22nd International Conference

ENGINEERING MECHANICS 2016

Svratka, Czech Republic, 9 – 12 May 2016

TEMPERATURE DEPENDENCE OF MAGNETORHEOLOGICAL FLUID YIELD STRESS AND BINGHAM VISCOSITY

J. Roupec, I. Mazůrek, Z. Strecker, M. Kubík, O. Macháček [***]

Abstract: *This contribution describes results of measurement of magnetorheological fluid MRF-140CG by LORD Corporation. Results of this measurement are used as an inputs to the CFX model. MR fluid has been measured in special slit-flow rheometer at temperature range from 25 to 60 °C and at magnetic field of 0, 35, 70 and 105 kA/m. The flow curves were compiled with the respect of Bingham model of MR fluid Non-Newtonian behavior. Bingham model has two parameters – yield stress and Bingham (plastic) viscosity. Thanks to high precise measurement of pressure drop, the temperature dependence of yield stress is visible. All measured rheological properties were used as an input to the model described MR fluid behavior in dependence on temperature and magnetic field.*

Keywords: Magnetorheological fluid, slit-flow rheometer, high shear rates, yield stress

1. Introduction

Magnetorheological fluids (MRF) are a class of smart and intelligent materials. Their initial discovery is credited to Jacob Rabinow in 1948 (Rabinow, 1948). MR fluids mainly consist of three basic compounds: micron-sized iron particles, carrier oil and additives. Immediately upon the application of external magnetic field, the MR fluid can change its state from fluid to semi-solid or plastic state, in which the MR fluid shows viscoplastic behavior, characterized by the initial stress (yield stress), varying based on the extent of the applied magnetic field (Bossis, Lacis, Meunier, & Volkova, 2002; Carlson & Jolly, 2000; Klingenberg, 2001). MRF shows a Non-Newtonian behavior – the dependence of shear stress and shear rate is not linear. If the flow curve is measured and described at high shear rates, the Bingham model for MRF description can be used. Particularly, it is valid for On-state, when the considerable yield stress is occurred. The significant deviation of this model from the reality is only at low shear rates (Ngatu & Wereley, 2007), where the MRF exhibits viscoelastic behavior which can be described better by Herschel-Bulkley model than by Bingham model (Choi, Cho, Choi, & Wereley, 2005). When we need a CFX model describing a MRF flow (for example at process of designing of a new MR device), parameters describing MRF have to be inserted to the model. Parameters obtained from commercial rheometers are not suitable for their very low range of measured shear rates and inaccurate determination of a real shear rate and stress. Therefore, it is necessary to measure a MRF in a special rheometer.

This paper describes results from measurement at high shear rates and corresponding flow curves. The equation for calculation of yield stress and Bingham viscosity in dependence on temperature and magnetic field intensity was built.

2. Methods

The measured MRF was made by LORD Corporation, type MRF-140CG. Solids content by weight (Fe-particles) in MRF is 85 %. MRF was measured at temperature range from 25 to 60 °C and at magnetic fields of 0, 35, 70 and 105 kA/m. The corresponding shear rate (calculated from Bingham model) reaches up to 160 000 s^{-1}. The MRF was measured in a special slit-flow rheometer in version 2 (see Fig. 1). Unlike a previous version, the new rheometer has high precise measurement of temperature (before and behind the MR valve) and the shear stress is not calculated from measured force of piston but from the pressure drop in the MR valve, which is acquired by two accurate pressure sensors. The advantage of this

[***] all authors: Institute of Machine and Industrial Design, Brno University of Technology; Technická 2896/2; 616 69, Brno; CZ, roupec.j@fme.vutbr.cz

solution is an absence of all passive resistances, e.g.: influence of friction from piston and piston rod sealing, influence of friction from sealing and sliding tapes of floating pistons, absence of hydraulic loss caused by flow of hydraulic oil in the system, etc. The method of evaluation and determination of flow curves is described in the paper (Mazůrek, Roupec, Klapka, & Strecker, 2013; Roupec).

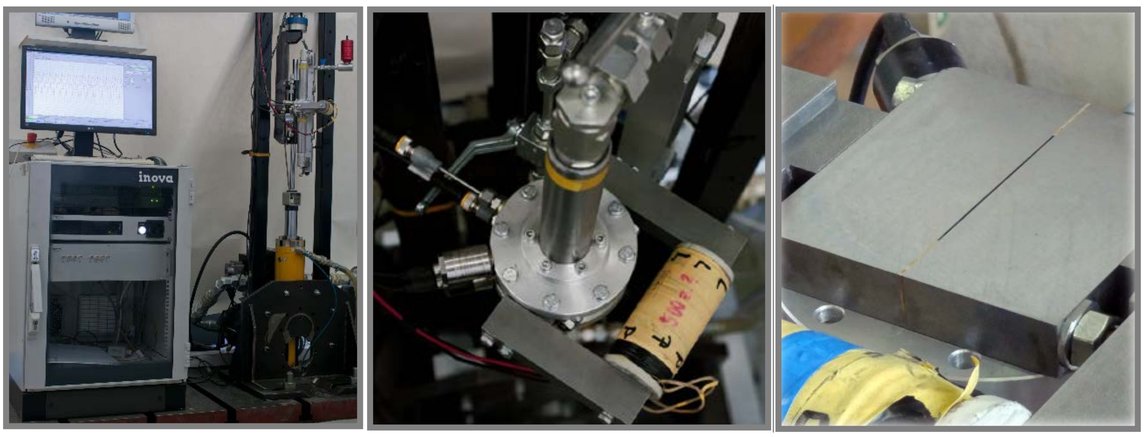

Fig. 1: Built-in rheometer in dynamometer with DAQ and RTC station (left); detail of MR valve with sensors (center); detail of MR valve – active zone (right)

3. Results and discussion

Figure 2(a) shows flow curves measurement of MRF-140CG at zero magnetic field. Without magnetic field, the MRF exhibits almost Newtonian fluid. A small deviation from linear course is visible at 25 and 30 °C. Figure 2(b) shows viscosity dependence on temperature. The dependence has exponential character with very good interlay of points.

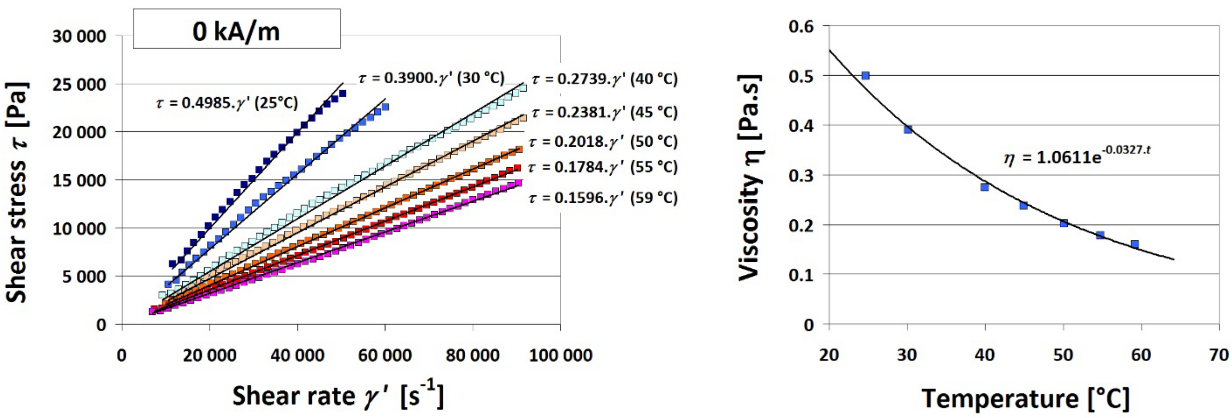

Fig. 2: MRF-140CG measured at zero magnetic field by slit-flow rheometer (a) flow curves; (b) viscosity dependence on temperature

Figure 3(a) shows flow curves measured at magnetic field of 146 kA/m. There are flow curves at different temperature and the difference among the temperature is obvious. Figure 3(b) shows a detail on flow curves and equation of linear regression. The last term in equations determine a yield stress and the first term determines a Bingham viscosity (plastic viscosity). There is evident dependence of yield stress and Bingham viscosity on temperature. The same measurements were carried out also for higher magnetic field intensities of 280 and 368 kA/m. Figure 4 shows a dependence of yield stress and viscosity on temperature for all measured magnetic fields. Unfortunately, the magnetic field is not increased about the identical step of intensity but it corresponds to exciting current to the electromagnet coil. However, we can calculate that the ratio of 368 and 280 kA/m is 1.31. But ratio of corresponding yield stress, for example at 50 °C, is only 1.22. So we can deduce that the Fe-particles approach to their saturation limit, in other words the saturation of Fe-particles is in the area of permeability decreasing. The course of viscosity is, excluding temperature, also magnetic field dependent. The higher magnetic field is, the lower viscosity dependence on temperature is and the lower absolute value of viscosity is. Maybe, some future study will describe this phenomenon by the model describing directly the interaction among single particles and carrier fluid.

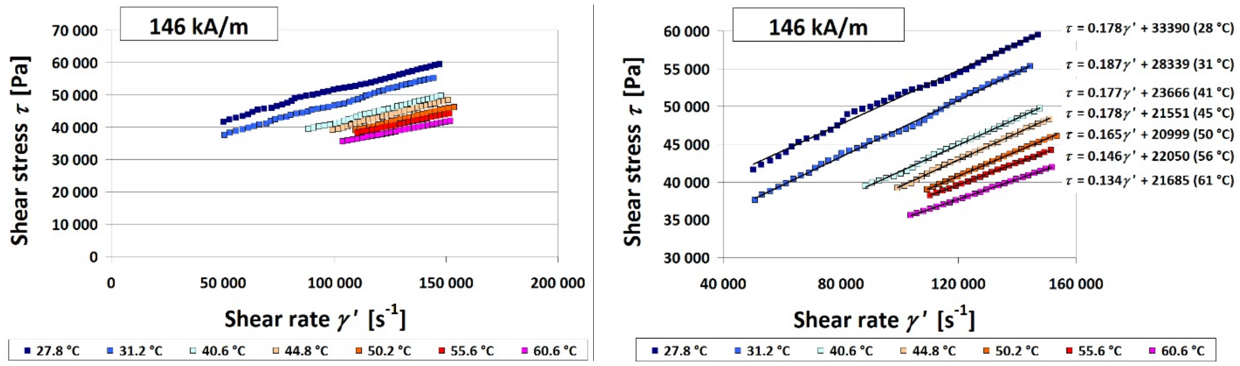

Fig. 3: MRF-140CG measured at magnetic field of 146 kA/m by slit-flow rheometer (a) flow curves; (b) detail with equations of regression

The equation valid for Bingham model is as follows:

$$\tau(\dot{\gamma}, H, t) = \tau_0(H, t) + \eta_{plastic}(H, t) \cdot \dot{\gamma} \quad (1)$$

The yield stress dependence on temperature is interlaid by power function characterized by this equation:

$$\tau_0(H, t) = A(H) \cdot t^{B(H)} \quad (2)$$

The viscosity dependence on temperature can be described by exponential function as follows:

$$\eta_{plastic}(H, t) = C(H) \cdot e^{D(H) \cdot t} \quad (3)$$

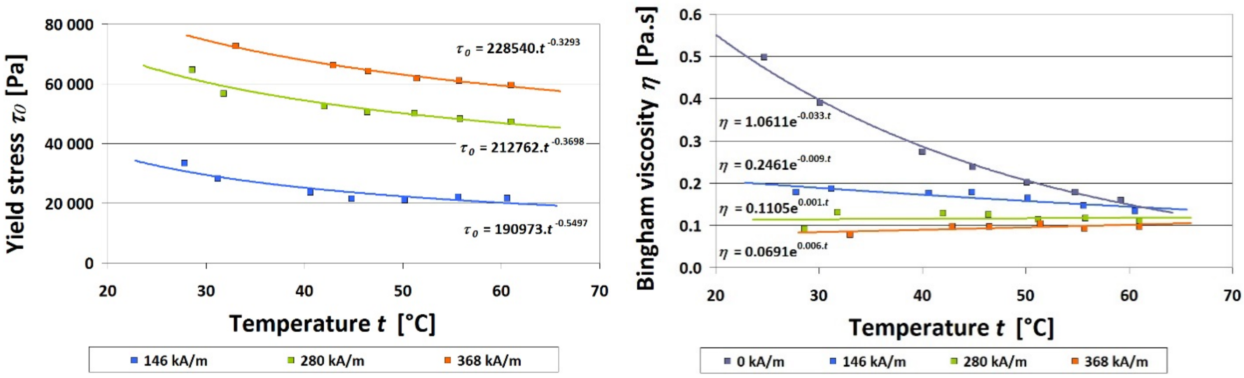

Fig. 4: Dependence of (a) yield stress and (b) viscosity on temperature at different magnetic fields

Figure 5(a) shows the dependence of parameter A and B' on magnetic field intensity.

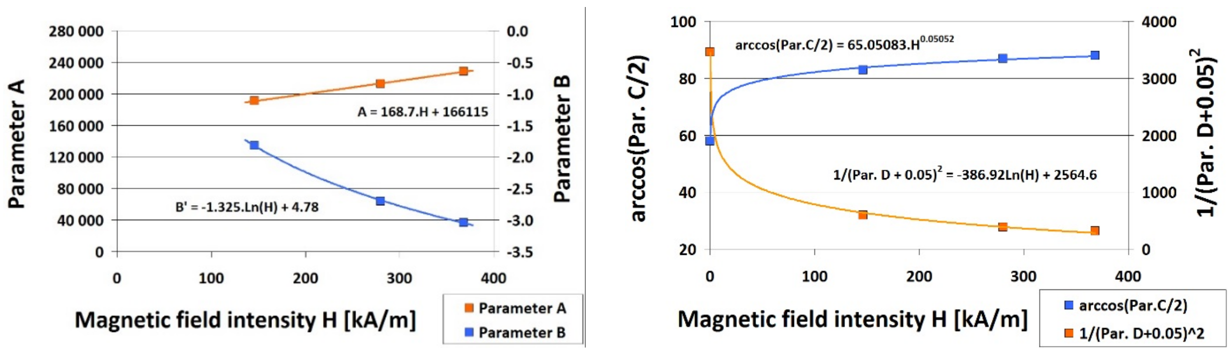

Fig. 5: (a) dependence of parameter A and B on magnetic field; (b) dependence of parameter C and D on magnetic field

Parameter B can be determined from the equation (4). This procedure were done for better fitting of points:

$$B(H) = \frac{1}{B'(H)} = \frac{1}{-1.325 \cdot \ln(H) + 4.78} \tag{4}$$

If these parameters are constituted to eq. (2), the yield stress is obtained. Parameters C and D were not able to fitted with simple function. Therefore more complicated procedure for the best fitting was used. Parameter C is characterized by this equation:

$$C = 2 \cdot \cos(65.051 \cdot H^{0.05052}) \tag{5}$$

Parameter D is characterized by this equation:

$$D = \frac{1}{\sqrt{-386.92 \cdot \ln(H) + 2564.6}} - 0.05 \tag{6}$$

The relationship for τ determination can be obtained by substituting equations (2) and (3) into (1) as follows:

$$\tau(\dot{\gamma}, H, t) = A(H) \cdot t^{B(H)} + C(H) \cdot e^{D(H) \cdot t} \cdot \dot{\gamma} \tag{7}$$

Complete model with substituting parameters A, B, C and D as follows:

$$\tau(\dot{\gamma}, H, t) = (169 \cdot H + 166115) \cdot t^{\frac{1}{-1.33 \cdot \ln(H) + 4.8}} + 2 \cdot \cos(65.1 \cdot H^{0.05}) \cdot e^{\left(\frac{1}{\sqrt{-387 \cdot \ln(H) + 2565}} - 0.05\right) \cdot t} \cdot \dot{\gamma}$$

Thanks to this equation the shear stress for corresponding magnetic field, temperature and shear rate can be calculated.

4. Conclusion

The MRF-140CG was measured in a special slit-flow rheometer. The results were evaluated for Bingham model describing accurately a flow at high shear rates. There were investigated several new phenomena: (a) yield stress dependence on temperature and (b) viscosity dependence on magnetic field intensity. The model of a MRF-140CG flow character was created and used as input to the analytical model and CFX model for simulation of flow in the MR valve with bypass.

Acknowledgement

There is very appreciated a kind sponsorship of many grants of numerous agencies, which granted as little as they could. The research leading to these results has received funding from the MEYS under the National Sustainability Programme I (Project LO1202), FSI-S-14-2329, FEKT/FSI-J-15-2777 and GAČR 13-31834P.

Abbreviations

CFX = high-performance Computational Fluid Dynamics (CFD); MEYS = Ministry of Education, Youth and Sports; MR = Magnetorheological; MRF = Magnetorheological Fluid

References

Bossis, G., Lacis, S., Meunier, a., & Volkova, O. (2002). Magnetorheological fluids. Journal of Magnetism and Magnetic Materials, 252, pp. 224–228.

Carlson, J. D., & Jolly, M. R. (2000). MR fluid, foam and elastomer devices. Mechatronics, 10, pp. 555–569.

Choi, Y. T., Cho, J. U., Choi, S. B., & Wereley, N. M. (2005). Constitutive models of electrorheological and magnetorheological fluids using viscometers. Smart Materials and Structures, 14, pp. 1025–1036.

Klingenberg, D. J. (2001). Magnetorheology : Applications and challenges. American Institute of Chemical Engineers, 47, pp. 246–249.

Mazůrek, I., Roupec, J., Klapka, M., & Strecker, Z. (2013). Load and rheometric unit for the test of magnetorheological fluid. Meccanica, 48, pp. 631–641.

Ngatu, G. T., & Wereley, N. M. (2007). Viscometric and sedimentation characterization of bidisperse magnetorheological fluids. IEEE Transactions on Magnetics, 43, pp. 2474–2476.

Rabinow, J. (1948). The Magnetic Fluid Clutch. Transactions of the American Institute of Electrical Engineers, 67,

Roupec, J., Mazůrek, I., Strecker, Z., & Klapka, M. (2013). The behavior of the MR fluid during durability test. Journal of Physics: Conference Series, 412, pp. 012024.