COMMENTS ON GAS-FLUIDIZED MAGNETIZABLE BEDS IN A MAGNETIC FIELD

Part 1: Magnetization FIRST mode

by

Jordan Y. Hristov

Review paper
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The fluidization in a magnetic field in presence of external magnetic fields is an attractive technique over 35 years. The fundamental studies concerning the phenomena are rare and strongly affected by the author interpretations. That is the reason to focus the attention on the results of several scientific schools as well as on their interpretations and problems in the area of the so-called "Magnetization FIRST" mode of operation

INTRODUCTION

The paper discusses the gas fluidization of ferromagnetic particles in presence of external magnetic fields. The changes in bed behaviour in contrast to the well known fluidization behaviour of fluidized coarse particles are attractive for many scientists. The magnetic field induces new regimes that may be employed in different applications. However, the correct use of this new fluidization technique requires a deep understanding of the phenomena in the bed. In the last four decades the fluidization in a magnetic field was a technique that did not escaped from the laboratory. The possibility to find a large scale applications depends on the knowledge of the phenomena and correct interpretations of the bed behaviour.

The article concerns the hydrodynamic aspects of the gas fluidization of ferromagnetic particles in a magnetic field from an experimental point of view. Recently a number of reviews [1–5] have appeared. The article focuses on some experimental results and data interpretations, which are matter of argument as wells origins of discussions. The historical development and applications will not be commented here.

The papers is dedicated to Prof. Dimitar Elenkov, the foundator of the Chemical Engineering in Bulgaria, in ocasion of his 80th birthday

TRADITIONAL APPROACHES – MODES OF OPERATIONS

The classical fluidized bed is a two-phase system with an intensive movement of dispersed solids. The balance of the forces acting upon particles determines the behaviour of fluidized bed systems: gravitational forces, fluid/particle drag forces and friction forces between the particles [6]. The application of additional external fields (such as magnetic or electric) affects fluidization [7–10]. The influence depends both on the intensity and on the orientation of the field lines [11]. The fluid flow and the magnetic field may be applied independently so two modes of operation are possible.

Magnetization FIRST mode

The mode involves the application of the field on a fixed bed and fluidization after that (Fig. 1). The term has been introduced by Siegel [12]. In this mode, the fluidization and the bed structures formed as the flow rate increases, arise under the simultaneous action of gravitational forces, friction forces (fluid/particle and interparticle friction) and the external field. The starting state is ordinary fixed bed. In this case the interparticle forces play a much more important role than the fluid/particle interaction.

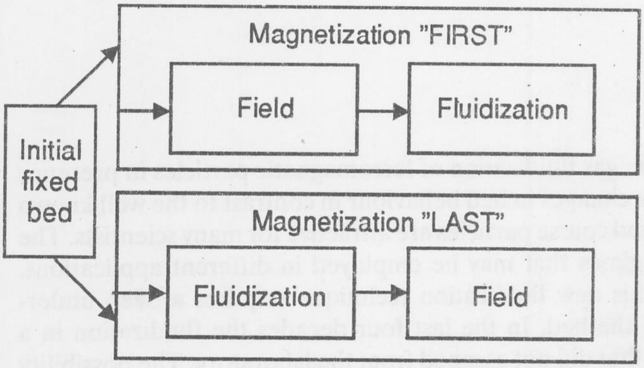

Figure 1. Operating model

Most of previous work on the fluidization behaviour of ferromagnetic particles in a magnetic field has been performed by the "Magnetization FIRST" mode [1, 7–10, 13, 14].

The main attraction of this operating mode is "the magnetically stabilized bed" (MSB) [1].

Magnetization LAST mode

The second mode involves the application of the field on preliminarily fluidized bed (Fig.1). The structure of an already fluidized bed depends on the type of the fluidizing agent (gas or liquid), its velocity and the particle size.

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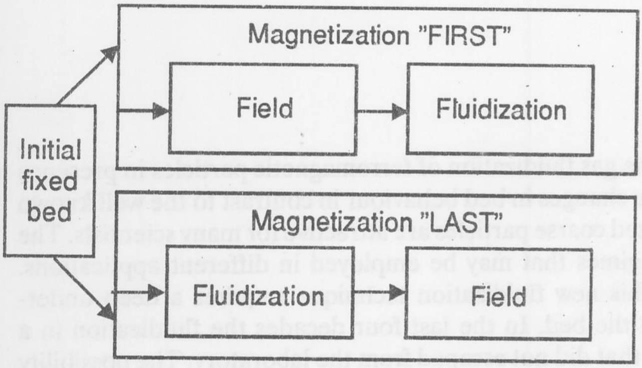

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of magnetic stabilization, is the occurrence of central channel and poor fluidization. Thus, the non-homogeneous fields decrease the efficiency of the fluid-particle contactors. This is the reason for large use of homogeneous fields (see also the comments in the next section) despite the fact that from a physical point of view every field may create a stabilized bed.

Magnetic fields used

The magnetic systems used more than 4 decades have been build on the basis of solenoid (long or short) generating axial magnetic fields (*i. e.* parallel to the fluid flow). Some of them are shown schematically in Fig. 3a. Those of them generating non-homogeneous field (mainly by short solenoids) are not shown. Penchev and Hristov [13], Fig. 1 have reported a comprehensive summary. A magnetic system based on windings with a central symmetry generates homogeneous field in a small zone around its axis. This zone does not exceed 30% of the volume inside the windings. Moreover, the axial magnetic systems provoke a channelling in the bed (see further comments).

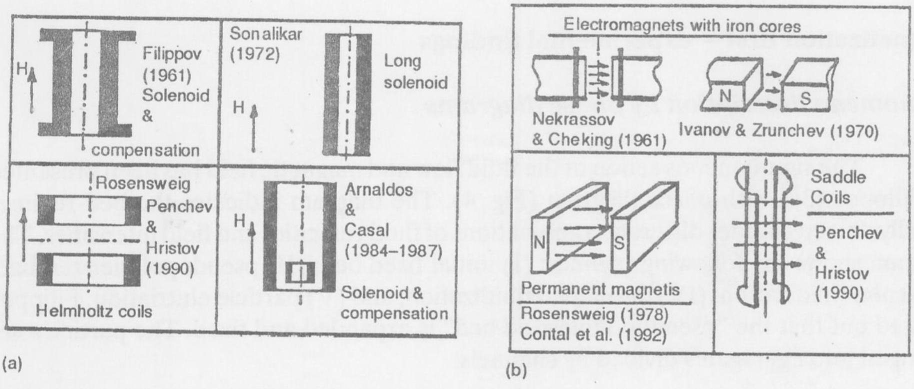

Figure 3. Magnetic systems used in previous works
(a) Magnetic systems for axial fields; (b) Magnetic systems for transverse fields

On the other hand the use of transverse fields (Fig. 3b) is not so popular among the investigators. Probably, one of the reasons is the use of magnetic systems based on electromagnets that contain iron details [28, 29]. Further, some authors made attempts to use magnetic systems based on permanent magnets [30–33]. All of these magnetic systems have significant disadvantages. The first of them is that the energy consumption is in proportion of 3rd power of the distance between the poles (the length of the air gap). This limits the use of such electromagnets for laboratory use only. Moreover, the required amounts of iron and the weights of such electromagnets are terrible.

The second and more important disadvantage is that the magnetic field generated by parallel poles (equipotential magnetostatic surfaces) has a strong non-uniformity along the lateral symmetry axis, *i. e.* from the centre of the gap toward the pole. The homogeneous zone occupies no more of 30% of the gap, around its centre.

Both disadvantages, the first one by the troubles emerging from the unpleasant spend of materials and the small working volume, and the second one due to principle problems of the lateral magnetic gradients, hindered the applications of transverse field for many years.

An attempt to overcome the problems of the magnetic systems commented above was made by Penchev and Hristov [14]. The saddle coils used by these authors have two principle advantages:

(I) The zone with a homogeneous field hold more than of 98% of the volume inside the windings. The cooper wire amount is reduced significantly with respect the requirements of the axial magnetic systems. Thus, a step toward the build-up of large-scale devices was done.

(II) The field orientation does not allow a channelling in the bed.

MAJOR RESULTS

Magnetization first – experimental findings

Phenomena description by phase diagrams

The simultaneous action of the fluid flow and magnetic field has been presented by Filippov [34] with phase diagram (Fig. 4). The diagram indicates the bed regimes visually detected under different combinations of fluid velocities and field intensities. The diagram shows the following regimes: (I) initial fixed bed; (II) pseudopolimerized bed; (III) calm fluidization; (IV) developed fluidization, and (V) particle elutriation. Filippov pointed out that the "pseudopolimerized bed" is expanded and fixed. The particles are arranged into aggregates divided by channels.

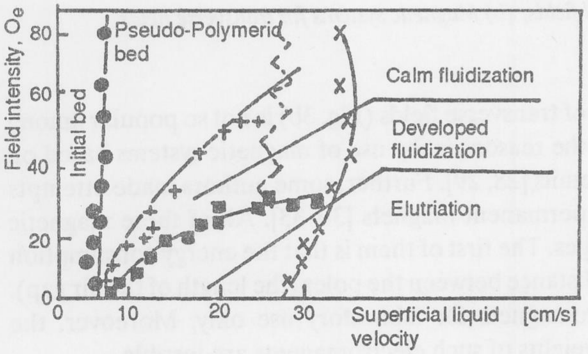

Figure 4. Filippov's phase diagram [34]. Water-magnetite systems. For more details see [13]

Filippov's second principle result is that the transition between the initial fixed bed and the pseudopolimerized bed is close to the minimum fluidization point in absence of a filed. Moreover, he stated that the pressure drop curve has plateau and that there is no effect of the field intensity on it.

Using these results, Filippov claimed that the minimum fluidization velocity is independent of the field intensity and assumed the transition from the initial bed into the pseudopolimerized state as the fluidization onset.

In 1978–1979, Rosensweig [1, 30] reported a similar phase diagram (Fig. 5a). He replaced the term "pseudopolimerized bed" by "magnetically stabilized fluidized bed" using the terminology introduced by Tuthill in 1969 [35].

Rosensweig explains the phase diagrams in the "Magnetization FIRST" mode through an analogy concerning the velocity as an analogue of pressure. According to Rosensweig (see Fig. 2 in [30]) the phase diagrams in the "Magnetization" mode resemble a thermodynamic phase diagram of a pure substance : solid state (initial fixed bed); liquid phase (stabilized bed) and a vapour phase (fluidized state with bubbling).

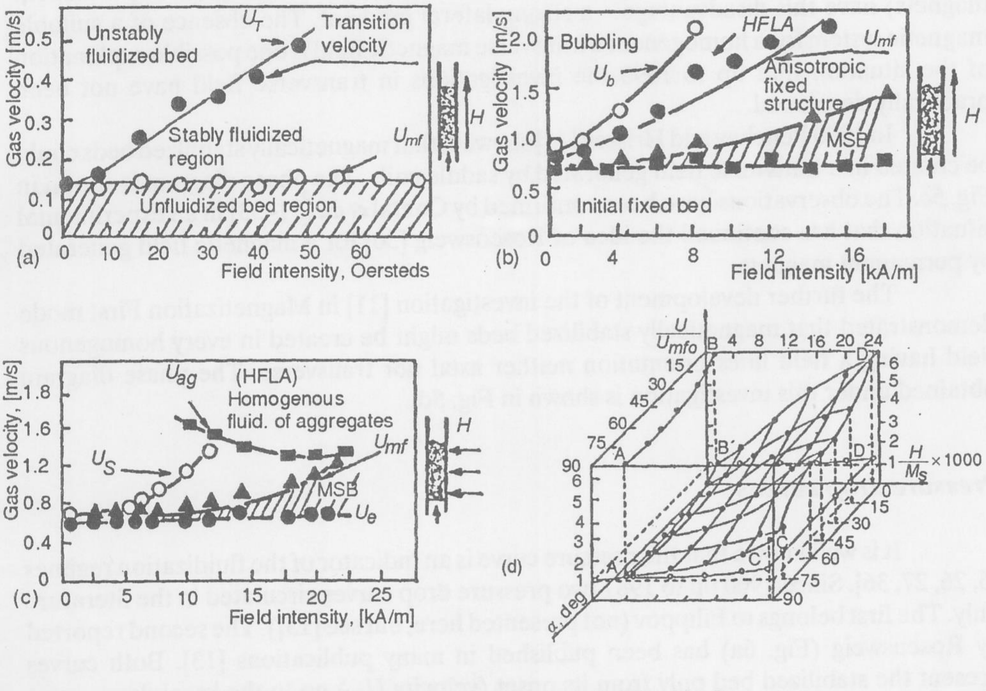

Figure 5. Phase diagrams for gas-fluidized beds

(a) Axial field. Rosensweig data [1, 30]; (b) Axial field. Penchev & Hristov [13]; (c) Transverse field. Penchev & Hristov [14]; (d) A homogenous field with various orientations. Effect of the field lines orientation and the field intensity. Magnetite, $h_{bo} = 50$ *mm,* $d_p = 400 - 500$ *mm, H/Ms – a logarithmic scale*

○ – *Velocity* U_e *(surface A' B' D' C')*; ● – *Velocity* U_{mf} *(surface A' B' D C)*

The curve AB presents the minimum field intensity required for bed stabilization

Rosensweig's data repeat in their sense the results of Filippov. The statement has been proved experimentally by Penchev and Hristov in 1990 [13]. The phase diagram obtained under this study is shown in Fig. 5b.

The experiments of Fillippov and Rosensweig have been performed in homogenous axial magnetic field (steady state). This experimental situation dominated over 35 years while the use of a transverse magnetic field was rare [30] and unsuccessful [28–29]. Moreover, these early results do not allow a comparison of the results. Rosensweig [30] pointed out that in a transverse field the bed expands at a velocity close to the minimum fluidization point without a field. However, the data have been published in a patent only and no further developments have been reported.

Rosensweig reported that the lateral gradient of the field is important for the quality of the **stabilized bed** (Rosensweig did not use this term in [30]. He used it for the regime observed in an axial field only. For comments on the terms see [20]). Under a field with a significant lateral gradient the bed fluidization has been impossible. Probably this unpleasant result stopped further studies in a transverse field. Unfortunately, the result of Rosensweig is an artefact produced by the magnetic system used. As mentioned above, all the magnetic system based on parallel flat poles (electromagnets or permanent magnets) have this disadvantage – a strong lateral gradient. The absence of a suitable magnetic system for a homogeneous transverse magnetic field is one possible explanation of the situation that up to 1990 the investigations in transverse field have not been practically developed.

In 1990 Penchev and Hristov [14] showed, that magnetically stabilized beds could be created in a transverse field generated by saddle coils. The phase diagram is shown in Fig. 5c. The observations have been confirmed by Contal *et al.* [31–33] in an experimental situation that has continued the idea of Rosensweig [30] for a magnetic field generated by permanent magnets.

The further development of the investigation [11] in Magnetization First mode demonstrated that magnetically stabilized beds might be created in every homogenous field having a field lines orientation neither axial nor transverse. The phase diagram obtained under this investigation is shown in Fig. 5d.

Pressure drop curves

It is well known that the pressure curve is an indicator of the fluidization regimes [6, 26, 27, 36]. Since 1960 up to 1987 two pressure drop curves circulated in the literature only. The first belongs to Filippov (not presented here, but see [13]). The second reported by Rosensweig (Fig. 6a) has been published in many publications [13]. Both curves present the stabilized bed only from its onset (velocity U_{mf}) up to the breakdown point at the velocity U_T [1, 30]. In spite of dominating presence of the Rosensweig's fluidization curve, in. Casal pointed out [8, 37, 38] that there is "abnormal" bed behaviour after the transition velocity U_T. The results obtained after 1990 [13, 39, 40] indicated that Casal's "abnormal" curve (Fig. 6b) is the typical fluidization curve for beds fluidized in axial magnetic field (Fig. 6c).

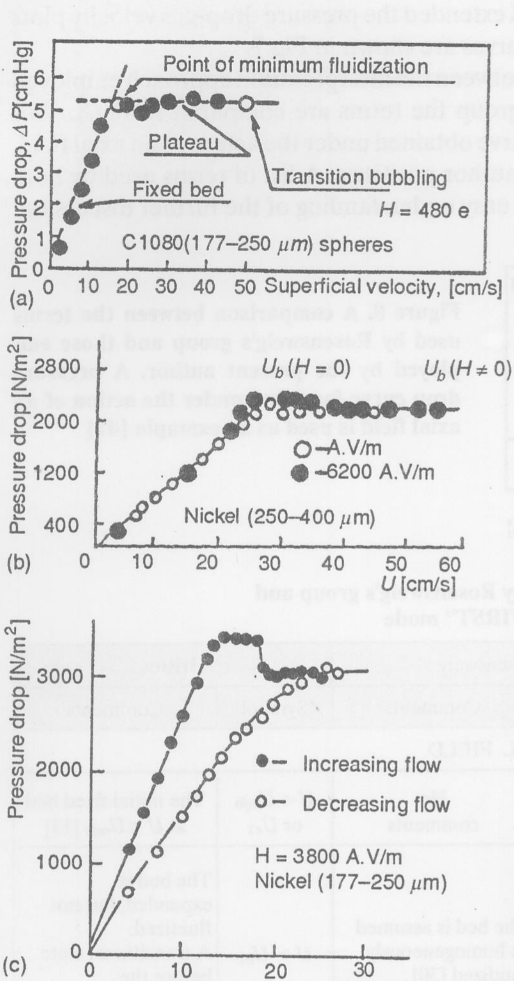

Figure 6. Pressure drop curves available in the literature before 1990

(a) Rosensweig's curve [1, 30] Axial field. Air – steel spheres C1080: 177–250 μm. The blank circles indicate U_{mf} and U_T. For more comments see [13]

(b) Casal's curve [8, 37] at low field intensities. Axial field. Nickel-air. There is no effect of the magnetic forces. The last right point corresponds to U_T

(c) Casal's "abnormal" curves [8, 37]. Axial field. Nickel-air. The last right point (the onset of the sharp pressure drop decrease) of the first plateau corresponds to U_T

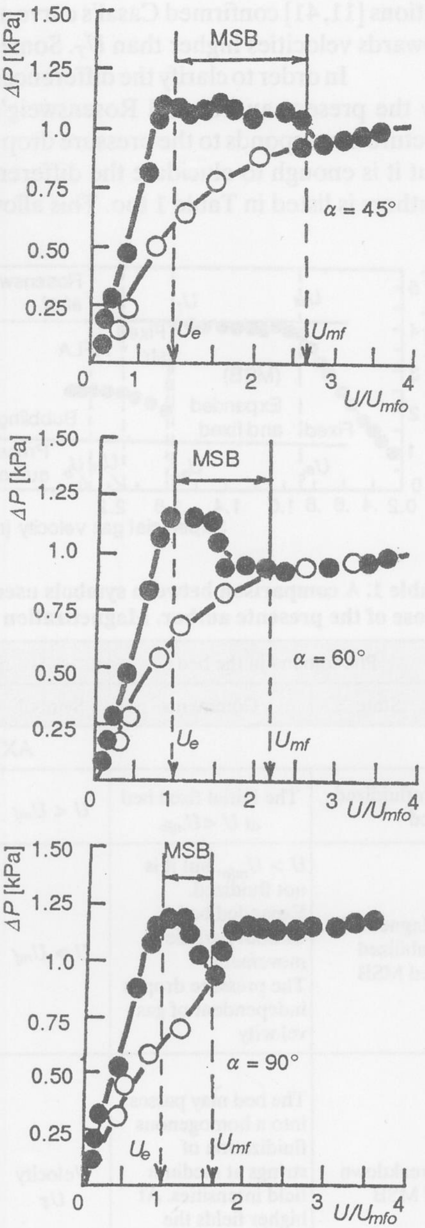

Figure 7. Pressure drop curves under a magnetic field with different field lines orientations. Adapted from [11, 41].
Magnetite, h_{bo} = 75 mm; H = 14 kA/m

The recent results obtained in homogeneous magnetic fields with various orientations [11, 41] confirmed Casal's curve and extended the pressure drop-gas velocity plots towards velocities higher than U_T. Some curves are shown in Fig.7.

In order to clarify the differences between the interpretation approach employed by the present author and Rosensweig's group the terms are compared in Fig.8. This picture corresponds to the pressure drop curve obtained under the action of an axial field, but it is enough to elucidate the different author positions. A list of terms used by both authors is listed in Table 1 too. This allows easy understanding of the further discussion.

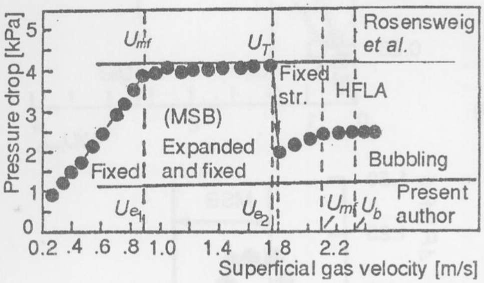

Figure 8. A comparison between the terms used by Rosensweig's group and those employed by the present author. A pressure drop curve for a bed under the action of an axial field is used as an example [41]

Table 1. A comparison between symbols used by Rosensweig's group and those of the presente author. Magnetization "FIRST" mode

Phenomena in the bed		Rosensweig		Hristov	
State	Comments	Symbol	Comments	Symbol	Comments
		AXIAL FIELD			
Unfluidized bed	The initial fixed bed at $U < U_{mfo}$	$U < U_{mf}$	No comments	$U < U_{mfo}$ or U_{e1}	The initial fixed bed at $U < U_{mfo}$ [13]
Magnetically stabilized bed MSB	$U > U_{mfo}$, but it is not fluidized. Expanded bed without particle movement. The pressure drop is independent of gas velocity	$U > U_{mf}$	The bed is assumed as homogeneously fluidized [30]	$U > U_{e1}$	The bed is expanded, but not fluidized. A transitional state before the fluidization onset [13]
Breakdown of MSB	The bed may passes into a homogenous fluidization of strings at medium field intensities. At higher fields the next state is a fixed structure of strings	Velocity U_T	The onset of bubbling *At* $U > U_T$ the bed is nonhomogeneously fluidized [30]	$U = U_{e2}$	Breakdown of MSB The bed may passes into a homogenous fluidization of strings at medium field intensities. At higher fields the next state is a fixed structure of strings [13]

Table 1. *Continuation*

Phenomena in the bed		Rosensweig		Hristov	
State	Comments	Symbol	Comments	Symbol	Comments
Fluidization onset	The fluidization onset may occur at that point under the action of medium intensity field	U_T	No comments	U_{mfh}	$A_{\iota} U > U_{mfh}$, there is no gas bubbles. The fluidized elements are the particle aggregates (strings), but not separate particles [13]
Onset of bubbling	Slender bubbles start to move between the strings	U_T	No comments	U_b	Slender bubbles destroy the homogeneously fluidized strings [13]
TRANSVERSE FIELD					
Unfluidized bed	The initial fixed bed at $U < U_{mfo}$	$U < U_{mf}$	No comments [30]	Unfluidized bed	The initial fixed bed at $U < U_{mfo}$ [14]
Magnetically stabilized bed MSB	$U > U_{mfo}$, bluidized witmovemesure drop decreases as the gas velocity increases	$U > U_{mf}$	The bed resembles like that in the axial field [30]	$U > U_e$	The bed is expanded, but not fluidized. A transitional state before the fluidization onset [14]
Breakdown of MSB	The bed passes into a fluidization with bubbles at medium field intensities. At higher fields the next state is a slugging fluidization strings	No symbol	No comments	U_m $(U_{mf}=U_b)$	The bed passes into a fluidization with bubbles at medium field intensities. At gas velocities the next state is a slugging fluidization strings [14]. The transition depends on the magnetic properness of the particles and the field intensity [14]
Fluidization onset	Coincides with the breakdown of MSB	No symbol	No investigations No Comments	$U_{mf} = U_b$	Fluidization with gas voids oriented transversely to the column axis. The bubbling precedes the homogeneous fluidization [14]

Table 1. *Continuation*

Phenomena in the bed		Rosensweig		Hristov	
State	Comments	Symbol	Comments	Symbol	Comments
Homogeneous fluidization of particle strings	Like in an axial field, but the aggregates are oriented transversely with respect the gas flow	No symbol	No investigations No comments	U_{ag} (Fig. 5c)	*At* $U > U_{ag}$, there is no gas bubbles. The fluidized elements are the particle aggregates (strings), but not separate particles [14]. However, they are oriented transversely with respect the gas flow [14]
Slugging	The regime occurs at higher gas velocity and low field intensities			U_s (Fig. 5c)	The bed is shifted in this regime at $U > U_{mf}(=U_b)$ [14]

Minimum fluidization point

The minimum fluidization point is the problem that causes many conflicts in the interpretations of fluidization behaviour of ferromagnetic particles in a magnetic field. The doctrinal interpretations will be discussed in the next chapter. Here we will comments the major approaches in determination of the fluidization onset in presence of an external magnetic field.

The minimum fluidization point may be determined by two principle methods well documented and discussed in the literature [6, 26, 27, 42]. The first approach is based on visual observations and his origin may be found in the earlier years of fluidization technique [26, 42]. It is well documented in the literature and used the fact that at that critical point an unrestricted motion of the particles starts. Its corresponds exactly to the behaviour of Geldart's B particles [36] studied intensively in 1960s. In the interpretation of the fluidization of A powders and more cohesive C materials the approach determines the bubbling point (Geldart's interpretation - see also [7] and [27]), but not the point with a velocity termed U_{mf}. The opinion of the present author differs from that commented above and it will be explained further. Some details of this opinion may be found elsewhere [11, 13, 14].

The **second** approach is based on a graphical treatment of pressure drop – gas velocity curve. The first modification is well described by Leva [42]. The minimum fluidization point corresponds to the intersection of two lines approximating the sections of the packed bed (for increasing gas flow) and the plateau with a constant pressure drop. The estimated value must be corrected with 1.10–1.15 in order to coincide with the experimentally observed minimum fluidization state.

The second method has been developed by Davidson and Harrison [26]. The fluidization onset corresponds to the intersection of the lines approximating the plateau and the packed bed (decreasing gas flow). Both methods have been proposed for fluidized beds of Geldart's B powders. In a fluidized bed with such "sand like" material the values of Davidson and Harrison ($U_{mf\text{-}DH}$) and Leva ($U_{mf\text{-}L}$) are practically equal. Both approaches use the fact that for B materials the hysteresis corresponding of the initial particle rearrangement (the over pressure "hunch") does not exceed 15%.

The commented methods are well known. Their repetition is due to the fact that all the investigations on MSB have been performed with cohesionless materials (*i.e.* B powders). The first experiments of Filippov [7, 15, 16], Bologna and Syutkin [17] and those of Rosensweig [1, 25, 30] (known as pioneering works in the Western literature) work with the Leva approach in determination of U_{mf}. All these authors reported that the minimum fluidization point is unaffected by the field intensity. The opinion may be found in the phase diagrams (Figs. 4, 5a).

Both graphical methods are illustrated on Fig. 9. The use of the plateau or the line approximating the fluidized state curve is strongly influenced by the opinion of the investigator. Two examples of the application of Leva approach will be discussed:

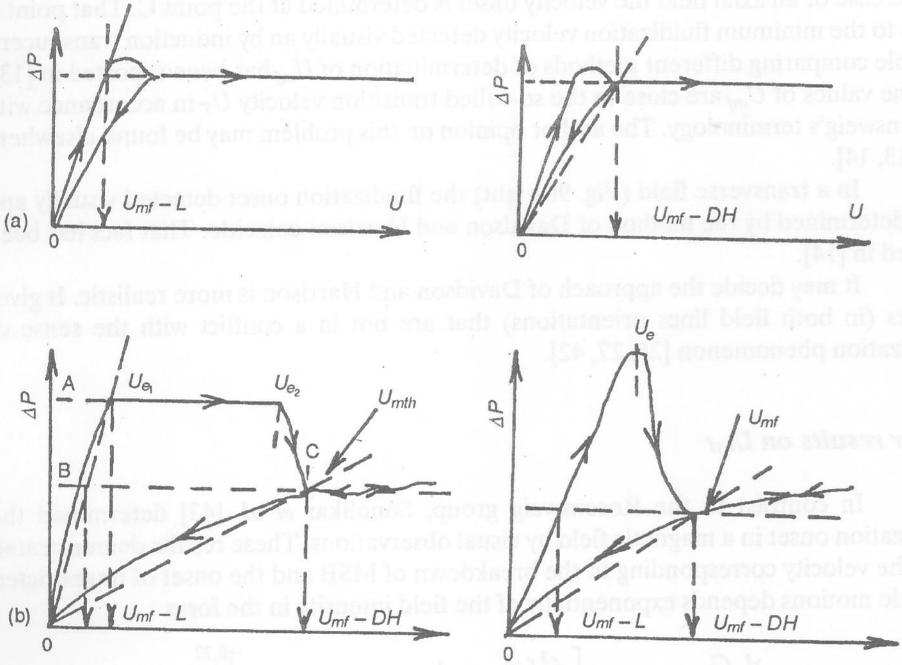

Figure 9. Graphical determination of U_{mf}
(a) Non-magnetic B powders. U_{mfo} (in absence of a magnetic field) determined by both graphical methods: Left – Leva's approach $U_{mfo} = U_{mf} - L$; Right – Davidson and Harrison approach $U_{mfo} = U_{mf} - DH$

An axial magnetic field (Fig. 9b left)

In this case there are two plateaux. One corresponds to the regime of MSB (between U_{e1} and U_{e1}) and the second one corresponds to the fluidized state ($U > U_{mfh}$).

The plateaux determine the $U_{mf\text{-}L}$ close to U_{mfo} (dotted lines and the intersections A and B in Fig. 9b- left. Both values are unrealistic: the intersections B corresponds to the state of a unfluidized bed and determines $U_{mf\text{-}L} < U_{mfo}$, while the intersection A corresponds to the onset of MSB and $U_{mf\text{-}L} = U_{e1}$. The dilemma is that both values of U_{mf} contradict the physical situation in the bed- there are no particle motions (a fixed bed or MSB). On the other hand the point A approach is in agreement with Rosensweig's interpretation (the dotted lines in Fig. 6a and the straight lines intersection in Fig. 10a).

A transverse magnetic field (Fig. 9b right)

The Leva approach determines the fluidization onset in a velocity range below the velocity U_e, which is close to U_{mfo} [14]. The intersection corresponding to $U_{mf\text{-}L}$ is at the middle of the line approximating the fixed bed state.

The method of Davidson and Harrison [26] gives more realistic values of $U_{mf\text{-}DH}$. In the case of an axial field the velocity onset is determined at the point C. That point is close to the minimum fluidization velocity detected visually an by induction transducers. A table comparing different methods of determination of U_{mf} has been reported in [13]. All the values of U_{mf} are close to the so-called transition velocity U_T in accordance with Rosensweig's terminology. The author opinion on this problem may be found elsewhere [11, 13, 14].

In a transverse field (Fig. 9b-right) the fluidization onset detected visually and that determined by the method of Davidson and Harrison coincide. That fact has been proved in [14].

It may decide the approach of Davidson and Harrison is more realistic. It gives results (in both field lines orientations) that are not in a conflict with the sense of fluidization phenomenon [26, 27, 42].

Other results on Umf

In contrast to the Rosensweig group, Sonolikar *et al.* [43] determined the fluidization onset in a magnetic field by visual observations. These results demonstrated that the velocity corresponding to the breakdown of MSB and the onset of unrestricted particle motions depends exponentially of the field intensity in the form

$$\frac{d_p G_{mb}}{\nu \rho_f} = 0.0213 \left[\frac{d_p^3 (\rho_s - \rho_f) g}{\nu^2 \rho_f^2} \exp(0.000125 H \right]^{0.72} \qquad (1)$$

where G_{mb} is the minimum mass gas bubbling velocity.

The same approach in determination of U_{mf} has been used in earlier Bulgarian investigations [44–46]. A typical relationship is that

$$\mathrm{Re}_{mf} = (5.7 \cdot 10^{-4} + 10^{-2} B)\mathrm{Ar} \tag{2}$$

where B is magnetic induction (in Wb/m^2).

Moreover these authors proposed a correlation for the velocity where bubbles appear in the beds

$$\mathrm{Re}_{mb} = \frac{U_{mb} d_p}{\nu}\left(3.1 + \frac{4.11}{W} B\right) 10^{-4}\,\mathrm{Ar} \tag{3}$$

where W is the bed weight in kilograms.

It must be noted that in the earlier studies of Bulgarian authors strongly heterogeneous fields axial have been used. Furthermore, in the derivation of Eqs. (2–3) the basic assumption is that at the minimum fluidization point the pressure drop is equal of the bed weight per unit area of the grid. This assumption has been combined with experimentally determined values of U_{mf}. It follows from both equations that U_{mf} depends on the field intensity. Thus, there is a conflict because the bed weight is unaffected by the field. In spite of this these studies are important because they pointed out that the fluidization in a magnetic field might be interpreted in accordance with the classical postulations of fluidization.

In 1986 Arnaldos [47] proposed a similar expressions for the bubbling velocity, *i. e.* the velocity U_T in accordance with Rosensweig's terminology.

$$\frac{U_b}{U_{mf}} = \mathrm{e}^{(a+bH)\mu_0 H} \tag{4}$$

All the equations give relationships for the velocity at which the gas flow breaks down the stabilized bed. The matter of argument is the interpretation the phenomena in the bed. Arnaldos and Casal follow the Rosensweig terminology in the description of bed while Sonolikar [43] and all Bulgarian investigators of the group of Ivanov interpret bed hydrodynamics in sense of the fluidization phenomena described by Davidson and Harrison [26] and Leva [42].

Figure 5d shows recent results about the simultaneous effect of the field intensity and field lines orientation on the critical velocities U_e and U_{mf} [41]. The figure illustrates in a more informative way the results published in [11].

Thus the principle question arising from these studies is does U_{mf} depends or not on the field intensity. This is the major dilemma in that attractive fluidization technique. It comes from the fact that the pressure drop curves (Fig. 6) in the regime of MSB have plateaux. Thus, using the well-established facts in the literature [26, 27, 42] **the stabilized bed can be assumed as fluidized in contrast of its fixed structure.**

The existence of a plateau in the pressure drop curve was established as an indicator for the fluidized state at the very beginning of the fluidization and corresponds to the fluidization of coarse particles (Geldart's B particles, 1973 [36]). In this case the interparticle forces are negligible and the unrestricted particle motions corresponds to a pressure drop which is independent on the gas velocity.

In all the experiments with MSB coarse particles (*B*-materials) have been used [13, 14]. It is easy to understand the position of Filippov in the determination of the minimum fluidization point. His knowledge corresponds to the facts available in the literature up to 1960. Unfortunately, despite the significant amount of fluidization results on the behaviour of cohesive materials in 1970 s and 1980 s there are no developments of the data interpretation. In fact Rosensweig's description repeats that of Filippov, despite the "pseudothermodynamic" approach.

The recent investigations [11, 13,14, 41] gave new results and interpretations of the fluidization onset. The pressure drop curves shown on Fig. 7 have been obtained in a homogeneous field with an orientation that is neither axial nor transverse. The plateau disappears, as the field orientation becomes more different than the axial one. In a transverse field there is no plateaux corresponding to the regime of MSB. This is strong indicator that the shape of the pressure drop must be used carefully for phenomena interpretation in complicated cases of fluidization.

Pressure drop across the bed

Since 1960 (Filippov experiments) in the literature dominates the assumption that the pressure drop across the bed is equal to its weight per unit column cross-section area. Rosensweig [1, 25, 30] has claimed the same postulation. Despite this the data reported by Rosensweig ([30] Table IV) contradict this postulate. They are presented graphically on Fig. 10a, . On the other hand Fig. 10b shows the pressure drop in MSB

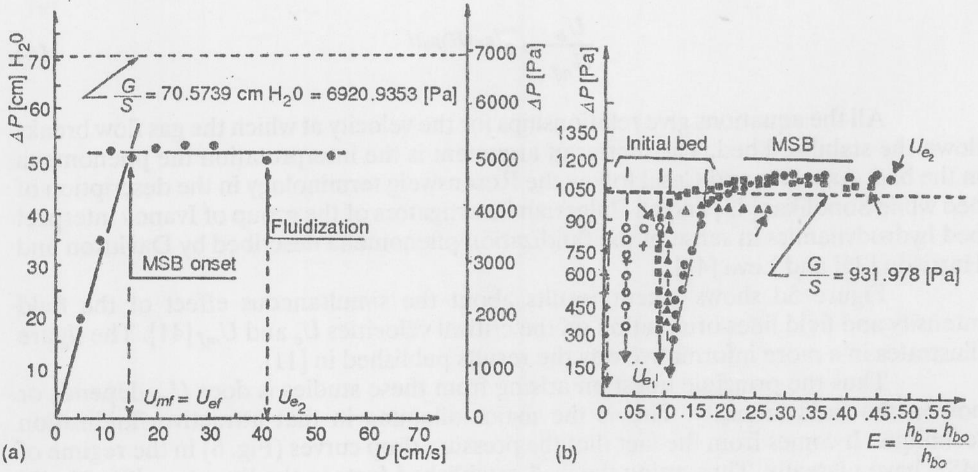

Figure 10. Presure drop across the MSB

(a) Rosensweig's data [30]. Air – steel spheres. The ratio G/S and the dotted lines have been added by the present author in [41]

(b) Pressure drop versus the relative bed expansion, E. Adapted from [13]. Dotted lines are added for the present paper. More details are available in [13].

H, kA/m: + – 0; ○ – 8.5; ■ – 20; ▲ – 30; ● – 42 may be lower or greater than the value defined by the ratio G/S(bed weight, G, per unit cross-section area of the bed, S).

The effect of the field intensity and the magnetic properties of the particle material need special experiments. The recent results [11, 41] indicated that all the case the pressure drop across MSB is always lower than G/S. This may be attributed of the existence of strong interparticle forces which allow to "support the particle weight" in contrast with the "normally fluidized particles", *i. e.* the "magnetic cohesion helps the fluid flow.

The recent results of Hristov [11] demonstrated that the pressure drop required for shifting the bed from the fixed bed into the stabilized one increases parallel of both the field intensity and the particle magnetization. Moreover it increases as the field orientation aspires from axial toward transversal.

Bubbles

One of the main ideas for the creation of magnetically controlled fluidized beds was to eliminate the gas bubbles. Moreover, the experiments have been performed with Geldart's group *B* (see detailed data in [13, 14]) demonstrating an intensive bubbling just above the point corresponding to U_{mf} in absence of a magnetic field. Figure 11(a, b) shows Rosensweig's explanation of the magnetic field effect on gas void collapse in MSB. In accordance with Rosensweig's result the bubbles appear after the breakdown point of the stabilized bed (the so-called transition velocity U_T). The magnetic forces tend to "shrink" the gas void (Fig. 11b).

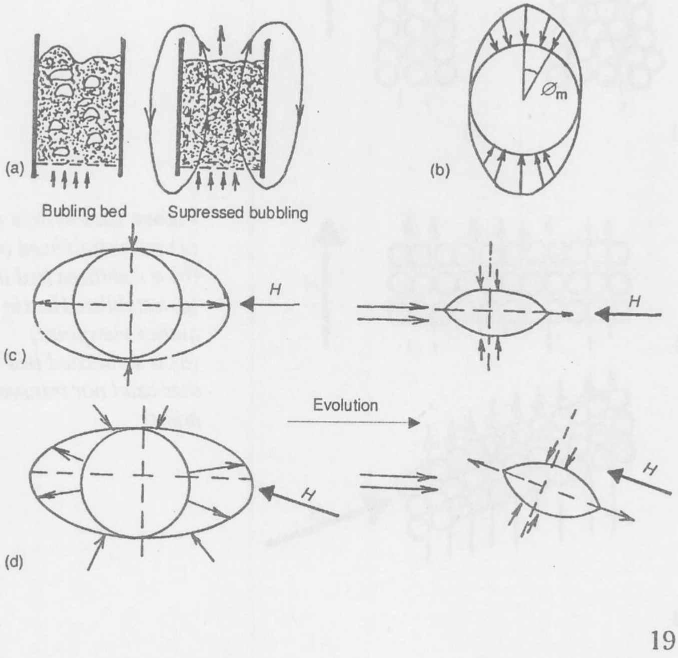

Figure 11. The basic idea of MSB
(a) Elimination of gas bubbles [1, 30]
(b) The mechanism of the gas void (bubble) collapse in a magnetizable medium [1, 30]
(c) Gas void evolution in a transverse magnetic field (the present author viewpoint)
(d) Gas void evolution in a field with orientations different from axial and transverse ones (the present author viewpoint)

In the studies [13, 14] it has been commented that the onset of bulling depends on the field line orientation. In the axial field [13] there is a narrow regime of a homogenous fluidization between the breakdown of MSB and the onset of bubbling. The particle arrangement in MSB and the regime of a homogeneous fluidization may be rigorously explained by Arnaldos' structural model [47] (Fig. 12a, b) .On the other hand in a transverse field [14] the bubbles (transversely oriented gas voids – Fig. 11c) have appeared just after the break-down of MSB [14]. These results are illustrated on the phase diagrams (Figs. 5), presented as the minimum bubbling points. Figure 11d shows schematically the gas void evolution in a field that is neither axial nor transverse.

These changes in the order of the bed regimes have been confirmed in the recent study [11]. They may be explained by the particle arrangement along the filed line and orientation of the fluid flow (Fig. 12c, d). The evolution of a gas void (Fig. 11c, d) and the particle arrangement (Fig. 12c, d) explain the order of the bed regime after above the velocity U_{mf}. It is clear that in the case of a gas flow parallel with the field lines the magnetic forces suppress the gas voids in a lateral direction. They become more slender and have a longitudinal dimension close to the bed height (this corresponds to the experimental data available in the literature with shallow beds). In a transverse field the particle

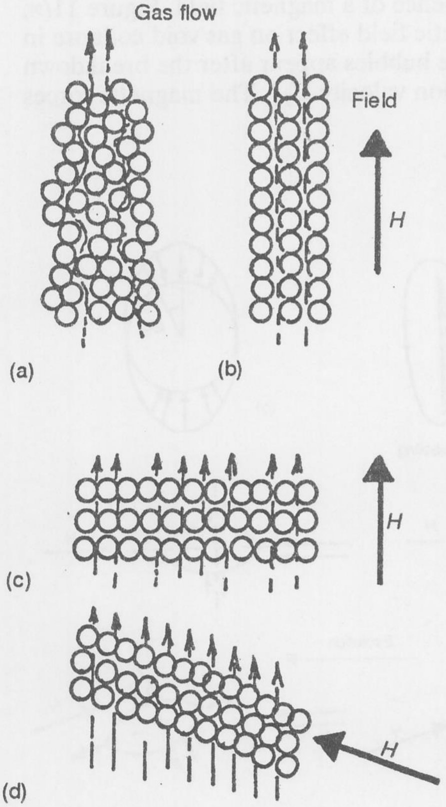

Figure 12. Particle arrangement in MSB
(a) an unstabilized bed [47]
(b) a stabilized bed in an axial field [47]
(c) a stabilized bed in a transverse field (the present author viewpoint)
(d) a stabilizied bed in a homogeneous field neither axial nor transverse (the present author viewpoint)

arrangements and the gas voids evolution indicate that the magnetic field tolerates the formation of bubbles which may reach the column wall. As reported in [14] under strong fields a slugging regime is available (Fig. 6c).

Furthermore, most of the experimental studies have been carried out on the effect of field intensity on bubbles in preliminarily fluidized beds (magnetization LAST). These interesting results will be commented in the next part of the series.

Phenomena – relationships with known results from non-magnetic fluidization

In order to estimate the origin of the different data interpretations (and some times conflicts in the literature) it can be concluded that the plateau in the pressure drop curve is not an undoubted argument for the assumption that the bed is fluidized without **proved particle motions.** The plateau that is observed in an axial field (and the reason of the conflicts) is a special effect of the collinearity of the field flow and the field lines.

The viewpoint of the present author is that Rosensweig's interpretation leads to data treatments conflicting with the sense of fluidization as well as isolates the fluidization of ferromagnetic particles from the other fluidization techniques. On the other hand the interpretation performed by some small groups (Sonolikar, Ivanov and all) are realistic, but they did not obtained a win in the struggle du to the lack of documented experimental data (for comments see [13, 14]. The recent results [11, 13, 14, 41] indicate that Rosensweig's interpretation is inadequate with the fluidization phenomena. These results give a new chance of the of the so-called "eastern country" interpretations to prove their adequacy with the support of well documented and published results.

In a fundamental aspect, the magnetofluidized bed (a term used by Sonolikar [3]) is an artificial system showing transitions in the fluidization behaviour. These transition are particularly attributed to the interparticle forces (like in the Geldart interpretation) controlled by an external field. Figure 13 shows a summarized graphical collection of pressure drop curves obtained under different physical fields. It is evident that the external fields (magnetic or electric) acting on polarizating materials controls the behaviour transitions. In all the case "humpbacked" pressure drop curves emerge.

From a fundamental point of view and following Geldart's description the magnetically stabilized beds demonstrate B–A and A–C transitions [13, 14]. This analogy has been commented in [11, 13, 14], but it will be described briefly here for the clarity of explanation.

It is well known that under increasing interparticle forces (mainly due to the decrease of the particle diameter) sand like material, which is normally fluidizable (B behaviour) may exhibit A behaviour. These two behaviour are shown schematically in Figs. 13a and 13b.

All the experiments in magnetic field (see summarized data in [13, 14]) have been performed with coarse materials. In absence of a magnetic field they exhibit "normal" B fluidization behaviour. Under the action of the induced interparticle forces an extension of the "humpback" emerge along the gas velocity axis. In an axial field the "hump" behaves as a plateau from U_{e1} up to U_{e2} (Fig.13e) or from U_{mf} to U_T as shown in Fig. 13c, d like in the case of fluidization on non-magnetic A powders. In a transverse field the "humpback" is sharp (from U_e to U_{mf} – Fig. 13f).

The physical state of the magnetizable bed (in spite the field lines orientation) corresponding to the "humpback" resembles that demonstrated by non-magnetic cohesive A materials: an expanded bed volume at $U > U_{mfo}$ and a fixed structure of particles and cavities without particle motions. Thus under controllable "magnetic cohesion forces" the normally fluidizable B materials demonstrate A fluidization. Two examples obtained under an electric field and dielectric powders are shown in Figs. 13g, h. In these cases the electric field applied had a transverse orientation (by means of parallel plates). It is clear that in spite of the nature of the induced interparticle forces (magnetic or

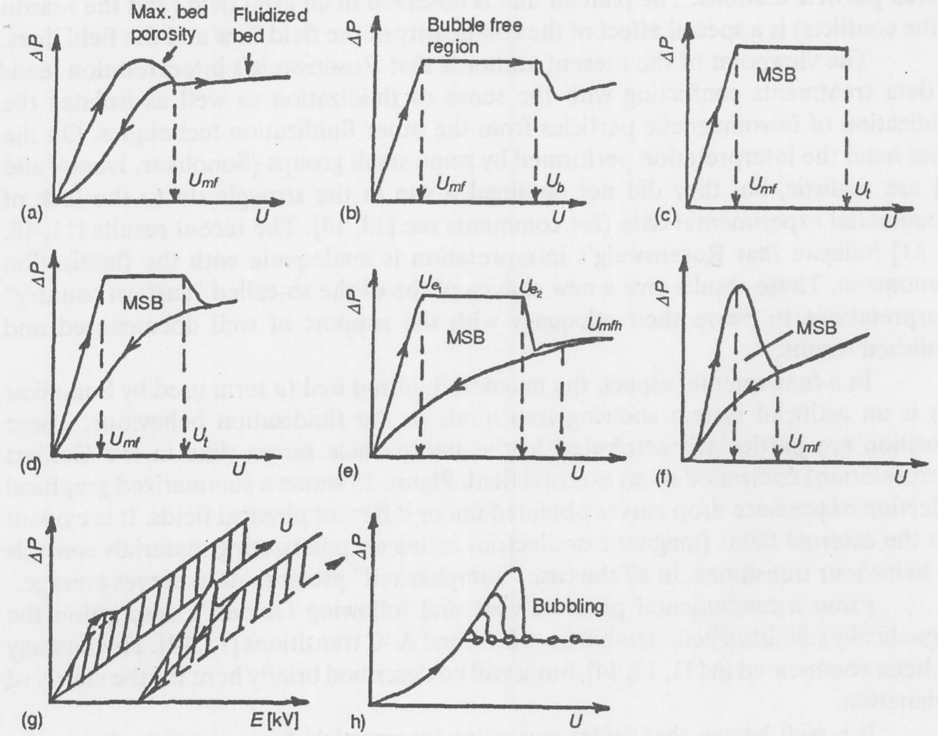

Figure 13. Effects of the interparticle forces on the shape of the present drop curves
(a) B – powders; (b) A – powders; (c) Axial field: Rosensweig [1];
(d) Axial field: Casal [8]; (e) Axial field: Penchev and Hrisotv [13];
(f) Transverse field: Penchev and Hristov [14];
(g) and (h) Transverse electric field and dielectric powders;
Johnson and Melcher [9]

electric) the qualitative bed behaviour is the same – the "humpback" emerges as the interparticle forces increases.

The A–C transition can be easily seen in the case of fluidization in an axial field. At stronger field the fluidization is impossible and the broken MSB (at U_{e2} or U_T) passes into a fixed structure of strings. Channels avoiding fluidization divide these strings. That structure may be destroyed at higher gas velocities. A pressure drop curve showing this transition is shown in Fig. 8. Detailed description of the phenomenon is available in [13] (first report) and [39].

Thus the physical behaviour of magnetizable bed under strong magnetic fields (strong interparticle forces) resemble that of non-magnetic C powders (the left corner of Geldart's diagram available in many sources: [6], [36], [48]).

The above remarks focus the attention on the definition of the fluidization onset. Obviously the fluidization starts at the point when the drag forces overcomes the interparticle forces and an unconstrained flow of the particulate material inside the container begins. From this position, the fluidized system is a system with continuous interparticle dynamic contacts. The above sentences may be assumed as a general definition of the fluidization onset. It covers the particular case of the fluidization of non-cohesive materials in a gravitational field as well as the cohesion effects (van-der Waals, electric and magnetic) on the fluidization behaviour.

Finally, the comments in the present paper show that MSB is not a laboratory trick and the results obtained can be easy incorporated in the existing fluidization theory.

CONCLUSIONS

The present paper focuses on some problems having contradicting interpretations in the published articles. The attempt of the author is to demonstrate that the data interpretations may be different from those dominating in the literature without. The opinion of the author is that the new look on the phenomena in magnetically controlled beds and the possibility to arrange the data in this specific area among the data well known from the classic field of fluidization.

Nomenclature

Ar – Archimedes number
d_p [m] – particle diameter
E – relative bed expansion, $E = (h_b - h_{bo})/h_{bo}$. Defined in [13, 14]
G [kg] – bed weight
G_{mb} [kg/m^{2}s] – minimum bubbling mass velocity
H [A/m] – magnetic field intensity
h_b [m] – bed height
h_{bo} [m] – initial bed height (before the fluidization onset)

M_s [A/m] – magnetization at saturation (for comments see [1, 11, 13, 14, 30])
s [m^2] – area of contact between two particles
P [Pa] – pressure
ΔP [Pa] – pressure drop
r [m] – a distance between the centres of magnetically interacting particles
S [m^2] – area of the column cross-section
U [m/s] – gas superficial velocity
U_{ag} – gas velocity at the onset of the regime of a "homogeneous fluidization of particle strings in a transverse field". For details see [7, 14]
U_b [m/s] – minimum bubbling velocity
U_e [m/s] – gas velocity at the onset of MSB (all field orientations except the axial one [11, 14])
U_{e1} [m/s] – gas velocity at the onset of MSB – an axial field only [11, 13]
U_{e2} [m/s] – velocity at the breakdown of MSB [11, 13]
U_{mf} [m/s] – minimum fluidization velocity
U_{mfo} [m/s] – minimum fluidization velocity in absence of a magnetic field
U_{mfh} [m/s] – minimum fluidization velocity in an axial magnetic field
Note: U_{mfh} is the velocity at which the regime of a "homogeneous fluidization of particle strings" starts. For details see [11, 13]
U_T [m/s] – transition velocity
U_s [m/s] – slugging velocity

Greek letters

ρ_s [kg/m^3] – particle density
ρ_f [kg/m^3] – fluid density
ν [m^2/s] – fluid kinematic viscosity
μ – magnetic permeability

Abreviations

MSB – magnetically stabilized beds
HFLA – homogeneous fluidization of aggregates (particle strings)
FIXED STR. – Fixed Strings – a state available in axial field only [13]

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