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Characterization of simple magnetorheological fluids with potential application in engineering

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Abstract*— In this work, the authors wonder if it is possible to easily create affordable and simple-made magnetorheological fluids with interesting properties in order to design speed control devices. The focus is on simplicity and magnetorheological characterization. In that way, this paper describes the experiments done with magnetorheological fluids (MRF) which were designed, developed and tested. Studied fluids were easily prepared. Their chosen components are widely used in local industry. The magnetic fields used were generated with permanent magnets from commercial availability. Two types of fluids were created. One of them was composed of iron oxide particles widely used in non destructive tests (NDT) in the petroleum industry. The other component was printer's toner. These fluids were manufactured and experimented with different concentrations of magnetic material and also with different additives in order to avoid sedimentation and agglomeration. In all cases, circumferential flow was studied in cylindrical containers subjected to stationary, unidirectional, transverse magnetic fields. Significant increments of viscosity against imposed magnetic fields are highlighted. Unfortunately, it was not possible to prevent particle sedimentation without making more complex, expensive and difficult to create the fluids. However, a good redispersion is observed when these fluids are stirred. From these results, the design of magnetorheological devices employing MRF with the characteristics studied for control applications is planned. This paper aims to describe the behavior of magnetorheological fluids created in simple steps and from elements widely used in industry in order to obtain an application in engineering.

***Index Terms*— Magnetorheological fluids, additives, viscosity.**

I. INTRODUCTION

The study of new materials can be oriented into two branches: smart materials whose response is proportional to the external stimulus, and nanomaterials, whose microscopic structure is specifically designed. Magnetic fluids exhibit both qualities, they are designed and their response is proportional to the external excitation. Following Rosensweig and Odenbach [1]-[2], magnetorheological fluids (MRF) are those with controlled viscoelastic properties by means of external magnetic fields, composed of ferromagnetic particles dispersed in a liquid carrier. Citing Alves [3], when comparing different MRF formulations for practical uses, the most expected behavior would be that of material with highest yield stress under magnetic field, lowest viscosity without field, minimum sedimentation rate, and be easily redispersible after a long time at rest. There are a lot of articles concerning applications (see, for instance, Carlson and Jolly [4]). Many devices have been carried out such as actuators of different types, valves, seals, shock absorbers, vibration resistant elements, polishing and finishing techniques. Blast resistant and elastomers applications, gripping application, tactile displays, lubricants and directional solidification could be pointed out. Biomedical applications such as therapeutic cancer treatment could be mentioned too. Behavior of particles has been experimentally studied. Some topics of interest are friction between particles, the influence of particle shape and size dispersion and emulsions with micro- and nanoparticles, and nanoparticle generation. As example of these topics are very interesting the work of de Vicente *et al.* [5], Holm and Weis [6], Iglesias *et al.* [7], Kim *et al.* [8], de Vicente and Ramírez [9], respectively. As mentioned before, some MRF have been designed (Olabi and Grunwald [10], Rinaldi *et al.* [11], Bossis *et al.* [12], Vékás *et al.*[13]) as foams or films (Elias *et al.* [14]) with nanotubes (Li *et al.* [15]) or particles stabilized by surfactants (Hong *et al.* [16]). Water-in-oil emulsions (Park *et al.* [17]) and nanoparticles encapsulated in microgels (Tan *et al.* [18]) have been studied. As regard experimentation, could be mentioned studies of droplet impact (Rahimi and Weihs [19]), wear (Hu *et al.* [20]), squeezing (de Vicente *et al.* [21], Mazlan *et al.* [22], Mazlan *et al.* [23]), fluid compressibility (Rodríguez-López *et al.* [24]), the influence of the continuous phase (Taran *et al.* [25]), aggregates dispersion (Williams and Vlachos [26]) and aggregation effects (López-López *et al.* [27]). Yield, creep and recovery (Bossis *et al.* [28], Kim *et al.* [29] and Li *et al.* [30]) have been studied. Heat and momentum transport (Li *et al.* [31]) are also of interest. Sedimentation and redispersion (López-López [32]), fiber suspensions (López-López [33]), characteristics of surfactants (Alves [3]), instruments validation (Laun *et al.* [34]) and inverse ferrofluids (Ramos [35]) call investigator's attention, also. This long but resumed list of publications shows that while magnetorheology is a science of recent development and much has been studied, magnetorheological fluids are inherently complex in their manufacture and behavior. Obviously, this brings various issues when developing technology, especially if there is interest in devices whose cost and reliability is a determinant of the facility where it will be part. In this sense, this paper will focus on the manufacture of magnetic fluids with the following characteristics: (i) the components of the fluids are typically used in the local industry; (ii) the cost of these components is a crucial factor for potential technological

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application; (iii) the fluid manufacturing process involves using equipment usually present in industry; (iv) the magnetic fields used are obtained from commercial magnets of relatively low cost. These four characteristics define author’s concept of “simple magnetorheological fluid”. Clearly, the research of the authors is technology, however, the study of the magnetorheological behavior of fluids created is inevitable, and this study involves the comparison with the work of other researchers. This comparison will highlight, as the main conclusion, if the behavior of fluids in this work presented is of interest or not. The procedures for fluid generation, experiments and results obtained will be presented in the following sections.

II. EXPERIMENT

A. Lay out

All emulsions were tested for practical uses (the overall objective of the author`s investigation line) with commercial magnets whose magnetic field was in transverse direction, in cylindrical Couette flow. A device containing the different suspensions was designed and constructed in order to prove the magnitude of the MR effect and tested into a wind tunnel, see Table I.

In order to avoid remaining magnetization, each sample was used only once in a single experiment.

B. Materials

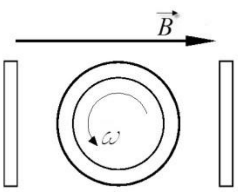
Magnetorheological fluids were coded FE1, FE2, FE3 and T. The earlier three are composed of iron as magnetic material, and the latter has printer toner.

1. Particles

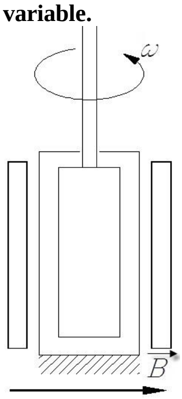
By scanning electron microscopy with secondary electrons (SEM-SE) images of the iron oxide particles were obtained, see Table II.

Table II and Fig. 1 show iron oxide particles with irregular shape, an average size of 83,9µm and a standard deviation of 52,3µm. A histogram of the iron oxide particles size is presented in Fig. 1, showing a considerable dispersion.

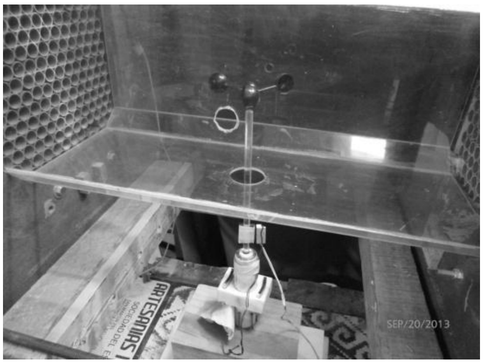
Table I. Measuring system sketch and photograph. Distance between magnets is variable.



(a) Circumferential flow.

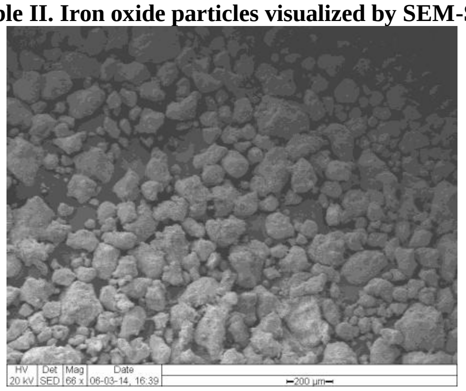


(b) Transverse magnetic field.

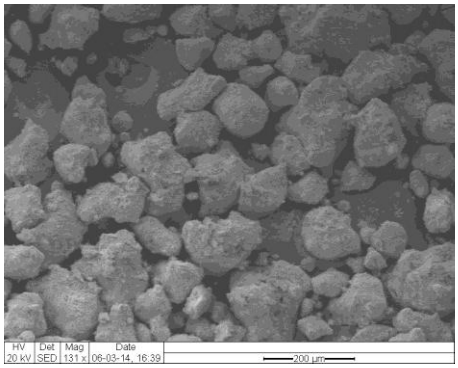


(c) Magnetorheological device.

Table II. Iron oxide particles visualized by SEM-SE.



(a) SEM-SE of iron particles.



(b) SEM-SE of iron particles.

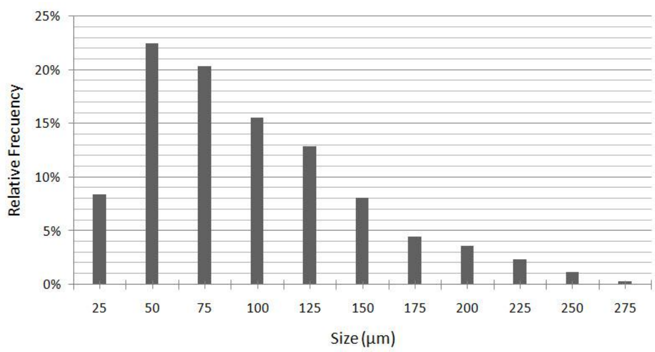


Fig. 1. Particle size histogram for the iron oxide.

Table III shows SEM-SE images of toner, where appear particles with irregular shape, an average size of 11,5µm and a standard deviation of 3,51µm. A histogram of the toner particles size is presented in Fig. 2.

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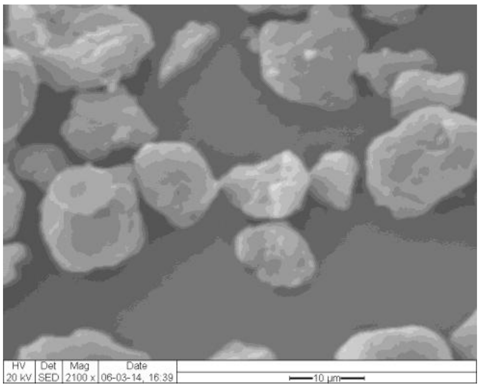
Table III. SEM-SE images of toner.

(a) SEM-SE of toner.



(b) SEM-SE of toner.

The toner used was characterized by X-ray fluorescence spectrometry and X-ray diffractometry. The following elements were detected: iron, sulfur, lanthanum, chlorine, zinc, cerium, chromium, strontium, potassium, titanium, praseodymium, manganese and silicon. Considering the characteristics of the spectrometer used, light elements such as carbon and oxygen were difficult to detect in helium atmosphere.

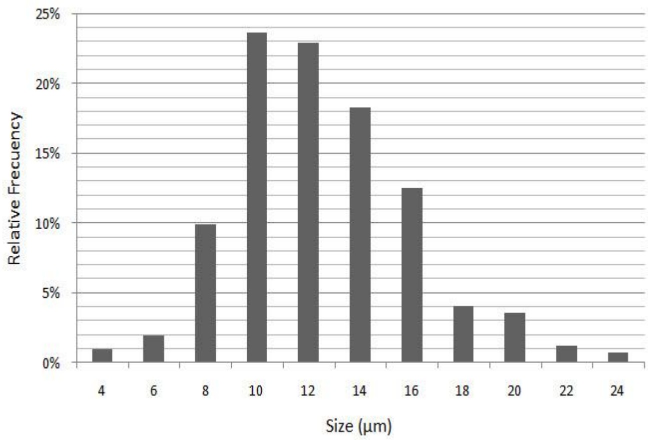


Fig. 2. Particle size histogram of toner

Presence of calcium and phosphorus in the samples couldn't be assured because they were part of the composition of the support film. The result of the diffraction is shown in Fig. 3.

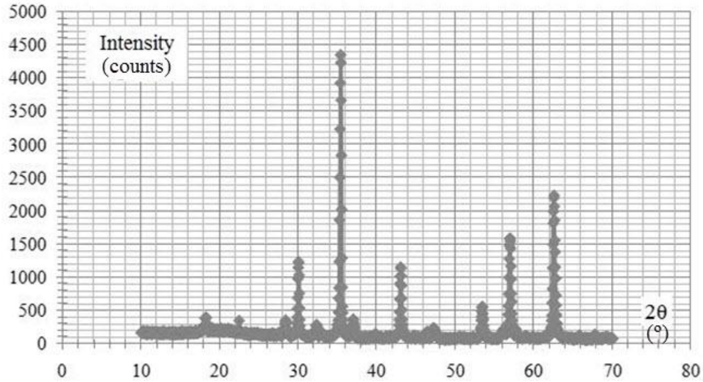


Fig. 3. X-ray diffractometry (XRD) of toner.

The following components were identified (see Table IV):

Table IV. Components present in toner.

Fe_3O_4	Iron oxide (magnetite)
$(La_{0,8}Sr_{0,2})FeO_3$	Iron, lanthanum, strontium oxide
CeO_2	Cerium oxide
$Sr_2FeTiO_{5,5}$	Titanium, strontium, iron oxide

2. Fluid 1 (FE1): with iron particles

The first emulsion (FE1) is composed of an oily carrier, distilled water, iron particles and a surfactant in order to obtain water-in-oil (W/O) emulsion. The methodology for obtaining it has been empirically modified based on results. Including water as a component was studied by other investigators (Park *et al.* [17]) in order to reduce particle aggregation and settling, so the use of it was decided. For emulsion FE1, the chosen oil was Dow Corning 200®, a silicone oil whose viscosity is 215mPa·s and density 1.075kg/m^3 at 25,2ºC. The surfactant used was an acid salt of sodium dodecylbenzenesulfonate ($C_{18}H_{29}NaO_3S$, also known as SDBS), the Fluka Chemical 44200® product. It is an anionic substance, with HLB (hydrophilic-lipophilic balance) index over 30 and works as an emulsifier. Iron particles are Magnaflux 8A Magnavis red®, magnetic particles used for non destructive testing.

3. Fluid 2 (FE2): with iron particles

The second fluid (FE2) consists of an oily carrier, iron particles and a surfactant. No water was included unlike emulsion FE1. The chosen oil was Dow Corning 200®, with a viscosity of 5,37mPa·s and density 1.075kg/m^3 at 25,2°C. Versamul® in solution was used as surfactant for emulsion FE2. Versamul is a product of the MI Swaco Company. Its HLB index varies between 3 and 8, which makes it useful for achieving W/O emulsions. This surfactant is used in the petroleum industry to carry out W/O emulsions (Schramm [36]).

4. Fluid 3 (FE3): with iron particles

The incidence of the surfactant was investigated. In that sense, a fluid (FE3) was prepared with a nonionic surfactant, Triton X-100® (HLB ≅ 10, used to achieve O/W emulsions), plus distilled water. Details can be seen in Tables X and XI.

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5. Fluid 4 (T): with toner

The fourth fluid tested was one composed of vegetable oil (density 882,7kg/m^3 and viscosity 218mPa·s at 24,8ºC) and a laser printer toner. Only two components were used.

C. Preparation of the suspensions

In all cases, the preparation steps were the following: (i) different oil-surfactant solutions were prepared; (ii) magnetic particles were added; (iii) the suspensions were hand shaken and sonicated to destroy any flocculi; (iv) the samples were stirred during one hour at 1000rpm to allow adsorption of surfactant on the particles. It was always use plastic flasks. In the case of FE1 and FE2 fluids, suspensions with acceptable settling were obtained according to visual inspection. Table V and Table VI show the composition of the FE1 fluid. Different stages of mechanical and sonic agitation in different intensities and durations were part of the process.

Table V. Components and preparation of FE1

Distilled water [ml]	Iron [g]	Surfactant (SDBS) [ml]	Oil (215mPa·s) [ml]
2	2	3,6	341,53

Table VI. Constitutive relations of FE1

water / oil vol/vol	water / surfactant vol/vol	oil / iron [ml/g]	oil / iron wt/wt
0,59%	56%	170,76	5,46%

Due to opacity of emulsions, sedimentation was qualitatively analyzed by visual inspection. Components and proportions of FE2 fluid are shown in Table VII and Table IIX. Little precipitation was observed 24 hours after the last stirring for FE1 and FE2 fluid. The suspensions emulsified immediately by means of manual stirring.

Table VII. Components and preparation of FE2

Iron [g]	Surfactant (Versamul®) [ml]	Oil (5,37mPa·s) [ml]
0,92	0,72	72

Table IIX. Constitutive relations of FE2

oil / surfactant vol/vol	oil / iron [ml] / [g]	oil / iron wt/wt
100	**78,26**	**2,50%**

Details of FE3 can be seen in Table IX and Table X.

Table IX. Components and preparations of FE3

Distilled water [ml]	Iron [g]	Surfactant (Triton X-100®) [ml]
150	**37**	**23**

Table X. Constitutive relations of FE3.

water / surfactant vol/vol	water / iron [ml] / [g]	water / iron wt/wt
6,52	**4,05**	**0,12%**

Three samples with toner were tested: TA, TB and TC, with the following characteristics (see Table XI):

Table XI. Components of different fluids with toner

	TA	TB	TC
Vegetable oil [ml]	200	200	90
Toner [g]	2,014	4,033	88,851
Oil / Toner [ml/g]	100	50	1
Oil / Toner wt/wt	1,14%	2,28%	111,84%

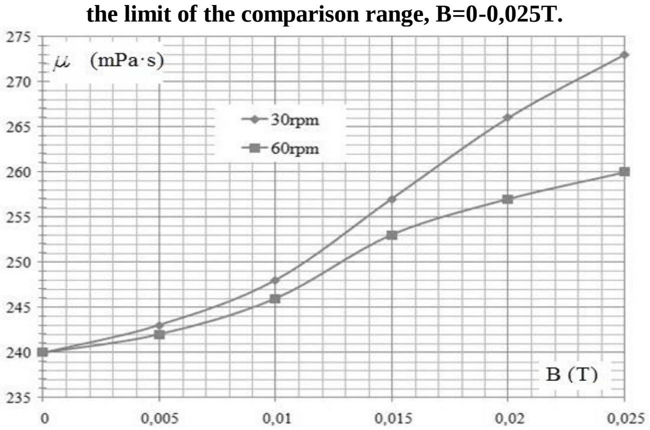
III. RESULTS AND DISCUSSION

A. Fluid with iron

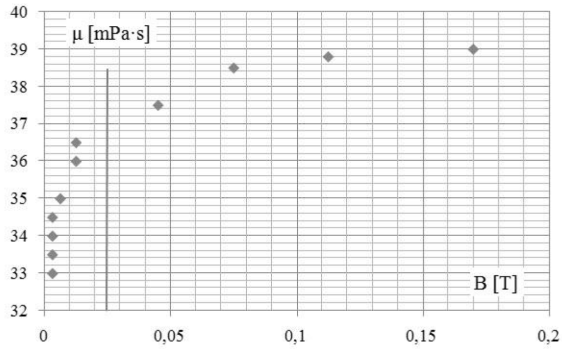
1. Effect of SDBS

Permanent magnets from commercial availability and industry electromagnets were used. The magnetic field was qualitatively and quantitatively evaluated. Magnetic flux density at different points in space was measured. Viscosity (μ) was measured with a Brookfield DV-II viscometer for different rotation speeds and magnetic flux densities (B). Data presented in Table XII (a) show a viscosity increment of 13% compared with the emulsion viscosity without magnetic field (242mPa·s), for 30rpm shear rate, and 8% for 60rpm. These increments were found by other investigators (e.g. Vékás *et al*. [13]) in their research; see Table XII (b). It can be seen that in the range of B=0 to 0,025T, viscosity increments are in the order of 10%.

Table XII. Results comparison between the FE1 fluid at left and Vékás et al. [13] at right, in which the thick solid line indicates the limit of the comparison range, B=0-0,025T.



(a) Viscosity increments compared with the emulsion viscosity without magnetic field, for 30rpm shear rate, and 60rpm.



(b) Increments found by Vékás et al. [13]) are in the same order of one's presented in this work.

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*2. **Effect of Triton X-100®***

The emulsions FE2 and FE3 were tested with commercial magnets with a magnetic flux density of B=0,04T in transverse direction. The sample temperature was 24,43°C. The viscosity increment for FE3 (with Triton X-100®, for O/W emulsions) fluid in the presence of the magnetic field is shown in Fig. 4 along with the FE2 (with Versamul®, for W/O emulsions) fluid. The rheological behavior in both fluids and sedimentation, as said before, are similar. The viscosity of the continuous phase in both fluids are similar (FE2 has an oil with viscosity close to five and FE3 close to one). Table XIII shows the different particle contents. FE3 suspension supports greater amount of iron at the expense of higher surfactant content. Then, Versamul® is a kind of surfactant that allows more iron content. Water in oil emulsions seems to be a good choice for making a MRF with the iron particles size used in this study.

Table XIII. Comparison of constitutive relations

Oil (5mPa·s) / Versamul® vol/vol	oil / iron wt/wt	Δμ (2-10s^{-1})
FE2		
100	2,50%	~10
Water / Triton X-100® vol/vol	**water / iron wt/wt**	
FE3		
6,52	0,12%	~2

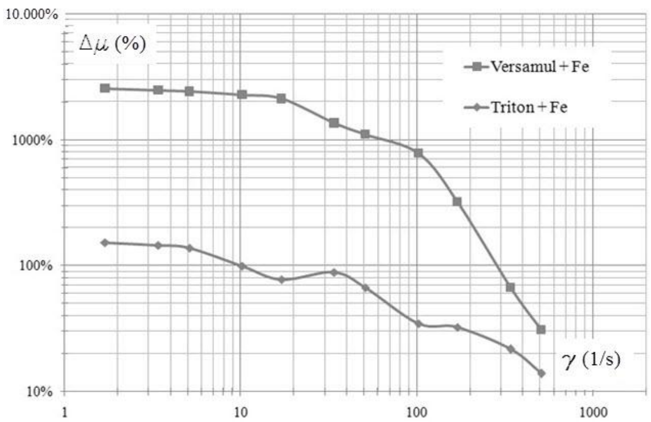


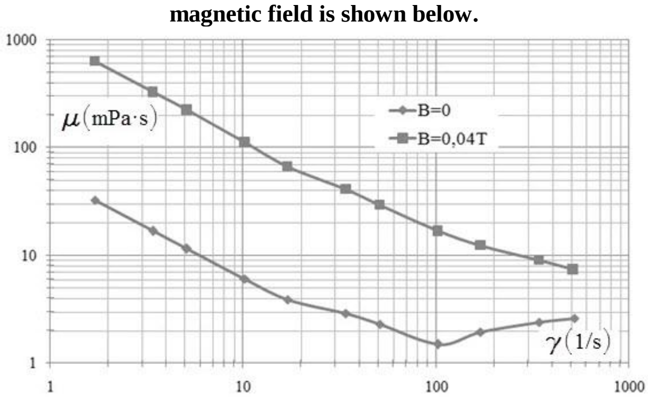
Fig. 4. Percentage viscosity increments Δμ for FE2 (with Versamul®) and FE3 (with Triton X-100®).

As shown in Fig. 4, at low shear rates viscosity is increased by ten times for FE2 or two times for FE3, approximately. Viscosity variations remain approximately constant until γ=10s^{-1} (6rpm).

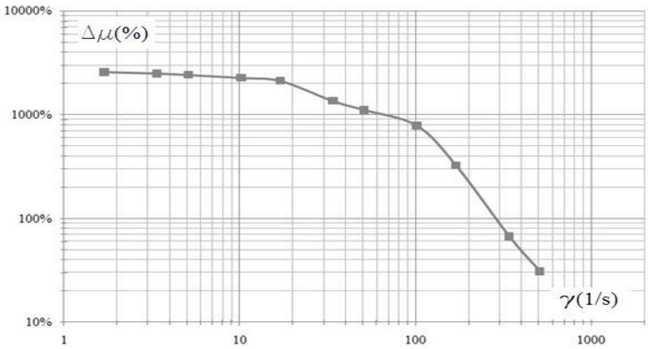
*3. **Effect of Versamul®***

The fluid FE2 was studied through permanent magnets with a magnetic flux density of 0,04T in transverse direction. The instrument used was the OFITE Model 900 viscometer. The sample temperature was 24,43°C. Table XIV presents the results of measurements of viscosity versus strain rate for the emulsion FE2; see Table XIV(a). Table XIV(b) shows a significant increment in fluid viscosity in the presence of the magnetic field for FE2. The increasing order varies between 25 and 12 times in the range of γ=1-30rpm. The maximum increment corresponds to 1rpm. Finally, the Versamul® incidence in sedimentation was searched. In that order, turbidity of three samples was measured with a spectrophotometer along almost two hours (115 minutes). Table XV presents the samples, and Fig. 5 shows the results of turbidity (nephelometric turbidity units, NTU, versus time for different oil-surfactant volume fractions). A volume fraction of 5% results in a turbidity reduction of 10%. This reduction is proportional to iron deposition increasing.

Table XIV. Behavior of the fluid FE2 in the presence of magnetic field is shown below.



(a) Viscosity μ versus strain rate γ for FE2 fluid, with B=0 and B=0,04T.



(b) Percentage increment Δμ in FE2 viscosity with a magnetic field of B=0,04T.

Table XV. Constitutive relations for the three fluids FE2 type.

	Oil [ml]	Versamul®	Iron [g]
Sample 1	72	5%	0,92
Sample 2	72	0,50%	0,92
Sample 3	72	1,25%	0,92

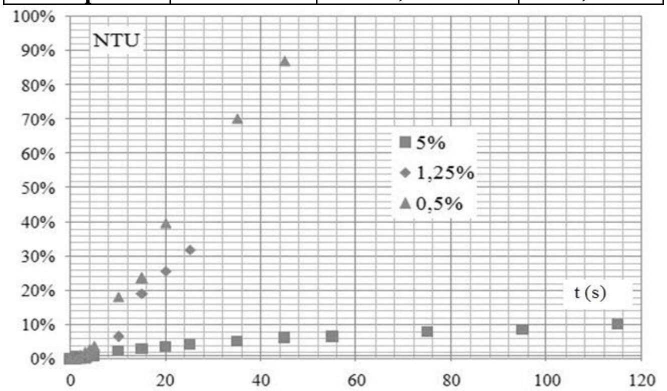


Fig. 5. Variation of turbidity for FE2 emulsions versus Versamul® content.

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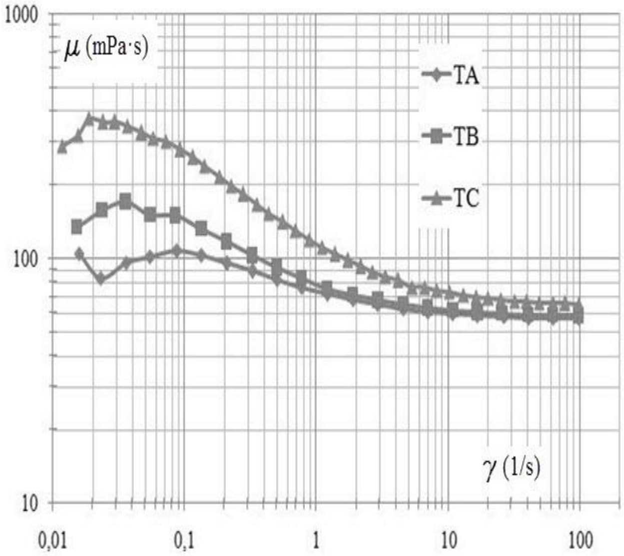
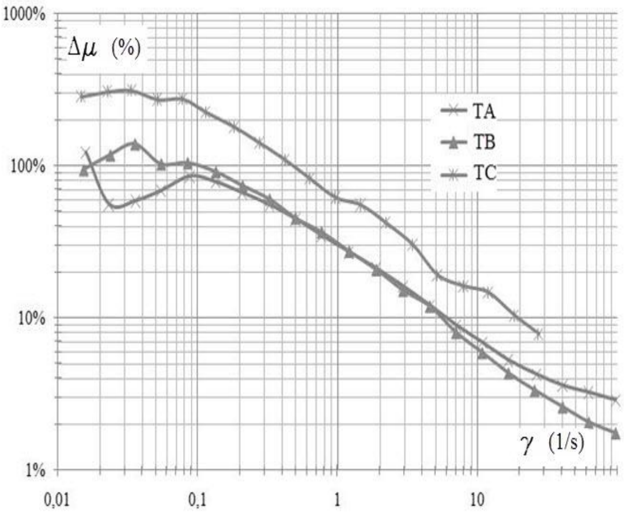
B. Fluid with toner

Table XVI shows the behavior of emulsions TA, TB, TC and the vegetable oil used in the presence of a magnetic field of B=0,02T. The instrument used was the AR2000ex rheometer. As expected, it is observed that at greater amount of toner, the higher is the magnetorheological effect. A peak in viscosity is noted at γ≈0,02.

Table XVI. Behavior of fluids with toner in the presence of magnetic field is shown below.



(a) Viscosity of toner suspensions with B=0,02T.



(b) Percentage change in viscosity Δμ for different suspensions.

Table XVI(a) shows the increment of viscosity in the presence of the magnetic field relative to the absence of magnetism. Viscosity peaks are given for γ=0,02s-1 and γ=0,09s-1. Notice the continuous decrease of viscosity variation with shear rate. Fig. 6 highlights the influence of the oil-toner fraction with the variation of viscosity in the presence of the magnetic field.

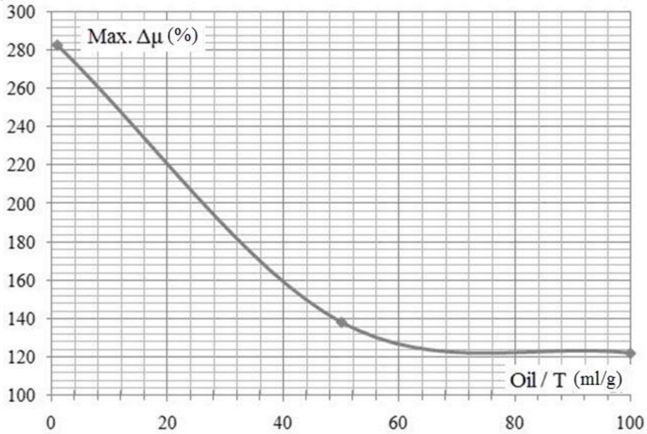


Fig. 6. Percentage increments in viscosity for TA, TB and TC, in relation to the oil-toner fraction.

IV. CONCLUSIONS

Easily prepared fluids with iron and toner powder were studied. The chosen components are widely used in local petroleum industry. Despite of the significant increment of viscosity, simplicity in the creation procedure of these fluids plays an undesired role in the behavior of the suspensions (agglomeration and settling). However, a good redispersion is observed when these fluids are stirred, which could allow a potential application in engineering. Water in oil emulsions seems to be a good choice for making a MRF with the iron particles size used in this study. As expected, a low viscosity oil (5mPa·s versus 215mPa) reflects higher magnetorheological effects, increasing viscosity 25 times and 10 times from the range 1rpm to 30rpm (FE2). See Table XVII. Fluids with iron particles and low viscosity oil (FE2 and FE3) present their viscosity increments approximately constant in the range between 1rpm to 6rpm. In order to obtain an acceptable sedimentation, the proper amount of surfactant was sought. This search yielded a value of 5% for FE2 emulsion type. Versamul® surfactant (HLB 3-8) provided better results than Triton X-100® (nonionic) and SDBS (anionic) surfactants. In the case of fluids with toner (T), viscosity increments vary between 1 to 3 times in the presence of magnetic field. These increments were found for $\gamma \approx 0{,}02 s^{-1}$. The four kinds of fluids studied show the most significant increments in viscosity at speeds of the order of 1rpm. This is the useful range for MR devices design with the sort of fluids in this work studied.

Table XVII. Characteristics of fluids.

Additive/ Continuous phase	**Surfactant proportion**	**Continuous phase/ particles**	**Δμ (γ=2-10s^{-1};1-30rpm)**
FE1			
water / oil 215	water / SDBS	oil 215/ iron	~0,10
0,6%	55,6%	5,5%	
FE2			
	oil 5 / Versamul	oil 5 / iron	~10-25

	100	2,5%	
FE3			
	water / Triton	water / iron	~2
	6,5	0,12%	
TC			
		vegetable oil / toner	~1-3
		111%	

V. ACKNOWLEDGMENT

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