



(51) International Patent Classification:

G01N 11/00 (2006.01) G01N 11/02 (2006.01)

(21) International Application Number:

PCT/IB2020/053357

(22) International Filing Date:

08 April 2020 (08.04.2020)

(25) Filing Language:

English

(26) Publication Language:

English

(30) Priority Data:

115447 08 April 2019 (08.04.2019) PT

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(81) Designated States (unless otherwise indicated, for every kind of national protection available): AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DJ, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, JO, JP, KE, KG, KH, KN, KP, KR, KW, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, WS, ZA, ZM, ZW.

(54) Title: MAGNETO-RHEOLOGICAL ADAPTER

FIGURE 4

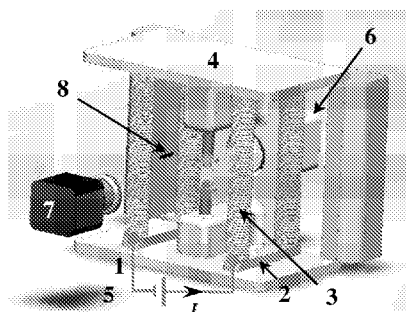


Fig. 4a

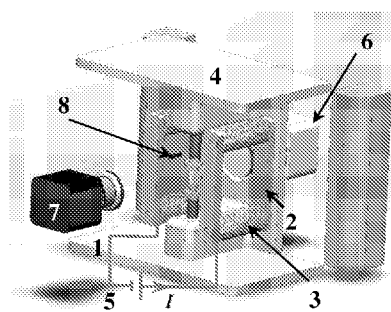


Fig. 4b

(57) Abstract: An adapter device (A) for Capillary Breakup Extensional Rheometer (CaBER), comprising: - solenoid coils (S) with a copper wire wound around the cylindrical solid core of iron, each solenoid (S) having the same winding number of turns and the same number of layers, being the winding copper wire wrapped around the iron core from left to right to complete the first layer, then from right to left to complete the second layer, and so on until completing the required number of layers for each solenoid coil (S), - a plastic scaffolds structure for holding the solenoid coils (S), - the terminals of the solenoid coils (S) with means to be connected in series to an external source of tunable DC current (1), wherein - the adapter (A) is provided in 2 configurations, in a parallel configuration (A1) and/or in a perpendicular configuration (A2), wherein: - in the parallel configuration (A1) the solenoid coils (S) are arranged in a squared configuration and parallel to the shaft of the CaBER, - in the perpendicular configuration the solenoid coils (S) are arranged in a squared configuration and perpendicular to the shaft of the CaBER

(84) Designated States (*unless otherwise indicated, for every kind of regional protection available*): ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Published:

- *with international search report (Art. 21(3))*
- *before the expiration of the time limit for amending the claims and to be republished in the event of receipt of amendments (Rule 48.2(h))*
- *in black and white; the international application as filed contained color or greyscale and is available for download from PATENTSCOPE*

DESCRIPTION

MAGNETO-RHEOLOGICAL ADAPTER

Technical field

The present invention relates to a device designed to adapt with the Capillary Breakup Extensional Rheometer (CaBER).

By applying the adapter (A) to a CaBER-device it is possible to characterize the rheological properties of magnetic fluid samples, under a simultaneous extensional flow exerted by the CaBER, and an external tunable homogenous magnetic field generated using an external DC power source with tunable electric current.

The adapter (A) has two different configurations, a parallel configuration (A1) and a perpendicular configuration (A2), for imposing a homogeneous magnetic field in the parallel and/or in the perpendicular direction of the extensional flow.

This invention is thus in the technical field of magnetic fluids (MFs) with rheological properties for measuring and characterizing of said properties of a magnetic fluid.

Background of the invention

Magnetic fluids (MFs), or magnetic field responsive fluids are those fluids that have particles suspended in a base (carrier) fluid. They are considered a class of smart materials, due to their rheological properties that change immediately once a magnetic field is applied.

These fluids can be classified into two main categories depending on the size of suspended particles to magnetorheological fluids (MRFs) if the particle size is in micron size, or ferrofluids (FFs) if the size is in nano.

The rheological properties of MFs are nearly Newtonian in the absence of magnetic field, while under an applied magnetic field, dispersed particles align creating long chains in the direction of the magnetic field defining three possible cases of MFs: a purely micron or nano size particles, or a mixed micron-nano size particles.

It is realized that MFs are involved in many conventional and intelligent applications. For example, MRFs were introduced in the 1940's and since that time, it is used in designing many commercial well-known applications such as dampers, actuators, valves, sealing, refrigerants, brakes, or clutches.

Later, in the 1960's FFs were synthesized and used in frequent applications related to thermal management, medicine, refrigerants, sealing of rotary shafts, galvanometer, or sensors.

Nowadays, MFs are a very active topic with a wide potential of applications, which require a better understanding of their rheological characteristics.

Accordingly, for a complete description and better understanding of the performance of MFs under real applications, the rheological properties must be measured under a simultaneous effect of magnetic field and uniaxial extensional flows, which are still relatively new.

The first step for characterizing the behavior of MFs was done by Galindo-Rosales et. Al. (Galindo-Rosales, F., Segovia-Gutiérrez, J., Pinho, F., Alves, M., and de Vicente, J., 2015, "Extensional rheometry of magnetic dispersions," *Journal of Rheology*, 59(1), pp. 193-209.), using a fixture equipped with permanent magnets, which is considered here as a limitation towards characterizing MFs, due to the fact that permanent magnets have only one single value for the intensity of magnetic field.

In this document it is also mentioned the possibility of using solenoids in order to tune the intensity of the magnetic field, nevertheless, they never designed nor built-up an add-on able to provide a tunable and homogeneous magnetic field within the volume sample.

However, electromagnets are not herein mentioned and thus it is not possible to work with multiple values for the intensity of magnetic field by using an external DC power source of a tunable electric current.

Therefore, there is a need of developing a tool that allows the characterization of the rheological properties of a wide range of MFs, under magnetic field and uniaxial extensional flows simultaneously in a CaBER-device.

With this aim, the present invention proposes a simple tool having a function of an adapter, which when fixed to a CaBER-device allows the application of an external magnetic field parallel or perpendicular to the flow kinematics undergone by the fluid sample while the extensional characterization is taking place.

Description of the figures

Figure 1 is a representation of an embodiment of the adapter (A) of the invention having two different configurations, a parallel configuration **(A1)** and a perpendicular configuration **(A2)**, wherein:

Fig.1a represents the parallel configuration for imposing a homogeneous magnetic field in the parallel direction of the extensional flow, and

Fig.1b represents the perpendicular configuration for imposing a homogeneous magnetic field in the perpendicular direction of the extensional flow.

The following reference numbers represent:

1. Cable to connect the coils to the power source,
2. Scaffold material to hold the coils in the right position,
3. Coils.

Figure 2 shows another embodiment of the invention, wherein external electrical DC power source (DC), for generating the required magnetic field is assembled with the adapter (A) in the parallel configuration **(A1)**, thus allowing the sample fluid in the CaBER-device undergoing to a simultaneous magnetic field and an extensional flow.

The following reference numbers represent:

1. Cable to connect the coils to the power source,
2. Scaffold material to hold the coils in the right position,
3. Coils.
4. CaBER device

5. Power source
6. Light source
7. High Speed Camera
8. Laser

Figure 3 represents the different components of the adapter (A) assembled in a CaBER-device, for magnetorheological measurements, wherein a magnetorheological fluid (MRF) sample tested on the CaBER-device undergoes under a simultaneous effect of a homogeneous magnetic field and extensional flow in the parallel configuration **(A1)** of a stretched unbroken filament of MRF.

Fig.3a represents a 3D view of the assembly,

Fig.3b represents the front view of the assembly,

Fig.3c represents a cross-sectional view at A-A',

Fig.3d represents a cross-sectional view at B-B'.

Herein, the adapter (A) of the invention is either in the parallel configuration (A1) or in the perpendicular configuration (A2) and comprises four solenoid coils (S) with a copper wire winded around a cylindrical solid core of iron, each solenoid (S) having the same winding number of turns and the same number of layers and the terminals of the solenoid coils (S) are connected in series to an external DC power source of tunable current (1).

Further, the origin of the Cartesian coordinate axis (x, y, z) of the fixture is designed to be at the center of the volume sample, as shown in Fig.3b and Fig.3c, with the solenoid coils arranged to be in equal spacing from the origin, as shown in Fig.3c.

The following reference numbers represent:

1. Cable to connect the coils to the power source,
2. Scaffold material to hold the coils in the right position,
3. Coils.
4. CaBER device
5. Power source

Figure 4 represents the different components of the adapter (A) assembled in a CaBER-device, which is equipped with two measuring systems to facilitate measuring the time evolution of the filament diameter over time simultaneously by the laser system and by a high-speed camera. As shown herein, the designed assembly gives the user the option of using both laser and high-speed camera simultaneously, where it can be observed that the adapter (A) neither blocks the view of the laser nor of the camera.

Fig.4a represents the assembly with the adapter (A) in the parallel configuration (A1), and

Fig.4b represents the assembly with the adapter (A) in the perpendicular configuration (A2), wherein

The following reference numbers represent:

1. Cable to connect the coils to the power source,
2. Scaffold material to hold the coils in the right position,
3. Coils.
4. CaBER device
5. Power source
6. Light source
7. High Speed Camera
8. Laser

Figure 5 shows the variation of the magnetic field intensity with the applied intensity current and the distance from the center of the fluid sample for both configurations of the adapter (A).

Fig.5a represents the dependence of the intensity of the magnetic field with the intensity current for both configurations of the adapter (A), and

Fig.5b represents the dependence of the intensity of the magnetic field in the direction of the extensional flow from the center of the fluid sample for the parallel configuration(A1), and

Fig.5c represents the dependence of the intensity of the magnetic field in the direction of the extensional flow from the center of the fluid sample for the perpendicular configuration(A2).

Figure 6 shows the time evolution of the minimum diameter in a filament thinning process, where each plotted profile represents a recorded time evolution of each filament corresponding to a single magnetic field intensity. Thus, empty triangle represent the filament thinning process for glycerin without the presence of any magnetic field; the filled triangle the MRF without the presence of any magnetic field; circle and squared empty symbols represent correspond to the MRF under magnetic fields of increasing intensities: 1.5 and 2.9 kA/m for the parallel configuration (A1) and 0.6 and 1.2 kA/m for the perpendicular configuration(A2), respectively.

Fig. 6a and **Fig. 6b** show the filament thinning process using the parallel and perpendicular configuration, respectively wherein glycerin was used as reference fluid and MRF was tested.

It is possible to observe that MRF samples behave as Newtonian fluids, showing a linear relationship between time and minimum filament diameter ($D_{\min}$).

However, when an electric current of 0.2 A is imposed in each assembly, magnetic fields equivalent to 1.5 kA/m and 0.6 kA/m are imposed by the parallel and perpendicular configuration the filament behavior delays in comparison to the cases of no magnetic field.

When the imposed electric current increased to 0.4 A, the magnetic field further increased up to 2.9 kA/m for parallel configuration, and 1.2 kA/m for perpendicular configuration.

Then it is observed that the filament does not break when the magnetic field is imposed in parallel to the deformation axis, while if a perpendicular a magnetic field is imposed the filament break faster than the case of MRF with none magnetic field, as shown in Fig. 6b.

Figure 7 shows the filament thinning behavior for MRF in parallel and perpendicular configurations, at different magnetic field intensities. The image was recorded immediately before the instance of filament breakup, except the cases where the filament never breaks when using the parallel configuration, at a magnetic field of 2.9 and 3.7 kA/m.

Fig.7a-f represent how the last image of the filament thinning process depends on the intensity of the magnetic field for the parallel configuration of the adapter (A1).

Fig.7g-l represent how the last image of the filament thinning process depends on the intensity of the magnetic field for the perpendicular configuration of the adapter (A2).

Description of the invention

The present invention relates to a device designed to adapt with the Capillary Breakup Extensional Rheometer (CaBER). The adapter (A) allows the CaBER to characterize the rheological properties of magnetic fluid samples, under a simultaneous extensional flow exerted by the CaBER, and an external tunable homogenous magnetic field generated using an external DC power source with tunable electric current.

The adapter (A) has two different configurations, a parallel configuration (A1) and a perpendicular configuration (A2), for imposing a homogeneous magnetic field in the parallel and/or in the perpendicular direction of the extensional flow.

The adapter (A) of the invention, either in the parallel (A1) or in the perpendicular (A2) configuration comprises solenoid coils (S) with a copper wire wound around the cylindrical solid core of iron, each solenoid (S) having the same winding number of turns and the same number of layers.

To create an effective magnetic field, the winding copper wire is wrapped around the iron core from left to right to complete the first layer, then from right to left to complete the second

layer, and so on until completing the required number of layers for each solenoid coil (S).

In a preferred embodiment, the adapter (A) of the invention, comprises four solenoid coils (S).

In another preferred embodiment, in the parallel configuration (A1) each solenoid coil (S) is wound with 140 turns and with 10 layers, while in the perpendicular configuration (A2) each solenoid coil (S) is wound with 40 turns and 14 layers.

Typically, in each solenoid coil (S) the copper wire wound around the cylindrical solid core of iron is of 0.6 mm diameter.

The terminals of the solenoid coils (S) are connected in series to an external source of tunable DC current (1). The origin of the Cartesian coordinate axis (x, y, z) of the device is designed to be at the center of the volume sample (4, 6 and 8 mm), with the solenoid coils (S) arranged to be in equal spacing from the origin.

The magnetic field can be generated by an external DC power source (1) with tunable electric current, thus providing an external tunable homogenous magnetic field.

Therefore, in another preferred embodiment, the adapter (A) is provided with an external electrical power source capable of generate a magnetic field.

The dependency of the magnetic field with the intensity of the current is different when applied to the adapter (A) in

parallel configuration (A1) or in perpendicular configuration (A2) as represented in Fig.5.

It is observed that the filament does not break when the magnetic field is imposed in parallel to the deformation axis, while if a perpendicular a magnetic field is imposed the filament break faster than the case of MRF with no magnetic field.

This external power source is able to provide an imposed current of 0.0A (when disconnected) to 1.5A, preferably it provides a current of 0.2A to 0.5A and more preferably of 0.25A to 0.4A, corresponding to the magnetic field intensities shown in Fig.5a.

Any CaBER-device commercially available is suitable to be connected to the adapter (A) of the invention, thereby providing the application of an external magnetic field parallel or perpendicular to the flow kinematics undergone by the fluid sample, while the extensional characterization is taking place.

The magnetic field intensity was measured by means of a Hall probe at the center of the configuration, where the fluid sample is located. The results are shown in Fig.5.

Examples

Example 1. Set-up of an adapter in parallel configuration (A1)

The scaffold material (Fig.1a-2) has been printed in a conventional 3D printer. The coils consist of a core bar made out of a soft iron and the winding made out of copper, precisely a 0.6 mm diameter copper wire was used, and 140 turns and 10 layers were used to form the coils (Fig.1a-3).

The coils are distributed in a quadrangular disposition, so that the total magnetic field is maximal at the center of prism, and homogeneous (Fig.5b).

The distance between the coils is that that allow the fitting the scaffold material inside the commercial CaBER device, without blocking the laser path nor the normal functioning of the rheometer.

The coils are connected in series so that for a given power source, the intensity current is fully used in generating the magnetic field. Additionally, the inlet and outlet of the four coils are wrapped in a single cable (Fig.1a-1) to be connected to the power source.

Example 2. Set-up of an adapter in perpendicular configuration (A2)

The scaffold material (Fig.1b-2) has been printed in a conventional 3D printer. The coils consist of a core bar made out of a soft iron and the winding made out of copper, precisely a 0.6 mm diameter copper wire was used, and 40 turns and 14

layers were used to form the coils (Fig.1b-3). The coils are distributed in a quadrangular disposition, so that the total magnetic field is maximal at the center of prism, and homogeneous (Fig.5c).

The distance between the coils is that that allow the fitting the scaffold material inside the commercial CaBER device, without blocking the laser path nor the normal functioning of the rheometer.

The coils are connected in series so that for a given power source, the intensity current is fully used in generating the magnetic field. Additionally, the inlet and outlet of the four coils are wrapped in a single cable (Fig.1b-1) to be connected to the power source.

Example 3. Rheological characterization of a MRF

The rheological behavior of two fluid-samples was investigated, being the first a Newtonian fluid (glycerin) and the second an MRF.

Experiments were performed both with the parallel and the perpendicular configurations of the adapter.

MRF sample was tested under an extensional flow with and without the application of the magnetic field, while glycerin was used as a reference fluid.

MRF sample was prepared at a concentration of 18 %wt, prepared from micron-sized quasispherical carbonyl iron solid particles

suspended in glycerin (i.e. a Newtonian viscous fluid that can slow down particles sedimentation).

Prior to each experiment, a fresh sample of MRF was prepared and redispersed in an ultrasound bath (Velleman VTUSC3) for 8 min in order to improve the rheological properties of the sample.

Time evolution of the filament thinning process was accessed for the two mentioned samples using a parallel and perpendicular configuration under different applied current.

In Fig. 6, each plotted profile represents a recorded time evolution of a single filament thinning process undergoing deformation, which is post-processed using an in-house Matlab code.

Accordingly, Fig.6a and Fig.6b show the filament thinning process using the parallel and perpendicular configuration, respectively. As a reference fluid, a sample of glycerin is used at $H = 0.0$ kA/m. The 4 mm diameter measuring plates was used, with an initial gap between plates of 2 mm. The final axial gap between plates is fixed and set to be 6 mm. The filament stretch profile is set to be linear with a "strike time" of 20 ms.

From Fig. 6, it is possible to observe that under extensional flow and no magnetic field ($I = 0.0$ A) both the reference fluid and the MRF samples behave as Newtonian fluids, showing a linear relationship between time and minimum filament diameter ($D_{\min}$).

However, when an electric current of 0.2 A is imposed in each configuration, magnetic fields equivalent to 1.5 kA/m and 0.6

kA/m are imposed by the parallel and perpendicular configuration, respectively, as shown in Fig.6a and Fig.6b, the filament behavior delays in comparison to the cases of no magnetic field.

Nevertheless, if the imposed electric current increased to 0.4 A, the magnetic field increased further and up to 2.9 kA/m for parallel configuration and 1.2 kA/m for perpendicular configuration, then it is observed that the filament does not break when the magnetic field is imposed in parallel to the deformation axis, as shown in Fig.6a, while if a perpendicular a magnetic field is imposed the filament break faster than the case of MRF with none magnetic field, as shown in Fig.6b.

The filament thinning behavior for MRF 18 %wt, using the assembly in the parallel and perpendicular configuration, at different magnetic field intensities was also measured.

Fig.7 represents records made immediately before the instance of filament breakup, except in the cases where the filament never breaks, such as when using the parallel configuration at a magnetic field of 2.9 and 3.7 kA/m.

This observation confirms that the fixture parallel and perpendicular configurations apply the magnetic field properly to the sample, which clearly affects the rheological response of the MRF.

CLAIMS

1. An adapter device (A) for Capillary Breakup Extensional Rheometer (CaBER) **characterized for** comprising:
 - solenoid coils (S) with a copper wire winded around the cylindrical solid core of iron, each solenoid (S) having the same winding number of turns and the same number of layers, being the winding copper wire wrapped around the iron core from left to right to complete the first layer, then from right to left to complete the second layer, and so on until completing the required number of layers for each solenoid coil (S),
 - a plastic scaffolds structure for holding the solenoid coils (S),
 - the terminals of the solenoid coils (S) with means to be connected in series to an external source of tunable DC current (1), wherein
 - the adapter (A) is provided in 2 configurations, in a parallel configuration (A1) and/or in a perpendicular configuration (A2), wherein:
 - in the parallel configuration (A1) the solenoid coils (S) are arranged in a squared configuration and parallel to the shaft of the CaBER,
 - in the perpendicular configuration the solenoid coils (S) are arranged in a squared configuration and perpendicular to the shaft of the CaBER, and
2. An adapter device (A) according to claim 1 **characterized for** comprising four solenoid coils (S) in both configurations A1 and A2.

3. An adapter device (A) according to any of the claims 1 or 2 **characterized for** comprising:
 - in the parallel configuration (A1) each solenoid coil (S) is winded with 140 turns and with 10 layers, and
 - in the perpendicular configuration (A2) each solenoid coil (S) is winded with 40 turns and 14 layers.
4. An adapter device (A) according to claim 1 **characterized for** further comprising an external DC power source (1) able to provide an imposed controlled and tunable electric current of at least 0.0A to 1.5A, preferably of 0.1A to 0.5A.

FIGURE 1

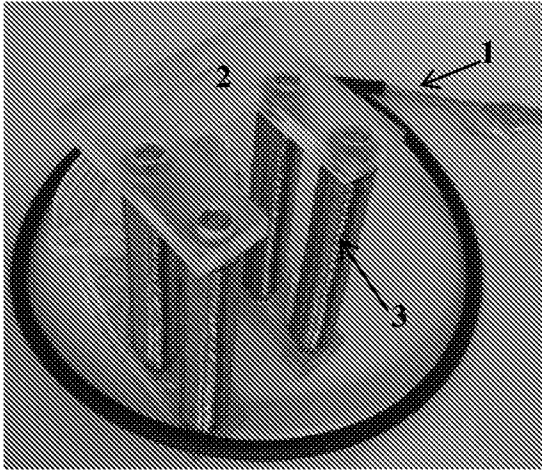


Fig.1a

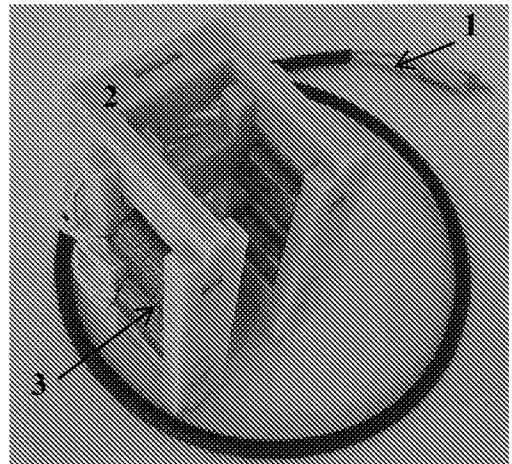


Fig.1b

FIGURE 2

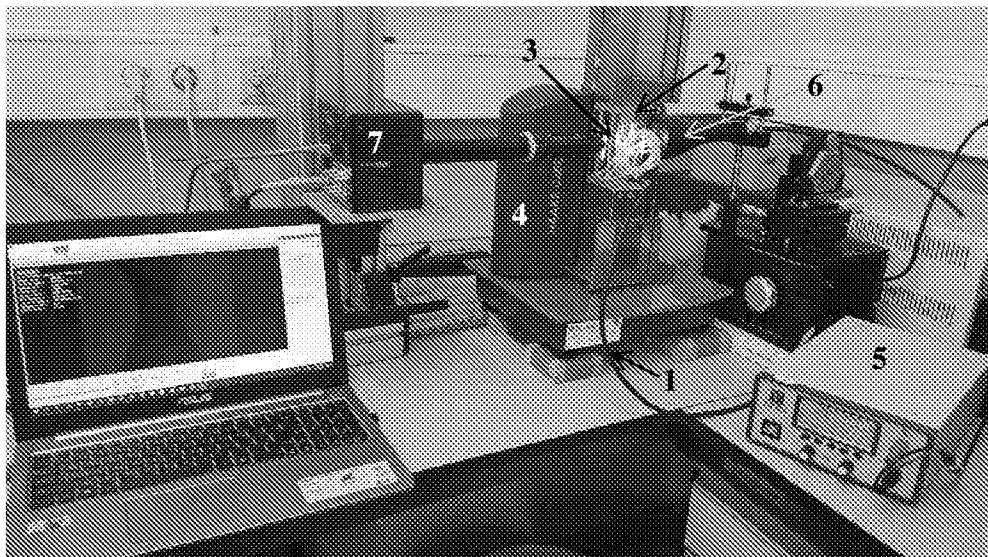


FIGURE 3

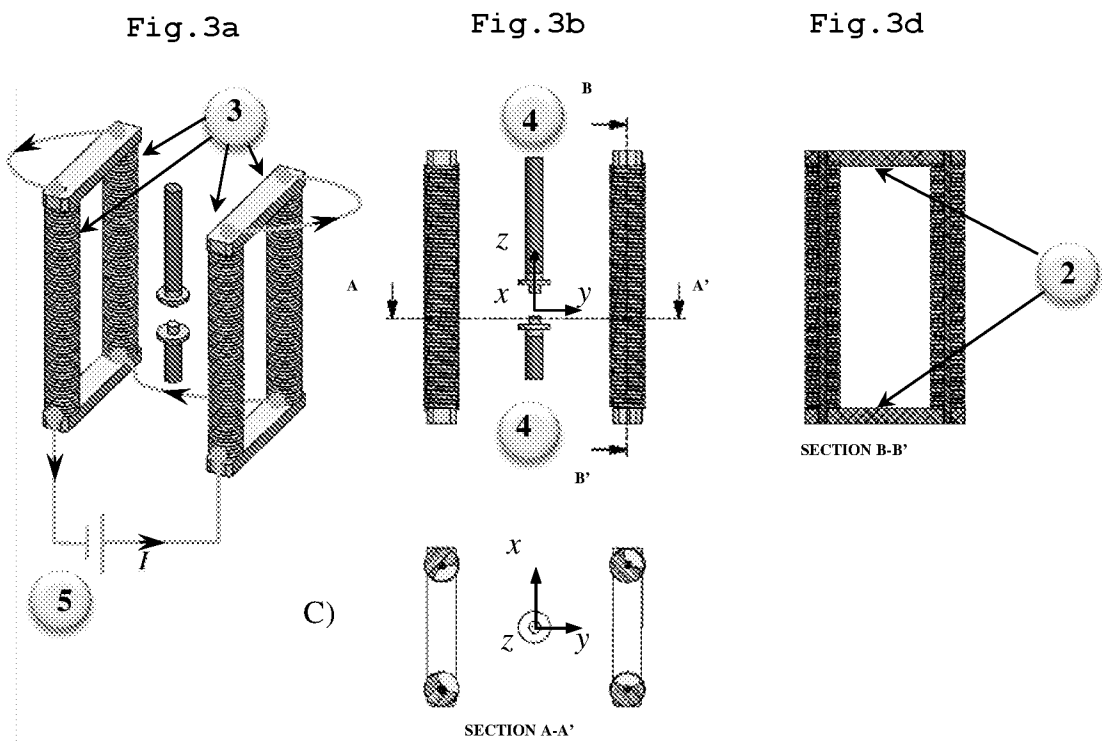


Fig.3c

FIGURE 4

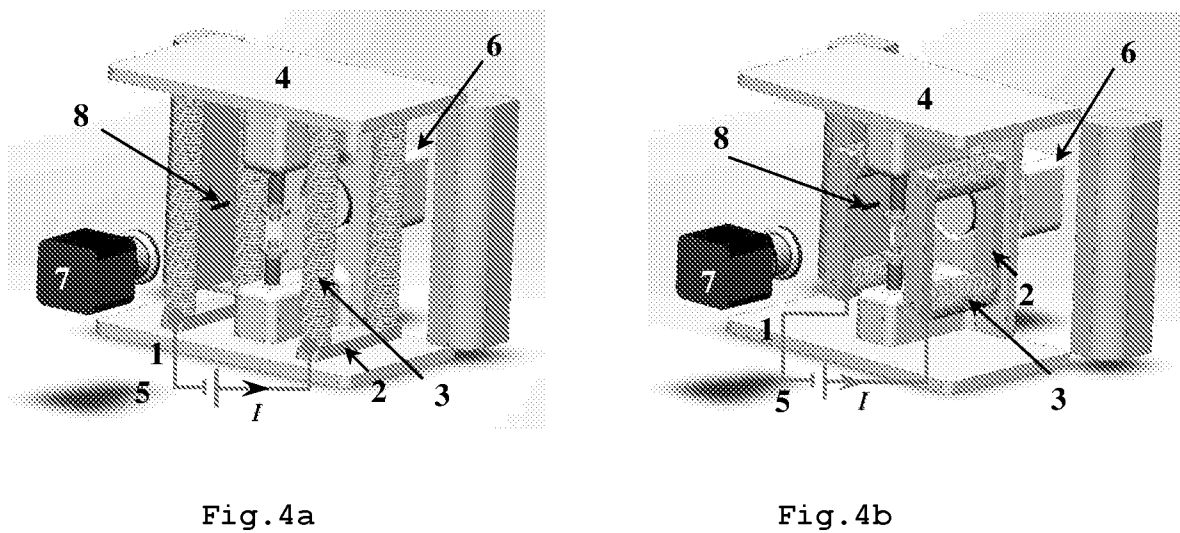


FIGURE 5

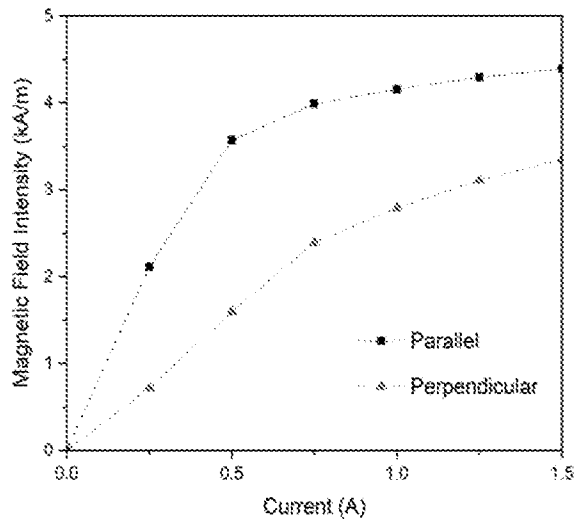


Fig.5a

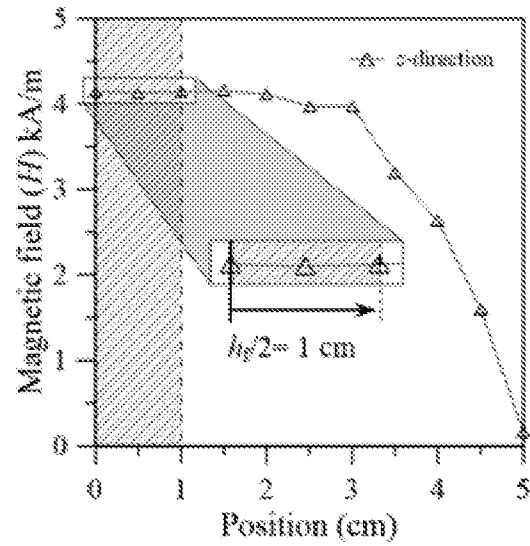


Fig.5b

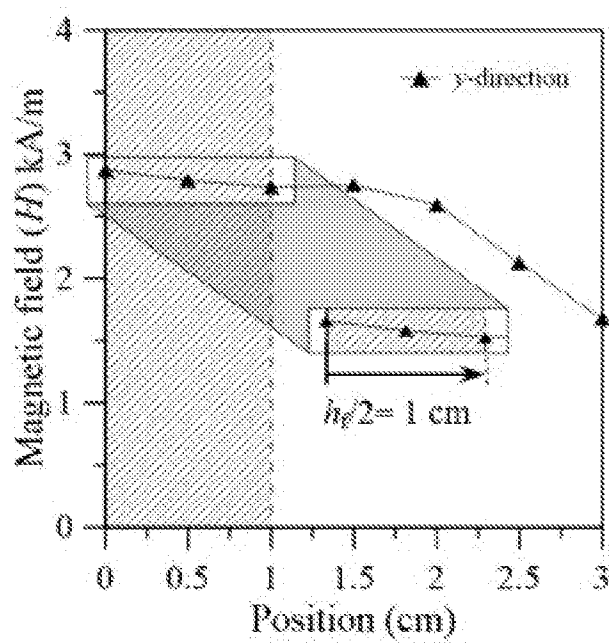


Fig.5c

FIGURE 6

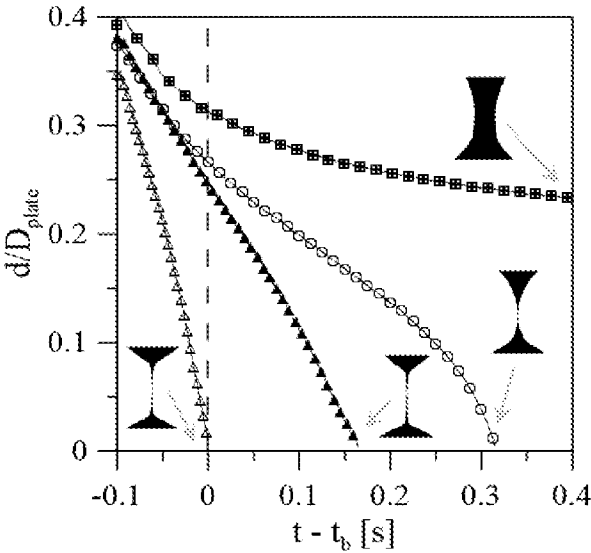


Fig.6a

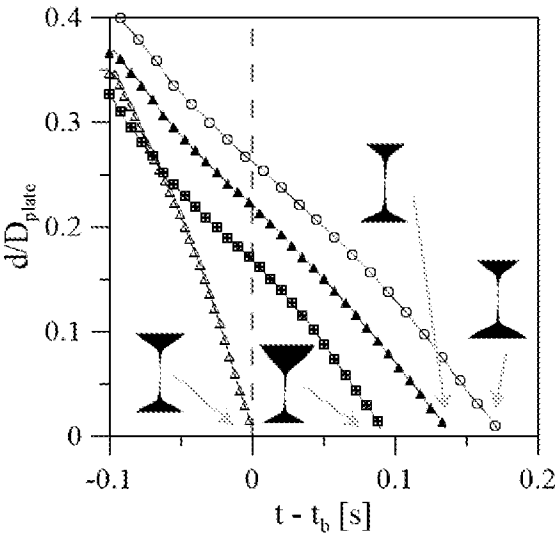


Fig.6b

FIGURE 7

Parallel Configuration		Perpendicular Configuration	
a 0.0 kA/m	b 0.8 kA/m	g 0.0 kA/m	h 0.3 kA/m
c 1.5 kA/m	d 2.3 kA/m	i 0.6 kA/m	j 0.9 kA/m
e 2.9 kA/m	f 3.7 kA/m	k 1.2 kA/m	l 1.6 kA/m

INTERNATIONAL SEARCH REPORT

International application No
PCT/IB2020/053357A. CLASSIFICATION OF SUBJECT MATTER
INV. G01N11/00 G01N11/02
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
G01N

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

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C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	GALINDO-ROSALES ET AL: "Extensional rheometry of magnetic dispersions", JOURNAL OF RHEOLOGY ACTA, SOCIETY OF RHEOLOGY, US , vol. 59, no. 1 12 December 2014 (2014-12-12), pages 193-209, XP009521641, ISSN: 0148-6055, DOI: 10.1122/1.4902356 Retrieved from the Internet: URL:https://sor.scitation.org/doi/pdf/10.1122/1.4902356 [retrieved on 2020-07-16] page 199 ----- -/--	1-4



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INTERNATIONAL SEARCH REPORT

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PCT/IB2020/053357

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	F J Galindo-Rosales ET AL: "Supplementary Information For: Extensional rheometry of magnetic dispersions", 12 December 2014 (2014-12-12), XP055715538, Retrieved from the Internet: URL:https://sor.scitation.org/doi/suppl/10.1122/1.4902356/suppl_file/magneticfixture.sjor2014_supplementaryinformation%5B1%5D.pdf [retrieved on 2020-07-16] page 1 - page 2 page 3; figure S.1 page 2 page 4 page 5; figure S.4 figure S.2	1-4
X,P	J. Hermenegildo García-Ortiz: "Influence of the Polarity of the Electric Field on Electrorheometry", 4 December 2019 (2019-12-04), pages 55-65, XP055714297, Retrieved from the Internet: URL:https://www.mdpi.com/2076-3417/9/24/5273/htm [retrieved on 2020-07-13] page 56; figure 1 figure 3 page 56, column 2	1-4