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Magnetorheological fluids: A concise review of composition, physicochemical properties, and models

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Abstract

Magnetorheological fluids (MRFs) are classified as intelligent materials whose rheological and mechanical properties can be modified by interaction with an external magnetic field. These unique features allow for a controlled change of their viscosity, which is applied in technology to build adaptive devices and effectively suppress vibrations in various mechanical systems. In this paper, we overview and discuss our previous results regarding advances and physicochemical MRF properties in the context of broader literature. We concentrated on such properties as flow, yield strength, and viscoelastic behavior under shearing flows. We briefly discussed continuum and discrete MRFs modeling. Since the magnetic core is mainly based on iron or its compounds, depending on its chemical composition, morphology, stabilizing agents, and the liquid medium's viscosity, its rheological and micromechanical properties can be moderated. To predict the behavior of such a fluid, it is necessary to propose and implement an appropriate model. Simple models like Bingham can consider the quasi-static and dynamic behavior of the MRFs, while discrete models are applied to the development and implementation of the MRF control algorithms. Thus, analytical and numerical simulation compromise the accuracy, quantity of considered phenomena, and computational cost.

Keywords

Magnetorheological Fluids (MRF), rheology, smart materials, intelligent fluid, functional materials

1. Introduction

Magnetorheological Fluids (MRF) belong to one of the most functional materials, which are determined as fluids fast change in a few milliseconds, the rheological and micromechanical properties under the application of the external excitation in the form of the magnetic or electrical field (Acharya et al., 2021; Jaafar et al., 2021). For that reason, they are also classified as smart/intelligent materials. Magnetorheological Fluids are non-colloidal suspensions of micron-sized magnetically polarizable particles in the carrier fluid (Rabinow, 1948a, 1948b), where the carrier fluid is a non-magnetic component, mainly oils. Depending on the application, the temperature range of MRFs operation is −40°C to 150°C. In the absence of external excitation (so-called "off" state), their nature is similar to known liquids, and their viscosity remains in the range of 0.1–1.0 Pa s (Bell et al., 2007). When an external magnetic or electric field is applied (so-called "on" state), their apparent viscosity begins to increase. The MRF magnetic response is based on this viscosity change under the external field through the formation of the chain-like structure (Ashour et al., 1996). In this case, fluid starts to behave quasi-statically as solid-like structures of

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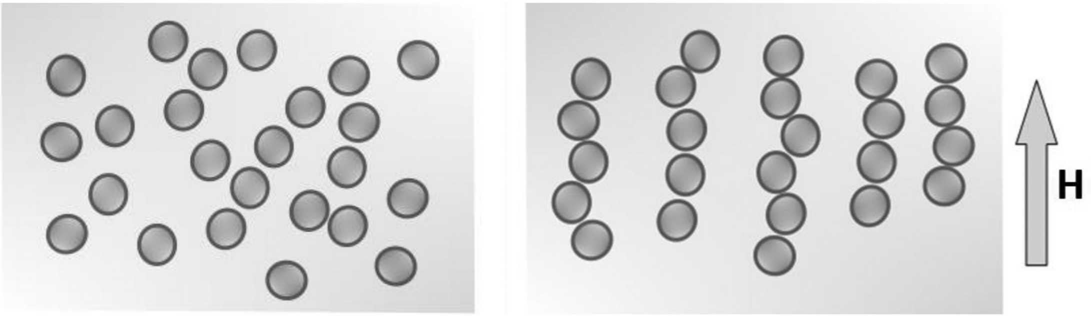


(a) (b)

Figure 1. Magnetic particles ion MRF: (a) without the magnetic field and (b) under the magnetic field (H).

fibril shapes. It is caused by the inter-particle dipole-dipole interactions (attractions) between particles parallel to the applied magnetic field, where along with the change of the direction of the magnetic field, the direction of the chain-like structures changes.

In recent decades, considerable effort has been made to model the Magnetorheological Fluids, particularly in the context of yield stress regarding as the most important parameter of MRFs strongly depends on the applied magnetic field and volume fraction of the magnetic nanoparticles (Khajehsaeid et al., 2022). There are several models proposed for the determination of the dependency of the MRF's yield stress on their above-mentioned parameters—magnetic field and volume fraction of magnetic particles. Claracq et al. (2004) proposed based on their experiments the exponent 1.5 dependencies between the yield shear stress τ_y and the strength of the applied magnetic field H

$$\tau_y \propto \sqrt{H^3} \tag{1}$$

In turn, in Vereda et al. (2011) the equation for determination of the yield stress τ_y depending on the particle magnetization M_p and particle fraction φ as follows

$$\tau_y = 2.19 \times 10^3 \phi \langle M_p \rangle \tag{2}$$

was proposed.

There are several studies on the dependency of the yield stress τ_y on the particle fraction φ and the strength of the applied magnetic field H (Bossis et al., 2002), and based on their results the general formula can be written (Khajehsaeid et al., 2022):

$$\tau_y \propto \phi^n H^m \tag{3}$$

where:

- there is a linear dependency for particle volume fraction $n = 1$;
- $m = 0$ means that the saturation magnetization is achieved and the value of yield stress does not change with the applied magnetic field;

$m = 2$ and $m3/2$ are applied for linear magnetic materials at low and intermediate magnetic fields respectively (Khajehsaeid et al., 2022).

In Rosensweig (1995) the static stress is described by a mean-field continuum model. In Bossis et al. (1997) the yield stress of an MRF based on a mesoscopic description of the organized microscopic structures is calculated. Jolly et al. (1996) have improved a quasi-static, one-dimensional model, while in Ginder et al. (1996) the nonlinearity effect was included in the descriptions of magnetization and the field distribution of chain-like structures. It is known that without the magnetic field, they behave often like Newtonian fluid (Bica, 2006) while in the presence of an external magnetic field MRF can turn into non-Newtonian fluid (Kumar et al., 2022). The strength of the chain-like structures increases with the rise of the magnetic field just within milliseconds leading to increased viscosity due to the formation of chain-like structures, see Figure 1.

Under the adjusted magnetic field, the viscosity can be increased many times with stable shear resistance (An et al., 2017; Susan-Resiga et al., 2012). The same behavior is observed for the shear stress of MRF that increases with the applied external magnetic field until becoming field-independent. MRF is usually made of ferromagnetic, ferrimagnetic, or superparamagnetic colloidal suspension dispersed in liquid media like oil (Elizabeth Premalatha et al., 2012; Galindo-Gonzalez et al., 2016; Jinaga et al., 2019; Zhu et al., 2019), so the magnetic properties of the MRF depend on magnetization. Although MRF reveals the ability to respond rapidly to the magnetic field, they tend to sediment, decreasing their long-term stability (Park et al., 2009; Prajapati and Lakdawala, 2022; Wereley et al., 2006). For that reason, much progress has been made toward improving the stability of the MRF, including fluids differing from iron particles-based have been investigated (Guo et al., 2018; Seo et al., 2016).

According to unusual properties, Magnetorheological Fluids are widely applied in different branches of industry (Ahamed et al., 2018), in particular in many commercial devices, especially operating on the LORD Corporation's MR fluids (Ashtiani and Hashemabadi, 2015; Dyniewicz et al., 2014; Kciuk and Turczyn, 2006; Mangal and Kumar, 2015). Most of the applications are based on mechanical devices like clutches (Johnston et al., 1998; Olszak et al., 2019), seals (Zhou et al., 2020), shock absorbers, (Deng et al., 2019; Yoon et al., 2020; Zhong et al., 2020), vibration dampers (Carlson and Charzan, 1994; Wang et al., 2018; Wei et al., 2020; Yuan et al., 2019), valves (Hu et al., 2019), brakes (Wu et al., 2018; Zhu and Geng, 2018), or even seismic vibration dampers (Caterino et al., 2022; Christie et al., 2019; Gordaninejad et al., 2002; Jung et al., 2003; Li et al., 2007; Liu et al., 2001, 2005; Zareie et al., 2022) to reduce different vibrations. They offer quiet, rapid-response, and simple interfaces between the mechanical and electronic systems used for mechanical energy dissipation. MRF is also applied in the adoption of earthquake mitigation in civil engineering (Hamidia et al., 2022; Kurata et al., 1998; Xu and Guo, 2008; Xu et al., 2013). As the MRF is placed in the shear-valve mode dampers fast-dynamic energy dissipation is possible with the low power requirements. Another, the application field is connected with physical security in the form of body armor (Kang et al., 2015). An interesting MRF application in the medical sector as a single-port laparoscopic surgery was shown (El Wahed, 2020).

In this paper, we overview experimental results regarding advances and physicochemical MRF properties like flow, yielding, and viscoelastic behavior under shearing flows. We also briefly discuss continuum and discrete MRF modeling. Particular emphasis was placed on new measurement techniques that enable the measurement of the properties of MRFs and theoretical models. The paper is organized as follows. In Section 2, we briefly review the micromechanical properties of the Magnetorheological Fluids. In Section 3, we present different MRFs chemical compositions, including stabilization and tribological properties. Section 4 contains the measurement techniques of the MRFs rheological and micromechanical properties like magnetorheometry and split-Hopkinson pressure bar. In Section 5 we consider several continuums, and discrete MRF modeling approaches. Section 6 includes plans and the final remarks.

2. Micromechanical properties

Several factors influence the Magnetorheological Fluids' rheological properties, that is external factors (shear flow, temperature, compression, magnetic fields, and boundary conditions) (Hemmatian et al., 2020; Li et al., 2002; Pei and Peng, 2021) and intrinsic factors (properties of the magnetic particles, viscosity of the carrier fluid, and type of additives) (Jung et al., 2016; Zhang et al., 2021), see Figure 2. Thus, MRFs can be characterized by several micromechanical properties, including flow, yield strength, viscoelastic behavior under shearing flows (de Vicente et al., 2010). One of the most important MRF properties is yield strength (also called yield stress), which is the minimum stress value required to start the flow. It is proportional to the force required to break up field-induced structures, that is particle chains. Typical commercially available MRF yield strength varies in the range of 0–100 kPa (Wang and Meng, 2001). Yield strength is mainly dependent on the volume fraction and the saturation magnetization increasing with an increase in the magnetic field intensity, where the average value of that parameter for iron-based magnetic carriers is about $\mu_0 M_s = 2.1$ T average (Ghaffari et al., 2015). Moreover, it is also determined by the type of MRF stabilizer. It can be determined experimentally, directly, or, indirectly, including steady shear and oscillatory tests (Terkel et al., 2022). There are three types of yield strength, that is elastic-limit yield strength, static yield strength, and dynamic yield strength. The first one is the maximum shear stress that can be applied for complete recovery after the stress has been removed. The second is the minimum stress that will cause the fluid flow, and it is determined by the creep test. The third one is the stress after applying which plastic deformations and thermal effects begin to occur in the material. It can be calculated using the models presented in Section 4.3 The modeling of Magnetorheological Fluid. Depending on the model the yield strength may increase linearly with increasing volume fraction (Ginder and Davis, 1994; Ginder et al., 1995, while at raising high volume fractions, the yield stress increases exponentially (Chin et al., 2001; Volkova et al., 1998). In turn, in Lee and Chang (2020) the devices for MRFs shear force measurement, which enables a determination of the relationship between yield stress and magnetic flux density, were proposed. Modeling and experimental validation

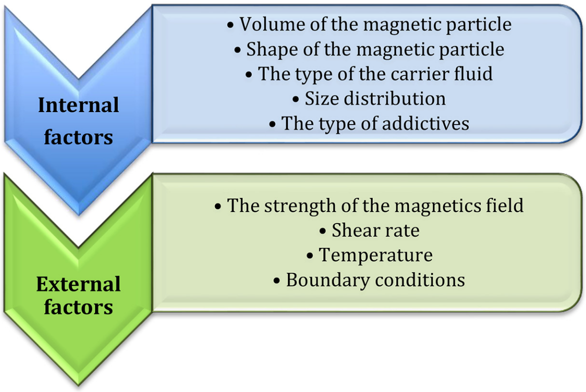


Figure 2. Factors influencing the properties of the Magnetorheological Fluids.

of the fluid flow subjected to a magnetic field under consideration of static and dynamic yield strength was presented in Upadhyay and Choi (2021).

Since MRFs shear stress and viscosity depend on the temperature, this also translates into the effectiveness of the suspension. The shear stress increases with the magnetic field strength increases under the same temperature condition, while it declines with the temperature growth under the same magnetic field strength, in particular, in the range of −40°C to 100°C (Chen et al., 2015). In Rabbani et al. (2015) it was shown that the maximum yield stress increased rapidly when the temperature or the magnetic field strength decreased. Moreover, the critical temperature corresponding to the maximum dimensionless viscosity depends on the shear rate and the magnetic field strength (Li et al., 2022). The effect of temperature also depends on the MRF type, some can decompose at around 100°C and others thicken during working after high or low-temperature cycles (Chen et al., 2015). The medium viscosity influences the sedimentation rate of the dispersed particles. In Ruiz-López et al. (2012) it was shown that the concentration of the particles is significantly more important than the viscosity of the surrounding fluid. Thus, MRF thermal conductivity increases with the increase of the magnetic field strength and the increase of the percentage of particles in the total volume of the fluid (Rahim and Ismail, 2015). The spherical shape of magnetic particles causes the smallest increase in thermal conductivity (Timofeeva et al., 2009). As a consequence, the replacement of spherical particles with cylindrical particles or the introduction of a cylindrical additive will have a positive effect on thermal conductivity. The improvement of the conductivity coefficient with increasing thermal temperature is connected with particle size reduction (Teng et al., 2010). On the other hand, even a 10% rise in the volume ratio of magnetic particles in the MRF can change the results for even one order of magnitude of the rheological properties (Lim et al., 2010).

3. Formulations

It is known that MRFs are composed of two phases: solid particles that can be attracted by the magnetic field and non-magnetizable fluid being a medium for particles (Jaafar et al., 2021). Taking into account good magnetic properties and tunable structures a wide variety of magnetic particles, in particular sizes in the range from 0.1 to 20 μm, have been applied as MRFs compounds (de Vicente et al., 2011; Genc, 2022). Thus, the most preferred magnetic particle size is a range of 1–10 μm, while smaller particle sizes do not provide sufficient yield strength, and bigger particle sizes generate problems with sedimentation (Pei and Peng, 2022). According to the magnetic properties, the most common magnetic particles occur in ferromagnetism, while also superparamagnetic particles can be used (Osial et al., 2022). In turn, fluid phases are commonly used in silicone oils (Chae et al., 2016), mineral oils, lubricant oil (Kim et al., 2011), vegetable oils, liquid paraffin, petroleum, kerosene, poly-alpha olefin synthetic oil, polyesters, polyethers, synthetic hydrocarbons, ionic liquids (Guerrero-Sanchez et al., 2007), glycol, perfluorinated polymers, poly (phenyl ethers), high alkylated cyclopentanes, or water (Cheng et al., 2009. Commercial MRFs and most investigated MRFs are based on carbonyl iron magnetic particles (CI), with typical yield stresses of 30–60 kPa for a magnetic induction of 0.4–0.6 T (Gorodkin et al., 2009; Guo et al., 2018; Kciuk et al., 2009), which provides high magnetic permeability and large saturation magnetization (Ashtiani and Hashemabadi, 2015). Carbonyl iron nanoparticles are mostly obtained in spherical or fiber shapes via the thermal decomposition of iron pentacarbonyl compounds usually (de Vicente et al., 2011). The spherical shape allows for reducing the wear effect on the walls where MRFs are utilized to work. However, the fiber-shaped CI nanoparticles exhibit higher yield strength and low off-state viscosity (de Vicente et al., 2011; Kumar et al., 2019; Kwon et al., 2019). The specific magnetic susceptibility of CI linearly depends on particle size and as Gorodkin et al reported for particles in the range between 1 and 9 nm the magnetic susceptibility varied (Gorodkin et al., 2009) with the increase of particle size. Moreover, Kim et al. (2011) obtained viscoelastic MF fluids based on soft magnetic CI dispersed in a polyisobutylene (PIB)/polybutene (PB) solution known as a Boger fluid. Such prepared MR fluid showed typical MR features and thanks to the elastic properties of PIB/PB matrix medium exhibited better sedimentation stability.

Apart from CI nanoparticles, also iron (II and III) oxide (Fe_3O_4) (Choi et al., 2020; Osial et al., 2022), iron (Fe), and Fe-based alloys like FeCo, Ni-Fe, FePt, and iron-based composites are reported to be used in MRF. The response of the MRF under the external magnetic field mainly depends on the magnetic properties of the particles, although the size and shape of particles have a significant influence on the magnetic properties of magnetic particles (Gutiérrez et al., 2021).

One of the crucial MRFs issues is sedimentation due to the density mismatch between the magnetic particles and carrier fluid. For that reason, magnetic particles are widely substituted with materials having a lower density than iron particles. One of them is iron oxide in magnetite (Fe_3O_4), magnetite (Fe_2O_3), or iron alloys (Kim et al., 2016; Pei et al., 2019; Ruan et al., 2017). Metal and metal oxide-based particles of that material can be obtained with controlled shape and size within several methods (Ashtiani and Hashemabadi, 2015; Hilgendorff and Giersig, 2003; Rybczynski et al., 2003), where the most common is the sol-gel method from

Table 1. The summary of the chemical composition of the Magnetorheological Fluids.

Chemical composition of the Magnetorheological Fluids

Reference	Carrier fluid	Reference	Magnetic particles
Chae et al. (2016), Dong et al. (2012)	Silicone oils	Bossis et al. (2016), Cheng et al. (2009), Choi et al. (2006), Fang et al. (2012), Gorodkin et al. (2009), Guo et al. (2018)	Carbonyl iron
Kim et al. (2011)	Mineral oils	Choi et al. (2020), Kim et al. (2016), Osial et al. (2022), Shimada and Oka (2005)	Iron (II and III) oxide (Fe_3O_4)
Kim et al. (2011)	Lubricant oil	He et al. (2020)	Fe-based alloys like FeCo, Ni-Fe, FePt iron (Fe) iron-based composites
Guerrero-Sanchez et al. (2007)	Silicone oils		
Guerrero-Sanchez et al. (2007)	Vegetable oils		
Guerrero-Sanchez et al. (2007)	Liquid paraffin	Choi et al. (2020), Kim et al. (2016), Osial et al. (2022)	Iron (II and III) oxide (Fe_3O_4)
Guerrero-Sanchez et al. (2007)	Petroleum	Elizabeth Premalatha et al. (2012), He et al. (2020)	Fe-based alloys like FeCo, Ni-Fe, FePt iron (Fe)
Guerrero-Sanchez et al. (2007)	Kerosene		
Guerrero-Sanchez et al. (2007)	Poly-alpha olefin synthetic oil	Reference	Additives
Guerrero-Sanchez et al. (2007), Park et al. (2001), Rankin et al. (1999)	Polyesters	Elizabeth Premalatha et al. (2012)	Grease
Guerrero-Sanchez et al. (2007)	Polyethers	Zhang et al. (2009)	Thixotropic agent emulsifiers
Cheng et al. (2009)	Synthetic hydrocarbons		Tween-80
Cheng et al. (2009)	Ionic liquids	Zhang et al. (2009)	Span-80
Cheng et al. (2009), Fang et al. (2007, 2009)	Perfluorinated polymers,		Single wall carbon nanotubes (SWCNT)
Cheng et al. (2009), Lim et al. (2004)	Poly (phenyl ethers)	Zhang et al. (2009)	Graphite nanofiber
Cheng et al. (2009)	High alkylated cyclopentanes		
Cheng et al. (2009)	Glycol		
Cheng et al. (2009), Kim and Choi (2022)	Water		

solutions through gel intermediates (Chae et al., 2016) and co-precipitation method from the solutions containing the source of metal ions (Osial et al., 2022). On the other hand, Magnetic Nanoparticles (NPs) based on iron oxide (Fe_3O_4) have received considerable attention according to their excellent characteristics like relatively high magnetization saturation in comparison to the classical iron-based MRFs, and small hysteresis values (Espin et al., 2005; Rabbani et al., 2019). Despite the wide application of micron-sized particles in classical MRF, recent studies show the high potential of nano-sized particles in MRF preparation (Chae et al., 2015; Saha et al., 2019; Wu et al., 2016). They can be formed even in nanosize, have low density, and are easily functionalized and exhibited, resulting in better stability in Magnetorheological Fluids (Worden et al., 2015). To solve the problems related to MRFs stability, various chemical modifications were applied, for example, Fe_3O_4/PMMA composite (Cao et al., 2008), which contribute to the increase of the fluid stability and reduction of the density of the magnetic particles. An interesting modification is Fe_3O_4-modified nanolignocellulose (Fe_3O_4/NLC) composite fiber, which offers unique advantages such as low density, soft magnetism property, and high specific surface (Shixu et al., 2021; Wang et al., 2020). The summary of the MRFs chemical composition was shown in Table 1.

4. Stabilization and tribological properties

Another critical factor, which determined the MRFs effectiveness under the application toward dynamic energy dissipation is stability (Kumar et al., 2019; Peng et al., 2006; Prajapati and Lakdawala, 2022). That parameter is dependent on multiple factors and usually decreases in function of time, and changes under the large magnetic field-induced yield stress. Magnetic particles interact between themselves leading to the agglomerates formation and following settlement due to the structural reinforcement and larger dynamic moduli with an increase of the magnetic particle content in MRF. To increase the stability several methods are applied, including commonly applied core-shell structures, where the functional groups present on the surface of magnetic particles repulse particular particles increasing the stability of MRF (Zhang et al., 2021).

Another technique is to change the shape and size of the particles. de Vicente et al. (2010) was shown that rod-like magnetic particles have had a larger storage modulus and yield strength, while flake-like particles affect the reduction of MRFs viscosity (Laherisheth and Upadhyay, 2017).

Magnetic particles are widely coated with surfactants fulfilling the function of preventing their aggregation due to magnetic interactions. In Chae et al. (2016) the stability of the colloidal suspension is suppressed with the treatment of iron oxide with dodecyltrimethoxysilane (DTM) leading to the formation of the core-shell $Fe_3O_4@SiO_2$ particles (Chae et al., 2016). The silica-based coating can be also formed from other precursors like poly(trimethylsilyloxyethyl) (PHEMATMS) (Aruna et al., 2021; Cvek et al., 2018). The addition of surfactants reduces the interfacial tension at the magnetic particle-liquid medium surface and increases wettability, where the surfactant contains both, the polar and nonpolar groups (Lijesh et al., 2016; Son, 2018; Wu et al., 2016). Besides many compounds as surfactants mainly organic acids are used having carboxyl group but different carbon chain lengths like citric acid, stearic acid (Yagnasri et al., 2021), oleic acid (Charles, 2002; López-López et al., 2005; Sarkar and Hirani, 2015), palmitic acid (Ashtiani and Hashemabadi, 2015; Fonseca et al., 2016; Rabbani et al., 2015), myristic (Ashtiani and Hashemabadi, 2015; Carlson and Jolly, 2000), and lauric acid (Ashtiani and Hashemabadi, 2015; Bica et al., 2007; Carlson and Jolly, 2000; Huang et al., 2015). Surfactants improve the interfacial activity of magnetic particles and their dispersion. Besides organic acids, magnetic particles are widely coated with polymers. Their addition can improve the yield strength, stability, and durability of the MRF.

Stability enhancement can be also achieved by coating magnetic particles with polymers. The literature points out many different polymers for that purpose including polydimethylsiloxane bis(3-aminopropyl) (Fei et al., 2020), polystyrene (Park et al., 2001), styrene isoprene block copolymer, organogelatore—N,N,N″,N′″-1,2,4,5-tetra alkyl/alkenyl pyromellitamide (PMDA-R) with two 2-ethyl hexyls and two oleyls as branched alkyl groups (Quan et al., 2014), poly(methyl methacrylate) (PMMA) (Cao et al., 2008; Kaide et al., 2021), poly(butyl acrylate) (PBA) (Jiang et al., 2010), poly (vinyl butyral) (PVB) (Mrlik and Pavlinek, 2016), poly (glycidyl methacrylate) (PGMA) (Cvek et al., 2015; Kwon et al., 2019; You et al., 2007), polyimide gels (Kim et al., 2014), polyethylene glycol (PEG) (Dong et al., 2011; Fuchs et al., 2005; Quan et al., 2014).

In Armijo et al. (2015) the guar gum is used as a stabilizer of the magnetic particles. The addition of natural polymers improved the sedimentation stability and also strengthened the yield stress of the MR fluid (Wu et al., 2006). Literature also refers to the high effectiveness of that green additive (Wu et al., 2006). In Fang et al. (2005) guar gum and xanthan gum are shown as low-cost additives offering not only economic benefits but also maintaining the promising performance of the MRF that can be effectively used for engineering applications demanding controllability in operations. In Sukhwani and Hirani (2007) xanthan gum was used as a shell coating the carbonyl iron (CI)-based suspension reducing the density gap between the medium oil and dispersed particles (Sukhwani and Hirani, 2007). Arabic gum is also proposed in the literature as an effective stabilizer improving rheological properties (Alghamdi et al., 2014; Kwon et al., 2019; Sim et al., 2013).

Another group of compounds that offer enhancement of the stability and performance in the magnetic field is conducting polymers, widely used also in electrorheological fluids. In Turczyn and Kciuk (2008) polyaniline (PANI) which is a well-known electrically conducting material is used as a coat of particles. Its application decreases the base viscosity and has a negligible influence on the MR properties under an external magnetic field. It offers the change in the viscoelastic properties in the small-strain oscillatory shear flow (Kim et al., 2008; Sedlačík et al., 2010) proposed using it as polyaniline (PANI)/nano-sized Fe_3O_4 composite, while in 2020 (Kim et al., 2020) also presented its effectiveness in the MRF. PANI is widely applied in literature for its cost-effective synthesis, good thermal stability, and electrical conductivity (Kim et al., 2020). In Kwon et al. (2016) the polypyrrole (PPY) was used as a nanosized coat of magnetite, where the weight ratio was adjusted to 5% to avoid possible deterioration of the magnetic properties of the Fe_3O_4 particles. In Fang et al. (2013) poly(diphenylamine) (PDPA) is proposed as a shell coating $ZnFe_2O_4$ toward the effective shear and dynamic response. improvement of the dispersion stability of the MR fluid.

To increase the stability of MRF also the following thixotropic agents can be added to the MR suspension (de Vicente et al., 2003; Kang et al., 2015): ferrous oleate, lithium stearate, Aerosil 200, Arsil 1 100 (Xu et al., 2018), ferrous naphthalate or ferrous oleate, fumed silica (Aruna et al., 2021), wormlike surfactant micelles (Wu et al., 2006), polystyrene (Dorosti et al., 2020; Kumbhar and Patil, 2014; Quan et al., 2014), microcrystalline cellulose (Chuah et al., 2015), nanowires (Pu and Jiang, 2005), silica nanoparticles (Bae et al., 2017) fullerene powder, carbon nanotubes, graphene nanoplatelets, and others (Cvek et al., 2018). Another way to enhance MRFs stability is applied as a media poly(vinyl pyrrolidone) and carbon nanotubes (Ngatu et al., 2008), ionic liquids (Pu and Jiang, 2005) compounds like aluminum stearate (López-López et al., 2005) tetramethylammonium hydroxide (Fonseca et al., 2016), soy lecithin (Kolekar et al., 2019), N-glucose ethylenediamine triacetic acid (GED3A) stearate and oleate (Chin et al., 2001; Kolekar et al., 2019),

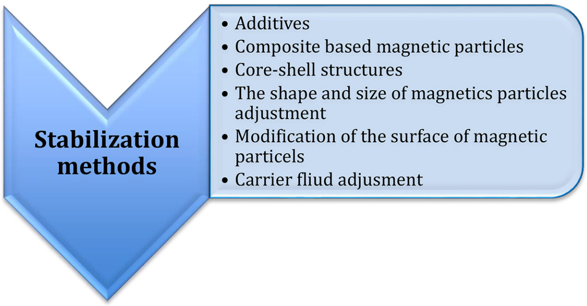


Figure 3. The summary of the MRF stabilization methods.

emulsifiers like Tween-60, Span-60, OP emulsifier, Tween-80, and Span-80 (Zhang et al., 2009), n-tetradecyltri-ethoxysilane, diethyl-n-octyl-, and n-tetradecylphos-phonates (Belyavskii et al., 2006), oleylamine (Fei et al., 2020; Lu et al., 2016; Song et al., 2009), hydrophilic carbon shell (Lu et al., 2016).

To overcome the sedimentation and agglomeration problems graphene oxide nanoparticles (GO NPs) are also added to the MRFs. The addition of GO NPs improves particle dispersion and reduces MRFs' gravity (Chen et al., 2014). GO NPs exhibit similar physical properties to CNTs however their surface area is much larger and their production costs are lower compared to CNTs which makes them a better additive material for MRFs (Zhang and Choi, 2012).

The MRF is also made of composites coupling the magnetic particles with non-magnetic materials to improve the sedimentation stability and obvious magnetorheological behaviors like apparent viscosity depending on the applied field. In Wang et al. (2021) carbon nanotubes (CNT) are coated with iron oxide CNT/Fe_3O_4 nanocomposites reducing the apparent density of the material and improving the stability of the obtained MRF. Fei et al. (2020) was shown that MRFs have good sedimentation stability in the case when surfactants are based on sodium lauryl alcohol phosphate, compound sodium fatty acid methyl ester sulfonate, ethylene glycol monostearate, and glyceryl monostearate. Moreover, the optimal proportion of additives includes sodium lauryl alcohol phosphate (1.5 wt%), compound MES (1.0 wt%), ethylene glycol monostearate (1.5 wt%), glycerol monostearate (1.5 wt%), and hydrophobic fumed silica (1.0 wt%). On the other hand, the results obtained by Di et al. (2022) indicated that Fe_3O_4 nanospheres-based MRF is characterized by greater sedimentation stability than CI particles-based ones. An interesting solution based on the bi-dispersed magnetic grease was proposed by Hu et al. (2022). It turned out that the addition of bentonite increased the stability by 17.873%. To assess the effect of additives on sedimentation, the indicator was proposed by Prajapati and Lakdawala (2022). Also, the redispersion index was determined.

The tribological behavior of silicon oil-based MRF was analyzed by Jang et al. (2010). It turned out that compounds like molybdenum disulfide and graphite can reduce the friction coefficient, while polytetrafluoroethylene (PTFE) contributes to the increment in both, wear resistance and friction coefficient. Besides the improvement of stability, the addition of the surfactants also improves the polishing properties MRF also has excellent polishing properties (Kittipoomwong et al., 2005). The summary of the methods, which are used as stabilization techniques was presented in Figure 3.

The rheology of MRF under the magnetic field depends, inter alia, on the shape and size distribution of magnetic particles (Foister, 1997; Ghaffari et al., 2015). In Weiss et al. (2000) and Lemaire et al. (1995), it has been shown that MRF containing particles of two different diameters (i.e. average diameters of 1.25 and 7.9 μm) exhibit higher field yield strength than monodisperse ones. For the small size of the magnetic particles, the yield stress is strongly enhanced with the increase in the particle size (Wu and Conrad, 1998). In turn, Bell et al. (2007) it was presented that bidisperse Electrorheological Fluids (ERFs), which contain two different diameters (i.e. average diameters of 6 and 100 μm) exposed to the field manifest smaller yield stresses than monodisperse ones. The apparent yield strength of MRFs containing, both spheres, and wired magnetic particles is comparable, while the high values of the external magnetic field contribute to the fact that any effects resulting from shape anisotropy will be masked (Hagenbüchle and Liu, 1997).

Regarding the chain formulation, in Anupama et al. (2019) field-induced chain formation in the dilute MRFs using dynamic light scattering in the context of chain length was investigated. MRF with a lower concentration of magnetic particles (i.e. bidisperse Mn–Zn ferrite spherical particle) form a single chain, and consequently, the fluid has less strength. High concentrations of magnetic particles lead to the formation of stronger and thicker chains, resulting in larger yield strength (Portillo and Iglesias, 2017). Moreover, Kumar et al. (2019) it has been experimentally shown that the addition of magnetic nanoparticles increases the yield strength, while nanoparticles occupy voids between the microparticles and form regular chains when the external magnetic field is applied. It turned also out that shear stress is greater in the case of MRF with magnetic nanoparticles included (Portillo and Iglesias, 2017). According to the superparamagnetic-based MRF, Brownian motion influences the particles much less than the interactions between particles and with the external magnetic field. The dynamics of the particles in presence of the magnetic field is decreasing with the rise of the particle's concentration or decrease of their size. Theoretical and experimental data presented by Donado et al. (2017) show that the distribution of the chain length over time has a significant effect on the rheology of MRF and it is decreasing exponentially.

According to the sedimentation, the kinetic characteristics of the MRF are under extensive study in the literature including the initial spatial distribution of particles, interparticle interactions, and concentration dependence effect on the stability and relaxation of the MRF (Raikher and Shliomis, 1993). Consequently, the kinetics of aggregation and disaggregation in MRF is of key importance in practice because it governs the control process (turn-on and turn-off response times). One of the most promising magnetic particles for the MRF application, in this case, are superparamagnetic materials offering not only a lower density mismatch but also a lack of the magnetic memory of the colloidal suspension. Besides many factors affecting the kinetics of the MRF is the control over particle size, size distribution, the thickness of the surfactant layer, and the response of the material to the presence of the magnetic field (Giersig and Hilgendorff, 2005). The first model of the kinetics of chain formation under the magnetic field has been developed by See and Doi (1991) while it is based on the magnetizable particles model. Based on ferromagnetic particles many other models describing the evolution of the chain structure due to the chain–chain aggregation was described (Bossis et al., 2011).

It is known that MRFs present not only hydrodynamic interactions of particles or external forces but also electrostatic interactions. For the superparamagnetic-based suspensions, the main feature influencing the aggregation and disaggregation of the MRF is based on the surface potential of the coated suspension. Particles coated with organics maintain certain functional groups leading to the repulsion between the same groups of two particles. In the case of the aqueous-based superparamagnetic suspension addition of salts deliver additional charges to the system leading to increased stability of the fluid due to the increased electrostatic interactions among the chains and between particles (Domínguez-García et al., 2011). Aggregation and disaggregation, as well as the stability of the MRF in the organic media, can be improved with the surfactants as well, and the application of bidisperse particles brings superparamagnetic suspension and the commercial CI particles at the same MRF. In that case, the electrostatic interactions between particles provide better chaining properties and protection against agglomeration and sedimentation (Nejatpour et al., 2020).

Formation of the organic coating can be performed within the chemisorption, for example, adsorption of stabilizers onto the surface of magnetic particles mainly in the hydrophobic solvents, physisorption within the application of organic salts in polar organic solvents like THF, or charging of the magnetic particles within the application of the compounds in aqueous media (Giersig and Hilgendorff, 2005). Depending on the coating the chain-like structures in presence of a magnetic field can be arranged not only to the formation of single chains but even well-arranged 2D hexagonal ordered domains that create larger 3D structures. In presence of high magnetic fields, magnetic particles can form multi-dimensional structures ranging even micron size (Giersig and Hilgendorff, 2002).

Magnetic colloids can be also influenced by different parameters associated with the sample preparation or even drying including the particle's concentration in the suspension, the viscosity of the media, vapor pressure, surface tension of the solution, temperature, pressure, and even the substrate that is used to dry particles. All these features may affect the formation of the size and shape of particles leading to the formation of different chain-like structures under the magnetic field (Hilgendorff et al., 2001).

The kinetics of the aggregation, disaggregation, and sedimentation for superparamagnetic particles is also dependent on the thickness of the oxides coating magnetic metal-based particles (Wiedwald et al., 2003). The formation of the passivation layer onto the metal core opens possibilities for chemical modifications with organic shells. Wiedwald and co-authors indicate that the magnetic properties of the cobalt particles and Co/CoO, like the magnetic moment the local magnetic anisotropy energy, as well as the sign and magnitude of the magnetic coupling, depending on the type of chemicals used for magnetic particles formation, especially when the metal-based particles are coated with oxides. Authors present that depending on the experimental conditions the oxides shell thickness can be controlled and make it possible to easily tailored with the organic shell (Wiedwald et al., 2005). In other work, it is described that the organic coating makes it possible to manipulate the magnetic moment and magnetic properties of the nanosized magnetic particles in the MRF including the blocking temperature. Haracz et al. (2015) describe an influence of the magnetic behavior of particles within the application of various ligands presenting the correlation of the dynamic response of the superparamagnetic particles based on cobalt with the relaxation time. Authors show the influence of the oleic acid (OA), cethyltrimethylammonium bromide (CTAB), sodium hyaluronan (HA), and modified polyacrylic acid (mPAA) and O-(2aminopropyl)O′(2-methoxyethyl)polypropylene ethylene glycol (PEG) coat on the interactions between particles indicating that the magnetic properties of the particles changes. They show that the application of the OA over CTAB increases blocking temperature likewise the HA over mPAA-PEG. The nanoparticles coated with mPAA-PEG and HA are superparamagnetic, while in presence of the two other shells the interactions between particles increase decreasing the relaxation time. Based on the literature it is seen that the kinetics of MRF is mainly dependent on the shape and size of the magnetic core as well as the chemical composition.

MR fluids have been classically investigated within several techniques for the determination of their physicochemical including composition, stability, durability (Desrosiers et al., 2013; Lucking Bigué et al., 2019), and rheological properties (Frąś, 2015; Gabriel and Laun, 2009; Güth et al., 2013; Laun and Gabriel, 2007; Wang et al., 2008) like shearing flow conditions (Maurya and Sarkar, 2021) or dynamic energy dissipation.

MRF is known for being strain-rate dependent on the viscoplastic behavior of the magnetic suspension in the liquid media that is highly sensitive to mechanical stress (Church et al., 2014). Due to its ability to dissipate dynamic energy, MRF can be investigated with the Split Hopkinson Pressure Bar (SHPB), known in the literature as the Kolsky bar. That technique enables testing the compression response, principally of metals, but more recently for polymers and MRF (Lim et al., 2010; Panowicz and Janiszewski, 2016; Shim and Mohr, 2009).

Initially, Kolsky (Chen et al., 1999) generated the stress waves in the incident bar with detonation and condenser microphones, while over decades, this technique was modified (Wang et al., 2016) to measure the dissipation of the dynamic energy of the material undergoing deformation at a high strain rate from 10^2 to 5×10^4/s (Saha et al., 2019; Wang et al., 2008). The MRF can be tested within SHPB by placing it into the elastic vessel between two bars, where a pulse wave propagates through the sample. The measurement is based on the wave generation in the MRF by the incident bar passing through the specimen to the transmitted hollow bar connected with a full-bridge sensor system. The equipment can generate different magnetic field values.

MRF are materials with a low Young's modulus (about 1 MPa) strongly responsive to speed deformation (Frąś and Pęcherski, 2018). It was necessary to use nylon rods with a lower wave impedance than steel bars during measurements. This modification allows changing the SHPB configuration from the bar-bar system into the bar-hollow (tube), making it possible to measure even small MRF's deformations. At the same time, the distortions are recorded as the reflected wave changes. Thanks to that modification, the rearrangement of magnetic particles depending on the applied stress is measured (Zhang et al., 2019). In Osial et al. (2022), the MRF, which reacts reversibly and immediately to stresses occurring at high yield stress, was proposed. The nominal stress varied from 0.001 to 200 MPa during 0.5 ms during the measurements. It has been experimentally shown that the deformation rate of similar chain structures changes with the striker's speed. As a consequence, this fluid is suitable for the minimization of damping of vibrations. Ahmadkhanlou et al. (2010) presented the compression behaviors and energy absorption studies of porous copper materials with three different pore sizes showing controllable energy-absorbing material within the SHPB technique.

5. The mathematical modeling of magnetorheological fluid

Another important direction of research in the field of Magnetorheological Fluid is related to its modeling (Bingham, 1916; Pei and Peng, 2022). MRF modeling can be divided into two categories: continuum approach (i.e. MRF operational modes, rheological models, and structural models), and discrete approach, including modeling based on Newton's law, and using kinetic models (Ghaffari et al., 2015). Several MRF rheological models are proposed, including two common ones, that is the Bingham plastic model (Bingham, 1916) and the Herschel–Bulkley model (Herschel and Bulkley, 1926). The basic Bingham body model, which is adapted from classical mechanics of non-Newtonian fluids, describes the properties of an elastic-viscoelastic material (Bingham, 1916). The characteristics of such a body can be divided into two distinct areas separated by the critical shear stress so-called yield stress τ_0, beyond which plastic deformations and thermal effects begin to occur in the material. Bingham fluids describe the following dependencies:

$$\begin{aligned} \tau_B &= G\gamma \text{ for } \tau < \tau_0 \\ \tau_B &= \eta\dot{\gamma} \text{ for } \tau \geqslant \tau_0, \end{aligned} \tag{4}$$

where G is shear modulus, τ—shear stress corresponding to the material flow limit, η denotes the dynamic viscosity of a fluid, and $\dot{\gamma}$ is a velocity of shear deformation of the fluid, that is share rate. This approach is equivalent to modeling the device combing dashpot, and Coulomb friction element (representation as mechanical elements). Note, that this model is an idealized one, which treats the MRF as a solid before the yield stress. It accurately follows the behavior of the MRF at a high strain rate but is not accurate for the low strain rate behavior. In Pei and Peng (2021) it was shown that the highest prediction error was achieved for the Bingham model (which has only two parameters), that is 0.324.

To address the large changes in shear stress the Eyring model was proposed (Choi et al., 2005).

$$\tau_E = \tau_0 \sinh^{-1}(\lambda_E \dot{\gamma}), \tag{5}$$

where λ_E is a parameter that determines the MRFs rheological behavior. It presents the continuous shear stress versus shear rate behavior, and smooth tension on pre-yield regions, which are much closer to the behavior of the real MRF than the Bingham model.

In the case of Magnetorheological Fluids yield strength, τ_0 is expressed as a function dependent on the external magnetic field acting on it. In turn, the Herschel-Bulkley model is described by the following equation (De Kee and Turcotte, 1980)

$$\tau_{HB} = (\tau_0 + K\gamma|\dot{z}|)^{\left(\frac{1}{m}\right)}, \tag{6}$$

where K is the consistency constant, which plays a role in the fit parameter, and is experimentally determined, m denotes the flow index. In the case of $\tau < \tau_0$ MRF behaves as a non-deformable solid, while in the case of $\tau \geqslant \tau_0$ as fluid. If we assume the value of m is equal to 1, the Herschel-Bulkley model becomes the Bingham MRF model. For flow index, $m > 1$ shear-thickening behavior occurs, while for $m < 1$ shear-thinning.

The generalized model of Magnetorheological Fluid was proposed by Claracq et al. (2004). The De Kee-Turcotte model is described by the equation

$$\tau_{DK-T} = \tau_0 + \eta_1\dot{\gamma}e^{-t_1\dot{\gamma}}, \tag{7}$$

Where t_1 is a constant, which has a unit of seconds, and η_1 is the parameter, which can be estimated from equation (8) assuming a zero shear rate.

The Bingham model makes it possible to derive equations describing the constant flow of a liquid using analytical solutions, while the solution of the equations exists under the assumption of the mediums' non-inertial character. It can be used to support the design of MFR devices or to predict the behavior of existing MRF devices. The disadvantage of this model is the lack of a correct response in the range of very low and very high shear rates. Another limitation of Bingham's model is the fact that it does not reflect good MRF behavior in the case of velocity deformation below 10/s. Then the characteristic is no longer linear and yield strength even disappears. For small deformation velocities, the Cross model (Sahu et al., 2007) was proposed

$$\tau_C = \left[\eta_\infty + \frac{\eta_0 - \eta_\infty}{1 + \lambda\dot{\gamma}}\right]\dot{\gamma}, \tag{8}$$

where η_0 and η_∞ denote low viscosity and viscosity for high strain rates, respectively.

Herschel–Bulkley model enables the behavior of the fluid to be predicted in the range of high shear rates (El Wahed and Balkhoyor, 2018; Zubieta et al., 2009). Additionally, it allows considering the phenomenon of shear thickening and shear thinning. However, it has a weak point, which is the experimental verification of its parameters (El Wahed and Balkhoyor, 2018). Another model that makes it possible to consider the same effects as the Herschel–Bulkley model is the Casson model (Carlson et al., 2001; Spencer et al., 1997), which was originally used to describe the rheological properties of blood. If we treat blood as a suspension of solid cells, by analogy, we can compare it to the Magnetorheological Fluid. It is described by the equation

$$\frac{\eta}{\eta_\infty} = 1 + \left(\frac{M_n}{M_n^*}\right)^{-1} + 2\left(\frac{M_n}{M_n^*}\right)^{-1/2}, \tag{9}$$

where M_n denotes Mason's critical number, which determines the transition from magnetization to hydrodynamic control of the suspension structure. It can be, in the most general form, assumed by the relation

$$M_n \equiv \frac{72\eta_c\dot{\gamma}}{\mu_0\mu_{cr}{M_P}^2}, \tag{10}$$

where η_c is the continuous phase viscosity, μ_0 denotes magnetic permeability of vacuum, μ_{cr} is the relative magnetic permeability of the continuous medium, M_P is particles' mean magnetization, which in particular in a quasi-linear regime is equal to

$$\langle M_P \rangle = 3\beta H_0 = 3\frac{(\mu_{pr} - \mu_{cr})}{(\mu_{pr} + 2\mu_{cr})}H_0, \tag{11}$$

where μ_{pr} is the relative magnetic permeability of the particles.

On the other hand, to enable modeling behavior of the medium in terms of very low shear rates by describing the MRF bilinear constitutive relation, the bi-viscous model was proposed (Goldasz and Sapinski, 2012; Sahoo et al., 2022; Wereley et al., 2004; Williams et al., 1993)

$$\tau_{BV} = \begin{cases} \mu_r\dfrac{\mathrm{d}u}{\mathrm{dz}} \text{ for } \tau \leqslant \tau_1 \\ \tau_0 + \mu\dfrac{\mathrm{d}u}{\mathrm{dz}} \text{ for } \tau > \tau_1 \end{cases}, \tag{12}$$

where $\frac{du}{dz}$ is velocity gradient and μ_r denotes pre-yield viscosity. Dynamic yield shear stress τ_1 can be determined from the relation $\tau_0 = \tau_1(1 - \gamma)$, where γ is viscosity ratio $\gamma = \mu\mu_r^{-1}$, In the case viscosity ratio $\gamma = 1$ and $\mu_r = \mu$ the fluid flow is Newtonian, while in the case $\mu_r \to \infty$ or $\gamma \to \infty$ bi-viscous model becomes the Bingham model. Mostly, the value of the γ varies in the range 10^{-5} to 20^{-2} (Wang et al., 2008).

The extensions of the bi-viscous model enable us to take into account that the dynamic pre-yield hysteresis is the hysteretic bi-viscous model (Chopra and Sirohi, 2003). It is described by the following equations

if $\dot{\gamma} > 0$ than

$$\tau_{HBV}\,(\dot{\gamma}) = \begin{cases} \mu_p\dot{\gamma} - \ \tau_0 \text{for } \dot{\gamma} \leqslant -\dot{\gamma}_1 \\ \mu_{pr}(\dot{\gamma} - \ \dot{\gamma}_0)\text{for } -\dot{\gamma}_\gamma \leqslant \dot{\gamma} \leqslant \dot{\gamma}_1 \\ \mu_p\dot{\gamma} + \tau_0 \text{for } \dot{\gamma} \leqslant -\dot{\gamma}_\gamma \end{cases} \tag{13}$$

if $\dot{\gamma} \leqslant 0$ than

Table 2. The commonly used MRFs models.

Model	Number of the parameters	Parameters	Reference
Bingham	2	$\tau_0,\ \eta$	Bingham (1916)
Casson		$\tau_0,\ \eta$	Carlson et al. (2001), Sahoo et al. (2022)
Eyring		$\tau_0,$	De Kee and Turcotte (1980)
Cross	3	$\eta_0, \eta_\infty,$	Sahu et al. (2007)
Herschel–Bulkley		$\tau_0,\ \gamma,\ z$	Choi et al. (2005), De Kee and Turcotte (1980), Herschel and Bulkley (1926)
de Kee–Turcotte		$\tau_0,\ \eta_1, t_1$	Claracq et al. (2004)
Robertson-Stiff		$K_1,\ \gamma,$	Elsaady et al. (2021)
Mizrahi - Berk		$K_1,\ \gamma,$	Cvek et al. (2016)
Bi viscout	4	$\tau_0,\ \gamma, \mu_p,\ \frac{du}{dz}$	Sahoo et al. (2022), Wereley et al. (2004), Williams et al. (1993)
Hysteretic viscous		$\tau_0,\ \gamma, \mu_p,\ \mu_{pr}$	Chopra and Sirohi (2003)
Cho-Choi-Jhon model	6	$\tau_0,\ t_2, \alpha,\ \eta_\infty,\ t_3, \beta$	Cho et al. (2005)

$$\tau_{HBV}\ (\dot{\gamma}) = \begin{cases} \mu_p \dot{\gamma} +\ \tau_0 \text{for } \dot{\gamma} > -\dot{\gamma}_1 \\ \mu_{pr}(\dot{\gamma} -\ \dot{\gamma}_0) \text{for } -\dot{\gamma}_\gamma \leqslant \dot{\gamma} \leqslant \dot{\gamma}_1 \\ \mu_p \dot{\gamma} + \tau_0 \text{for } \dot{\gamma} \leqslant -\dot{\gamma}_\gamma \end{cases} \tag{14}$$

where μ_{pr} denotes pre-yield viscosity and $\dot{\gamma}_\gamma$ is yield strain rate.

In Lim et al. (2010) it was shown that the Herschel–Bulkley model is more suitable to describe MRF behavior in higher magnetic fields, while the Bingham model was appropriate for lower magnetic flux densities. Both, the Bingham plastic model, and Herschel–Bulkley model are suitable for one-degree of freedom, rectilinear devices, while they operate in 1-D macroscale, and treat MRF like a single continuum system. Thus, the results obtained by (Panowicz and Janiszewski, 2016) indicate that MRF can be more modeled with the Robertson–Stiff model (so-called Vocadlo model) (Chen et al., 1999), which was proposed to describe the rheological behavior with non-linear characteristics of the concrete solutions, gels, and polymers. The Robertson–Stiff model is described by the following equations being the combination of the Bingham plastic model (4), and the Ostwald de Waele equation (Elsaady et al., 2021)

$$\tau_{R-S} = K_1(\dot{\gamma}_0 + \dot{\gamma})^n, \tag{15}$$

where parameters K_1 and n can be considered similar to those in the H–B model, and $\dot{\gamma}_0$ is a shear rate correction factor. Another model that was applied for the modeling of the Magnetorheological Fluid is Mizrahi–Berk model, which was commonly used in food engineering (Cvek et al., 2016). It is described by the equation

$$\tau_{M-B}{}^{\frac{1}{2}} = \tau_0{}^{\frac{1}{2}} + K_1 \dot{\gamma}^n \text{ for } \quad \dot{\gamma} = 0, \text{ and } |\tau| < \tau_0 \tag{16}$$

In Robertson and Stiff (1976) it was successfully used in the modeling of concentrated xanthan gum.

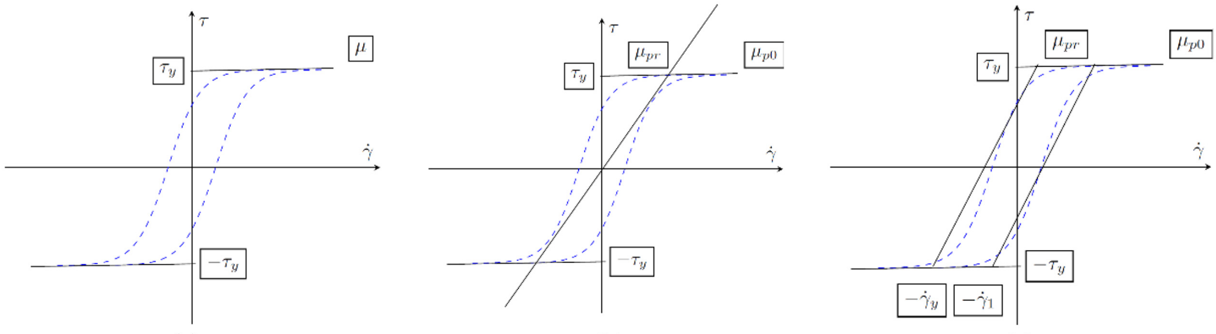
An interesting fluid model was proposed by Cho et al. (2005). It provides a better fitting of poly(acene quinone) radicals-based electrorheological fluids. This model is described with the following equations

$$\tau_{c-c-J} = \frac{\tau_0}{1 + (t_2 \dot{\gamma})^\alpha} + \eta_\infty \left(1 + \frac{1}{(t_3 \dot{\gamma})^\beta}\right) \dot{\gamma} \tag{17}$$

where t_2 and t_3 denotes time constants, α is a parameter, which is related to the decrease in the stress, β is a dimensionless parameter in the range (0,1>. It can be successfully applied to the modeling of the MRF (Ahn et al., 2015; Kim et al., 2013).

The commonly used models of the Magnetorheological Fluid taking into account numbers and types of parameters are summarized in Table 2. The schematic behavior of the Magnetorheological Fluid according to model type was shown in Figure 4.

We can distinguish several types of MRF devices, but most of them resist a similar principle of operation, in particular, three operation modes, that is flow mode, shear mode, and squeeze mode (Li et al., 2019; Wang and Meng, 2001), see Figure 5. This division results from the way of moving the liquid in relation to the magnetic field vector. Also, the method of converting the stress in the fluid into an external force is bear in mind. Flow mode (Figure 5(a)) relies on the operation of a throttled valve (Cvek et al., 2016). MRF flows with pressure in the gap between two fixed surfaces. The external magnetic field is perpendicular to this gap. In this regime work such devices as dampers (Pelegrine et al., 2002), shock absorbers (Song et al., 2006), and servo-valves (de Vicente et al., 2011). Additionally, in the case of flow mode to describe yield stress the Bingham model is applied (Ghaffari et al., 2015; Kostamo et al., 2012). Shear mode is presented in Figure 5(b). In this case the surfaces between which the fluid is located move with speed. Clutches (Qiu et al., 2022), brakes (Milecki and Hauke, 2012), and some types of vibration dampers are based on this principle. Squeeze mode (de Vicente et al., 2011; Ruiz-López et al., 2012), which is the least common, is shown in



(a) (b) (c)

Figure 4. The schematic behavior of the Magnetorheological Fluid according to: (a) the Bingham model, (b) the bi-viscous model, and (c) the hysteretic viscous model. The solid lines denote modeling, while the dashed lines denote actual behavior.

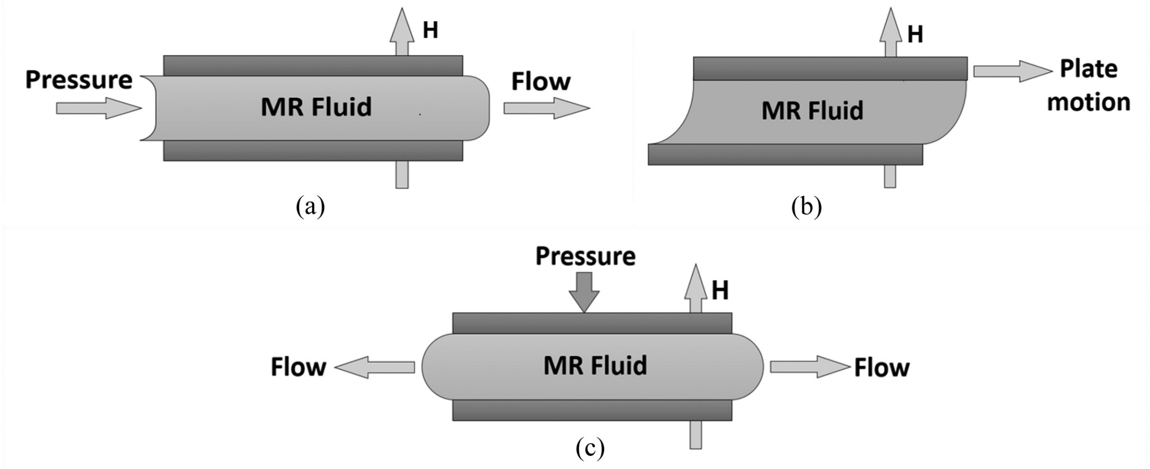


Figure 5. The operating modes of the MRF devices are under the magnetic field (H) under: (a) flow (MRF between two stationary plates), (b) shear (MRF between movable plates), and (c) squeeze.

Figure 5(c). In this case, the surfaces between which the MRF is located may approach or move away from each other, causing fluid compression. The magnetic field strength depends on the coil supply current and the variable gap width, as a consequence squeeze operation mode is difficult to control. Thus, it can be applied to low-amplitude vibration dampers (Salloom and Samad, 2011), and MRF–elastomer vibration isolators. In practical applications, there may also be combinations of these operating modes (Kavlicoglu et al., 2002).

Another modeling approach, that is Discrete MRF modeling methods allows us to model such phenomena as the flow field of the continuous phase, motion, and interaction of particles in a discrete phase, and the distribution of a magnetic field based on the physical laws (Ghaffari et al., 2015). The discrete approach, assuming the appropriate initial and boundary conditions, is based on Newton's second law, that is Newton's motion equations in the case of discrete particles, and Navier-Stokes equations for continuum fluid (Huang et al., 2002). The particle's translational motion described by Newton's second law can be expressed as

$$\begin{aligned} m_i \frac{dv_i}{dt} &= \sum\nolimits_j F_{ij}^c + \sum\nolimits_k F_{ik}^{nc} + F_i^f + F_i^{ext} \\ u_i &= \frac{dx_i}{dt} \quad \text{for } i = 1, \ldots, N, \end{aligned} \tag{18}$$

where m_i is i-particle mass, u_i is i-particle velocity, x_i is i-particle position, F_{ij}^c the contact force between i-particle, and j-particle, F_{ik}^{nc} the non-contact force acting on i-particle by k-particle, F_i^f denotes the force of the particle-fluid interactions, and F_i^{ext} is external force, which acts on i-particle (Olabi and Grunwald, 2007), see Figure 6.

Thus, the behavior of any suspension can be described by applications of the Navier-Stokes equations (See et al., 2006), which can be presented in compact form as:

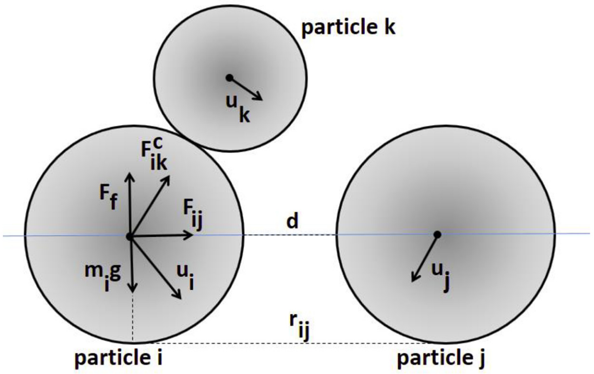


Figure 6. Acting forces in the MRF, according to the discrete approach.

$$\begin{aligned} \eta^* \nabla^2 u - \nabla p &= 0 \\ \nabla \cdot u &= 0, \end{aligned} \tag{19}$$

where u denotes fluid velocity, p is fluid pressure, and η^* is fluid dynamic shear viscosity. The system of equation (18) described the conservation of momentum for moving fluid. The changes in the momentum of a fluid element depend only on the mass forces, external pressure, and internal viscous forces in the fluid. The no-slip or slip boundary conditions hold at the particle surfaces and in general, the particles are entrained by an ambient flow. Typically, the MRF's flow field is laminar or stationary, or both, which is very close to Stokes flow ($Re < 1$). To provide different particulate flows in Magnetorheological Fluids the use of modified with correction factor Navier-Stokes equations (Kim and Karrila, 2005). Correction factor f is equal to the product of the inertial correction factor C_1 (which includes the effects of inertial forces on the particles), Cunningham factor C_c (modification assumption of no-slip ashore), and correction factor C_f (including the presence of other particles in the vicinity of the given particle). The equation (9) are often combined with other equations, for example, in Han et al. (2010) Ohm's law and Maxwell's equations were combined with the Navier–Stokes equations to model the response of the linear damper with MRF. On the other hand, Pappas and Klingenberg (2006) consider the effect of particle forces on the flow field in the MRF's modeling.

On the other hand, MRFs hysteresis can be identified from experimental tests. It turned out that the experimental test of the MRFs dampers, which are working in valve or shear mode show that hysteresis appears only around points of change of direction assuming sinusoidal displacement forces (Bai et al., 2015). In the case of the MRF damper, which is working in squeeze mode, can be described using the force-displacement relation-based model–Bouc-Wen model (Chen et al., 2018) and resistor-capacitor operator-based models (Bai et al., 2019). Thus, the above behavior can be also analyzed with the application of the dipole model of particle energy interaction, in which the magnetic effect is considered a function of particle magnetization (Jolly et al., 1996). In this approach, phenomena such as dynamic effects of the magnetic field and inertial and rate-dependent effects of the particles are omitted. According to it, the homogenous magnetic particles can be modeled as identical induced dipole moments. Moreover, it is assumed that shear strains and associated stresses are uniformly distributed over the length of the particle chain. In turn, Bai and Chen (2019) introduce the hysteresis mechanism of MRFs at different excitation amplitudes.

6. Conclusions

In this paper, we overview and discuss the physicochemical properties of the Magnetorheological Fluids and issues connected with their preparation methods, experimental measurements, and behavior modeling. MRFs are unique intelligent fluids whose rheological responsiveness and transition under external magnetic fields are quite fast. It turned out that, unlike the modeling of the magnetic field distribution, modeling of the fluid flow has a more complex nature, while it combined different types of flows and non-linearities in the rheological behavior of fluids. Still, some modeling approaches do not allow this but can map the dynamic behavior of the system. Continuum approaches do not provide a particle level. Due to its simplicity, the most commonly used model of Magnetorheological Fluid is the Bingham model. It enables the modeling of both, the quasi-static and dynamic behavior of the fluids. The Herschel–Bulkley model is rarely applied to dynamic MRF modeling. Other models have found use in modeling MRF devices, but are rarely used to model the static and dynamic behavior of the fluid itself. The important disadvantage of more complex analytical and numerical MRFs models is the requirement of the experimental data, for example, yield stress ratio and the viscosity ratio. Discrete models are used in the development of MRFs control algorithms. Models that do not take into account the shear behavior of the fluid give less accuracy. Thus, the modeling of Magnetorheological Fluids is a compromise between the accuracy of the selected model and the number of phenomena that occur in it, and the computational cost.

The most commonly used magnetic compound used for MRF is carbonyl iron dispersed in viscous media like silicone oil, while CI has high magnetism permeability and high saturation magnetization. The shape of the magnetic particles used also affects the rheological properties of the MRFs. Spherical shapes are usually synthesized; however, spheroidal and plate-like shapes have a greater thermal conductivity. In turn, fiber-shaped particles have had better yield strength. Reducing the size of the magnetic particles with increasing temperature improves the thermal conductivity of the solid suspension (Rahim and Ismail, 2015). Moreover, the MRFs tribological properties can be modified by increasing graphite percentage, while the optimal proportion is below a few percent (Hu et al., 2022). In order to prevent the separation of the particles, the viscosity of the magnetorheological fluid should be sufficiently high. Sedimentation of the fluid is reduced before adding additives such as stearic acid, guar gum, xanthan gum, silica gel, stearates, carboxylic acids, iron naphthalate, and iron stearate. In turn, adding anti-friction compounds reduces the effect of erosion (Kumar et al., 2019).

Recently, MRF has been applied in many fields and brought attention to new sectors, including medicine. Reducing the production cost of the fluid is still a challenge. Currently, due to the high MRFs price, its volume is minimized in the structures, in particular in large isolation systems. Tactile knobs based on smart fluid have also been developed, which will be integrated with electrical devices in the next few years. MRFs are increasingly used in the medical field, for example, in gait-rehabilitation robots, prosthetic knees, or even finger rehabilitation (Oh et al., 2022). Still, these are unit solutions, the popularity of MRF in commercial solutions is also low due to the low level of trust in the customers who are not aware of the benefits of solutions based on them. Breaking down these barriers remains a challenge. On the other hand, also energy-efficient control algorithms are of huge importance as well as production of the adequate magnetic fields without requiring large amounts of electrical power. Here, the electro-permanent magnets-based power system may be a good solution (Mcdonald et al., 2022).

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