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Temperature effect on the magneto-rheological behavior of magnetite particles dispersed in an ionic liquid

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Abstract. The magneto-rheological properties of iron(II, III) oxide particles dispersed in the ionic liquid 1-butyl-3-methylimidazolium hexafluorophosphate were investigated in the temperature range from 25 °C to 76 °C. The experimental results have revealed that the apparent viscosity of the dispersion slightly changes with the temperature when a constant magnetic field is applied and its value mainly depends on the shear rate and the strength of the magnetic field. The viscosity of the dispersion remains practically unmodified with both the temperature and the magnetic field intensity as the magnetic saturation of the material is reached; in this regime the viscosity will only depend on the applied shear rate. In contrast, the yield stress values of the dispersion as well as the corresponding shear stress *vs.* shear rate curves have shown and inversely proportional behavior with temperature for a constant magnetic field. Moreover, a power law model was utilized to predict the temperature dependence of the yield stress under the presence of a constant magnetic field.

1. Introduction

The use of ionic liquids (ILs) has been recently proposed for the preparation of magneto-rheological fluids (MRFs) with outstanding properties [1-6]. This is mainly due to the interesting and intriguing properties shown by ILs (*e.g.,* negligible vapor pressure and flammability, outstanding chemical and physical stabilities in a broad range of temperature, possibility of tuning their properties, etc.) [7]. Thus, it is thought that ILs will play an important role in the preparation of advanced MRFs in the coming years, which might find novel applications (and/or improve the existing ones) in several fields of science and engineering. To our best knowledge, there are only a few reports in the open literature addressing the effect of the temperature (T) on the magneto-rheological properties of MRFs and magnetic fluids [8-10]. Indeed, the lack of investigations in this particular aspect may be related to the fact that, so far, MRFs have been prepared in very specific liquid carriers (e.g. hydrocarbon, silicon and mineral oils) [4]. Due to their remarkable thermal stability and negligible vapor pressure, ILs might be considered as suitable liquid carriers to perform detailed studies of MRFs in a broad range of temperature. Based on these facts, this contribution addresses the magneto-rheological properties of iron(II, III) oxide (magnetite) particles dispersed in the hydrophobic

IL 1-butyl-3-methylimidazolium hexafluorophosphate (BMI-PF_6) in the temperature range from 25 °C to 76 °C.

2. Experimental part

The MRF investigated in this work was prepared and characterized following similar procedures as reported elsewhere [4]. Iron(II, III) oxide (magnetite) powder (Aldrich, <5 μm, 98%, density 4.8-5.1 g cm^{-3} (25 °C)) was dispersed in BMI-PF_6 (obtained from Solvent-Innovation GmbH as a kind gift). BMI-PF_6 is an hydrophobic IL with a density and viscosity values of 1.37 g cm^{-3} (20 °C) and 211 mPa s (25 °C), respectively. MFR used in this study had a content of 12.5% wt of magnetite particles dispersed in BMI-PF_6. The dispersion process was performed in a cylindrical polyethylene container using polyethylene stirring paddles. The mixing process was achieved by mechanical stirring at a rate of 2400 rpm for 15 min at 20 °C. Magneto-rheological measurements of the prepared MRF were carried out at the desired temperatures under steady shear and at several shear rates using a Physica MCR 301 rheometer (Anton Paar) coupled with a commercial magneto-rheological device (MRD180/1T magneto-rheological cell). The homogeneous magnetic field was oriented perpendicular to the shear flow direction. A circular parallel plate measuring system (PP20/MR made of nonmagnetic metal to prevent the occurrence of radial component of magnetic forces on the shaft of the measuring system) with a diameter of 20 mm and a gap of 1 mm between the plates was used. Before performing the magneto-rheological measurements, the prepared MRF was additionally and vigorously shaken in order to ensure the homogeneity of the dispersion (*e.g.* no supernatant clear layer formation (sedimentation of the dispersed particles) was observed for at least two days).

3. Results and discussion

The first investigations in this study correspond to the rheological measurements of the liquid carrier (BMI-PF_6) of the prepared MRF. Figure 1 reveals that the BMI-PF_6 IL has a Newtonian behavior in the investigated range of temperature. Furthermore, Figure 1 also shows that the viscosity (η) of BMI-PF_6 obeys an Arrhenius model at the investigated experimental conditions.

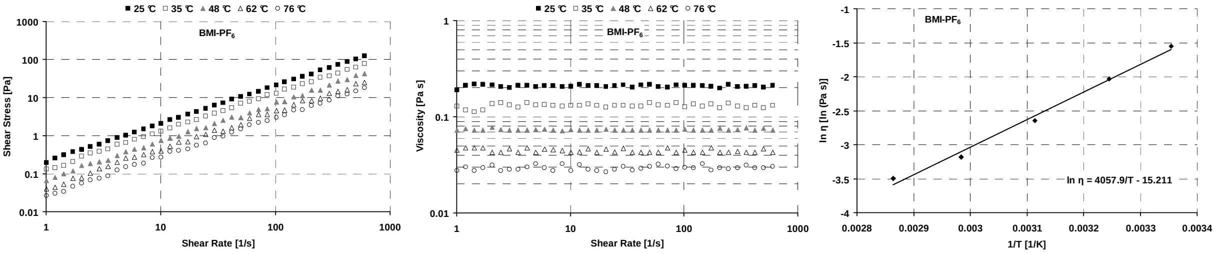

Figure 1. Temperature effect on the rheological characteristics of the hydrophobic ionic liquid 1-butyl-3-methylimidazolium hexafluorophosphate (BMI-PF_6).

The flow curves of the investigated MRF at several temperatures and under the influence of a magnetic field of different intensities (H) are displayed in Figure 2. Note that the shape of the curves resembles more to a pseudo-plastic system with a yield stress than to the Bingham model [11] conventionally used to describe MRFs under the presence of a magnetic field. This is also demonstrated in Figure 2 (bottom right) for a selected case of the obtained experimental data. In this specific case, two pseudo-plastic models (*e.g.* Ostwald (power law) and Carreau-Yasuda) [11], and the Bingham model are fitted and compared to experimental data. From this latter plot, it is clear that both pseudo-plastic models are more suitable to predict the experimental data than the Bingham model; similar findings were obtained for the rest of the obtained experimental data. Yield stresses of the MRF at the investigated conditions (different temperatures and magnetic field intensities) were estimated by using a yield stress analysis method incorporated in the software package of the utilized commercial rheometer. This analysis method estimates the yield stress by calculating the flexion point in a stress-strain curve in a logarithmic plot. The evaluation does a regression on the input data and checks for the point with the largest distance to the regression curve; this point is taken as the yield point. The yield stresses of the MRF obtained by this latter method are displayed in Figure 3.

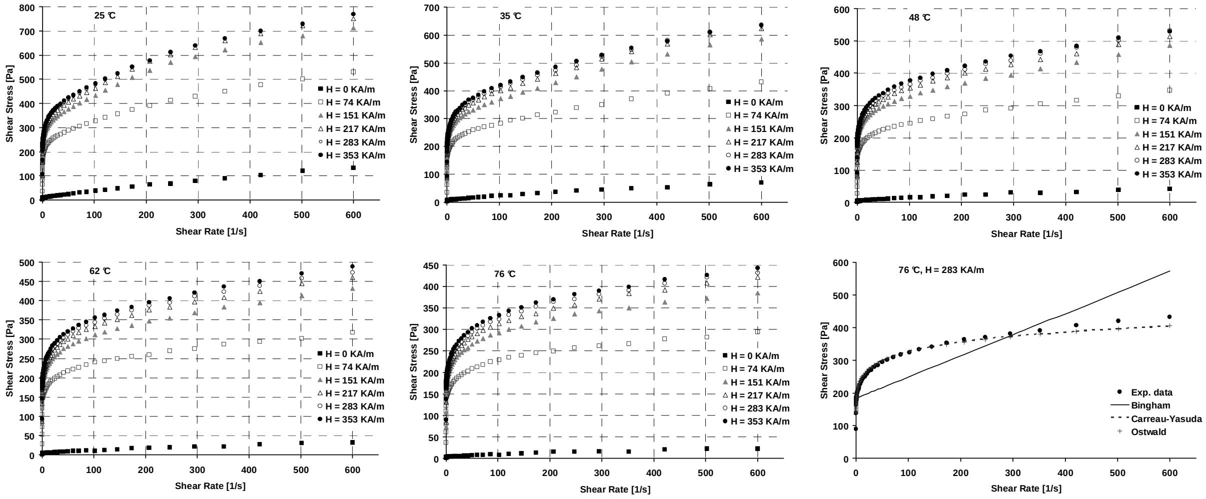

Figure 2. Flow curves of the investigated magneto-rheological fluid (MRF) at different temperatures and intensities of a magnetic field (H). Bottom right plot compares the predictions of two pseudo-plastic models (Ostwald and Carreau-Yasuda), and the Bingham model with the experimental data obtained for the investigated MRF at 78 °C and H = 283 KA m^{-1}.

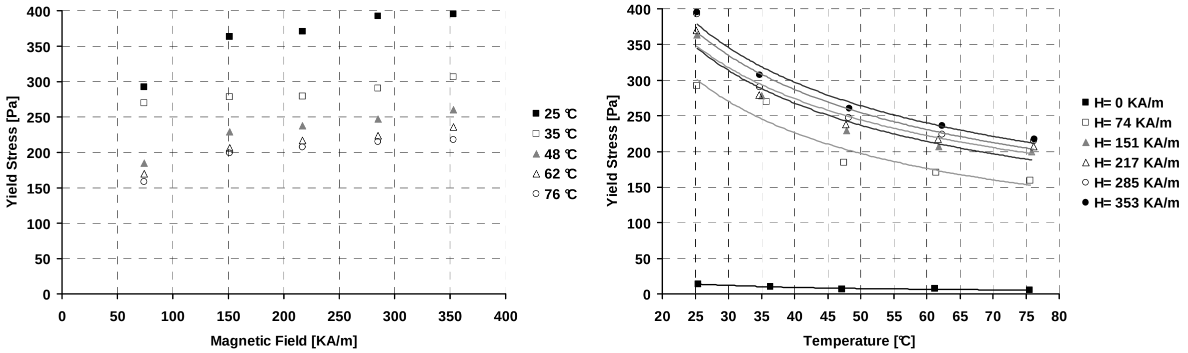

Figure 3. Yield stresses of the investigated magneto-rheological fluid (MRF) as a function of the temperature and of the magnetic field intensity (H).

As observed in the plots of Figures 2 and 3, the shear stress (τ) vs. shear rate ($\dot{\gamma}$) curves as well as the estimated yield stress (τ_o) values of the investigated MRF reveal an inversely proportional behavior with temperature for a fixed magnetic field intensity. The curves shown as solid lines in the plot on the right hand side of Figure 3 correspond to fittings of the obtained data with a power law model as represented by equation (1)

$$\tau_o = kT^n \tag{1}$$

where τ_o, k, and T are the yield stress, a fitting constant, and the temperature, respectively. The results in the plot on the right hand side of Figure 3 reveals that the temperature dependence of the yield stress in a MRF under the influence of a constant magnetic field can be qualitatively approached by using the power law model of equation (1).

In addition, the experimental results of this study have revealed that the apparent viscosity of the investigated MRF slightly changes with the temperature when a constant magnetic field is applied, and its value mainly depends on the shear rate and the strength of the magnetic field. Furthermore, the viscosity of the MRF remains practically unmodified with both the temperature and the magnetic field intensity as the magnetic saturation of the material is reached; in this regime the viscosity will only depend on the applied shear rate. These effects can be observed in the plots of Figure 4.

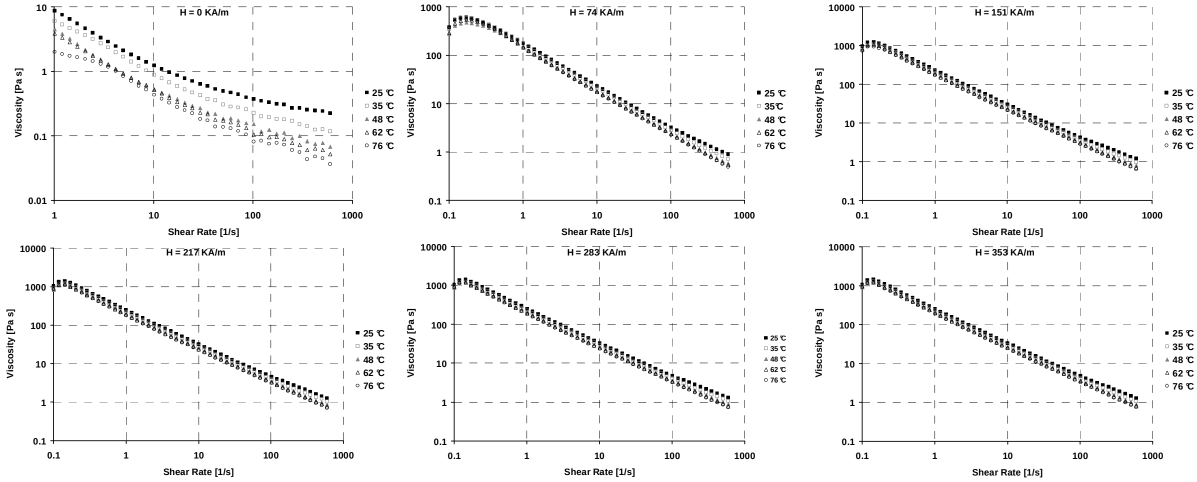

Figure 4. Viscosity curves of the investigated magneto-rheological fluid (MRF) as a function of the shear rate at different temperatures and intensities of a magnetic field (H).

4. Conclusions

In this contribution, the magneto-rheological properties of magnetite particles dispersed in the hydrophobic IL BMI-PF$_6$ were investigated in the temperature range from 25 °C to 76 °C. The use of ILs for the preparation of MRFs is very convenient to perform detailed temperature dependence magneto-rheological studies in this kind of dispersions due to the fact that ILs are in liquid state in a broad range of temperature, and they have a remarkable thermal stability and negligible vapour pressure.

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References

[1] Guerrero-Sanchez C, Rasa M and Schubert U S *WO/2008/055645*
[2] Kieburg C, Pfister J, Gabriel C, Oetter G, Laun M and Lochtman R *WO/2008/034820*
[3] Dodbiba G, Park H S, Okaya K and Fujita T 2008 *J. Magn. Magn. Mater.* **320** 1322
[4] Guerrero-Sanchez C, Lara-Ceniceros T, Jimenez-Regalado E, Rasa M and Schubert U S 2007 *Adv. Mater.* **19** 1740
[5] Guerrero-Sanchez C, Lara-Ceniceros T, Jimenez-Regalado E, Rasa M and Schubert U S 2007 Ionic liquids as carriers of magnetorheological fluids (5P7) *11th Int. Conf. on Magnetic Fluids,* July 23-27
[6] Altin E, Gradl J and Peukert W 2006 *Chem. Eng. Technol.* **29** 1347
[7] Deetlefs M and Seddon K R 2006 *Chim. Oggi* **24(2)** 16
[8] Kordonsky V I, Shulman Z P, Gorodkin S R, Demchuk S A, Prokhorov I V, Zaltsgendler E A and Khusi B M 1990 *J. Magn. Magn. Mater.* **85** 114
[9] Weiss K D and Duclos T G 1994 *Int. J. Mod. Phys. B* **8** 3015
[10] Chooi W W and Oyadiji S O 2005 *Int. J. Mod. Phys. B* **8** 1318
[11] Macosko C W 1994 *Rheology: Principles, measurements, and applications* VCH Publishers