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BEHAVIOR OF MAGNETOFLUIDIZED BEDS AS AFFECTED BY PARTICLE SIZE AND FIELD ORIENTATION

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ABSTRACT
Fluidized beds of magnetized particles may experience a transition from bubbling to a solidlike stable state determined by the formation of particle chains due to induced interparticle attractive forces, which become arrested at the transition to stability and confer the stabilized bed a yield stress. Our setup allows us for taking measurements of the transition velocity as well as the yield stress of the bed stabilized by a magnetic field oriented either in the vertical or horizontal direction (co-flow and cross-flow field configurations, respectively). The effect of field strength on the yield stress is a function of the field orientation. In the cross-flow field configuration, the magnetic yield stress is increased with particle size, whereas it is decreased as particle size is increased in the co-flow field configuration. This is interpreted as due to the dependence of the interparticle magnetostatic force on the angle between the normal contact and the field, which is on average affected by particle size in the slightly consolidated stabilized bed. The results indicate therefore a close link between the yield stress, particle structuring and magnetostabilization. A main conclusion is that short ranged interparticle attractive forces induced by the magnetic field determine magnetic stabilization. These forces are relevantly affected by particle size, field orientation and operation mode as shown in our work.

INTRODUCTION

Bubbling beds can be stabilized by sufficiently strong attractive forces between the particles, which can be induced by externally applied fields, as seen when a magnetic field is imposed on bubbling beds of magnetizable particles (Rosensweig (1), Espin et al. (2)). Generally, it is observed that application of the magnetic field results in the formation of chainlike particle aggregates that eventually become arrested when the magnetic field strength is strong enough and the gas velocity is decreased below a critical value larger than the minimum fluidization velocity. At the jamming transition the bed acquires a solidlike stable structure characterized by a non-negligible yield stress (Espin et al. (2)). This is an analogous situation to stabilization of bubbling beds of dielectric particles when they are subjected to a strong enough electric field (van Willigen et al. (3)). In this case, and due to the induced electrostatic forces between the polarized particles, chainlike aggregated structures are developed in the so-called electrofluidized bed (EFB) that eventually lead to a transition from bubbling to a solidlike stable behavior. Magnetic stabilization of fluidized beds has been proposed for aerosol filtration because of its potential for continuous particulate removal at high temperatures and pressures (Rosensweig (1)). While fixed-bed filters provide in general high collection efficiency, the progressive increase of the pressure drop across the bed due to clogging with the collected aerosol particles eventually drives to an inevitable downtime for regeneration or replacement. In order to better understand the role of interparticle contact forces on magnetic stabilization, measurements on the yield stress of MFBs as a function of the intervening physical parameters and conditions would provide useful information to be incorporated on stability models. We show in the present paper experimental results on the yield stress of magnetically stabilized beds as affected by field orientation.

EXPERIMENTAL SETUP AND PROCEDURE

Figure 1 is a sketch of the setup used in our experimental work. The magnetic powder sample is held in a vertically oriented cylindrical vessel (2.54 cm internal diameter) and rests on a non-magnetizable porous plate that acts as gas distributor (5 μm pore size). By means of a series of computer controlled valves and a mass flow controller, a controlled flow of filtered and dried air is pumped through the powder bed while the gas pressure drop across it is read from a differential pressure transducer. The height of the bed, which gives an average value of the particle volume fraction ϕ, is measured by means of an ultrasonic sensor placed on top of the vessel. A uniform magnetic field is externally imposed by means of a pair of square Helmholtz coils (50 x 50 cm) with each coil consisting of 500 turns of 2 mm diameter copper wire. The coils can be rotated in order to change the orientation of the field relative to the gas flow. In the present study the field has been applied both in the vertical and horizontal directions (co-flow and cross-flow field configurations, respectively). The strength of the field has been fixed to B=2.6 mT.

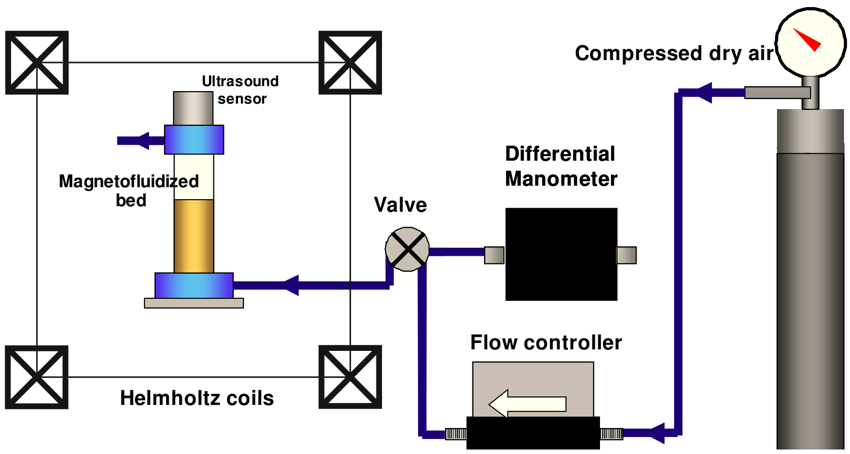

Figure 1. Sketch of the experimental setup used in the magnetofluidization experiments reported in this work. The powder bed is subjected to a controlled gas flow in the vertical direction in the presence of a uniform magnetic field that can be applied either in the vertical or horizontal direction.

The powders tested consisted of spherical magnetite particles of nominal particle size: d_p = 65 μm, 50 μm, and 35 μm with small particle size dispersion (Geldart A) and particle density ρ_p=5060 kg/m^3. Magnetic characterization of the powders used in our experiments was made by means of a SQUID magnetometer and also using the L-method (Espin et al. (2)). The initially demagnetized samples behaved linearly in the range of field strengths applied in our MFB experiments with similar bulk magnetic susceptibilities (χ between 3 and 4). Using the coherent potential approximation and the measured bulk susceptibilities, the particles' magnetic susceptibility was obtained as $\chi_p \approx 11.5$. Since magnetite is a conductive material possible efects due to accumulation of electrostatic charge are avoided.

In the experimental procedure generally followed in our experiments the bed is first driven to the bubbling regime by imposing a large gas velocity v_b at which the gas pressure drop Δp is around the powder weight per unit area W. Once the bubbling bed has reached a stationary state in which it has lost memory of its previous history, the gas velocity is slowly decreased. As the gas velocity is decreased Δp falls below W at a critical gas velocity v_c indicating that part of the powder becomes then sustained by permanent interparticle contacts in a solidlike stable state. This is the jamming transition, delimiting the unstable bubbling regime and the solidlike stable regime, in which the bed is stabilized by interparticle attractive forces. As the gas velocity is further decreased below the jamming transition, Δp decreases below W. At a gas velocity $v_0<v_c$, there is a consolidation stress on the bed at its bottom σ_c, which is given by $\sigma_c = W - \Delta p(v_0)$ if wall effects are neglected. Wall effects can be neglected if bed height is similar or smaller than bed diameter. Once the bed is stabilized at a given gas velocity $v_0<v_c$, and in order to put the bed under tension, it is now subjected to a slowly increasing gas velocity. For small increments of the gas velocity, the solidlike structure remains stable and Δp, which is just due to frictional resistance, increases linearly as v_g is increased. Δp balances W at the point of minimum fluidization velocity v_{mf}. Further increment of the gas velocity subjects the bed to a tensile stress $\sigma = \Delta p - W$, which is maximum at the bottom of the bed. As the tension builds up there comes a point at which the bed breaks, which is detected by an abrupt drop of Δp due to fracture of the bed. The tensile yield stress σ_t needed to break the powder is thus obtained as the maximum value of σ, which is located just before the breaking point. The procedure described above can be used to measure the tensile yield stress of stabilized beds of the magnetizable powders used in our study as affected by an externally applied magnetic field of fixed strength, which was oriented either in the horizontal or vertical direction (cross-flow and co-flow field configurations, respectively). All the experimental runs were started by subjecting the bed to a large gas flow in order to drive it into a bubbling state in the absence of the magnetic field. Then the field was applied and was kept fixed, being the initial gas flow large enough to maintain a bubbling state even after the magnetic field was applied.

EXPERIMENTAL RESULTS AND DISCUSSION

Examples of pressure drop curves obtained to measure the tensile yield stress are shown in Fig. 2. Figures 2a and 2b illustrate the effect of the magnetic field on the slope of the linear regime and on the yield stress. The slope of the linear regime, which is inversely proportional to the bed permeability to the gas flow, is decreased when the field is present since magnetic stabilization gives rise to beds with smaller particle volume fraction. Note however in Figs. 2a and 2b that this effect is not marked in the case of the cross-flow field configuration. Yet it is quite important in the case of the co-flow field configuration, indicating that expansion of the stabilized bed is significantly enhanced in the co-flow field configuration as compared to the cross-flow field configuration.

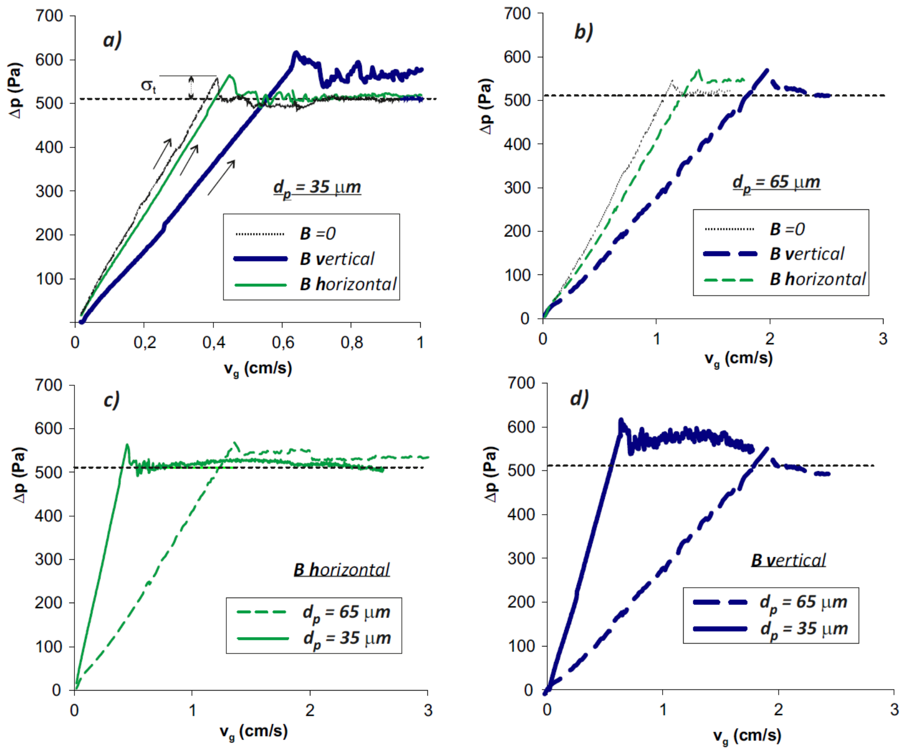

Figure 2. Gas pressure drop across the bed as the gas velocity is increased for beds stabilized in the absence of magnetic field and in the presence of magnetic fields applied either in the vertical or horizontal direction. In a) particle size is 35 μm and results are shown for a vertical field, horizontal field, and zero field. In b) particle size is 65 μm and results are shown for a vertical field, horizontal field, and zero field. In c) the field is horizontal and results are shown for 35 μm and 65 μm particle size. In d) the field is vertical and results are shown for 35 μm and 65 μm particle size. The horizontal dashed lines indicate the value of the powder weight per unit area W=510 Pa.

Figures 2a and 2b show that the yield stress is enhanced by the magnetic field. Yet the role of field orientation on yield stress enhancement depends on particle size. This is seen in Figs. 2c and 2d, where pressure drop curves for a given field configuration are plotted for different particle sizes. As can be observed, the yield stress is enhanced for the powder with smaller particle size when the field is applied in the co-flow field configuration. Contrarily, the yield stress is increased in the cross-flow field configuration for the powder with larger particle size.

In order to assess the yield stress just due to the induced magnetostatic forces between the particles σ_t^m, it must be taken into account that the overall yield stress measured σ_t contains also the contribution from the yield stress due to nonmagnetic attractive forces between the particles σ_t^0. In the absence of humidity, nonmagnetic attractive forces arise mainly from the universal van der Waals interaction. In Fig. 3 we plot the yield stress measured for the beds stabilized in the presence of a magnetic field and in the absence of magnetic field as a function of the consolidation stress σ_c. As it is well reported in the literature, we see that σ_t^0 increases with σ_c , which is generally due to the increase of the average number of contacts per particle as the structure is consolidated and also to plastic deformation of asperities at interparticle contacts.

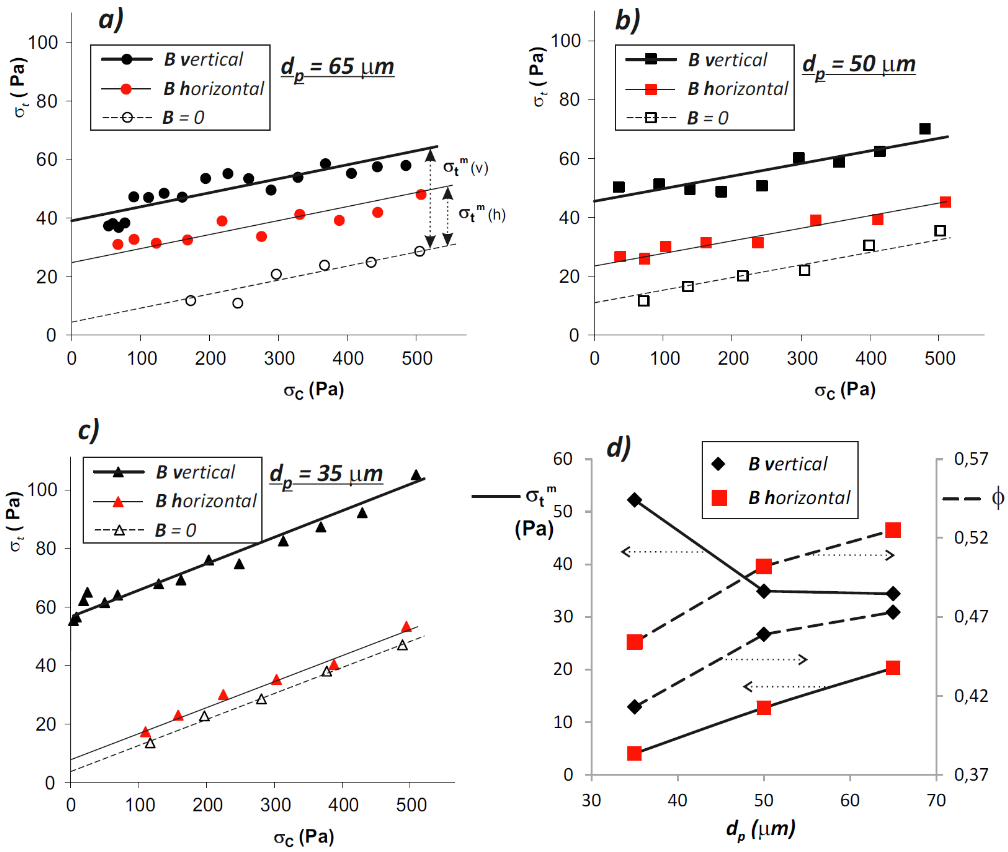

Figure 3. Yield stress measured as a function of the consolidation stress for beds stabilized in the absence of magnetic field and in the presence of a magnetic field applied either in the vertical or horizontal direction (B=2.6 mT) for different particle sizes (a,b, and c). Figure 3d shows the magnetic yield stress (obtained as illustrated in Fig. 3a) for beds stabilized by vertical and horizontal magnetic fields (left axis) as well as the particle volume fraction for σ_c=W as a function of particle size (right axis).

The compressibility of fine powders increases as the granular Bond number (defined as the ratio of interparticle attractive force to particle weight) is increased, which implies that the rate of increase of the average number of contacts per particle with σ_c is increased as particle size is decreased. Accordingly, we see in Figs. 3a, 3b, and 3c that $\partial\sigma_t/\partial\sigma_c$ is increased as particle size is decreased. Furthermore, it can be noticed that $\partial\sigma_t/\partial\sigma_c$ remains unchanged in the presence of the magnetic field, which indicates that the magnetic yield stress ($\sigma_t^m = \sigma_t - \sigma_t^0$) is approximately independent of σ_c in the range of consolidation stresses tested. Using the data plotted in Figs. 3a, 3b, and 3c, a magnetic yield stress σ_t^m can be thus calculated independently of the consolidation stress of the stabilized bed. The calculated values of σ_t^m are plotted in Fig. 3d as a function of particle size, showing that σ_t^m increases with particle size for the cross-flow field configuration whereas it decreases with particle size if the field is applied in the co-flow field configuration. Data on the particle volume fraction ϕ of the beds in the presence of the magnetic field are plotted also in Fig. 3d. As previously indicated, ϕ is decreased as particle size is decreased. Moreover, the co-flow field configuration yields relatively smaller values of ϕ since the bed is stabilized in states of higher expansion.

A typical value of the universal van der Waals force of attraction between uncompressed fine particles ($\sigma_c = 0$) is f_{vdW} =10 nN (Quintanilla et al. (5)). The yield stress σ_t^0 arising from the existence of an interparticle attractive force f can be estimated by means of Rumpf's averaging equation as $\sigma_t^0 \sim f \zeta \phi / \pi d_p^2$, where ζ is the average number of contacts per particle that can be related to the particle volume fraction ϕ by the equation (Quintanilla et al. (5)) $\zeta = (\pi/2)(1-\phi)^{-3/2}$. Using the data measured for the naturally stabilized beds at the transition to stability ($\sigma_c \cong 0$), it is σ_t^0=3 Pa for d_p=35 μm (ϕ=0.38 and v_0=0.5 cm/s at the transition to stability), which is in agreement with our experimental results. When the field is applied, the attractive force between the particles is increased by the addition of the anisotropic magnetic force f_m:

$$f_m = f_m^0 \left(\frac{d_p}{r} \right)^4 \left[\left(2 f_{\parallel} \cos^2 \theta - f_{\perp} \sin^2 \theta \right) \hat{u}_r + f_{\Gamma} \sin 2\theta \hat{u}_\theta \right] \tag{1}$$

Here r is the distance between the centers of the two spheres, $f_m^0 = (3/16\mu_f)\pi d_p^2 \beta^2 B^2$, where $\beta = (\mu_p - \mu_f)/(\mu_p + 2\mu_f)$, μ_p is the particle's magnetic permeability, μ_f is the fluid permeability ($\mu_f \approx \mu_0 = 4x\pi x10^{-7}$ H/m in our case), θ is the angle that forms the line between the centers of the two spheres and the field direction, and the terms f_i are the so-called force coefficients. These coefficients can be obtained in terms of the multipole moments and depend on the magnetic permeabilities and the distance between the particles. The main effect of increasing the magnetic permeability of the particles is a significant increase of $f_{\parallel}$, which greatly enhances the attractive component of the force (Espin et al. (2). Due to the significant increase of $f_{\parallel}$ with the magnetic susceptibility, it is explainable that a MFB can be stabilized even by a horizontal field because of the induced attractive forces between chained particles forming a large angle with the field, which gives rise to a finite tensile yield stress in the horizontal plane as measured in our experiments. Using Eq. 1 and the calculated force coefficients, it can be estimated that two chained particles in contact ($r=d_p$) typically forming an angle θ_c =60 deg (Espin et al. (4)) with a horizontal field of strength B =2.6 mT are attracted by a force $f_m \approx 10$ nN for d_p = 35 μm, which is similar to the van der Waals force. Accordingly, the increment of the yield stress measured for d_p=35 μm is small when the bed is stabilized in the presence of a horizontal field (Figs. 3c and 3d). On the other hand, if the field is applied in the vertical direction, f_m is increased up to 50 nN (for two particles in contact co-aligned with the field). As seen in Figs. 3c and 3d the magnetic yield stress is appreciably increased for d_p = 35 μm, in agreement with the increase of the interparticle magnetic force. However, since f_m scales proportionally to d_p^2 and $\sigma_t^m \sim f_m/d_p^2$, the magnetic yield stress should be independent of particle size, which is in contradiction with the experimental results obtained in our work.

As inferred from Eq. 1, the interparticle magnetostatic force is strongly dependent on the orientation of the normal to the contact between particles relative to the field direction, which gives rise to anisotropic chainlike aggregation. In the fluidized bed, chains become oriented on average at an angle θ_c in the cross-flow field configuration and they become preferentially aligned along the vertical field lines in the co-flow field configuration. Our measurements of the particle volume fraction ϕ (Fig. 3d) indicate that the bed structure is critically affected by particle size when the bed is consolidated. As particle size is increased, particles in the stabilized bed subjected to a small consolidation stress would pack more closely (ϕ is increased). This would affect the average angle between the field and the interparticle contact normal in the consolidated structure and therefore would have an influence on the average interparticle magnetostatic force.

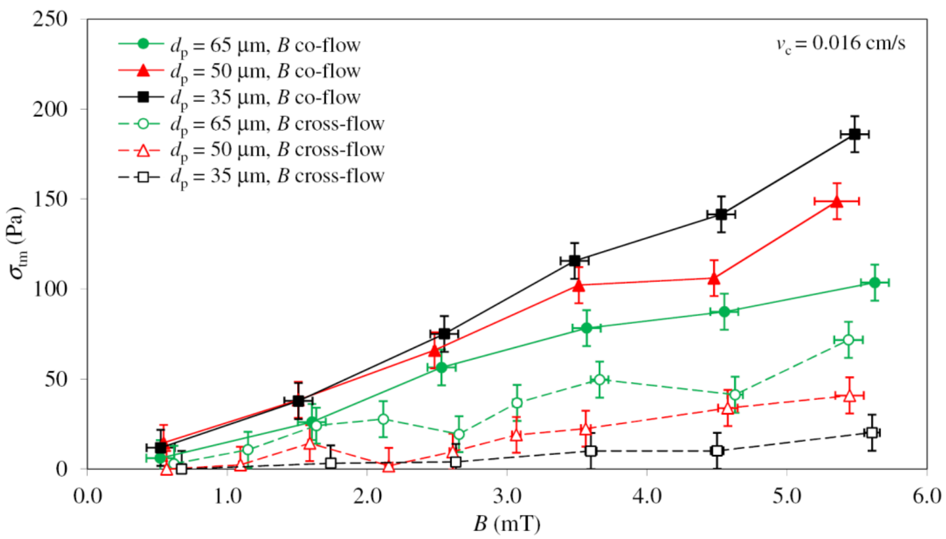

Figure 4. Magnetic yield stress as a function of field strengths for magnetite beads of different particle size in the co-flow and cross-flow field configurations.

The increase of ϕ with particle size (Fig. 3d) implies that interparticle contacts become on average more closely oriented to the horizontal direction as particle size is increased. As the angle with the horizontal decreases on average, higher magnetostatic forces of attraction between the particles would be expected in the case of a horizontal field and thus the magnetic yield stress should increase with particle size as seen experimentally. On the other hand, attractive forces would be on average smaller as particle size is increased in the case of a vertical field since the average angle of the contact normal with the field would increase in this case as particle size is increased. As a result, it would be expected that the magnetic yield stress decreases with particle size as observed in the experiments reported in the present paper on the co-flow field configuration. Further experimental results are shown in Fig. 4, where average values of the magnetic yield stress are plotted as a function of the field strength B. As expected from Eq. 1, σ_t^m increases with B. Moreover, the dependence of σ_t^m on particle size, as affected by field orientation, is seen to be confirmed in all the range of field strengths tested.

CONCLUSIONS

The magnetic yield stress of magnetically stabilized beds subjected to small consolidations is critically affected by particle size and field orientation. A co-flow field favors the formation of vertically oriented chains and stabilizes the bed in states of relatively higher expansion. On the other hand, chains in a cross-flow field are oriented along a preferential angle depending on the balance between the vertical gas flow drag and the attractive magnetostatic force, which is maximum in the horizontal direction. As a consequence the magnetic yield stress is relatively larger in beds stabilized by a co-flow field. As regards the influence of particle size, since stabilized beds subjected to a consolidation stress become more closely packed as particle size is increased, the contact angle between particles becomes on average closer to the horizontal direction. Thus, it is plausible that the yield stress is increased as particle size is increased in the cross-flow field configuration but it is decreased as particle size is increased in the co-flow field configuration as seen experimentally.

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