New Driving Unit for the Direct Measurement of Yield Stress with a Stress Controlled Rheometer

Hamid Shahnazian*, Stefan Odenbach

Institute of Fluid Mechanics, Chair of Magnetofluiddynamics,
George-Bähr-Str. 3, 01062 Dresden, Germany

* Email: hamid.shahnazian@tu-dresden.de
Fax: x49.351.4633384

Received:20.12.2007, Final version: 17.4.2008

Abstract:
Investigations of rheological properties of ferrofluids have shown strong changes of the viscosity in magnetic fluids with an applied magnetic field. The change of the viscosity – the magnetoviscous effect – can theoretically be described with chain and structure formation under the influence of a magnetic field. Moreover, the formation of these structures leads to the appearance of viscoelastic effects or other non-Newtonian features like yield stress in ferrofluids with an applied magnetic field. With a shear rate controlled rheometer – as it as been used in former experiments – the yield stress could not be investigated directly. Therefore the results concerning a field dependent yield stress based on an extrapolation of shear controlled measurements. For the direct investigations of the yield stress, a dedicated stress controlled rheometer is required, allowing direct investigations of the magnitude and field dependence of this effect. In this work the design of the stress controlled rheometer with its main parameters has been described in detail. The rheological investigations with differently composed fluids show that the stress controlled rheometer enables direct measurements of even small yield stresses in ferrofluids as well as large effects like they are found in magnetorheological fluids (MRF).

Zusammenfassung:
Ferrofluide zeigen unter der Einwirkung eines Magnetfeldes starke Änderungen ihrer Viskosität. Die Änderung der Viskosität – der magnetoviskose Effekt – kann theoretisch mit Ketten- und Strukturbildung der magnetischen Partikel unter Magnetfeldeinfluss beschrieben werden. Neben dieser Viskositätserhöhung sind in Ferrofluiden, bedingt durch die Bildung der kettenartigen Strukturen unter der Einwirkung eines Magnetfeldes, viskoelastische Effekte oder andere nicht-Newtonsche Eigenschaften wie z. B. das Auftreten einer Fließgrenze beobachtet worden. Für die ersten Fließgrenzenuntersuchungen ist ein scherratenkontrolliertes Rheometer verwendet worden, womit die Fließgrenze nicht direkt bestimmt werden konnte. Daher musste bei diesen Untersuchungen die feldabhängige Fließgrenze in Ferrofluiden durch Extrapolation der Fließkurven ermittelt werden. Um eine detaillierte und direkte Untersuchung der Fließgrenze durchführen zu können, ist ein schubspannungsgesteuertes Rheometer notwendig, das die direkte Untersuchung der Fließgrenze unter dem Einfluss variabler Magnetfelder erlaubt. Im Rahmen dieser Arbeit sollen das scherratenkontrollierte Rheometer und dessen wichtigste Komponenten im Detail beschrieben werden. Die rheologischen Untersuchungen an verschiedenen Flüssigkeiten zeigen, dass das hier vorgestellte schubspannungsgesteuerte Rheometer einerseits direkte Messungen sehr kleiner Effekte, wie z. B. der Fließgrenze in Ferrofluiden, und andererseits von sehr großen Effekten, wie z. B. der Fließgrenze in magnetorheologischen Flüssigkeiten (MRF), erlaubt.

Résumé:
Les recherches sur les propriétés rhéologiques des ferrofluides ont démontré que la viscosité change fortement lorsque un champ magnétique est appliqué sur les fluides magnétiques. Le changement de la viscosité -l'effet magnétovisqueux- peut être décrit théoriquement par la formation de chaînes et de structures induites par l'effet du champ magnétique. De plus, la formation de ces structures conduit à l'apparition d'effets viscoélastiques ou d'autres caractéristiques non Newtoniennes comme une contrainte seuil pour les ferrofluides avec un champ magnétique appliqué. Avec un rhéomètre à vitesse de cisaillement contrôlée – type de rhéomètre utilisé dans des expériences précédentes – la contrainte seuil ne pouvait pas être étudiée directement. Il en est de même pour les résultats concernant la contrainte seuil en fonction du champ obtenus sur la base d'une extrapolation des mesures effectuées en vitesse de cisaillement contrôlée. Pour l'étude directe de la contrainte seuil, un rhéomètre spécial à contrainte contrôlée est requis, qui permet l'étude directe de la grandeur de cet effet ainsi que de sa dépendance en fonction du champ. Dans cette étude, la conception du rhéomètre à contrainte contrôlée est décrite en détail, avec ses principaux paramètres. Les études rhéologiques menées avec des fluides de compositions différentes montrent que le rhéomètre à contrainte contrôlée rend possible la mesure directe de petites contraintes seuils dans les ferrofluides, aussi bien que des grands effets comme ceux rencontrés avec les fluides magnétorhéologiques.

Key words: yield stress, stress controlled rheometer, driving unit, ferrofluids, rheology, magnetic fluids

This is an extract of the complete reprint-pdf, available at the Applied Rheology website
http://www.appliedrheology.org

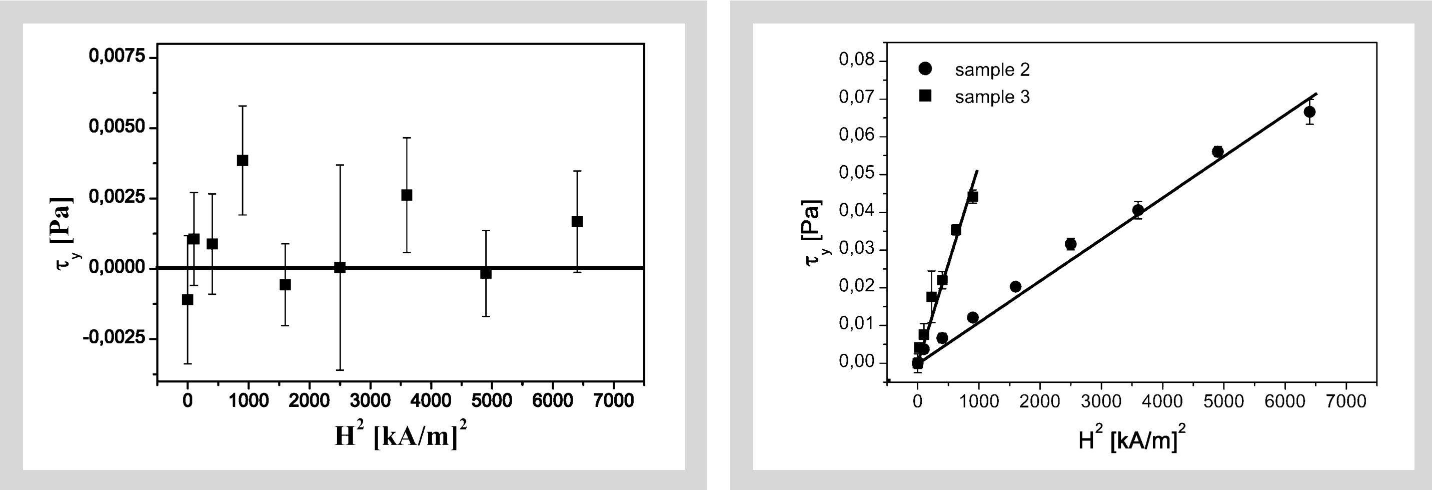

Figure 9:
(a – left)
Small particles (d = 10 nm) contained in sample 1 do not form structures. For this ferrofluid, a yield stress τ_y could not be observed.
(b – right)
Yield stress τ_y for both ferrofluids depends quadratically on the strength of the applied magnetic field. For the cobalt based ferrofluid (sample 3) with a higher λ stronger effect is observed compared to magnetite based ferrofluid (sample 2).*

GmbH - have been investigated. In Fig. 9a and 9b the dependence of the yield stress on interparticle interaction for the samples 1 – 3 is presented.

The interaction of the particles can be described with a modified interaction parameter [24], which has been proven to be the determining parameter for the appearance of the magnetoviscous effect [2]. This parameter describes the relation between the interparticle interaction energy of the surfacted particles in the fluids and their thermal energy. For $\lambda^* > 1$ structure formation becomes possible. For sample 1 in Figure 9a with a mean particle size of about 10 nm and a surfactant layer s = 2 nm one can easily calculate the modified interaction parameter $\lambda^* = 0.5$ [2, 24] being less than the critical value $\lambda^* = 1$. The interaction of these small particles is not strong enough to overcome the thermal energy; i.e. no chain-like structures can be formed under the influence of the magnetic field. For this magnetite based ferrofluid (Figure 9a) no yield stress could be detected independent from magnetic field strength applied. The other magnetite based ferrofluid (sample 2 in Figure 9b) has a small amount of large particles with a mean diameter of 16 nm and a surfactant layer s = 2 nm ($\lambda^* = 2.87$), which contribute to the formation of chain-like structures. For this ferrofluid a yield stress is observed and the expected proportionality to H^2 is confirmed. The experimental results obtained for these two magnetite based samples agree with the presumption that there is a correlation between the interparticle interaction of large particles and the yield stress.

For sample 3 an interaction parameter of $\lambda^* = 5.26$ is calculated, being about 2 times higher than for the sample 2. Due to the stronger interparticle interaction the values for the yield stress for sample 3 (Figure 9b) are dramatically higher than for the magnetite-based ferrofluid (sample 2). For a magnetic field strength of 30 kA/m the values differ by a factor of about 3.5. The effects found here confirm the existence of yield stress for the ferrofluids depending on magnetic field strength. Experiments have shown that the stress controlled rheometer is capable to measure effects like yield stress in ferrofluids directly.

4 DISCUSSION

The results presented here have shown that the stress controlled rheometer enables direct investigations of very weak effects like yield stress in ferrofluids as a function of the strength of an applied magnetic field. This has been the main requirement for the stress controlled rheometer.

At first MR fluids have been used to verify the performance of the rheometer. Additionally, the rheological investigations presented here with MR fluids have shown that the stress controlled rheometer enables direct investigations of strong effects like yield stress in MR fluids; with the new driving unit of the stress controlled rheometer a shear stress up to 10 Pa could be applied directly to the fluid. In the experiments with ferrofluids the dependence of yield stress on interparticle interaction of large particles could be confirmed. This has been proven by results using ferrofluids with different modified interaction parameters. Moreover it has been shown that the yield stress depends quadratically on the strength of the applied magnetic field.

As a next step, investigations with different size and material of the magnetic particles are planned followed by a comparison of the experimental results with the different theoretical assumptions. Furthermore experiments concerning wall effects - interaction of particles with the walls - will have to be performed. Both, material and roughness of the walls will be varied.

ACKNOWLEDGEMENTS

Financial support by Deutsche Forschungsgemeinschaft (DFG) under grant Od18/8 providing the basis for our investigations is gratefully acknowledged

This is an extract of the complete reprint-pdf, available at the Applied Rheology website
http://www.appliedrheology.org

REFERENCES

[1] Buschow KHJ: Handbook of Magnetic Materials, Elsevier-Verlag, Volume 16 (2006).
[2] Odenbach S: Magnetoviscous Effects in Ferrofluids, Lecture Notes in Physics m71, Springer-Verlag, Berlin (2002).
[3] Odenbach S: Magnetoviscous and viscoelastic effects in ferrofluids, International Journal of Modern Physics B 14 (2000) 1615.
[4] Odenbach S and Stoerk H: Shear dependence of field-induced contributions to the viscosity of magnetic fluids at low shear rates, Journal of Magnetism and Magnetic Materials 183 (1998) 188.
[5] Pop LM and Odenbach S: Investigation of the microscopic reason for the magnetoviscous effect in ferrofluids studied by small angle neutron scattering, Journal of Physics - Condensed Matter 18 (2006) 2785.
[6] Pop LM: Investigations of the microstructure of ferrofluids under the influence of a magnetic field and shear flow, Dissertation of Universität Bremen (2006).
[7] Pop LM, Odenbach S, Wiedenmann A, Matoussevitch, Bönnemann H: Microstructure and rheology of ferrofluids, Journal of Magnetism and Magnetic Materials 289 (2005) 303.
[8] Thurm S and Odenbach S: Magnetic separation of ferrofluids, Journal of Magnetism and Magnetic Materials 252 (2002) 247.
[9] Thurm S and Odenbach S: The influence of magnetic separation on the magnetoviscous behavior of ferrofluids, Magnetohydrodynamics 3 (2001) 291.
[10] Odenbach S, Rylewicz T, Heyen M: A rheometer dedicated for the investigation of viscoelastic effects in commercial magnetic fluids, Journal of Magnetism and Magnetic Materials 201 (1999) 155.
[11] Odenbach S, Rylewicz T, Rath H: Investigation of the Weissenberg effect in suspensions of magnetic nanoparticles, Physics of Fluids 11 (1999) 2901.
[12] Tang X and Conrad H: Quasi-Static Measurements on a Magnetorheological Fluid, Journal of Rheology 40 (1996) 1167.
[13] Bossis G, Mathis C, Mimouni Z, Paparoditis C: Magnetoviscosity of micronic suspensions, Europhysics Letters 11 (1990) 133.
[14] Lemaire E, Bossis G, Volkova O: Deformation and rupture mechanisms of ER and MR fluids, International Journal of Modern Physics B 10 (1996) 3173.
[15] Mou T, Flores GA, Liu J, Bibette J, Richard J: The Evolution of Field-Induced Structure of Confined Ferrofluid Emulsions, International Journal of Modern Physics B 8 (1994) 2779.
[16] Volkova O, Bossis G, Guyot M, Bashtovoi V, Reks A: Magnetorheology of magnetic holes compared to magnetic particles, Journal of Rheology 44 (2000) 91.
[17] Ginder JM, Davis LC, Elie LD: Rheology of magnetorheological fluids: models and measurements, Proceedings of the 5th International Conference on Electro-Rheological Fluids, Magneto-Rheological Suspensions and Associated Technology (1996).
[18] Rosensweig RE: Ferrohydrodynamics, Cambridge University Press, Cambridge (1985).
[19] www. femlab.de.
[20] Bossis G, Lemaire E, Volkova O: Yield stress in magnetorheological and electrorheological fluids: a comparison between microscopic and macroscopic structural model, Journal of Rheology 41 (1997) 687.
[21] Lemaire E and Bossis G: Yield stress and wall effects in magnetic colloidal suspension, Journal of Physics D 24 (1991) 1473.
[22] Bossis G and Lemaire E: Yield stresses in magnetic suspensions, Journal of Rheology 35 (1991) 1345.
[23] Lemaire E, Bossis G, Grasselli Y: Yield stress and structuration of magnetorheological suspensions, Journal of Magnetism and Magnetic Materials 122 (1993) 51.
[24] Thurm S and Odenbach S: Particle size distribution as key parameter for the flow behavior of ferrofluids, Physics of Fluids 15 (2003) 1658.

This is an extract of the complete reprint-pdf, available at the Applied Rheology website
http://www.appliedrheology.org