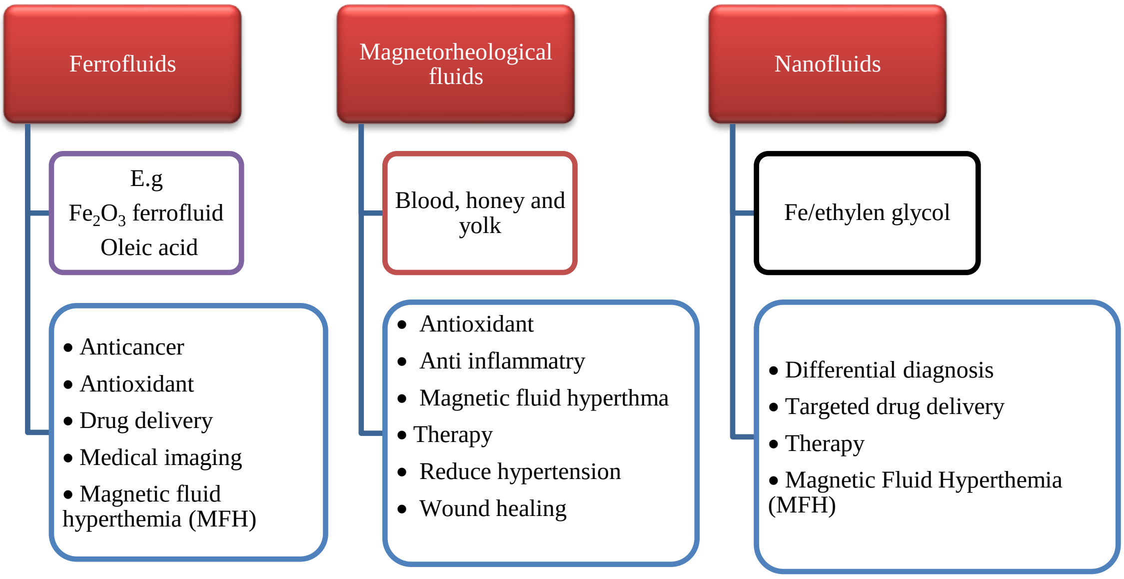


Figure 10. Medical application of smart fluids.

The medical applications of Ferrofluid, magnetorheological fluids and nanofluids are summarized as shown in Figure 10.

Both blood and honey are natural antioxidants, which are effective in reducing heart disease, cancer, anemia, and in improving the immune system. The study of Gu et al. [29] indicates that egg yolk proteins possess multiple biological activities which improves human health and well-being, such as anti-obesity, anti-atherosclerosis, anti-osteoporosis, diagnosis and SARS-CoV-2 therapy. Yilmaz and Ağagündüz [30] reported that egg yolk proteins and ovalbumin have significant role in the recovery of Fe deficiency anemia in rats. This is an equivalent of ferrofluid of Zn-doped iron oxides. Smart fluids, particularly MRFs, ferrofluids, and nanofluids have promising uses in medicine. They are widely used in drug targeting, hyperthermia, cell separation, contrast agent, and magnetic resonance imaging. In medicine, ferrofluids have been used for localization and diagnosis of brain and cardiac in facets, and liver lesions. Nanofluids of ZnO and $Zn_xFe_{2-x}O_3$ are used mainly as antibiotics and in wound healing. Engineered lava fluid is used in remote sensing. It can be cooled down to liquid form for medicinal applications, particularly hyperthermia and thermotherapy. Smart fluids are also used in smart robots, nanobiosensors, nanoelectromechanical systems, and nanobiotechnology. In general, smart fluids have valuable applications in day-to-day life from vitamins to medicine and from electronics to electricity generation. Therefore, investing on smart fluids has significant role in solving society's problem.

CONCLUSION

In this research, the properties and applications of both classical and quantum smart fluids are studied. The study reveals the three most important magnetically tunable smart fluids, namely MRFs, ferrofluids, and nanofluids. They consist of iron and oxygen which determines their physiochemical behavior. The study also reveals that all the studied fluids exhibit positive response to the external magnetic field. From the study, it is realized that the applied magnetic field has inverse relations with thermodynamic temperature and shows a high degree of dependence on the density and viscosity.

Though these fluids resemble classical fluids, their composition, typically acidity, carbonyl groups, iron oxide nanoparticles, and proteins make them valuable materials in contemporary technologies. Unlike phonon dispersion relations (solids), the frequency of smart fluids typically ferrofluids, MRFs, and nanofluids are directly proportional to square root of wave vector. The calculated dispersion relation for smart fluids reveals that the angular frequency is a function of mass, electric charge, magnetic field, and position. It also proves that the angular frequency is directly proportional to the square root of wave vector, *K*. This relation shows that smart fluids, typically ferrofluids, MRFs, and nanofluids are suitable in magnetic resonance imaging, magnetic fluid hyperthermia, thermodynamic therapy, diagnosis, drug delivery, and ultrasonic measurement. Moreover, they have potential applications in dampers, elastomers, electromechanical systems, actuators, smart robots, solar collectors, nanosensors, and nanobiotechnology. In the future, we will further look at strain-induced energy generation and the importance of smart fluids in flexible medical equipment.

Acknowledgements

I would like to express my deepest thanks to Jimma University for its material allocation.

REFERENCES

1. Ismail I, Mazlan SA, Zamzuri H, Olabi AG. Fluid-particle separation of magnetorheological fluid in squeeze mode. Jap J Appl Phys. 2012; 51 (6): 301–305. doi: 10.1143/JJAP.51.067301.
2. Phule PP. Magnetorheological (MR) fluids: principles and applications. Smart Mater Bull. 2001; 2 (2): 7–10. doi: 10.1016/S1471-3918(01)80040-X.
3. Vékás L. Ferrofluid and magnetorheological fluids. Adv Sci Technol. 2008; 54: 127–136. doi: 10.4028/www.scientific.net/AST.54.127.
4. Lecomte JTJ. Hemoglobin: some (dis)assembly required. Biophys J. 2020; 118: 1235–1237. doi: 10.1016/j.bpj.2019.12.041.
5. Caughey WS, Smythe GA, O'Keeffe DH, Maskasky JE, Smith MI. Heme A of cytochrome c oxidase. Structure and properties: comparisons with hemes B, C, and S and derivatives. J Biol Chem. 1975; 250 (19): 7602–7622.
6. Bayaniahangar R, Ahangar SB, Zhang Z, Lee BP, Pearce JM. 3-D printed magnetic soft magnetic helical coil actuators of iron oxide embedded polydimethylsiloxane. Sensors Actuators B Chem. 2021; 326: 128781. doi: 10.1016/j.snb.2020.128781.
7. Dietterich HR, Grant GE, Fasth B, Major JJ, Cashman KV. Can lava flow like water? Assessing applications of critical flow theory to channelized basaltic lava flows. J Geophys Res Earth Surface. 2022; 127: 1–26. doi: 10.1029/2022JF006666.
8. Scherer C, Figueiredo Neto AM. Ferrofluid: properties and applications. Brazil J Phys. 2005; 35 (3A): 718–727. doi: 10.1590/S0103-97332005000400018.
9. Rajagopalan B, Hayagrivan M, Praveenkumar M. Ferrofluid actuated thermal overload relay. Smart Grid Renew Energy. 2012; 3: 62–66. doi: 10.4236/sgre.2012.31009.
10. Usman M, Amin S, Saeed A. Magnetohydrodynamic hybrid nanofluids flow with the effect of Darcy–Forchheimer theory and slip conditions over an exponential stretchable sheet. Adv Mech Eng. 2022; 14 (8). doi: 10.1177/16878132221116479.
11. Lone SA, Anwar S, Saeed A, Seangwattana T, Kumam P, Kumam W. A comparative analysis of the time-dependent magnetized blood-based nanofluids flow over a stretching cylinder. Heliyon. 2023; 9 (4): e14537. doi: 10.1016/j.heliyon.2023.e14537.
12. Furlani EP. Magnetophoretic separation of blood cells at the microscale. J Phys D Appl Phys. 2006; 40: 1313–1319.
13. Shi D, Sun L, Mi G, Sheikh L, Bhattacharya S, Nayar S, Webster TJ. Controlling ferrofluid permeability across the blood–brain barrier model. Nanotechnology. 2014; 25 (7): 075101. doi: 10.1088/0957-4484/25/7/075101.
14. Ayari A, Abbassi F, Hammami MA, Landoulsi A. Physicochemical and antimicrobial properties of Tunisian honeys: honey inhibited the motility of bacteria. Afr J Microbiol Res. 2013; 7 (32): 4138–4145. doi: 10.5897/AJMR12.2154.
15. Darvish H, Khoshtaghaza MH, Zarein M, Azadbakht M. Ohmic processing of liquid whole egg, white egg and yolk. Agric Eng Int CIGR J. 2012; 14 (4): 224–230.
16. Philip J. Magnetic nanofluids (ferrofluids): recent advances, applications, challenges, and future directions. Adv Colloids Interface Sci. 2023; 311: 102810. doi: 10.1016/j.cis.2022.102810.
17. Kamble VG, Kolekar S, Madivalar C. Preparation of magnetorheological fluids using different carriers and detailed study on their properties. Am J Nanotechnol. 2015; 6 (1): 7–15. doi: 10.3844/ajnsp.2015.7.15.

18. Kim DK, Voit W, Zapka W, Bjelke B, Muhammed M, Rao KV. Biomedical application of ferrofluid containing magnetite nanoparticles. MRS Online Proc Lib. 2001; 676: Article 832. doi: 10.1557/PROC-676-Y8.32.
19. Hong KS, Hong TK, Yang HS. Thermal conductivity of Fe nanofluids depending on the cluster size of nanoparticles. Appl Phys Lett.2006; 88: 031901. doi: 10.1063/1.2166199.
20. LotfizadehDehkordi B, Ghadimi A, Metselaar HSC. Box-Behnken experimental design for investigation of stability and thermal conductivity of TiO_2 nanofluids. J Nanopart Res. 2013; 15: 1369. doi: 10.1007/s11051-012-1369-4.
21. Wang X, Gordaninej F. Study of magnetorheological fluids at high shear rates. Rheol Acta 2006; 45: 899–908. doi: 10.1007/s00397-005-0058-y.
22. Choi SB. Sedimentation stability of magnetorheological fluids: the state of the art and challenging issues. Micromachines (Basel). 2022; 13 (11): 1904. doi: 10.3390/mi13111904.
23. Taylor CA, Hughes TJR, Zarins CK. Finite element modeling of blood flow in arteries. Computer Methods Appl Mech Eng. 1998; 158: 155–196. doi: 10.1016/S0045-7825(98)80008-X.
24. Kittel C. Introduction to Solid State Physics. 8th edition. New York, NY, USA: John Wiley& Sons; 2005.
25. Ashcroft NW, Mermin ND. Solid State Physics. New York, NY, USA: Holt-Saunders; 1976.
26. Arab Hassani F, Shi Q, Wen F, He T, Haroun A, Yang Y, et al. Smart materials for smart healthcare – moving from sensors and actuators to self-sustained nanoenergy nanosystems. Smart Mater Med. 2020; 1: 92–124. doi: 10.1016/j.smaim.2020.07.005.
27. Socoliuc V, Avdeev MV, Kuncser V, Turcu R, Tombácz E, Vékás L. Ferrofluid and bio-ferrofluids: looking back and stepping forward. Nanoscale. 2022; 14 (13): 4786–4886. doi: 10.1039/D1NR05841J.
28. Hadjivassiliou M, Croall ID, Zis P, Sarrigiannis PG, Sanders DS, Aeschlimann P, et al. Neurologic deficits in patients with newly diagnosed celiac disease are frequent and linked with autoimmunity to transglutaminase 6. Clin Gastroenterol Hepatol. 2019; 17 (13): 2678-2686.e2. doi: 10.1016/j.cgh.2019.03.014.
29. Gu L, Liu Y, Zhang W, Li J, Chang C, Su Y, Yang Y. Novel extraction technologies and potential applications of egg yolk proteins. Food Sci Biotechnol. 2023; 32: 121–133. doi: 10.1007/s10068-022-01209-6.
30. Yilmaz B, Ağagündüz D. Bioactivities of hen's egg yolk phosvitin and its functional phosphopeptides in food industry and health. J Food Sci. 2020; 85 (10): 2969–2976. doi: 10.1111/1750-3841.15447.