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Review article

An overview on properties and applications of magnetorheological fluids: Dampers, batteries, valves and brakes

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ABSTRACT

This paper presents a review of literature that introduces the properties and applications of Magnetorheological fluids(MRFs). first, magnetic particles (iron or cobalt), base fluids(oil (mineral-synthetic) or water), and how to prepare magnetorheological fluids are discussed. Then, in the continuation of this research, considering that magnetorheological fluids are smart and soft liquids, the methods of stability and properties (viscosity, hysteresis loop, Shear yield stress, etc) Of these magnetorheological fluids are discussed. Due to the different properties of Magnetorheological fluids, the behavior of these fluids in different states is discussed. These intelligent fluids change their properties when exposed to an external magnetic field. The most important and obvious feature of magnetorheological fluids is their reversibility from liquid to semi-solid state or vice versa in the Presence or the absence of a magnetic field in a fraction of a second. This change in state and properties is known as the magnetorheological effect. This effect depends on various factors, such as the concentration of magnetic particles, the distribution of magnetic particles, the strength of the magnetic field, additives, and so on. The low magnetic effect and instability of magnetorheological fluids are the most important problems against their widespread use in modern industries. According to research, carbonyl iron particles are the most promising particles for the dispersed phase in MRF. The choice of carbonyl iron particles contributes to their high saturation magnetism, relatively low cost, low coercion, and widespread availability. Finally, according to the different properties and behaviors of these fluids, different applications of magnetorheological fluids are discussed. MRF-based control systems are increasingly used in engineering applications such as rheological magnetic electrolytes in batteries, anti-lock braking systems, magnetic clutches, vibrating dampers, shock absorbers, control valves, and various types of vibrating dampers. One of the newest applications of magnetic fluids is the magnetorheological electrolyte. The use of MRFs in batteries introduces a new class of magnetic field-sensitive electrolytes that has the potential to increase impact resistance, safety, thermal conductivity, and energy storage in electronic devices through reversible active switching electrolyte mechanical properties.

1. Introduction

MRFs were first discovered by Rabinow in 1948 [1,2]. MRFs are a group of fluids whose main characteristic, i.e. viscosity is changed due to an MF. The range of these changes is so extensive so that they are converted from liquid with a linear viscosity to a semi-solid state with very high viscosity. The main cause of these changes is H [3]. These fluids can be controlled, their properties change rapidly in milliseconds because of the MF, and they have good stability and performance in a high-temperature range. Since yield stress of these fluids which corresponds to the applied MF can be controlled, they can also be used to control the vibrations of mechanical systems due to electronic systems [4–7]. These fluids behave as Newtonian fluids when the MF is absent. When the MF is applied, the particles within the MRFs are joined together in long chains, causing abrupt and significant changes in their behavior (Fig. 1). Hence, MRFs are changed to semi-solid materials [7–9].

In recent decades, due to the development of MR technology and its applications in various industries, many studies have been performed on magnetorheological fluids. In a research project, Esmaeilnejad et al. [10] Studied magnetorheological fluids based on carbonyl iron. In this study, they added synthesized magnetite nanoparticles to a carbonyl iron suspension and investigated its amplified magnetic properties using

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a rotary rheometer. In this study, they introduced two models to evaluate the yield stress and shear viscosity in terms of carbonyl iron concentration, additive concentration, and magnetic field strength. Their analysis shows that magnetic nanoparticles increase the deposition stability of carbonyl iron particles and increase the MR properties. Yamaguchi et al. [11] Focused on the rheological properties of a magnetic fluid in a magnetic field. They found that the viscosity and tensile strength of MRFs were significantly affected by the magnetic field and the concentration of metal particles. In research work, Manzoor et al. [12] Studied the increase in MRF efficiency due to two-dimensional hybrid additives (rGO-MoS2). In this study, they synthesized two different types of hybrid additives called non-magnetic rGO-MoS2 and magnetic Fe-rGO-MoS2, using the hydrothermal method. The addition of Fe-rGO-MoS2 to MRF showed 24% higher shear stress compared to rGO-MoS2 to MRF. In this study, they showed that hybrid additives have a significant effect on the stability and efficiency of MRFs.

Shock absorbers [13], vibrating dampers [14], earthquake vibration dampers [15], clutches [16], fences [17] and magneto-rheological electrolytes (MR electrolytes) in batteries [18,19] are the most important applications of MRFs are the most important applications of MRFs [20–24]. Important operational parameters of machines are the fluid rheological behavior, the operational mode of the device, the magnetic circuit design [25], and the shape of the coil [26].

This review article provides a comprehensive study of the properties, preparation, stability, various methods to improve the stability and application of MR fluids. In addition, the behavior of MRF when used in dampers, batteries, valves, and brakes, leading to increased safety, energy storage, cooling, lubrication, etc. is discussed. The application of MRF in modern and contemporary industries is also examined.

2. MRFs combinations

MRFs consist of three constituents: magnetic particles with a volume percentage of 20 to 45%, carrier fluid, and a set of additives. Suitable selection and composition of these components are effective in determining the mechanical properties of the fluid such as the viscosity with no application of the MF, the maximum shear yield stress, the resistance against the sedimentation, and the operating temperature range [27–29].

2.1. Magnetic particles

The maximum attractive force between the particles and, therefore, the maximum fluid yield stress is enhanced with the square saturation magnetization of the particles [30–32]. Iron carbonyl is the most widely used material as a magnetic particle due to its high saturation magnetization [33]. Iron carbonyl is formed by the thermal separation of pentacarbonyl ($Fe(CO_5)$) into 0.1- to 10-μm spherical particles. Its spherical shape is one of the desire parameters due to a reduction in the particle corrosion effect, making its dimensions more durable. These particles are identified and evaluated through the structure of the onion skin on its cross-section and the iron content above 97.8% (Fig. 2) [34]. Iron powder, which is produced by various techniques and so cheaper than iron carbonyl, is also available for MRFs. It should be noted that iron powder particles have a dimension of about 10–100 μm that are larger than that of iron carbonyl. Also, iron powder particles have irregular and non-spherical forms, which have undesired effects on the resistance and durability of powder particles [35]. It has been proved that the presence of particles with irregular shapes leads to a greater viscosity than spherical particles with the same volume fraction [36,37].

2.2. Carrier fluid

The criteria for the selection of carrier fluids are intrinsic viscosity, temperature stability, and compatibility with other composite materials as well as the type of operator equipment [38,39]. The most commonly used carrier fluids are hydrocarbon oils because of their appropriate lubrication, durability, and combination with various additives [40–42]. They can be classified as mineral oils, synthetic oils, or a compound of both. Silicon oils, which are made from mineral oils, can be employed to obtain a wide range of temperature and compatibility with other system components [43,44]. In 1998, Julie et al. [45] reviewed a comprehensive study of the temperature range of various MRFs and their compatibility with the materials of the other related equipment.

2.3. Additives

Various types of additives are used for MRFs. Various purposes such as prevention of the sedimentation and accumulation of particles in the carrier fluid, reduction of the amount of corrosion between the particles, and prevention of the oxidation and loss of particles are the advantages of the application of these additives [46–49]. The most prominent

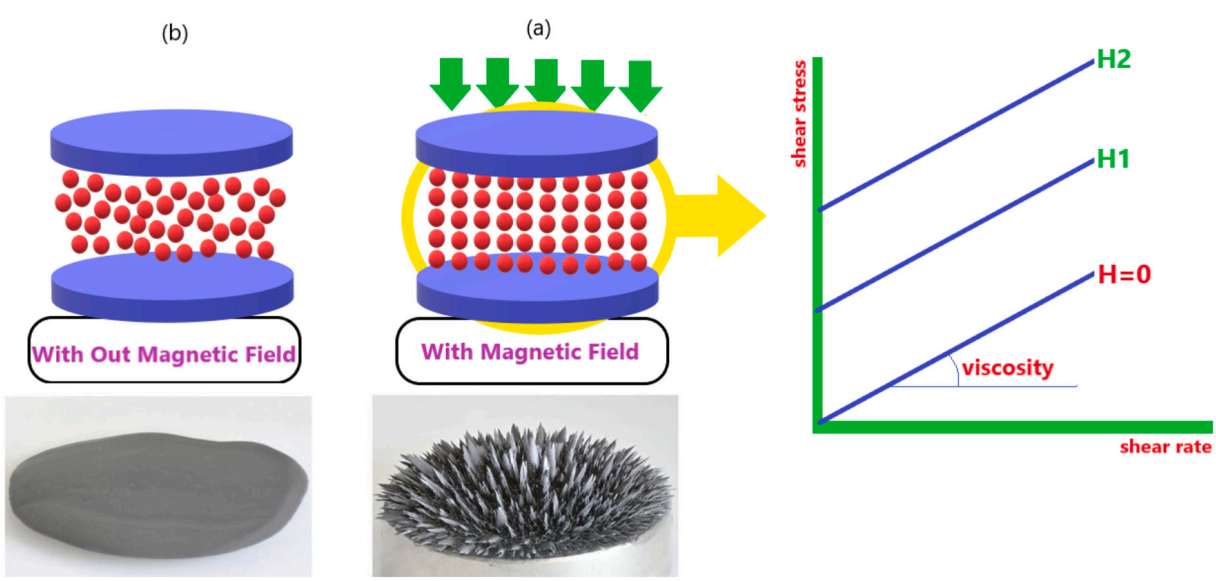
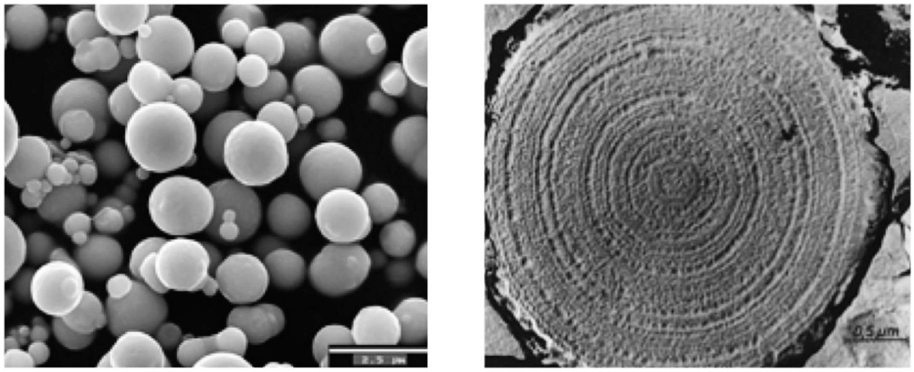


Fig. 1. Mechanical behavior of MRFs: (a) in the presence of a MF, and (b) in the absence of a MF.



(a) (b)

Fig. 2. Microscopic image of iron carbonyl powder: (a) spherical shape of particles, and (b) the onion skin structure of particles [34].

feature of these additives is to strengthen fluid stability and durability. The realization of this purpose has a decisive role in expanding the range of applications of MRFs in industries [46,50]. Hence, in recent years, many studies have been carried out on the development of new additives to improve the quality of the MRFs [43,45].

Sedimentation of suspended particles in MRFs is due to differences in the density of particles and a carrier fluid, which may be associated with the accumulation of particles, which means that the particles stick together when an MF is not applied. This effect can be enhanced due to the magnetic residual particles. Although low-particle sedimentation in systems in which fluids are naturally mixed during the process such as dampers and shock absorbers, is not discussed, in systems such as earthquake dampers, in which the system is rarely active, their accumulation should be avoided as much as possible due to that the rediffusion of these particles is difficult [51,52].

Table 1 summarizes the components of MRFs.

3. Magnetorheological fluid preparation

MRFs are controllable magnetic suspensions consisting of magnetic particles, a non-magnetic carrier fluid, and a stabilizing agent. MRF is prepared by mixing these compounds in appropriate concentrations (Fig. 3). A non-magnetic base fluid (oil) is a carrier medium in which magnetic particles are suspended by stabilizing agents. Stabilizing additives reduce the deposition rate of MR fluid, which is caused by a density mismatch between the magnetic particles and the carrier fluid [53].

To prepare MRF, the base fluid and the surface activator are first mixed with a stirrer. It is worth noting that a small amount of heat must be given to the container to dissolve the surfactant in the base fluid, otherwise the mixing process will be very time-consuming.

Table 1
Components of MRFs [27,28].

MRFs combinations	Materials	Description
Magnetic particles	Iron carbonyl	Occupies 40 to 45% of the total volume of the fluid - having high magnetic saturation capacity - low cost and availability.
Carrier fluid	Hydrocarbon-, silicone- or mineral oils	The carrier selection criterion is based on viscosity, temperature stability, and compatibility with other components of MRFs.
Additives	Greases and high-viscosity thixotropic materials – Nafta Nites - Iron elites and metal soaps such as lithium stearate and sodium stearate	To reduce friction, reduce the amount of sedimentation, prevent oxidation and increase the lifetime of particles.

Due to the fact that magnetic particles are very important for the magnetic effect. To do this, these magnetic particles must be mixed in such a way that they do not accumulate and remain in a homogeneous mixture. A simple and stable MRF is then obtained by dispersing the magnetic particles in the oil using quantitative surfactants to prevent aggregation [54].

Many researchers believe that the dispersion of additives in the carrier fluid leads to the formation of stable MR fluids before the magnetic particles are added to the base fluid (oil) [53].

MR fluid preparation has two phases:

1. Dispersed phase
2. Continuous phase

In the dispersed phase, in addition to the use of ferromagnets, some paramagnets are used. Among the most important ferromagnets used in MR suspension are: iron-cobalt alloy, nickel-zinc alloy, iron-zinc alloy, ceramic alloy [43,55,56]. Also among the most important paramagnets used in MR suspension are iron carbonyl, iron, magnetite, maghemite, chromium [57,58].

Among all the above, iron carbonyl particles have an effective role in reversibility and magnetic effect due to their high magnetic permeability, soft magnetic nature [59], and magnetic saturation [60], and they can be easily magnetized and demagnetized [61,62].

The relationship between concentration, particle size [63,64], and magnetic capacity is a linear one. That is, with increasing the volume fraction and the size of the iron particles, the shear stress of MR fluids also improves. The use of variable size particles shows better results than small and large particles [65].

In the continuous phase, the base fluids (mineral oils, synthetic oils, organic oils, oil combinations, water) are known as the continuous phase [53,56]. In the continuous phase, the properties of MRF depend on the two parameters of base fluid viscosity and particle volume fraction. Because the base fluid is a continuous phase, the viscosity of the base fluid is very important in MRF preparation. For MRF preparation that has the maximum MR effect, the viscosity of the base fluid should be below [50,66,67].

In Table 2, a number of MR fluids are collected along with the constituent particles and the base fluid.

4. MRFs stability methods

MRFs must achieve certain properties that can be presented in industries. These characteristics are appropriate performance at different

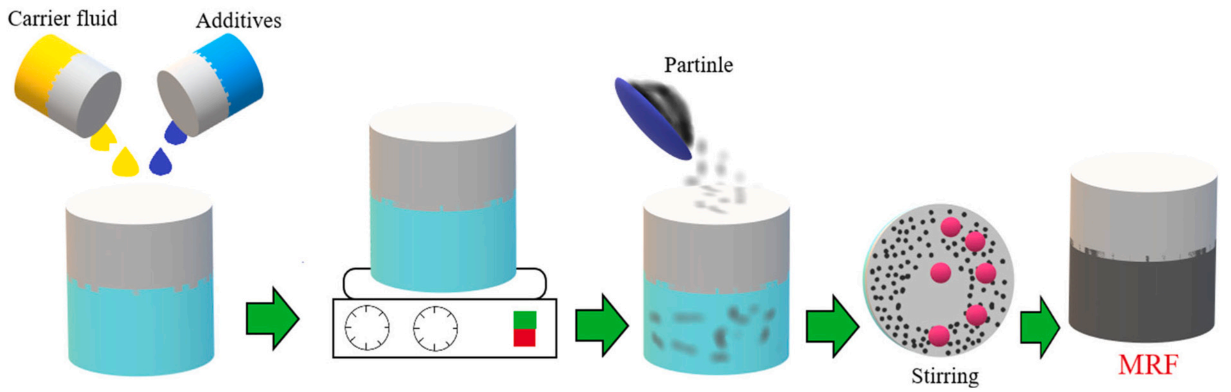


Fig. 3. MRF preparation.

Table 2
Tayp of MRFs.

Particle type with avg. size	Base oil	References
Carbonyl iron (4.5–5.2 μm)	Silicone oil	[131]
Carbonyl iron (7 μm)	Mineral oil	[268]
Carbonyl iron (4.5–5.2 μm)	Mineral oil	[269]
Carbonyl iron (28 μm)	Silicone oil	[50]
Carbonyl iron (44–53 μm)	Mineral oil and silicone oil	[123]
Fe3O4 (120 nm)	YUBASE − 8	[58]
ϒ- Fe2O3 (0.5 μm)	YUBASE − 8	[270]
Fe3O4 greater than 50 nm	Mineral oil	[271]
Carbonyl iron nano-particles (4 nm)	YUBASE - 3	[270]
Carbonyl iron nano-particles (4 nm)	YUBASE - 3	[95]
Co-ϒ- Fe3O4 Ferromagneticferrimagnetic (5 μm)	Silicone oil	[97]
Fe3O4 (10 nm)	Kerosene oil	[272]
Iron nano-particles (30 nm)	Silicone oil/ hydraulic oil	[69]
Magnetite nano-particles (7.8 ± 0.3 nm)	Mineral oil SN-60	[273]
Fe3O4 (100 nm)	Silicone oil	[10]
Carbonyl iron particles (4.5 μm)	Silicone oil	[274]
Carbonyl iron particles (2.57 μm)	Mineral oil	[78]
Carbonyl iron particles (2.57 μm)	Mineral oil	[79]
Carbonyl iron particles (2.57 μm)	Mineral oil	[275]
Carbonyl iron particles (3 to 5 μm)	Silicone oil	[276]
Carbonyl iron particles (4.5 μm)	YUBASE oil	[88]
Carbonyl iron particles (1 to 3 μm)	Silicone oil	[277]
Carbonyl iron particles (1.9 μm)	Methyl SO	[278]
Carbonyl iron particles (4.25 μm)	Silicone oil	[279]
Carbonyl iron particles (5 μm)	Silicone oil	[127]
Iron microwires (260 nm)	Silicone oil	[99]
Iron nanowires Dia. (5 to 250 nm) & Length (7.6 ± 5.1 μm)	Silicone oil	[101]
FeSib flattened shape (20–80 μm)	Mineral oil	[103]
Fe nanowires particles (60–90 nm)	Silicone oil	[67]
Graphene oxide (micron size)	Mineral oil	[280]
Fe3O4/MoS2 2D nanocomposites (0.9–1.7 μm)	Silicone oil	[281]
rGo-MoS2 hybrid particles	PAO	[12]
MRF carbonyl iron particles with (1–10 μm)	Hydraulic oil/MO	[282]
MRF (MRF-132) and EI fluid carbonyl iron particles with (1–5 μm)	Hydraulic oil	[283]
MRF carbonyl iron particles with (3–4 μm)	Ionic liquid	[284]
Coated carbonyl iron particles based MRF	Silicone oil	[285]
Coated carbonyl iron particles based MRF	PAO oil	[286]
Ferrofluid and MRF	Not available	[287]
MRF carbonyl iron particles with (1–4 μm)	MRF-132DG	[288]
MRF	MRF-132DG	[289]
Carbonyl iron particles	Silicone oil	[290]
Magnetite (5 μm), carbonyl iron (4.5–5.2 μm)	Silicone oil	[97]
Carbonyl iron particles (7 μm)	Silicone oil	[75]
Polystyrene (0.5–1)	Distilled water and excess SDS	[291]
Carbonyl iron particles(1–2 μm)	Silicone oil	[292]

temperatures, chemical and sedimentation stability, reversible clotting, and high magnetic saturation. In addition, an MRF must show high and low yield stress in the presence and absence of an MF [6,68]. One of the main challenges in producing MRFs is to prevent particle deposition and accumulation. Sedimentation limits the widespread use of MRFs because of a high-density mismatch between magnetic particles and the carrier fluid. Thus, it is necessary to overcome the gravitational forces between particles for uniform particle distribution and fluid stability [69,70].

The stability and uniform distribution of magnetic particles in MRFs is a major problem, like other fluids that contain suspended particles, especially for high values of φ. There are two methods for determining the amount of sedimentation in MRFs, including measurement of the amount of change in the upper layer magnetic permeability and the laser passage through a column of MRFs [69]. There is no auspicious technique to estimate the stability of MRFs. Ordinary methods for estimating the stability of other fluids that contain suspended particles, such as light scattering and turbidity, are not used to determine the stability of MRFs. In particle fluids, on the other hand, practical methods are based on the use of X-rays and gamma rays but are relatively expensive and complex [71].

Since there is no standard and reproducible method, it is very difficult to determine the number of particles distributed [72,73]. No suitable method for particle redistribution has been proposed. However, several techniques have been modified by researchers to control this problem by changing MRFs compounds, such as [71]:

- Reduction of particle size
- Addition of thixotropic substances, including carbon fiber, silica nanoparticles, and organisms
- The use of surfactants
- Use of viscoplastic fluids
- Use of an emulsion as a continuous phase

Different densities of the particles and the carrier fluid as well as the various particle sizes make the fluid fouling. When sedimentation occurs, the redistribution of particles is difficult due to the magnetic force between the particles [74].

This phenomenon can often be largely modified by using thixotropic fluids and surfactants, including xanthan gum, silica gel, stearate, and carboxylic acids [30]. Therefore, to overcome this problem in the industrial applications of MRFs, special attention should be paid to the components of these fluids.

Erosion is created due to friction between particles in the fluid flow that limits the use of MRFs. One of the most frequently employed particles in MRFs is carbonyl iron. They have an onion-like structure that may be easily altered by friction. Erosion results in irreversible thickening behavior and thus a decrease in the performance of MRFs. Many attentions have been paid to surface behavior to extend the life of MRFs [75].

Some parameters significantly affect the stability and redistribution of particles in magnetic fluids. They include density, shape distribution, and size of particles, magnetic saturation, forced field, base fluid properties, surfactants, antimatter abrasion, MF, and temperature [60,76].

In an experimental paper, Vekas et al. [77] assessed the impact of fluid chemical composition and bipolar particle interactions on the flow characteristics of MRFs. They demonstrated that flow properties are more influenced by chemical composition compared to system and environment. Some restrictions have hindered the extensive use of magnetorheological technology in industries. Deposition and low magnetic impact are the two main magnetorheological questionings.

Some methods that are proposed to enhance the stability and magnetic effect include (Fig. 4):

- the coating of magnetizable particles [55,67,78–88]
- use of spherical nanoparticles [59,89–98]
- use of nanowires [99–103]
- the use of gels or other polymeric fluids [66,104–114]
- use of stabilizing additives [63,115–126]
- etc.

5. Properties of MRFs

MR fluids are known as intelligent fluids because when exposed to a magnetic field, their rheological properties show a rapid change and reversibility from a fluid-based structure to a semi-solid base structure. Until the magnetic field is applied, the fluid has a Newtonian behavior [127,128]. The effect of MR can be controlled by the rheological properties of the magnetic fluid components and the intensity of the magnetic field. The controllable rheological properties of an MRF are directly attributed to the polarity of the suspended particles due to the magnetic field [43]. Each metal particle, in the presence of a magnetic field, turns into a dipole and forms a chain with its adjacent particles that can withstand failure for a certain shear rate, resulting in a semi-solid structure [129]. The interactions between these induced dipoles cause the particles to be in one direction along the applied field and form a columnar structure. The chain-like structure prevents the movement of the fluid and thus increases the viscosity of the suspension. To overcome this chain-like structure by increasing the applied magnetic field, the required mechanical energy is increased [30]. When the cutting rate exceeds a sharp value, the chain structure breaks, and fluid flows. The stress that MRF withstands at this extreme shear rate is called the apparent fluid yield stress [130]. In other words, the yield stress is the maximum stress that can be applied before the MRF continuous current which is a function of the magnetic field [43] and on the other hand the yield stress is linearly related to the volume fraction of the particles and is associated with increased viscoelasticity because viscoelastic environment Leads to increased MRF stability [131]. (Viscoelastic properties of MR fluids are very high Temperature dependent.) [7]. This factor depends on the shape, size distribution [74,78], particle volume fraction, applied magnetic field strength [130], particle interaction, and agglomerate formation [77]. The rheological properties of MRF have been studied by several researchers. According to their study, shear stress is directly related to the intensity of the magnetic field, which increases with increasing current [12].

Fig. 5 schematically shows the arrangement of suspended ferromagnetic particles for four loading positions without stress, pre-yield stress, yield stress and post-yield stress [132].

Thus, fluid shear stress due to the viscosity is determined in a given fluid velocity field of fluid layers. In this case, if a certain MF is applied, the local shear stress of the layers is affected by H and the displacement of the layers requires the overcoming of this component of the shear stress [133,134].

Table 3 summarizes the properties of MRFs.

It should also be noted that, since viscosity is the most effective factor in magnetorheological fluids, the thermal conductivity of these fluids is a function of viscosity. Various researchers (Ding et al. [136], Colla et al. [137], Yang et al. [138], Zambrano et al. [139], Martínez et al. [140], Forero-Sandoval et al. [141]) showed that with increasing volume fraction, viscosity increases and consequently thermal conductivity increases, but the increase in thermal conductivity remains stable after a while even if the viscosity increases. This behavior indicates that the thermal conductivity at high viscosities is almost insensitive. If the magnetic field increases, the viscosity continues to grow but the thermal conductivity remains constant. The explanation for this behavior is based on the assumption that increasing the volume fraction and using the magnetic field significantly form strong chain structures that lead to increased viscosity. On the other hand, when these chains are subjected to shear stress, they partially disappear and reduce the viscosity. Viscosity and thermal conductivity can be related to a dimensionless quantity called the parenthesis number. The researchers showed that [141–144] Prandels decreased with increasing volume fraction and magnetic field strength, increasing and decreasing shear stress.

5.1. Viscosity: independent of the MF

If the viscosity is independent of the MF in the carrier fluid, it is a very important factor in determining the kind of fluid. Since the fluidity

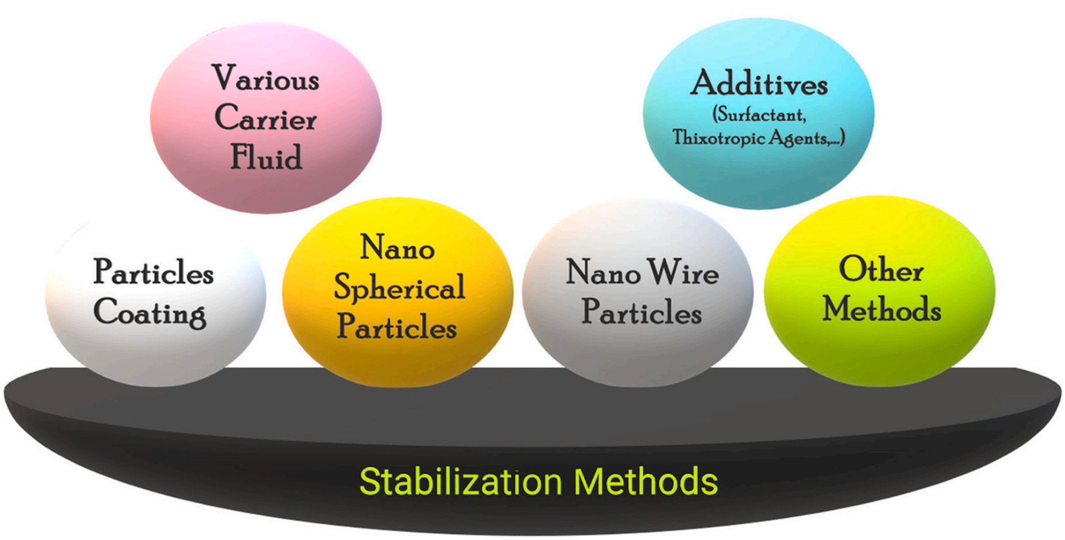


Fig. 4. MRFs stability methods.

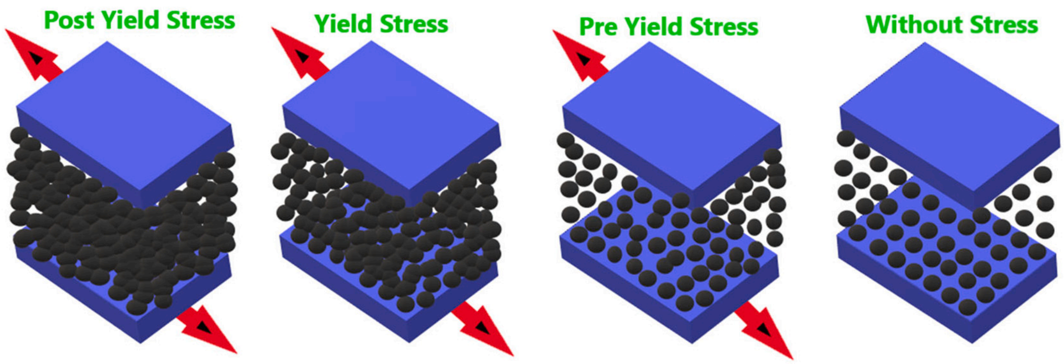


Fig. 5. Particle arrangement in a MF for four different loading conditions.

Table 3
Properties of MRFs [135].

Particulate material	Particle size	Suspending fluid	Density (g/cc)	Off viscosity (mPa-s)	Required field	Field induced changes	Device excitation
Iron, ferrites, etc.	0/1–10 μm	Nonpolar oils, polar liquids, water and other	3–5	100–1000	~3 kOe	$\tau_y(B)$~100 kPa	Electromagnets or permanent magnets

Table 4
Some general properties of magnetorheological fluids.

Property	MRFs
Response time	ms
Plastic viscosity	0.2–0.3 Pa.s
Operation temperature range	-40-15 C
Maximum current	250 kA/m
Required power	2–25 V 1–2 A 2–50 W
η/τ_y^2	$10^{-10} - 10^{-11}$ s/Pa
Density	$3 \times 10^3 - 4 \times 10^3$ kg/m^3
Maximum energy density	10^5 J/m^3
Stability	Without affecting more impurities

Table 5
MRF dampers.

Type	Improved method	Ref
Piston type damper with flow mode.	Integrating four axial fan-shaped magnetic poles on magnetic core to enhance output performance.	[185]
Piston type damper with flow mode.	Optimizing magnetic field distribution.	[186]
Piston type damper with squeeze mode.	Integrating the characteristics of pumping hydraulic damper and MR valve with squeeze mode.	[187]
MA MRF type damper with flow mode.	Proposing a structural control element for high performance of control system.	[188] [189] [190]
Blade valve type damper with flow mode.	Combining blade and two MR valves with parallel plate damping channel in compact structure.	[191]
Integrated shock absorber with flow and shear mode.	Combining inerter, damper and spiral spring to realize adjustable inertance and damping characteristics.	[192]
Piston type damper with flow mode.	Optimizing structure design parameters.	[193]
Piston type damper with shear mode.	Utilizing ferromagnetic and paramagnetic materials to adjust damping Coefficient.	[194]
Combined dampers with shear mode.	Assembling drum-type damper and disc-type damper.	[195]

Table 6
MRF brakes.

Type	Improved method	Ref
Disc type brake with shear mode.	Coupling multiple brakes to conduct the torsional forward of snake-like robot.	[187]
Disc type brake with squeeze and shear mode.	Adopting an automatic squeeze and shear mode to improve the torque output.	[218]
Disc type brake with squeeze and shear mode.	Using squeeze-shear mode and water-cooling way simultaneously to improve the brake performance.	[219]
Multi drum type brake with shear mode.	Designing a hollowed casing structure to fill with actuator.	[220]
Rotary micro brake with shear mode.	Combining with turbine generator with compact structure.	[221]
Piston type brake with shear mode.	Combining MRF and baffle with simple structure to control the electronic joystick.	[222]
Permanent magnets and coil type brake with shear mode.	Using permanent magnets to absorb MRF to reduce the energy loss caused by zero field viscosity.	[223]
Multi-coil type brake with shear mode.	Adopting three coils on each side of the brake housing to improve magnetic field Strength.	[224]
Multi-drum type brake with shear mode.	Adding the number of layers in the drum to increase the working area of MRF.	[225]
Multi-pole-and-layer type brake with shear mode.	Using two layers structure with six pairs of coils to improve magnetic field strength.	[226]

Table 7
Overview of primary and secondary batteries [234–236].

Primary batteries	Secondary batteries
Low internal resistance	High internal resistance
Reversible chemical reactions and complex design	Higher capacity and smaller design
Made from liquid or molten salt.	They are dry (with paste instead of liquid), which makes them resistant to leakage.
They are suitable for portable devices due to their light weight and small design.	Not suitable for portable devices.
Good charge maintenance	Low charge maintenance
Not suitable for costly applications.	Highly recommended for cost support and applications.
Limited to specific applications.	Due to the great variety, they have a wide range of applications.
Low initial cost	High initial cost

of the material changes with temperature, the impact of the viscosity on temperatures, forces, and resistance momentums of the MRFs is due to the temperature conditions [145].

MRF viscosity is mainly influenced by the natural viscosity of the carrier fluid and the volume fraction of suspended particles. An increase in the volume fraction of particles enhances the fluid viscosity. At room temperature, the MRF viscosity range is from 50 mPa.s to 200 mPa.s [33].

5.2. Shear yield stress

Due to the direct effect of the shear flow stress, which is related to the applied MF, on the control of the amount of force or torque generated in the systems of the MRF, determination of the variations of this type of stress indicates the variations of the force or torque [146].

Since the particle type affects the amount of magnetic saturation in an MF, its proper choice affects the maximum shear yield stress [30,147]. The second factor affecting the generation of maximum shear yield stress is the volume percentage of magnetic particles in the solution. Rabinow in 1948 [1,2] proved that an increase in the φ enhances the torque output from the magnetorheological clutch. Many scientists have investigated this feature [148,149]. It was shown that the maximum shear yield stress is enhanced with particle size [97,150]. The fluid viscosity increases in the absence of an MF by increasing the volumetric percentage of magnetic particles in the fluid (Fig. 6) [150], reducing the range of dynamic potentials, i.e. the ratio of the maximum force or the torque with and without the MF.

Another way to enhance the maximum yield stress is to intensify the size of the suspended particles in the MRF. The advantage is that the viscosity can be lower for the same percentage of the particle size [151]. One particular case of this method is the use of the distribution of two groups of particles, in which two groups of particles are combined with different sizes [150,152,153]. As shown in Fig. 7, the increment in yield stress can be obtained with a slight enhancement (about 25% by weight) in the small particle ratio. It can be argued that the presence of smaller particles among coarse particles causes associate particles to be found in tightly arranged chains.

Fig. 8 shows the yield stress in terms of H for MRFs of Lord *Co.* [154] and the ISC Co. [155].

This figure reveals that different formulations of MRFs exhibit different behaviors by changing the percentage of particles. In addition, the difference between the results of Lord Co. and the ISC *Co.* can be related to how tests are performed to measure the yield stress. For fluids produced by the Lord *Co.*, the yield stress begins to saturate for H higher than 250 kA/m because the increase in the H does not have much effect on the shear stress.

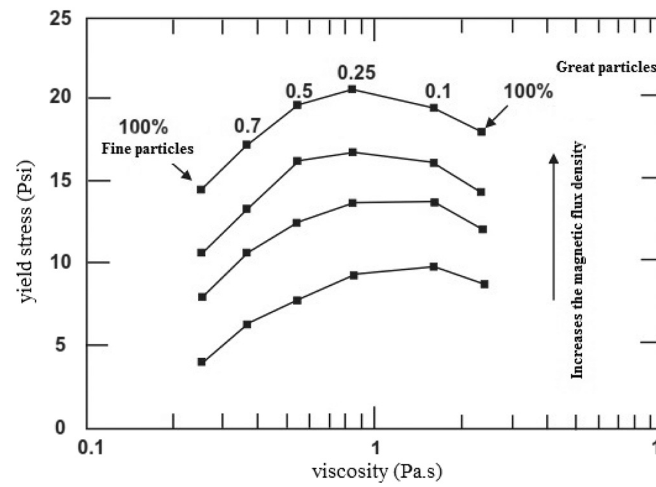


Fig. 7. Maximum yield stress versus viscosity for the formulation of two different classes (constant weight percentage of total particles 25%) [150].

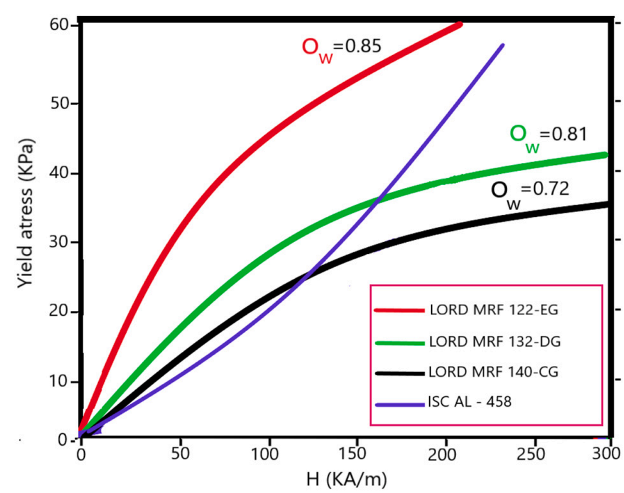
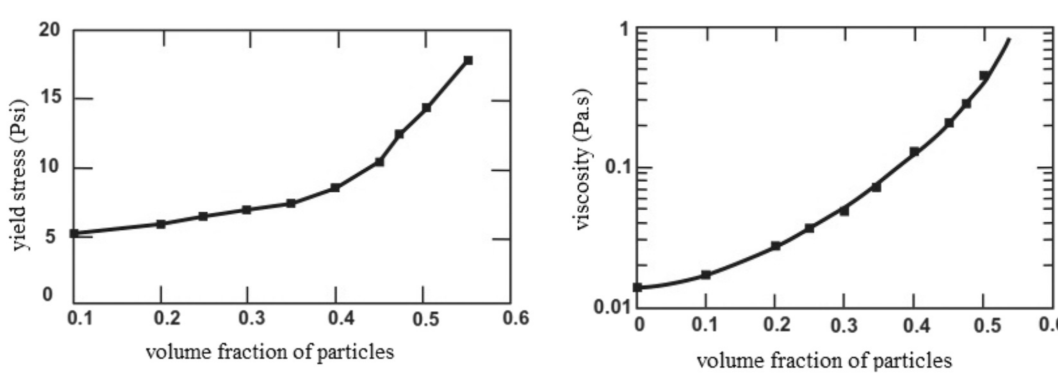


Fig. 8. The maximum yield stress versus the MF (is particle weight percentage) [155].

5.3. The hysteresis loop (B—H curve)

A hysteresis loop (HL) has much information about the magnetic characteristics of matter. This loop can be expressed in terms of the



(a) (b)

Fig. 6. (a) The maximum yield stress versus the volume fraction of particles (under the B of 1 Tesla, (b) the viscosity versus the volume fraction of particles [150].

relationship between the magnetic flux density (B) and the intensity of the MF (H) and is usually referred to as the B—H curve [110]. The material with a wide HL has low permeability, high residual flux density, high magnetic resistivity, and high strength. In contrast, a narrow-HL material has opposite properties. A sample of an HL for a ferromagnetic substance is shown in Fig. 9 [156].

The dashed line drawn in Fig. 9 shows the magnetization of a ferromagnetic substance that does not have any magnetic properties until it reaches magnetic saturation. The points S and S′ express the magnetic saturation values on the positive and negative sides of the H axis. When the value of H approaches zero, the curve moves from point S toward point B_r. At this point, some amount of B remains. This remaining field of B_r is called residual magnetism. When the value of H is placed on the negative side, or in other words, H is stored, the curve moves toward $-H_c$ when B is zero. With increasing H in the negative direction, the material is saturated magnetically and reaches a point of S′, while the magneto force increases in the negative direction. On the opposite side, when H returns to zero, the curve moves from the point S′ to the point $—B_r$. The value of B_r on both sides is equal. The curve moves toward H_c at a zero value of B when H is positive. A further increase in H leads to the return of the curve to the point S and the loop is completed [156].

Fig. 10 shows the HLs of the solid and soft magnetic materials. The shape and size of the HL depend on the type of material. If the material is easily magnetized, the loop is narrow. But if the material is not easily magnetized, the loop is broad. In addition, various magnetic materials are saturated under different amounts of B, affecting the height of the loop. The area of the loop depends on the maximum magnetic density generated in the material [157].

5.4. Fluid properties

Performing the first stability tests on magnetorheological operators at the end of the 1990s shows that the fluid will be thicker if MRFs are exposed to high shear stress and high shear rate for a long time [52]. This phenomenon, called In-Use-Thickening (IUT), is explained by the fact that the repeated use of a specific magneto-logical fluid with its specific preparation results in the corrosion and destruction of fluid particles. This leads to the conversion into a thick paste with very fine particles that loses its capability to control the force and momentum due to its high viscosity. This is especially true for iron carbonyl particles that have an onion-skin structure. The use of higher hardened particles or the use of 3 to 5% anti-corrosion additives are solutions for this phenomenon [151]. In Table 4, some general properties of MRFs are summarized [158,159].

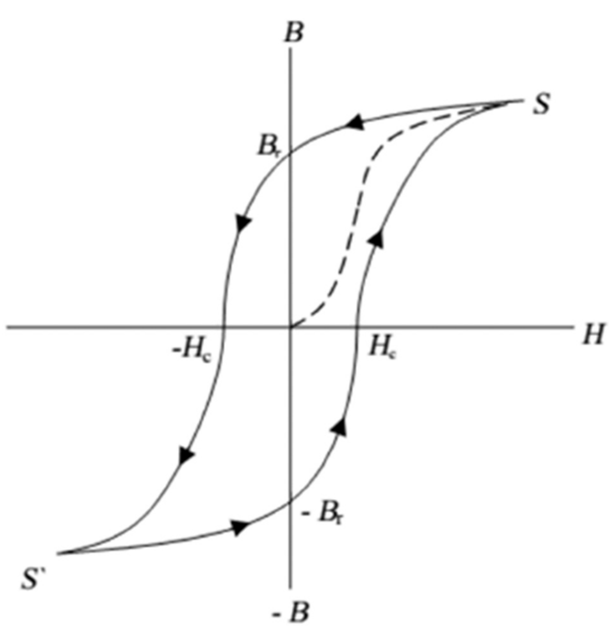


Fig. 9. B in terms of H [156].

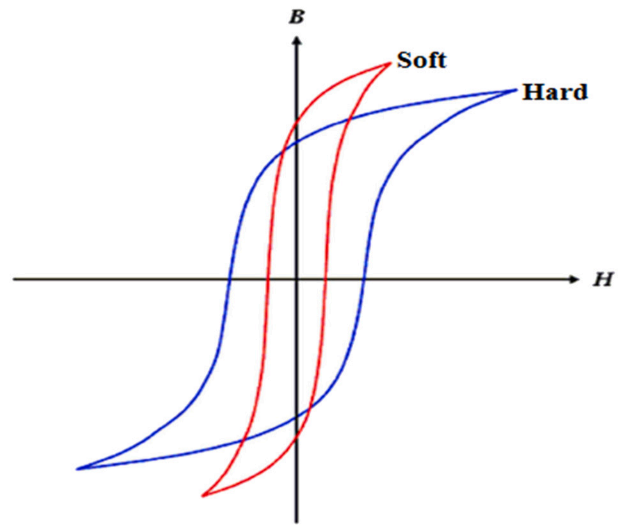


Fig. 10. HL for soft and hard magnetic materials [157].

6. Magnetorheological fluid behavior

The behavioral effects of these fluids (Fig. 11) depending on their applications are as follows [104,160–172]:

6.1. Magnetorheological fluid behavior in shear mode

The fluid is mounted between the two moving plates and the direction of the applied MF is perpendicular to the plates (Fig. 12). In this case, the shear yield stress that depends on H changes against the relative motion of the plates [43,104,160–172].

6.2. Magnetorheological fluid behavior in the valve mode

The fluid flows through the walls of a valve and the MF is applied perpendicular to the direction of the fluid flow. Suspended particles in the liquid that are aligned along the field resist the fluid flow and change the actual cross-section of the flow by varying H (Fig. 13) [25,97,104,150–159].

6.3. Magnetorheological fluid behavior in squeeze-flow mode

This mode is used to make a small-displacement change. The fluid is located between two plates that can move in a vertical direction relative to each other. By applying an MF in the vertical direction on the plates, the magnetic particles enter a force on the plates by the formation of chains in the direction of the field. They significantly apply the force on the plates and move them slightly to each other (Fig. 14) [43,104,160–172].

7. Magnetorheological fluid applications

Potential applications of MRFs are in the devices that require rapid, continuous, and reversible changes in rheological properties [30,173]. Magnetorheological devices have received a great deal of attention in recent decades because the magnetic fluid puts the mechanical devices in direct contact with an electronic system, making it possible to continuously determine the mechanical properties of the devices. Some of these devices that use MRFs are a new generation of dampers,

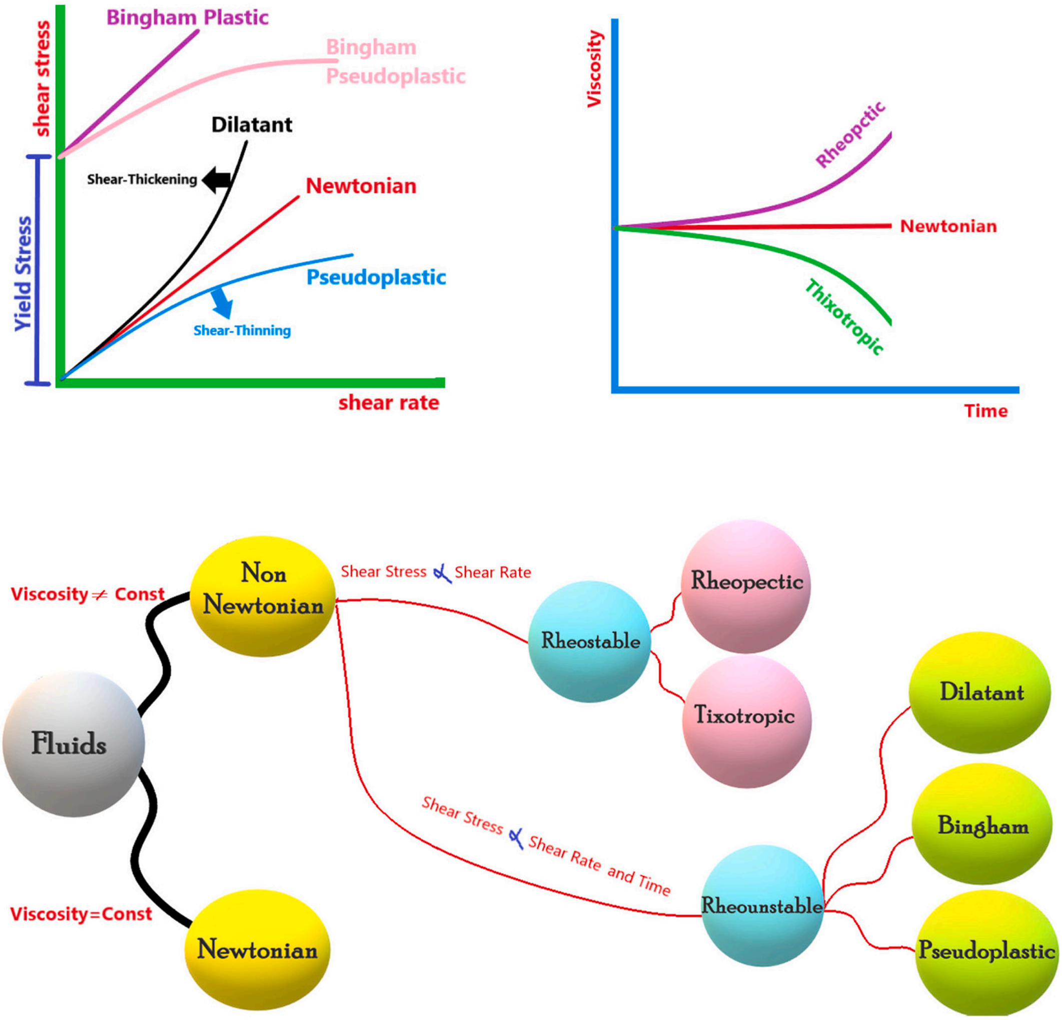


Fig. 11. Fluid behavior.

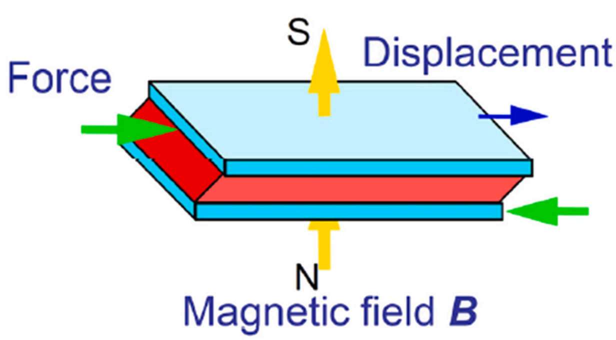


Fig. 12. MRFs behavior in shear mode [43].

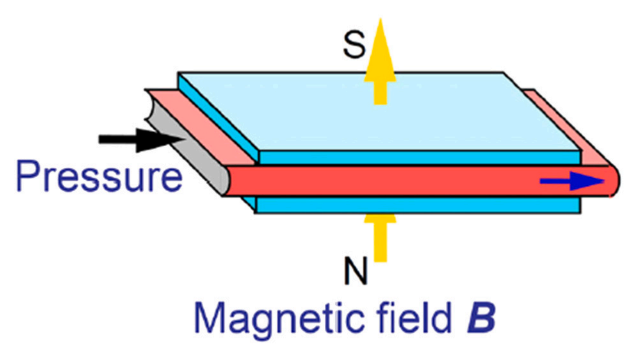


Fig. 13. MRFs application in valve mode [43].

clutches, and brakes. Magnetic dampers are the most widely used such devices, especially as shock absorbers [49,174]. power steering pumps, Control valves, artificial connections, alternators, chemical sensor applications, and others are some of these examples [7,106].

7.1. Dampers

Magnetorheological dampers can be used in active vibration control systems. Such equipment that can produce large damping with low power consumption is known as other types of active control dampers such as electrorheological dampers. Due to the mechanisms used in their design, there are several types of magnetorheological dampers [175]. In general, according to the practical conditions of magneto-optical fluids, four different categories of magnetorheological dampers can be classified.

7.1.1. Magnetorheological dampers in valve mode

These types of dampers, which are used for reciprocating motion in linear paths, usually have a piston-cylinder arrangement (Fig. 15). The duct that is designed for fluid flow through a two-cylinder enclosure is controlled using an MF. According to their structure, they can be divided

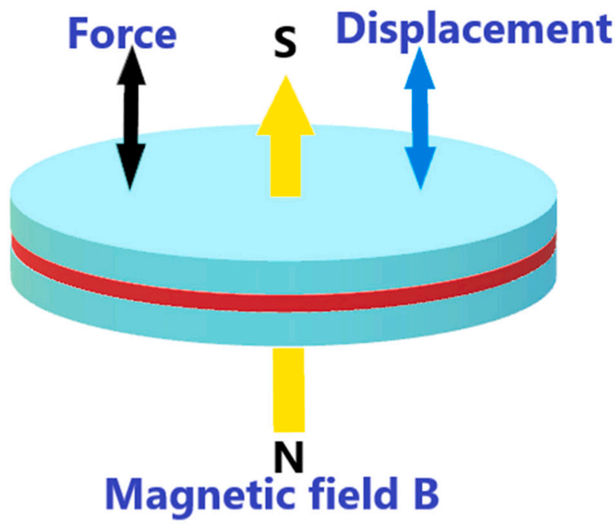


Fig. 14. MRFs application in squeeze-flow mode [43].

into two types of one-way and two-way dampers [175–179].

7.1.2. Magnetorheological dampers in shear mode

These dampers originally consist of an enclosure, an electromagnet, a shaft bar, a disk, and an MRF. When the shaft turns into the vibration rotationally, the connected disc moves and the resistant shear stress applied by the MRFs causes the loss of vibrational energy [181,182].

7.1.3. Magnetorheological dampers with the combined effect of valve and shear modes

This type of damper has a structure like a valve one. The difference is that there is a distance for fluid flow between the cylinder and piston (winding). In such mechanisms, there are two walls at the fluid passage between the two-cylinder space, one on the cylinder and the other on the piston. They move due to the motion of the piston relative to the cylinder. These types of dampers are still divided into one-way and two-way piston rods [183].

The motion of the piston causes the fluid to move, leading to the generation of shear stress in the space between the piston body and the cylinder. The rewind may be wrapped on the piston or cylinder wall. For a one-way piston damper, the volume that is changed due to the piston motion must be considered in the calculations. For a two-way piston damper, the fluid volume set on both sides of the piston is always constant and there is no need to compensate for the volume as it is common for one-way mechanisms. This damper is used to study earthquake response control as semi-active in buildings.

7.1.4. Magnetorheological dampers in squeezed mode

This damper with a very low response time is used for active simultaneous control in many industrial applications. This damper operates with a low motion of a disk or a suspended steel plate in an MRF. The main control is axial motion, but there are also lateral and rotational motions [178,179,181–184]. Following Table 5, the types of dampers and their improvement methods are presented

7.2. Valves

One type of control valve is the magnetorheological control valve [196], which uses a new intelligent material called magnetorheological fluid, as the working environment [197–199]. magnetorheological control valve with simple structure, simple operation and fast response without relative movement between parts is widely used in hydraulic systems in different sizes. Actually When an MRF passes through a valve, an MF is applied to the fluid, increasing the fluid viscosity. This change in viscosity causes resistance to fluid flow through the valve. Thus, the inlet pressure increases and the fluid flow decreases or stops completely. There are many studies on the cyclic structure of the MR valve [200–203]. In summary, all MR valve researchers examined the MR fluid path inside the valve based on three criteria: placement of the coil in the valve, the number of permanent coils or magnets engaged in a valve, and the geometric arrangements of the MR fluid path inside the valve [204–209].

7.3. Brakes

A magnetorheological brake is a device used to transmit torque. A rotating magnetorheological brake can change the braking torque quickly in the presence of an MF. Simplicity and ease of control make the MRF be a very cost-effective choice for a wide range of applications [91,92].

Magnetorheological brakes consist of MR fluid between the rotor disk and the fixed chamber with an electromagnetic coil embedded in the chamber. When the brake is to be applied, current flows through the

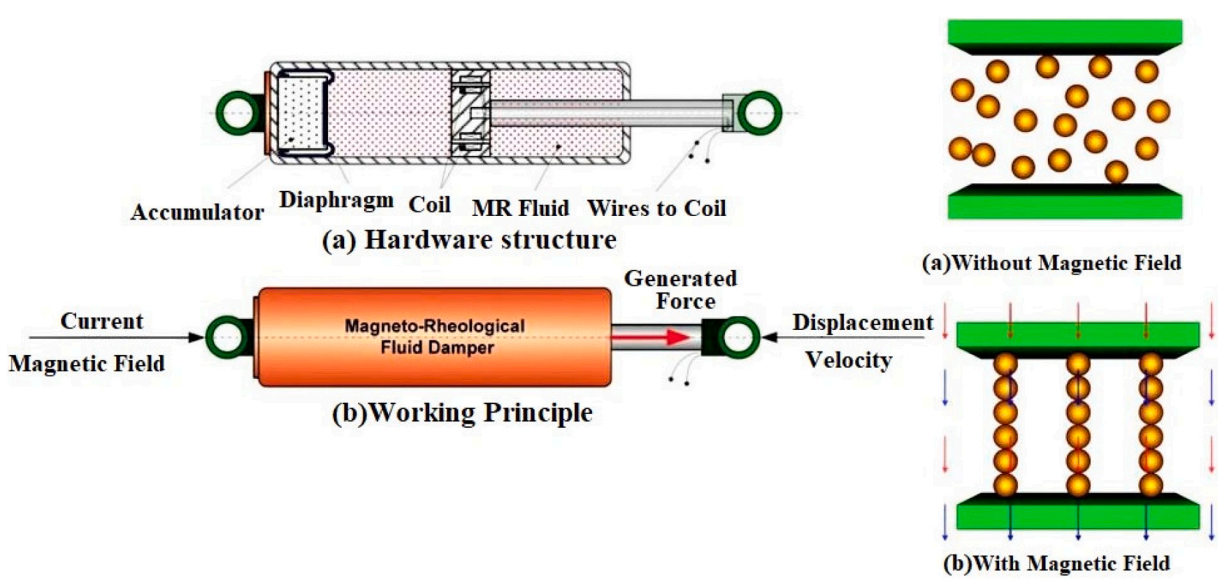


Fig. 15. Magnetorheological linear damper [180].

brake coils, creating a magnetic field around it, which changes the viscosity of the MR fluid, resulting in braking on the rotor surface. Much research has been done on MR brakes in the recent past because these brakes have the potential to overcome the shortcomings of friction brakes. Various configurations of MR brakes such as single disc brakes, multi-disc brakes, drum brakes, reverse drum brakes and T-shaped rotor brakes with different coil designs have been designed by many researchers (Table 6). However, compact single-disc MR brakes are lighter in weight and very easy to make [210–217].

7.4. Batteries

Quite simply and clearly, the battery can be defined as a cell or a chemical power pack, which, when needed, converts chemical energy into electrical energy by performing chemical reactions within itself. In the battery, the mechanism of electron transfer is in the form of chemical reactions in which the electron moves from one side to the other, and by changing these reactions, the type of battery changes, which can even be made a rechargeable battery with the help of reversible reactions. That works for us for several years and does not need to be replaced, while if we use materials whose electron transfer reaction is not reversible, the built-in battery will be a non-rechargeable battery and will need to be replaced. The reversibility of a reaction means that the reaction in the opposite direction can also be performed [227–230].

Batteries can be classified according to their structure (Fig. 16) [231–233]:

According to Fig. 17, primary batteries or primary cells are disposable and can not be recharged from any external source. This type of battery shortens its useful life if it is polarized. Chemical degradation is used to prevent battery life by reducing the effect of polarization; In this way, hydrogen is oxidized with water by adding an oxidizing agent to the cell. The applications of primary batteries include various items, such as watches, toys, small appliances, personal computers, inverters, essential portable lights, and so on. The types of primary batteries are shown in Fig. 17 [234,235].

According to Fig. 17, secondary batteries are the same as rechargeable batteries and are reusable. Rechargeable batteries generally cost more than disposable batteries, but the total cost of ownership and environmental impact of these batteries is lower, as they can be recharged and reused several times before replacement. Applications of secondary batteries include various items such as smart gadgets, such as health bracelets and smartwatches, military applications and submarines, medical equipment, cameras, and artificial pacemakers, and so on. The types of secondary batteries are shown in Fig. 17 [236]. Also, according to Table 7, the primary and secondary batteries are briefly compared.

Also, according to Fig. 17, fuel batteries source their active ingredients from external sources so that they generate electrical energy if the active ingredients are fed through the electrodes. In this battery, the proton exchange membrane uses hydrogen gas and oxygen as fuel. The reaction takes place inside the cell and results in the production of water, electricity, and heat. This type of battery consists of anode, cathode, electrolyte, and catalyst. This type of battery is used in transportation, including cars, buses, and other motor vehicles, and for backup to generate electricity during power outages. Fuel batteries have many advantages, including the following [237–239]:

- The process of direct conversion of chemical potential energy into electrical energy prevents thermal blockage.
- This battery is convenient and very safe due to the lack of moving components.
- Due to the production of hydrogen in an environmentally friendly manner, it causes relatively less damage to the environment than other cages.

Batteries have different lifespans depending on the structural specifications and the type of use.

Each battery has two different parts, which are:

1. Battery compartment or cover: Batteries need a way to hold their various components together. Covers are the only mechanical structures intended to hold the internal components of the battery. Battery covers can be made with almost anything. Plastic, steel, soft polymer foil bags, etc. are the materials used to make battery covers. The battery compartment must be resistant to corrosion from inside and outside and therefore must be resistant to chemical attack by the electrolyte, active ingredients, and the environment at operating temperature [240].
2. Cell: The main part of the battery that provides the necessary electrical energy is called the cell. The battery cell consists of three main components: the positive electrode (Cathode), the negative electrode (Anode), and the electrolyte [241–243].

✓ **The negative electrode (Anode):** is an electrode in which an oxidation reaction takes place and in fact, it is an electrode that gives electrons.

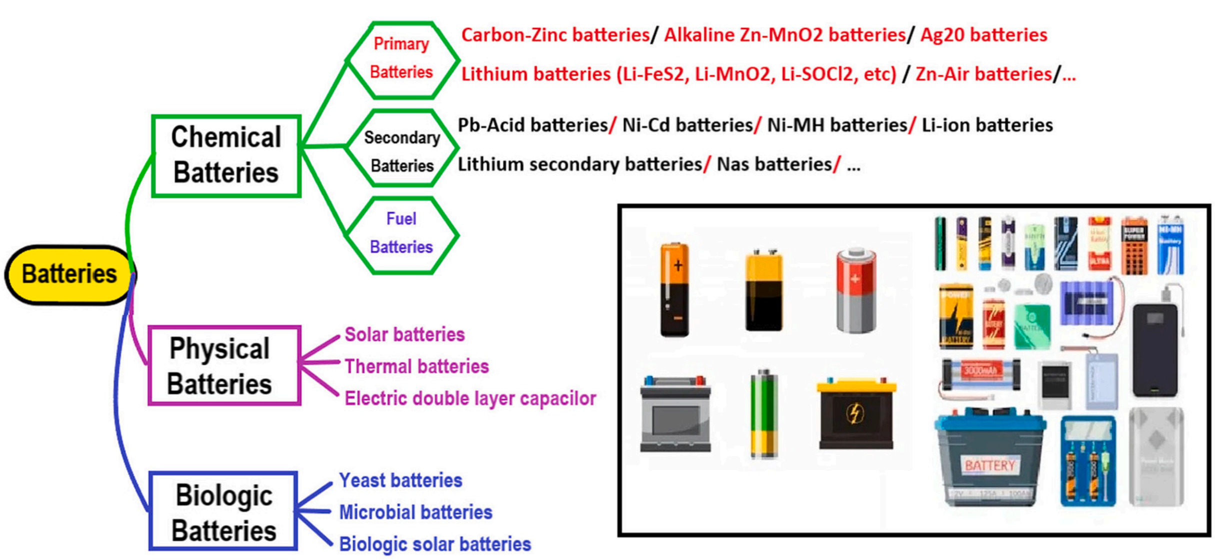


Fig. 16. Battery Categories and Type.

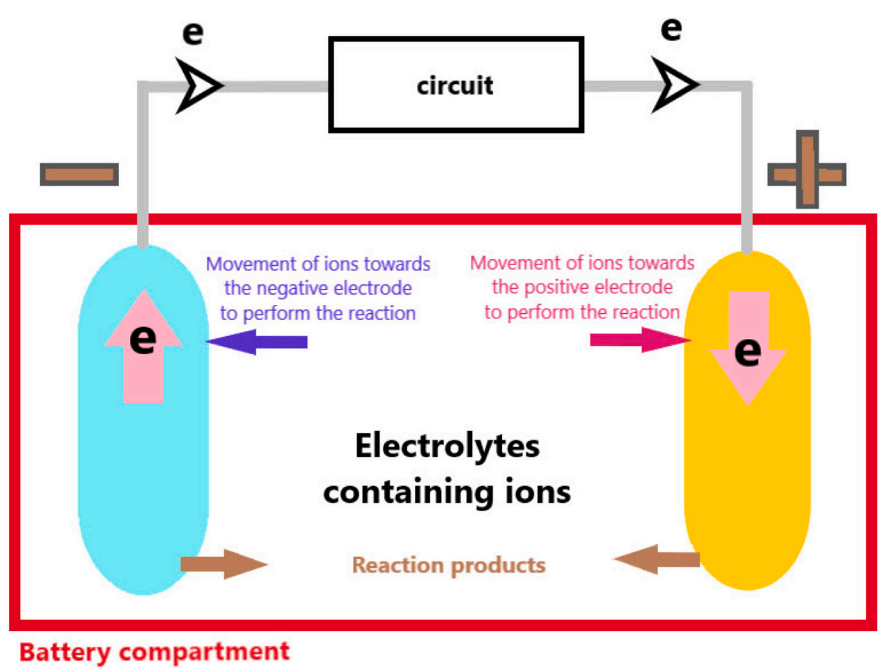


Fig. 17. Schematic inside the battery.

- ✓ **The positive electrode (Cathode):** is an electrode in which a reduction reaction occurs and is an electrode that receives electrons.
- ✓ **Electrolyte:** This substance can transfer ions between the reactions occurring at the anode and cathode. The electrolyte also blocks the flow of electrons between the anode and the cathode. This makes it easier for electrons to flow in the external circuit.

Also, to isolate the cell from the outside environment and also to provide safety and ease of use, the cell is placed inside an external case made of metal or plastic. In this outer package, there are two electrodes, one with a positive pole and the other with a negative pole, which is connected to two internal electrodes of the cell [243].

The electrolyte is very important and vital in battery performance and therefore energy storage devices need a reliable electrolyte environment [23]. Liquid electrolytes provide better power than solid electrolytes and are widely used in batteries and supercapacitors [24,244,245], but the use of liquid electrolytes causes many safety problems because liquid electrolytes are very susceptible when exposed to air [246,247]. They are flammable and unstable. Subsequently, solid electrolytes are opposed to liquid electrolytes [248–250]. Solid electrolytes have better environmental stability than liquid electrolytes and have higher impact resistance [251,252]. In fact, in solid electrolytes, the conductivity decreases dramatically with increased mechanical strength. This is one of the reasons for not using solid electrolyte technology. Therefore, due to the drawbacks of using liquid and solid electrolytes, there is a class of electrolytes as magneto-rheological electrolyte (MR electrolyte), which has led to a new perspective on batteries. MR electrolytes are made by combining magnetic nanoparticles with a silica coating in ionic liquids. These MR electrolytes have a low viscosity when there is no magnetic field, but as soon as they are exposed to the magnetic field, they change phase from liquid to solid (gel), which leads to an increase in viscosity (Fig. 18). It is noteworthy that during the application of an external magnetic field, the MR electrolyte conductivity is maintained despite the increase in viscosity. Therefore, it can be concluded about MR electrolyte that by applying a magnetic field and increasing viscosity, in addition to maintaining the MR electrolyte conductivity, so the impact resistance is increased and the use of magnetic liquid electrolyte will be very safe. Batteries that have an MR electrolyte have better performance and efficiency than other batteries in terms of conductivity and safety [253].

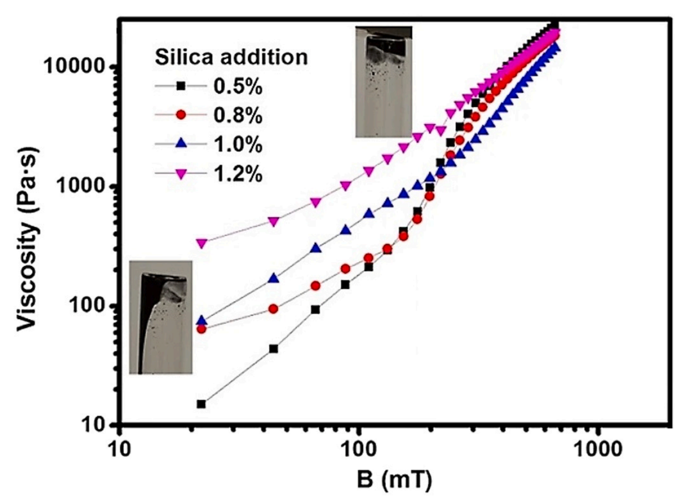


Fig. 18. Increase viscosity with the increasing magnetic field [253].

Of all batteries, lithium-ion batteries (LIBs) are currently the fastest-growing segment of the global battery market and the preferred electrochemical energy storage system for portable applications. Lithium-ion batteries (LIBs), as an alternative energy storage technology, can play an important role in moving fossil fuels without emitting greenhouse gases [254].

Since energy storage devices require a reliable electrolyte environment, the use of MR electrolytes in lithium ion batteries has a high durability [105] and improved stability [255] because their base fluid is ionic liquids. Ionic liquids are materials that are fluid at ambient temperatures [255,256] and are widely used in energy storage devices due to their low vapor pressures, thermal stability, and non-flammability [257–259].

Magnetism is one of the most influential parameters on this type of battery that can affect electrochemical reactions by changing the properties of the electrolyte, electrode kinetics, mass transfer, and sediment morphology by applying a magnetic field. Proper control of these magnetic forces can lead to higher performance of lithium-ion battery structures and the development of innovative concepts [260–262]. In general, the use of MR electrolyte in lithium-ion batteries controlled by a magnetic field can provide more impact resistance and leakage prevention for energy storage devices, while having little effect on MRE conductivity and electrochemical performance of the device. In addition, the external magnetic field makes it possible to improve the charge/discharge behavior of lithium-ion batteries by adjusting the lithiation/removal process [263,264].

7.5. Other applications

Other applications of MRFs include:

- Military industries: to damp the mechanical impact resulting from the propulsion of a projectile in weapons such as balls and other light and heavy weapons [158].
- Medicine: to control the torque from joints in artificial prosthetics of the body, such as knee prosthesis, ankle prostheses, etc., magnetic imaging for the diagnosis of diseases (cancer), drug delivery to specific parts of the body (diabetes), and the removal of cancerous tumors by thermal therapy [132].
- Car design: the design of suspension systems, brakes, clutch, etc. to improve maneuverability and safe driving speed, improve stability, reduce the risk of left-turning, and reduce boring of the driver and occupants [158].
- Industrial machinery: to prevent unwanted vibrations in industrial machinery [158].
- Design of home appliances: damp vibrations in appliances such as washing machines, dishwashers, etc. [4,158].
- Design of robots: for precise and rapid control of joints in robots [158].
- Polishing: Cleaning and polishing of the optical surfaces with high precision [265,266].
- Auto mechanic: Low space occupancy, high lifetime, and high efficiency of MRF dampers have made this technology one of the best alternatives to existing suspension systems in automobiles [158].
- Art: Make attractive and impressive advertising fountains and displays [4].
- Heat transfer: continuous change of MF on a fluid containing metal particles causes a new phenomenon called the thermomagnetic heat transfer. This kind of heat transfer is used in microchannels and situations where conventional methods of heat transfer are not suitable [4].
- The optical polishing that was first developed by Kordonsky et al. [160] is another important application of MRFs [267]. These fluids contain a non-magnetic abrasive material, resulting in that the surface of the material is removed under high shear rates. The most commonly used abrasive/carrier material for optical polishing of glasses and crystals is the oxidation of cyanide/water. Abrasives such as alumina and diamonds are used for materials other than glass.

8. Current scenario and future scope

Science and technology are changing rapidly, and the use of intelligent materials is the solution to many complex engineering problems. One of these smart materials is magnetorheological fluid. This fluid can change viscosity and become semi-solid under the influence of an external magnetic field. Due to its extensive magneto-rheological fluid properties, it is used as a solution to many engineering challenges in various fields. The deposition and formation of a hard mass of magnetic particles limit the response of the magnetorheological fluid to the magnetic field and can lead to the failure of the device containing the magnetorheological fluid; Therefore, more attention has been paid to the methods of sediment reduction and the factors affecting it to expand the application of magnetorheological fluids. So far, a lot of research has been done on magnetic nanoparticles, biocompatible base fluids, and surfactants to reduce this problem. One of the parameters that strongly affects the properties of MRF is the affinity of iron carbonyl particles and the carrier fluid, which should be carefully considered.

Since the discovery of MR fluids, finding a new suspension composition that is more robust and cost-effective is still essential.

Due to the use of this fluid in various industries, it is necessary to know and obtain the properties and parameters affecting it. Future area MRF in various industries such as military industries (light and heavy weapons), medical industries (knee prostheses, ankle prostheses, magnetic resonance imaging to diagnose diseases (cancer), drug delivery to certain parts of the body (diabetes)) Used in the automotive industry (brakes, clutches), industrial machinery, home appliance design, robot design, polishing, art, heat transfer, battery cooling, battery electrolyte, and energy storage. Magnetorheological electrolyte dramatically changes the safety, conductivity, and impact resistance of batteries, so the use of magnetic electrolyte in batteries is very beneficial.

9. Conclusions

MRFs are intelligent materials in which the suspension of magnetic particles (iron-cobalt alloys and sometimes manganese and nickel nanoparticles) in a base fluid (hydrocarbon or silicone oils) with stabilizing additives represent the behavior of a semi-solid in the presence of a magnetic field. Two major challenges in the field of MRFs are the reduction of the deposition of magnetic particles due to gravity and the acquisition of high yield stresses (strong magnetic effect). The main reason for these two challenges usually depends on the type, shape, size, and volume fraction of magnetic particles, which significantly affects the rheological properties of these fluids. To select the type of magnetic particles, special attention should be paid to various factors such as stability, the effect of MR, compatibility with the base fluid, etc. However, according to research, carbonyl iron particles are the most promising particles for the dispersed phase in MRF. The choice of carbonyl iron particles contributes to their high saturation magnetism, relatively low cost, low coercion, and widespread availability. Due to the importance of the stability of these fluids, various methods such as increasing the viscosity of the carrier fluid using high viscosity liquids, reducing the density of magnetic particles by coating them, modifying the particle surface by adding stabilizing surfactant, and using materials There are nanostructures. One of the best ways to increase the stability that enhances the magnetic effect is to use magnetic microparticles in related ferrosilicon. The use of a combination of fine particles and nanoparticles in MRFs creates a bond between these particles, which results in a significant increase in yield stress, and on the other hand, the presence of nanoparticles in the base fluid increases the viscosity of the base fluid, which simultaneously reduces sediment.

According to studies and research, MRF is an excellent candidate for replacement with conventional fluids in fluid-based systems. In summary, MRF-based systems improve system performance in terms of controllability, rapid response, and wide applications compared to conventional fluid-based systems.

9.1. Controllability

Due to the variable viscosity of MRF and switching between semi-solid and fluid phases after applying a magnetic field, they provide precise output control.

9.2. Quick response

MRF-based systems respond to applied magnetic fields on a millisecond scale, making them a good candidate for real-time control applications.

9.3. Extensive applications

From MRF-based control systems, increasingly in engineering applications such as rheological magnetic electrolyte in batteries, anti-lock braking systems, magnetic clutches, vibrating dampers, shock absorbers, control valves, various types of vibrating dampers, various applications Medicine such as artificial joints and the military and automotive industries are used to increase the performance of systems to achieve the desired outputs.

CRediT authorship contribution statement

Hamed Eshgarf: Writing – original draft. **Afshin Ahmadi Nadooshan:** Supervision, Writing – review & editing, Methodology. **Afrasiab Raisi:** Conceptualization, Writing – review & editing.

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.

References

[1] J. Rabinow, The magnetic fluid clutch, Electr. Eng. 67 (1948) 1167.
[2] R. Jacob, Magnetic fluid torque and force transmitting device, in, Google Patents, 1951.
[3] E. Guglielmino, T. Sireteanu, C.W. Stammers, G. Ghita, M. Giuclea, Semi-active Suspension Control: Improved Vehicle Ride and Road Friendliness, Springer Science & Business Media, 2008.
[4] D.J. Klingenberg, Magnetorheology: applications and challenges, American Institute of Chemical Engineers, AIChE J. 47 (2001) 246.
[5] Y. Jianjian, Y. Hua, Z. Hui, Review and prospect of tribology study of magneto-rheological fluid [J], Chem. Ind. Eng. Prog. 32 (2013) 1855–1861.
[6] A. Spaggiari, Properties and applications of magnetorheological fluids, Frattura ed Integrità Strutturale 7 (2013) 48–61.
[7] J. De Vicente, D.J. Klingenberg, R. Hidalgo-Alvarez, Magnetorheological fluids: a review, Soft Matter 7 (2011) 3701–3710.
[8] D.S. Levi, N. Kusnezov, G.P. Carman, Smart materials applications for pediatric cardiovascular devices, Pediatr. Res. 63 (2008) 552–558.
[9] J. Wang, G. Meng, Magnetorheological fluid devices: principles, characteristics and applications in mechanical engineering, Proc. Inst. Mech. Eng. L J. Mater. Des. Appl. 215 (2001) 165–174.
[10] E. Esmaeilnezhad, H.J. Choi, M. Schaffie, M. Gholizadeh, M. Ranjbar, S.H. Kwon, Rheological analysis of magnetite added carbonyl iron based magnetorheological fluid, J. Magn. Magn. Mater. 444 (2017) 161–167.
[11] H. Yamaguchi, X.-D. Niu, X.-J. Ye, M. Li, Y. Iwamoto, Dynamic rheological properties of viscoelastic magnetic fluids in uniform magnetic fields, J. Magn. Magn. Mater. 324 (2012) 3238–3244.
[12] M.T. Manzoor, J.E. Kim, J.H. Jung, C. Han, S.-B. Choi, I.-K. Oh, Two-dimensional rGO-MoS2 hybrid additives for high-performance magnetorheological fluid, Sci. Rep. 8 (2018) 1–9.
[13] P. Skalski, K. Kalita, Role of magnetorheological fluids and elastomers in today's world, Acta Mech. Autom. 11 (2017) 267–274.
[14] K.-J. Kim, C.-W. Lee, J.-H. Koo, Design and modeling of semi-active squeeze film dampers using magneto-rheological fluids, Smart Mater. Struct. 17 (2008), 035006.
[15] F.-H. Xu, Z.-D. Xu, X.-C. Zhang, Y.-Q. Guo, Y. Lu, A compact experimentally validated model of magnetorheological fluids, J. Vib. Acoust. 138 (2016), 011017.
[16] R. Rizzo, An innovative multi-gap clutch based on magneto-rheological fluids and electrodynamic effects: magnetic design and experimental characterization, Smart Mater. Struct. 26 (2016), 015007.
[17] A. Lämmle, Development of a new mechanic safety coupling for human robot collaboration using magnetorheological fluids, Procedia CIRP 81 (2019) 908–913.
[18] K. Shu, C. Wang, W. Li, T. Bussell, J. Ding, Electrolytes with reversible switch between liquid and solid phases, Curr. Opin. Electrochem. 21 (2020) 297–302.
[19] S. Bachate, A. Choudhari, M. Gurav, S. Desai, L. Asule, S. Killedar, Development of Magneto-rheological Fluid Suspension System for Two Wheeler, 2020.
[20] A. El Wahed, L. Balkhoyor, Characteristics of magnetorheological fluids under single and mixed modes, Proc. Inst. Mech. Eng. C J. Mech. Eng. Sci. 231 (2017) 3798–3809.
[21] S. Kaluvan, J. Park, Y. Lee, M. Han, S. Choi, A new measurement method for operation mode dependent dynamic behavior of magnetorheological fluid, Proc. Inst. Mech. Eng. C J. Mech. Eng. Sci. 231 (2017) 3358–3369.
[22] J.-S. Oh, S.-B. Choi, State of the art of medical devices featuring smart electro-rheological and magneto-rheological fluids, J. King Saud Univ.Sci. 29 (2017) 390–400.
[23] M.R. Palacin, Recent advances in rechargeable battery materials: a chemist's perspective, Chem. Soc. Rev. 38 (2009) 2565–2575.
[24] K. Chen, Z. Yu, S. Deng, Q. Wu, J. Zou, X. Zeng, Evaluation of the low temperature performance of lithium manganese oxide/lithium titanate lithium-ion batteries for start/stop applications, J. Power Sources 278 (2015) 411–419.
[25] M.G. Muriuki, W.W. Clark, Design issues in magnetorheological fluid actuators, in: Smart Structures and Materials 1999: Passive Damping and Isolation, Vol. 3672, International Society for Optics and Photonics, 1999, pp. 55–64.
[26] R. Boelter, H. Janocha, Design rules for MR fluid actuators in different working modes, in: Smart Structures and Materials 1997: Passive Damping and Isolation, Vol. 3045, International Society for Optics and Photonics, 1997, pp. 148–159.
[27] H. Janocha, Adaptronics and Smart Structures, Springer, 1999.
[28] B.K. Kumbhar, S.R. Patil, A study on properties and selection criteria for magneto-rheological (MR) fluid components, Int. J. ChemTech Res. 6 (2014) 3303–3306.
[29] P.P. Phule, Magnetorheological (MR) fluids: principles and applications, Smart Mater. Bull. 2001 (2001) 7–10.
[30] J.D. Carlson, M.R. Jolly, MR fluid, foam and elastomer devices, Mechatronics 10 (2000) 555–569.
[31] J.M. Ginder, L. Davis, L. Elie, Rheology of magnetorheological fluids: models and measurements, Int. J. Modern Phys. B 10 (1996) 3293–3303.
[32] A.H. Pordanjani, S. Aghakhani, M. Afrand, M. Sharifpur, J.P. Meyer, H. Xu, H. M. Ali, N. Karimi, G. Cheraghian, Nanofluids: physical phenomena, applications in thermal systems and the environment effects-a critical review, J. Clean. Prod. 320 (2021), 128573.
[33] B. Kasemi, A.G. Muthalif, M. Rashid, M. Rahman, Optimizing dynamic range of magnetorheological fluid dampers: modeling and simulation, in: 2011 4th International Conference on Mechatronics (ICOM), IEEE, 2011, pp. 1–4.
[34] H. Hsu C.R. Bisbee III M.L. Palmer R.J. Lukasiewicz M.W. Lindsay S.W. Prince, Magnetorheological fluid compositions and prosthetic knees utilizing same, in, Google Patents, 2006.
[35] R. Alizadeh, J.M.N. Abad, A. Ameri, M.R. Mohebbi, A. Mehdizadeh, D. Zhao, N. Karimi, A machine learning approach to the prediction of transport and thermodynamic processes in multiphysics systems-heat transfer in a hybrid nanofluid flow in porous media, J. Taiwan Inst. Chem. Eng. 124 (2021) 290–306.
[36] M.T. Avraam, MR-fluid Brake Design and Its Application to a Portable Muscular Rehabilitation Device, Universite Libre de Bruxelles, 2009.
[37] A. Ghaffari, S.H. Hashemabadi, M. Ashtiani, A review on the simulation and modeling of magnetorheological fluids, J. Intell. Mater. Syst. Struct. 26 (2015) 881–904.
[38] L.H. Kumar, S. Kazi, H. Masjuki, M. Zubir, A review of recent advances in green nanofluids and their application in thermal systems, Chem. Eng. J. 429 (2022), 132321.
[39] J.M.N. Abad, R. Alizadeh, A. Fattahi, M.H. Doranehgard, E. Alhajri, N. Karimi, Analysis of transport processes in a reacting flow of hybrid nanofluid around a bluff-body embedded in porous media using artificial neural network and particle swarm optimization, J. Mol. Liq. 313 (2020), 113492.
[40] Y. Shen, D. Hua, X. Liu, W. Li, G. Krolczyk, Z. Li, Visualizing rheological mechanism of magnetorheological fluids, Smart Mater. Struct. 31 (2022), 025027.
[41] A.A. Al-Rashed, R. Ranjbarzadeh, S. Aghakhani, M. Soltanimehr, M. Afrand, T. K. Nguyen, Entropy generation of boehmite alumina nanofluid flow through a minichannel heat exchanger considering nanoparticle shape effect, Physica A 521 (2019) 724–736.
[42] M.H. Esfe, M. Reiszadeh, S. Esfandeh, M. Afrand, Optimization of MWCNTs (10%)–Al2O3 (90%)/5W50 nanofluid viscosity using experimental data and artificial neural network, Physica A 512 (2018) 731–744.
[43] A.-G. Olabi, A. Grunwald, Design and application of magneto-rheological fluid, Mater. Des. 28 (2007) 2658–2664.
[44] S. Thiagarajan, A.S. Koh, Performance and stability of magnetorheological fluids—a detailed review of the state of the art, Adv. Eng. Mater. 23 (2021) 2001458.
[45] M.R. Jolly, J.W. Bender, J.D. Carlson, Properties and applications of commercial magnetorheological fluids, J. Intell. Mater. Syst. Struct. 10 (1999) 5–13.
[46] J. Zhang, J. Zhang, Y. Kong, Y. Gao, J. Jia, H. Wang, Summarization of magnetorheological fluid and its application, J. Acad. Armored Force Eng. 24 (2010) 5–10.
[47] O. Mahian, L. Kolsi, M. Amani, P. Estellé, G. Ahmadi, C. Kleinstreuer, J. S. Marshall, M. Siavashi, R.A. Taylor, H. Niazmand, Recent advances in modeling and simulation of nanofluid flows-part I: fundamentals and theory, Phys. Rep. 790 (2019) 1–48.
[48] A. Ghasemi, M. Hassani, M. Goodarzi, M. Afrand, S. Manafi, Appraising influence of COOH-MWCNTs on thermal conductivity of antifreeze using curve fitting and neural network, Physica A 514 (2019) 36–45.
[49] R. Alizadeh, J.M.N. Abad, A. Fattahi, M.R. Mohebbi, M.H. Doranehgard, L.K. Li, E. Alhajri, N. Karimi, A machine learning approach to predicting the heat convection and thermodynamics of an external flow of hybrid nanofluid, J. Energy Resour. Technol. 143 (2021), 070908.
[50] S.E. Premalatha, R. Chokkalingam, M. Mahendran, Magneto mechanical properties of iron based MR fluids, Am. J. Polym. Sci 2 (2012) 50–55.
[51] F. Weibang, Review on magnetorheological fluid technology [J], Mar. Electr. Electron. Eng. 6 (2012).
[52] J.D. Carlson, What makes a good MR fluid?, in: Electrorheological Fluids and Magnetorheological Suspensions World Scientific, 2002, pp. 63–69.
[53] M. Ashtiani, S. Hashemabadi, A. Ghaffari, A review on the magnetorheological fluid preparation and stabilization, J. Magn. Magn. Mater. 374 (2015) 716–730.

[54] G. Bossis, O. Volkova, S. Lacis, A. Meunier, Ferrofluids Magnetically Controlable Fluids and Their Applications, Springer, Berlin, 2002.
[55] J.-B. Jun, S.-Y. Uhm, J.-H. Ryu, K.-D. Suh, Synthesis and characterization of monodisperse magnetic composite particles for magnetorheological fluid materials, Colloids Surf. A Physicochem. Eng. Asp. 260 (2005) 157–164.
[56] S. Kumar, R. Sehgal, M. Wani, M.D. Sharma, Stabilization and tribological properties of magnetorheological (MR) fluids: a review, J. Magn. Magn. Mater. 538 (2021), 168295.
[57] J. De Vicente, J. Segovia-Gutiérrez, E. Andablo-Reyes, F. Vereda, R. Hidalgo-Álvarez, Dynamic rheology of sphere-and rod-based magnetorheological fluids, J. Chem. Phys. 131 (2009), 194902.
[58] M.K. Hong, B.J. Park, H.J. Choi, Preparation and physical characterization of polyacrylamide coated magnetite particles, Phys. Stat. Solidi A 204 (2007) 4182–4185.
[59] S. Genç, P.P. Phulé, Rheological properties of magnetorheological fluids, Smart Mater. Struct. 11 (2002) 140.
[60] A. Muhammad, X.-L. Yao, Z.-C. Deng, Review of magnetorheological (MR) fluids and its applications in vibration control, J. Mar. Sci. Appl. 5 (2006) 17–29.
[61] J.H. Kim, F.F. Fang, H.J. Choi, Y. Seo, Magnetic composites of conducting polyaniline/nano-sized magnetite and their magnetorheology, Mater. Lett. 62 (2008) 2897–2899.
[62] A.J. Bombard, M. Knobel, M.R. AlcANtara, Phosphate coating on the surface of carbonyl iron powder and its effect in magnetorheological suspensions, in: Electrorheological Fluids And Magnetorheological Suspensions, World Scientific, 2007, pp. 187–194.
[63] M.J. Hato, H.J. Choi, H.H. Sim, B.O. Park, S.S. Ray, Magnetic carbonyl iron suspension with organoclay additive and its magnetorheological properties, Colloids Surf. A Physicochem. Eng. Asp. 377 (2011) 103–109.
[64] F.F. Fang, H.J. Choi, M.S. Jhon, Magnetorheology of soft magnetic carbonyl iron suspension with single-walled carbon nanotube additive and its yield stress scaling function, Colloids Surf. A Physicochem. Eng. Asp. 351 (2009) 46–51.
[65] C. Sarkar, H. Hirani, Effect of particle size on shear stress of magnetorheological fluids, Smart Sci. 3 (2015) 65–73.
[66] S. Mazlan, N. Ekreem, A. Olabi, An investigation of the behaviour of magnetorheological fluids in compression mode, J. Mater. Process. Technol. 201 (2008) 780–785.
[67] W. Jiang, Y. Zhang, S. Xuan, C. Guo, X. Gong, Dimorphic magnetorheological fluid with improved rheological properties, J. Magn. Magn. Mater. 323 (2011) 3246–3250.
[68] H. Choi, I. Jang, J. Lee, A. Pich, S. Bhattacharya, H.-J. Adler, Magnetorheology of synthesized core-shell structured nanoparticle, IEEE Trans. Magn. 41 (2005) 3448–3450.
[69] N. Wereley, A. Chaudhuri, J.-H. Yoo, S. John, S. Kotha, A. Suggs, R. Radhakrishnan, B. Love, T. Sudarshan, Bidisperse magnetorheological fluids using fe particles at nanometer and micron scale, J. Intell. Mater. Syst. Struct. 17 (2006) 393–401.
[70] I. Kazemi, M. Sefid, M. Afrand, A novel comparative experimental study on rheological behavior of mono & hybrid nanofluids concerned graphene and silica nano-powders: Characterization, stability and viscosity measurements, Powder Technol. 366 (2020) 216–229.
[71] G. Iglesias, M. López-López, J. Duran, F. González-Caballero, A. Delgado, Dynamic characterization of extremely bidisperse magnetorheological fluids, J. Colloid Interface Sci. 377 (2012) 153–159.
[72] E.C. Okonkwo, I. Wole-Osho, I.W. Almanassra, Y.M. Abdullatif, T. Al-Ansari, An updated review of nanofluids in various heat transfer devices, J. Therm. Anal. Calorim. 145 (2021) 2817–2872.
[73] R. Alizadeh, J.Mohebbi Najm Abad, A. Fattahi, E. Alhajri, N. Karimi, Application of machine learning to investigation of heat and mass transfer over a cylinder surrounded by porous media—the radial basic function network, J. Energy Resour. Technol. 142 (2020).
[74] N. Rosenfeld, N.M. Wereley, R. Radakrishnan, T.S. Sudarshan, Behavior of magnetorheological fluids utilizing nanopowder iron, Int. J. Modern Phys. B 16 (2002) 2392–2398.
[75] J. Claracq, J. Sarrazin, J.-P. Montfort, Viscoelastic properties of magnetorheological fluids, Rheol. Acta 43 (2004) 38–49.
[76] A. Kumar, A.K. Tiwari, Z. Said, A comprehensive review analysis on advances of evacuated tube solar collector using nanofluids and PCM, Sustain. Energy Technol. Assess. 47 (2021), 101417.
[77] L. Vekas, D. Bica, D. Gheorghe, I. Potencz, M. Raşa, Concentration and composition dependence of the rheological behaviour of some magnetic fluids, J. Magn. Magn. Mater. 201 (1999) 159–162.
[78] M.S. Cho, S.T. Lim, I.B. Jang, H.J. Choi, M.S. Jhon, Encapsulation of spherical iron-particle with PMMA and its magnetorheological particles, IEEE Trans. Magn. 40 (2004) 3036–3038.
[79] J. Choi, B. Park, M. Cho, H. Choi, Preparation and magnetorheological characteristics of polymer coated carbonyl iron suspensions, J. Magn. Magn. Mater. 304 (2006) e374–e376.
[80] Y.D. Liu, C.H. Hong, H.J. Choi, Polymeric colloidal magnetic composite microspheres and their magneto-responsive characteristics, Macromol. Res. 20 (2012) 1211–1218.
[81] R. Gu, X. Gong, W. Jiang, L. Hao, S. Xuan, Z. Zhang, Synthesis and rheological investigation of a magnetic fluid using olivary silica-coated iron particles as a precursor, J. Magn. Magn. Mater. 320 (2008) 2788–2791.
[82] H.B. Cheng, J.M. Wang, Q.J. Zhang, N. Wereley, Preparation of composite magnetic particles and aqueous magnetorheological fluids, Smart Mater. Struct. 18 (2009), 085009.
[83] M. Mrlík, M. Ilčíková, V. Pavlínek, J. Mosnáček, P. Peer, P. Filip, Improved thermooxidation and sedimentation stability of covalently-coated carbonyl iron particles with cholesteryl groups and their influence on magnetorheology, J. Colloid Interface Sci. 396 (2013) 146–151.
[84] F.F. Fang, M.S. Yang, H.J. Choi, Novel magnetic composite particles of carbonyl iron embedded in polystyrene and their magnetorheological characteristics, IEEE Trans. Magn. 44 (2008) 4533–4536.
[85] Y.D. Liu, H.J. Choi, S.-B. Choi, Controllable fabrication of silica encapsulated soft magnetic microspheres with enhanced oxidation-resistance and their rheology under magnetic field, Colloids Surf. A Physicochem. Eng. Asp. 403 (2012) 133–138.
[86] W.P. Wu, B.Y. Zhao, Q. Wu, K.A. Hu, The strengthening effect of guar gum on the yield stress of magnetorheological fluid, Smart Mater. Struct. 15 (2006) N94.
[87] C. Galindo-Gonzalez, M.T. Lopez-Lopez, J. Duran, Magnetorheological behavior of magnetite covered clay particles in aqueous suspensions, J. Appl. Phys. 112 (2012), 043917.
[88] F.F. Fang, Y.D. Liu, H.J. Choi, Carbon nanotube coated magnetic carbonyl iron microspheres prepared by solvent casting method and their magneto-responsive characteristics, Colloids Surf. A Physicochem. Eng. Asp. 412 (2012) 47–56.
[89] M. López-López, P. Kuzhir, S. Lacis, G. Bossis, F. González-Caballero, J.D. Durán, Magnetorheology for suspensions of solid particles dispersed in ferrofluids, J. Phys. Condens. Matter 18 (2006) S2803.
[90] S.W. Charles, The preparation of magnetic fluids, in: Ferrofluids, Springer, 2002, pp. 3–18.
[91] M.A. Patil, A.S. Zare, Theoretical studies on magnetorheological fluid brake, Int. J. Res. Mech. Eng. Technol 2 (2012) 12–14.
[92] R. Patel, Mechanism of chain formation in nanofluid based MR fluids, J. Magn. Magn. Mater. 323 (2011) 1360–1363.
[93] M. Kciuk, S. Kciuk, R. Turczyn, Magnetorheological characterisation of carbonyl iron based suspension, J. Achievements Mater. Manuf. Eng. 33 (2009) 135–141.
[94] C. Burda, X. Chen, R. Narayanan, M.A. El-Sayed, Chemistry and properties of nanocrystals of different shapes, Chem. Rev. 105 (2005) 1025–1102.
[95] B.J. Park, K.H. Song, H.J. Choi, Magnetic carbonyl iron nanoparticle based magnetorheological suspension and its characteristics, Mater. Lett. 63 (2009) 1350–1352.
[96] K.H. Song, B.J. Park, H.J. Choi, Effect of magnetic nanoparticle additive on characteristics of magnetorheological fluid, IEEE Trans. Magn. 45 (2009) 4045–4048.
[97] B.D. Chin, J.H. Park, M.H. Kwon, O.O. Park, Rheological properties and dispersion stability of magnetorheological (MR) suspensions, Rheol. Acta 40 (2001) 211–219.
[98] K. Shimada, Y. Akagami, T. Fujita, T. Miyazaki, S. Kamiyama, A. Shibayama, Characteristics of magnetic compound fluid (MCF) in a rotating rheometer, J. Magn. Magn. Mater. 252 (2002) 235–237.
[99] R. Bell, J. Karli, A. Vavreck, D. Zimmerman, G. Ngatu, N. Wereley, Magnetorheology of submicron diameter iron microwires dispersed in silicone oil, Smart Mater. Struct. 17 (2008), 015028.
[100] M.T. López-López, P. Kuzhir, G. Bossis, Magnetorheology of fiber suspensions. I. Experimental, J. Rheol. 53 (2009) 115–126.
[101] G. Ngatu, N. Wereley, J. Karli, R.C. Bell, Dimorphic magnetorheological fluids: exploiting partial substitution of microspheres by nanowires, Smart Mater. Struct. 17 (2008), 045022.
[102] P. Kuzhir, M.T. López-López, G. Bossis, Magnetorheology of fiber suspensions. II. Theory, J. Rheol. 53 (2009) 127–151.
[103] H. Chiriac, G. Stoian, M. Lostun, Magnetorheological fluids based on amorphous magnetic microparticles, J. Phys. Conf. Ser. 149 (2009) 012045. IOP Publishing.
[104] X. Wang, F. Gordaninejad, Study of magnetorheological fluids at high shear rates, Rheol. Acta 45 (2006) 899–908.
[105] C. Guerrero-Sanchez, T. Lara-Ceniceros, E. Jimenez-Regalado, M. Raşa, U. S. Schubert, Magnetorheological fluids based on ionic liquids, Adv. Mater. 19 (2007) 1740–1747.
[106] J.H. Park, B.D. Chin, O.O. Park, Rheological properties and stabilization of magnetorheological fluids in a water-in-oil emulsion, J. Colloid Interface Sci. 240 (2001) 349–354.
[107] M.S. Kim, Y.D. Liu, B.J. Park, C.-Y. You, H.J. Choi, Carbonyl iron particles dispersed in a polymer solution and their rheological characteristics under applied magnetic field, J. Ind. Eng. Chem. 18 (2012) 664–667.
[108] B. Wei, X. Gong, W. Jiang, L. Qin, Y. Fan, Study on the properties of magnetorheological gel based on polyurethane, J. Appl. Polym. Sci. 118 (2010) 2765–2771.
[109] J.E. Kim, H.J. Choi, Magnetic carbonyl iron particle dispersed in viscoelastic fluid and its magnetorheological property, IEEE Trans. Magn. 47 (2011) 3173–3176.
[110] J. Viota, J. De Vicente, J. Duran, A. Delgado, Stabilization of magnetorheological suspensions by polyacrylic acid polymers, J. Colloid Interface Sci. 284 (2005) 527–541.
[111] L. Rodríguez-Arco, A. Gómez-Ramírez, J.D. Durán, M.T. López-López, New perspectives for magnetic fluid-based devices using novel ionic liquids as carriers, in: Smart Actuation and Sensing Systems-Recent Advances and Future Challenges, 2012.
[112] X. Zhang, W. Li, X. Gong, Thixotropy of MR shear-thickening fluids, Smart Mater. Struct. 19 (2010), 125012.
[113] S. Bednarek, Non-linearity and hysteresis of Hall effect in magnetorheological suspensions with conducting carrier, J. Magn. Magn. Mater. 264 (2003) 251–257.
[114] M.T. López-López, P. Kuzhir, G. Bossis, P. Mingalyov, Preparation of well-dispersed magnetorheological fluids and effect of dispersion on their magnetorheological properties, Rheol. Acta 47 (2008) 787–796.

[115] B.G. Shetty, P. Prasad, Rheological properties of a Honge oil-based magnetorheological fluid used as carrier liquid, Def. Sci. J. 61 (2011).
[116] X. Liu, Z. Fu, X. Yao, F. Li, Performance of magnetorheological fluids flowing through metal foams, Meas. Sci. Rev. 11 (2011) 144.
[117] S.T. Lim, M.S. Cho, I.B. Jang, H.J. Choi, Magnetorheological characterization of carbonyl iron based suspension stabilized by fumed silica, J. Magn. Magn. Mater. 282 (2004) 170–173.
[118] D. Bica, L. Vékás, M.V. Avdeev, O. Marinică, V. Socoliuc, M. Bălăsoiu, V. M. Garamus, Sterically stabilized water based magnetic fluids: Synthesis, structure and properties, J. Magn. Magn. Mater. 311 (2007) 17–21.
[119] J. Viota, A. Delgado, J. Arias, J. Duran, Study of the magnetorheological response of aqueous magnetite suspensions stabilized by acrylic acid polymers, J. Colloid Interface Sci. 324 (2008) 199–204.
[120] A. Lebedev, S. Lysenko, Magnetic fluids stabilized by polypropylene glycol, J. Magn. Magn. Mater. 323 (2011) 1198–1202.
[121] S.T. Lim, H.J. Choi, M.S. Jhon, Magnetorheological characterization of carbonyl iron-organoclay suspensions, IEEE Trans. Magn. 41 (2005) 3745–3747.
[122] M. Sedlacik, V. Pavlinek, M. Lehocky, A. Mracek, O. Grulich, P. Svrcinova, P. Filip, A. Vesel, Plasma-treated carbonyl iron particles as a dispersed phase in magnetorheological fluids, Colloids Surf. A Physicochem. Eng. Asp. 387 (2011) 99–103.
[123] P.J. Rankin, A.T. Horvath, D.J. Klingenberg, Magnetorheology in viscoplastic media, Rheol. Acta 38 (1999) 471–477.
[124] M. López-López, A. Zugaldia, A. Gómez-Ramirez, F. González-Caballero, J. Durán, Effect of particle aggregation on the magnetic and magnetorheological properties of magnetic suspensions, J. Rheol. 52 (2008) 901–912.
[125] M. López-López, A. Zugaldía, F. González-Caballero, J. Durán, Sedimentation and redispersion phenomena in iron-based magnetorheological fluids, J. Rheol. 50 (2006) 543–560.
[126] P. Kuzhir, G. Bossis, V. Bashtovoi, O. Volkova, Flow of magnetorheological fluid through porous media, Eur. J. Mech.B/Fluids 22 (2003) 331–343.
[127] M. Machovsky, M. Mrlik, I. Kuritka, V. Pavlinek, V. Babayan, Novel synthesis of core–shell urchin-like ZnO coated carbonyl iron microparticles and their magnetorheological activity, RSC Adv. 4 (2014) 996–1003.
[128] O. Mahian, A. Kianifar, C. Kleinstreuer, I. Pop, A.Z. Sahin, S. Wongwises, A.-N. Moh'd A, A review of entropy generation in nanofluid flow, Int. J. Heat and Mass Transf. 65 (2013) 514–532.
[129] M. Michalec, P. Svoboda, I. Krupka, M. Hartl, Tribological behaviour of smart fluids influenced by magnetic and electric field-a review, Tribol. Ind. 40 (2018).
[130] A. Hajalilou, S.A. Mazlan, H. Lavvafi, K. Shameli, Field Responsive Fluids as Smart Materials, Springer, 2016.
[131] J.H. Park, M.H. Kwon, O.O. Park, Rheological properties and stability of magnetorheological fluids using viscoelastic medium and nanoadditives, Korean J. Chem. Eng. 18 (2001) 580–585.
[132] K.H. Guðmundsson, Design of a Magnetorheological Fluid for an MR Prosthetic Knee Actuator With an Optimal Geometry, 2011.
[133] O. Ashour, C.A. Rogers, W. Kordonsky, Magnetorheological fluids: materials, characterization, and devices, J. Intell. Mater. Syst. Struct. 7 (1996) 123–130.
[134] K.D. Weiss, T.G. Duclos, J.D. Carlson, M.J. Chrzan, A.J. Margida, High strength magneto-and electro-rheological fluids, SAE Trans. (1993) 425–430.
[135] J. Ginder, Rheology controlled by magnetic fields, in: Digital Encyclopedia ofApplied Physics, 2003.
[136] Y. Ding, H. Chen, Z. Musina, Y. Jin, T. Zhang, S. Witharana, W. Yang, Relationship between the thermal conductivity and shear viscosity of nanofluids, Phys. Scr. 2010 (2010), 014078.
[137] L. Colla, L. Fedele, M. Scattolini, S. Bobbo, Water-based Fe2O3 nanofluid characterization: thermal conductivity and viscosity measurements and correlation, Adv. Mech. Eng. 4 (2012), 674947.
[138] Y. Yang, E.A. Grulke, Z.G. Zhang, G. Wu, Thermal and rheological properties of carbon nanotube-in-oil dispersions, J. Appl. Phys. 99 (2006), 114307.
[139] M. Zambrano-Arjona, R. Medina-Esquivel, J. Alvarado-Gil, Photothermal radiometry monitoring of light curing in resins, J. Phys. D. Appl. Phys. 40 (2007) 6098.
[140] P. Martínez-Torres, A. Mandelis, J. Alvarado-Gil, Photothermal determination of thermal diffusivity and polymerization depth profiles of polymerized dental resins, J. Appl. Phys. 106 (2009), 114906.
[141] I. Forero-Sandoval, A. Vega-Flick, J. Alvarado-Gil, R. Medina-Esquivel, Study of thermal conductivity of magnetorheological fluids using the thermal-wave resonant cavity and its relationship with the viscosity, Smart Mater. Struct. 26 (2016), 025010.
[142] K.-Q. Xia, S.-Q. Zhou, Temperature power spectra and the viscous boundary layer in thermal turbulence: the role of Prandtl number, Physica A 288 (2000) 308–314.
[143] J.R. Booker, Thermal convection with strongly temperature-dependent viscosity, J. Fluid Mech. 76 (1976) 741–754.
[144] M. Hassan, M. Pathak, M.K. Khan, Rayleigh–benard convection in Herschel-Bulkley fluid, J. Non-Newtonian Fluid Mech. 226 (2015) 32–45.
[145] X. Biao, L. Yiping, R. Hongjuan, Review on magneto-rheological fluid and its application, Am.J. Nanosci. Nanotechnol. 2 (2014) 70–74.
[146] G. Bossis, P. Khuzir, S. Lacis, O. Volkova, Yield behavior of magnetorheological suspensions, J. Magn. Magn. Mater. 258 (2003) 456–458.
[147] G. Bossis, E. Lemaire, O. Volkova, H. Clercx, Yield stress in magnetorheological and electrorheological fluids: A comparison between microscopic and macroscopic structural models, J. Rheol. 41 (1997) 687–704.
[148] S. Genç, Synthesis and Properties of Magnetorheological (MR) Fluids, University of Pittsburgh, 2002.
[149] W. Kordonski, The influence of ferroparticle concentration and size on MR fluid properties, in: Electro-rheologicalFluids, Magneto-rheological Suspensions and Their Applications, Yonezawa, Japan 1997, 1997.
[150] R. Foister, Magnetorheological fluids, US Patent Specification, 5667715 (1997).
[151] F.D. Goncalves, J.-H. Koo, M. Ahmadian, A review of the state of the art in magnetorheological fluid technologies–part I: MR fluid and MR fluid models, in: The Shock and Vibration Digest 38, 2006, pp. 203–220.
[152] V. Sukhwani, H. Hirani, Synthesis and characterization of low cost magnetorheological (MR) fluids, in: Behavior and Mechanics of Multifunctional and Composite Materials 2007 6526, International Society for Optics and Photonics, 2007, p. 65262R.
[153] K.D. Weiss J.D. Carlson D.A. Nixon, Method and magnetorheological fluid formulations for increasing the output of a magnetorheological fluid device, in, Google Patents, 1999.
[154] http://www.lord.com.
[155] http://www.isc.fraunhofer.de/.
[156] F.D. Goncalves, M. Ahmadian, J. Carlson, Behavior of MR fluids at high velocities and high shear rates, Int. J. Modern Phys. B 19 (2005) 1395–1401.
[157] E. Świtoński, A. Mężyk, S. Duda, S. Kciuk, Prototype magnetorheological fluid damper for active vibration control system, J. Achievements Mater. Manuf. Eng. 21 (2007) 55–62.
[158] D. Wang, W.H. Liao, Magnetorheological fluid dampers: a review of parametric modelling, Smart Mater. Struct. 20 (2011), 023001.
[159] M. Jolly, J. Carlson, J. Bender, SPIE 5th Annual Int. Symposium on Smart Structures and Materials, San Diego, CA 15, 1998.
[160] M.R. Jolly, J.W. Bender, J.D. Carlson, Properties and applications of commercial magnetorheological fluids, in: Smart Structures and Materials 1998: Passive Damping and Isolation 3327, International Society for Optics and Photonics, 1998, pp. 262–275.
[161] X. Zhang, X. Gong, P. Zhang, Q. Wang, Study on the mechanism of the squeeze-strengthen effect in magnetorheological fluids, J. Appl. Phys. 96 (2004) 2359–2364.
[162] W. Li, H. Du, G. Chen, S. Yeo, Experimental investigation of creep and recovery behaviors of magnetorheological fluids, Mater. Sci. Eng. A 333 (2002) 368–376.
[163] E.C. McIntyre, F.E. Filisko, Squeeze flow of electrorheological fluids under constant volume, J. Intell. Mater. Syst. Struct. 18 (2007) 1217–1220.
[164] J.C. Ulicny, M.A. Golden, C.S. Namuduri, D.J. Klingenberg, Transient response of magnetorheological fluids: Shear flow between concentric cylinders, J. Rheol. 49 (2005) 87–104.
[165] H. See, A. Gordin, Response of carbonyl iron-based magneto-rheological suspensions under step changes in magnetic fields, Nihon Reoroji Gakkaishi 36 (2008) 59–64.
[166] W. Li, H. Du, G. Chen, S. Yeo, N. Guo, Nonlinear rheological behavior of magnetorheological fluids: step-strain experiments, Smart Mater. Struct. 11 (2002) 209.
[167] H. See, Transient response of a magneto-rheological suspension after a double-step shear strain, Colloid Polym. Sci. 281 (2003) 788–793.
[168] P. Kulkarni, C. Ciocanel, S.L. Vieira, N. Naganathan, Study of the behavior of MR fluids in squeeze, torsional and valve modes, J. Intell. Mater. Syst. Struct. 14 (2003) 99–104.
[169] J. De Vicente, F. González-Caballero, G. Bossis, O. Volkova, Normal force study in concentrated carbonyl iron magnetorheological suspensions, J. Rheol. 46 (2002) 1295–1303.
[170] H. See, R. Tanner, Shear rate dependence of the normal force of a magnetorheological suspension, Rheol. Acta 42 (2003) 166–170.
[171] H.M. Laun, C. Gabriel, G. Schmidt, Primary and secondary normal stress differences of a magnetorheological fluid (MRF) up to magnetic flux densities of 1 T, J. Non-Newtonian Fluid Mech. 148 (2008) 47–56.
[172] M. Keentok, H. See, Behaviour of field-responsive suspensions under oscillatory shear flow, Korea-Australia Rheol. J. 19 (2007) 117–123.
[173] O. Mahian, A. Kianifar, S.A. Kalogirou, I. Pop, S. Wongwises, A review of the applications of nanofluids in solar energy, Int. J. Heat Mass Transf. 57 (2013) 582–594.
[174] W.W. Chooi, S.O. Oyadiji, Design, modelling and testing of magnetorheological (MR) dampers using analytical flow solutions, Comput. Struct. 86 (2008) 473–482.
[175] J. Carlson, D. Catanzarite, K.S. Clair, Lord Corporation, Cary, NC 27511 USA, in: Commercial Magneto-rheological Fluid Device, Proceedings of the 5th International Conference on ER Fluids, MR Fluids and Associated Technology, U. Sheffield, UK, 1995, pp. 20–28.
[176] J. Carlson, CISM Course: Semi-active Vibration Suppression–The Best From Active and Passive Technologies, Udine, Italy, 2007.
[177] D. Jeon, C. Park, K. Park, Vibration suppression by controlling an MR damper, Int. J. Modern Phys. B 13 (1999) 2221–2228.
[178] R. Boelter, H. Janocha, Performance of long-stroke and low-stroke MR fluid dampers, in: Smart Structures and Materials 1998: Passive Damping and Isolation, Vol. 3327, International Society for Optics and Photonics, 1998, pp. 303–313.
[179] R. Bolter H. Janocha, Demands on MR fluid energy transducers in shock absorbers, in: Actuator, Vol. 98, 1998, pp. 426-429.
[180] D. Truong, K. Ahn, MR fluid damper and its application to force sensorless damping control system, in: Smart Actuation and Sensing Systems-Recent Advances and Future Challenges, 2012, pp. 383–425.
[181] A. Pinkos, E. Shtarkman, T. Fitzgerald, An actively damped passenger car suspension system with low voltage electro-rheological magnetic fluid, in: SAE Technical Paper, 1993.

[182] S. Marathe, F. Gandhi, K.-W. Wang, Helicopter blade response and aeromechanical stability with a magnetorheological fluid based lag damper, J. Intell. Mater. Syst. Struct. 9 (1998) 272–282.
[183] J.C. Poynor, Innovative designs for magneto-rheological dampers, in: Virginia Tech, 2001.
[184] X. Tang, X. Wang, W. Li, P. Zhang, Testing and modeling of an MR damper in the squeeze flow mode, in: Proceedings of the 6th International Conference on ER Fluids, MR Suspensions and Their Applications, 1998, pp. 870–878.
[185] D. Zhao, J. Zhao, Z. Zhao, Y. Liu, S. Liu, S. Wang, Design and experimental study of the porous foam metal magnetorheological fluid damper based on built-in multi-pole magnetic core, J. Intell. Mater. Syst. Struct. 31 (2020) 687–703.
[186] W. Elsaady, S.O. Oyadiji, A. Nasser, Magnetic circuit analysis and fluid flow modeling of an MR damper with enhanced magnetic characteristics, IEEE Trans. Magn. 56 (2020) 1–20.
[187] X. Zhang, Y. Yang, K. Guo, S. Sun, G. He, Z. Li, Methodology on a novel magnetorheological valve controlled damper synthesis design, Smart Mater. Struct. 29 (2020), 045006.
[188] S. Zareie, M.S. Alam, R.J. Seethaler, A. Zabihollah, Stability control of a novel frame integrated with an SMA-MRF control system for marine structural applications based on the frequency analysis, Appl. Ocean Res. 97 (2020), 102091.
[189] S. Zareie, A. Zabihollah, A semi-active SMA-MRF structural stability element for seismic control in marine structures, Appl. Ocean Res. 100 (2020), 102161.
[190] S. Zareie, M.S. Alam, R.J. Seethaler, A. Zabihollah, Effect of shape memory alloy-magnetorheological fluid-based structural control system on the marine structure using nonlinear time-history analysis, Appl. Ocean Res. 91 (2019), 101836.
[191] M. Wei, X. Rui, W. Zhu, F. Yang, L. Gu, H. Zhu, Design, modelling and testing of a novel high-torque magnetorheological damper, Smart Mater. Struct. 29 (2020), 025024.
[192] W.-M. Zhong, A.-D. Zhu, X.-X.F. Bai, N.M. Wereley, N. Zhang, Integrated shock absorber with both tunable inertance and damping, Front. Mater. 7 (2020) 204.
[193] B.-H. Kang, J.-Y. Yoon, G.-W. Kim, S.-B. Choi, Landing efficiency control of a six-degree-of-freedom aircraft model with magnetorheological dampers: part 1—modeling, J. Intell. Mater. Syst. Struct. 32 (2021) 1290–1302.
[194] B.-G. Kim, D.-S. Yoon, G.-W. Kim, S.-B. Choi, A.S. Tan, T. Sattel, Design of a novel magnetorheological damper adaptable to low and high stroke velocity of vehicle suspension system, Appl. Sci. 10 (2020) 5586.
[195] L. Deng, S. Sun, M.D. Christie, J. Yang, D. Ning, X. Zhu, H. Du, S. Zhang, W. Li, Experimental testing and modelling of a rotary variable stiffness and damping shock absorber using magnetorheological technology, J. Intell. Mater. Syst. Struct. 30 (2019) 1453–1465.
[196] M.H. Idris, F. Imaduddin, S.A. Mazlan, S.-B. Choi, A concentric design of a bypass magnetorheological fluid damper with a serpentine flux valve, in: Actuators 9, Multidisciplinary Digital Publishing Institute, 2020, p. 16.
[197] P. Chen, L.-J. Qian, X.-X. Bai, S.-B. Choi, Velocity-dependent characteristics of magnetorheological fluids in squeeze mode considering the hydrodynamic and the magnetic field interactions, J. Rheol. 61 (2017) 455–465.
[198] X. Ruan, Y. Wang, S. Xuan, X. Gong, Magnetic field dependent electric conductivity of the magnetorheological fluids: the influence of oscillatory shear, Smart Mater. Struct. 26 (2017), 035067.
[199] M. Versaci, A. Cutrupi, A. Palumbo, A magneto-thermo-static study of a magneto-rheological fluid damper: a finite element analysis, IEEE Trans. Magn. 57 (2020) 1–10.
[200] A.Y. Abd Fatah, S.A. Mazlan, T. Koga, H. Zamzuri, Increasing effective region in magnetorheological valve using serpentine flux path method, in: The 2013 World Congress on Advances in Structural Engineering and Mechanics, 2013, pp. 2916–2929.
[201] Q. Nguyen, S.B. Choi, Y. Lee, M. Han, Optimal design of high damping force engine mount featuring MR valve structure with both annular and radial flow paths, Smart Mater. Struct. 22 (2013), 115024.
[202] A.Y. Abd Fatah, S.A. Mazlan, T. Koga, H. Zamzuri, M. Zeinali, F. Imaduddin, A review of design and modeling of magnetorheological valve, Int. J. Modern Phys. B 29 (2015) 1530004.
[203] G. Hu, M. Liao, W. Li, Analysis of a compact annular-radial-orifice flow magnetorheological valve and evaluation of its performance, J. Intell. Mater. Syst. Struct. 28 (2017) 1322–1333.
[204] J.D. Carlson M.J. Chrzan F.O. James, Magnetorheological fluid devices, in, Google Patents, 1994.
[205] J.-H. Yoo, N.M. Wereley, Performance of a MR hydraulic power actuation system, in: Smart Structures and Materials 2002: Smart Structures and Integrated Systems, Vol. 4701, International Society for Optics and Photonics, 2002, pp. 9–19.
[206] M. Brigley, Y.-T. Choi, N.M. Wereley, S.-B. Choi, Magnetorheological isolators using multiple fluid modes, J. Intell. Mater. Syst. Struct. 18 (2007) 1143–1148.
[207] E. Cook, W. Hu, N.M. Wereley, Magnetorheological bypass damper exploiting flow through a porous channel, J. Intell. Mater. Syst. Struct. 18 (2007) 1197–1203.
[208] H. Böse, J. Ehrlich, Magnetorheological dampers with various designs of hybrid magnetic circuits, J. Intell. Mater. Syst. Struct. 23 (2012) 979–987.
[209] I.I.M. Yazid, S.A. Mazlan, H. Zamzuri, M. Mughni, S. Chuprat, Parameters consideration in designing a magnetorheological damper, in: Key Engineering Materials 543, Trans Tech Publ, 2013, pp. 487–490.
[210] K. Karakoc, E.J. Park, A. Suleman, Design considerations for an automotive magnetorheological brake, Mechatronics 18 (2008) 434–447.
[211] E.J. Park, L.F. da Luz, A. Suleman, Multidisciplinary design optimization of an automotive magnetorheological brake design, Comput. Struct. 86 (2008) 207–216.
[212] B. Assadsangabi, F. Daneshmand, N. Vahdati, M. Eghtesad, Y. Bazargan-Lari, Optimization and design of disk-type MR brakes, Int. J. Automot. Technol. 12 (2011) 921–932.
[213] Y. Shiao, Q.-A. Nguyen, Development of a multi-pole magnetorheological brake, Smart Mater. Struct. 22 (2013), 065008.
[214] O. Topcu, Y. Tascioglu, E.I. Konukseven, Design and analysis of a lightweight disc-type magnetorheological device, in: Proceedings of the World Congress on Engineering 2, 2015.
[215] H. Shamieh, R. Sedaghati, Design optimization of a magneto-rheological fluid brake for vehicle applications, in: Smart Materials, Adaptive Structures and Intelligent Systems, Vol. 50497, American Society of Mechanical Engineers, 2016. V002T003A008.
[216] E. Attia, N. Elsodany, H. El-Gamal, M. Elgohary, Theoretical and experimental study of magneto-rheological fluid disc brake, Alex. Eng. J. 56 (2017) 189–200.
[217] A. Poznic, D. Miloradovic, A. Juhas, A new magnetorheological brakes combined materials design approach, J. Mech. Sci. Technol. 31 (2017) 1119–1125.
[218] H. Wang, C. Bi, Study of a magnetorheological brake under compression-shear mode, Smart Mater. Struct. 29 (2019), 017001.
[219] N. Wang, X. Liu, G. Królczyk, Z. Li, W. Li, Effect of temperature on the transmission characteristics of high-torque magnetorheological brakes, Smart Mater. Struct. 28 (2019), 057002.
[220] H. Qin, A. Song, Y. Mo, A hybrid actuator with hollowed multi-drum magnetorheological brake and direct-current micromotor for hysteresis compensation, J. Intell. Mater. Syst. Struct. 30 (2019) 1031–1042.
[221] J. Dai, H. Chang, R. Zhao, J. Huang, K. Li, S. Xie, Investigation of the relationship among the microstructure, rheological properties of MR grease and the speed reduction performance of a rotary micro-brake, Mech. Syst. Signal Process. 116 (2019) 741–750.
[222] C.M. Elliott, G.D. Buckner, Design optimization of a novel elastomeric baffle magnetorheological fluid device, J. Intell. Mater. Syst. Struct. 29 (2018) 3774–3791.
[223] H. Shamieh, R. Sedaghati, Development, optimization, and control of a novel magnetorheological brake with no zero-field viscous torque for automotive applications, J. Intell. Mater. Syst. Struct. 29 (2018) 3199–3213.
[224] N.D. Nguyen, T. Le-Duc, L.D. Hiep, Q.H. Nguyen, Development of a new magnetorheological fluid–based brake with multiple coils placed on the side housings, J. Intell. Mater. Syst. Struct. 30 (2019) 734–748.
[225] H. Qin, A. Song, X. Zeng, S. Hu, Design and evaluation of a small-scale multi-drum magnetorheological brake, J. Intell. Mater. Syst. Struct. 29 (2018) 2607–2618.
[226] X. Wu, C. Huang, Z. Tian, J. Ji, Development of a novel magnetorheological fluids transmission device for high-power applications, Smart Mater. Struct. 28 (2019), 055021.
[227] A. Dehghani-Sanij, E. Tharumalingam, M. Dusseault, R. Fraser, Study of energy storage systems and environmental challenges of batteries, Renew. Sust. Energ. Rev. 104 (2019) 192–208.
[228] M. Winter, B. Barnett, K. Xu, Before Li ion batteries, Chem. Rev. 118 (2018) 11433–11456.
[229] P. Meister, H. Jia, J. Li, R. Kloepsch, M. Winter, T. Placke, Best practice: performance and cost evaluation of lithium ion battery active materials with special emphasis on energy efficiency, Chem. Mater. 28 (2016) 7203–7217.
[230] J. Betz, G. Bieker, P. Meister, T. Placke, M. Winter, R. Schmuch, Theoretical versus practical energy: a plea for more transparency in the energy calculation of different rechargeable battery systems, Adv. Energy Mater. 9 (2019) 1803170.
[231] C. Iclodean, B. Varga, N. Burnete, D. Cimerdean, B. Jurchiş, Comparison of different battery types for electric vehicles, in: IOP Conference Series: Materials Science and Engineering 252, IOP Publishing, 2017, p. 012058.
[232] N. El Ghossein, J.P. Salameh, N. Karami, M. El Hassan, M.B. Najjar, Survey on electrical modeling methods applied on different battery types, in: 2015 Third International Conference on Technological Advances in Electrical, Electronics and Computer Engineering (TAEECE), IEEE, 2015, pp. 39–44.
[233] M.R. Jongerden, B.R. Haverkort, Which battery model to use? IET Softw. 3 (2009) 445–457.
[234] X. Yu, S. Licht, Advances in Fe (VI) charge storage: part I. Primary alkaline super-iron batteries, J. Power Sources 171 (2007) 966–980.
[235] Z. Wei, J. Cheng, R. Wang, Y. Li, Y. Ren, From spent Zn–MnO2 primary batteries to rechargeable Zn–MnO2 batteries: A novel directly recycling route with high battery performance, J. Environ. Manag. 298 (2021), 113473.
[236] S. Sun, Q. Yan, M. Wu, X. Zhao, Carbon aerogel based materials for secondary batteries, Sustain. Mater. Technol. 30 (2021), e00342.
[237] T. Chaikaew, K. Punyawudho, Optimal voltage of direct current coupling for a fuel cell–battery hybrid energy storage system based on solar energy, Energy Rep. 7 (2021) 204–208.
[238] M. Shen, Solid oxide fuel cell-lithium battery hybrid power generation system energy management: a review, Int. J. Hydrog. Energy 46 (2021) 32974–32994.
[239] H.-B. Yuan, W.-J. Zou, S. Jung, Y.-B. Kim, Optimized rule-based energy management for a polymer electrolyte membrane fuel cell/battery hybrid power system using a genetic algorithm, Int. J. Hydrog. Energy 47 (12) (2022) 7932–7948, https://doi.org/10.1016/j.ijhydene.2021.12.121.
[240] G. Pistoia, Chapter 2 - battery categories and types, in: G. Pistoia (Ed.), Battery Operated Devices and Systems, Elsevier, Amsterdam, 2009, pp. 17–73.
[241] T.R. Crompton, T.P. Crompton, T.R. Crompton, Battery reference book, Newnes, 2000.

[242] K. Schmidt-Rohr, How batteries store and release energy: explaining basic electrochemistry, J. Chem. Educ. 95 (2018) 1801–1810.
[243] Y. Liang, C.Z. Zhao, H. Yuan, Y. Chen, W. Zhang, J.Q. Huang, D. Yu, Y. Liu, M. M. Titirici, Y.L. Chueh, A review of rechargeable batteries for portable electronic devices, in: InfoMat 1, 2019, pp. 6–32.
[244] C.L. Schmidt, P.M. Skarstad, The future of lithium and lithium-ion batteries in implantable medical devices, J. Power Sources 97 (2001) 742–746.
[245] S. Bruno, K. Abraham, W. van Schalkwijk, J. Hassoun, Lithium Batteries: Advanced Technologies and Applications, 2013.
[246] N. Williard, W. He, C. Hendricks, M. Pecht, Lessons learned from the 787 dreamliner issue on lithium-ion battery reliability, Energies 6 (2013) 4682–4695.
[247] Q. Wang, P. Ping, X. Zhao, G. Chu, J. Sun, C. Chen, Thermal runaway caused fire and explosion of lithium ion battery, J. Power Sources 208 (2012) 210–224.
[248] S. Saricilar, D. Antiohos, K. Shu, P.G. Whitten, K. Wagner, C. Wang, G.G. Wallace, High strain stretchable solid electrolytes, Electrochem. Commun. 32 (2013) 47–50.
[249] X. Li, Z. Zhang, K. Yin, L. Yang, K. Tachibana, S.-I. Hirano, Mesoporous silica/ionic liquid quasi-solid-state electrolytes and their application in lithium metal batteries, J. Power Sources 278 (2015) 128–132.
[250] S. Zhang, G.-Y. Dong, B. Lin, J. Qu, N.-Y. Yuan, J.-N. Ding, A polymer gel electrolyte with an inverse opal structure and its effects on the performance of quasi-solid-state dye-sensitized solar cells, J. Power Sources 277 (2015) 52–58.
[251] J.W. Fergus, Ceramic and polymeric solid electrolytes for lithium-ion batteries, J. Power Sources 195 (2010) 4554–4569.
[252] B. Smitha, S. Sridhar, A. Khan, Solid polymer electrolyte membranes for fuel cell applications—a review, J. Membr. Sci. 259 (2005) 10–26.
[253] J. Ding, G. Peng, K. Shu, C. Wang, T. Tian, W. Yang, Y. Zhang, G.G. Wallace, W. Li, Novel reversible and switchable electrolytes based on magneto-rheology, Sci. Rep. 5 (2015) 1–11.
[254] P. Nejat, F. Jomehzadeh, M.M. Taheri, M. Gohari, M.Z.A. Majid, A global review of energy consumption, CO2 emissions and policy in the residential sector (with an overview of the top ten CO2 emitting countries), Renew. Sustain. Energy Rev. 43 (2015) 843–862.
[255] G. Clavel, J. Larionova, Y. Guari, C. Guérin, Synthesis of cyano-bridged magnetic nanoparticles using room-temperature ionic liquids, Chem. A Eur. J. 12 (2006) 3798–3804.
[256] D.R. MacFarlane, J.M. Pringle, K.M. Johansson, S.A. Forsyth, M. Forsyth, Lewis base ionic liquids, Chem. Commun. (2006) 1905–1917.
[257] M. Egashira, H. Todo, N. Yoshimoto, M. Morita, J.-I. Yamaki, Functionalized imidazolium ionic liquids as electrolyte components of lithium batteries, J. Power Sources 174 (2007) 560–564.
[258] C.A. Angell, N. Byrne, J.-P. Belieres, Parallel developments in aprotic and protic ionic liquids: physical chemistry and applications, Acc. Chem. Res. 40 (2007) 1228–1236.
[259] J. Ding, D.W. Armstrong, Chiral ionic liquids: synthesis and applications, Chirality 17 (2005) 281–292.
[260] L. Wang, A. Menakath, F. Han, Y. Wang, P.Y. Zavalij, K.J. Gaskell, O. Borodin, D. Iuga, S.P. Brown, C. Wang, Identifying the components of the solid–electrolyte interphase in Li-ion batteries, Nat. Chem. 11 (2019) 789–796.
[261] D. Ganguly, A.P. VS, A. Ghosh, S. Ramaprabhu, Magnetic field assisted high capacity durable Li-ion battery using magnetic α-Fe2O3 nanoparticles decorated expired drug derived N-doped carbon anode, Sci. Reports 10 (2020) 1–10.
[262] J.K. Koper, The influence of magnetohydrodynamic power on the deposition of silver dendrites on the titanium the surface of titanium after anodic oxidation, Int. J. Electrochem. Sci. 13 (2018) 699–707.
[263] J. Zhang, X. Zhu, M. Zeng, L. Fu, Magnetically controlled on-demand switching of batteries, Adv. Sci. 7 (2020) 2000184.
[264] P. Singh, N. Khare, P. Chaturvedi, Li-ion battery ageing model parameter: SEI layer analysis using magnetic field probing, Eng. Sci. Technol. 21 (2018) 35–42.
[265] W. Kordonski, S. Jacobs, Model of magnetorheological finishing, J. Intell. Mater. Syst. Struct. 7 (1996) 131–137.
[266] M. Kumar, A. Kumar, R.K. Bharti, H. Yadav, M. Das, A review on rheological properties of magnetorheological fluid for engineering components polishing, Mater. Today Proc. In Press (2021), https://doi.org/10.1016/j.matpr.2021.11.611.
[267] F. Gordaninejad, S.P. Kelso, Magneto-rheological fluid shock absorbers for HMMWV, in: Smart Structures and Materials 2000: Damping and Isolation 3989, International Society for Optics and Photonics, 2000, pp. 266–273.
[268] F. Fang, I. Jang, H. Choi, Single-walled carbon nanotube added carbonyl iron suspension and its magnetorheology, Diam. Relat. Mater. 16 (2007) 1167–1169.
[269] S.T. Lim, M.S. Cho, I.B. Jang, H.J. Choi, M.S. Jhon, Magnetorheology of carbonyl-iron suspensions with submicron-sized filler, IEEE Trans. Magn. 40 (2004) 3033–3035.
[270] Y.H. Kim, B.J. Park, H.J. Choi, Y. Seo, Coating of magnetic particle with polystyrene and its magnetorheological characterization, Phys. Status Solidi A 204 (2007) 4178–4181.
[271] B.J. Park, J.L. You, H.J. Choi, S.Y. Park, B.Y. Lee, Synthesis and magnetorheological characterization of magnetite nanoparticle and poly (vinyl butyral) composite, IEEE Trans. Magn. 45 (2009) 2460–2463.
[272] K. Shimada, H. Oka, Magnetic characteristics of magnetic compound fluid (MCF) under DC and AC magnetic fields, J. Magn. Magn. Mater. 290 (2005) 804–807.
[273] R.K. Sharma, S. Das, A. Maitra, Enzymes in the cavity of hollow silica nanoparticles, J. Colloid Interface Sci. 284 (2005) 358–361.
[274] W.H. Chuah, W.L. Zhang, H.J. Choi, Y. Seo, Magnetorheology of core–shell structured carbonyl iron/polystyrene foam microparticles suspension with enhanced stability, Macromolecules 48 (2015) 7311–7319.
[275] J.L. You, B.J. Park, H.J. Choi, Magnetorheological characteristics of carbonyl iron embedded suspension polymerized poly (methyl methacrylate) micro-bead, IEEE Trans. Magn. 44 (2008) 3867–3870.
[276] C. Fang, B.Y. Zhao, Q. Wu, N. Liu, K.A. Hu, The effect of the green additive guar gum on the properties of magnetorheological fluid, Smart Mater. Struct. 14 (2004) N1.
[277] S.-P. Rwei, J.-W. Shiu, R. Sasikumar, H.-C. Hsueh, Characterization and preparation of carbonyl iron-based high magnetic fluids stabilized by the addition of fumed silica, J. Solid State Chem. 274 (2019) 308–314.
[278] Y.-Q. Guo, C.-L. Sun, Z.-D. Xu, X. Jing, Preparation and tests of MR Fluids with CI particles coated with MWNTs, Front. Mater. (2018) 50.
[279] F.F. Fang, H.J. Choi, W. Choi, Two-layer coating with polymer and carbon nanotube on magnetic carbonyl iron particle and its magnetorheology, Colloid Polym. Sci. 288 (2010) 359–363.
[280] W.L. Zhang, S.D. Kim, H.J. Choi, Effect of graphene oxide on carbonyl-iron-based magnetorheological fluid, IEEE Trans. Magn. 50 (2013) 1–4.
[281] G. Wang, Y. Ma, G. Cui, N. Li, X. Dong, Two-dimensional Fe3O4/MoS2 nanocomposites for a magnetorheological fluid with enhanced sedimentation stability, Soft Matter 14 (2018) 1917–1924.
[282] V.R. Iyengar, A.A. Alexandridis, S.C. Tung, D.S. Rule, Wear testing of seals in magneto-rheological fluids©, Tribol. Trans. 47 (2004) 23–28.
[283] P. Wong, W. Bullough, C. Feng, S. Lingard, Tribological performance of a magneto-rheological suspension, Wear 247 (2001) 33–40.
[284] A. Bombard, F. Gonçalves, K. Shahrivar, A. Ortiz, J. De Vicente, Tribological behavior of ionic liquid-based magnetorheological fluids in steel and polymeric point contacts, Tribol. Int. 81 (2015) 309–320.
[285] P. Zhang, Y.Z. Dong, H.J. Choi, C.-H. Lee, Tribological and rheological tests of core-shell typed carbonyl iron/polystyrene particle-based magnetorheological fluid, J. Ind. Eng. Chem. 68 (2018) 342–349.
[286] A.J. Bombard, J. de Vicente, Boundary lubrication of magnetorheological fluids in PTFE/steel point contacts, Wear 296 (2012) 484–490.
[287] K. Shahrivar, A. Ortiz, J. De Vicente, A comparative study of the tribological performance of ferrofluids and magnetorheological fluids within steel–steel point contacts, Tribol. Int. 78 (2014) 125–133.
[288] W.-L. Song, S.-B. Choi, J.-Y. Choi, C.-H. Lee, Wear and friction characteristics of magnetorheological fluid under magnetic field activation, Tribol. Trans. 54 (2011) 616–624.
[289] P. Zhang, K.-H. Lee, C.-H. Lee, Friction behavior of magnetorheological fluids with different material types and magnetic field strength, Chinese Journal ofMechanical Engineering 29 (2016) 84–90.
[290] J.A. Ruiz-López, R. Hidalgo-Alvarez, J. de Vicente, On the validity of continuous media theory for plastic materials in magnetorheological fluids under slow compression, Rheol. Acta 51 (2012) 595–602.
[291] D.W. Felt, M. Hagenbuchle, J. Liu, J. Richard, Rheology of a magnetorheological fluid, J. Intell. Mater. Syst. Struct. 7 (1996) 589–593.
[292] O. Volkova, G. Bossis, M. Guyot, V. Bashtovoi, A. Reks, Magnetorheology of magnetic holes compared to magnetic particles, J. Rheol. 44 (2000) 91–104.