Jamming and Rheology of Fluidized Beds of Magnetized Particles

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Received: 13.12.2010, Final version: 7.4.2011

Abstract:
The interaction between magnetic particles in a bed fluidized by a gas is determined by the magnetizing action of an externally applied magnetic field. As the strength of the field is increased there comes a point at which the bed transits from a fluidlike to a solidlike stable state. Interparticle attractive forces induced by the applied field causes chainlike agglomeration of the particles, which confers the stabilized structure with a mechanical strength. In this paper we report experimental results on the yield stress of fluidized beds of fine magnetic particles stabilized by an externally applied magnetic field. Our results show that, in analogy with magnetorheological fluids (MRFs), particle structuring determines essentially the yield stress of magnetofluidized beds (MFBs). Moreover, our work shows that the dependence of the yield stress on particle size, which stands as a controversial issue in the study of MRFs, can be understood from the analysis of the jamming transition as affected by the size of the particles and the strength of the field.

Zusammenfassung:
Die Wechselwirkung zwischen magnetischen Partikeln in einem durch Gas fluidisiertem Bett wird von einem externen magnetischen Feld beeinflusst. Wird die magnetische Feldstärke erhöht, so findet ein Übergang von einem flüssigen zu einem festkörperähnlichen stabilen Zustand statt. Die attraktiven Wechselwirkungen zwischen den Teilchen, die durch das Magnetfeld induziert werden, verursachen eine kettenähnliche Agglomeration der Teilchen, die der Partikelstruktur eine gewisse mechanische Festigkeit verleiht. In diesem Artikel wird über die experimentellen Ergebnisse eines fluidisierten Betts aus feinen magnetischen Partikeln berichtet, das eine Fließspannung besitzt und von einem externen Magnetfeld stabilisiert wird. Unsere Resultate zeigen, dass, in Analogie zu magnetorheologischen Flüssigkeiten (MRF), die Partikelstruktur die Fließgrenze des magnetofluidisierten Betts (MFB) wesentlich beeinflusst. Darüber hinaus zeigt unsere Arbeit, dass die Abhängigkeit der Fließgrenze von der Partikelgröße, die einen kontroversen Punkt bei der Untersuchung von MRF darstellt, aus einer Analyse des Agglomerationsübergangs verstanden werden kann, der von der Größe der Partikel und der Stärke des Bettes beeinflußt wird.

Résumé:
L'interaction entre des particules magnétiques dans un lit fluidisé par un gaz est déterminée par l'action magnétisante d'un champ magnétique extérieur. Au fur et à mesure que la force de champ est augmentée, il arrive un point où le lit passe d'un état de type liquide à un état de type solide stable. Les forces inter particulaires attractives induites par le champ appliqué provoquent une agglomération de type chaine des particules, qui confère une structure stabilisée et une force mécanique. Dans cet article nous reportons des résultats expérimentaux sur la contrainte seuil des lits fluidisés de particules magnétiques fines stabilisées au moyen d'un champ magnétique. Nos résultats montrent que, par analogie avec les fluides magnétorhéologiques (MRFs), la structuration des particules détermine principalement la contrainte seuil des lits magnétofluidisés (MFBs). De plus, notre travail montre que la dépendance de la contrainte seuil en fonction de la taille de particule, qui est un problème controversé dans l'étude des MRFs, peut être expliquée à partir de l'analyse de la transition de blocage qui est affectée par la taille des particules et la force du champ.

Key words: viscosity, composites, Cox-Merz rule, Carreau model, magnetic particles

 DOI: 10.3933/ApplRheol-21-35179

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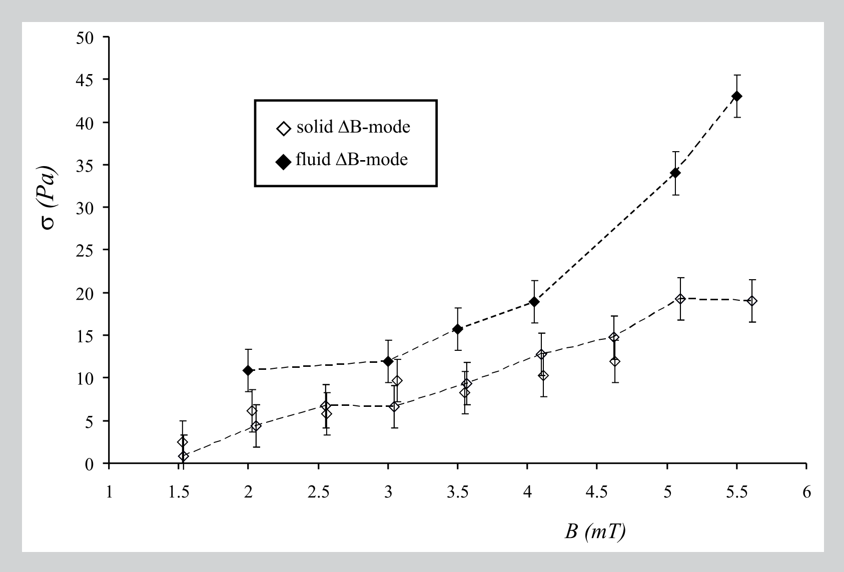

Figure 14: Tensile yield stress of stable MFBs (d_p = 65 μm) as a function of the magnetic field strength B. In the fluid ΔB-mode the bed is stabilized in the presence of a magnetic field of strength B. In the solid ΔB-mode the bubbling bed was stabilized in the presence of a magnetic field of strength B_o = 1 mT and, once this stable state was reached, the strength of the field was increased up to B = 5 mT.

ERFs, where data on the yield stress as a function of the magnetic field stress is usually plotted for a fixed particle volume fraction. Following our argument, measurements of particle volume fraction at the jamming transition as affected by the applied field and particle size would be useful when analyzing yield stress data for these fluids since it may determine the strength of the structure at higher values of the particle volume fraction.

To further stress the role of history on the yield stress of MSBs the measuring process described above has been performed according to a different operation mode. In this mode (solid ΔB-mode), the MFB is bubbled in the presence of a magnetic field B_o and the gas velocity is decreased in the presence of this field until the bed reaches a stabilized state at a gas velocity $v_o < v_c(B_o)$. Once the bed is stabilized the magnetic field strength is increased up to a value $B > B_o$. Then σ is measured as described above. Figure 13 shows data of the gas pressure drop Δp measured as the gas velocity is increased when the bed is stabilized at a gas velocity $v_o = v_c(B = 0) \cong 1.4$ cm/s. The bed was stabilized in the presence of a field B_o = 1 mT, whose strength was increased up B = 5 mT after stabilization. For comparison data is also shown when the bed was stabilized in the presence of a field B = 5 mT at the same gas velocity according to the first procedure (fluid ΔB-mode). As can be seen the data is remarkably influenced by the history of the process even though the strength of the field finally applied to the stabilized bed (B = 5 mT) is the same in both operation modes. The gas pressure drop in the stabilized state at a gas velocity v_o is larger for the solid ΔB-mode than for the fluid ΔB-mode ($\Delta p_s > \Delta p_f$ or $\phi_s > \phi_f$). Since chainlike particle aggregation is enhanced by the magnetic field it is explainable that the the stabilized bed porosity is larger when the high strength field is imposed in a bubbling fluidlike state prior to stabilization. On the other hand, increasing the magnetic field after the bed is stabilized in the presence of a small strength field has no effect on further particle chaining since particles are already jammed. Thus, the size of mechanically stable chains would also have an effect on the mechanical strength of the stabilized bed. This is seen in Figure 14, where it is shown that the yield stress of the MSB operated in the fluid ΔB-mode is relatively increased ($\sigma_f > \sigma_s$). In spite that the field strength finally applied in the solid ΔB-mode is large, the yield stress measured is small. Thus, it is the bed microstructure, instead of the actual strength of the field, the essential factor determining the strength of the MFB. Interestingly, these results remind of the results reported on the angle of repose of magnetized powders obtained from numerical simulations [25]. The data in that study indicated that the angle of repose of magnetized grains was just slowly increased as a consequence of the partial cancelation of interparticle magnetic forces between unstructured grains.

4 CONCLUSIONS

In this work we have investigated the behavior of beds of magnetic particles fluidized by a gas flow in the presence of a horizontal magnetic field. As the gas velocity is decreased there comes a point at which the bubbling fluidized bed is jammed. The critical gas velocity at the jamming transition v_c depends essentially on the strength of the field and on particle size. As particle size is increased, the strength of the induced magnetostatic interaction between the particles is increased, which gives rise to enhanced particle chaining and thus stabilization of the magnetofluidized bed at relatively larger gas velocities. Hence, the mechanical strength of the stabilized bed at a given gas velocity $v_o < v_c$ is increased as particle size is increased for a given field strength. Our results demonstrate that the jamming transition, as affected by particle size, determines the mechanical strength of the stabilized bed. The yield stress is appreciably increased with the magnetic field because of particle chaining due to the induced magnetostatic forces in the fluidlike regime. Once the structure is jammed the effect of increasing the magnetic field on the yield stress is not relevant.

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5 ACKNOWLEDGEMENTS

We acknowledge Spanish Government Agency Ministerio de Ciencia y Tecnologia (contract FIS2006-03645) and Junta de Andalucia (contract FQM-5735).

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