

III.2.3.3.4. The "apparent" viscosity concept – comments – The rheology section of the review started with the early experiments of Nekrassov and Chekin (1962) on bed rheology employing the Stokes' law concept. Lee's analysis has finished on the same concept. However, the comparison is formal. The experiments of Nekrassov and Chekin (1962) are purely phenomenological with an "ad hoc" accepted Stokes' law concept. On the other hand the analysis and the experimental results of Lee follow a slender theoretical concept well established in the powder mechanics. The analysis starts from the fact that MSB exhibits a fixed bed structure from a macroscopic point of view. However, its easy deformation due to the fluid drag forces focuses the attention on its flowability. The concept has been formulated on the experimental results obtained by simple and well-formulated experimental techniques.

III. 2.3. Rheology based on data from fluidization experiments

The facts discussed in the following points are results of macroscopic fluidization experiments. However, they allow some information to be recovered relating to the rheology of the stabilized beds.

III 2.3.1. Some macroscopic facts related to the rheology of batch MSB

III.2.3.1.1. Bed surface inclination in fields different from axial – The rheological data mentioned above have been obtained in axial fields only. However, what happens if the field is oriented in a different direction? The experiments reported by Hristov (1996) and discussed in Part I confirmed the bed stabilization in homogeneous fields of various directions (from axial to transverse). The experimental observations gave some facts related to the bed rheology. First of all the top surface of the bed is not horizontal and tends to orient itself along the field lines (Fig. 49).

The evolutions of the angle β (as defined in Fig. 49) with the gas velocity under fields of different orientations and intensities are illustrated in Fig. 50). The data indicate that top bed inclination does not depend linearly on the gas velocity, or in other words the bed deformation is not a linear phenomenon. The points corresponding to various field orientations are closely distributed (except those for $\alpha = 75$ in Fig. 50b) and vary in the range from 0 to almost 30 degrees.

More informative data are shown in Fig. 51. The maximum bed top surface inclination (represented by the value of $\beta_{\max}$) follows the direction

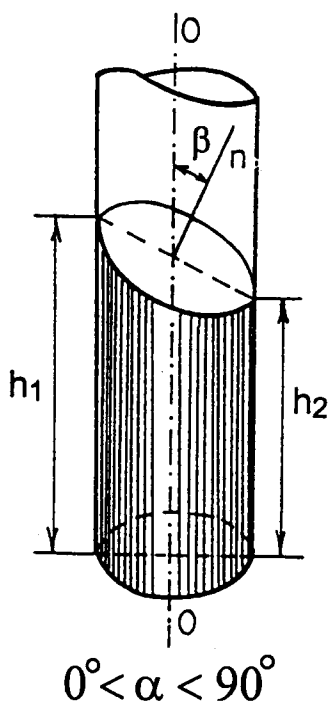


Fig. 49: Typical bed shape in the regime of MSB in a homogeneous field neither axial nor transverse. From Hristov (1996)

imposed by the field lines in the range of $\alpha = 0-15^\circ$ and in the symmetrical range of $\alpha = 0-75^\circ$ (Hristov, 1996). The data confirm (macroscopically) that MSB rheology is closer to that of granular solids than that of liquid-like fluidized bed.

This may suggest, in accordance with the results of Lee (1983, 1991), that bed surface inclination indicates the situation (i.e. the moment) when the driving stresses from the gas flow become as close as to bed yield stresses induced by the gravity and the field. The fact that the angle β does not coincide with the value of α has no simple explanation. Further experiments and a suitable theory are needed for elucidation of the problem.

III. 2.3. 1. 2. Bed stability under tilt – Tilting bed experiments with fields of three different orientations (axial, transverse and 45°) were performed (Hristov, 1998d) with rotating square Helmholtz coils (Hristov, 1996) in the

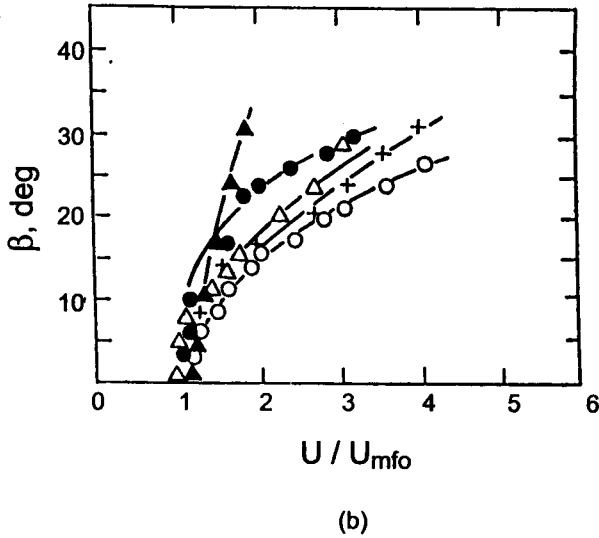
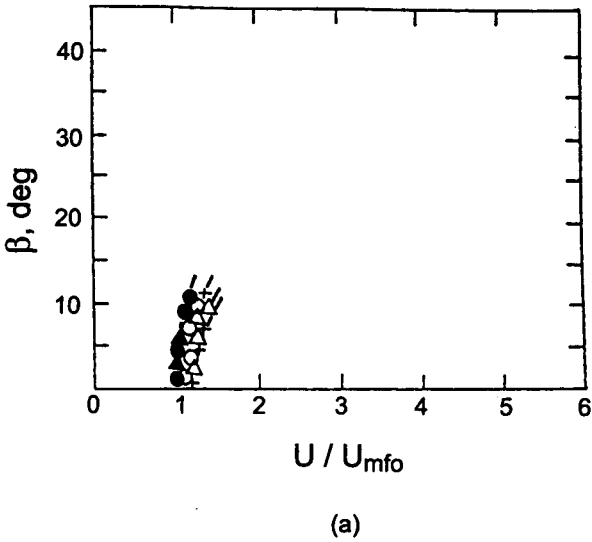


Fig.50: Evolution of the angle β with the gas velocity ($U_e < U < U_{mf}$) at different filed intensities. Particle magnetite bed (100- μ m); h_{bo} = 75 mm; D_c = 50 mm. From Hristov (1994, 1996). Symbols: The field direction defined by the angle α (deg): $\circ$ - 15; + - 30; Δ - 45; $\bullet$ - 60; $\blacktriangle$ - 75.

a) H = 4.71 kA/m;
b) H = 7.06 kA/m;

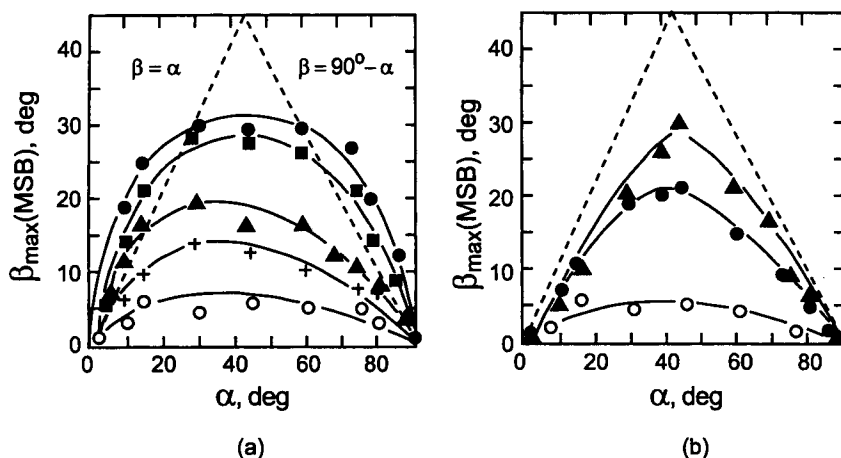


Fig.51: Maximum inclinations of the bed top surfaces (the regime of MSB) v/s the field direction (Hristov, 1994, 1996).

- a) Magnetite particles ($100 - 200 \mu\text{m}$); $h_{\text{bo}} = 50 \text{ mm}$; H (kA/m): $\circ$ - 2.3; $+$ - 4.7; $\blacktriangle$ - 9.5; ∇ - 11.76; $\bullet$ - 15.2;
- b) INVAR particles ($100 - 200 \mu\text{m}$); $h_{\text{bo}} = 75 \text{ mm}$; H (kA/m): $\circ$ - 2.3; $\bullet$ - 4.7; $\blacktriangle$ - 7.1;

sense of the originally idea of tilting bed (Mutsers and Rietema, 1977) (see further the more extended results on tilting beds). For clarity of explanation the angle of bed tilt determined in these experiments is the angle between the column axis and the horizon (see further Fig. 58) where the bed surface failure occurs.

The results shown in Fig. 52 clearly indicate that beds stabilized with a transverse field exhibit a tilting angle of 1.2 - 15 higher than that in axial fields, and the values correspond to those of medium situation (45°) lie among those of both limiting cases.

The results in Fig.52 have a simple physical explanation. Any forces produced by a fluid flow or by an external magnetic field compressing the bed in a direction toward the bottom will stabilize the bed and increase the value of β_t (see the introductory comments in III.2.2.1.3). In the case of a transverse field, the field constriction forces (see Fundamentals in Part 1 (Hristov, 2002)) compress the bed toward the bottom and extend it along its radius. Both actions increase the stability of the interparticle contacts and the bed-to-wall friction. The final results are the increased values of the tilting

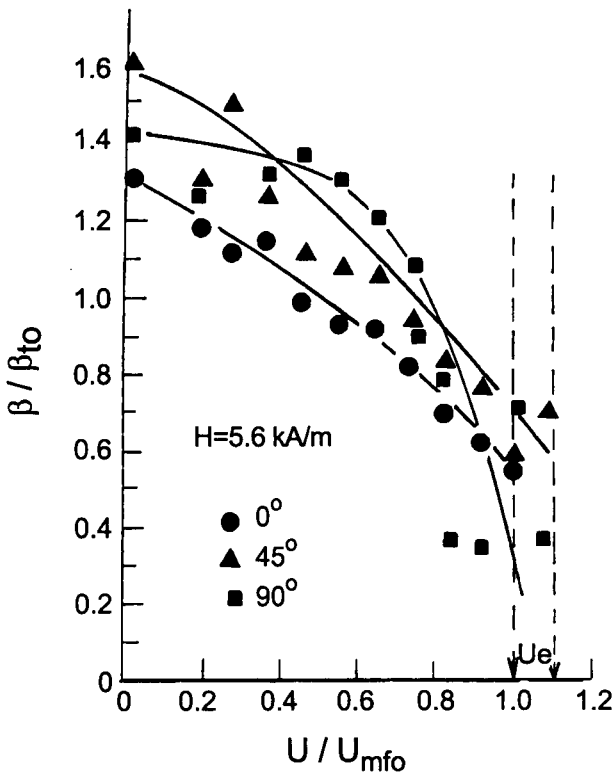


Fig. 52: Tilting bed experiments in field with orientation different from axial. Metallurgical dross particles (100-200 μm); $h_{bo} = 50 \text{ mm}$; $D_c = 50 \text{ mm}$. $U_{mfo} = 0.14 \text{ m/s}$. Dimensionless tilting angles as function of the dimensionless gas velocity in the regime of a fixed bed demonstrating the stabilization action of the field and the destructive action of the fluid flow. β_{to} (deg) in absence of a gas flow: Axial field - 40° ; Transverse field - 62° ; Field orientation at 45° - 51° . **First time published data.**

angle. Under the conditions imposed by exactly the opposite situation (axial field) the field extends the bed body along the field lines (i.e. in a direction parallel to the fluid flow) and compresses it along the radius. The field effects are reduced bed-to-wall friction and powder compression along the bed axis, so the tilting angles are approximately 25 % lower than those in the transverse field. The case of 45° field inclination is intermediate and some

effects attributed to the concurrent action of the axial and the transverse components of the magnetic field vector were discussed in Part 1 (Hristov, 2002). Deeper results derived from tilting bed experiments will be commented upon further in the paper.

III.2.3.2. Characteristics derived from bed expansion-pressure drop data

III. 2.3.2.1. *Van Wyk's equation* – The bed expansion in MSB is a result of the fluid drag forces. This well-known result may be considered as the one-dimensional extension of a porous body due to fluid drag forces. An attempt in that direction has been performed by Hristov (1998c) on the basis of Van Wyk's equation (van Wyk, 1946a, Dunlop, 1983) derived as relationship between the pressure drop p and the volume v of a fiber mass during compression:

$$p = \frac{kY.m^3}{\rho_w^3} \left(\frac{1}{v^3} - \frac{1}{v_0^3} \right) \quad (27)$$

Hristov (1998c) applied the Van Wyk's law for a macroscopic description of MSB deformation due to the following macroscopic facts:

- fluid driven deformation of a porous body
- quasi one-dimensional extension
- large scale deformations (up to 70 %)

The experiments were carried out with magnetite particles under conditions described elsewhere (Penchev and Hristov, 1990b, 1990c). The particles tested were sand-like B in accordance with Geldart (1973), with a negligible native cohesion. Pressure drop-relative bed expansion curves are available in Fig.40d of Part 1 (Hristov, 2002). The data obtained in both fields indicate a rigid plastic flow behaviour, due to the existence of a critical pressure drop required for the onset of bed deformation (expansion). Moreover, during the expansion the pressure drop remains practically constant in axial fields. In the transverse field the pressure drop decreases under the expansion process.

A simple form (van Wyk, 1946b) of the equation (27) treated the data as :

$$\Delta P = aV^n \quad (28)$$

The corresponding data concerning bed expandability due to fluid drag forces are shown in Fig. 53a,b. The coefficient a varies in the range of 1200-1250 ($\text{Pa}\cdot\text{cm}^3/\text{g}$) while n takes values from 0.070-0.085. These values are independent of the field orientation and are valid for the deformation

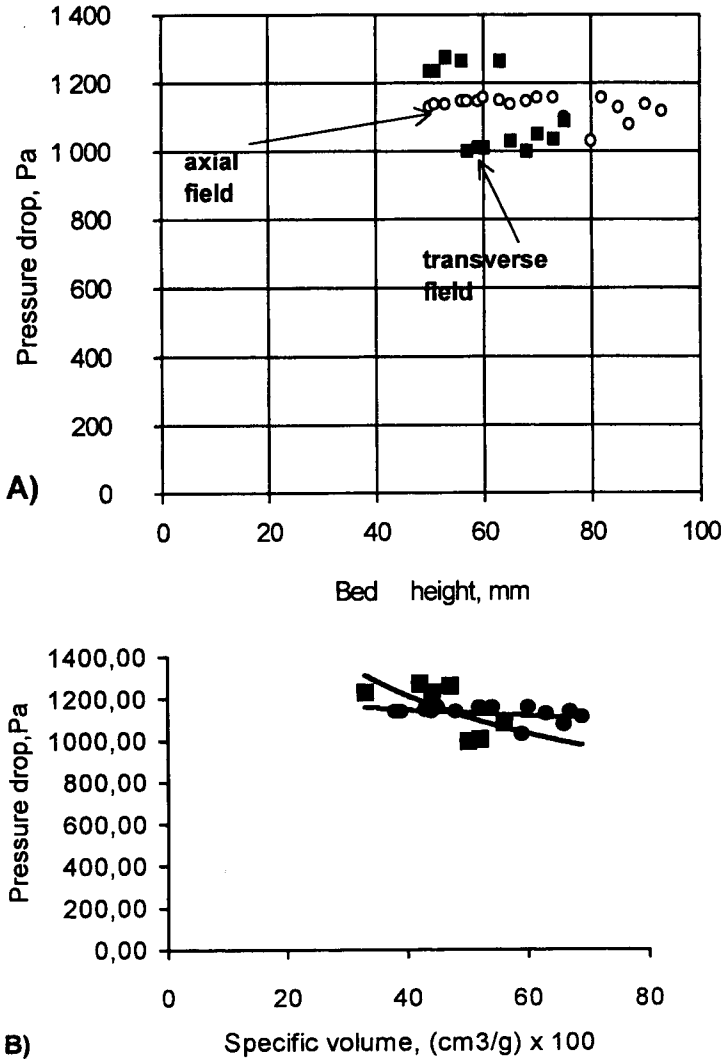


Fig. 53: Bed expandability due to the fluid stresses: Pressure drop v/s the specific volume. Magnetite (315-400 μm); $h_{b0} = 50\text{ mm}$. Bed weight, $G = 263\text{ g}$; $D_c = 65\text{ mm}$; $H = 11840\text{ A/m}$. From Hristov (1998c).

(expansion) range of 40 % (relative bed expansion, E). However, the expandability is strongly affected by the magnetic properties of the powders and the field intensity. The materials having greater M_s demonstrate higher ability to expand under the fluid stress (data not reported here – see Hristov (1998d)). The field line orientation affects the field intensity required to obtain the desired value of V . For example, in a transverse field the required field intensities are approximately twice that those in an axial field. The final form of Eq. (28) covering a narrow sized magnetite fractions in the range of 100 to 500 μm under the particular conditions (Hristov, 1998c) is

$$\Delta P = 1200 \cdot V^{-0.070} \quad (29)$$

The simple equation derived from the application of the van Wyk' equation permits the establishment of a reliable relationship concerning bed expansion. The main idea that follows from that is to apply the complete form (Eq. 27) for a broad range of particulate materials exhibiting different magnetic properties. A second, and also important, idea is to arrange the equation in a dimensionless form via the choice of suitable scale defining the bed stabilization and expandability. Thus, a wide area for investigations is opened.

III.2.3.2.2. Hausner Ratio – The Hausner ratio (Hr) reflects on the cohesiveness of the powders (Hausner, 1972) and is defined as the ratio of the bulk density of a fine powder after a prolonged tapping (usually 100 cycles per minute) to aerated density (Geldart *et al*, 1984; Fatah and Cavois, 1998). The Hausner index generally is $Hr > 1.4$ for Geldart's C powders and $Hr < 1.2$ for aeratable beds of A powders (Geldart *et al*, 1984). The Hausner ratio (Hr) is defined as

$$Hr = \frac{\rho_t}{\rho_a} \quad \text{or} \quad Hr = \frac{h_t}{h_a} = \frac{1/\rho_a}{1/\rho_t} \quad (30)$$

under the assumption of a constant cross-section of the bed

Under the magnetic fluidization, no preliminary tapping is required since the particles are not cohesive in absence of a field, so the maximum bed density is available due to the gravitational forces only. The consequently applied external field creates the interparticle forces (induced magnetic cohesion) rather than allow the "homogeneous" bed expansion. The Hausner

index expressed by Eq. (30) may be easily presented as a ratio of the bed height at the corresponding conditions (Hristov, 2001) in the case of a bed stabilized by an axial magnetic field:

$$H_r^M = \frac{h_{bed-U_{e2}}}{h_{bed-mfo}} = 1 + E(U_{e2}) \quad (31)$$

where $E = \frac{h_b - h_{bo}}{h_{bo}}$ (Penchev and Hristov, 1990a; Hristov, 2002).

The variations of the magnetic Hausner ratios are shown in Figs. 54a,b. Two correlations were tested. The first one addressed the explicit effect of the field intensity to the bed expandability (the ability to deformation due to the

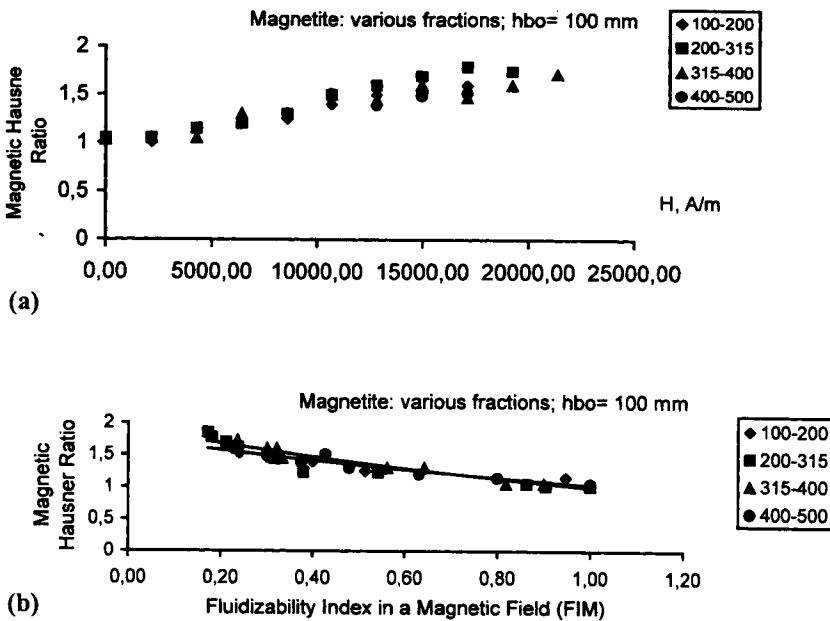


Fig. 54: Variations of the magnetic Hausner ratio with the field intensity and the fluidizability index FIM in axial field. From Hristov (2001c):

a) $H_r^M = f(H)$

b) $H_r^M = f(FIM)$. The solid lines - correlations in Table 15.

gas flow). The second one looked for a relationship with the fluidizability index (FIM) (Penchev and Hristov, 1990a; Hristov, 2002). The regressions are summarized in Table 15. The definition of the Hausner index (Eq.30) is a ratio of the inverse bed densities. This is an analogue to the approach applied in the test of the van Wyk equation mentioned above in a similar situation.

III.2.3.2.3. Plastic deformation coefficient - "Gas Colloid Structure" concept – Kono *et al.* (1988, 1998) have conceived the plastic deformation coefficient as a key rheological parameter of homogeneously aerated fine powders in the velocity range $U_{mf} < U < U_{mb}$ (Geldart's classification – Geldart (1973)). The aerated powder is assumed as a bed of N uniform particle layers and N is defined as

$$N = \frac{h_{bed-mf}}{d_p} \quad (31)$$

The minimum bubbling point ($U = U_{mb}$), the first fracture occurs causing the first bubble appearance. Kono's approach (Fig. 55a) is based on the difference of $(\Delta P^H - \Delta P_D)$, where (ΔP^H) is a hypothetical pressure drop across the bed with unchanged voidage, but corresponding to the velocity range $U_{mf} < U < U_{mb}$. The difference $\Delta P^*(U_{mb}) = (\Delta P^H - \Delta P_D)$ was termed the excess pressure drop (Fig.55a). Further, considering a homogeneous structure consisting of N layers the value of $\Delta P^{**}(U_{mb})$ per unit layer was defined as

$$\Delta P^{**}(U_{mb}) = \frac{\Delta P^*(U_{mb})}{N} \quad (32)$$

In view of the energy balance per unit volume and per unit time the plastic deformation energy (E_σ) necessary to expand the particle bed is to be supplied by the excessive flow causing the pressure drop ΔP^{**} (i.e. the energy E_D). Thus, $E_\sigma = \int_{U_{mf}}^{U_{mb}} \sigma_f(U) dU$ and $E_D = \int_{U_{mf}}^{U_{mb}} \Delta P^{**}(U) dU$. From the equality of the energy required for bed expansion (E_D)(deformation) and that for a repetitive fracture work (E_σ), i.e. $E_\sigma = E_D$, the fracture strength $\sigma_{f,mb}$ was defined as

$$\sigma_{f,mb} = \frac{\Delta P^{**}}{\left[1 + \left(\frac{\epsilon_{mb}}{\epsilon_{mf}} \right) \left(\frac{1 - \epsilon_{mf}}{1 - \epsilon_{mb}} \right) \right]} \quad (33)$$

Table 15
Hausner ratio (magnetic) relationships. For all cases $h_{b0} = 100\text{mm}$.
Hristov (2001)

Material	Equation $\Rightarrow$ Fraction, μm $\downarrow$	$H_r^M = f(H)$	$H_r^M = f(\text{FIM})$
Magnetite	100-200	$H_r^M = 4.10^{-5}H + 0.98, R=0.97$	$H_r^M = 1.72e^{-0.49\text{FIM}}$
	200-315	$H_r^M = 4.10^{-5}H + 0.98, R=0.95$	$H_r^M = 1.88e^{-0.69\text{FIM}}$
	315-400	$H_r^M = 3.10^{-5}H + 1.003, R=0.79$	$H_r^M = 1.92e^{-0.66\text{FIM}}$
	400-500	$H_r^M = 3.10^{-5}H + 1.002, R=0.89$	$H_r^M = 1.75e^{-0.53\text{FIM}}$
	Average	$H_r^M = 3.5.10^{-5}H + 1$	$H_r^M = 1.8e^{-0.59\text{FIM}}$
Metall. dross	0.800-1.00	$H_r^M = 1.5 - 0.49e^{-K.H};$ $K=1.56$ (Penchev and Hristov, 1990b)	$H_r^M = 1.55e^{-0.425\text{FIM}}$
Ammonia catalyst	0.800-1.00	$H_r^M = 1.54 - 0.54e^{-K.H}$ $K=3.1$ (Penchev and Hristov, 1990b)	$H_r^M = 1.62e^{-0.48\text{FIM}}$

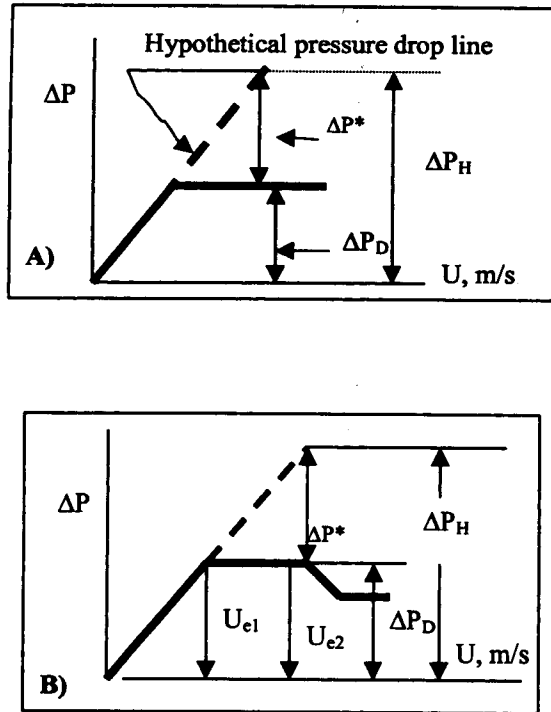


Fig.55: Plastic deformation coefficient defined for MSB. From Hristov (2001c):

- Basic definitions of Kono's approach.
- Definitions of the principle pressure drops in the case of magnetically stabilized bed upon the action of an axial magnetic field.

The strain of deformation (S) expressed as $S = (h_{\text{bed-mb}} - h_{\text{bed-mf}}) / h_{\text{bed-mf}}$ leads to the plastic deformation coefficient

$$Y^K = \frac{\Delta P^{**}}{S} \quad (34)$$

The physical meaning of the above equations is that the energy per unit volume consumed by repetitive fracture works is compensated by the

excessive flow energy. The value of the plastic deformation coefficient indicates the rigidity of the “pseudo-plastic” bed body during the expansion in the regime of homogeneous fluidization of A non-magnetic powder.

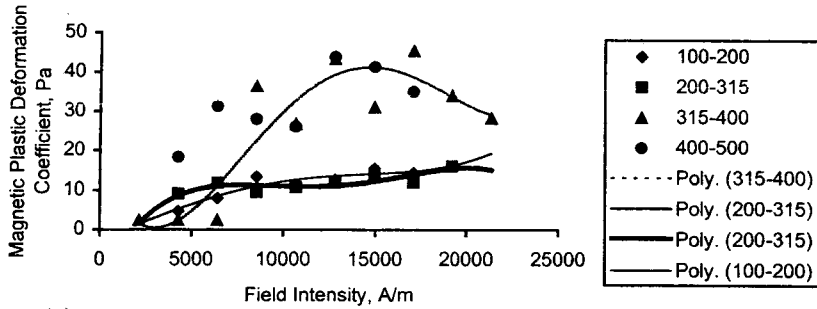
Recently, Kono's approach was applied on beds stabilized in axial fields (Hristov, 2001). The definitions of Kono's parameters are shown on a schematic pressure drop curve of a magnetically stabilized bed (Fig. 55b). Following Eqs. (31-34) and the conditions imposed by the fluidization experiments a modified magnetic plastic deformation coefficient (Y^M) could be expressed as (Hristov, 2001):

$$Y^M = \frac{\Delta P^{**M}}{S} = \frac{1}{\left(\frac{h_{Ue2}}{d_{Pav}} \right)} \frac{\Delta P^H - \Delta P(MSB)_{av}}{\frac{h_{Ue2} - h_{bo}}{h_{bo}}} = \frac{[\Delta P^H - \Delta P(MSB)_{av}]}{N.E.(U_{e2})} \quad (35)$$

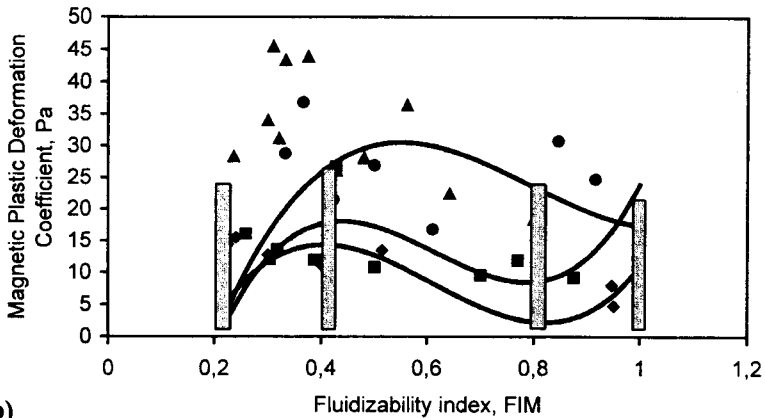
The expression uses the relative bed expansion ($E = \frac{h_b - h_{bo}}{h_{bo}}$) (Penchev and Hristov, 1990b; Hristov, 2002). This gives a more unified presentation of the results and links the macroscopic results (Hristov, 2002) and the rheological parameters. It corresponds to the definition of the strain (S) employed by Kono. For example, the idea of the introduction of E (Penchev and Hristov, 1990b) ten years ago was to focus the attention on mechanical characteristics and the deformation behaviour of MSB due to the fluid drag forces (see Fig. 40 of Hristov, 2002).

The plastic deformation coefficient data are presented in Figs.56a, b. In both cases Y^M increases monotonic monotonously with the field intensity. The weak maxima demonstrated might be related to increased interparticle forces. Fig.56b gives more qualitative information. As commented (Penchev and Hristov, 1990b; Hristov, 2002) in the range of $FIM = 0.4 - 0.8$ the bed exhibits the stabilization behaviour in the better way. The other two ranges (see the gray bands in Fig. 56b) correspond to limiting situations: $FIM = 0.8-1.0$ corresponds to a weak magnetic field effect, whilst at $FIM = 0.2-0.4$ the bed fluidization is hindered and stabilization effects are available only.

The calculations of the fracture strength σ_{Ue2} through Eq. (33) at two values of the bed porosity of the initial fixed bed (at $U < U_{mfo}$: $\varepsilon = 0.4$ and $\varepsilon = 0.5$) is shown in Fig. 57a,b. The plot in Fig.57a demonstrates the intuitively predicted fact that the bed stability increases with field intensity. The data fittings (solid lines) are almost linear (not commented here). The data in Fig. 57b are a test of Kono's approach (Kono *et al.*, 1998) to apply Griffith's



(a)



(b)

Fig.56: Plastic deformation coefficient of magnetite beds (various narrows fractions-see the legend) stabilized by axial fields From Hristov (2001): $h_{bo}=100$ mm; $D_c=65$ mm. The solid lines are polynomial approximations showing the tendency in the data evolution.

- a) $Y^M = f(H);$
 b) $Y^M = f(FIM).$

(Griffith, 1920) theory of small cracks to a plastic body of Irwin (1957) in the formulation of a “Quasi Solid Body”. The data correlations give a simple relationship in the form

$$\sigma_{U_{c2}} = K_{\sigma} \exp(M_{\sigma-Y} \cdot Y^M) \quad (36)$$

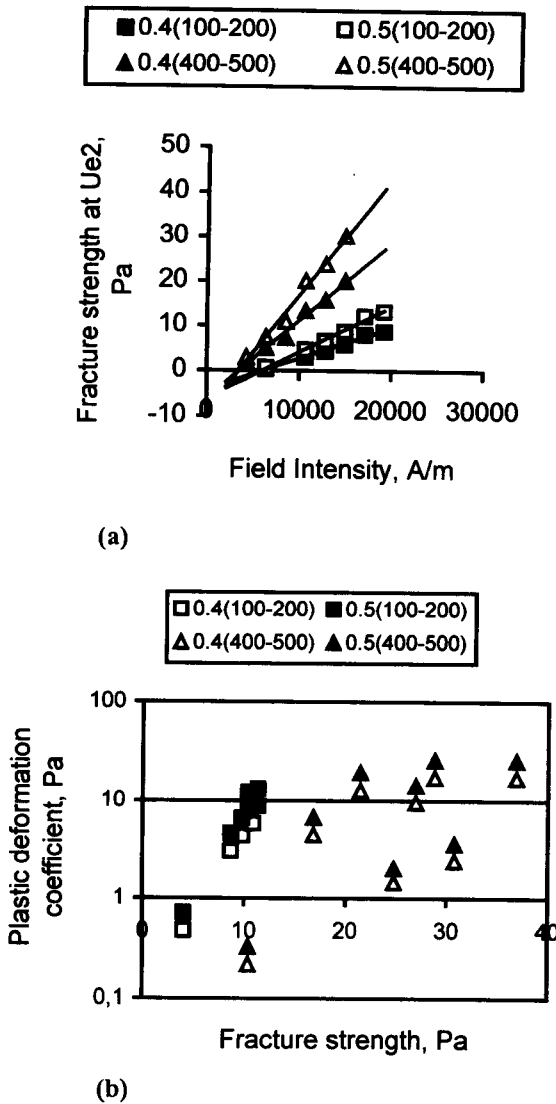


Fig. 57: A test of Kono's ideas for "Quasi Solid Body" concept in the case of magnetically stabilized bed. Various narrow fractions (see the legend) of magnetite beds stabilized by axial fields. Data presented for two porosities ($\epsilon = 0.4$ and ($\epsilon = 0.5$) of the fixed bed before the bed body deformation. From Hristov (2001):

- Fracture strength as a function of the field intensity. Solid lines - linear data fittings (not commented upon here).
- Plastic deformation coefficient - fracture strength relationships.

For example the experimental fits for two fractions of magnetite ($h_{b0} = 65$ mm) are:

$$\sigma_{U_{e2}} = 0.814 \exp(0.38 Y^M) \text{ for fraction of } 100\text{-}200 \text{ } \mu\text{m} \quad (37a)$$

$$\sigma_{U_{e2}} = 0.0514 \exp(0.47 Y^M) \text{ for fraction of } 400\text{-}500 \text{ } \mu\text{m} \quad (37b)$$

In contrast to the non-magnetic powders investigated by Kono (Kono *et al.*, 1988, 1988), where $\sigma = 0.1 Y^K$, the magnetizable beds demonstrate a non-linear behaviour of the relationship $\sigma_{U_{e2}} = f(Y^M)$. Obviously, this is strongly related to their non-conventional fluidization behaviour, which needs further investigations.

III.2.3.3. Deeper results from tilting bed experiments

Recently, the tilting bed experiments of Girenko and Hristov (2001) gave information about the field orientation effects on the shear and normal stresses behaviour under the conditions of bed deformation (the stabilized state) by the flowing gas. The experiments with two different field orientations (axial and transverse) were performed by square Helmholtz coils (Hristov, 1996) in the sense of the original idea of the tilting bed (Mutsers and Rietema, 1977; Piepers *et al.*, 1984; Rietema, 1984) mentioned above.

The tilting fluidized bed experiments are particularly designed to measure the shear strength of powders at low compressive stresses. A schematic presentation of the tilting bed experiments is shown in Fig. 58a. When a

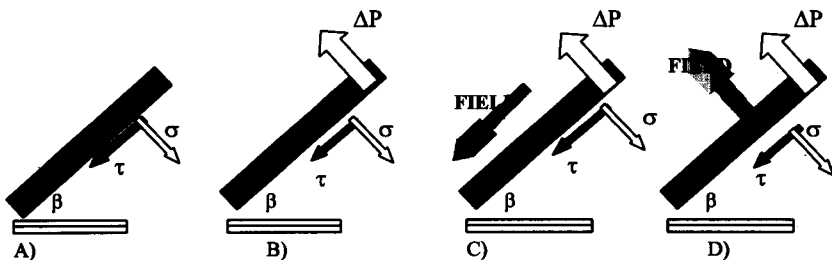


Fig. 58: Force balance for a powder bed layer in a tilting bed

- a) Non-magnetic bed - No gas flow;
- b) Non-magnetic bed - With a gas flow;
- c) Magnetizable bed - With a gas flow in an axial field;
- d) Magnetizable bed - With a gas flow in a transverse field.

fluidized bed of a powder layer is formed by a collapse from a homogeneously fluidized state and then the bed is tilted to angle β_t (Fig. 58b) the following forces act upon a layer with a depth Z (Piepers *et al.*, 1984)

$$\sigma = \rho_P(1 - \varepsilon)Z \cos \beta_t \quad (38a)$$

$$\tau = \rho_P(1 - \varepsilon)Z \sin \beta_t \quad (38b)$$

When at the same time gas is passed through the bed a force due to the pressure drop, ΔP , also acts on the layer:

$$\sigma = \rho_P(1 - \varepsilon)Z \cos \beta_t - \Delta P \quad (39a)$$

$$\tau = \rho_P(1 - \varepsilon)Z \sin \beta_t \quad (39b)$$

Thus, the shear strength τ at which the failure occurs can be measured with decreasing values of the normal stress by increasing the pressure drop over the powder layer. Figures 58c,d show tilting beds upon the simultaneous action of the gas flow and the stabilizing field.

III. 2.3.3.1. Data for pure magnetic beds – Typical tilting bed data are shown in Fig. 59. The magnetite beds tested had greater stability in packed bed: higher values of β_t correspond to higher shear stresses required for bed failure. The increase of the field intensity stabilizes the bed, so greater tilts of the column are required to destroy its structure. The data are consistent with those shown in Fig. 45 and Fig. 52. Moreover, the absence of values of β_{t-YL} close to zero at $U/U_{mf0} = 1$ and the further decrease towards the breakdown point of the stabilized bed ($U = U_{c2}$) clearly indicate that MSB has a fixed structure. In both field orientations the value of β_t decreases as the velocity approaches the fluidization onset that is consistent with the classical results of Mutsers and Rietema (1977). This confirms again the analysis done in (Hristov, 1996; 2002) and contradicts the postulation that the stabilized bed can be assumed as fluidized.

The shear stresses calculated through Eq. (39b) demonstrate a behaviour that does not contradict the results in the absence of a field (Fig. 59b). They decrease, but do not become zero at the onset of the stabilized bed regime. This is a typical behaviour for both orientations of the field applied.

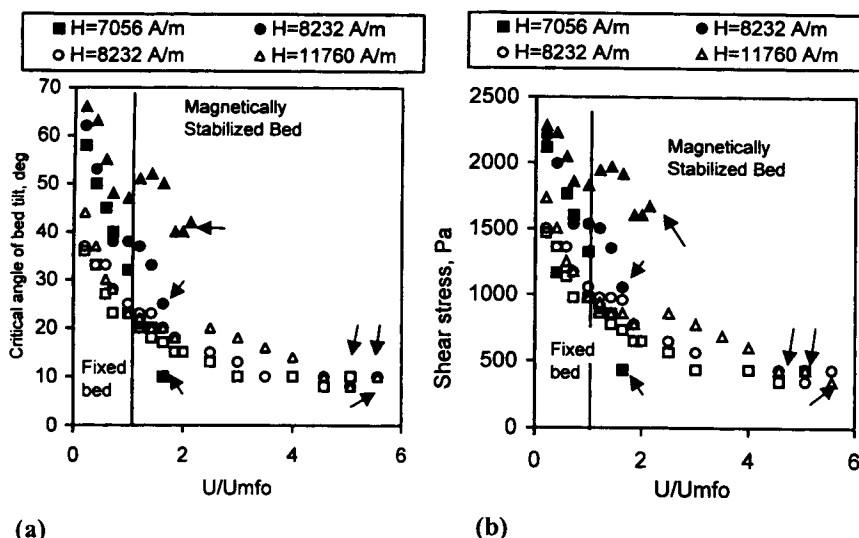


Fig. 59: Data from tilting bed experiments with magnetite (100 - 200 μm) beds: $h_{b0} = 100$ mm; $D_c = 50$ mm; Labels: white labels - Axial field; solid labels - Transverse field

a) Critical angle of bed tilt as a function of the dimensionless gas velocity. **First time published data.**

b) Shear stresses as a function of the dimensionless gas velocity. From Girenko and Hristov (2001).

More interesting results were obtained through the calculations of the normal stresses (Eq.39a) (Fig. 60). The normal stresses drop to zero as the gas velocity approaches the onset of stabilization ($U/U_{mfo} \approx 1$) and they change their sign (i.e. the direction). The phenomenon is most strongly demonstrated under the action of a transverse field and slightly exhibited by beds stabilized by axial magnetic fields. In accordance with Eqs. (39) the powder layer is compressed by the normal pressure, whilst the results in Fig. 60b indicate that in the regime of MSB the layer is under a tension (a quasi one-dimensional axial tension along the column axis).

III.2.3.3.2. Data for mixtures – The tests performed (Girenko and Hristov, 2001) covered a wide range of mixture compositions (Fe_3O_4 varies from 10 to 90 %,vol.). Here, results with two representative mixtures will illustrate

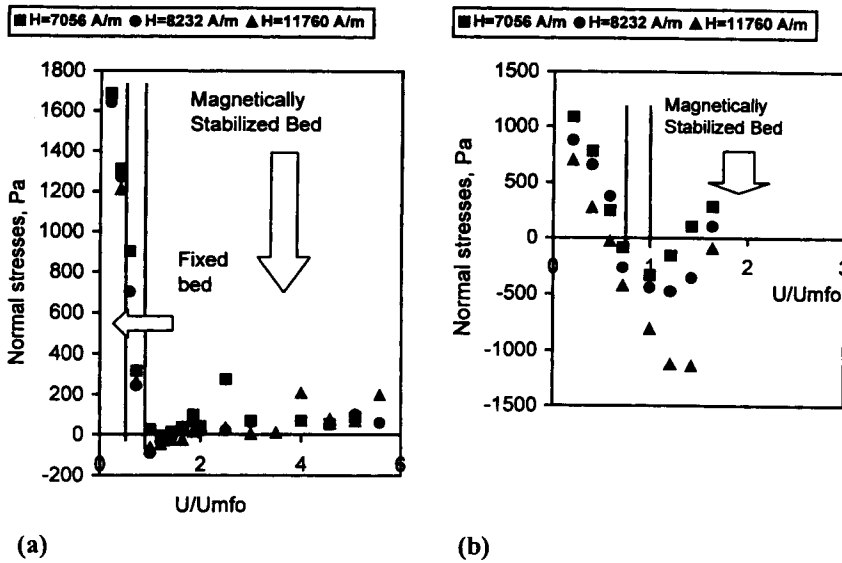


Fig. 60: Normal stresses' evolution with the dimensionless gas velocity. Magnetite bed (100 - 200 μm); $h_{bo} = 100$ mm; $D_c = 50$ mm;

a) Axial field. **First time published data.**

b) Transverse field. The vertical lines close to $U/U_{mfo} = 1$ mark the transition region (from positive to negative normal stresses, i.e. from the fixed bed into the stabilized regime). From Girenko and Hristov (2001).

the general behaviour under the tilting experiments. Fig. 61a presents the tilting angles of an admixture under the simultaneous action of the fluid flow and the magnetic field (both directions). As in the case of pure magnetic beds, the greater tilting angles belong to the transverse field. Figure 61b shows the shear stresses evolution with the increase of the gas velocity. The normal stresses (Fig. 61c) change their signs at the stabilization onset as in the case of pure magnetic bed. The tendency is stronger in beds subjected to a transverse magnetic field.

The data in Fig. 61 were calculated replacing $\rho = \rho_{adm}$ and $\varepsilon = \varepsilon_{adm}$, where (Thouglimp *et al.*, 1984) (see Table. 16):

$$\frac{1}{\rho_{adm}} = \frac{X_M}{\rho_M} + \frac{1 - X_M}{\rho_N} \quad (40a)$$

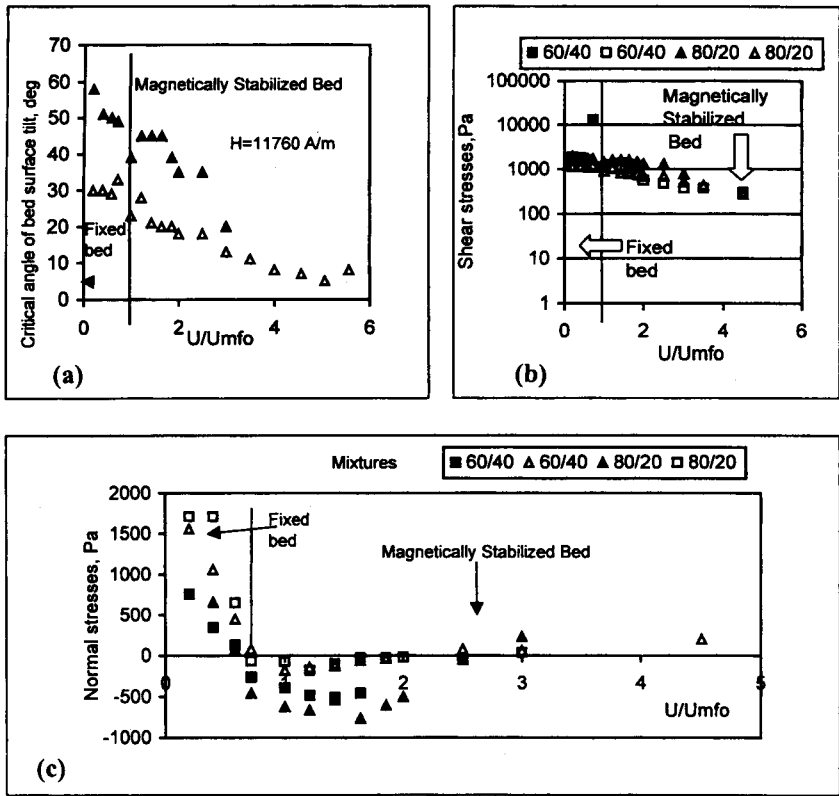


Fig. 61: Tilting bed data for magnetite-glass mixtures. From Girenko and Hristov (2001).

- Critical angle of tilt as a function of the dimensionless gas velocity. (80 % Fe_3O_4 - 20% glass). $h_{b0} = 100$ mm; $D_c = 50$ mm; White-labels: Axial field; Solid labels: Transverse field.
- Shear stresses obtained through tilting bed experiments for two representative mixtures: 80 % Fe_3O_4 - 20% glass (squares) and 60 % Fe_3O_4 - 40% glass (triangles). The other conditions are like those in Fig. 60. White-labels: Axial field; Solid labels: Transverse field.
- Normal stresses vs. the gas velocity. Conditions as in Fig. 61b.

$$\epsilon_{adm} = 1 - \frac{1}{A_C h_b} \left(\frac{G_M}{\rho_M} + \frac{G_N}{\rho_N} \right) \quad (40b)$$

Table 16
Materials used in the tilting bed experiments with stabilized mixtures.
Girenko and Hristov (2001)

Material	Fraction, μm	Solid Density, kg/m^3	U_{mfo} , m/s
Magnetite	100-250	5100	0.140
Glass spheres	315-400	2300	0.140
Mixture 80%vol F_3O_4 & 20%vol glass	Apparent mixture diameter 222.194 μm	Mixture density 4337.05 (Thouglimp et al., 1984)	0.140
Mixture 60%vol F_3O_4 & 40%vol glass	Apparent mixture diameter 287.1121 μm	Mixture density 3698.47 (Thouglimp et al., 1984)	0.140

III.2.3.4. Comments and some developments of the rheological data derived from macroscopic fluidization experiments

III. 2.3.4.1. Several major facts – The results obtained by these simple experiments indicate several major facts in bed mechanics:

- The bed interparticle forces significantly increase with the field intensity. The Hausner ratio (see Fig. 54) varies in the range of from 1.2 to 1.4 that corresponds to FIM variations from 0.8 down to 0.4. As noted by Penchev and Hristov (1990b), this corresponds to the best performance of the stabilized regime and the pseudo-A fluidization behaviour. The decrease of FIM below 0.3-0.2 leads to breakdown of MSB and a transformation in a “fixed structure of particle strings” (Penchev and Hristov, 1990b; Hristov, 2002) bounded by the velocities U_{c2} and U_{mf} . Thus, a pseudo-C fluidization behaviour corresponds to Hausner ratios $H_r^M > 1.35$ (or more correctly $H_r^M > 1.45$). Therefore, the magnetic version of the Hausner index is almost the same indicator of the effect of the interparticle forces like its non-magnetic original. Further studies in fields different from axial are required in that direction.
- The application of Kono’s ideas indicates that the bed mechanics during the powder body deformation by the simultaneous action of both the fluid flow and the magnetic field is strongly non-linear. The plastic deformation coefficient (Fig. 56) shows that the bed may exhibit a fluid-like behaviour at low field intensities (or FIM = 1.0-0.8) or a plastic deformation upon moderate field strengths (or FIM = 0.4-0.8). The further increase of the interparticle forces (i.e. for FIM < 0.4) transforms the powder bed in a “quasi solid body” that forms channels during the fluidization.
- The tilting bed experiments commented upon here show that the bed mechanics is strongly affected by the field orientation. The main fact derived from these experiments is that the yield stresses (or the shear stresses) in the bed do not become zero in the velocity range near the transition to $U/U_{mf0}=1$ and indicate a granular bed structure of both the fixed and the stabilized bed. Is it a correct result? Certainly YES, because it is supported by the macroscopic bed behaviour (no particle mixing motions- i.e. a pseudo-fluid behaviour). Moreover, it is supported by the corresponding behaviour of the normal stress

occurring in the bed. This conclusion is also supported by the results of Lee (1983) presented in the map shown in Fig. 38. The map indicates that the yield stress does not vanish at the velocity U_e , so the stabilized bed is not fluidized. Furthermore, the transformation of these data into a plot shown in Fig. 62 confirms the data obtained by the tilting bed experiments.

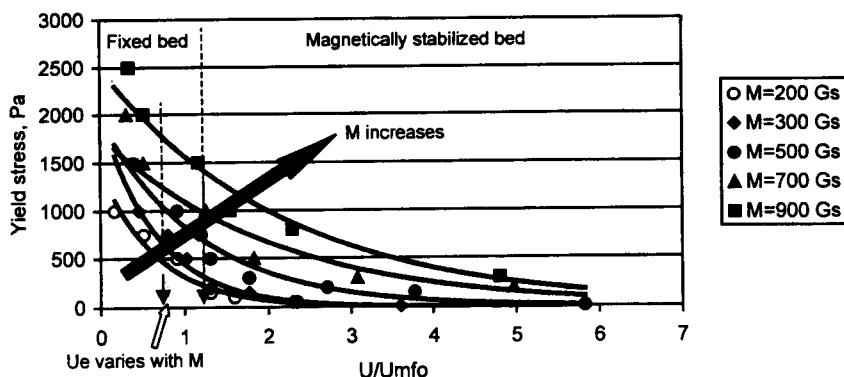


Fig.62: Yield stresses (τ^Y) evolution with the dimensionless gas superficial velocity. Data from the drawing-plate experiments (Lee, 1983) shown on Fig. 38. Present author's data rearrangement showing the analogy with the results from the tilting bed experiments. The solid lines approximate exponentially the points (the correlations are not commented here). **First time publication.**

III.2.3.4.2. Flow curves of MSB – It is well known from the powder mechanics (Brown and Richards, 1970; Chulia, 1984) that the flow curve is the yield locus of the Mohr circles defined by the stress-strain behaviour of the powder and the Jenike cell (Jenike, 1964) for example. However, the magnetically stabilized beds do not support strong normal stresses (a compaction) employed in the conventional Jenike cell. Furthermore, the fluidization situation is inadequate for the experiments in that cell. Jones *et al.* (1987) reported that the Mohr circles of magnetizable powders become ellipsoids. This indicates the complex situation of magnetizable bed mechanics.

The tilting bed experiments described above allow creation of the flow curves of the stabilized bed upon the fluid-driven deformation. Figure 63 shows the flow curves of pure magnetic beds. The points on both figures indicate that at low field intensities are arranged almost linearly, while the increase in the field strength leads to more convex flow curves.

The rigorous assumption of the Coulomb law was assumed in the present paper to derive some representative data for MSB

$$\tau = C_O + \sigma \cdot \tan \phi \quad (41)$$

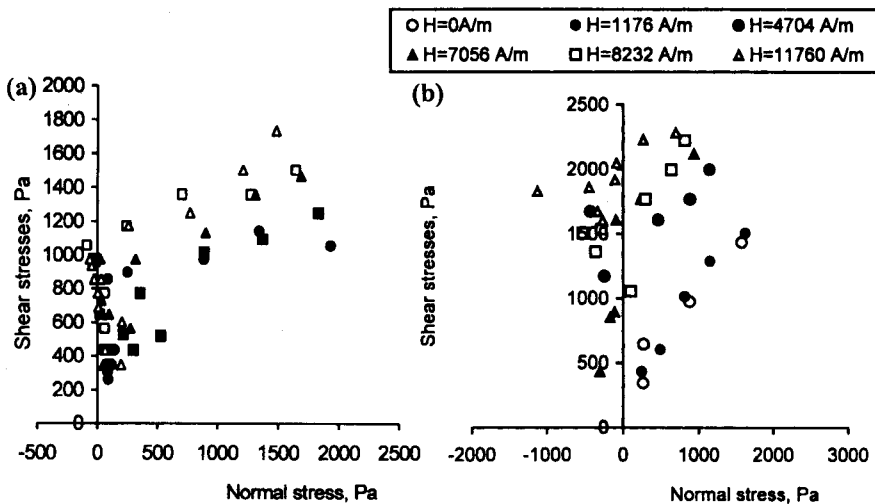


Fig. 63: Flow curves $\tau = f(\sigma)$ for magnetite beds (100 - 200 μ m) obtained through tilting bed experiments. $h_{b0} = 100$ mm; $D_c = 50$ mm. First time data publication.

- a) Axial Field
- b) Transverse Field

The data for the cohesion and the tensile strength of the powders as functions of the field intensity are shown in Fig. 64. The beds stabilized by transverse fields demonstrate stronger cohesion (approximately threefold) than those created by axial fields. The cohesion defined by the approximation of the Coulomb law is a complex characteristic including the simultaneous contribution of the particle-particle interaction, aggregation into strings and

the orienting action of the field (considered as an internal moment of rotation- see Fundamentals of Part 1 (Hristov, 2002)). The plots (Fig. 64a) show almost linear relationships in the case of axial fields.

The tensile strengths shown in Fig. 64b should be assumed as tentative. They were obtained as the intercepts between the straight line of Eq. (41) and the abscissa in the left quadrants if the flow curves. It is well known that the approximation in that zone is not linear (Brown and Richards, 1970; Chulia, 1984), so the values of T should be accepted as overestimated ones.

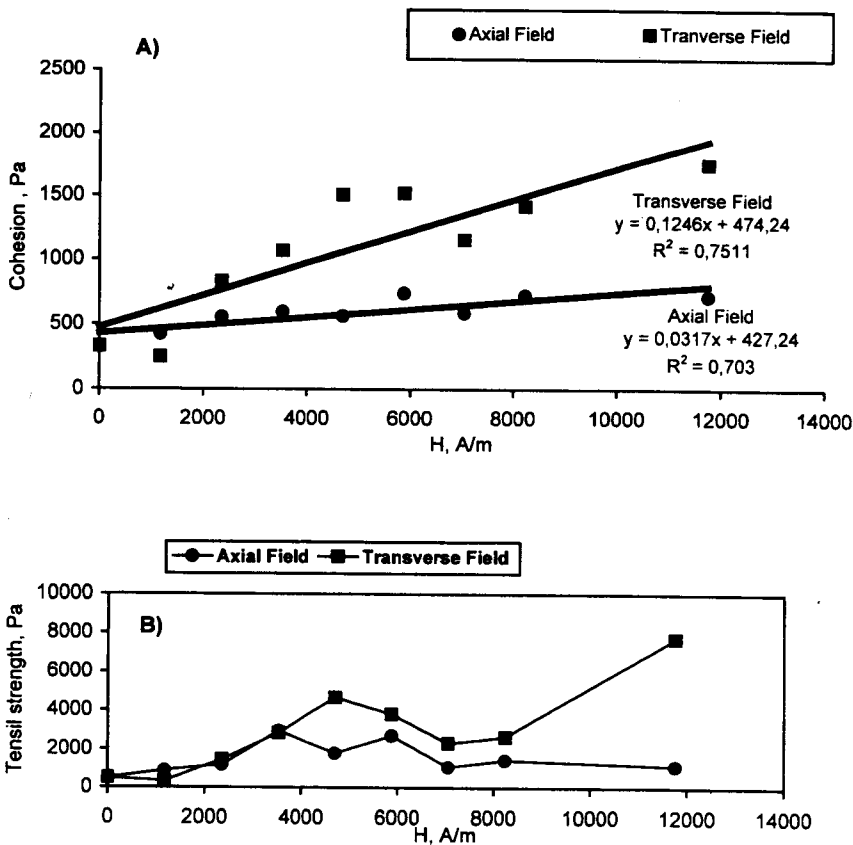


Fig. 64: Cohesion (a) and Tensile strength (b) as functions of the field intensity. Data obtained from the flow curves on Fig. 63 through a regression analysis upon the assumption of a Coulomb law. **First time published data.**

III.2.4. MSB rheology - some remarks

At the end of this section it is appropriate to make several additional comments on the concept describing the mechanics of MSB that is closely related to its rheology. Thirty years ago Gupalo and Cherepanov (1967, 1969) and Cherepanov (1972a,b) have considered the plane (two-dimensional) problem of the fluidization. The analysis has been developed on the granular media mechanics (see for example the excellent book of Sokolovskii (1965). Gupalo and Cherepanov have decided that:

- The loss of stability of a granular bed penetrated by a fluid occurs at the point where the stresses satisfy a certain condition (yield criterion) for a transition in motion defined usually by the locus of the Mohr's circles (see for example Brawn and Richards, 1970 as well as Jenike, 1964).
- The analysis of a bed with interparticle forces (Gupalo and Cherepanov, 1969) leads to the result that transition into the fluidized bed should satisfy the associated plasticity law (Sokolovskii, 1965; Brown and Richards, 1970; Hill, 1950). Jones *et al* (1987) developed such an analysis for ferromagnetic powders. (1987) (See comments in the Fundamentals of Part 1.) Unfortunately it has not been developed for the purposes of MSB mechanics.
- The results obtained from the "Gas Colloidal Structure" concept and the tilting bed experiments try to fill (step by step) the gap in knowledge about the law ruling the transitions in bed behaviour.
- A successful combination between the rheology developed by Lee (1983, 1984, and 1991) and the mechanics of Jones *et al*. (1987) would be fruitful for the further development of MFAF. Some suitable measuring devices for flow curve determination should be developed in the future. An interesting tendency noted here is the derivation of the rheological data from macroscopic fluidization experiments. Obviously, this requires deeper analysis of the bed mechanics and development of adequate rheological models.

**IV. FINAL COMMENTS ON THE REVIEWED RESULTS AND
SOME IDEAS FOR FUTURE TRENDS**

The second part of this review series finishes with the hydrodynamics of batch solids fluidized beds in a magnetic field. The results discussed here were extracted from various sources that in most cases are solitary reports.

The analysis done (in accordance with the unified approach accepted) arranges these results in a form that allows easy comparison with the classical results discussed at large in Part 1. Despite the absence of data in some cases the unified data presentation offers new horizons for further development of the techniques based on the different versions of batch solids MFAF.

Some of the basic concepts derived for the batch solids modes especially concerning the mechanics and the rheology of magnetized fluidized solids have been developed further in two major directions (discussed separately in the subsequent parts of the series):

- Magnetically controlled bed with a continuous solid throughput (Coulaloglou and Siegel, 1981; Siegel and Coulaloglou, 1984a; 1984b, 1985; Siegel *et al.*, 1985, 1986)
- Magnetic valves and magnetic distributor-downcomer for flow control of solids (Jaraiz, 1983; Jaraiz *et al.*, 1983, 1984a, 1984b; Fitzgerald and Levenspiel, 1984; Jaraiz and Estevez, 1987;)

The results discussed here and the attempts to unify the presentation of a lot of scarce data allow conclusions to be drawn regarding some future trends in the magnetically controlled gas-fluidized batch-solids beds:

- The magnetic version of the semifluidization is a new technique that should be developed for better understanding of the basic operating parameters. The magnetic field controlled partition allows flexible solids flow control through the fluidization volume. This enhances the possibility to create various types of new mass and heat transfer devices.
- The frozen beds conceived by Siegel are practically unexplored.
- The fluidization of permanently magnetized particles needs more detailed studies and further systematization for better design of simple fluidization devices.
- The rheology of magnetizable beds penetrated by a fluidizing gas is a challenging field for investigations. The fact that the strain-stress condition of MSB is in the area of low normal stresses needs a development of suitable measuring techniques.
- The fluidization experiments permit application of the data from them in various rheological models such as that of the "Gas Colloidal Structure" explored in the present paper. The development of adequate mechanical and rheological models should allow the creation of adequate design procedures of devices based on MSB.