

A Magneto-rheological Suspension for a Prosthetic Knee Joint

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ABSTRACT

A perfluorinated polyether-based magneto-rheological suspension is presented that is tailored for a prosthetic knee. Rheological measurements of monodisperse and bidisperse mixtures are described. An MR suspension is sought with a suitable balance between field-induced yield stress, off-state viscosity and sedimentation rate. This relates directly to the qualities of the knee.

INTRODUCTION

Magneto-rheological (MR) fluids are a class of smart materials whose rheological properties can be varied with a magnetic field. In general, MR fluids are composed of micron-sized, usually 1-10 μm , ferromagnetic particles, suspended in a carrier fluid. With the application of a magnetic field, the dispersed particles form chain structures, aligned with the magnetic field direction. MR fluids have many industrial applications and are increasingly being considered in a number of devices, such as, dampers, valves, brakes, clutches, and prosthetic devices; see for example¹⁻⁵.

Motivated by the use of MR technology in an actuator for a prosthetic knee⁵⁻⁷, the purpose of our project is to investigate ways to improve the strength of MR fluids for use in small devices, without sacrificing the stability of the fluid. In the beforementioned prosthetic knee actuator, the MR fluid is

contained between a number of thin steel blades that move relative to one another. As the knee rotates into flexion or extension, the blades shear the particle chains to create resistance; the result is a varied fluid shear force within the knee. The MR fluid gap in the knee actuator is micron-sized and hence in order for the fluid to be active in the gap it can not be loaded with particles bigger than a few microns. Due to this size limitation, we are looking towards nano particles as a feasible option.

A common goal in the design of MR fluids is to have a high yield-stress, good dispersion stability, and keep a reasonably low off-state viscosity. A number of research groups have investigated how to enhance the strength of MR fluids. Perhaps the most widely employed technique for increasing the yield stress in MR fluids is increasing the volume fraction of iron powder⁸⁻¹¹. However, it is well documented that increasing the particle loading will increase the field-independent plastic viscosity of the fluid¹².

The effect of particle size and particle size distribution on the rheological behaviour of MR fluids has been studied to some extent by several groups. To name a few, Genc and Phule⁹ studied the rheological properties of two grades of carbonyl iron (CI) powder, coarse powder with an average particle size of 7-9 μm and fine powder with an average particle size of

2 μm . They found that the fluid with coarse powder exhibited higher yield stress values than the fluid with smaller powder. This result is consistent with the results by Ginder and Davies¹⁰ who found the interaction forces to increase with saturation magnetization values of the particles, and bigger particles have higher saturation magnetization than smaller particles. Trendler and Böse¹³ investigated different particle sizes, including bimodal particle size distribution. Their results showed that the bimodal distribution gave the highest yield stress, indicating a strengthening of the particle interactions in the magnetic field. However, the results showed a decrease in the off-state viscosity when increasing the ratio of coarse to fine particles. Kittipoomwong and Klingenberg¹⁴ concluded that the yield stress of bidisperse suspensions is larger than that of monodisperse suspensions, at the same particle volume. They believe it is because the smaller particles cause the larger particles to form more chainlike aggregates than those formed in monodisperse suspensions.

All of the studies mentioned above dealt with micron-sized particles. Several researchers have studied the effect on rheological behavior of adding nano-sized particles to MR fluids. Wereley et al.¹⁵ found that replacing microparticles with nanoparticles, in small concentrations, tended to increase the field dependent yield stress. Furthermore, the nanoparticles reduced the sedimentation rate. However, a clear drawback for using nanoparticles is the increase in off-state viscosity which is associated with the high surface area to weight ratio for nano particles. Similar results were seen by Chauduri et al.¹⁶ who found an increase in yield stress by doping a certain percent of nano powder in the MR fluid. However, although stability was improved, Burguera et al.¹⁷ found that yield stress decreased with increasing concentration of nanoparticles.

Although a variety of MR fluids have been investigated there still is a need for further studies and analysis of rheological properties for specific devices. In this paper the perfluorinated polyether (PFPE) base fluid, the particle size and particle loading is described, and it is investigated how these properties affect the field-induced strength and the off-state viscosity. Furthermore, we investigate and try to clarify the influence of CI nanoparticles on the rheological behavior of MR fluids. Both on-state and off-state rheological measurements are carried out for a monodisperse and bidisperse fluid mixtures and the resulting rheological flow curves are presented.

MR SUSPENSION COMPOSITION

The base fluid that is chosen for this study is a perfluorinated polyether (PFPE) fluid¹⁸, specifically it is 95% PFPE UNIFLORTM oil¹⁹ and 5% functionalized PFPE KrytoxTM oil²⁰. A PFPE liquid is a chain of carbon, oxygen and fluorine atoms where the molecular structure can be either linear or pendent^{19,20}. It is heavier than water with a relative density of approximately 1.9.

Two grades of CI particles were used to prepare the MR fluid samples. The micron-sized particles are extra fine grade HS powder from BASF²¹ with an average diameter of 2 μm . The nano particles are commercially available from NanoAmor²² and have an average size of 25 nm.

The monodisperse PFPE-based MR fluid has a particle loading of about 60% by mass which is about 28% by volume. This is somewhat lower than used in commercially available MR fluids²³. The main reason for the low particle loading is that problems arise when a MR fluid with a high particle loading is to be injected into the prosthetic knee. Furthermore, low off-state viscosity is important which gives a preference for a low particle loading.

MAGNETIC BEAVIOUR

In the absence of a magnetic field, the MR fluid exhibits a strong shear thinning behaviour resulting in a very high viscosity at low shear-rates. At high shear-rates the fluid approaches a lower viscosity limit. When a magnetic field is applied the fluid exhibits a yield stress behaviour. The yield stress behaviour of the fluid can be characterized by the Bingham plastic model. The constitutive equation for the Bingham model is²⁴:

$$\tau = \tau_y + \mu_{BP} \cdot \dot{\gamma} \quad (1)$$

where τ is the total shear stress exerted by the fluid, τ_y is the field-induced shear yield stress, μ_{BP} is the post-yield viscosity, and the time derivative of γ is the shear rate. This linear model is applied to rheological measurements of the PFPE-based MR fluid and the parameters obtained are used to compare the properties of the PFPE-based MR fluid to other MR fluids.

Measurements of the field-induced behaviour were carried out with an Anton-Paar Physica MCR 100 rheometer²⁵ with a parallel plate measuring system. Plates with a diameter of 20 mm were used with a gap of 1 mm. The measurements were conducted at a temperature of 20°C, for shear rates ranging from 0.1 s⁻¹ to 1.0 x 10³ s⁻¹, and for values of the magnetic flux density ranging from 0.1 T to 0.55 T.

Monodisperse MR suspension

One monodisperse MR fluid sample was prepared and measured. The sample contains only micron-sized particles with a particle loading of 60% by mass. Fig. 1 shows the field-induced shear stress, as a function of the shear-rate and the magnetic flux density. The linear Bingham model is fitted to the measured flow curves, using a least-squared error fit. The fit is based on shear-stress values for shear-rates between 200 s⁻¹ and 1000 s⁻¹; these values are representative for the shear-rates in the

prosthetic knee. Fig. 1 shows the fitted model and the experimental data.

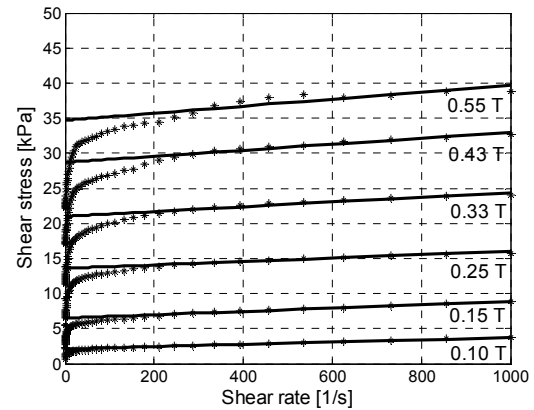


Figure 1. Measurements for a monodisperse MR fluid with the Bingham model fitted to the flow curves.

The linear fit is appropriate at high shear-rates. However, at low shear-rates the fluid does not exhibit the yield-stress implied by the Bingham model. The Bingham model is adequate for the current application since the shear-rate in the prosthetic knee is fairly high. Also, for the purpose of comparison to other fluids, the Bingham model is employed rather than the non-linear Herschel-Bulkley model.

Fig. 1 shows a still increasing shear stress at 0.55 T, for a shear-rate of 1000 s⁻¹. The maximum magnetic flux density of the MR fluid in the current design of the prosthetic knee is about 0.6 T. These results indicate that the torque output of the knee can be further increased by improving the magnetic circuit in knee and obtaining a higher magnetic flux density in the MR fluid.

Bidisperse MR suspension

Six bidisperse MR fluid samples were prepared and measured with various concentrations of micron-sized and nano-sized particles. Table 1 shows the solid concentrations of the bidisperse samples.

Table 1. The solid concentration of six bidisperse PFPE-based MR fluid samples.

Sample	Micron-sized particles [% mass]	Nano-sized particles [% mass]	Total solid concentration [% mass]
2	58.75	1.25	60.00
3	57.50	2.50	60.00
4	56.25	3.75	60.00
5	55.00	5.00	60.00
6	57.50	4.17	61.67
7	56.25	6.25	62.50

To illustrate the effect of nano-sized particles on the field-induced shear stress of the MR fluid, Fig. 2 shows the shear stress of samples 3 and 6 with a constant concentration of micron-sized particles but a variable concentration of nano-sized particles, at a magnetic flux density of 0.55 T. The samples have a micron-sized particle concentration of 57.50% and nano-sized particle concentration of 2.5% and 4.17%.

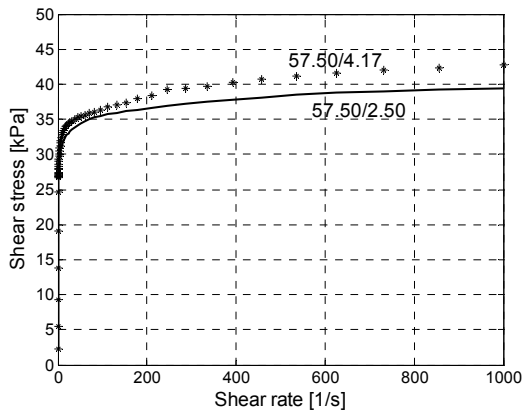


Figure 2. The shear stress in fluid samples 3 and 6, with a constant micron-sized particle concentration of 57.5% and a variable nano-sized particle concentration, at magnetic flux density of 0.55 T.

Fig. 2 shows that by increasing the nano-sized particle concentration from 2.5% to 4.17% results in a 9% increase in shear stress at a shear-rate of 1000 s^{-1} . This is, of course, by increasing the total solid concentration from 60% to 61.17%. For samples 4 and 7, with a micron-sized particle concentration of 56.25%, the increase in shear stress is 5% going from a

nano-sized particle concentration of 3.75% to 6.25%. Table 2 shows the effect of adding nano-sized particles to a constant concentration of micron-sized particles.

Table 2. Difference in shear stress, for a constant concentration of micron-sized particles, with variable concentration of nano-sized particles, at a shear-rate of 1000 s^{-1} and a magnetic flux density of 0.55 T.

Sample	Micron-sized particles [% mass]	Nano-sized particles [% mass]	Increase in shear stress [%]
2 & 5	57.50	2.50 → 4.17	8.7
3 & 6	56.25	3.75 → 6.25	5.3

By allowing the total solid concentration to increase, by adding nano-sized particles to a constant concentration of micron-sized particles, the shear stress increases at magnetic flux density of 0.55 T.

Pursuing this further, it is interesting to investigate the effect of nano-sized particles on the shear stress while holding the total solid concentration to a constant value of 60.00%. Fig. 3 shows how the shear stress of bidisperse samples 3 and 4, with a total solid concentration of 60.00%, compares to the monodisperse sample 1, at a magnetic flux density of 0.55 T.

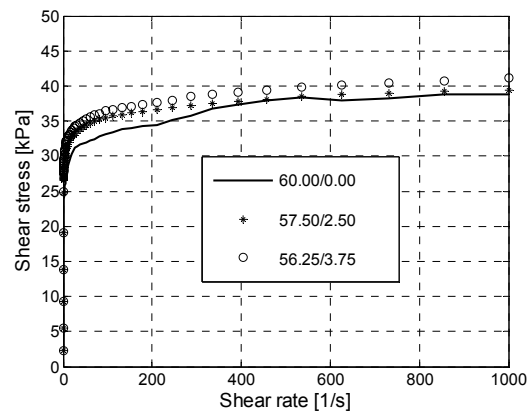


Figure 3. The shear stress of bidisperse samples 3 and 4, compared to that of a corresponding monodisperse sample, at a magnetic flux density of 0.55 T. All samples have a constant total solid concentration of 60.00%.

Interestingly, the shear stress increases when micron-sized particles are replaced by nano-sized particles, holding the total solid concentration to a constant value. The increase is larger for sample 4 which has a higher concentration of nano-sized particles. This does, however, not hold true when the concentration of nano-sized particles is increased further. A decrease is observed in shear-stress when the concentration of nano-sized particles is increased to a higher value of 5.00%. Table 3 shows the amount of change in shear stress for samples that have a total solid concentration of 60.00%, at a magnetic flux density of 0.55 T.

Table 3. Difference in shear stress for a constant total solid concentration of 60.00%, at a shear-rate of 1000 s^{-1} and a magnetic flux density of 0.55 T.

Sample	Nano-sized particles [% mass]	Shear stress change [%]
2	1.25	2.9
3	2.5	1.5
4	3.75	6.1
5	5	-4.4

Notably, sample 5, with a nano-sized particle concentration of 5%, shows a decrease in shear stress when compared to a corresponding monodisperse fluid. For a total solid concentration of 60.00%, the measurements show a peak in shear stress at a nano-sized particle concentration of 3.75% but a decrease when the concentration is increased further. This implies that some optimum in shear stress exists for given value of the total solid concentration.

Fig. 4 shows measured flow curves for sample 4 with a total solid concentration of 60.00% and nano sized particle concentration of 3.75%. This sample has exhibited the highest shear stress for samples with a total solid concentration of 60.00%.

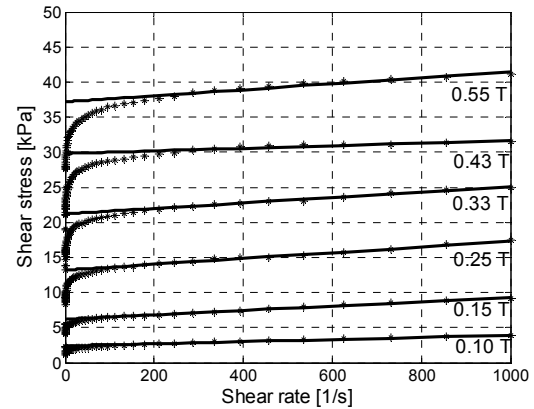


Figure 4. Measurements for a bidisperse MR fluid with a total solid concentration of 60.00% and a nano sized particle concentration of 3.75%. The Bingham model is fitted to the flow curves.

The linear Bingham model is fitted to the measured flow curves, using a least-squared error fit. The fit is based on shear stress values for shear-rates between 200 s^{-1} and 1000 s^{-1} . The bidisperse sample 4 shows moderately higher shear stress when compared to the monodisperse sample 1.

OFF-STATE BEHAVIOUR

For a potential application in the prosthetic knee, the off-state viscosity of the MR fluid is of importance. The off-state viscosity determines how fast the knee joint can rotate in the absence of a magnetic field.

Monodisperse MR suspension

The off-state viscosity of the monodisperse MR fluid was measured with a StressTech rheometer using a coaxial cylinder geometry at a temperature of 20°C . The diameters of the inner and outer cylinders were 25 mm and 27 mm, respectively. Fig. 5 shows the off-state viscosity of the monodisperse MR fluid along with the viscosity of its PFPE carrier liquid.

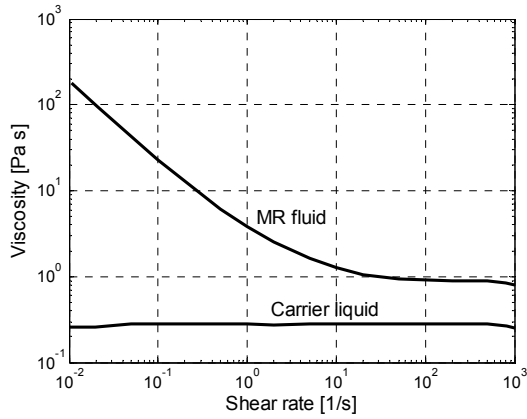


Figure 5. The off-state viscosity of the monodisperse MR fluid and the viscosity of its PFPE carrier liquid, measured with a StressTech rheometer.

The well known shear thinning property of MR fluids can be seen in Fig. 5. The carrier liquid behaves like a Newtonian fluid with a constant, shear-rate independent, viscosity. The viscosity of the PFPE carrier liquid is approximately 0.3 Pa·s and high shear rate viscosity limit of the MR fluid is 0.8 Pa·s.

The off-state viscosity of the PFPE-based monodisperse MR fluid is relatively high compared to other hydro-carbon based MR fluids²³. Although the current applications gives preference to low off-state viscosity, stability and low sedimentation velocity is required. Therefore, a higher viscosity carrier liquid is selected compared to carrier liquids used in commercially available MR fluids²³. The shear-rate in the prosthetic knee is fairly high, about 1000 s^{-1} , which leaves the knee unaffected by the high viscosity at low shear-rates. The maximum rotational speed of the knee joint is, therefore, determined by the off-state viscosity of the MR fluid at high shear-rates.

Bidisperse MR suspension

The off-state viscosities of the bidisperse MR fluids were measured with a Anton-Paar Physica MCR100 rheometer²⁵ at a temperature of 20°C. Plates with a diameter of 20 mm were used with a gap of 1 mm.

Fig. 6 shows the off-state viscosities of bidisperse MR fluids with a total solid concentration of 60.00%. The figure also shows the viscosity of the corresponding monodisperse MR fluid.

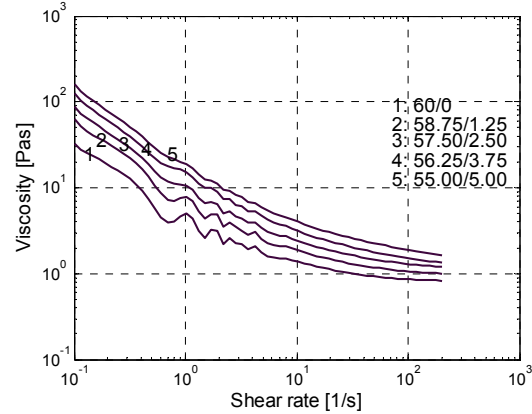


Figure 6. The off-state viscosities of bidisperse MR fluid samples with a total solid concentration of 60.00% along a corresponding monodisperse MR fluid.

Fig. 6 shows an increasing off-state viscosity with an increasing nano-sized particle concentration holding the total solid concentration to a constant value of 60.00%. Table 4 shows the viscosities of MR fluid samples at a low and a high shear-rate of 0.1 s^{-1} and 200 s^{-1} , respectively.

Table 4 shows a dramatic increase in viscosities at low shear-rates when replacing micron-sized particles with nano-sized particles. The increase is somewhat less at high shear-rates. The fluid sample that has shown the most increase in the field-induced shear stress is sample 4. This sample exhibits a 60.00% increase in off-state viscosity at high shear rates. For a potential application in a MR prosthetic knee, this will have a substantial effect on the rotary speed of the knee joint in the absence of a magnetic field.

Table 4. The off-state viscosities of bidisperse MR fluid samples with a total solid concentration of 60.00%

Sample	Viscosity at shear-rate of 0.1 s^{-1} [Pa·s]	Viscosity at shear-rate of 200 s^{-1} [Pa·s]
1: 60.00/0.00	32.6	0.83
2: 58.75/1.25	62.6	1.00
3: 57.50/2.50	87.4	1.20
4: 56.25/3.75	124.5	1.34
5: 55.00/5.00	159.6	1.64

A rapid increase in off-state viscosity has been observed for samples with a high concentration of nano-sized particles. This makes the bidisperse samples with the highest concentrations of nano-sized particles undesirable for the current application. These samples also exhibit a decrease in shear stress. Lower concentrations of nano-sized particles are more prominent. It remains a subject for further research to determine which will be the exact fluid composition for the MR fluid in the prosthetic knee joint.

CONCLUSIONS

The magnetic-field-induced shear stress and the off-state viscosity are competing factors when developing MR suspensions. The applicability of a MR suspension will be determined by the application at hand. The current study has revealed valuable information on bidisperse MR suspension and their applicability to a prosthetic knee joint. Nano-sized particles have been shown to have an undesirable effect on the off-state viscosity while moderately increasing the field-induced shear yield stress. It remains to be decided if this is desirable for the proposed application.

In future research, other factors in MR suspension design will be considered. These factors are the carrier liquid and particle sizes where different particle sizes of both micron-sized and nano-sized particles will be examined.

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