Instabilities in the Poiseuille flow of a magnetorheological carbonyl-iron suspension.

Méndez A Pérez L Rivera I and Paniagua A
Escuela Superior de Física y Matemáticas, Instituto Politécnico Nacional, Edif. 9
Unidad Profesional Adolfo López Mateos, Col. San Pedro Zacatenco, C. P. 07730,
Ciudad de México, MÉXICO.
E-mail: arturo@esfm.ipn.mx, leopt@esfm.ipn.mx

Abstract. The flow of a magnetorheological suspension in the Poiseuille flow is studied in this work. A capillary rheometer was constructed and designated in order to adapt a magnetic field perpendicular to the flow direction covering the entire capillary zone; this restricts the maximum length of the glass capillary. A Newtonian suspension of carbonyl iron in glycerol at 20% in volume was studied at several intensities of magnetic field. The results showed a close-Bingham behavior at lower intensities of magnetic field. But a deviation is seen at higher intensities accompanied with a clearly shear thinning behavior with flow instabilities. These instabilities were evidenced by oscillations in shear rate and increased with the magnetic field and the shear stress.

1. Introduction
Magnetorheological fluids (MRF) are composed of magnetic particles dispersed in to a non-magnetic continuum phase like silicon oils. These suspensions are characterized by an abrupt increase of viscosity as well as the presence of yield stress under the presence of an external magnetic field, as result of a structure formation of the magnetic particles in the magnetic field direction. Its physical properties decrease when the magnetic field is removed due to the breaking structure. The magnetorheological suspensions have a Newtonian behavior but under the presence of the magnetic field, a close-Bingham fluid is the typical rheological behavior seen [1-5]. However, a variety of models are used to adjust the shear thinning observed on them [6-8]. In addition, the formation of the structured chain gives a high anisotropic behavior, and it is expected that phenomena like slip are observed in this kind of MRF.

Shorey et al. [1] designed and tested a parallel-plate magnetorheometer and observed poor data reproducibility when a smooth aluminum surface and sand paper were used. They used magnetic particles embedded in the surface by using a thin layer of epoxy in order to avoid slip in the boundary. de Vicente et al. [9] investigated the wall slip phenomena at low magnetic fields in stainless steel parallel plates by using different rheometer gaps and found that the wall slip thickness increased as a function of the Mason number. Volkova et al. [10] showed that a Carbonyl iron in silicon oil suspension gave the same yield stress but the flow curve differed at low shear rates (1-10s⁻¹) when a stainless-steel cone-plate is replaced by a glass one. Those authors suggest that the observed behavior is due to the aggregates slipping on the walls but the structure is remained. On the other hand, Pappas and Klingenberg [11] simulated the flow of a magnetorheological suspension in the Poiseuille plane considering interparticle magnetic forces approximated at the point-dipole limit as well as magnetizable walls. They showed that slip boundary condition fails to capture the Bingham-like behavior, and thick lamellar microstructures oriented in the flow direction were developed. In contrast, the no-slip boundary condition reproduces the Bingham-like behavior and thin lamellar aggregates were observed in the microstructure. These differences may be caused by the boundary nature (magnetic and non-magnetic walls). However, more
research should be done in this direction, because it is very likely that phenomena like those appear in melts (instabilities like: spurt and oscillations among others) could be experimentally seen in MRF.

Since the variety of designs and applications of this kind of suspension like prosthesis, clutches, etc, it is important to study their behavior in ducts and capillary geometry. However, the majority of researches are performed in rotational rheometers (simple shear flow) as pointed out by Pappas and Klingenberg [11], due to the relative facility of incorporating a uniform magnetic field to the flow. There are few researches about magnetorheological suspensions in capillary flow [6, 7, 11, 12, 13]. Nevertheless, only the Pappas and Klinglenberg [11] simulation deals with the pressure-driven flow (Poiseuille flow). So, the goal of this work is to analyze a 20% vol MR suspension of carbonyl iron in glycerin at several intensities of magnetic field, by using a capillary magnetorheometer constructed with a pressure-driven flow.

2. Experimental work

2.1. Capillary rheometer

The theory of the Poiseuille flow is well known and can be found elsewhere [14]. Figure 1 show the experimental setup used. The constituent parts of the rheometer constructed were similar to that employed by one of us [15] but modifications were made in order to adjust the magnetic field.

![Figure 1. Experimental arrangement. (1) Reservoir at constant pressure, (2) fluid container, (3) glass capillary, (4) pressure transducer, (5) collector container, (6) electromagnet, (7) pressure displayed.](image)

The constructed rheometer consists of a pressurized constant reservoir with the fluid under study. The fluid moves from the container of high H through the glass capillary and it is collected by the catch and measure technique in order to obtain the volumetric flow (Q). The geometrical parameters of the capillary are L=0.035 m of length and D=0.00125 m of diameter. In this case, the length to diameter ratio was L/D=28, and the contraction ratio was H/D>26. The pressure (ΔP) between the ends capillary is measured by a differential pressure transducer. The wall shear stress (τw) and the apparent shear rate (γa) were calculated by using the well known formulas [16]:

\[ \tau_w = \frac{D \Delta P}{4L} \]  
\[ \gamma_a = \frac{32Q}{\pi D^3} \]

The capillary rheometer calibration was performed using Newtonian oil. The experiments were carried out at 22°C and the viscosity results were compared with those obtained using a Thermo Electron rolling ball viscometer, the difference not exceed 0.5%
2.2. Magnetic field
An electromagnet was adapted on the capillary region in order to apply a magnetic field perpendicular to the flow direction. The electromagnet is composed of soft iron core of square shape and 0.04m of side. Considering these dimensions the maximum length of the capillary is restricted to 0.04m. Two coils with 250 turns, resistance of 0.6 Ohms and 2.2mH inductance each. In addition, a DC power supply was employed of 24V and 0-10A constructed in our electronic laboratory. The electromagnet was located at 0.0225m from the capillary center in such a way that it covers the entire capillary region. Figure 2 shows the magnetic field lines with the help of iron filings, in actual scale. It can be seen that the field is homogeneous throughout the capillary, ie in the area where carried out flow measurements. The magnetic flux density was obtained by direct measurement in the capillary area using a Leybold brand model 51662 teslameter as a function of the applied current. Electric currents of 1, 2, 3, 4 and 5 ampers were used and the corresponding values of magnetic field strength B were 12.4, 24.8, 36.9, 48.7 and 60.95 mT.

![Figure 2](image)

**Figure 2.** Magnetic field lines in actual measurement area, B=12.4 mT. (a) Reservoir at constant pressure, (b) electromagnet, (c) glass capillary, (d) iron filings tangents to the magnetic field lines.

2.3. MR experiments
MR suspension used in this work consists of spherical Carbonil Iron particles with 3.56 g/cm$^3$ density. SEM observations yielded a diameter that does not exceed 2 microns. Particles were dispersed at 20% volume in glycerol with 1.241 g/cm$^3$ density. The suspension was vigorous shaken and sedimentation effects were seen after 8 hrs. This time was enough to perform capillary rheometry.

Experiments with the MRF were carried out at 24°C, pressure injection was kept constant. Then, the capillary ends pressure and the volumetric flow rate were obtained without magnetic field. After that, the magnetic field was applied during 10 minutes, while capillary ends pressure and flow rate were measured. Subsequently, the magnetic field was removed and pressure and the flow rate were determined once more. These values were consistent with those measured before to apply the magnetic field. This protocol was repeated by increasing the injection pressure. To produce different magnetic fields, currents of 1, 2, 3 and 4 amperes were used. The currents values were chosen because a two-phase separation of the MRF was seen in the container (number 2 in figure 1) due to the magnetic field gradient when a current of 5 A is used. In fact, for times longer than 20 minutes, a decrease in flow followed by blocking was observed. Figure 3 shows the shear rate decrease until blocking and the corresponding shear stress increase. For times shorter than 20 minutes, shear stress is kept constant and shear rate is oscillating. At later times, shear rate dramatically decreases.
3. Results and Discussion

Figure 4 shows the flow curve at several current intensities. Corresponding fitting, where possible, is included. Flow curve at B=0 mT, shows Newtonian expected behavior, with \( \mu=0.87 \) Pa\( \cdot \)s and the interjection with the shear stress axis is within the experimental error (\( \tau_y=-1.76\pm2.18 \) Pa). The flow curve at B=14.26 mT, shows Bingham like behavior, with \( \tau_y=20.70\pm0.56 \) Pa the yield stress value. However, at B=28.57 mT the obtained flow curve observes a substantial deviation of the Bingham model. In this case, the behavior is close to the Herschel-Bulkley model, since the flow index decrease (n=0.72) showing a shear thinning behavior with yield stress (\( \tau_y=77.38\pm4.71 \) Pa). At B=42.85 and 57.14 mT, the yield stress values were \( \tau_y=210.3 \) and 415.4 Pa, respectively. Moreover, flow instabilities evidenced by the presence of shear rate oscillations were seen from these values. In this case, experimental data corresponds to the mean value on the oscillations and in such cases a fitting was considered inappropriate as the Rabinowitsch correction. To our knowledge the presence of flow instabilities evidenced by oscillations on shear rate on MRF have not been reported in literature. These oscillations are comparable to those seen in melts due to wall slip [17].

Furthermore, the shear rate oscillations amplitude are increased when shear stress increases at fixed magnetic field, as well as oscillations are enlarged when magnetic field strength is increased to the same shear rate value. For example, oscillations amplitude goes from 2 s\(^{-1}\) at B=14.28 mT and until 96 s\(^{-1}\) at B=57.14 mT were observed and these are shown in figures 5 and 6, respectively. Pappas and Klingenberg [11] in their simulation, attribute the fluctuation velocity to breaking and reformation of structures of the magnetized particles. In our case, we believe that a decrease in shear rate is the result of the capillary blockage due to the structures formation of the particles on the magnetic field direction. On the other hand, the increase on shear rate results from the transient breaking structured chain on the
capillary due to the pressure increment that outcomes from the blockage on the capillary. This hypothesis might be supported by the presence of pressure oscillations (like spurt in melts). We suspected slight pressure oscillations, but we were not able to quantify them, due to these being in the experimental error. It is important to mention that at this time we are not able to distinguish if the breaking chain is full or partial (due to an adhesion failure at the wall), because the chain can slip due to the roughness of the wall without beginning to break [10]. In addition, some kind of slip could be involved in these results, but we have doubts about real wall slip, since Pappas and Klingenberg [11] have shown that wall slip boundary does not reproduces the yield stress behavior observed in this kind of suspensions. In our experiments, a non-magnetic wall was employed (glass capillary). At this point more research should be done in order to elucidate the slip nature.

![Figure 5](image1.png)

**Figure 5.** Apparent shear rate values with lowest magnetic field applied (full symbols), and without magnetic field (open symbols).

![Figure 6](image2.png)

**Figure 6.** Apparent shear rate values with highest magnetic field applied (full symbols), and without magnetic field (open symbols). Amplitude of the oscillations is evident.

![Figure 7](image3.png)

**Figure 7.** Yield stress vs Magnetic field induction. Solid line corresponds to a power-law fit.

Figure 7 plots yield stress versus magnetic field induction; a non-linear behavior can be seen and is shown by the included fitting in the same figure. The power index of B was 2.164 and is due to the local saturation of the magnetized particles [18], and this value is in accord with low applied magnetic field [18, 19] and a micromechanics and statistical approach of the MRF model [20].
4. Conclusions:
A pressure driven capillary was adapted to study the MR behavior and a protocol was established to
determine the rheological properties of the 20%vol of CI in Glycerol. At low intensities of magnetic
field a close Bingham behavior was seen but deviates from it, when the magnetic field is increased and
a shear thinning Herschel-Bulkley behavior is obtained. Also a close-quadratic relation between magnetic
field induction and yield stress was obtained.
Flow instabilities, not reported before to MR fluids, were observed evidenced by the presence of
shear rate oscillations, which increased with shear stress and magnetic field induction. This result may
help to better understanding about mechanisms that occur when this phenomenon is presented in other
complex fluids. Finally, a direct application of the results obtained in this work could be that the presence
of flow instabilities could improve the operation of dampers and suspension systems, although more
research must be done.

5. References
[1] Shorey A B Kordonski W I Gorodkin S R Jacobs S D Gans R F Kwong K M and Farny C H 1999 Rev. Sci. Inst. 70 4200-06
[2] López-López M T Kuzhir P Lacis S Bosis G González-Caballero F and Duran J D G 2006 J. Phys.: Condens. Matter 18 S2803-13
[3] Ngatu G T Wereley N M Karli J O and Bell R C 2008 Smart Mater. Struct. 17 045022
[4] Kuzhir P López-López M T Vertelov G Pradille C and Bosis G 2008 Rheol. Acta 47 179-87
[5] Galindo-Gonzalez C Ponton A Bee A Chavalet J Talbot D Perzynski R and Dubois E 2016 J. Rheol. Acta 55 67-81
[6] Laun H M Kormann C and Willenbacher N 1996 Rheol. Acta 35 417-32
[7] Jha S and Jain V K 2009 Int. J. Adv. Manuf. Technol. 42 (7-8) 656-68
[8] Lim S T Cho M S Jang I B Choi H J 2004 Journal of Magnetism and Magnetic Materials 282 170-3
[9] De Vicente J Lópezlópez M T Durán J D G and González-Caballero F 2004 Rheol. Acta 44 94-103
[10] Volkova O Bossis G Guyot M Bashtovoi V and Reks A 2000 J. Rheol 44(1):91-104
[11] Pappas Y and Klingenberg D J 2006 Rheol. Acta 45 621-29
[12] Wang X and Gordaninejad F 2006 Rheol. Acta 45 899-908
[13] Gabriel C and Laun H M 2009 Rheol. Acta 48 755-78
[14] Walters K 1975 Rheometry (John Wiley & Sons NY)
[15] Méndez-Sánchez A F Pérez-González J de Vargas L Castrejón-Pita J R Castrejón-Pita A A and Huelsz G 2003 J. Rheol. 47(6) 1445-66
[16] Macosko C W 1994 Rheology principles, measurements and applications (Wiley-VCH, Inc. NY)
[17] Pérez-Trejo L 2005 Triboelectrificación de polietilenos fundidos en extrusión continua Ph. D. Thesis (ESIQIE Instituto Politécnico Nacional, México D. F., México)
[18] Liu Y D and Choi H J 2014 Magnetorheology Advances and Applications (Norman Wereley RSC Smart Material No 6.The Royal Society of Chemistry)
[19] Yang L Duan F and Eriksson A 2008 Smart Mater. Struct. 17 015047
[20] Peng X and Li H 2007 Smart Mater. Struct. 16 2477-85