

investigations on magnetic semifluidization on a broader spectrum to judge its suitability to different process applications along the lines that have become common for other fluid-solid systems such as packed and fluidized beds.

II.3. Batch solids mode - Several solitary but important results

II.3.1. Siegell's frozen beds

II.3.1.1. Regimes

Siegell (1988) reported a unique study of beds imposed on the action of such strong field intensities that the bed has lost its fluidizability. Siegell termed such beds “frozen beds”. At high magnetic fields the fluidized solids change from operations in the stabilized regime to operations in the magnetically frozen regime. In the frozen bed the particles are locked together in relative position and do not flow. In accordance to the description of Siegell (1988) the magnetization mode employed is magnetization FIRST (see details below).

Figure 25 shows a phase diagram demonstrating the position of the frozen bed in accordance with the magnetization FIRST mode. Three distinct

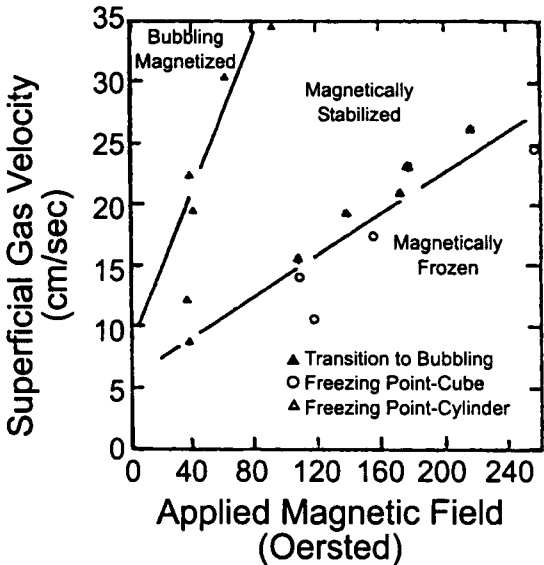


Fig. 25: Phase diagram of gas-fluidized beds. Experiments of Siegell (1988) on frozen beds of magnetite (-60+80 U.S. sieve). No additional data about the experiments are available.

regimes are detectable: i) the magnetized bubbling; ii) stabilized bed (MSB); and iii) the magnetically frozen. Table 10 gives a comparison of the properties as they pertain to possible use in process industry applications.

It should be noted again that despite the term “frozen”, Siegell’s frozen beds differ from those obtained with the Magnetization LAST mode (Hristov, 1998b) (see also the comments in Part 1 (Hristov, 2002) and sometimes termed “condensed” beds (Zhu and Li (1996) for example) – see Table 10.

II.3.1.2. Limits of the magnetically frozen regime

The magnetically frozen bed has many of the properties of a packed bed. The tests performed by Siegell (1988) for the definition of the demarcation line between magnetically stabilized and magnetically frozen bed are of special interest since under fluidization both beds exhibit fixed bed behaviour. Testing the range within which a large lead weight would be supported by the bed, the transition to the frozen regime (see Fig. 25) was detected. Siegell (1988) employed a 1-in cube and a cylinder (1-in long and 1-in in diameter). In a normal fluidized bed and the stabilized bed the weights would sink through the bed to the distributor. However, when the bed is frozen the weight is supported by the top surface of the bed.

Siegell (1988) first applied a field of over 300 Oe ($\approx 24\,000$ A/m) on a magnetizable particle bed. Then the fluid was increased to obtain the desired fluidization velocity. One or two weights were placed on the top of the bed. The lower limit of the frozen regime was determined by slowly decreasing the magnetic field until the weight just begins to sink into the bed. The results are shown in Fig. 25.

The values of the minimum field intensities required to create frozen bed detected by Siegell may be evaluated by a simple graphical procedure developed here. The graphical treatment of Siegell’s plot (see Fig. 26) allows detection of the minimum field intensities required to support the test weights. Two critical values of the gas superficial velocity are chosen corresponding to $FIM = 0.2$ and 0.33 respectively. The data obtained are summarized in Table 11 together with values of H collected in Part 1 (Hristov, 2002) on the basis of a simple graphical treatment of FIM - H curves of magnetite beds. The data in Table 11 indicate that the minimum field intensities required to detect the transition from stabilized into the frozen regime are from 1.16 to 1.6 greater than those determined as the upper field intensity range of the stabilized bed (Hristov, 2002). The data summarized in Table 11 show that the field intensity of 300 Oe ($\approx 24\,000$ A/M) initially applied by Siegell assures a value of $FIM = 0.2$ approximately.

Table 10
Comparison of fluid/solid/magnetics operating regimes - axial fields.
Magnetization FIRST mode

Properties ↓	Operating regime →	Siegel's comments: Siegel (1988)			Comments - Present work	
		Bubbling Magnetized	Magnetically stabilized	Magnetically frozen	Bubbling Magnetized	Magnetically stabilized Magnetically frozen
Fluid velocity range	Below particle terminal velocity	Below particle terminal velocity	Limited by the loss of bed fluidity at high magnetic fields	Limited by the pressure drop but must be retained in the vessel	Below particle terminal velocity	- In the range of (1-5) U_{mt} in an axial field. $0.8 > FIM > 0.2$ (Kirko and Filippov, 1960) Penchev and Hristov, 1990b)
Bed pressure drop	Low	Low	Low	Moderate. None to high	Low	- Low but varies with the field intensities - Approaches the bed weight (see comments in Part1 based on the results of Hristov (1994)
Bed fluidity	High	Low	Low	None	High	- NONE -under the fluid drag forces. - YES -under tilting bed experiments - None. - Visually detected "piston" like behaviour (Kirko and Filippov, 1960) Penchev and Hristov, 1990b)
Bed structure *	Continuous particle mixing*	Continuous particle mixing*	Anisotropic*	Like a conventional packed bed*	Mixing of particle and aggregates with gas bubbles	- Like a conventional packed bed. - There are no possibilities for particle rearrangements
Bed wall-heat transfer	High	High	Low	Low	High	- Not investigated yet - Hristov, 2002 and Part3 (Hristov, 2003)

* - comments inserted by the present author on the basis of the description given by Siegel (1988)

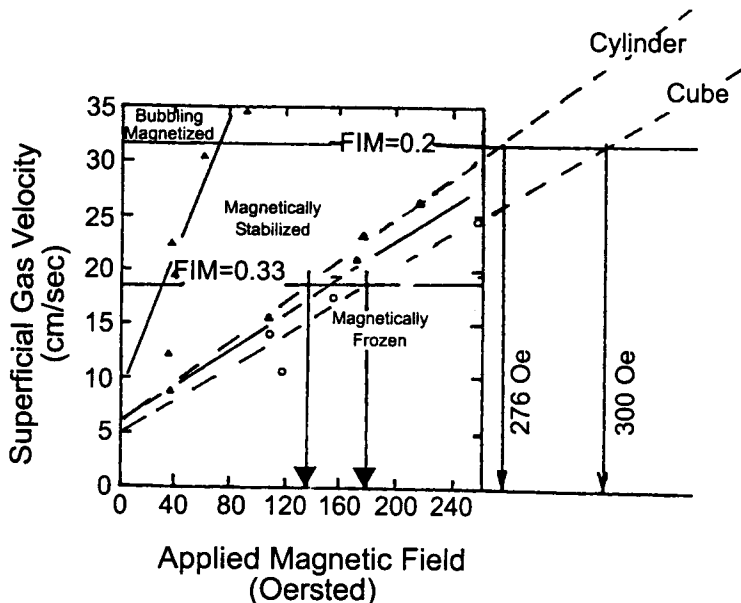


Fig. 26: Graphical treatments of the Siegel's phase diagram for two values of FIM. Present author's arrangements by extrapolations of: i) lines of the transition point of each test weight; and ii) the all phase diagram towards the higher field intensities.

Table 11

Minimum field intensities required to create a frozen bed and data from experiments with Magnetization FIRST mode - Magnetite particle bed.

Siegel's experiment with weights. Siegel (1988) (graphical treatment of the data)			Data obtained from experiments with MSB Hristov (2002)
Minimum field intensity required to create the frozen regime			
Probe and procedure	Cube	Cylinder	Graphical treatment of FIM- H curves in an axial field (Fig. 58a and Table 15)
Field intensity applied	> 300 Oe	> 300 Oe	< 15 kA/m
Determined graphically by the present author - see the arrows for FIM= 0.33 in Fig. 26 - the original Siegel's plot	180 Oe (14.4 kA/m)	135 Oe (10.8 kA/m)	10.8. kA/m at FIM= 0.33*
Determined graphically by the present author - see the arrows in Fig. 26 - extrapolated Siegel's plot for FIM= 0.2	300 Oe (24 kA/m)	276 Oe (22.080 kA/m)	14.2 kA/m at FIM = 0.2+
+ not reached in the experiments; *- reached in the experiments			

11.3.1.3. Qualitative experiments

The experiments with sinking test weights clearly indicate that heavy bodies may destroy the loose anisotropic structure of the stabilized bed while in the case of ordinary packed beds the test body cannot destroy the interparticle contacts. Siegel reported similar information from qualitative experiments with a probe moving into the bed. A probe placed into a stabilized bed was easily moved from side to side to through the bed, while such movement was very difficult inside the frozen bed. Moreover, its sinking toward the distributor followed the release of the probe, while in a frozen bed it rested in position.

Furthermore, the removal of the probe led to a collapse of the void inside the body of the stabilized bed. The effect is a result of the loose bed structure and the tendency of the ferromagnetic mass to collapse (i.e. to minimize its volume – Earnshaw's theorem (Weinstock, 1976) commented upon in Part 1 of the series). In contrast to MSB in the frozen regime a permanent channel occurred at the place of the probe when it was removed. The bed did not fill the gap.

Siegel mentioned the bed behaviour from the position that the yield stress within the bed (see for the details the section Rheology) depends on the field intensity (i.e. the strengths of the interparticle contacts) and the distance between the solids. The empirical relationship of Rosensweig (1985) gives a simple explanation of the yield stresses required to cause particle movement (flow) as function of bed voidage.

$$\tau = \frac{AM_P^2}{4\pi \epsilon^{12}} \quad (4)$$

for $0.48 < \epsilon < 0.59$.

The value of the constant A is a function of the solids and the type of the field ($A = 3.3 \cdot 10^{-5}$ in a steady field and $0.5 \cdot 10^{-5}$ in a time varying field) (Rosenzweig, 1985).

Typically, the frozen regime begins at particle magnetization M_p of around 1000 Gauss (Lee, 1984) i.e. $M_p > 80$ kA/m. The corresponding field intensity for magnetite particles is around 20 kA/m (Geuzens, 1985; see also the inset in Fig. 59 of Hristov (2002) that confirms the results of the above discussion.

II.3.1.4. Frozen bed of mixtures

Siegl reported that a mixture of iron steel spheres and Ottawa sand exhibited similar behaviour to that illustrated by Fig. 27. It was found that under certain conditions the bed began to rise up as a piston. This levitation is shown in Fig. 27 as a transition phenomenon between the MSB and the frozen bed.

II.3.1.5. Bed levitation and transport

Siegl (1988) reported a test experiment on a bed moving as a slug through the vessel. The minimum bed depth required to obtain a stable slug was established of about 50% of the vessel diameter. The shallow beds did not keep their cylindrical shapes and the gas appeared through several channels.

The minimum superficial gas velocity required to initiate the slug movement decreases as the field intensity is increased (Fig. 28a). At higher field intensities lower gas velocities are needed to transport the frozen bed as a cylinder with flat top and bottom surfaces. The experiments on the

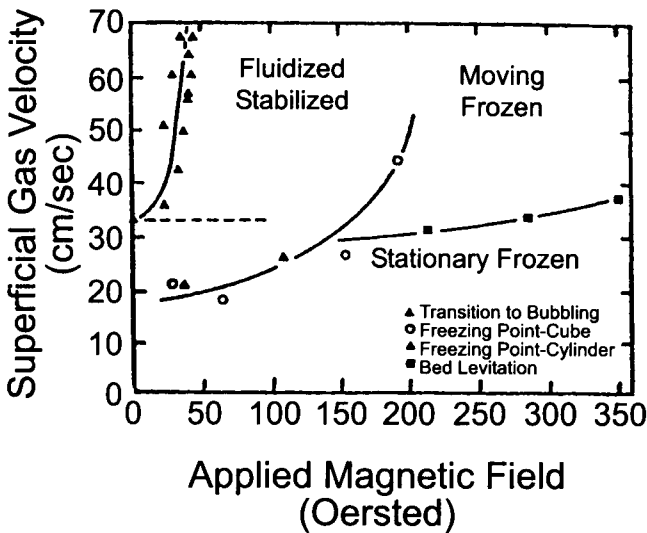


Fig. 27: Regimes of fluid/solids magnetic operations of admixtures: 50 % steel spheres (-45+50 U.S. sieve) and 50% (-30+50 U.S. sieve) Ottawa sand. From Siegl (1988). No additional data about the experiments are available.

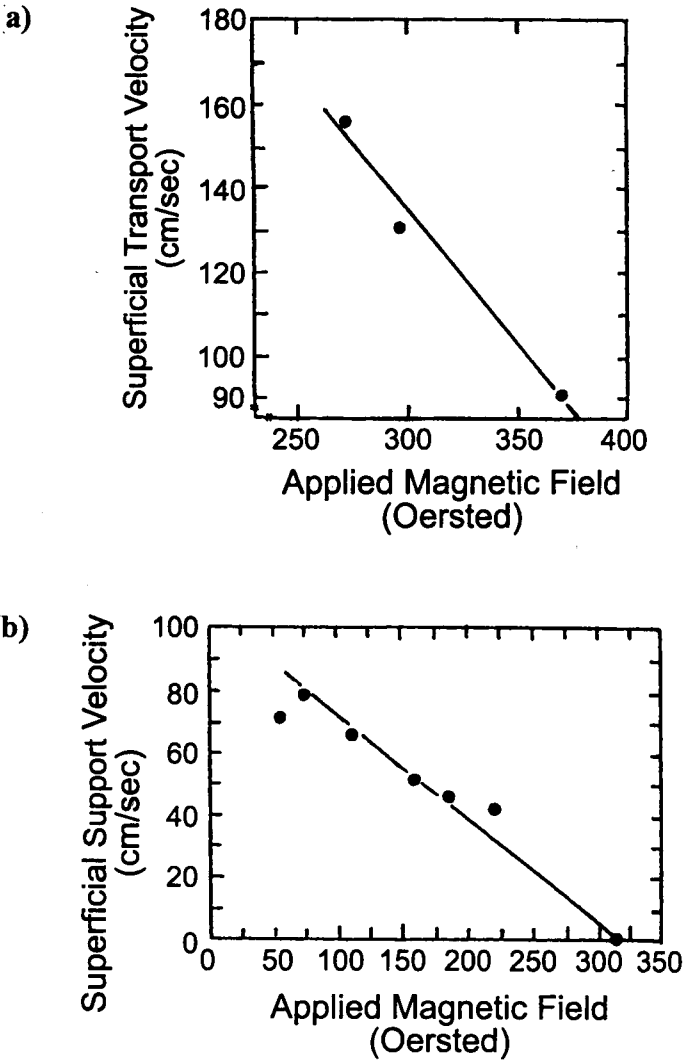


Fig.28: Minimum gas superficial velocities required to cause frozen bed movement. From Siegel (1988). Particle beds of -50+60 U.S. Sieve steel spheres

- a) Minimum superficial gas velocity required to initiate frozen bed transport
- b) Minimum superficial gas velocity required to support a magnetically frozen bed without a gas distributor.

determination of the minimum field velocity required to support the slug without a gas distributor are shown in Fig. 28b. The tests were performed under field intensity over 350 Oe and a restraining screen avoided the bed escape. The minimum gas velocity at which the slug began to fall down was recorded (at a given field intensity).

The transport tests have initiated experiments on the continuous addition and removal of solids and a continuous operation maintained with steel spheres (-18+20 U.S. sieve) and $U = 160$ cm/s under the action of a field intensity of about 240 Oe applied on the top third of the bed).

II.3.1.6. Comments on Siegell's frozen beds relevant to the problems of MSB

The magnetically frozen bed (designed and developed by Siegell, 1988) demonstrates in a very strong form the stabilizing action of the interparticle magnetic forces. This problem was discussed in Part 1 (Hristov, 2002). However, the experiments with test weights clearly indicate several major facts that are relevant to the fundamentals of MFAF:

- i) The phase diagram U - H defines three fixed bed states: an initial fixed bed, a frozen bed and a stabilized bed. The first two beds have practically equal structures since in accordance with the Magnetization FIRST mode the field applied on the initial fixed bed does not destroy the particle packing. Thus, both beds have fixed structures with maximum available densification of the powder body because the B particles (Geldart, 1973) do not form loose beds in a gravitational field only. The frozen bed structure is more stable due to increased stability of the interparticle contacts.
- ii) Due to dense particle packing discussed in (i) the heavy test weights do not sink into the bed. The cube (or a cylinder) weight is not enough to destroy the interparticle contacts and to initiate a particle flow inside the vessel. However, if the weight of a test body is decreased (an imaginary experiment with a wooden or a plastic body) lower field intensities would be enough to support it on the top surface even in the regime of the stabilized bed. For example experiments with light bodies (cork stoppers and celluloid balls) immersed in the bed have been performed by Rosensweig (1980). In these limited cases the objects have been released toward the top surface of the bed.

- iii) The comments in (ii) lead to the well-known fact that MSB exhibit a fixed bed structure. Moreover, the relationship between the shear stresses and the bed voidage (Eq.4) indicates that the surfaces forces (magnetic forces of attraction) at the interparticle contacts and the shear stresses required to induce a particle flow are of the same order. The increase of the bed voidage (i.e. the bed expansion) is available if the fluid drag forces may initiate local shear stresses in the bed body equal to or slightly greater than the interparticle forces (considered as normal forces at the points of the interparticle contacts). These local deformations cause the bed expansion.
- iv) Thus, the shear stresses induced by the fluid drag are comparable (of the same order) with the normal stresses (at the interparticle contacts) considered as a sum of those produced by the particle weight and interparticle magnetic forces. It is well known that: a) the velocity U_e is close to U_{mfo} (in the range of 1- 1.3 U_{mfo} – see Fig. 30 of Hristov (2002) for example) and b) the superficial gas velocity required to initiate the frozen bed levitation decreases as the field is increased (Fig. 28). Both facts indicate that the onset of particle movement (by local deformations in MSB or like a frozen slug) is caused by fluid drag forces limited by the bed weight as a scale (see for example Fig. 42 in Part 1 (Hristov, 2002).
- v) The comments in (iv) and (v) may be employed to create a definition of the minimum field intensity required for frozen bed regimes – H_{mfr} based on the macroscopic fluidization behaviour despite the field orientation:
- The value of H_{mfr} is the minimum field intensity that does not permit an incipient bed expansion (at a desired gas superficial velocity) under the conditions of the Magnetization FIRST mode. In other words, H_{mfr} is the minimum field intensity that hinders the transition from a fixed bed into a stabilized regime (MSB).
- vi) The simple graphical procedure developed in Part 1 (Hristov, 2002) for the determination of the maximum field intensity required for bed stabilization is applicable for the determination of H_{mfr} . The graphical procedure applied here on the results of Sieggell (Fig. 26) is a version of that technique.
- vii) The comments above focus on the physical interpretations of the phenomena. The author's attempts try to relate the scarce data distributed in different sources in accordance with a common

fluidization concept. The data of Siegel (1998) help to fill the gap in knowledge concerning the particle bed behaviour under strong fields. Moreover, they demonstrate how the field intensity ranges upon which bed flowability (not fluidizability) may be hindered could be defined.

- viii) The facts reviewed have been obtained in axial fields only. The ability to build up long saddle-shaped coils (Penchev and Hristov, 1990c) discussed in Part 1 is an opportunity for further investigations on frozen bed transport of magnetizable particle (or admixture) beds. The problems have not yet been investigated.

II.3.2. Fluidization of particles exhibiting a remanent magnetism

The particle beds discussed in Part 1 and the previous papers are created by magnetically soft particles with a negligible remanent magnetism. That fact means that in the absence of a field the magnetic attractive forces disappear or are negligible to affect the fluidization behaviour. The problem is important from a point of view of multiple use of ferromagnetic catalysts and their fluidizability after the turning off of the field.

II.3.2.1. First published results

The first non-systematized, but very professional (from a fluidization point of view), communication has been published by Agbim *et al.* (1971). The experiments have been performed with three fractions of iron shot (mean diameters of 125, 194 and 280 μm) in a 14-cm ID column. Two of the materials (125 and 280 μm fractions) have been spontaneously (accidentally) magnetized by a permanent magnet under an uncontrolled recovering of material after particle mixing experiments.

Figure 29 presents the pressure drop curves of all the three particulate materials. Different quantities of the particulate materials have been employed. The minimum fluidization velocity (U_{mf}) is defined by the intersection of the packed bed pressure drop line and the line defined by the bed weight per unit column cross sectional area. The approximation gives values that are close to the points where the packed bed pressure drop line breaks up, that is an indicator of the bed incipient expansion. All the three curves demonstrate that pressure drop beyond U_{mf} is lower than that defined by the bed weight.

The bed expansion data expressed in a dimensionless form are shown in Fig. 30. The magnetized fractions demonstrate bubble free expansion in the

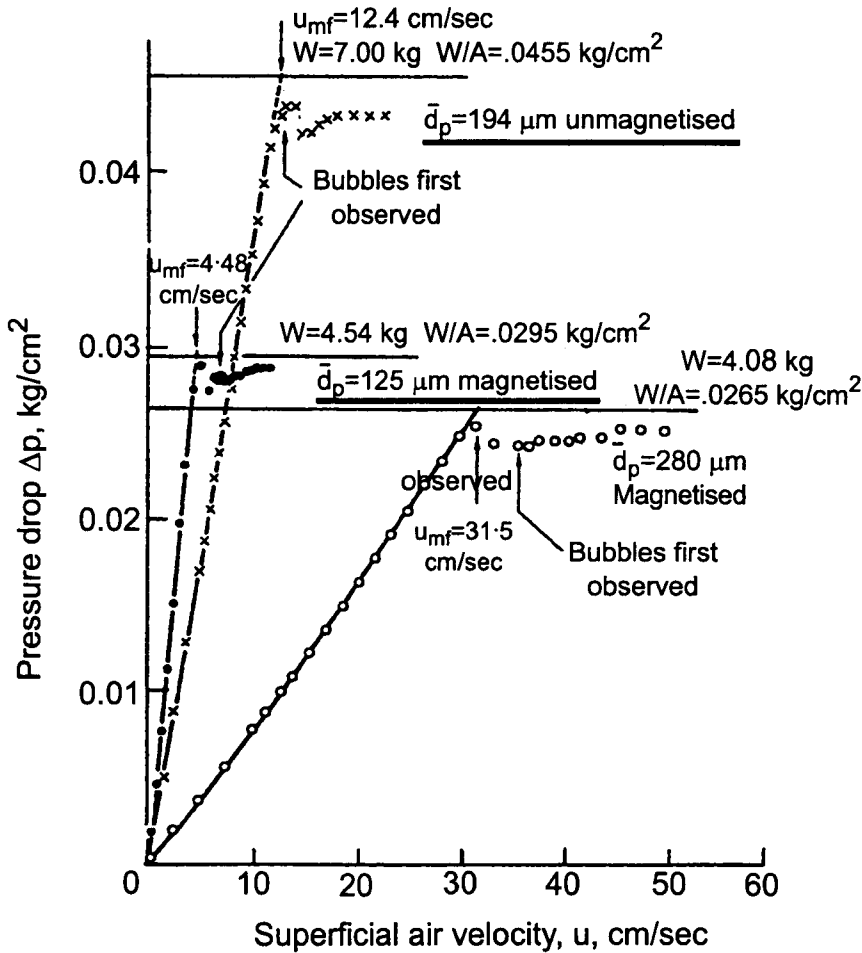


Fig. 29: Pressure drop curves of accidentally magnetized iron steel shot.
From Agbim *et al.* (1971)

range of $h_b/h_{b0} = 1 - 1.1$ and an increase of the velocity where the bubbles first appear of 1.2- 1.5 with respect to U_{mf} defined graphically.

In this early investigation the bed behaviour has been analyzed from the position of gas-fluidization of cohesive materials. The flowability of the materials measured by the angles of repose shows the unmagnetized fraction (194 μm) exhibited an angle of repose of 24° (a typical value for sand-like materials), while the increased magnetization of the other two fractions led to 28.5° (for 280 μm particles) and to 31.5° (for 125 μm particles). The

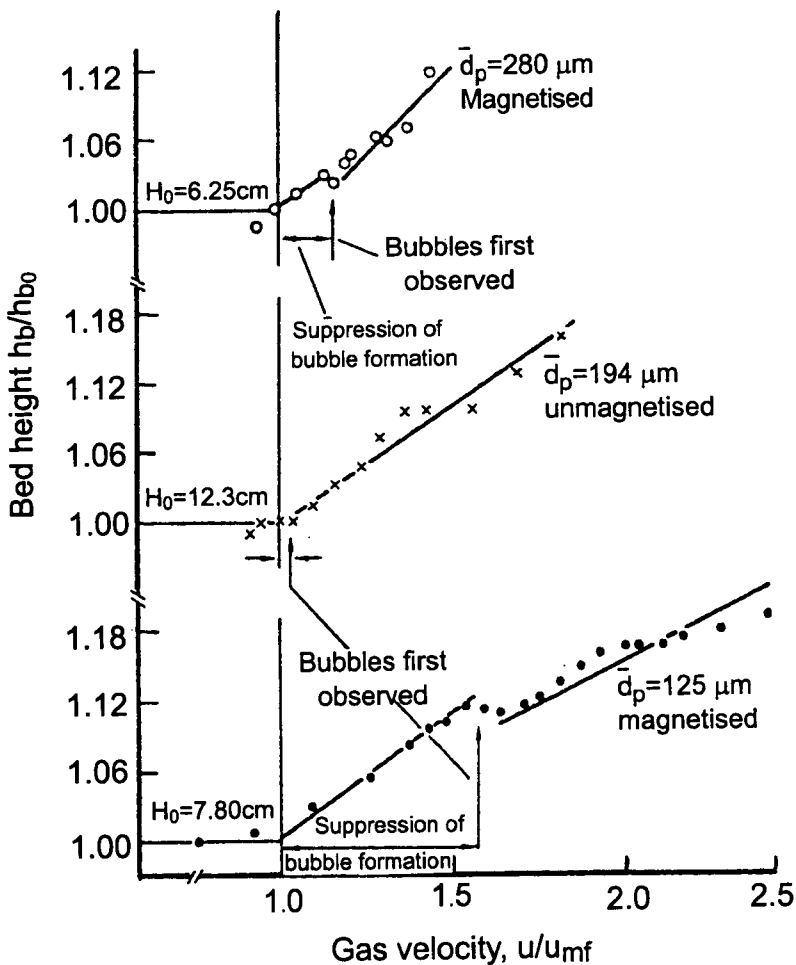


Fig. 30: Bed expansion data corresponding to the pressure drop curves on Fig. 29. From Agbim *et al.* (1971).

difference of the angle of repose indicates that the two materials were not equally magnetized.

These experiments (Agbim *et al.*, 1971) have been treated by Foscolo *et al.* (1985) by a graphical procedure of the plot of U_g versus ϵ for $U_{mf} < U < U_b$. They defined an exponent of 3.2 of Richardson-Zaki's equation (1954) - see comments in Part 1 (Hristov, 2001a). The value of 3.2 is consistent with Richardson-Zaki exponents exhibited by fine catalysts Foscolo *et al.* (1987).

II.3.2.2. Rosensweig's experiments in axial fields

The experiments have been described by Rosensweig (1980a) as a patent example. The test experiments have been performed in a column of 36.75-mm ID (589 mm long) length. A bed of 39 mm settled height has been tested. The saturation moment of the particles (G87RS powder) was established by vibrating sample magnetometer - 13.8 e.m.u at 3500 gauss and a remanence (see below) of about 3 e.m.u/g

The transition velocity (i.e. the first bubble occurrence) defined in accordance with Rosensweig's terminology (Hristov, 2002) was determined in the presence of a steady and an alternating axially oriented field (generated by a Helmholtz pair). The results are shown in Fig. 31.

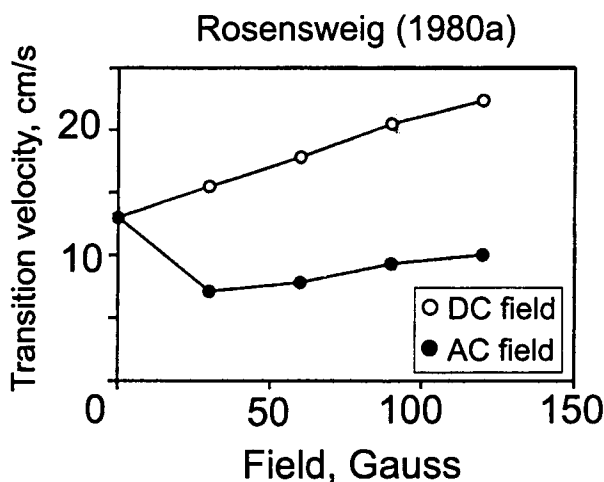


Fig. 31: Influence of alternating and direct current field sources on surface bubbling of a magnetic powder having a remanent magnetism. Present author's graphical illustration of data extracted from Rosensweig (1980a).

The plots show that the DC field increases the transition velocity that is consistent with all the results reviewed here. On the other hand, the AC field decreases the transition velocity relative to value observed in absence of a field.

Rosenweig (1980a) considered the angular displacement of a bed particle having a remanent moment in response to the magnetic torque set up by the

reversing field, a criterion may be defined indicating the range over which AC fields tend to upset the bed stabilization. The criterion defined by Rosensweig is :

$$N_C \begin{cases} > 1 \text{ unstable} \\ < 1 \text{ stable} \end{cases} \quad (5)$$

where

$$N_C = \frac{5\sigma_r H}{8\pi R_p^2 f^2} \quad (6)$$

Rosensweig (1980a) tested two particulate materials: iron spheres ($R_p = 0.16$ cm, $\sigma_r = 1.5$ e.m.u./g) and catalyst powder G87RS (0.021 cm, $\sigma_r = 1.5$ e.m.u./g). The values of N_C calculated at $f = 60$ Hz and field intensities of 35 Oe (iron) and 30 Oe (catalyst) are: N_C (iron) = 0.13 and N_C (catalyst) = 11 that predict correctly the outcome of the experimental tests.

II.3.2.3. Coualoglou's experiments with hard magnetic materials

Coualoglou (1979) described the fluidization of permanently magnetic particles in a series of patent examples. Coualoglou pointed out that sufficiently high fluidizing velocities without bubbling and slugging (i.e. a bed stabilization) were available in beds of particles having a coercivity of at least 50 Oe (≈ 4000 A/m)- see Fig. 32 (see also Fig 4 in Part 1). Coualoglou commented upon the magnetically soft particles. Agbim *et al.* (1971) had a tentative coercivity of less than 50 Oe (based on the data concerning the lists steel published in *Handbook of Chemistry and Physics*, 47th ed, 1966-1967, Chem. Rubber Company).

The coercitivity H_c and the residual magnetization M_p present the tendency of the material to retain its residual magnetization after the field turns off. The particle magnetization is a combined measure of these features of remanence. Of these two factors the coercitivity contributes more strongly to high particle magnetization. As mentioned in Part 1 (Hristov, 2002) the ferromagnetic materials can be grouped in two main groups – “soft” and “hard” materials. The main difference between both types of materials is their coercitivity. For example, Coualoglou has tested two materials: a soft (1%carbon steel) with $M_p = 140$ Gauss, $H_c = 50$ Oe and a hard ferrite (Indox 5) with $M_p = 2900$ Gauss and $H_c = 2300$ Oe.

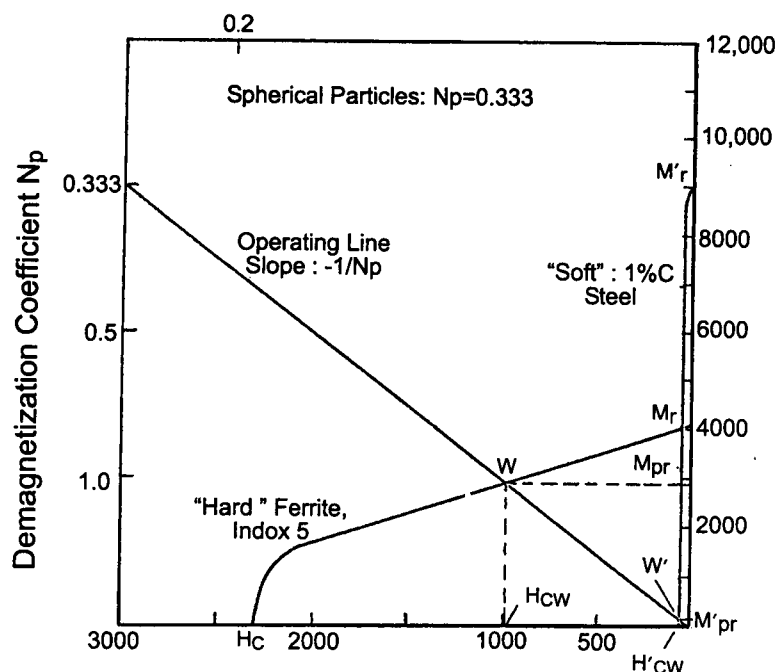


Fig. 32: Residual magnetization and coercivity of soft (1% C steel) and hard (ferrite Indox 5) spherical particles. W - working point defined by the demagnetization curve and the operating line slope $-1/N_p$ (N_p - demagnetization factor (see Part1). For spherical particles $N_p = 1/3$. From Coulaloglou (1979).

Coulaloglou pointed out that particles with a desired coercivity might be manufactured as compounds of soft particles, hard powder and a wax or impregnating commercially available zeolites by cobalt or nickel in the form of metal oxides. For example wax composite particles were prepared by suspending finely ground ferrite powder ($< 44 \mu\text{m}$) in a molten Carnuba wax.

The fluidization examples of Coulaloglou consider experiments in two vertical fluidization vessels (2 and 3 inch ID Plexiglas column). The preliminary procedure includes a magnetization of tightly packed narrow cuts of the virgin (unmagnetized) solid placed in a Plexiglas cylinder. Generally transverse magnetic fields are employed, except for several magnetization runs in axial fields (see Table 12).

After the magnetization procedure the solids were placed on the fluidization column and fluidized by air. The preliminary magnetization of

the particles affects their arrangement in a packed bed. For example (Coulaloglou, 1979 – Example 1) 1430 grams of unmagnetized $\text{Ba}_0.6\text{Fe}_2\text{O}_3$ ferrite particles exhibit an initial bed voidage ϵ_0 of 0.598 and $U_{mfo} = 6.1$ cm/s. After the magnetization in the described manner (by a field of $1420 \text{ Oe} \approx 114 \text{ kA/m}$) the magnetization M_p becomes 480 gauss and a bed of initial bed height of 180 mm is attained.

The classical fluidization experiments gave a bed voidage at the point of incipient fluidization of 0.651 and a value of $U_e = 27.97$ cm/s. The bed expansion of $h_b/h_{bo} = 1.144$ (ϵ_0 of 0.693) was attained. Under these conditions the transition velocity (i.e. the onset of bubbling) reached the value of 67.3 cm/s. Thus the ratio of U_t/U_{mfo} is about 11. More details of the experiments of Coulaloglou are summarized and discussed in the next point.

II.3.2.4. An attempt to systemize the data available on fluidization of permanent magnetic particles.

II.3.2.4.1. Remanence Energy Factor – The data obtained by Coulaloglou (1979) with various permanently magnetic powders are summarized in Tables 12 and 13. These tables contain several additional columns with data calculated here as follows:

- i) The specific magnetic energy of a permanent magnet (in the outer space) is

$$W = \frac{B_w H_{CW}}{2}, \text{ J/m}^3 \quad (5a)$$

- ii) or in accordance with the data shown in Fig. 32 and those summarized in Table 12

$$W = \frac{M_{pr} H_{CW}}{2}, \text{ J/m}^3 \quad (5b)$$

- iii) The quantities employed by Coulaloglou in (5b) and those in Fig. 32 and Table 12 are not in SI units. Despite this all the data calculated hereafter are converted into SI units.

- iv) The particle energy density (PED) in a gravitational field may be present by the product

$$\text{PED}(\text{single particle}) = \frac{2}{3} g \rho_s d_p \quad (6)$$

Table 12
Some data collected from the experiments of Coualoglou (1979)
and values of REF and REF*.

Material	Run/Key	Data of Coualoglou (1979)						Present work	
		dp, μm	ρ_s , kg/m^3	ε_0 ($M_p=0$)	Hc, Oe	M_{pr} , Gauss	H_A , Oe	REF	REF*
Steel shot	1 ○	150	7800	0.65	50	150	15 100	TF 5.21	14.897
Steel shot	2 ●	220	7800	0.62	60	150	15 100	TF 3.56	9.366
Reduced Iron Ore	3 +	80	4800	0.42	30	95	15 100	TF 6.035	10.390
Reduced Iron Ore	4 *	150	4800	0.44	30	95	15 100	TF 3.22	5.76
Reduced Iron Ore	5 □	220	4800	0.44	30	95	15 100	TF 2.2	3.925
Ferrite Index 5	6 ■	220	5000	0.54	130	140	1000	TF 13.48	29.94
Ferrite Index 5	7 △	220	5000	0.54	520	470	1700	TF 180.58	392.58
Ferrite Index 5	8 ▲	340	5000	0.53	530	480	1700	TF 101.274	215.703
Ferrite Composite 14%vol in Wax	9 #	220	1500	0.53	150	160	4000	TF 59.269	126.04
Ferrite Index 5	11 ⊕	200	5000	0.598	160	140	700	AF 22.01	54.812
Ferrite Index 5	12 ▼	200	5000	0.598	570	480	1420	AF 246	612.25
Ferrite Index 5	13 ◆	300	5000	0.560	570	480	1420	AF 148.518	337.54
Alnico 5	16 ✕	165	7620	0.573	100	180	400	AF 11.66	27.31
Alnico 5	17 ∅	165	7620	0.573	205	400	550	AF 124.06	376.407

Note1: REF was calculated at 1 Gauss = 10^{-4} T and 1 Oe = 80 A/m ; **Note2:** TF- transverse field; AF-axial field
Note 3: The run numbers correspond to the original experiment numeration of Coualoglou. The keys are introduced here for better graphical presentation of the data.

Table 13
Some data collected from the experiments of Coualoglou. Present's author
data treatment and symbols used in accordance to the unified data
presentation. The data are arranged in order of increasing of REF*

Experiments and corresponding REF* values		Initial bed		Onset of MSB		Onset of fluidization	
Material	Run/Key	REF*	ε_0 (Mp=0)	ε (Ue) (Mp>0)	Ue cm/s	ε (Umf) (Mp>0)	U _t = Umf
Reduced Iron Ore	5 □	3.925	0.44	0.49	8.8	0.55	17.7
Reduced Iron Ore	4 *	5.76	0.44	0.46	3.4	0.55	10.4
Steel shot	2 ●	9.366	0.62	0.66	26.5	0.70	41.2
Reduced Iron Ore	3 +	10.390	0.42	0.44	1.35	0.59	4.9
Steel shot	1 ○	14.897	0.65	0.69	14.5	0.72	21.6
Alnico 5	16 ✕	27.31	0.573	-	10.1 +	0.689	31.4
Ferrite Indox 5	6 ■	29.94	0.54	0.55	7.9	0.68	17.7
Ferrite Indox 5	11 ⊕	54.812	0.598	-	-	0.721	43.8
Ferrite Composite 14%vol. in Wax	9 #	126.04	0.53	0.55	2.5	0.64	8.0
Ferrite Indox 5	8 ▲	215.703	0.53	0.58	24.3	0.64	49.0
Ferrite Indox 5	13 ◆	337.54	0.560	-	12.0 +	0.756	108.0
Alnico 5	17 Ø	376.407	0.573		10.1 +	0.704	43.1
Ferrite Indox 5	7 Δ	392.58	0.54	0.59	11.6	0.68	39.0
Ferrite Indox 5	12 ▼	612.25	0.598	0.651	27.9	0.693	67.3
Note: + data of Umfo (Table 12). There are no data in Coualoglou (1979).							
							Nm ₀ -pm x 10
							9.41
							575.25
							58.84
							1.276
							16.17
							23.18
							0.709
							48.93
							0.375
							5.21
							25.3
							8.846
							3.442
							9.829

- v) The packed bed of permanently magnetic particles subjected to the action of an upward fluid flow will resist the destruction of the interparticle contacts (incipient bed expansion or incipient fluidization) by the two components of the interparticle forces generated of the fields commented above. Thus, a characteristic ratio of both energy densities (conceived here) may be considered as REF (Remanence Energy Factor):

$$\text{REF} = \frac{3}{2} \cdot \frac{\mu_0 M_{pr} H_{CW}}{2g\rho_S d_P} \quad (\text{SI units}) \quad (7)$$

Taking into account that Table 12 does not contain the values of M_{pr} and H_{CW} the following simplifying assumptions may be performed in order to develop a more useful form of (7). First, for any material the value of H_{CW} is proportional to H_C and M_{pr} is proportional to M_p , so

$$\frac{3}{2} \cdot \frac{\mu_0 M_{pr} H_{CW}}{2g\rho_S d_P} = \frac{\mu_0 M_p H_C}{g\rho_S d_P} \quad (\text{SI units}) \quad (8)$$

Therefore, the REF may be expressed as

$$\text{REF} = \frac{\mu_0 M_p H_C}{g\rho_S d_P} \quad (9a)$$

in SI units

$$\text{or} \quad \text{REF} = \frac{M_p H_C}{g\rho_S d_P} \quad (9b)$$

in the Gauss system employed by Coulaloglou (1979).

The particle arrangement in a particle bed depends on the magnetic interparticle forces induced by an external field (Jones, 1988). In the case of permanent magnetic particles the beds before the magnetization procedure and those formed in the fluidization column have different bed voidage. The magnetized bed voidages $\epsilon_0(M_p > 0)$ are always greater than that of unmagnetized particle beds $\epsilon_0(M_p = 0)$ (see Table 13). Therefore, taking into account that the fluid drag forces depend on the bed porosity, the particle

energy density per unit volume of the bed may be expressed as

$$PED(\text{bed}) = \frac{2}{3} g \rho_S d_P (1 - \epsilon_0) \quad (10)$$

where ϵ_0 corresponds to a magnetized bed ($M_p > 0$).

The introduction of (10) in (9) gives

$$REF^* = \frac{\mu_0 M_p H_C}{g \rho_S d_P (1 - \epsilon_0)} \quad (11a)$$

in SI units

$$\text{or } REF^* = \frac{M_p H_C}{g \rho_S d_P (1 - \epsilon_0)} \quad (11b)$$

in the Gauss system employed by Coulaloglou (1979).

The values of REF and REF* calculated by means of the data in Tables 12 and 13 are listed in the last columns of Table 12.

The data summarized in Table 13 indicate that the ratios U_e/U_{mfo} and U_{mf}/U_{mfo} increase as the value of REF* is increased. The data plotted in Fig. 33 were correlated by a non-linear regression analysis in the forms:

$$\frac{U_e}{U_{mfo}} = 1.247 e^{(0.0338 \cdot REF^*)} \quad (12a)$$

at $R^2 = 0.3407$

$$\frac{U_{mf}}{U_{mfo}} = 2.3962 e^{(0.0804 \cdot REF^*)} \quad (12b)$$

at $R^2 = 0.3407$

$$\frac{U_e}{U_{mfo}} = 1.212 \cdot REF^*^{(0.1579)} \quad (13a)$$

at $R^2 = 0.2514$

$$\frac{U_{mfo}}{U_{mfo}} = 2.207 \cdot REF^*^{(0.3807)} \quad (13b)$$

at $R^2 = 0.2892$

The approximations are shown in Fig. 33.

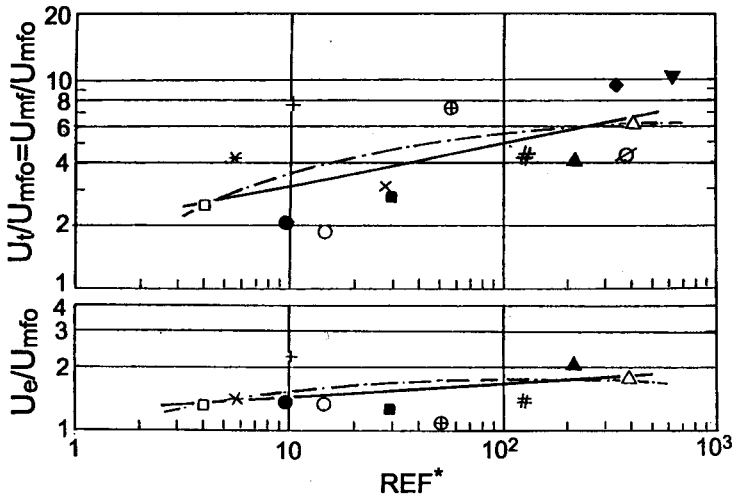


Fig. 33: Variations of U_e/U_{mfo} (bottom) and (U_{mf}/U_{mfo}) with REF^* . The key labels are available in Tables 12 and 13. Present author's data treatment: Solid lines - Eqs.(12); Dashed lines - Eqs. (13). First publication.

II.3.2.4.2. Rosensweig's criteria for bed stability- an attempt for application to beds of permanently magnetized particles – Rosensweig (1979, 1980) and Rosensweig *et al.* (1981) have introduced a stability criterion for magnetically soft beds fluidized in an axial field (not discussed in detail here):

$$\begin{aligned}
 &> \text{unstable} \\
 Nm.Nv & \\
 &< \text{stable}
 \end{aligned}
 \tag{14}$$

where

$$Nm = \frac{\rho_s U^2}{M^2}
 \tag{15a}$$

is the ratio of the kinetic energy to magnetostatic energy of the bed solid
and

$$Nv = f(\epsilon, \chi, \chi_0, \gamma)
 \tag{15b}$$

Rosensweig has expressed experimental data by the relationship

$$Nm = f(\text{bed void fraction at the transition velocity}) = \frac{3}{2} \epsilon^6 \quad (16)$$

Equation gives that $U \propto \epsilon^3$, so the bed expansion satisfies the Richardson-Zaki (1954) equation as discussed in Part 1 (Hristov, 2002) and $N_V \approx \frac{3}{2} \epsilon^6$.

The number Nm may be defined for the permanently magnetic particles too (a present work attempt) in the form

$$Nm_{-pm} = \frac{\rho_s U^2}{M_p^2} \quad (17)$$

The values of Nm_{-pm} based on the data of Coualaloglou (1979) are summarized in Table 13 (the last column).

The plot $Nm_{-pm} = f(\epsilon)$ at $U = U_{mf}$ (for data summarized in Tables 12 and 13) is shown in Fig. 34.

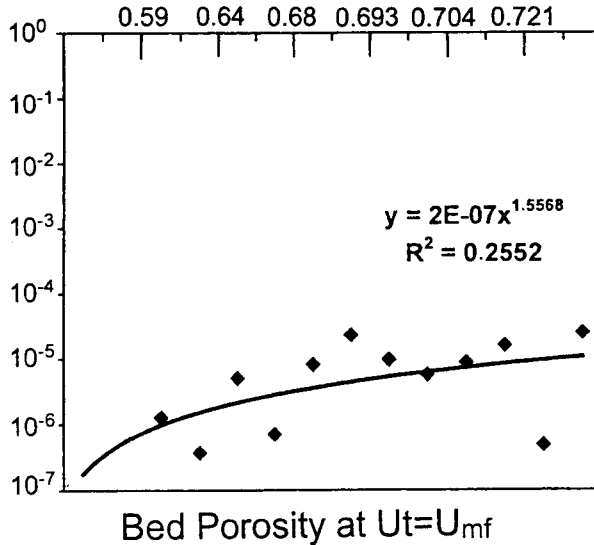


Fig. 34: Variations $N_{-pm} = f(\epsilon)$ for the data summarized in Table 13. Present author's data treatment. The regression analysis includes Runs 10 and 14 of Coualaloglou (1979), but excludes Runs 4 and 5 (reduced iron ore) due to enormous discrepancy of the data.

The data correlation gives that

$$Nm_{-pm} \propto \varepsilon^{1.5568} \quad (18a)$$

or

$$U \propto \varepsilon^{1.24} \quad (18b)$$

The value of 1.24 is lower than the data obtained by Hristov (1999) for moderate field stabilization of magnetically soft particles (see Part 1) and the data of Richardson-Zaki (1954) for non-spherical particles (cylinders, cubes and plates). On the other hand, as mentioned earlier, the particles with a weak remanence (but enough to create MSB regimes) (Agbim *et al.*, 1971) demonstrate values of $n=3.2$ (Foscolo *et al.*, 1985). Therefore, the expansion (at $U_e < U < U_{mf}$) of weak permanent magnetic particle beds resemble (formally) A fluidization behaviour of cohesive catalyst particles (Foscolo *et al.*, 1987 with values of n in the range $4 < n < 5.4$).

The experimental data show that the increased particle remanence changes the bed behaviour under fluidization. The data available are not enough to suggest a possible mechanism of that. A lot of experimental test should be done in the future if the technique would be used for particulate technological applications.

II.3.2.5. Comments on fluidized permanent magnetic particles

The data on gas-fluidized ferromagnetic particles exhibiting a remanent magnetism are scarce and non-systematized. The efforts of the present analysis (based on the unified approach of phenomena interpretation) give the following results:

- The ferromagnetic particles with a strong magnetic remanence exhibit fluidization behaviour similar to that of magnetically soft particles in the presence of an external field.
- The above conclusion employs several facts allowing a parallel between MFAF and that of zero field fluidization of permanent magnetic particles:
 - A bubble free expansion occurring at $U=U_e$, close to, but higher than, U_{mf0} (Agbim *et al.*, 1971; Coualoglou, 1979)

- The value U_c/U_{mf0} varies in the range of 1-2 that is consistent with the results discussed in Part 1 (Hristov, 2002).
- The minimum fluidization point (first bubbling appearance) may be moved toward a high velocity range. The ratio U_{mf}/U_{mf0} may reach values of about 1- 1.5 for particle beds with relatively weak remanence (Agbim, *et al.*, 1971) and higher values of 2.5 up to 11 for sintered ferrite particles (Indox 5) (Coulaloglou, 1979).
- The bed height ratio h_b/h_{b0} in the regime of bubble free expansion (resembling the MSB behaviour) is in the range of 1.1- 1.30 for the beds studied by Coulaloglou (1979) (data not shown here). The range is relatively narrower than that exhibited by magnetically soft beds in external fields (Hristov, 2002).
- The introduction of Remanence Energy Factor (REF) is the first attempt to systematize the data. Unfortunately, only Coulaloglou's results allow such data treatment. The approach offers an area of further systematized investigations.
- There are no data on the qualitative bed behavior, so this knowledge gap should be filled with new results.
- The beds of permanently magnetic particles should be useful in simple operations (mass/ heat transfer or separations) that do not need special operations with magnetic systems by the personal. The Coulaloglou (1979) invention gives a trend in that direction.

III. RHEOLOGY OF SOLIDS BATCH GAS-FLUIDIZED BEDS

The induction of magnetic interparticle forces significantly changes the mechanics of the granular medium under the fluidization. This part of the paper focuses the attention on experiments carried out over 40 years and based on different rheological techniques.

II.1. Early experiments of Nekrassov and Chekin (1962)

The study of Nekrassov and Chekin (1962) is the first report concerning the rheology of a bed in a magnetic field. The experimental set up employed by these authors was shown in Fig.1 of Hristov (2002). The experiments have been carried out with nitrogen-fluidized iron ore (a polydisperse fraction with