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METHOD OF RESEARCH ON THE DYNAMIC VISCOSITY OF MAGNETIC FLUIDS AT HIGH SHEAR RATE

METODA WYZNACZANIA LEPKOŚCI DYNAMICZNEJ CIECZY MAGNETYCZNYCH W WYSOKICH SZYBKOŚCIACH ŚCINANIA

Key words: magnetic fluids, ferrofluids, rheology, high shear rate, flow curve.

Abstract: Magnetic fluids have an important position in the design of technical systems due to their unique properties. They are used primarily in mechanical energy dissipation systems, i.e. brakes and vibration dampers, as well as in the design of seals. In many applications, the magnetic fluid operates at high flow velocities through narrow slots. Therefore, there is a need to determine the rheological properties of this type of substance at high shear rates. Due to the high density of magnetic fluids and the associated occurrence of mass forces, as well as the requirements regarding the distribution of the magnetic field, the measurement of the viscosity of magnetic fluids at high shear rates is extremely difficult when conventional measuring systems are used. The paper presents a proposal for a new measuring system and a method to determine the viscosity of magnetic fluids at high shear rates, as well as the results of research on the possibility of using the presented structure in the case of ferrofluids.

Słowa kluczowe: ciecze magnetyczne, ferrociecze, reologia, wysoka szybkość ścinania, krzywe płynięcia.

Streszczenie: Ciecze magnetyczne ze względu na swoje unikatowe właściwości mają ugruntowaną pozycję w konstrukcji układów technicznych. Znalazły zastosowanie przede wszystkim w systemach dyssypacji energii mechanicznej, tj. hamulcach i amortyzatorach drgań, jak również w konstrukcji uszczelnień. W wielu aplikacjach ciecz magnetyczna pracuje w warunkach wysokich prędkości przepływu przez wąskie szczeliny. W związku z tym istnieje potrzeba wyznaczania właściwości reologicznych tego typu substancji przy wysokich szybkościach ścinania. Ze względu na znaczną gęstość cieczy magnetycznych i związane z tym występowanie sił masowych, jak również wymagania odnośnie do przestrzennego rozkładu pola magnetycznego pomiar lepkości cieczy magnetycznych w wysokich szybkościach ścinania w przypadku zastosowania konwencjonalnych układów pomiarowych jest istotnie utrudniony. W pracy przedstawiono propozycję nowego układu pomiarowego, metody pomiaru lepkości cieczy magnetycznych w wysokich szybkościach ścinania oraz wyniki badań dotyczących możliwości wykorzystania przedstawionej konstrukcji w przypadku ferrocieczy.

INTRODUCTION

Magnetic fluids are suspensions of ferromagnetic particles in a carrier fluid and belong to the group of smart materials. Their unique properties are based on the possibility of reversible, almost instantaneous change of their rheological parameters, and even the change of the flow direction is possible as a result of the magnetic field.

Depending on the size of the particles, two types of magnetic fluids can be distinguished:

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ferrofluids (FF) produced on the basis of magnetic particles with a diameter of nanometers (about 10 nm) **[L. 1]**, and magnetorheological fluids (MRF), in which there are particles with a size of the order of micrometers (about 15 μm) **[L. 2]**. To prevent coagulation, the particles are coated with a surfactant. This is most often a substance composed of long-chain molecules with a polar structure, e.g., oleic acid or polymer coatings. The surfactant has a significant influence on the hydrodynamic properties of the particles.

Ferrofluids, unlike magnetorheological fluids, are characterized by a relatively low saturation magnetization (below 40 kA/m) and the high stability of their properties in both the magnetic field and in the gravitational field. Depending on the application, different types of carrier fluids are used, such as mineral oils, water, synthetic fluids, or other substances. The volume fraction of magnetic particles in a typical ferrofluid amounts to about 7%, while, in magnetorheological fluids, it amounts to 20–50%.

Due to the differences in the properties of both substances, they are used in various technical devices. In mechanical devices, ferrofluids are used primarily in seals **[L. 2]**, audio speakers, and in biomedical applications, e.g., for the selective application of drugs **[L. 3]**. Magnetorheological fluids are used in vibration dampers, brakes, and clutches **[L. 4]**. Work is also underway on the development and implementation of fluid friction bearings in which a magnetic fluid would be used as a lubricant **[L. 5]**.

The changes in the properties of the fluid are due to many parameters, particularly the following: the volumetric fraction of magnetic particles in the liquid carrier, the magnetic properties of the material of the particles, the size and shape of the particles, and the parameters of the magnetic field. The range of property variability is much higher in MRF than in FF. The possibility of an almost instantaneous change in their properties results from changes in the internal structure as a result of the influence of the magnetic field.

METHODS OF MAGNETIC FLUIDS RHEOLOGICAL STUDIES

Due to the increasing application of magnetic fluids, the measurement of rheological properties is still a current topic and new measurement methods are being investigated. Over the years, various rheometer designs have been developed that use geometry in a shear mode, such as plate-to-plate, plate-cone, and two coaxial cylinders. The main problem in such devices is the suitable shaping of the magnetic field and keeping the fluid in a given place. The first rheometers enabling testing up to a shear rate of 10^6 s^{-1} were based on the design of computer hard drives **[L. 6]**. The geometry of the plate-cone system is characterized by the fact that there is a constant shear rate in the measuring gap. However, it is not preferable for magnetic fluids, because the internal structure of the fluid may depend on the dimensions of the gap **[L. 7]**. This particularly applies to magnetorheological fluids. This geometry has been used for rheological measurements in the case of ferrofluids **[L. 8]**. In addition, compared to the parallel plate method, the cone-shaped system takes up more space, which increases the required dimensions of the electromagnet.

There are also designs of rheometers in a two coaxial cylinder measuring system **[L. 9**, **10]**. In rheology, this method is most often used for fluids of low viscosity. Its disadvantage is that, at high speeds, flow instabilities (Taylor vortices) can develop and a large fluid volume is required. For fluids with high viscosities, the problem of air bubbles in the fluid often arises. An important issue in the case of magnetic fluids is also the spatial distribution of the magnetic field lines with respect to the fluid's shear plane. In the case of a system of coaxial cylinders, it is difficult to obtain the perpendicularity of the magnetic field intensity vector with respect to the velocity vector in the entire volume of the tested fluid.

Currently, most rheological tests of magnetic fluids are carried out with the use of plate-to-plate (parallel plates) measuring geometry **[L. 11, 12]**. The disadvantage of this method is that there is no constant shear rate in the measuring gap. Additionally, this system does not ensure a constant value of the magnetic field **[L. 13]**. In order to obtain reliable measurements, additional space is required, separating the electromagnet core and the magnetic fluid **[L. 14]**. Such a solution means that, in the magnetic fluid, there is no local increase in the value of the magnetic field caused by the edge of the electromagnet core. However, the value of the permissible shear rate at which the magnetic fluid is ejected from the measuring gap by the centrifugal force decreases. The solution to the problem of magnetic field distribution may be the measurement in the plate-plate system, where the fluid is in the form of a ring **[L. 15, 16]**.

Due to the measurement difficulties, there is currently no suitable method for determining the rheological properties at high shear rates. For example, designs based on a brake with magnetorheological fluid are used **[L. 17]**. In this system, there is a problem of the uneven distribution of the magnetic field and the lack of a constant shear rate in the measuring gap. Testing fluids at high shear rates in the flow mode can be performed using the geometry of capillary rheometers **[L. 18, 19, 20]**.

The presented publication describes a rheometer for examining the rheological properties of magnetic fluids in the shear mode, based on the geometry of two coaxial cylinders. Contrary to the classical method, this system is divided into a series of small-width annular stages.

TEST STAND

A diagram of the test stand is shown in **Fig. 1**. The main advantages include the following: a direct measurement of the friction moment generated in the tested magnetic fluid, a reduction of the possibility of the magnetic fluid flowing radially due to the action of mass forces, the small volume of the tested fluid and its location is only on the circumference of the measuring sleeve in the area of constant magnetic field strength.

The system is driven by an electric motor (1) with adjustable rotational speed. The main element of the measuring system is the torque transducer (2). On the shaft, a multi-stage measuring cylinder (10) is mounted. The tested magnetic fluid (9) is located between the stages of the cylinder and the inner wall of the pole piece (4). The source of the magnetic field is an axially polarized permanent magnet (5). A magnet with a coercive force of H_{bc} = 950 A/m and B_r = 1.21 T was used, with a volume of 12.3 cm^3.

The magnetic field circuit (8) is closed by the pole piece (4), the magnetic fluid (9), the multi-stage cylinder (10), and the air gap between the sleeve and the pole piece (7). Thermal stabilization during the test is ensured by the forced flow of fluid through the channels made in the housing (6).

An important aspect of the measuring system was the limitation of the axial and radial force on the torque transducer shaft resulting from the presence of a magnetic field. In the case of the TM305-Magtrol torque transducer, the permissible load on the shaft is 80 N in the radial direction and 100 N in the axial direction.

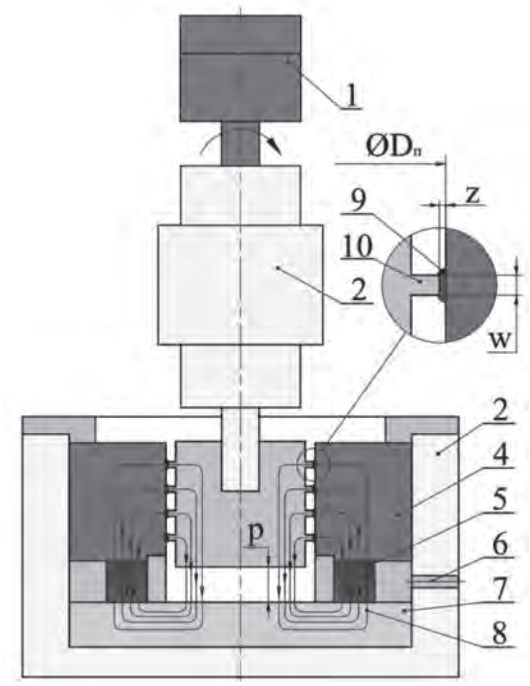


Fig. 1. Diagram of the test stand, 1 – electric motor, 2 – torque transducer, 3 – housing, 4 – pole piece, 5 – permanent magnet, 6 – coolant flow channels, 7 – pole piece, 8 – magnetic field lines, 9 – magnetic fluid, 10 – multi – stage cylinder

Rys. 1. Schemat stanowiska badawczego, 1 – silnik elektryczny, 2 – przetwornik momentu obrotowego, 3 – obudowa, 4 – nabiegunnik, 5 – magnes trwały, 6 – kanały przepływu cieczy chłodzącej, 7 – nabiegunnik, 8 – linie pola magnetycznego, 9 – ciecz magnetyczna, 10 – tuleja z występami

The radial force occurs only when there is an eccentricity between the multi-stage cylinder (10) and the pole piece (4), so its neutralization consists in ensuring the alignment of the elements of the measuring system.

The axial force is always present and its value depends mainly on the value of the magnetic field strength, the height of the gap (z), the distance between the multi-stage cylinder (10), and the pole piece (7). For the assumed parameters, on the basis of numerical simulations, it was determined that the force acting on the shaft should not exceed 74 N.

The nominal diameter of the measuring system was D_n = 50 mm. Multi-stage cylinders, in order to increase the accuracy of the measurement, were equipped with 4 ring stages, with the width w = 0.6 or 1 mm. The height of the measuring gap was z = 0.2 mm. Due to the rigidity of the stand elements and the manufacturing accuracy, the radial runout of the multi-stage cylinder during the tests was ± 0.02 mm.

THEORETICAL BASIS

The proposed measurement principle is based on "Couette flow" in which the flow of a viscous fluid is in the space between two surfaces, one of which is moving tangentially relative to the other.

The scheme of the measuring system with two coaxial cylinders is shown in **Fig. 2**. It consists of an inner cylinder with the radius R_1 and an outer cylinder with the radius R_2. The cylinder with the inner radius is rotating at the angular velocity ω. Assuming the non-slip condition at the interface between the cylinder and the fluid, the fluid layer adjacent to the cylinder moves at the same speed v_1. On the other hand, the fluid layer adhering to the surface of the stationary outer cylinder remains stationary, $v_2 = 0$ m/s.

The value of the shear stress τ in the fluid, calculated on the basis of the measured torque, is expressed by the following relationship:

$$\tau = \frac{M}{2\pi R_1^2 h} \tag{1}$$

where:
M – friction moment (torque),
R_1 – inner radius,
R_2 – outer radius,
ω – angular velocity,
h – measurement width.

The shear rate is calculated as:

$$\dot{\gamma} = \frac{2\omega R_2^2}{R_2^2 - R_1^2} \tag{2}$$

where $h = 4w$, which is the total measurement width of the fluid layer subjected to shear, because the tested ferrofluid is located on 4 annular measuring stages with the width w.

The presented model considers the case when the magnetic fluid is in contact only with the cylindrical surfaces of the stages. In the case of the considered system, in order to obtain reliable results, the magnetic fluid should also partially cover the side walls of the stages made on the cylinder. This will result in a higher value of the friction moment, but it eliminates the measurement uncertainty associated with the different position of the magnetic fluid along the stage and the contact surface.

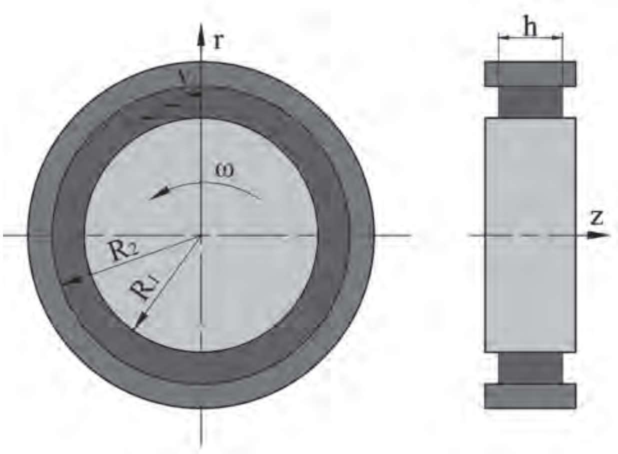


Fig. 2. Model of fluid flow in a two-cylinder arrangement
Rys. 2. Model przepływu cieczy w układzie dwóch cylindrów

The rheological tests in the discussed measuring system consisted in determining the flow curves of two magnetic fluids at a temperature of 25°C. The measurements were made at the shear rate in the range 0–33065 s^{-1}, which corresponds to the shaft rotational speed 0–50 s^{-1}. The tests were performed for two types of multi-stage measuring cylinder, differing in the width of measuring stages, i.e. w = 0.6 or 1 mm. For each measuring geometry, the test was conducted for 3 volumes of ferrofluid applied to the measuring gap V = 0.06, 0.1, and 0.2 ml.

The shape of the free surface of the tested fluid depends on the spatial distribution of the magnetic field strength. **Figure 3** shows the cross-section of a magnetic fluid ring, determined on the basis of a FEM numerical simulation. This position of the magnetic fluid results from the line of the constant magnetic induction value **[L. 21]**.

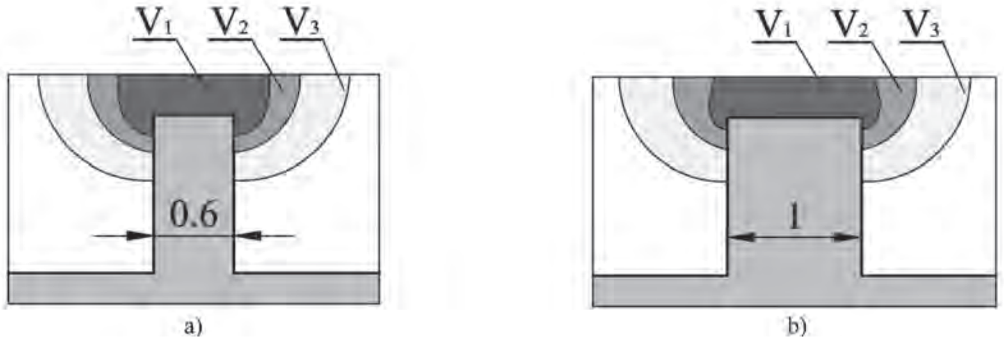


Fig. 3. Shape of free surfaces for different volumes of tested magnetic fluid, V_1 = 60 µl, V_2 = 100 µl, V_3 = 200 µl: a) stage width 0.6 mm, b) stage width 1 mm

Rys. 3. Kształt powierzchni swobodnych dla różnych objętości badanych cieczy magnetycznej, V_1 = 60 µl, V_2 = 100 µl, V_3 = 200 µl: a) szerokość występu 0,6 mm, b) szerokość występu 1 mm

DISTRIBUTION OF THE MAGNETIC FIELD IN THE TEST STAND

Determination of the magnetic field value in the measuring gap is one of the basic design requirements for the measuring system. The height of the gap in which the tested ferrofluid is located (z = 0.2 mm) makes it impossible to measure the magnetic induction distribution with use of the probe. Therefore, for this purpose, numerical simulations in the ANSYS 19 program were carried out. An axisymmetric model and Dirichlet boundary conditions were adopted i.e. the direction of the magnetic flux was assumed to be parallel to the edges of the analyzed area and the flux value at the area boundaries was assumed to be zero. The mesh size was compacted in the area of the fracture to an average size of about 0.02 mm. It was assumed that the ferromagnetic elements are made of structural steel (S235) and a corresponding B-H magnetization curve was adopted. In the case of magnetic circuit elements, such as air or aluminum, the relative magnetic permeability was assumed to be 1. The ferrofluid was treated similarly, because it is classified as a superparamagnetic material, which is characterized by high initial magnetic susceptibility in contrast to paramagnetic materials **[L. 22]**.

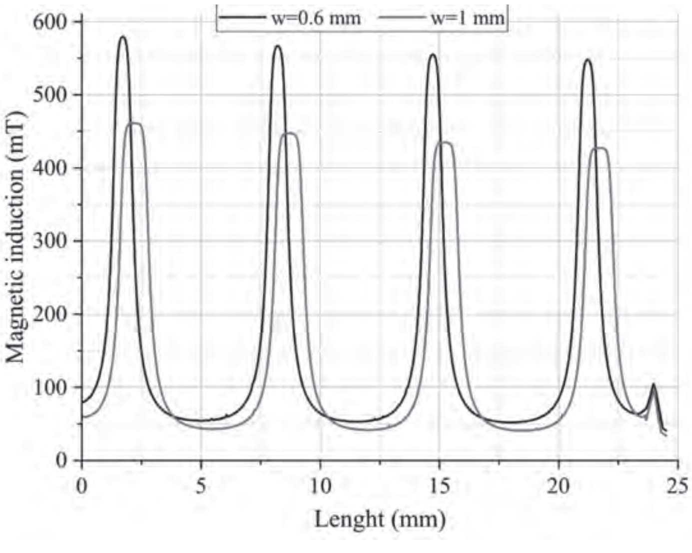


Fig. 4. Distribution of the magnetic field induction along the length of the measuring cylinder

Rys. 4. Rozkład indukcji pola magnetycznego wzdłuż długości cylindra pomiarowego

The magnetic induction distribution results for four annular stages with different widths are shown in **Fig. 4**. Along the width of the stage, the curve takes a constant value. Then, at a distance of about 0.5 mm, it drops to about 0.1 T. Some changes are observed in the case of the maximum values of the magnetic induction between the stages, due to the different distance from the magnetic field source, but the differences are no more than 9%. The highest values were observed for stage No. 1, i.e. the farthest from the magnetic field source, and the lowest values were observed for stage No. 4.

For a measuring system with a width of 0.6 mm, the maximum values of the magnetic induction at each of the stages are the minimum B = 550 mT, while, for w = 1 mm, the minimum B = 420 mT was obtained. These values are sufficient to ensure the magnetic saturation of the tested fluids, because their magnetic saturation (see 5.2) occurs at a magnetic induction of about 0.2 T.

RESEARCH METHOD

Examined ferrofluids

Two commercial ferrofluids, produced by FerroTec **[L. 23]**, were selected for the research. They are characterized by a similar value of saturation magnetization and density, and simultaneously differ in the dynamic viscosity. The catalog properties of the tested fluids are summarized in **Table 1**.

Table 1. Physical properties of the examined ferrofluids
Tabela 1. Właściwości fizyczne badanych cieczy ferromagnetycznych

No.	Ferrofluid	Saturation magnetization M_s	Density ρ	Viscosity H
		kA/m	g/ml	mPa·s B = 0 mT, t = 27°C
1	APGW05	30.66	1.299	500
2	APGW10	30.82	1.316	1000

Ferrofluid rheological properties

The initial stage of the research consists of determining the rheological properties of the tested ferrofluids with the use of a commercial MCR 301 rheometer. The results obtained with this method were the reference value for measurements using the new method proposed in this paper. The rheometer was equipped with an additional module (MRD 180), which was designed to perform tests in a magnetic field. The tests were carried out in a parallel plate measuring system. The 0.1 mm width of the measurement gap was adopted so that it was possible to carry out measurements in the maximum range of shear rate (5 – 20000 s^{-1}). The measurement above the value of 20000 s^{-1} turned out to be impossible due to the fluid being ejected from the measuring gap as a result of centrifugal forces. All tests were performed at 25°C.

Figure 5 shows the results of the magneto sweep measurement, at a constant shear rate (1000 s^{-1}), and the magnetic field induction being increased in the range from 0 to 200 mT.

It has been found that, above the value of 100 mT, the shear stress value begins to stabilize and the fluid is close to the saturation stage. The total change in value was 21% for APG W05 and 12% for APG W10, referring to the initial value. Based on the results of the magnetic induction distribution and the results from **Fig. 4**, it can be assumed that, in the case of the discussed new method, the rheological properties of ferrofluids will be the same in the entire volume, because the magnetic induction in the gap region will not be less than 100 mT.

Figure 6 shows the shear stress dependence on the shear rate of the tested ferrofluids, which constitutes a reference value for further tests with the use of the discussed measuring system. The tests were performed for the absence of a magnetic field and magnetic induction of 200 mT. This upper limit of the magnetic field induction value was selected to ensure the saturation magnetization of the ferrofluid.

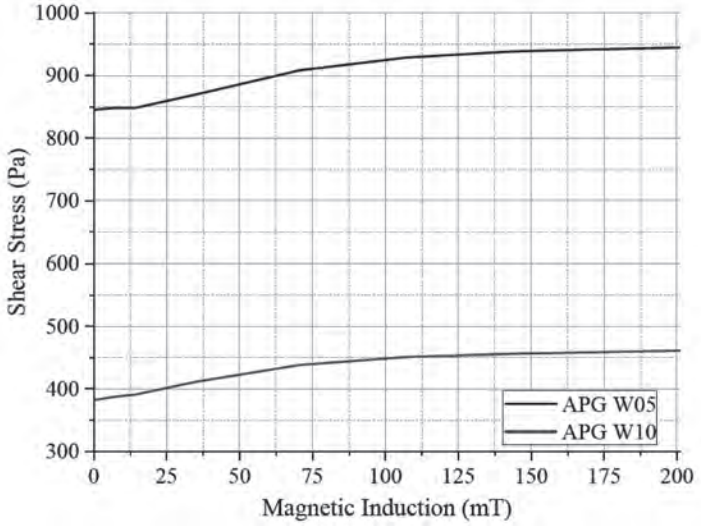


Fig. 5. Shear stress versus magnetic induction for a constant shear rate
Rys. 5. Zależność naprężenia stycznego od indukcji magnetycznej dla stałej szybkości ścinania

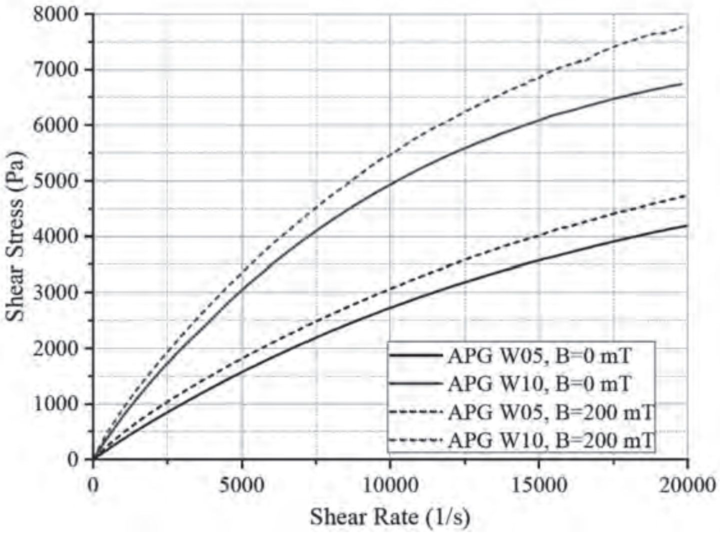


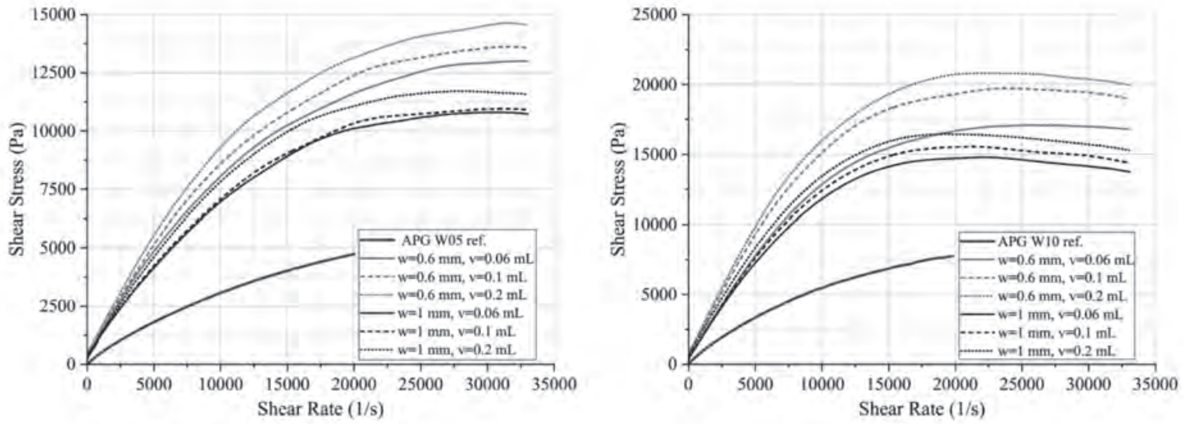
Fig. 6. Shear stress versus shear rate for ferrofluids and different values of magnetic induction
Rys. 6. Zależność naprężenia ścinającego od szybkości ścinania dla ferrocieczy i różnych wartości indukcji magnetycznej

RESULTS

The flow curves obtained with the use of the discussed measuring system, and the results using a rotational rheometer are presented in **Fig. 7**.

All shear stress values determined on the basis of the torque measurement and the equation (1) are higher than the values obtained with the use of a rheometer. Higher values of the shear stress are obtained for a stage with a smaller width, which is consistent with the equation (1). Increasing the ferrofluid volume for a given stage width results in higher shear stress, because the measured torque increases.

Comparing both methods, it can be seen that, despite the quantitative difference, all the curves show significant similarity in terms of quality. As a result of applying the coefficient C, significant improvement in curve fitting was obtained when compared to the reference value – **Fig. 8**.



a) b)

Fig. 7. Flow curves obtained for different volumes of magnetic fluids and different stage width: a) AGPW05 fluid, b) AGPW10 fluid

Rys. 7. Krzywe płynięcia uzyskane dla różnych objętości cieczy magnetycznych i różnych szerokości występu: a) ciecz AGPW05, b) ciecz AGPW10

$$\tau_{cor} = C \cdot \tau_{raw} \tag{3}$$

where:

C – correction factor,

τ_{cor} – shear stress after applying the correction coefficient C,

τ_{raw} – shear stress based on rheometer measurements.

The values of the C coefficient for the best fit are shown in **Table 2**.

The value of the C coefficient decreases when a larger fluid volume is used for a given width of the stage. Increasing the volume of the tested ferrofluid from 0.06 ml to 0.2 ml is responsible for a decrease in the C coefficient for the APG05 fluid by 10% (w = 0.6 mm) and 6% (w = 1 mm), while, for the APGW10 fluid, this change is 20% and 11%, respectively.

The change in the coefficient of variation (CV parameter) for the C coefficient is two times lower

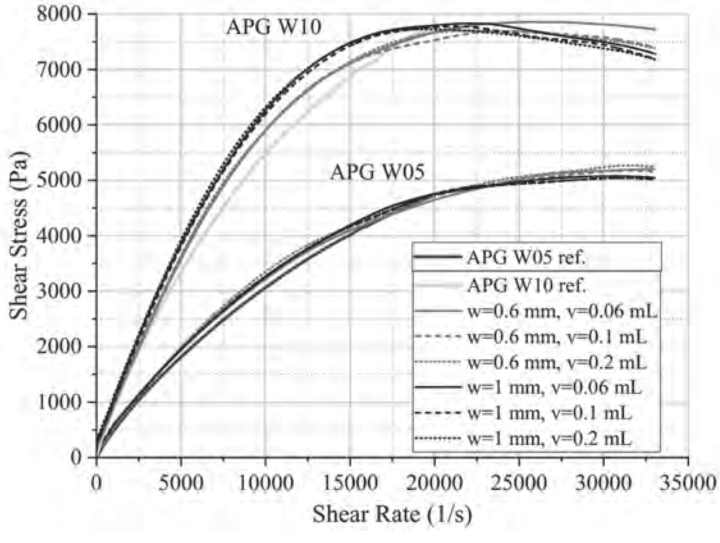


Fig. 8. Flow curves obtained after applying the correction coefficient *C*

Rys. 8. Krzywe płynięcia po zastosowaniu współczynnika korekcji *C*

Table 2. The values of the correction coefficient *C*
Tabela 2. Wartości współczynników korekcji *C*

No.	Stage width *w*	Ferrofluid volume *V*	APGW05	APGW10
	mm	Ml	-	-
1.	0.6	0.06	0.4	0.46
2.		0.1	0.38	0.39
3.		0.2	0.36	0.37
4.	1	0.06	0.47	0.53
5.		0.1	0.46	0.50
6.		0.2	0.44	0.47

for APG W05 (5% and 3%) than for APG W10 (12% and 6%), for w = 0.6 and 1 mm, respectively. Two times lower values of the coefficient of variation were obtained for the wider stage. This result indicates that it is more advantageous to use w = 1mm than 0.6 mm in the measuring system.

Analysis of the obtained results of shear stress shows that the direct measurement result is overestimated in relation to the expected value. With reference to the equation (1), coefficient C can be interpreted as a change in the actual width of the stage. By defining the parameter of the effective width of the stage $w_{eff} = w/C$, it can be seen that, for the width of the stage w = 0.6 mm, this parameter is w_{eff} = 1.53 mm, while for w = 1 mm, w_{eff} = 2.1 mm (w_{eff} calculated as the average for different volumes). This dependence may be related to the location of the ferrofluid (**Fig. 3**) and the contact of the fluid with the side surface of the stage. The values of the effective width are shown in **Fig. 9**.

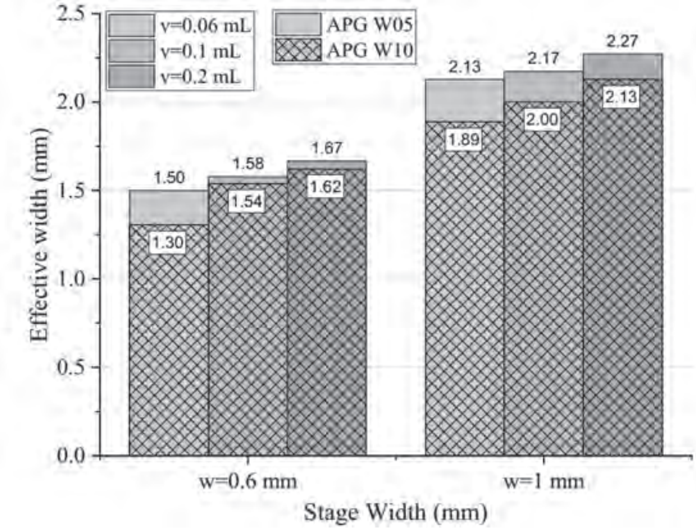


Fig. 9. Effective width w_{eff} versus stage width
Rys. 9. Zależność szerokości efektywnej w_{eff} od szerokości występu

CONCLUSIONS

The proposed method may be an alternative in the case of rheological tests of magnetic fluids, especially for high shear rates. Its disadvantage is that it allows the measurement of rheological properties only in the presence of a magnetic field, since, as a result of its absence, the liquid ring of the magnetic fluid cannot be held on the stage. Due to the measurement accuracy, the magnetic field should also have such a value so that the magnetic fluid exhibits the same properties throughout the entire volume.

In order to adapt the results of the flow curve tests to other methods, an appropriate correction factor should be used. The higher differences between the data obtained from the two methods were obtained for the APGW10 fluid, which is characterized by almost twice as high dynamic viscosity as APGW05. This is probably related to the generation of heat in the magnetic fluid volume, which lowers the dynamic viscosity. This is evidenced by the change of the upward trend into a downward trend of the shear stress in the range of 15 000–25 000 s^{-1}. In order to eliminate this phenomenon, it would be advisable to use a temperature stabilization system characterized by greater efficiency.

The research results presented in the paper indicate the potential usefulness of the proposed solution of the measuring system for determining the rheological characteristics of magnetic fluids. However, it is necessary to carry out further works to determine the influence of the accuracy of geometric parameters on the repeatability of the test method.

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