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ANALYSIS OF THE POTENTIAL USAGE OF SELECTED MAGNETIC FLUIDS IN THRUST SLIDE BEARINGS

ANALIZA MOŻLIWOŚCI ZASTOSOWANIA WYBRANYCH CIECZY MAGNETYCZNYCH WE WZDŁUŻNYCH ŁOŻYSKACH ŚLIZGOWYCH

Key words:

magnetorheological fluid, ferrofluid, rheological characteristics, normal stress, shear stress

Słowa kluczowe:

ciecz magnetoreologiczna ciecz ferromagnetyczna, charakterystyki reologiczne, naprężenie normalne, naprężenie styczne

Abstract

Magnetic fluids are substances whose rheological properties can be actively influenced by treatment with a magnetic field. Two main types of magnetic fluids can be distinguished: ferromagnetic fluids, and magnetorheological fluids. Ferrofluids are mostly used in sealing engineering, whereas magnetorheological fluids are usually applied in controlled systems for the dissipation of mechanical energy, like brakes and dampers. The ability to control the rheological properties

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of magnetic fluids opens new horizons for development in machine design, among others in the areas of bearing engineering.

The paper presents a comparative analysis of the rheological characteristics of selected magnetic fluids with a focus on the possible areas of the application of these substances in bearing engineering.

INTRODUCTION

A magnetic fluid is a suspension of particles made of ferromagnetic material immersed in a carrier fluid that does not exhibit magnetic properties. Due to the particle size, two types of magnetic fluids can be distinguished. Ferrofluids (FF) are produced based on particles with a diameter of several nanometres **[L. 1]**. Magnetorheological fluids (MRF) consist of particles with a size up to a few dozen micrometres **[L. 6]**. The particles in both types of magnetic fluid are usually covered with a surface-active compound (surfactant) in order to prevent aggregation and sedimentation of the suspension.

Magnetic fluids belong to the group of materials that can control their rheological properties with a magnetic field. The properties of the fluid may be different due to changes in the microstructure of the suspension occurring in the magnetic field **[L. 2]**. At a macroscopic scale, the magnetic field affects the stress state in a fluid, both in the tangential **[L. 2, 12]** and normal direction **[L. 3, 7, 10, 11, 12]**. The range of change in rheological properties is a function of several factors, in particular, volume fraction of the magnetic particles in the fluid, magnetic properties of the particle material, and particle size and shape.

Due to differences in the behaviour of FF and MRF, they are used in various technical applications. Ferromagnetic fluids are used primarily in seals **[L. 5]**, and magnetorheological fluids are used in vibration dampers, brakes, and clutches **[L. 9]**. Work is also underway on the development of bearings with these fluids **[L. 4, 8]**.

RESEARCH METHOD

Two magnetorheological fluids, MRF-10 and MRF-22 of the LORD Company, and two ferromagnetic fluids, APG-W05 and APG-W10 of the Ferrotech Company, were chosen for the studies. Selected properties of the fluids are shown in **Table 1**. The values were obtained based on the manufacturer's information **[L. 13, 14]** and from our own research in the case of zero field dynamic viscosity.

The examined MR fluids are characterized by similar physicochemical composition (the same carrier fluid and ferromagnetic particle parameters), except that the MRF-10 fluid has a 10% volume of particles, while the MRF-22 fluid contains 22% of ferromagnetic particles. This means there are different dynamic viscosity values between MR fluids when there is no magnetic field applied.

Table 1. Selected properties of examined magnetic fluids
Tabela 1. Wybrane właściwości badanych cieczy magnetycznych

No.	Magnetic fluid type	Fluid name	Saturation magnetization	Zero field viscosity
			kA/m	mPa·s (B = 0 T, t = 25°C, $\dot{\gamma} = 100\ s^{-1}$)
1	MRF	MRF-10	147.4	52.6
2		MRF-22	360.0	227.5
3	FF	APG-W05	30,7	550.5
4		APG-W10	30.8	1189.0

The tested Ferrofluids have very similar values of saturation magnetization. The APG-W10 fluid has a zero field dynamic viscosity twice as high as the second ferrofluid.

Magnetization is a crucial parameter that has an effect on the behaviour of the magnetic fluid attracted by a magnetic field. The magnetization curves of the tested fluids are shown in **Fig. 1**. Ferrofluids have much lower magnetization values compared to the tested MR fluids. The magnetization curves of the tested ferrofluids, due to the similarity of saturation magnetization, practically coincide. There are also significant differences between both MR fluids. The saturation magnetization of MRF-22 is almost 2.5 times higher than MRF-10. It should be noticed that increasing the magnetic field when the fluid is saturated does not cause further changes in magnetic fluid behaviour.

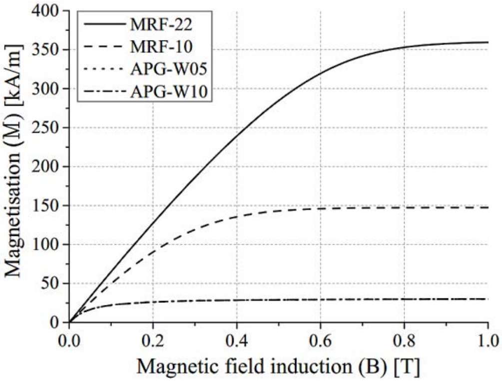
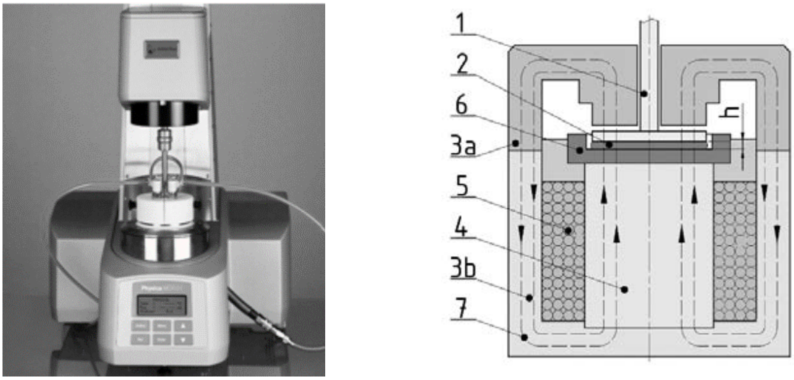


Fig. 1. Magnetization curves of the examined fluids [L. 13, 14]
Rys. 1. Krzywe magnetyzacji badanych cieczy magnetycznych **[L. 13, 14]**

Studies were performed on an MCR 301 rotational rheometer (**Fig. 2a**) equipped with an MRD 180 measuring cell that allows measurements to be carried out in a magnetic field.

A diagram of the test chamber is illustrated in **Fig. 2b**. The rotating plate (1) has a flat working surface. It is made of a material that has paramagnetic properties. The magnetic field is generated by the electromagnet (5). The power supply allows the current in the coil to be changed in the range of 0 to 5 A. This allows changes in the magnetic induction in the range of 0 to 1 T. The upper (3a) and lower (3b) components of the chamber and core of the electromagnet are made of a material with ferromagnetic properties. They form a closed magnetic circuit (7). The tested magnetic fluid (2) is placed between the rotating plate (1) and the fixed plate (6).



a) b)

Fig. 2. MCR 301 rheometer with an MRD 180 measuring cell [L. 15], b) schematic view of the measuring cell

Rys. 2. a) widok ogólny reometru MCR 301 z komorą MRD 180 **[L. 15]**, b) schemat komory badawczej

Studies were conducted with a constant gap height of h = 0.5 mm and a constant temperature of t = 25°C. The rotary plate diameter was 20 mm. The volume of the magnetic fluid was 175 µl.

The aim of the study was to determine the flow curves and the curves of normal stresses while logarithmically increasing the shear rate in the range 0.1–1000 s^{-1}. The study was performed at magnetic field inductions of B = 0, 100, 200, and 400 mT.

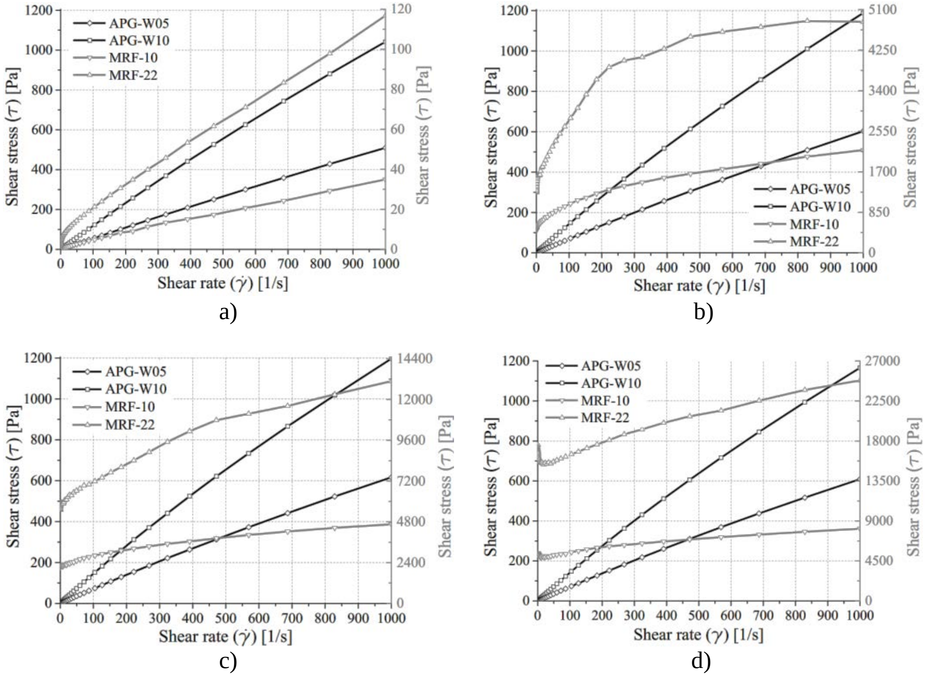
RESULTS

Shear stresses

The results of measurements of the shear stress registered with various values of magnetic field for the tested magnetic fluids are shown in **Fig. 3**. The scale on the left axis (black) refers to the FF, while the right axis (grey) of the graph refers to the MRF sample.

For the tested FF, the linearity of the flow curves was observed in all cases. This indicates behaviour typical of Newtonian fluids.

The examined FF untreated with a magnetic field (**Fig. 3a**) revealed the highest shear stress at the levels of 510 Pa (APG-W05) and 1040 Pa (APG-W10); whereas, after applied magnetic induction, regardless of its value, the measured shear stresses were obtained as 600 Pa for APG-W05 and 1180 Pa for APG-W10 (**Fig. 3b, c, d**). In both cases, this indicates a relatively small influence of magnetic field induction on the viscosity of the ferrofluid tested.



a) b) c) d)

Fig. 3. Flow curves: a) B = 0 mT, b) B = 100 mT, c) B = 200 mT, and d) B = 400 mT
Rys. 3. Krzywe płynięcia; a) B = 0 mT, b) B = 100 mT, c) B = 200 mT, d) B = 400 mT

It should be noted that the tested FF, due to low saturation magnetization, were saturated with less than B = 400 mT. Further increases in the magnetic field intensity (above the range analysed in this study) do not result in a change of the viscosity parameters of the tested FF.

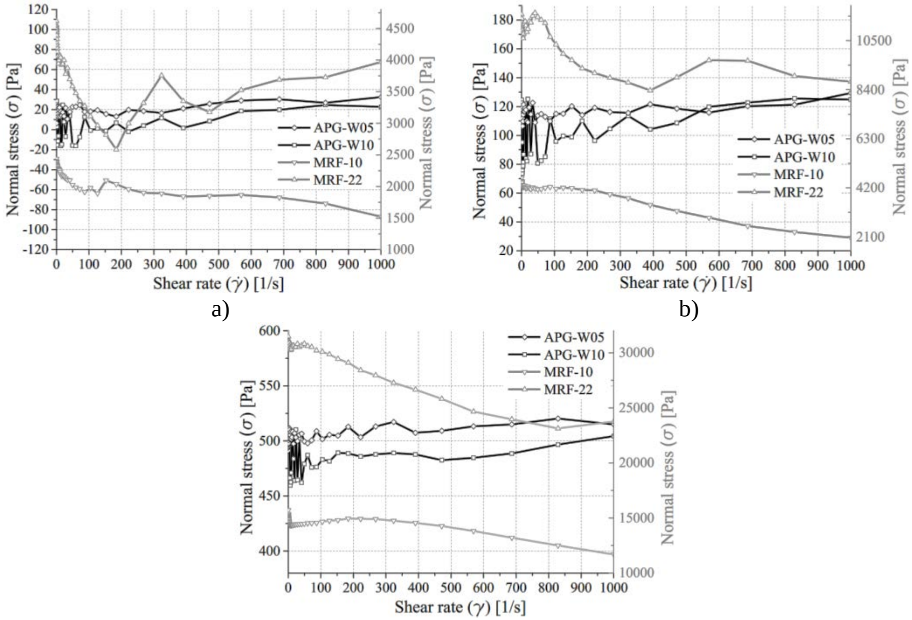
The results obtained for both examined MR fluids shows values of shear stress about 10 times lower in the case of magnetic field absence (**Fig. 3a**). Moreover, for MRF-22, some non-linearity of the flow curve can be noticed (only for a shear rate below 100 s^{-1}).

In the case of the magnetic field influence on the sample of MR fluids, flow curves indicate non-Newtonian rheological behaviour. In the lower range of shear rate, the presence of yield stress with a range of several hundred Pascal is clearly visible.

The range of shear stress variability observed for MR fluids is the shear stress variation registered during the test. This is very wide, both in terms of the magnetic field and in terms of shear rate. Flow curves indicate that, in the case of applied magnetic field, the behaviours of MR fluids are characteristic of shear thinning (pseudo-plastic) substances.

Normal stresses

The results of measuring the normal stresses of the examined fluids, obtained with various values of the magnetic field, are shown in **Fig. 4**. The scale on the left axis (black) refers to the FF, while the right axis (grey) of the graph refers to the sample MR fluids. As a result of the tests performed in the absence of magnetic field, there was no occurrence of normal stress; therefore, the results obtained for this case were omitted.



a)

b)

c)

Fig. 4. Normal stress curves: a) B = 100 mT, b) B = 200 mT, and c) B = 400 mT

Rys. 4. Wyniki pomiaru naprężeń normalnych; a) B = 100 mT, b) B = 200 mT, c) B = 400 mT

Normal stresses obtained for FF have similar values. Only a slightly higher normal stress was recorded for APG-W05 (a ferrofluid characterized by a lower zero field viscosity).

In the analysed range of shear rate, the mean normal stress values for B = 100 mT were about 20Pa, whereas, for B = 200 mT and 400 mT, they were about 110 Pa and 500 Pa. It may be noted that the duplication of the value of the magnetic induction caused an approximately 5-fold increase in the registered normal stress. Moreover, for both examined ferrofluids, there was no significant effect of the shear rate on the variation of normal stress.

For MR fluids, this was about twice the normal stress recorded for the MRF-22 fluid relative to MRF-10. This is due to the different amount of particles contained in the fluids. In all cases, increasing the shear rate reduced the obtained normal stress values. In all cases, the maximum value of this parameter was observed at shear rates below 1 s^{-1}.

At the highest of the analysed shear rates (1000 s^{-1}) and magnetic induction (B = 100 mT), the examined FF obtained a level of 25 Pa; whereas, for MRF-10 and MRF-22, for this same condition normal stress of 1500 and 4000 Pa was registered, respectively. The disproportion in the received values between the two types of magnetic fluids increases together with the value of the given magnetic field (for B = 400 mT, for both ferrofluids the obtained normal stress was about 0.5 kPa, whereas for MRF-10 it equalled 15 kPa and MRF-22 near 31k Pa. As can be seen, the values of normal stresses for MR fluids are significant.

CONCLUSIONS

The obtained results indicate significant differences in response to the magnetic field, depending on the type of magnetic fluid. In particular, this is visible in the response to changes in shear rate.

The use of ferrofluids in sliding bearings may be preferred due to their low friction. Moreover, the flow curves of the FF liquid indicate Newtonian behaviour without a significant influence of magnetic field on viscosity. Changes in the viscosity of the examined FF as a result of the magnetic field in the analysed magnetic induction range are about 200 mPa·s.

Due to the similarity of saturation magnetization, the differences in the behaviour of the two examined ferrofluids mainly result from differences in the zero field viscosity (mainly dependent upon the viscosity of the carrier liquid).

Ferrofluids allow normal stresses to be obtained, where:in the value slightly depends on the shear rate. The source of normal stress observed in the FF is the internal pressure, which arises under the impact of the magnetic field. This phenomenon is discussed in detail in the fundamental publication Rosensweig **[L. 1]**.

When considering the use of ferrofluids in bearing systems, significant advantages can be expected because of the potential achievement of a self-sealing effect. The result of this phenomenon is a reduction in the lubricant side outflow, so it is possible to increase the carrying capacity of the bearing.

The variation of shear stress obtained for the examined MR fluids indicates their non-Newtonian rheological behaviour. On the flow curves, yield stress can be seen (for low shear rates), and, at higher shear rates, the characteristics revealed behaviour typical for pseudo-plastic substances.

The range of shear stress changes visible on the MR fluid flow curves is very wide. Combining both effects, the magnetic field and shear rate are visible. This feature enables their use in bearing systems characterized by a considerable range of variability in the operating parameters. The validity of MR fluids in bearing systems is also indicated by the ability of such fluids to generate higher values of normal stresses, especially at lower deformation speeds. Due to the size of the particles in MR fluids, the source of normal stresses form column-like structures with a direction in line with the direction of the magnetic field. The large variability of shear and normal stress results from the cyclic destruction and reconstruction of these structures as a result of the shear force. Both relatively low internal friction and high values of normal stress occurring in MR fluids at low shear rates indicate the areas of the application of these fluids in systems with a relatively low strain in the bearing working gap.

Currently, research work is continuing on the possibility of using magnetic fluids as a lubricant in thrust bearings. The obtained values of normal stress in the test bearings have a much lower level than the fluid friction bearings lubricated hydrostatically and, in particular, hydrodynamically, which currently substantially restricts their use in traditional solutions. Expected areas of application are systems where: it is desirable to control the properties of the lubricant and its positioning. The ability to maintain the liquid at a certain position by a magnetic field can be important when the bearing works in zero gravity conditions.

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Streszczenie

Ciecze magnetyczne są to substancje, których właściwości reologiczne mogą być aktywnie kształtowane poprzez oddziaływanie na nie polem magnetycznym. Można wyróżnić dwa podstawowe typy cieczy magnetycznych: ciecze ferromagnetyczne oraz magnetoreologiczne. Znane są przemysłowe aplikacje cieczy ferromagnetycznych, przede wszystkim w konstrukcji uszczelnień, natomiast ciecze magnetoreologiczne znalazły zastosowanie głównie w układach dyssypacji energii mechanicznej o sterowanych parametrach pracy. Perspektywa wykorzystania możliwości sterowania właściwościami reologicznymi cieczy magnetycznych otwiera nowe horyzonty dla opracowywania konstrukcji urządzeń, między innymi w obszarze konstrukcji łożysk.

W pracy przedstawiono analizę porównawczą charakterystyk reologicznych wybranych cieczy magnetoreologicznych i ferromagnetycznych ze zwróceniem uwagi na możliwe obszary zastosowania tych cieczy w inżynierii łożyskowania.