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Effect of particle size polydispersity on the yield stress of magnetofluidized beds as depending on the magnetic field orientation

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HIGHLIGHTS

- Yield stress and jamming transition of magnetofluidized beds are measured.
- The effects of magnetic field direction and strength and particle properties are analyzed.
- The role of chainlike anisotropic arrangement on stabilization is analyzed.
- A model is proposed for the yield stress from an ensemble average of the interparticle magnetic forces.

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ABSTRACT

This work analyzes the influence of particle size polydispersity and shape, as well as orientation and strength of an externally imposed magnetic field, on the rheology of gas-fluidized beds of fine magnetizable particles. Samples consisted of nearly spherical magnetite beads and irregularly shaped steel particles of same average mean diameter but different particle size distributions and magnetization properties. The application of an external magnetic field to the unstable bubbling bed confers it a solid-plastic behavior suppressing the growth of large bubbles. The yield stress, the permeability to gas flow and the gas velocity at the jamming transition of the stabilized magnetofluidized beds (MFBs) have been measured. Steel MFBs have significantly larger values of the yield stress than magnetite MFBs particularly when the gas flow and magnetic field directions were parallel (co-flow configuration). Visual observations and permeability data shows that polydispersed steel particles arrange into more porous and expanded structures than magnetite beads by the application of co-flow magnetic fields. In the cross-flow configuration (when the external magnetic field is perpendicular to the vertical gas flow), it is observed just a moderate enhancement of the magnetic yield stress of steel MFBs as compared to magnetite, which is explained by a larger misalignment between the steel chained particles and the horizontal magnetic field. Finally, a theoretical model has been used to reproduce the observed trends of the magnetic yield stress by taking into account details on the interparticle magnetic forces and the microstructure arrangement.

1. Introduction

In a fluidized bed a gas or a liquid is pumped upwards through a solid granular material at a flow rate typically large enough to counterbalance the bed weight. Many industrial applications relying on an efficient contact between solid and gas phases use gas–solid fluidized bed reactors because of their multiple advantages such as good solids mixing and high mass and heat transfer rates [1]. Processing of granulated solids in pharmaceutical plants, production of plastics and catalyst reactions in chemistry industries, transportation and storage of seeds, grains and foodstuff in agriculture and food manufactures, energy production, air pollution control and manipulation of construction materials are some of the widespread uses of fluidization of granular materials in industry [2–5]. However, in spite of their huge economical impact, the control of granular materials still poses serious problems in practice and a better fundamental understanding on the driving physical mechanisms behind their behavior is needed.

The size of particles to be fluidized in diverse applications covers a wide range from sub–microns to several millimeters. As

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particle size becomes closer to these extremes, fluidization becomes highly heterogeneous as interparticle cohesive forces become significantly larger/smaller than particle weight, respectively [6–11]. According to the empirical Geldart's classification [8], when the gas velocity exceeds a critical value (the minimum fluidization velocity), beds of particles whose typical size are in the range of 25–40 μm to about 150–200 μm (Geldart A type) may show an apparently homogeneous fluidization regime, which is characterized by uniform bed expansion as the gas velocity is increased within a certain interval above minimum fluidization velocity and a transition at a critical gas velocity to a bubbling regime. As particle size decreases (Geldart C type), powders can not be fluidized homogeneously because of the development of stable channels through which most of the gas escapes while most of the powder bed remains stagnant and hardly expands. This phenomenon is generally imputed to the relatively intense interparticle cohesive forces (mainly due to the universal Van der Waals attractive interaction for dry beads) as compared to particle's weight, which leads to large-scale agglomeration, channelling and slugging phenomena [12]. Cohesiveness of fine powders is a main problem for industrial applications not only affecting the performance of gas fluidized bed reactors but also hindering transportation of powders and discharge of silos due to jamming, flowing intermittencies and segregation [13–15]. Two different procedures have been suggested to improve the fluidization of Geldart C powders: the breaking up of compact agglomerates by means of externally applied assistance methods and the modification of particles surface properties to reduce attractive forces [16]. The use of mechanical or acoustic vibration [17–20], stirring [21,22] and gas pulsation or high-velocity jets [23–25] are examples of the former. The fluidization with gases of high viscosity [26], the addition of surface additives [27] or particles of larger size as flowing agents [28,29] are proposed to mitigate the adverse effect of cohesive surface forces. On the opposite side in the window of particle sizes, Geldart B powders (particle size above 150–200 μm) fluidize heterogeneously with a very small bed expansion as soon as the gas velocity reaches the minimum fluidization velocity. The large inertia of the particles in this case leads to a strong segregation between the gas and solid phases and the gas rises mostly in the form of large bubbles which coalesce and grow as they rise up to reach a size limited only by the container size.

Bubbling is also observed in fluidized beds of Geldart A powders but only when gas velocities above a critical value larger than the minimum fluidization velocity are applied. The moderate value of interparticle attractive forces (of the order of particle weight) between the particles of Geldart A powders leads to stabilization of the bed in a solid-like expanded structure at gas velocities within a restricted interval above the minimum fluidization velocity [8,30,31,3,16]. Thus, several methods have been proposed to artificially increase the interparticle forces and suppress the growth of bubbles in fluidized beds of Geldart B powders. For instance, interparticle capillary forces may be induced by the addition of liquid to form bridges between the particles [32,33]. The application of magnetic or electric fields to beds of magnetically or electrically polarizable particles has been also considered as an alternative non invasive technique to enhance interparticle attractive forces in fluidized beds of Geldart B powders [34,35]. Since attractive forces between the polarized particles may be controlled non invasively by tuning the applied field strength, this procedure could be of interest for industrial applications to control the fluidization regime. The present manuscript is focused on the application of a magnetic field to extend the solid-like uniform fluidization regime of magnetizable particles by inducing attractive forces between them. Reports on the similar role of electric fields on the fluidization of dielectric particles can be found in [36,37,34,38–43].

1.1. Brief review on magnetofluidization

The behavior of a water-fluidized bed of iron particles in a time-varying magnetic field under a co-flow (coaxial) configuration (the magnetic field is applied parallel to the fluid flow) was reported in the beginning of the 1960s by Filippov and co-workers as a pioneer work on magnetofluidization [44–48]. Nekrassov and Chekin evaluated the influence of an alternating current (AC) magnetic field perpendicularly oriented to the gas (N_2) flow (so-called cross-flow or transverse configuration) on the fluidization of magnetite particles [49,50]. Ivanov applied uniform direct current (DC) magnetic fields to eliminate bubbles and reduce particle entrainment in fluidized beds of iron or iron–chromium particles for conversion of CO and ammonia synthesis [51–55]. A detailed review on these early studies can be found in [56–61,61]. Tuthill [62] proposed for the first time the term stabilized magnetic fluidized bed (MFB) to refer to the state of non-bubbling fluidization of particles magnetized by an external magnetic field. Concurrently, the stabilization of a gas fluidized bed of iron particles by applying a magnetic field (DC or AC) either axially or transversely relative to the fluidizing flow was studied by Katz [63] and Katz et al. [39]. In spite of the large number of experimental data and observations collected during these early investigations, a significant progress on the fundamental mechanisms driving the behavior of MFBs was not pursued until the late 1970s and beginning of the 1980s by Rosensweig [64–68] and others [69–73]. These works systematically analyzed the influence of different parameters such as the time evolution of the magnetic field (either AC or DC), the bed aspect ratio and the addition of nonmagnetic particles. At the same time, the first practical applications based on MFBs were being envisaged [74–78]. During the next two decades, the improvement of experimental devices and techniques for the synthesis of magnetizable particles cleared the way to further research on the effect of the imposed magnetic field orientation [79,80] or the use magnetizable particles with tailored properties [81–85] as well as gas–liquid–solid admixtures [86–88]. New industrial applications have emerged in bioreactors [89,90] and aerosol filtration [91]. The interested reader may find additional details on the historical aspects and current state of the art of MFBs in extended reviews reported elsewhere [56,58,59,61,60]. Histrov has more recently published a series of papers devoted to provide an unifying approach to the application of magnetic fields for assisting fluidization of Geldart B granular materials [57,92–99].

Empirical observations from different works indicate that the stabilization of MFBs is directly correlated to the formation of a solid network spanning the whole bed [84,100,101,35]. When a magnetic field of sufficiently large intensity is applied to the bubbling fluidized bed, the particles magnetize and aggregate into chainlike structures that eventually lead to a transition from bubbling to a solidlike stable behavior. In this stable fluidization regime (similar to Geldart A fluidization), the attractive forces between magnetized particles are strong enough for permanent interparticle contacts to partially support the bed weight giving rise to an expanded jammed state. The induced interparticle forces provide the MFB with an effective elastic modulus that stabilizes it against small disturbances and precludes the growth of large gas bubbles [102,103,3,35]. Thus, the solid-plastic behavior of MFBs [83] resembles the behavior of magnetorheological fluids –MFRs– (and the analogous electrorheological fluids, ERFs), which usually consist of a concentrated suspension of solid, micron-sized, highly magnetizable particles in a non-magnetizable liquid [104–107]. Stabilized MFBs (as well as MRFs and ERFs) behave as plastic solids