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Dynamical pattern formation in a low-concentration magnetorheological fluid under two orthogonal sinusoidal fields

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ABSTRACT

The dynamical pattern formation of clusters of magnetic particles in a low-concentration magnetorheological fluid, under the influence of a superposition of two perpendicular sinusoidal fields, is studied experimentally. By varying the frequency and phase shift of the perpendicular fields, this configuration enables us to experimentally analyze a wide range of field configurations, including the case of a pure rotating field and the case of an oscillating unidirectional field. The fields are applied parallel to the horizontal plane where the fluid lies or in the vertical plane. For fields applied in the horizontal plane, we observed that, when the ratio of the frequencies increases, the average cluster size exhibits a kind of periodic resonances. When the phase shift between the fields is varied, the average chain length reaches maximal values for the cases of the rotating field and the unidirectional case. We analyze and discuss these results in terms of a weighted average of the time-dependent Mason number. In the case of a rotating field on the vertical plane, we also observe that the competition between the magnetic and the viscous forces determines the average cluster size. We show that this configuration generates a series of physically meaningful self-organization of clusters and transport phenomena.

1. Introduction

A magnetorheological fluid (MR fluid) consists of a large number of micron-sized magnetic particles dispersed in an inert liquid, usually a mineral oil. When a magnetic field is applied on it, the particles acquire a dipolar magnetic moment, consequently they interact and aggregate forming complex elongated structures oriented in the magnetic field direction [1]. The formation of these complex structures causes strong changes in the physical properties of the dispersion, mainly in its rheological properties. The effective viscosity and yield stress of the MR fluid are some of the properties that have been more extensively studied [2–8], although other studies about the optical properties and sound propagation have been done [9–11]. By changing the particle concentration and the characteristics of the applied field, it is possible, up to a certain extent, to control the physical properties of these dispersions, going from those that closely correspond to a Newtonian fluid to those of a viscoelastic material. With respect to this widely diverse behavior, there are many important unanswered questions concerning basic science and, obviously, plenty of potential applications.

Most of the studies about the aggregation processes and the structural characteristics of aggregates in MR fluids have been conducted by applying steady magnetic fields. In Brownian particle-based MR fluids and in the low-particle-concentration regime, the application of a static magnetic field generates chain-shaped clusters. In that condition, mechanical fluctuations induce motion causing these chains to aggregate laterally in a slow process, resulting in the formation of columns. This happens by means of a zippering mechanism which has been studied in the literature. This mechanism is driven by inhomogeneities in the magnetic field caused by thermal fluctuations and particle polydispersity. Lateral aggregation contributes to the system reaching its lower energy configurations [12–18].

There has been some reported studies on systems under time-dependent fields, including sequential stages of a static magnetic field being turned on and off [19,20], constant ramping of a uniform magnetic field [12], rotating fields in the horizontal configuration [11,24–29], and oscillating fields [3,21–23]. Sequential stages of a static magnetic field being turned on and off provoke structural rearrangements that lead the system to configurations with lower energy [19,20]. In that case, it is observed that when the magnetic field is turned on and off alternately more compact structures are obtained, with Brownian motion playing a key role during the lateral aggregation process [20]. In Ref. [12] it is shown that using a constant ramping of uniform magnetic fields modifies the lateral aggregation producing multiple steps in the process. The horizontal configuration of the applied rotating field allows

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one to investigate the detailed competition between the magnetic bond among the particles and the viscous force acting on the rotating clusters. These forces determine the general shape and average size of the clusters. In the case of a low particle concentration MR fluid, the shape and average size of the clusters strongly depend on the ratio between the magnetic and the viscous forces acting on the clusters, this defines the Mason number [24]. The dominance of one of the forces can be controlled by the frequency and intensity of the rotating field. For low frequencies and low particle concentration, the clusters are elongated chain-shaped structures whose length decreases as the frequency increases. In this case, a constant Mason number describes the dynamics of the structures formed in the MR dispersion. It has also been observed that at high frequencies disk-like aggregates are produced.

When an oscillating field, produced by the superposition of a static field and a weak transversal sinusoidal field, is applied on a MR fluid sample it is observed that the average length of the generated chains and the effective viscosity reaches higher values in comparison to the case when only a steady field, of the same amplitude, is applied [3,22]. We have observed that oscillating fields enhance and hasten the lateral aggregation. In Ref. [22] we reported a comprehensive study of the effect of the oscillating field on the average chain length. We observed that the average chain length values are up to 300% higher than the corresponding values when a steady field is applied. In Ref. [3] we have reported effective viscosity changes that range up to 200%. In this case, a time dependent Mason number describes well the general behavior of the average chain length as a function of the oscillation frequency.

The general conclusion of these investigations is that the aggregation process, which controls the shape of the generated structures, and the changes in the physical properties of a MR fluid are strongly dependent on the characteristics of the time-dependent applied fields. By using two perpendicular-to-each-other sinusoidal fields, one can produce several time dependent field configurations, from which the rotating and the oscillating fields are two particular cases. The study of MR fluids under these more complex magnetic fields enable us to deal with a system characterized by a complex time dependent Mason number. It could as well allow us to study the lateral aggregation under unsteady magnetic fields. The idea behind the usage of time dependent fields is to produce lateral motion in the aggregates to enhance the aggregation of chains. Some of these time-dependent field configurations could produce major changes in structural and rheological properties.

In the sections below we discuss the structural characteristics of the aggregates formed in MR fluids based on non-Brownian particles generated by two perpendicular sinusoidal fields varying the amplitude, frequencies and phase shift between them. In Section 2 we briefly describe our experimental setup. In Section 3 we discuss the general trend of the structural characteristics of the clusters that are obtained by the application of this superposition of fields applied in the horizontal plane. In Section 4 we discuss the experimental results in terms of a theoretical model based on a weighted average Mason number. In Section 5 we discuss the results of numerical simulations. In Section 6 we discuss the dynamical self-organization and transport phenomena generated by a rotating field applied in the vertical plane perpendicular to the plane where the MR fluid lies. Finally, we make some comments and remarks.

2. Experimental

Our MR fluid is prepared by dispersing magnetite particles, with an average size of 65 μm and a mean square dispersion of 15 μm, in 76 cP Dexron-type mineral oil. The magnetite powder has a measured density of 5.1 g/cm^3 [22]. Fig. 1 shows the magnetite particles used in our experiments. The fields were produced by two pairs of Helmholtz coils that were fed by a power amplifier and controlled by a computer (see Fig. 2).

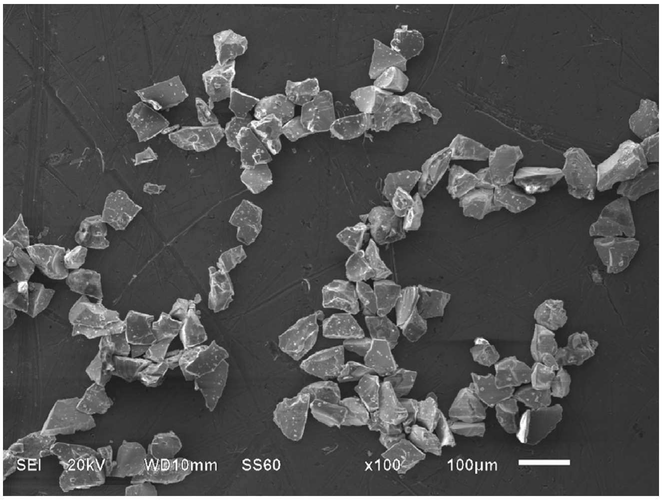

Fig. 1. SEM micrograph of the mineral magnetite particles. It observed the irregular shape of the particles.

The stages of the aggregation process under different physical conditions were observed using a Meiji EMZ-TR microscope. The processes were recorded with a video-camera coupled to the microscope. The samples were prepared by pouring the dilute MR dispersion into a rectangular cell made out of glass, with dimensions of 4 mm in width, 6 mm in length and 2 mm in height. The poured amount of the liquid dispersion was sufficient to form a wet layer. The whole cell area is spanned by the microscope.

When a horizontal static magnetic field is applied the particles aggregate forming elongated chain-shaped structures aligned in the field direction. When two alternating magnetic fields are applied horizontally and transverse to each other the chain-shaped clusters grow and deform as they try to align in the direction of the resulting magnetic field.

The average length of the clusters were determined from photographs taken 60 s after turning on the fields. Before taking another photograph the particles were stirred mechanically by using a tiny paintbrush, monitoring the process by the use of the microscope. At the very first preparation of the sample, the particles are easily dispersed in the liquid, however, the subsequent dispersions of the particles, when they have already acquired a remnant magnetization, are difficult and the particles tend to aggregate forming small aggregates at the initial stage. However, this remnant magnetization remains approximately constant after a few experiments; under these conditions we carried out the experiments. This procedure was repeated for different physical conditions. The photographs were digitally treated to enhance their contrast. The chain length of the clusters were determined by using the software package Sigma Scan Pro 5.0. Aside from the measurement itself, that yields a relatively small error, there is an error coming from the variations in the local concentration of particles. This is the largest contributor to the reported error in our graphs. The effect of the small clusters due to the remnant magnetization on the final average length of the aggregates is negligible, because the trace of small clusters disappears after a few seconds after the field is turned on.