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Studies in Magnetochemical Engineering: Part V. An Experimental Study of Fluidized Beds with Screen Packing and Applied Magnetic Field

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SUMMARY

An experimental study has been made of the characteristics of fluidized beds of ferromagnetic iron and/or paramagnetic manganese(II) oxide (MnO) particles subjected to both external magnetic field and internal screen packing. Key variables investigated include particle size and shape, magnetic properties of particles, superficial gas velocity, screen packing density, and applied field intensity. This study of screen-packed magnetofluidized beds (SPMFBs) has fundamental importance to the development of fluidized-bed high-gradient magnetic separation (FBHGMS) described in Part IV. The primary objective of the study is to gain some basic understanding of SPMFBs, focusing on the practical implications of experimental results to improve the technical performance of FBHBMS for dry coal desulfurization. This study also extends the concept of magnetic stabilization (that is, bubble elimination) in fluidized beds by examining the role of internal screen packing, in addition to that of external magnetic field.

The results show that in SPMFBs of ferromagnetic particles, magnetic stabilization can be achieved, but both the minimum fluidization velocity and the pressure drop at minimum fluidization significantly increase with increasing field intensity. By adding a small fraction of iron, SPMFBs of paramagnetic MnO particles can also be stabilized. Of particular interest to FBHGMS in the observation that magnetized screens tend to serve as distributor plates in SPMFBs, creating a staged bed appearance. The tendency to exhibit staging increases with increasing field intensity and increasing gas velocity. In addition, screens appear to promote the field-induced particle agglomeration. Both bed staging and particle agglomeration are undesirable in many applications of SPMFBs, and their occurrence can be effectively avoided by auxiliary mechanical vibrations as is done in FBHGMS. This study also shows that there exists a trade-off with increasing screen packing density in SPMFBs, particularly in FBHGMS. Denser screen packing increases the surface area for magnetic particle capture, but also increases the occurrence of particle agglomeration as well as bed staging and slugging, which degrades the performance of FBHGMS for dry coal desulfurization.

INTRODUCTION

This paper presents results from an experimental study of characteristics of fluidized beds with external magnetic field and internal screen packing, that is, screen-packed magnetofluidized beds (SPMFBs). A recent development of the SPMFB is the fluidized-bed high-gradient magnetic separation (FBHGMS) described in Part IV [1] and in [2]. Our study was motivated by the need for some basic understanding of and practical insights into SPMFBs, with emphasis on their potential applications to improve the technical performance of FBHGMS for dry coal desulfurization [2, 3].

The external magnetic field and internal screen packing, two key components of an SPMFB, have been applied individually to improve the gas–solid contacting efficiency

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in fluidized beds by suppressing or eliminating gas bubbles. A notable example of a fluidized bed subjected to an external magnetic field is the magnetically stabilized bed (MSB). A typical MSB uses a uniform applied field of relatively low intensity, often below 50 oersted (Oe), to completely eliminate bubbles from a fluidized bed of strongly magnetic or ferromagnetic particles [4]. Without gas bubbling, the gas–solid contacting efficiency and bed-to-wall heat transfer rates in an MSB approach those of a fixed bed, while the solid flowability and low pressure drop in an MSB resemble those of a conventional fluidized bed. Rosenweig [5] gives an excellent review of the theory and applications of MSBs.

Screens packed in a fluidized bed limit the bubble size much like an external magnetic field eliminates bubbles in an MSB. In fact, a screen-packed fluidized bed (SPFB) exhibits many interesting similarities to an MSB, as seen in Table 1.

While much is known about the individual role of magnetic field or screen packing in improving the quality of fluidization, a careful search of the literature [17] yielded no applicable information on fluidized beds with *both* screen packing and applied magnetic field such as FBHGMS. This study was thus initiated to gain a better understanding of the characteristics of SPMFBs, focusing on the practical applications of experimental results to FBHGMS. Our study also extended the concept of MSBs by examining the role of internal screen packing, in addition to that of external magnetic field.

EXPERIMENTAL

Figure 1 shows a schematic diagram of the screen-packed magnetofluidized-bed system used in this work, and Table 2 summarizes the design features of the system and ranges of experimental variables investigated.

TABLE 1

Comparison of screen-packed fluidized beds (SPFBs) with magnetically stabilized beds (MSBs)

Characteristic	SPFBs	MSBs
Minimum fluidization velocity	Slightly greater than conventional fluidized bed [6]	Same as conventional fluidized bed [5]
Pressure drop	Slightly less than conventional fluidized bed, indicating slight channeling [7]; packing partially supports bed [8]	Same as conventional fluidized bed [5]
Pressure-drop fluctuations (an indication of extent of gas bubbling)	Smaller than conventional fluidized bed since screens limit bubble size [9]	None in stabilized region [5]
Slugging	Delayed to significantly higher gas velocities [6]	Delayed to significantly higher gas velocities (above transition velocity to unstable bed)
Entrainment	Less than conventional fluidized bed when fine screens extend above bed [10]	Should be none in stabilized region
Particle attrition	Less than conventional fluidized bed	Less than conventional fluidized bed [4]
Radial gas dispersion	Less than conventional fluidized bed [11]	Less than conventional fluidized bed [12]
Effective thermal conductivity	Approaches conventional fluidized bed at high gas velocities [13]	Should approach fixed bed because of plug flow of solids
Bed-to-wall heat transfer	Slightly less than conventional fluidized bed [13]	Same as fixed bed
Countercurrent gas-solid flow	Yes [8, 11]	Yes with plug flow of solids [12]
Reaction conversion	Between fixed and fluidized beds; can approach fixed beds [13]	Not reported
Axial particle segregation	Segregation according to particle size and/or density [14, 15]	Segregation according to particle density [16]

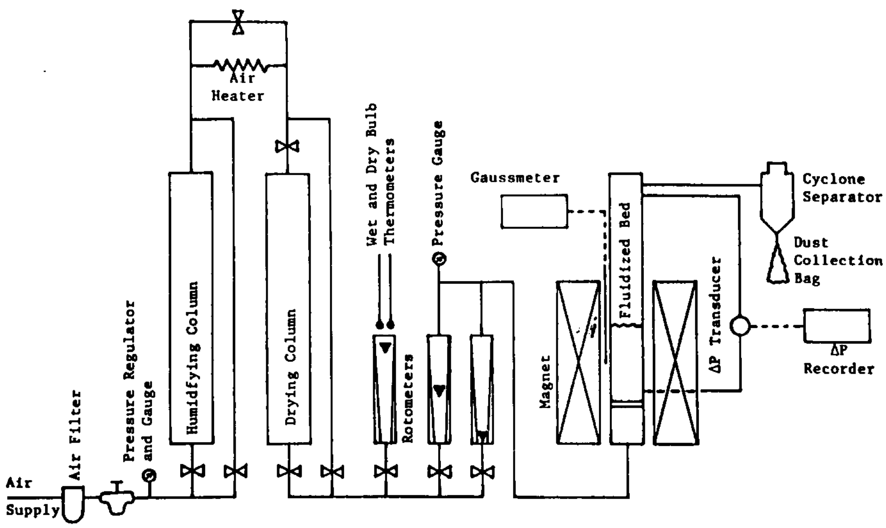


Fig. 1. Schematic diagram of the experimental system.

The following procedure was used to collect experimental data. Particles were sifted in a RO-TAP testing sieve shaker (C. E. Tyler, Mentor, OH). The screen packing was inserted into the Plexiglas column, if required, and a weighed quantity of particles poured into the column. Sufficient particles were added to obtain a settled bed height of approximately 88.9 mm after fluidization.

The relative humidity of the air was adjusted while all of the air was vented to the room. Once the relative humidity had been

TABLE 2

Summary of design features of the screen-packed magnetofluidized bed and ranges of experimental variables investigated

Item	Design feature or variable range
1. Bed geometry	Cylindrical Plexiglas column of 25.4-mm inside diameter and 88.9-mm settled bed height
2. Distributor plate	3.18-mm thick disk of sintered bronze with a pore size of 5 to 10 mm (grade 10P, Thermet, Inc., Gloucester, MA)
3. Screen packing	Stainless steel expanded-metal screens, packed at 25 screens and 1 screen per 25.4 mm of bed height, corresponding to void-volume fractions of 0.726 and 0.887, respectively (catalog number 15SS20-1/0, Exmet Corporation, Bridgeport, CT)
4. Magnetic field	Transverse to fluidizing gas flow: For iron particles, 0 to 100 Oe (with a homemade electromagnet); For MnO particles, 0 to 12 kOe (with a water-cooled Vavian V-4012A electromagnet).
5. Fluidizing gas	Filtered air at room temperature, with 25 to 35% relative humidity, at superficial velocities up to 150 cm/s
6. Solid particles	Ferromagnetic: Iron spheres (−40 +70 mesh, 0.21 to 0.42 mm) Iron filings (−50 +100 mesh, 0.149 to 0.297 mm) Iron powder (−100 +200 mesh, 0.074 to 0.149 mm) Paramagnetic (373 emu/cm^3) MnO particles (−50 + 100 mesh, 0.149 to 0.297 mm)
7. Measuring devices	
Field intensity	Model MG-3D Gaussmeter (Walker Scientific, Worcester, MA)
Bed pressure drop and its fluctuations	Baratron model 223A pressure transducers (MKS Instrument, Burlington, MA) connected to a model 1858 Visicorder (Honeywell Test Instruments Division, Denver, CO)

set between 25 and 35%, the bed was fluidized for several minutes in the absence of an applied field in order to eliminate any orientation effects caused by previously using the particles in a magnetic field. Then the bed was allowed to settle.

The applied field intensity was set to the desired value and the settled bed height recorded. The air flow rate to the fluidized bed was increased in discrete increments. At each increment of flow rate, the rotameter reading, rotameter pressure, bed pressure drop, bed height, and visual observations were recorded. Bed pressure drop fluctuations were recorded. The air flow rate was increased until vigorous bubbling or slugging was achieved. Then the air flow was decreased in discrete, but larger, increments and the same data recorded. The applied field intensity and relative humidity were checked at the maximum air flow and at the end of the run. The bed was maintained in zero magnetic field between each run.

Key experimental measurements included the effects of operating variables on both the superficial gas velocities and bed pressure drops at minimum fluidization, incipient bed expansion, and incipient instability (bubbling). Also recorded were bed pressure-drop fluctuations at different operating conditions. Photographic observations were made of some key characteristics of SPMFBs, including bubbling, channeling, slugging, staged bed appearance, and field-induced particle agglomeration. These characteristics are important to improving the performance of FBHGMS applied to dry coal desulfurization.

Further descriptions of the experimental program can be found in Colberg [17].

RESULTS AND DISCUSSION

This section presents the results from experiments in unpacked and screen-packed fluidized beds of magnetic particles [both ferromagnetic iron and paramagnetic manganese(II) oxide, MnO] that were exposed to a transversely applied magnetic field. The discussion is divided into six segments: (i) effects of particle shape, field intensity, and screen packing on the fluidization behavior of iron particles; (ii) pressure drop measurements in unpacked and screen-packed magnetofluidized beds; (iii) 'MSB phase diagrams' representing the minimum fluidization and transition (to unstable bubbling fluidization) velocities as a function of the field intensity; (iv) the field-induced agglomeration of iron particles and the effect of screen packing on particle agglomeration; (v) the effect of remanent screen-packing magnetization on fluidization behavior; and (vi) the effect of applied field and screen packing on the fluidization behavior of MnO particles, and of mixtures of iron and MnO particles.

Effects of particle shape, field intensity, and screen packing on the fluidization behavior of iron particles

Depending upon the particles used, the intensity of the transversely applied field, and the presence or absence of screen packing, a variety of interesting magnetofluidization behavior of beds of iron particles could be observed. Stable or bubbling fluidization could be achieved. Channeling, slugging and bed staging could be induced.

Effect of particle shape without screen packing

It is well known that spherical particles fluidize better than other shaped particles in the absence of an applied field. Iron spheres (−40 +70 mesh) fluidized much better than did iron filings (−50 +100 mesh) or iron powder (−100 +200 mesh) both with and without a transversely applied field. Iron filings showed a greater tendency to channel and 'rat tail' (that is, spout particles along the wall of the Plexiglas column above the bed). Iron filings also showed more intermittent bubbling than did iron spheres. The fluidization quality of iron powder was generally between that of iron spheres and iron filings. Figure 2 gives a series of photographs of a fluidized bed of iron filings at increasing fluidization velocities in an applied field of 80 Oe.

Effect of field intensity without screen packing

A transversely applied field without screen packing stabilized a bed of iron particles against bubbling over a wide range of fluidization velocities. Rosensweig [4, 5] observed a similar effect of a coaxially applied field.

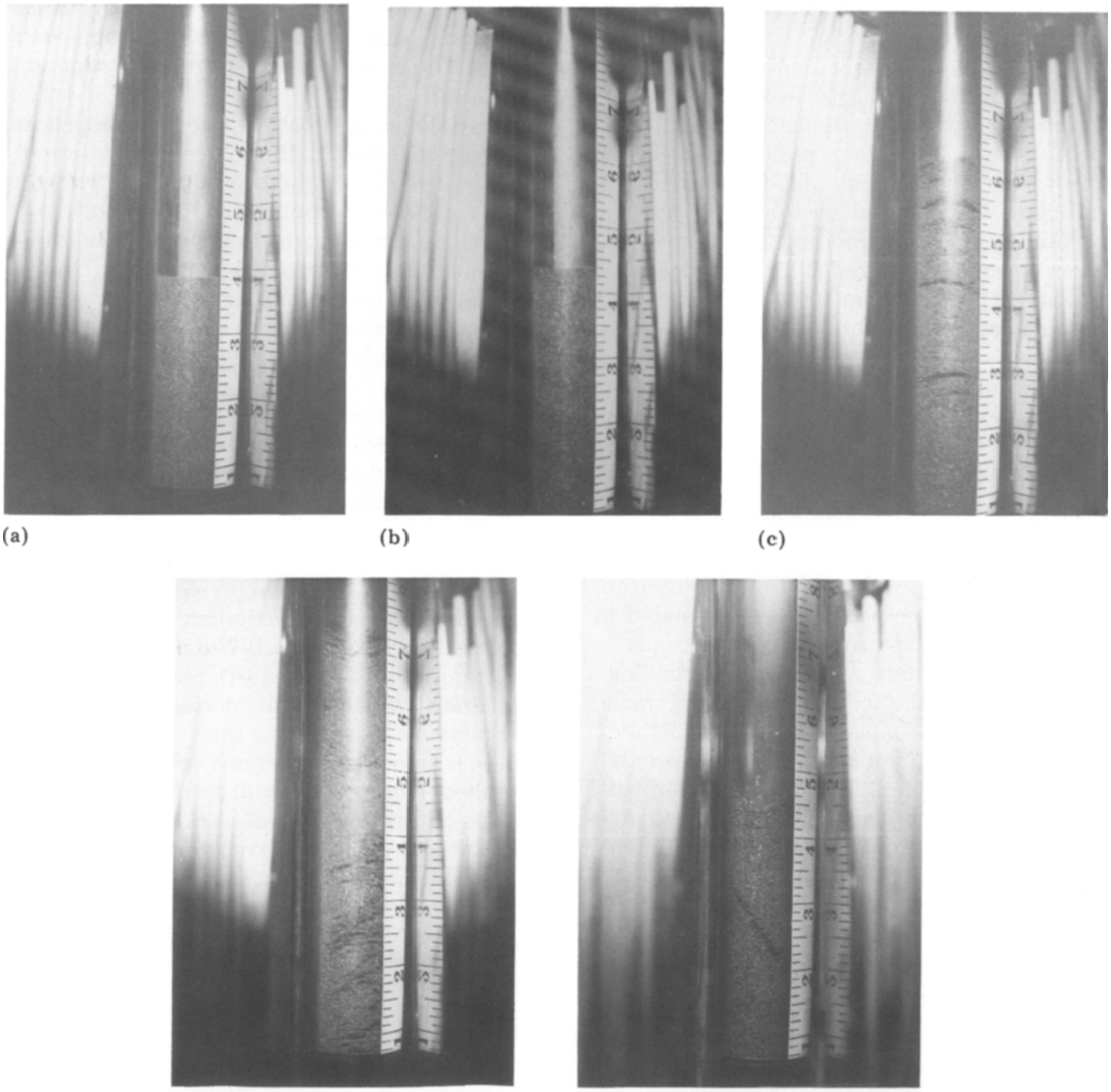


Fig. 2. Magnetofluidized bed of iron filings (−50 +100 mesh) at 80 Oe and different superficial gas velocity v without screen packing. (a), v = 0 cm/s, initial fixed bed; (b), v = 40.3 cm/s, stable expanded bed; (c), v = 58.9 cm/s, cracks grow as the bed expands higher; (d), v = 143.8 cm/s, slugging bed; (e), v = 66.5 cm/s, bed channeling appears as the gas velocity is decreased.

In a transversely applied field, the bed showed noticeable expansion with increasing gas velocity before the onset of bubbling (Fig. 2(b)). At low field intensities, typically less than 50 Oe, the bed expanded very uniformly. At higher field intensities, horizontal cracks appeared in the bed as it expanded. These cracks grew with increasing field intensity, until cracks became empty gaps between sections of the bed (Fig. 2(c)). These cracks and gaps were caused by iron particles clinging to each other and lining up along the lines of the applied field. In fact, iron particles could be seen to align with the lines of magnetic flux as the bed began to acquire a 'grainy' appearance (Fig. 2(b)). The magnetic field increased the tendency of the bed to channel (Fig. 2(e)).

Effect of screen packing without an applied field

The presence of screens noticeably improved the fluidization quality of iron filings, and slightly improved the fluidization quality of iron spheres. The screen packing decreased the visible bubble size, and reduced the bubbling intensity as measured by the amplitude of pressure drop fluctuations. Screens actually degraded the fluidization quality of iron powder, inducing channeling and increasing the bubbling intensity.

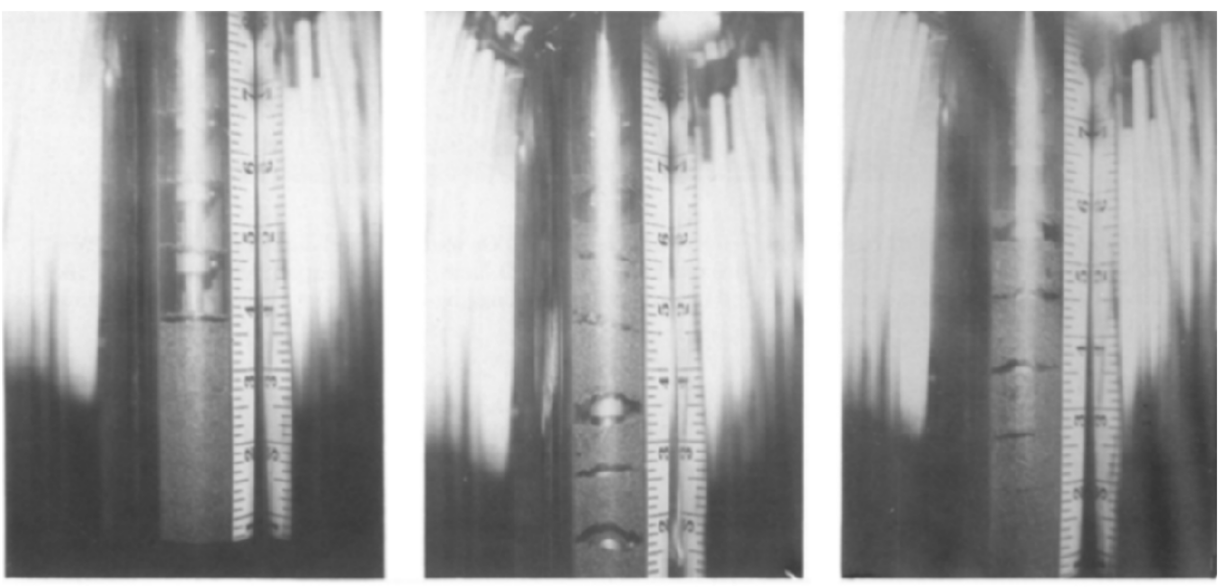
Effect of screen packing with an applied field

The presence of screen packing with a transversely applied field had some dramatic effects on the bed behavior, especially at higher field intensities (Fig. 3). At low field intensities (less than 40 Oe for iron spheres, 20 Oe for iron powder, and 30 Oe for iron filings), the screen-packed beds expanded in a manner similar to that of beds without screen packing, but with more channeling and slugging, and also more and larger cracks and gaps in the expanded bed. At higher field intensities, similarly-sized and evenly-spaced gaps formed above every screen (or screen support collar), giving the bed a uniform staged appearance (Fig. 3(c)). The bed was considered staged when fairly large gaps (say, larger than 6.35 mm wide) appeared above three or more screens or their support collars.

Bed staging as described above has appeared when perforated baffle plates were inserted in a conventional fluidized bed, but screen grids *without* an applied field are reportedly unable to form staged fluidized beds because of their large open areas [18 - 20]. Thus, a transversely applied field reduces the effective mesh size of screens, and promotes the formation of bed staging.

Pressure drop measurements in magnetofluidized beds of iron particles

In the absence of an applied field, both with and without screen packing, fluidized beds of all three types of iron particles (spheres, powder, and filings) exhibited pressure drop behavior (as a function of fluidization velocity) similar to that of conventional fluidized beds, including hysteresis (that is, the bed pressure drop was generally greater when increasing the gas velocity to a given value than when decreasing the gas velocity to the same value). With an applied field, pressure drop data obtained while decreasing the gas velocity were often distorted by the occurrence of channeling



(a) (b) (c)

Fig. 3. Screen-packed (1 screen per 25.4 mm) magnetofluidized bed of iron filings (—50 +100 mesh) at 50 Oe and different superficial gas velocities v. (a), v = 0 cm/s, initial fixed bed; (b), v = 49.0 cm/s, expanded bed with several gaps; (c), v = 70.1 cm/s, expanded bed with uniform staged appearance.

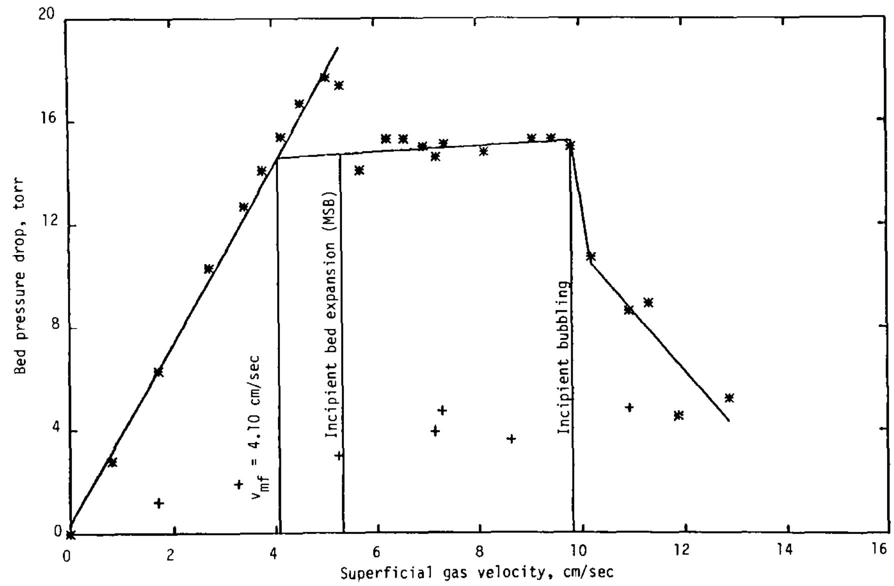


Fig. 4. Magnetofluidized bed behavior of iron powder (—100 +200 mesh) at 40 Oe without screen packing (8.10-cm settled bed height). *, Data taken with increasing gas velocity; +, data taken with decreasing gas velocity.

(for example, Fig. 4). Thus, the minimum fluidization velocity was always determined from data with increasing gas velocity.

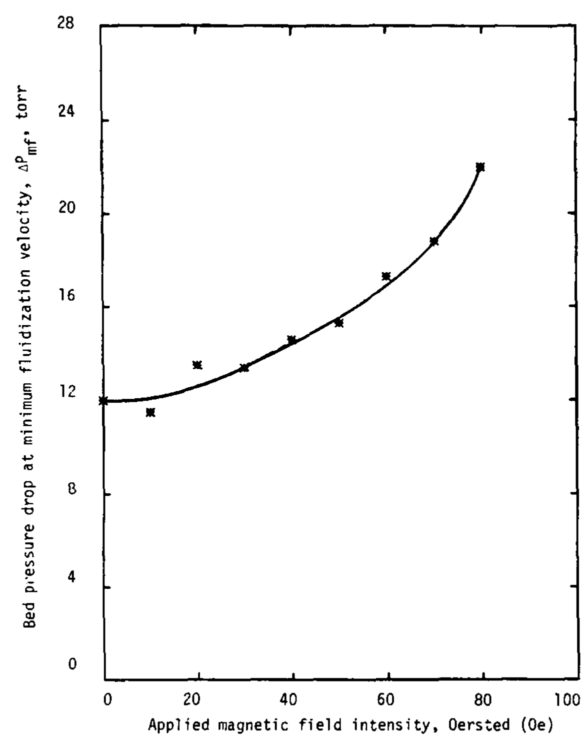


Fig. 5. Bed pressure drop at minimum fluidization velocity ΔP_{mf} as a function of applied magnetic field intensity in a magnetofluidized bed of iron powder (—100 +200 mesh) without and with screen packing (1 screen per 25.4 mm).

Both with and without screens, the bed pressure drop at the minimum fluidization velocity (ΔP_{mf}), increased with the applied field intensity, as shown in Fig. 5. This increase in pressure drop is probably due to the fact that iron particles cling to each other (agglomerate) along lines of magnetic flux perpendicular to the direction of gas flow. More energy (that is, higher pressure drop) is required to break particles apart and cause them to fluidize. The increase in ΔP_{mf} with increasing applied field intensity was not reported by Rosensweig [4, 5] for unpacked magnetofluidized beds such as MSB in which the field was applied coaxial with the direction of gas flow.

At incipient bubbling, the pressure drop decreased significantly in unpacked beds of iron powder or iron filings exposed to relatively high field intensities (30 Oe or higher for iron powder, and 60 Oe or higher for iron filings; see Fig. 4). This decrease in pressure drop occurred when the gas velocity was high enough to disrupt the iron particles clinging to each other. The reduced pressure drop may also be the result of channels which remain when bubble tracks refuse to collapse in the magnetic field. The bed pressure drop often decreased drastically when the bed staging occurred (for example, Fig. 6).

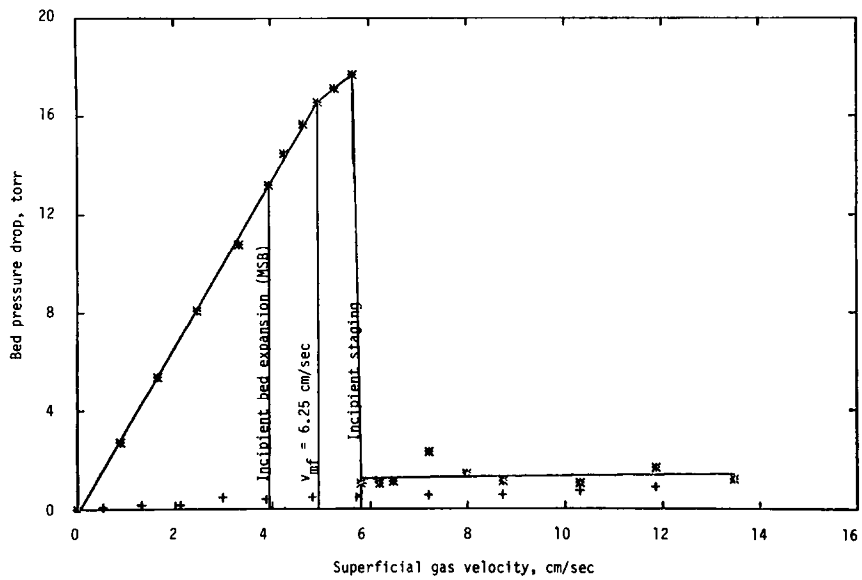


Fig. 6. Magnetofluidized bed behavior of iron powder (—100 +200 mesh) at 30 Oe with screen packing (1 screen per 25.4 mm) and 8.10-cm settled bed height. *, Data taken with increasing gas velocity; +, data taken with decreasing gas velocity.

'MSB phase diagrams' for magnetofluidized beds of iron particles

'MSB phase diagrams' can be constructed to characterize the behavior of magnetofluidized beds, both with and without screen packing (for example, Fig. 7). Adopting the representation by Rosensweig [4], these diagrams show, as functions of the field intensity, the minimum fluidization velocity and the superficial gas velocity at which the transition to an 'unstable' bed occurs ('incipient bubbling' or 'incipient staging'). The diagram can be divided into three 'operating' regions: the area below the minimum fluidization velocity is the fixed-bed region; the area between the minimum fluidization and transition velocity lines is the magnetically stabilized, fluidized-bed (MSB) region; and the area above the transition velocity line is the unstable bubbling (or slugging or staged) fluidized-bed region.

In magnetofluidized beds with a transversely applied field, the minimum fluidization velocity increased slightly with increasing field intensity; while in SPMFBs, it increased significantly with increasing field intensity (Fig. 7). Here, the traditional definition of minimum fluidization velocity was used; that is, the superficial gas velocity at the intersection of the fixed- and fluidized-bed pressure

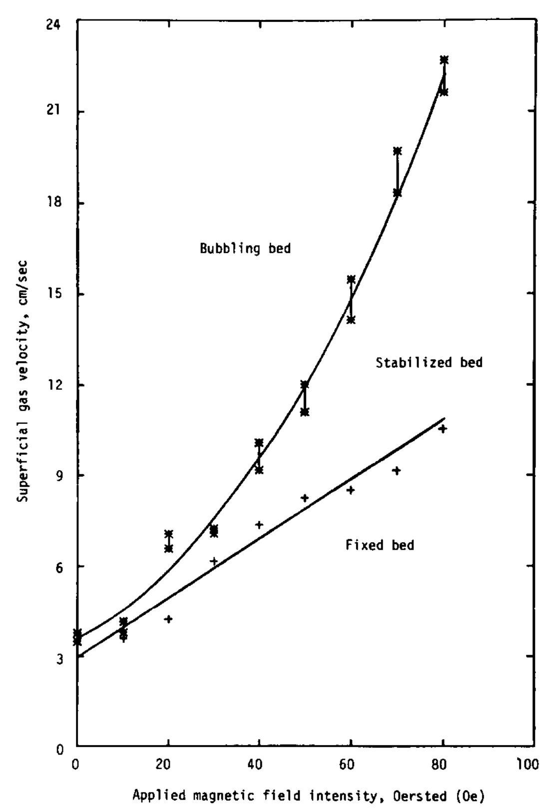


Fig. 7. Magnetically stabilized bed (MSB) 'phase diagram' of a screen-packed magnetofluidized bed of iron powder (—100 +200 mesh, 1 screen per 25.4 mm and 8.10-cm settled bed height). *, Minimum fluidization velocity; +, transition velocity.

drop lines. However, this definition was sometimes difficult to apply to an SPMFB. For instance, in Fig. 6, the bed pressure drop continues to rise even after the bed begins to expand.

In both unpacked and screen-packed magnetofluidized beds, the transition velocity increased with increasing field intensity. The transition velocity was well defined in magnetofluidized beds of iron spheres. The transition from a stable expanded bed to an unstable bubbling (or slugging) bed was very sharp and reproducible. However, in magnetofluidized beds of iron powder or filings, the transition velocity was not well defined, since the initial bubbling (or slugging) was intermittent and sporadic. In screen-packed magnetofluidized beds at applied field intensities high enough to cause bed staging, the transition velocity was taken as the superficial gas velocity at the first occurrence of staging.

The minimum fluidization and transition velocities would be expected to coincide in the absence of an applied field. However, as Fig. 7 shows, these velocities may not coincide in zero applied field. This results from using different definitions for the minimum fluidization and transition velocities.

Field-induced particle agglomeration in magnetofluidized beds of iron particles

Field-induced particle agglomeration is an undesirable phenomenon in magnetofluidized beds. Particle agglomeration reduces solid flowability [4] and gas-particle heat transfer [21] in magnetofluidized beds. In SPMFBs used for the separation of magnetic particles from essentially nonmagnetic particles (for example, FBHGMS applied to the separation of inorganic sulfur and ash from coal), particle agglomeration reduces separation efficiency [1].

Several observations provided evidence of field-induced particle agglomeration in magnetofluidized beds of iron particles. First, beds acquired a grainy appearance caused by iron particles clinging to each other along the flux lines of the transversely applied field (Fig. 2(b)). This grainy appearance became more noticeable as the field intensity increased. Secondly, cracks and gaps formed in the bed in the direction of the magnetic flux (Fig. 2(c)). Often, a sparse collection of particles in the gaps could be seen to align with the direction of the magnetic field. The number and size of cracks and gaps increased with increasing field intensity. Thirdly, cracks and gaps were more numerous and larger in magnetofluidized beds of iron filings than in beds of iron spheres. Particle agglomeration would be expected to be more significant with iron filings than with iron spheres, since filings can induce larger field gradients and larger interparticle magnetic attractive forces. Fourth, particle agglomeration probably contributed to the experimentally observed bed 'staging' (Fig. 3(c)). Particle agglomeration reduces the ability of particles to flow through the screens, thus enhancing the probability of the bed to stage. The tendency of staging increased with increasing field intensity. Fifth, the bed pressure drop at the minimum fluidization velocity, ΔP_{mf}, increased with increasing field intensity (Fig. 5). More energy (higher pressure drop) was required to break apart particle agglomerates aligned perpendicular to the direction of gas flow before particles could be fluidized.

Screen packing seemed to increase particle agglomeration. At the same field intensity, screen packing increased the number and size of cracks and gaps in the bed, and also increased the bed pressure drop at the minimum fluidization velocity.

A few experiments were conducted on an SPMFB of iron powder with a packing density of 25 screen grids per 25.4 mm of bed height. This packing density is closer to that used in FBHGMS than is a packing density of 1 screen per 25.4 mm. In the densely packed magnetofluidized bed of iron powder, the pressure drop rose to a value (e.g., 60 torr or 8 kPa in an applied field of 20 Oe) much higher than that encountered in an unpacked or a loosely packed (1 screen per 25.4 mm) magnetofluidized bed (for example, 20 torr or 2.34 kPa) as the superficial gas velocity increased. When the bed began to bubble, the pressure drop suddenly and drastically decreased. The maximum bed pressure drop increased with increasing field intensity. The high pressure drop is probably required in order to break apart a 'plug' of agglomerated iron powder. Even though the bed expanded while the pressure drop climbed to these high values, it was doubtful that the bed was actually fluidized.

Effect of remanent screen-packing magnetization on the behavior of magnetofluidized beds of iron particles

Some iron particles adhered to the stainless steel screen packing even after the applied field was adjusted to a negligible value (less than 0.3 Oe). This indicates that the stainless steel screen packing retains a remanent magnetic field. The effect of this remanent field on subsequent magnetofluidization behavior was the subject of three series of experiments: (i) new unmagnetized screen packing; (ii) new screen packing magnetized by a field of about 12 kOe for over 1 min; and (iii) screen packing previously used in experiments with a variety of field intensity.

Most of the superficial gas velocities at the minimum fluidization, incipient expansion, and incipient instability showed little change with screen treatment. Those superficial gas velocities which did change showed no discernable trend. Therefore, the remanent magnetism of the screen packing used in these experiments had no noticeable effect on the magnetofluidization behavior.

Effect of applied field and screen packing on the fluidization behavior of MnO particles and of mixtures of iron and MnO particles

Since an applied field of relatively low intensity can stabilize a fluidized bed of ferromagnetic particles, it is natural to ask whether a field of higher intensity can stabilize a fluidized bed of paramagnetic particles. Many paramagnetic particles were considered, and manganese(II) oxide (MnO) had the highest handbook value of volumetric magnetic susceptibility of 373 emu/cm^3 [22]. It was thus a paramagnetic compound considered likely to be magnetically stabilized.

An unmagnetized fluidized bed of MnO particles (−50 +100 mesh) behaved like any other conventional fluidized bed. Bubbling began at the minimum fluidization velocity, and grew more vigorous with increasing gas velocity until slugging was finally obtained. The addition of screen packing to the unmagnetized bed caused occasional channeling and actually increased bubbling intensity as measured by the amplitude of pressure drop fluctuations. The highest applied field intensity obtainable with the magnet used in this work (11.9 Oe) had no noticeable effect on the behavior of the unpacked fluidized bed. In other words, the unpacked fluidized bed of MnO particles was not stabilized by applying an 11.9-kOe magnetic field transverse to the direction of fluidizing gas flow.

The application of an 11.9-kOe magnetic field to a screen-packed (1 screen per 25.4 mm) fluidized bed of MnO particles (−50 +100 mesh) did affect the fluidization behavior. Bubbles and slugs rose in the bed with a jerky motion, almost as if one were viewing the bed under a stroboscopic light. When the bed was slugging vigorously, small gaps rising throughout the bed spontaneously appeared and disappeared. Even though the presence of screen packing was required for the applied field to alter the fluidization behavior, the fact that the applied field could alter the bed behavior at all seems to suggest that more intense fields may stabilize a fluidized bed of MnO particles. A coaxial field may be more effective, as suggested by Rosensweig [23].

In a later set of experiments, Hamby [24] studied the effects of applied field and screen packing upon the fluidization behavior of a mixture of iron powder (5, 10, and 15 vol.%) and MnO particles. Because of the different densities of iron (7.86 g/cm^3) and MnO (5.45 g/cm^3), iron particles used were smaller (−250 +270 mesh) than MnO particles (−50 +100 mesh) to prevent segregation of the fluidized mixture.

Even though a fluidized bed of pure MnO particles cannot be magnetically stabilized with an applied field as strong as 11.9 kOe, Hamby [24] found that a fluidized bed of the iron–MnO mixture without screen packing could be magnetically stabilized with as little as 5 vol.% iron in MnO with an applied field intensity as low as 10 Oe. Figure 8 illustrates Hamby's measurements of the minimum fluidization and transition (to complete bubbling) velocities as a function of volume per cent of iron in MnO and applied field intensity [24].

Hamby [24] reported that in unpacked beds, iron particles could be seen forming an interlaced network inside a bed of MnO particles during magnetic stabilization. These 'skeletal' regions were composed of iron 'polymers' aligned with the direction of the applied field which tended to entrap MnO particles in a lattice-type of arrangement. These lattice arrangements most often occurred

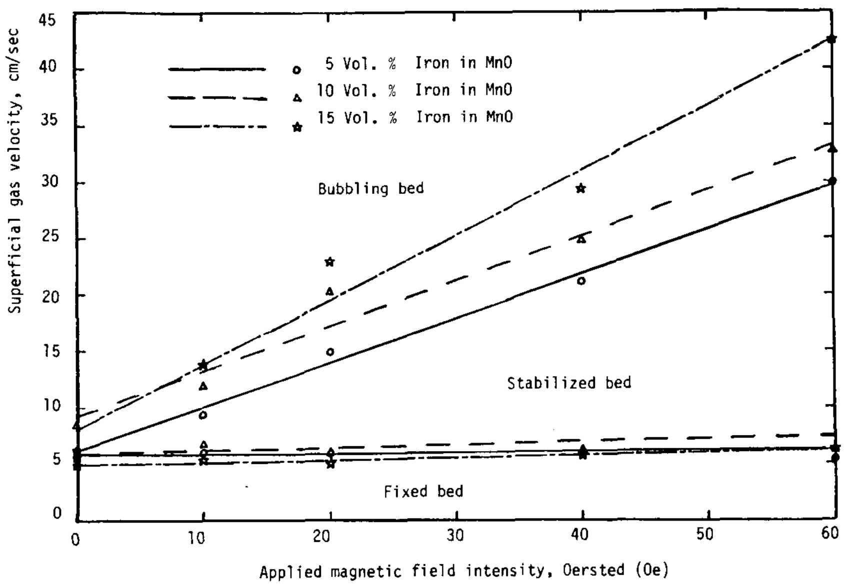


Fig. 8. Effect of transverse magnetic field intensity on the fluidization characteristics of beds of admixtures of iron and MnO particles [24].

in the vicinity of other iron particles agglomerated between the bed wall and the bulk of MnO particles. The regions in which the iron was not so heavily concentrated always showed noticeable bubbling and back-mixing before the rest of the bed. For air velocities between the minimum fluidization and transition velocities, channeling was often observed, especially at field intensities greater than 20 Oe. With increasing air velocity, more iron particles would tend to be removed from the field-induced agglomerates by the strong fluid shear force. As a result, the region of fluidized MnO particles would increase. Eventually, at the transition velocity, the entire bed became fluid-like with complete particle backmixing. The transition velocity was dependent upon both the field intensity and the composition of bed particles. Upon reaching the transition velocity, iron particles still appeared to be short polymeric chains, but could no longer stabilize a bed of MnO particles.

Hamby [24] found that, when packed with a single screen, fluidized beds of the iron–MnO mixture would exhibit staging with sufficiently high gas velocities in applied fields of 20 Oe or greater for mixtures of 10 vol.% iron in MnO, or 40 Oe or greater for mixtures of 5 vol.% iron in MnO. The screen, covered with frozen iron particles, served as a distributor plate for the upper stage. The two stages did not always exhibit the same behavior. Often, the top stage would be completely fluidized and slugging, while the lower stage might only be partially fluidized. The top stage almost always showed more intense gas bubbling and particle backmixing than the lower stage. The staging velocity increased with both increasing field intensity and increasing iron percentage.

PRACTICAL IMPLICATIONS OF EXPERIMENTAL RESULTS

Based upon some principles of magnetism and fluidization, the results from SPMFB experiments may be generalized to provide some insights into the coal beneficiation performance of FBHGMS.

Magnetic stabilization and FBHGMS

In a typical MSB, the fluidized bed is composed of ferromagnetic particles, or a mixture of ferromagnetic and diamagnetic particles [4]. By contrast, FBHGMS is applied to a naturally occurring mixture of paramagnetic and diamagnetic particles, namely, pulverized coal. Since most utility-boiler feed coals are subjected to sufficient grinding and pulverization to facilitate the liberation of micron-sized mineral impurities, it is conceivable that coal can be visualized as a mixture of discrete clean coal particles (diamagnetic or practically nonmagnetic) and discrete mineral impurity particles (paramagnetic or weakly magnetic).

With the intense magnetic field applied in the FBHGMS, typically 20 to 50 kOe (2 to 5 T), there is a fairly large magnetization imparted to the sulfur-bearing and ash-forming particles. The level of induced particle magnetization may be comparable to the useful level of 500 to 1000 G suggested for an MSB [4].

The experiments with MnO particles suggest that magnetic fields more intense than the 11.9 kOe obtainable with the present magnet may stabilize a fluidized bed of paramagnetic particles. Even though an 11.9-kOe magnetic field had no effect on an unpacked fluidized bed of MnO particles, the effect on an SPFB of MnO particles was significant. The experiments with mixtures of iron and MnO particles showed that an SPFB with as little as 5 vol.% ferromagnetic iron in MnO could be magnetically stabilized. Whether or not an applied field can stabilize a mixture of paramagnetic and diamagnetic particles remains to be determined, especially with as low a fraction of paramagnetic particles as iron pyrite in coal.

True magnetic stabilization is actually undesirable in FBHGMS. Magnetic stabilization eliminates solid motion in a batch fluidized bed (and allows only a plug-flow solid motion in a fluidized bed in which particles are continuously added and withdrawn). Solid motion is vital to FBHGMS for magnetic particle capture by the screen packing. Without particle capture, iron pyrite and ash cannot be separated from pulverized coal. The field gradients induced by screens attract magnetic particles toward them. Thus, magnetized screens may cause a secondary solid motion which can be superimposed upon the solid motion (or lack thereof) in an MSB. If magnetic stabilization does occur in FBHGMS, then this superimposed solid motion may be sufficient to cause separation of paramagnetic and diamagnetic particles.

Magnetic field-induced particle agglomeration and auxiliary mechanical vibrations

The presence of screen packing in an SPMFB seems to promote the field-induced particle agglomeration. In fact, our results show that particle agglomeration was more significant in SPMFBs with a screen packing density of 25 screens per 25.4 mm than in SPMFBs with 1 screen per 25.4 mm. The former packing density is close to that used in FBHGMS.

In a typical application of FBHGMS to dry coal beneficiation [1], clean coal particles can become mechanically entrapped within matrix packing materials. In addition, in the process of magnetically capturing paramagnetic mineral impurity particles, additional clean coal particles are trapped within field-induced agglomerates of these particles. In such a mechanism, clean coal particles, although nonmagnetic, are forced to adhere to magnetized packing materials, thus reducing the separation efficiency.

Auxiliary internal and external mechanical vibrations are used in FBHGMS to facilitate the removal of mechanically entrapped clean coal particles. When an automatic internal vibration/washing system (AIV/WS) is used, experimentally observed Btu recoveries are fairly constant and essentially independent of separation conditions. However, without using the AIV/WS, there is a notable decrease in Btu recovery from 94 to 84% when increasing the field intensity from 20 to 50 kOe [1]. The increased Btu recoveries observed when using the AIV/WS with an applied field intensity of 50 kOe reflect the ability of auxiliary internal vibration to minimize the occurrence of the field-induced agglomeration of pulverized coal particles with their associated mineral impurities.

Similar observations of field-induced particle agglomeration have been noted in MSBs. Rosensweig [4] refers to the tendency for particles in an MSB to aggregate and take the form of a slug at high field intensities (for example, 50 to 100 Oe for ferromagnetic particles). He further suggests that the maximum useful level for the magnetization of most particles is about 500 to 1000 G to achieve a reasonably fluid-like medium without excessive particles agglomeration. As a result, the significance of field-induced particles agglomeration in the FBHGMS is also indirectly validated by observations made in MSBs.

Screen packing density in FBHGMS

The preceding discussion suggests that there exists a trade-off with increased screen packing density in FBHGMS: increased packing density provides more surface area for magnetic particle capture, but it also promotes the occurrence of field-induced particle agglomeration. Particle agglomeration degrades the coal beneficiation performance of FBHGMS.

Our results from SPMFB experiments with two different screen packing densities (25 screens and 1 screen per 25.4 mm) also suggest the existence of an optimum packing density in FBHGMS for dry coal beneficiation [1]. Specifically, bed slugging tends to occur more easily in a densely-packed bed. This implies that in FBHGMS, pulverized coal particles pass through the length of the separator matrix in an essentially non-recirculating fashion as a bulk plug. The probability for paramagnetic mineral particles to contact with the magnetized matrix packing decreases. By contrast, for a loosely-packed bed, slugging does not appear important, but the excessive looseness of the separator matrix packing limits the probability of the magnetized matrix to capture mineral impurity particles.

Bed staging and FBHGMS

Bed staging observed in our SPMFB experiments limits the contact of fluidizing particles with at most two neighboring screens. Should bed staging occur in FBHGMS, the probability of capture of paramagnetic mineral particles by the magnetized screen packing would decrease. In our SPMFB experiments, bed staging seemed to be caused by the field-induced particle agglomeration along the lines of transversely applied magnetic flux perpendicular to the direction of gas flow. In FBHGMS, particle agglomeration would most likely occur along the lines of axially applied magnetic flux parallel to the direction of gas flow. It is uncertain whether bed staging takes place in FBHGMS, but we believe that auxiliary mechanical vibrations in FBHGMS tend to reduce the occurrence of bed staging. However, Yang *et al.* [25] and Fitzgerald and Levenspiel [26] have reported that a fluidized bed of iron spheres can exhibit staging above a screen in an axially applied field.

Further experiments

Further experiments are needed to confirm the above generalizations of present results to FBHGMS. These experiments should study unpacked and screen-packed magnetofluidized beds under the following conditions: paramagnetic particles with high applied field intensities (greater than 11.9 kOe); ferromagnetic and paramagnetic particles in axially applied magnetic fields; and mixtures of ferromagnetic and diamagnetic particles, and of paramagnetic and diamagnetic particles with a wide range of applied field intensities. In addition, the solid flowability should be measured at higher field intensities to determine if the 'magnetofluidized' beds are truly fluidized, and to further study the effect of field-induced particle agglomeration.

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LIST OF SYMBOLS

ΔP	bed pressure drop, [M L^{-1} T^{-2}]
ΔP_{mf}	bed pressure drop at minimum fluidized velocity, [M L^{-1} T^{-2}]
v	superficial gas velocity, [L T^{-1}]
v_{mf}	minimum fluidization velocity, [L T^{-1}]

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