

Magnetorheological fluids: A comprehensive review

Vinod Chauhan^{*}, Ashwani Kumar, and Radhey Sham

Department of Mechanical Engineering, Chandigarh College of Engineering and Technology (Degree Wing), Sector 26, Chandigarh 160019, India

Received: 27 August 2023 / Accepted: 11 February 2024

Abstract. The magnetorheological (MR) fluids contain magnetic micro-sized iron particles, non-magnetic-based fluid, and some additives in order to mitigate sedimentation and agglomeration. The various carrier fluids used in the preparation of MR fluids are mineral oil, silicon oil, castor oil, soybean oil, kerosene, synthetic oils, honge oil, organic oil, water-based oils, etc. However, for obtaining better vibration control, silicone oil is the most preferred one due to its higher viscosity index, lower friction characteristics, higher flash point, and higher shear strength. The MR fluids have various application areas such as dampers, prosthetic knees, valves, brakes, clutches, finishing processes etc. The dampers containing MR fluids are used in automobile cushioning for enhancing passenger comfort and MR suspensions significantly improve steering stability in vehicles. In case of MR brakes, the braking torque on the rotating disks is controlled using the generated shear stress. The carbonyl iron (CI) particles exhibit better rheological characteristics as compared to electrolytic iron (EI) particles. The use of MR fluids produces stable and natural limb movement in orthoses, lower limb prostheses, and exoskeletons. The MR fluids also prove to be very significant in polishing applications. There are various issues with preparation methods and difficulties in the storage of MR fluids. The problems encountered in the synthesis of MR fluids include sedimentation, agglomeration, in-use thickening, corrosion, erosion, etc. The impact of particle proportion, particle shapes, and size has been influential in evaluating MR characteristics. The viscosity and shear stress of MR fluid have been mitigated at higher values of temperature and even CI particles get oxidized at higher temperatures. The CI particles as compared to EI particles are the majority favourable particles used for dispersing state within the MR fluids due to their higher value of saturation magnetization, more availability, and lesser cost. The small-sized particles led to lower wettability, whereas larger-sized particles accounted for an increased sedimentation rate. The currently available MR fluids cost is still on the higher side and the preparation of economical MR fluid is still a big challenge for the researchers. The MR fluids storage is also a big concern. The future scope of MR fluid may be in heavy industries such as nuclear, shipbuilding, oil and gas, space and aviation, etc. to achieve the desired damping response.

Keywords: Magnetorheological fluids / viscosity / shear stress / agglomeration / sedimentation / additives

1 Introduction

A semi-active control system needs a lesser amount of power from an external source and the structure movement is used to enhance the control forces. These control forces in semi-active control systems predominately act to resist the structural motion. An appropriate mechanism to mitigate the steady and transient vibration is to alter the produced quantity of damping. Fresh advancement related to smart materials leads to the evolution of semi-active dampers that have a wide range of applications. In the past few decades, great curiosity has been induced for the utilization of structural systems for lowering the effects of vibration on

mechanical structures in order to provide comfort to human beings. These systems normally incorporate damping devices to enhance the ability of dissipated energy. The MR fluid particles start aligning as per the power of the magnetic field density, thereby forming a recognizable pattern. These magnetic fluids are categorized into two groups i.e.; ferrofluids and MR fluids. In ferrofluids, magnetic nano-size particles (5–15 nm) with volume proportion up to 10 percent are dispersed in a non-magnetic medium like water, synthetic oils, etc. so as to form a stable colloidal solution. In MR fluids micron-sized particles are suspended in a non-magnetic carrier medium [1,2]. Jacob Rabinow around 1948 developed MR fluid at the US National Bureau of Standards [3]. There is an unsymmetrical dispersal of magnetic particles in the carrier medium when the magnetic field is absent. On applying the

^{*} e-mail: vinodchauhan@ccet.ac.in

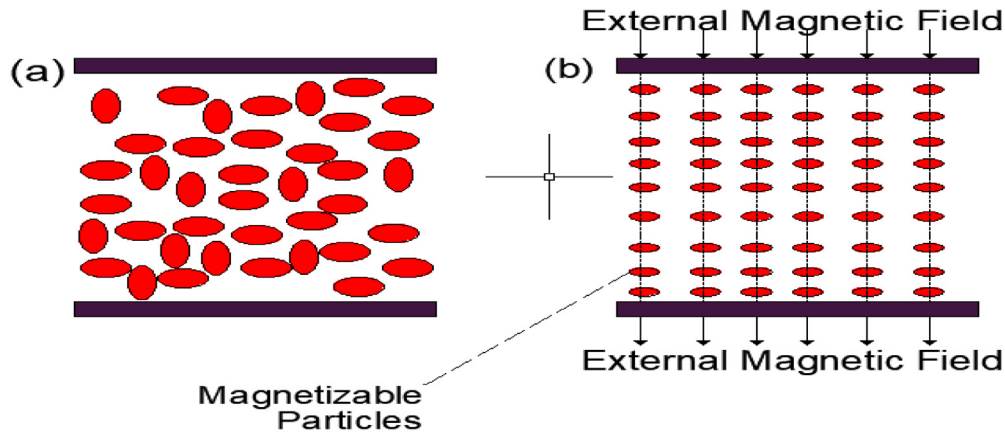


Fig. 1. (a) Particles orientation in the absence of magnetic field; (b) Particles orientation in the presence of magnetic field.

magnetic field, the MR fluids transform to a semi-solid state due to strong particle dipole-dipole attraction. A rugged structured chain formation (Fig. 1) occurs, which signifies the outstanding phase transition capability [4]. The various dispersal methods of suspensions of Fe particles (micron-sized) with surfactants in the MR solution exhibit that the yield stress is not much affected due to the dispersion quality of the suspension, but it significantly affects the induced viscosity. It has been also observed that the conversion of semi-solid state to liquid state occurs smoothly in case of well-dispersed particle suspensions, while this conversion is abrupt when suspensions are poorly dispersed [5]. The MR fluid yield stress value is enhanced with the particle concentration. The fluid with a higher particle volume fraction represents the pseudo-plastic behavior even when the magnetic field does not exist [6]. The MR fluids offer higher yield stress approximately 100 kPa, which is much greater than its counterpart electrorheological (ER) fluids [7].

Ashtiani and Hashemabadi [8] investigate the influence of the addition of magnetic and non-magnetic nano-structured particles (fumed silica and magnetite) on the prepared MR fluids. A rise of six times in the value of the MR effect has been observed when nano-structured magnetite particles are utilized in place of MR fluids free from nano-structured particles. The suspension stability is enhanced significantly by adding the non-magnetic silica particles. The data obtained experimentally fit very well to the Herschel-Bulkley model and shear thinning has been noticed in the prepared fluids. Ranjan et al. [9] identify the reasons for the sedimentation of MR fluids by making use of CFD simulation. The sedimentation rate is reduced by making use of the nano-coated Fe particles. The reaction procedure for the formation of hydrocarbon chains has been investigated with *ab initio* molecular dynamics simulation by utilizing the density function theory (DFT). The experimentation results exhibit that the nano-coated particles of MR fluids yield superior stability countering the sedimentation rate significantly. Zhu et al. [10] developed a direct current arc discharge technique for producing Fe nanoparticles. The crystal structures, framework, magnetic properties, and chemical composition

have been investigated, which verify the particle's nano size, greater purity, and higher value of saturation magnetization. The Fe nano-sized particles and commercially available CI micron-sized particles have been utilized as two dispersed phases for synthesizing the MR fluids. The results indicate that the Fe nano-sized particles-based fluids exhibit a slightly lesser value of MR effect, but relatively higher sedimentation stability compared to the fluids containing micron-sized Fe particles. Choi [11] reviews the methods utilized for the betterment of sedimentation stability of the MR fluids. The particle shape, weight proportion, size dispersion, mixing of various-sized particles, and coated materials have been included in the particle alteration stage. The improvement of the carrier liquid involved governing wettability, density increment, and utilization of natural oils, grease, and lubricant oil. Some additives e.g., aluminum stearate has been included to enhance the redispersibility of aggregated particles. The study extensively investigates the recipes for enhancing sedimentation stability. Some conceptual techniques have been presented to reduce the sedimentation arising as a result of the bottle's storage resting on the shelves of application setups. Roupec et al. [12] illustrate the impact of clay-based additive concentration on the rheological characteristics and sedimentation stability of MR fluids under the state of no magnetic field. The study reveals the exponential drop-in sedimentation rate on increasing the additive concentration and rise in the yield stress. The viscosity of carrier fluid and particle volume has a lesser impact on the sedimentation rate as compared to clay-based additives. The inclusion of additives dies down the sedimentation rate very significantly as compared to the fluid having no additives. Hà et al. [13] modify the surface of carbonyl iron powders (CIPs) with 3-amino-propyl triethoxysilane tetraethyl orthosilicate so as to enhance the sedimentation stability related to the suspensions, which do not make use of the harmful dispersants. The coated CIP surface improves the surface energy of used CIP powders. The wettability of modified CIPs enhanced which resulted in lower agglomeration. The sedimentation stability improves significantly in case of the modified CIPs.

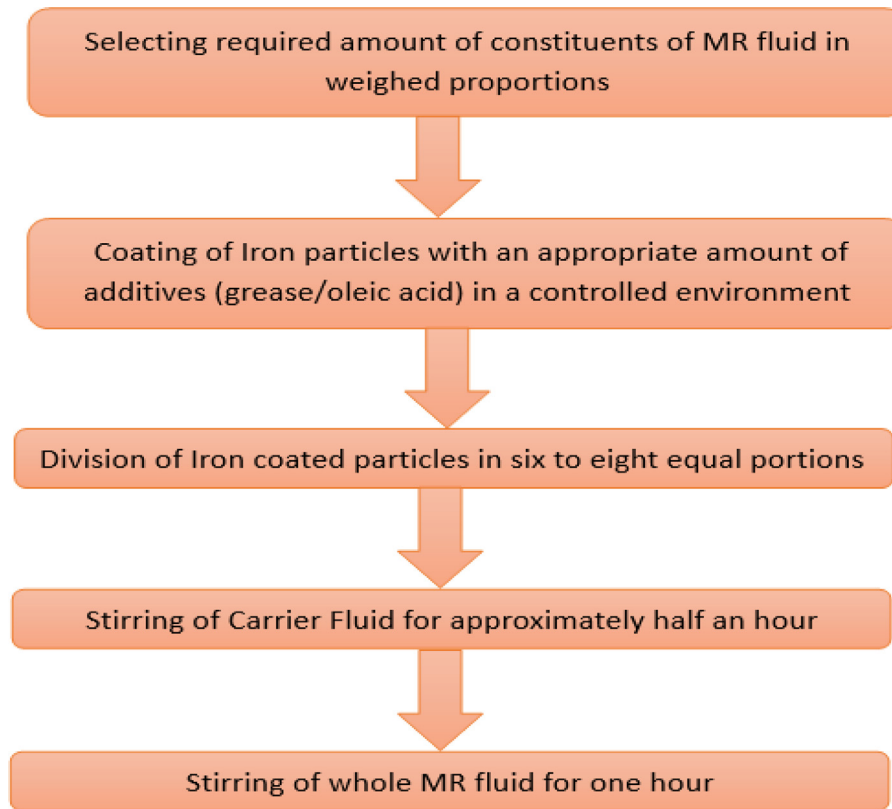


Fig. 2. Procedure for preparation of MR Fluid.

Nowadays the investigations on MR fluids along with their applications are intensifying due to the MR technological development. The researchers are focusing on mitigating the lubricating film thickness because thin film thickness consumes less amount of energy and the friction coefficient also reduces. In order to attain the optimal performance of the mechanism, wear as well as friction are required to be reduced which may be achieved by lubricating the contact surfaces. In severe operating conditions, the breakdown of the thin film brings a rise in friction and wear. Hence, it is unachievable to regulate the film thickness with the use of conventional fluids. Therefore, there is a necessity for nontraditional lubricants, such as smart fluids [14].

This review paper presents an exhaustive study on the preparation of MR fluids, stabilization methodologies, and several techniques to enhance sedimentation stability. In addition to this, issues such as oxidation, and corrosion is also discussed. The MR fluid behavior in the presence and absence of a magnetic field is thoroughly examined. The influence of temperature, particle proportion, size, and shape on rheological characteristics is also investigated. The various fluid models for investigating rheological behavior have been outlined.

2 Composition and preparation of MR fluids

MR fluid constitutes three leading elements: carrier fluid, magnetic particles, and surfactants/additives, and all these elements are mixed in proper proportions. The magnetic

particles such as CI particles etc., coated with additives like silica are suspended in a carrier medium like silicon oil. The particles are layered with silica to attain effective stability against the accumulation of particles. CI particles have a higher value of magnetic saturation. The carrier medium is non-reactive with the elements suspended in it. The boiling point, freezing point, and vapor pressure of the carrier medium have to be taken into consideration [15]. The MR fluid containing up to fifty percent in volume of the magnetic particles and the remaining percentage appropriately divided between the silicon oil and the additives i.e., grease or oleic acid have been produced. The carrier fluid used is non-magnetic and the additives play a significant role in the working of a MR fluid as they not only prevent the sedimentation of the Fe particles but also help in preventing the oxidation of the Fe particles [16]. A detailed procedure (Fig. 2) for preparing and analyzing the MR fluids has been outlined. The MR fluid samples contain a carrier fluid (silicon oil), Fe particles, and an additive (grease). The sedimentation rate and off-state rheological properties of the prepared samples have been determined [17]. The MR fluid with magnificent sedimentation stability by applying different surfactants for coating the CI powder has been developed. The sedimentation stability for various surfactants such as ethylene glycol monostearate, compound sodium fatty acid methyl ester sulfonate, and glyceride monostearate has been determined. The orthogonal techniques have been employed to obtain the optimal proportion of the thixotropic and surfactant agents [18].

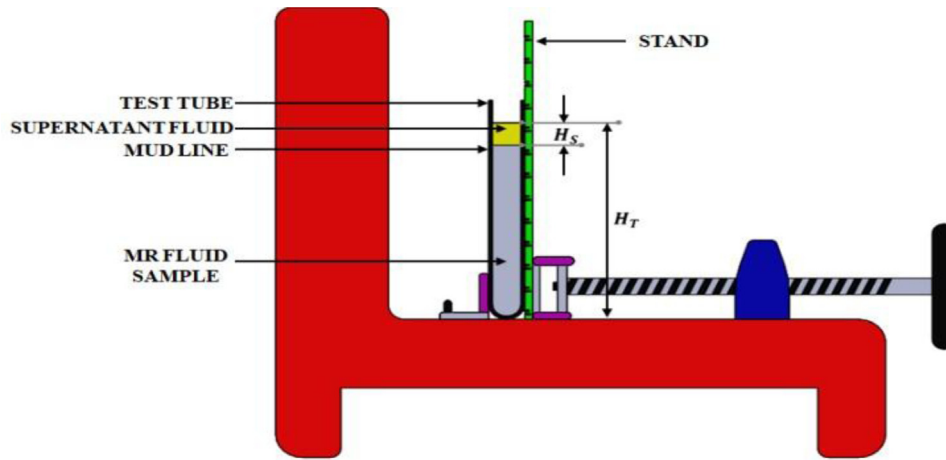


Fig. 3. Determination of sedimentation ratio [17].

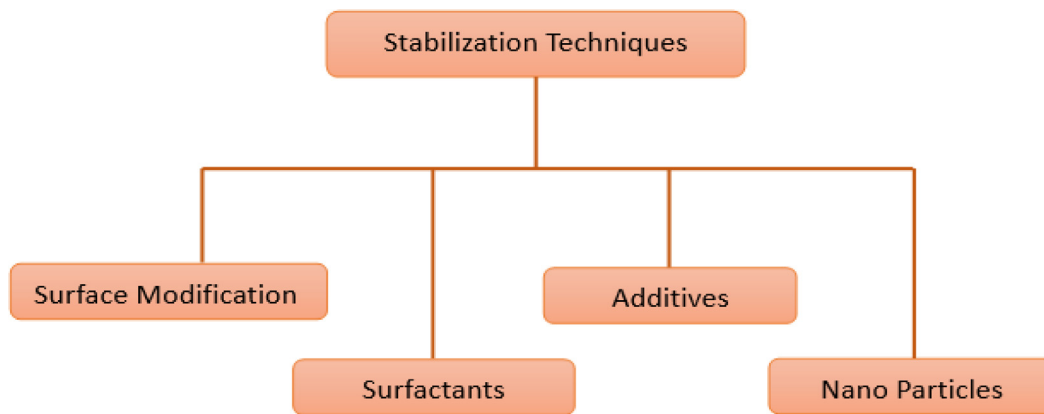


Fig. 4. Techniques to address sedimentation issue in MR fluids.

3 Techniques to address sedimentation issues in MR Fluids

The sedimentation resulting from the density difference between carrier medium and magnetic particles is a serious issue in MR fluids. These fluids undergo phase separation (Fig. 3) because of the density variation between carrier fluid (1 g/cm^3) and the dispersed phase (7.5 g/cm^3).

The relation for determining the sedimentation ratio is given in equation (1).

$$\text{Sedimentation ratio} = \frac{\text{Height of supernatant oil}(H_S)}{\text{Total height of fluid}(H_T)} \times 100. \quad (1)$$

The different techniques used to craft the stabilization issue are shown in Figure 4. These techniques, used to mitigate the sedimentation rate include magnetic particle surface modification, surfactants, non-magnetic additives, and inclusion of nano-particles.

3.1 Surface modifications in MR fluids

It has been seen that particle surface modification is the most used technique to mitigate the sedimentation rate. Sedlacik et al. [19] investigate the suitability of plasma-treated CI particles suspended in the MR fluids using a rheometer that is fitted with a magnetic field generator. The variation in viscoelasticity has been noted for a small-strained oscillating shear flow. The prepared MR fluid exhibits an increased value of suspension stability. Chuah et al. [20] enhance the sedimented stability of a CI-incorporated MR fluid by casing the CI particles with a polystyrene foam layer as shown in Figure 5. The density of particles mitigates due to the polystyrene layered foaming layer and polystyrene layered wrapping. Surface roughness increases without affecting the spherical shape of the particles. The sedimentation rate reduces remarkably as a result of decreased mismatch in the carrier medium and magnetic particle density. Huang et al. [21] prepare MR fluids based on micron-sized iron particles diffused into the silicone oil. The oleic acid along with lauric acid has been added to modify the iron particles. The electro-resistance exhibits a downfall from $6000 \text{ M}\Omega$ to $190 \text{ }\Omega$ when applied external field increases from 0–400 mT.

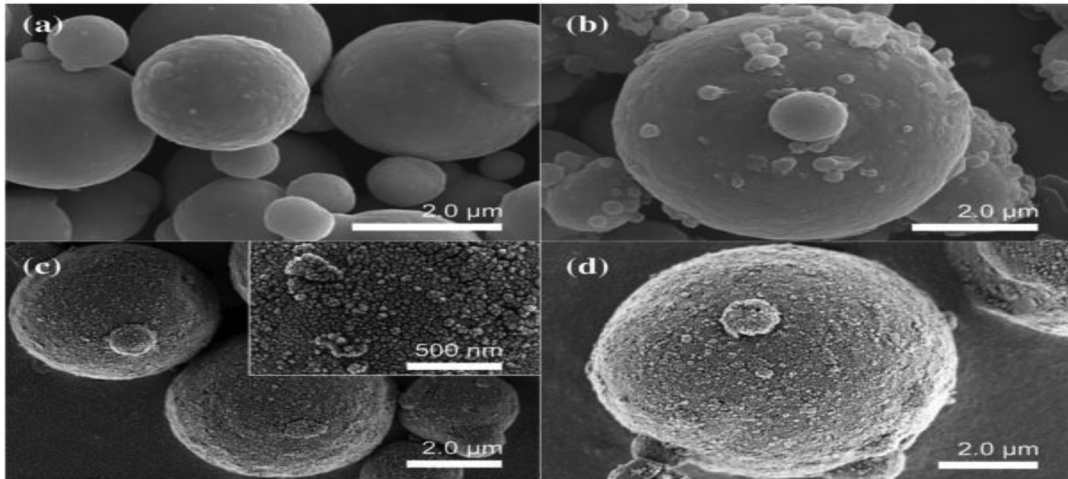


Fig. 5. SEM images of (a) pure CI (4.5 μm) particles; (b) polystyrene-coated CI (4.94 μm) particles; (c) foamed-polystyrene coated CI (5.16 μm) particles; (d) foamed-polystyrene coated CI (5.35 μm) particles [20].

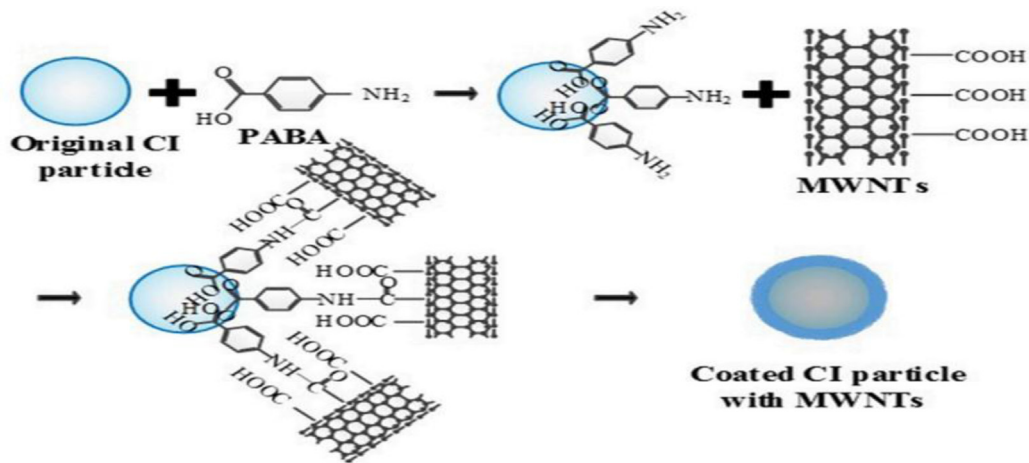


Fig. 6. Schematic diagram of the grafting process [24].

Rwei et al. [22] develop MR fluids incorporating multi-walled carbon nanotubes (MWCNT)/CI complex and graphene/CI complex. The inclusions maintain the saturation magnetization equivalent to CI particles without being hindered due to the blending with MWCNT or graphene. A broad dynamic range for yield stress has been achieved by the MR fluids with the inclusion of 69 percent MWCNT/CI and graphene/CI complex. The results indicate that the floating MWCNT/CI particles are oriented more readily in the direction perpendicular to the flow direction. Cheng et al. [23] synthesize the MR fluid samples by putting up CIPs into the silicon oil, having varying organic molecules and auxiliaries added on their surface. The sedimentation action has been quantitatively determined using a thermal conductivity sediment measurement technique. On replacing the organic molecule from octyl acyl ethylenediamine triacetate to lauryl acyl ethylenediamine triacetate and stearyl acyl ethylenediamine triacetate, the sedimentation rate exhibits mitigation of 53.9%, 64.2%, and 75.1% respectively. Guo et al. [24] utilize multi-walled carbon nanotubes for coating the CI

particles. The grafting process (Fig. 6) is not impulsive, hence mechanical stirring along with ultrasonication are adopted to improve the coating effect. The coating effect has been examined by the surface topography technique and stability testing of composite magnetic particles of the prepared MR fluids. The results exhibit a slight reduction in magnetic saturation but sedimentation stability shows significant improvement due to a reduction in the adsorption forces acting between the particles. Ronzova et al. [25] concentrate on coating the magnetic CI particles with a slim modified layer that acts as a surface shell by utilizing four organosilanes. The magnetization of the modified particles does not have adverse effects due to the organosilanes layered particles. Moreover, this modification enhances the chemical stability along with the thermal oxidation stability. The sedimentation stability, which has been expressed as a weight gain also enhanced significantly.

Shen et al. [26] focus on controlling the size and shapes of surface-modifying $\text{Fe}_3\text{O}_4@SiO_2$ particles included in the MR fluids. The surface modification using dodecyltrimethoxysilane (DTM) has been obtained under a silane

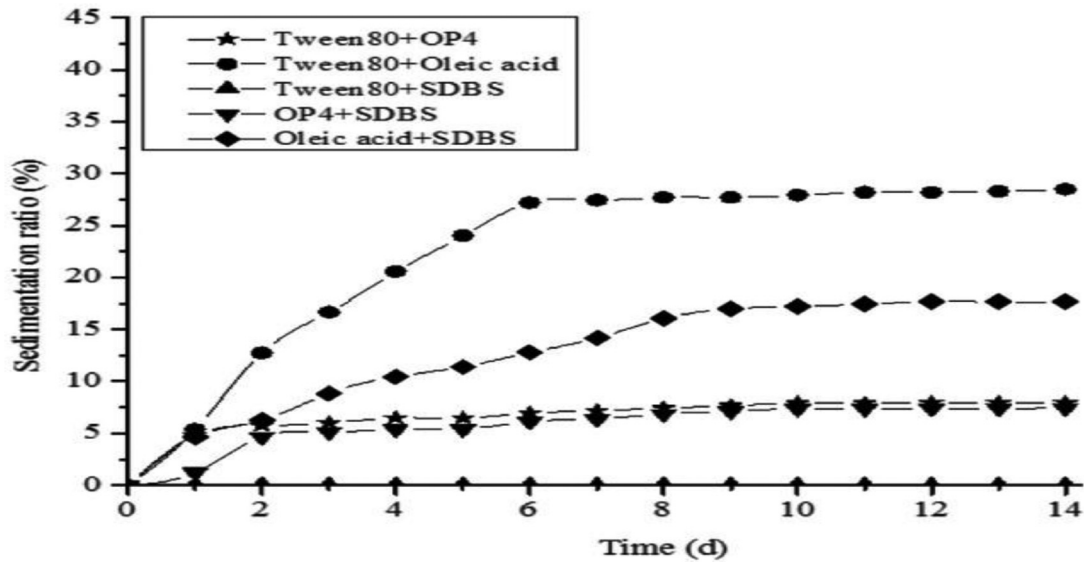


Fig. 7. Effect of surfactant compounding on sedimentation stability of MR fluid [27].

coupling reaction, which enhances the dispersal stability of particles. The rheological results exhibit that surface modification using DTM and enlargement of particle size have a positive impact on the MR characteristics.

3.2 Different types of surfactants in MR fluid systems

Surfactants may be utilized to elude the particle aggregation by improving steric repulsion within the suspended particles. Surfactants may enhance the polarity of the CI surface which makes it more synonymous with the carrier medium. Fei et al. [27] evaluate the efficacy of individual surfactants i.e.; oleic acid, Tween 80, sodium dodecyl benzene sulfonate, and OP₄ emulsifiers for their viscosity and sedimentation stability (Fig. 7). These surfactants are compounded for appreciable improvement in the sedimentation rate. Zuzhi et al. [28] prepare a high-performance MR fluid by utilizing bentonite and silane coupling agents as additives in the appropriate proportions. The analysis results exhibit an enhancement in the sedimentation stability with the addition of bentonite (3.60%) and silane coupling agent (2.88%). Yang et al. [29] prepare the MR fluid constituting CI particles mixed in the mineral oil along with the surfactant named 12-hydroxy stearic acid (HSA) and the inclusion of stearic acid results in higher shear stress with non-newtonian behavior. A concentration of 2 g/HSA contributes stronger flocculation in the solution and improves the stability.

Son et al. [30] describe the settling dynamics of the suspended particles into the MR fluids using the discrete element method (DEM). The impact due to stabilizing surfactants onto the interparticle interactions has been included while deriving a valid contact-impact model for DEM estimation. The significance of additives has been determined by considering stokes drag along with the shape and wall correction attributes. Dorosti et al. [31] prepare water-based MR fluid which consists of worm-like micelles (WLMs). Cetyltrimethylammonium bromide (CTAB) has been utilized as a disperser in the company of potassium

bromide. The influence of CTAB concentration on the structure, and characteristics has been studied and the stability as well as yield stress of the suspensions exhibit an improvement. Fei et al. [32] study the effect of including various surfactants i.e.; ethylene glycol monostearate, sodium lauryl alcohol phosphate, glyceride monostearate, compound sodium fatty acid, methyl ester sulfonate in the prepared MR fluid. The inclusion of surfactants enhances the sedimentation stability as well as the fluidity.

3.3 Additives in MR fluid

A lot of additives are being utilized to enhance the stability performance of the MR fluids but still, there is a scope for improvement. The critical criterion for choosing an appropriate additive is related to its compatibility with the carrier medium. Feng et al. [33] prepare the MR fluid composed of guar gum powder together with CI particles and silicone oil. The guar gum-coated particles exhibit enhanced sedimentation stability and thixotropy for the developed MR fluid. Lim et al. [34] make use of micron-sized organoclays to stabilize the MR fluid carrying CI particles. It enhances fluid stability without much impact on the MR effect. The yield stress initially mitigates but it amplifies due to an increase in the applied magnetic field. Piao et al. [35] correlate the attributes of MR fluids with and without a sepiolite additive by making use of a rotational rheometer and scanning electron microscope. The sedimentation problem has been addressed to a larger extent as the sepiolite is injected into the interspaces within the CI particles. Hong et al. [36] examine the influence of adding halloysite nano clay in varying proportions in the CI-based MR fluids. The obtained flow curves exhibit a variation in dynamic yield stress along with the occurrence of a solid-alike character. The sedimentation improves significantly on the inclusion of the additives. Esmailnezhad [37] investigated the additive effects by considering two models (two-factor interaction and quadratic model) to determine the shear viscosity, yield stress in terms of the

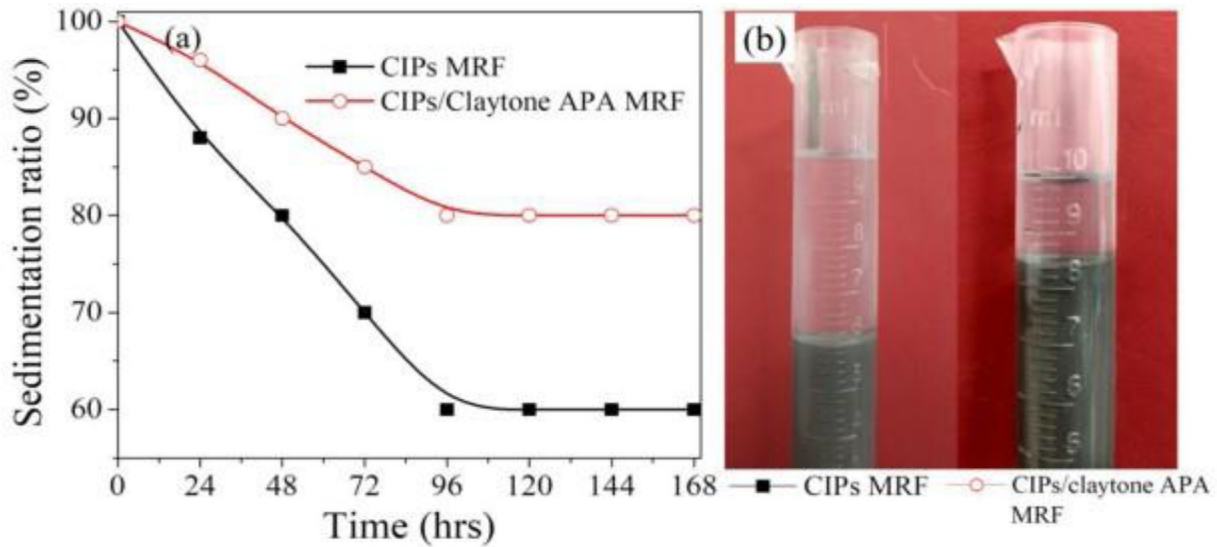


Fig. 8. (a) Sedimentation rate versus time in hours; (b) MR fluid flowed after complete settling of pure CIPs and CIPs/Claytone APA/friction reducer [38].

particle-additive concentration, and magnetic field strength. The confirmation of the model has been checked by carrying out an auxiliary experiment. Aruna et al. [38] developed the MR fluid samples by including pure CIPs, CIPs/Clayton APA/Molyvan 855 additive along with poly-alpha-olefin oil (Fig. 8b). The magnetic saturation predicted through the vibrating magnetometer exhibits that its value changes from 146.12 emu/g to 55.12 emu/g with the inclusion of the additive. The results indicate that the CIPs/Claytone APA/Molyvan enhances the sedimentation rate contrary to pure CIP MR Fluid (Fig. 8a). Maurya et al. [39] include laponite as an additive and oleic acid as a surfactant while preparing water-based MR fluid. A notable enhancement in the MR attributes has been achieved along with the improved sedimentation stability and the storage moduli exhibit a stable plateau area for various angular frequencies, indicating the illustrious solid-like behavior of the prepared fluid.

3.4 Nanoparticles as additives in MR fluid

The inclusion of nanomagnetic materials enhances the sedimentation stability and adversely affects the MR effect. Ngatu et al. [40] noticed the mitigation in sedimentation rate by partially replacing the micron-size particles with nanoscale particles but it caused a reduction in yield stress. The flow curves have been analyzed with a parallel-disk rheometer and the Bingham plastic flow model has been used to determine the generated yield stress. Iglesias et al. [41] examine the stability and redispersibility of the MR fluids on the inclusion of the nanoparticles. It has been noticed that the nanoparticles 3% (by volume) are sufficient for generating long-lasting stability to the MR fluids comprising 30% Fe micro-particles. In the event of the settling process, the most significant factor is the ease of redispersion of the sediment. The MR fluid performance has been determined by plotting

steady-state rheograms having varying volume proportions of the magnetite. The yield stress has been observed to be largely field-dependent. Jonkkari et al. [42] inspect the sedimentation stability along with the rheological attributes of the MR fluids containing a mixture of micro and nano-size particles. An addition of 10% (by weight) nanoparticles mitigates the sedimentation rate almost by 10 percent, while yield stress exhibits only a marginal decrease in its value. Wang et al. [43] investigate the nanocomposites comprising molybdenum disulfide (MoS_2) nanosheets, cobalt ferrite (CoFe_2O_4) nanoparticles and ($\text{CoFe}_2\text{O}_4/\text{MoS}_2$). The $\text{CoFe}_2\text{O}_4/\text{MoS}_2$ -based fluid presents excellent sedimentation stability which resulted due to the decreased particle-fluid density dissimilarity. Choi et al. [44] prepare hollow polydivinylbenzene@ Fe_3O_4 (h-PDVB@ Fe_3O_4) nanoparticles by settling Fe_3O_4 nanoparticles onto h-PDVB (Fig. 9). The MR performance of h-PDVB@ Fe_3O_4 and foamed PS/ Fe_3O_4 nano-particles has been investigated by employing a Turbiscan instrument. As a result of the reduction in the density dissimilarity between medium and particles, the h-PDVB@ Fe_3O_4 blend exhibits a considerable improvement in the sedimentation stability contrary to the pure Fe_3O_4 blend. He et al. [45] anchor the manganese ferrite nanoparticles onto the surface of MgAl-layer double hydroxide by using a facile two-step hydrothermal technique. The prepared nanoparticles are dispersed into the MR fluid, which produces a significant enhancement in sedimentation stability due to higher surface area and lowered density dissimilarity.

Zhu et al. [46] developed the Fe nano-particles by making use of a DC arc discharge technique. The prepared nanoparticles (NIPs) in combination with the micron CI particles (MIPs) have been utilized for the preparation of the MR fluids. The investigations show a marginal decline in the MR effect, whereas sedimentation stability has been effectively bettered (Fig. 10).

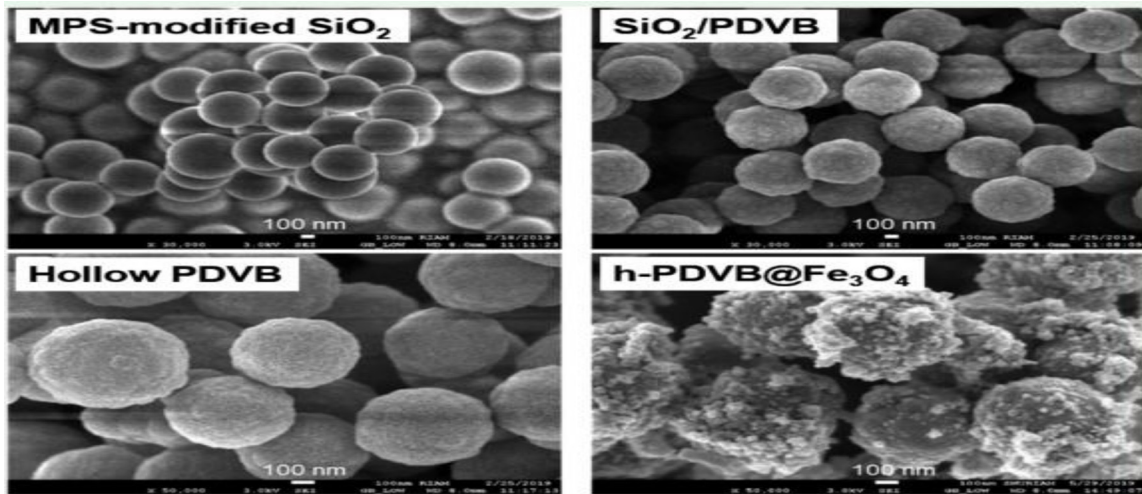


Fig. 9. Scanning electron microscopy images for (a) MPS-modified SiO₂; (b) SiO₂/PDVB; (c) h-PDVB; and (d) h-PDVB@Fe₃O₄ [44].

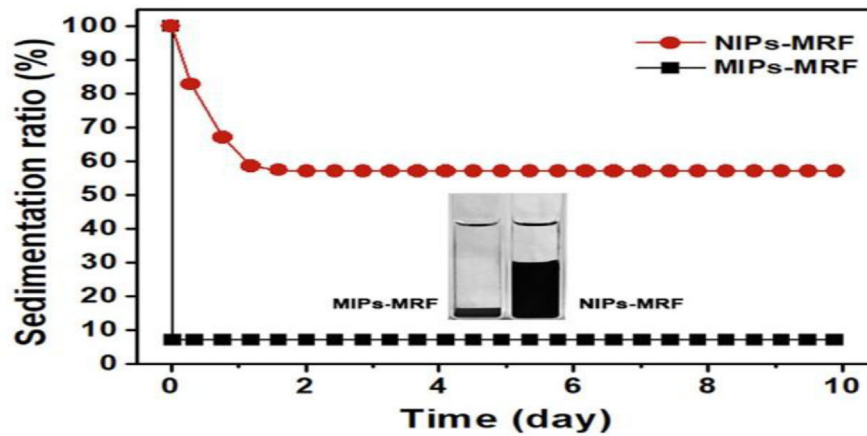


Fig. 10. Sedimentation ratio versus time for NIPs and MIPs MR Fluid [46].

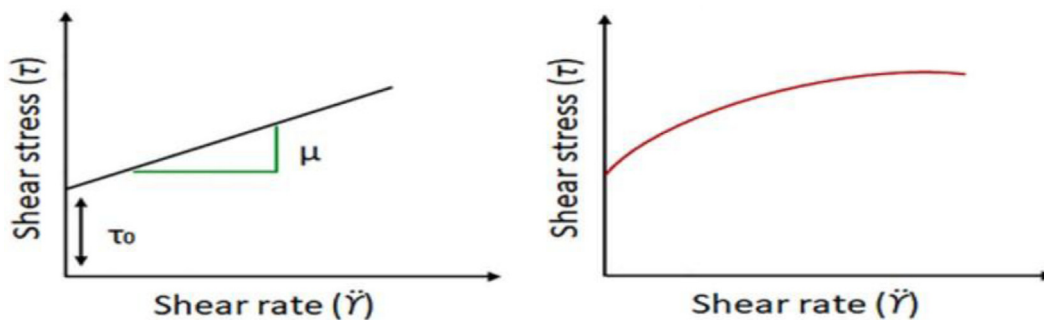


Fig. 11. Schematic of variation of shear stress v/s shear rate (a) Bingham model; (b) Herschel–Bulkley Model [48].

4 Models used in MR fluids

A fluid in which shear stress varies in direct proportion with respect to the shear rate is termed a Newtonian fluid whereas in case of non-Newtonian fluids, viscosity mitigates with an increase in the shear rate. The various models have been used by the researchers in order to predict the MR fluid behavior.

4.1 Bingham fluid model

It is the commonly applied model for investigating the rheology of non-Newtonian fluids. The relation exhibited by this model is given in equation (2), where τ is shear stress, τ_0 is initial yield stress, μ_p is plastic viscosity and $\dot{\gamma}$ is the shear rate

$$\tau = \tau_0 + \mu_p \dot{\gamma}. \quad (2)$$

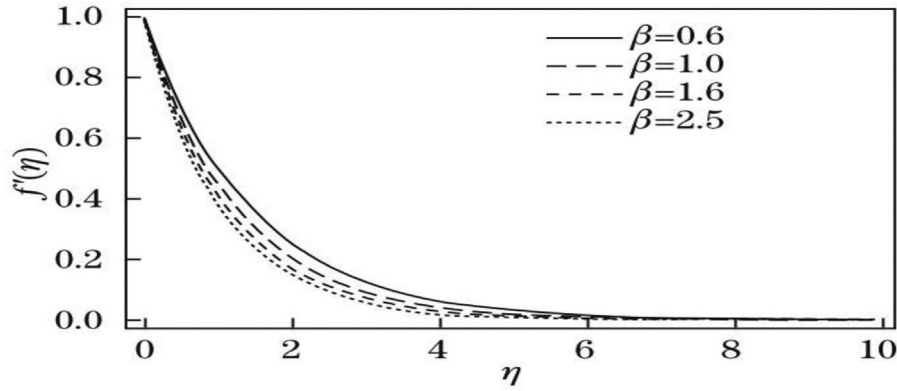


Fig. 12. Effects of β on $f'(\eta)$ at $H_a = 0.5$ [52].

The morphology, crystal structures, surface chemical composition, and magnetic properties of prepared fluid have been examined. The MR fluids show viscoplastic flows when the structured chain has been destroyed. The prepared MR fluids are fitted by utilizing the Bingham model (Fig. 11a) for characterizing the viscoplastic flow curves with the yield stress. The results indicate a slight mitigation in the MR effect, but there is a significant enhancement in the sedimentation stability [46]. The rheological attributes along with the dispersion stability for the MR fluids containing hydrophilic treated CI particles suspended in a water-in-oil emulsion have been investigated. The attracting forces between hydrophilic-treated CI particles and water emulsion play a crucial role in the enhanced stability of the packed CI particles against sedimentation. A constant stress has been produced within the limit of zero shear rate and the plateau of the flow curve agrees with the Bingham stress model. A localized magnetization saturation has been produced between the neighboring magnetic particles at lower values of magnetic fields [47].

4.2 Herschel–Bulkley fluid model

The Herschel–Bulkley fluid model is another regular model used for a non-newtonian fluid to investigate the yield stress which is given by equation (3), where τ is shear stress, τ_0 is yield stress, K denotes consistency coefficient, $\dot{\gamma}$ is the shear rate, and n is the fluid flow behavior index.

$$\tau = \tau_0 + K\dot{\gamma}^n. \quad (3)$$

On increasing the magnetic field strength, the value of K increases whereas n exhibits a reduction in its value. The MR fluid with silicon oil exhibits higher yield stress when compared with water-based MR fluid [49]. A MR finishing fluid using the Taguchi design of experiments has been evaluated for obtaining the generated yield stress. The rheological attributes using three models i.e.; Bingham plastic, Herschel–Bulkley, and Casson's fluid model have been obtained. The Herschel–Bulkley model (Fig. 11b) has been best fitted which is based on the value of the coefficient of regression. The optimized fluid (based on analysis of variance results) exhibits a significant drop in the average surface roughness value [50].

4.3 Casson model

The behavior of the prepared fluid (Eq. (4)) has been identified by utilizing a Mason number and a Casson number. The higher colloidal stability fluid has been utilized when the applied magnetic field does not exist, to keep the off-state viscosity as little as possible. The apparent viscosity along with magnetization values for the samples with varying particle volume proportions have been examined at various values of the magnetic field density. The Mason and Casson numbers may be reliably scaled for devices with varying sizes and varying operating conditions [51].

$$\sqrt{\tau} = \sqrt{\tau_c} + \sqrt{\eta_c \dot{\gamma}}, \quad (4)$$

where η_c is casson viscosity, τ is shear stress, τ_c is the casson yield stress, $\dot{\gamma}$ is shear rate.

The Soret and Dufour effects on the magnetohydrodynamic flow of the Casson fluid over a stretched surface have been investigated. The Casson parameter (β) reduces velocity ($f'(\eta)$) as well as boundary layer thickness (Fig. 12).

The increase in the Casson parameter and the Hartman number (H_a) reduces the velocity while increasing the concentration and temperature. The impact of the Casson parameter and Hartman number on the skin friction coefficient is entirely opposite [52].

5 Oxidation and corrosion effect on rheological attributes

Anupama et al. [53] prepare magnetic soft nickel zinc ferrite powder having a higher value of saturation magnetization with glycine as fuel and metal nitrate as a precursor. The response of the MR fluid has been greatly affected by the microstructure, morphology, and saturating magnetization. A lower particle's density results in a higher value of viscosity in off-state. The outstanding chemical stability as well as thermal oxidation of magnetic oxide particles relative to metallic magnetic particles made all the prepared MR fluids more dedicated towards the harsh working environments. Hong et al. [54] utilize silica coating on CI microspheres to prevent oxidation and polishing of

BK7 glass. The surface roughness besides material removal rate has been determined for investigating the grading of surfaces and optimum experimental state for polished wheel speed and induced magnetic field density. Plachy et al. [55] investigate the effect on the performance due to corroded CI particles immersed inside silicone oil-based suspensions. The thermal oxidation of CI particles has been accomplished and corroded covering on oxidizing particles surface has been studied by employing the X-ray diffraction (XRD) technique. The suspensions having oxidized particles give lesser yield stress values, which are remarkably exhibited at higher intensity of induced field caused due to lower saturating magnetization values.

6 Effect of particle proportion, shape, and size on rheological attributes

Cruze et al. [56] prepare six different MR fluids with the alteration in proportionality of CI particles in the carrier fluid. The mean size of the CI particle has been determined using XRD; employing SEM analysis the particle's morphology has been showcased as worm-shaped housing and magnetic saturation has been determined using vibrating sample magnetometer measurement. The synthesized samples having magnetec oil as carrier fluid are closely examined for rheological attributes. Jahan et al. [57] enquire about the influence of flake-shaped Fe particles immersed in the silicon oil-based MR fluid. The enhanced value of yield stress caused by adding nanoparticles has been matched up using a universal yield stress scaling equation. The cylindrical measurement technology has been utilized for investigating fluid stability with time. An improvement in dynamic efficiency has been observed resulting from the decrease in the value of sliding friction. Kwon et al. [58] synthesized the octahedral shape magnetite particles to improve the steadiness and the MR effect of CI-based MR Fluids utilizing a hydrothermal technique in an autoclave. The characteristics of the prepared suspensions containing and not-containing octahedral magnetite nano-sized particles have been experimentally examined. The shear stress, viscosity, and storage modulus exhibit a rise in their values with the inclusion of magnetic additives. Li et al. [59] investigated the particle spacing and particle size influence on the intensity of the magnetic field to determine the modeling flaw in single chain dipole. The results reveal that the influence of the particle spacing and its size have less impact as compared to the intensity of the induced magnetic field, which is the dominating component affecting the produced error. It has been depicted that the shear stress enhances with an increase in the particle radius because a larger particle area has been affected resulting in the enhanced magnetic force. Mohamad et al. [60] evaluate the transient as well as viscoelastic behavior of the plate-shaped CI particles-based MR greases. The plate-shaped particles are made from the spherical ones utilizing a milling operation through a rotating ball mill. The reaction time and storage modulus for the selected CI particles appreciably rely on the particle shape and mass proportions.

Kwon et al. [61] fabricate flake-shaped galfenol particles utilizing a traditional rolling and textured annealed process. The crystal structure and flake morphology have been explored by employing X-ray diffraction and SEM correspondingly. The fluids containing galfenol particles show a larger value of saturation magnetization and the storage modulus represents the stabilized plateau area for each value of the angular frequency that proposed prominent solid-like behavior. Qiu et al. [62] examine the magnetic particle chain structure and establish a mechanical model having distinct particle diameters. The MR fluid having silicon oil as a carrier medium and different particle volume proportion has been produced and tested to determine the shear characteristics. The results depict that the shear stress gets stable on increasing shear strain rate and the shear thinning phenomenon has been also observed. The linear rise in shear stress has been observed on increasing the particle proportion in the prepared MR fluid and the average error stays on the lower side in comparison to the existing model. Chen and Li [63] investigate different samples with varying magnetic particle sizes which have been generated using concentration control of the precursor solution in the co-precipitation method. The applied magnetic field enhances the formation of microstructures, causing higher viscosity. On the other side, shear rates rise tend to destroy the microstructures, which would reduce the viscosity. The magneto viscous effect gets vigorously improved and weakening of the viscoelastic effect takes place. Rabbani et al. [64] review the specifications, and characteristics of the magnetic particles diffused into additives along with their effect on rheological characteristics and the stability of the fluid. The surface-modified magnetic as well as non-magnetic micro and nanoparticles have been examined. The impact of coated layers, kinds of coating, density variation, coating thickness, and magnetic saturation on the stability along with the rheological properties of MR fluid has been analyzed.

7 Temperature effect on rheological attributes of MR fluids

The effect of temperature on the rheological attributes of MR fluids is highly notable. The working range of available MR fluids is -50^0 to 150^0 °C. The MR fluid viscosity cannot be governed beyond this range [65]. The consequences of the variation in temperature on MR fluid rheological properties have been examined and temperature rise leads to a reduction of shear stress and viscosity in off-state conditions. MR fluids exhibit excellent thermal stability below 100^0 °C. However, there is an irreversible decline in total stress when the temperature crosses 150^0 °C [66]. The plastic viscosity and bulk modulus reduced with increments in the temperature, while shear stress remained the same for the temperature ranging from 25^0 °C to 70^0 °C. The stiffness and energy dissipation exhibit a reduction in increasing the temperature of the fluid [67]. The characteristics of the carrier fluids and magnetic particles under high-temperature environments have been investigated. A MR fluid with greater temperature resistance has been

produced and a sedimentation rate of just 4.42 percent has been observed after a one-week duration. The yield stress mitigates by 4.03 percent when the temperature rises from 10°C to 70°C [68]. The prepared MR fluid has been investigated for various values of the temperatures along with varying magnetic field densities. The Herschel–Bulkley model has been employed to examine the non-linear behavior of the MR fluid by including the temperature effect. The results exhibit that the temperature jumps appreciably from atmospheric to approximately 125°C with a reduction in the damping force by 66.32% at higher load attributes. The particle characteristics analysis exhibits no change in the particle morphology but saturation magnetization gets mitigated by 57% at higher temperatures. The images taken by scanning electron microscope illustrate that the particles start to deteriorate beyond 200°C [69].

8 Applications of MR Fluids

The MR fluids also known as smart materials are nowadays used in automobile, medical, buildings, bridges, and finishing applications. Some of the applications of these fluids are discussed in this section.

8.1 Automobile applications

The dampers containing MR fluids found their use in automobile cushioning which reduces the extent of vibrations thereby enhancing passenger comfort. Forte et al. [70] present the squeezed film damper filled with the MR fluid. The MR damper utilizes the synergic effects of a magnetic damper and variable viscosity squeezed film damper. The developed device's experimental results show its high effectiveness which dampens the vibrations produced in the rotor. Rashid et al. [71] assess the impact of MR dampers for controlling the suspension and depict that these MR suspensions can be utilized very effectively in passenger vehicles with significantly improved steering stability and rider comfort. Yoo and Wereley [72] explore a highly efficient design for mesoscale MR valves. The valve size may be diminished and active core length may be enlarged for high choked pressure by selecting the material of high permeability. The non-dimensional plug thickness is used as an important measure of valve efficiency. Grunwald and Olabi [73] present the parametric analysis having magnetostatic simulations of a MR orifice and valve. The test device assembly having two controlling devices has been developed and the performances are empirically determined. The excellent features such as quick response and contactless control are great attractions in these control devices. Karakoc et al. [74] propose a brake comprising multiple rotatory disks which have been immersed into the MR fluid. On applying the current to the enclosed electromagnet, the solidification of MR fluid occurs because of an increase in the yield stress. The shear friction on the rotating disks is produced by controllable shear stress, which in turn generates the braking torque. Kumbhar et al. [75] synthesize the MR fluid for braking applications and conclude that the Csi 45% solution

(having 45% CI particles, 49% silicon oil, and 1% additive) exhibits a maximum yield strength of 92.34 kPa. CI powder proves to be a better alternative for braking applications as compared to EI powder. Jaindl et al. [76] designed an optimum disk-type MR fluid clutch. A continuously adjustable torque is induced by varying magnetic field intensity and the optimal torque value has been obtained by keeping weight as less as possible using fuzzy functions. Latha et al. [77] design and describe the manufacturing details of the MR fluid clutch comprising multi-layered disks. The clutch has been designed by making use of solid works software and ANSYS has been employed to simulate the results of the torque transfer capacity using magneto-static analysis. The manufactured clutch containing MR fluid exhibits reduced shocks, low wear, and variable loading conditions during its operation.

8.2 Medical applications

Jonsdottir et al. [78] present a perfluorinated polyether-based MR suspension customized for a prosthetic knee. A MR suspension exhibits an appropriate symmetry between generated yield stress, sedimentation ratio, and value of off-state viscosity which pertains to the qualities of the knee. Bapat et al. [79] model a prosthetic knee. The investigations concentrate on modeling the MR fluid knee and predicting the value of generated torque. The produced torque depends largely on the applied current, gap magnitude, and angle. The MR fluid knee features a noncircular rotor resulting in a varying gap magnitude between the rotor and stator. Nordin et al. [80] investigate the MR fluid damper that provides variable damping, relying on the amount of induced magnetic field density. The study aims to reduce injuries and give comfort to riders. Additionally, fuzzy-integrated-derivative controller is employed to ensure the smooth functioning of the MR fluid damper at varying frequencies. Liu et al. [81] study the advancement of medical applications of MR fluids with a focus on the exoskeleton, rehabilitation devices, lower limb prosthesis, orthosis, tactile display, and haptic master. By employing MR fluids, stable and natural limb movements in orthoses, lower limb prostheses, and exoskeletons have been noticed. A highly transparent and resolution haptic feedback and flexible muscle training in rehabilitation devices have been observed.

8.3 Finishing applications

Xiu et al. [82] present a new test procedure for reciprocating MR polishing. The micro-removal mechanism of reciprocating MR polishing and its characteristics have been analyzed. The results reveal the usefulness of the developed MR fluid and the functionality of the reciprocating polishing procedure. Guo et al. [83] investigate the removal rate of aluminium alloy in MR finishing and develop a removal model to determine the removal rate of the MR fluid. The developed model exhibits a high surface quality while machining the aluminium alloy using MR fluid. The reasonable surface roughness of 2.715 nm has been obtained and the tool marks formed as a result of turning operation

have been removed, which validates the reliability of the developed model. Srivastava et al. [84] develop a double-disc chemically aided MR finishing process for precise material removal of brittle materials viz. monocrystalline silicon wafer. The process largely depends on the MR fluid, which acts as a multi-point finishing tool. The applied magnetic field in the prepared MR fluid samples appreciably affects the quality of the finished wafer surface. The shear stress and viscosity exhibit reduction with the increase in the temperature.

8.4 Civil structure / building applications

Aly [85] exhibits vibration control of a building model subjected to earthquake loads. The MR damper is placed between the ground and the first floor of the building in order to determine the reduction in seismic response. A comparison between various control algorithms such as modulated homogeneous friction controller, decentralized bang-bang controller, maximum energy dissipation controller Lyapunov controller, and the clipped-optimal controller has been carried out. The developed controller exhibits the highest reduction in maximum inter-story drifts and highest absolute accelerations among all used control algorithms. Li et al. [86] developed a computational MR fluid damper model and simulated the generated flow field using the computational fluid dynamics process. Various inlet pressure profiles like the actual loading conditions have been designed and examined. The fluid velocity in the magnetic annular orifice reduces with respect to the magnetic field strength. The developed model accurately captures the damping characteristics of the MR fluid dampers. Behbahani et al. [87] investigated MR fluid damper for mitigation of the vibration in flexible truss bridge structures. Various truss bridges have been studied to determine stability and damping when subjected to seismic loads. The MR fluid damper used in the bridge deck reduces the vibration to a significant level by using the Bouc-wen model.

9 Current situation and future scope

In the last two to three decades ample research conducted on MR fluids marks huge refinement in the preparations and applicability of the MR fluids. The preparation of MR fluid and the impact of various additives to enhance the potential of these fluids have been probed. The selection of appropriate carrier fluid plays a significant role in the relationships between particle and fluid properties of the magnetic suspensions. EI powder suspended as a dispersal phase in the MR fluids presents higher yield strength due to its rod-like pattern. In the case of the continuous phase, biocompatible fluids like blended vegetable oils using synthetic oils are required to be prepared due to environmental issues. The highly dense fluids result in the mitigation of density difference between base fluid and suspended particles, which effectively reduces problems of instability and sedimentation. There is an unwanted rise in the fluid's viscosity in the absence of a magnetic field.

More investigation is to be carried out in search of a more conducive and economical carrier fluid. The problems of sedimentation and agglomeration are largely associated with the shape, size, and weight proportions of the magnetic particles, which have a countable impact on the rheological attributes of MR fluids and require more investigation. The stability method such as coating of iron particles with the polymerized materials and suspending a combination of nanoparticles and microparticles are methods employed for mitigating the sedimentation. However, the combination of additives for completely overcoming the problems of sedimentation and agglomeration in MR fluids still requires further research. The selection of magnetic particles depends on different factors such as stability concerns, affinity to carrier fluid, and the demanded value of the MR effect. The presently available MR fluids cost on the higher side and preparation of economical MR fluid is still a big challenge. The issues faced in storing the MR fluid are also a big concern.

The future scope of the MR fluid may be in heavy industries such as nuclear, shipbuilding, oil and gas, space, and aviation, etc. to achieve the desired damping response. The MR dampers may be exercised in the safety devices i.e.; vibrational control of engines on board ships, off-road vehicles, and additionally in prosthetic legs. Further, MR fluid may be exercised in the surface polishing. The promotion of smart materials at the nuclear scale is still required. In a mechanical system, vibration amplitude has a lower value during the initial stage and vibrations gradually enhance as may be viewed when the machining progresses. So, less damping is required at the beginning stage and higher damping is desirable at the later progress stage. In such a condition, the MR damper capable of varying the damping by regulating the control parameters as per the requirement through programmed logic working on the real-time sensor inputs of vibrations and the cutting parameters will be more productive. It shows that research related to variation in the damping capability of MR dampers having many variables has been least investigated.

10 Conclusion

MR fluids have a significant role to play in various industries due to their controllable rheological characteristics. The sedimentation, temperature effect, particle corrosion, and MR effect are the key challenges for producing an appropriate MR fluid. It has been noticed that the proper governing of the issues is required while preparing MR fluids, employing suitable additives, and fusing to ensure higher suitability for various applications.

- The various carrier fluids used in the preparation of MR fluids are mineral oil, silicon oil, castor oil, soybean oil, kerosene, synthetic oils, honge oil, organic oil, water-based oils, etc. However, for obtaining better vibration control, silicone oil is the most preferred one due to its higher viscosity index, lower friction characteristics, higher flash point, and higher shear strength.

- The off-state viscosity of the selected carrier fluid must be small so as to have a higher value of the dynamic range for the prepared MR fluid.
- The inclusion of small-sized Fe particles led to lower wettability, whereas larger-sized particles accounted for higher sedimentation rates.
- The sedimentation is a bigger concern related to the MR fluids. It may be mitigated using suitable additives such as lithium grease, oleic acid, aluminum stearate, laponite, guar gum, ethylene glycol monostearate, tetramethyl ammonium hydroxide, polystyrene, stearic acid, etc. The inclusion of nanomagnetic materials improves the sedimentation stability but adversely affects the MR effect.
- The MR suspensions incorporating the corroded Fe particles present lower values of generated yield stress under the influence of the applied magnetic field.
- The flaked Fe particles led to a lower value of shear strength and higher wear as compared to the spherically shaped Fe particles.
- The CI microparticles due to their higher value of saturation magnetization, more availability, and lesser cost are the majority favorable particles used for dispersing state within the MR Fluids.
- The on-state viscosity and yield stress of the MR fluids get mitigated at higher values of temperature and even CI particles get oxidized/corroded at higher temperatures. The favorable working temperature range for the MR fluids is -50°C to 150°C .
- The MR fluids have various application areas such as dampers, valves, brakes, clutches, finishing processes, etc. The MR suspensions significantly improve passenger comfort and steering stability in the vehicles. The MR fluids used for polishing exhibit high-quality finished surfaces.
- The MR fluids also found medical applications such as stable and natural limb movement in orthoses, lower limb prostheses, and exoskeletons.

Funding

This research received no external funding.

Conflict of interest

We have no conflicts to disclose.

Data availability

All data generated and analyzed during this study are included in this article.

Authors contribution

Vinod Chauhan: Conception of the work, Data collection, and its analysis
Ashwani Kumar: Data collection and drafting of the article
Radhey Sham: Data analysis and revision of the article.

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Cite this article as: Vinod Chauhan, Ashwani Kumar, Radhey Sham, Magnetorheological fluids: A comprehensive review, *Manufacturing Rev.* **11**, 6 (2024)