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Editors:

Dan Luss

University of Houston
Department of Chemical Engineering
Houston, TX 77004, U.S.A.

N. Brauner

Tel Aviv University
Department of Fluid
Mechanics and Heat Transfer
Faculty of Engineering
Ramat Aviv, Israel 69978

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MAGNETIC FIELD ASSISTED FLUIDIZATION – A UNIFIED APPROACH

Part 4. Moving Gas-Fluidized Beds

Jordan Hristov

*Department of Chemical Engineering
University of Chemical Technology and Metallurgy
Sofia 1756, 8 “Kliment Ohridsky” Blvd., Bulgaria
e-mail: jyh@uctm.edu ; jordan.hristov@mail.bg*

This paper is dedicated to the memory of Prof Dr. Eladio Jaraiz Maldonado, whose contribution to the subject of this paper was remarkable

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ACKNOWLEDGMENTS

LIST OF SYMBOLS

REFERENCES

SUMMARY

The fourth review discusses hydrodynamics problems of gas fluidized moving magnetizable solids. Various versions of moving beds are considered highlighting their hydrodynamic problems. The main targets of the discussion are the bed mechanics, magnetic field action (magnetization modes) and the bed rheology. The paper intends to analyze various devices and ideas investigated over 20 years since the 1980s. The approach of data treatment followed in the previous reviews yields a unified analysis which establishes relationships between the results of different variants of moving fluidized beds controlled by external magnetic fields.

I. INTRODUCTION

Moving solid beds are widely applied in the process industry and non-magnetic versions are well described by Kunii and Levenspiel (1989). Similar ideas, involving applications of external magnetic fields (see Fig. 1) and acting on magnetizable solids, have been developed since the 1980s. Figure 1 illustrates the attractiveness of the possibility to control the movements of the solid phase through induced interparticle magnetic forces. The moving magnetizable beds offer new horizons for large-scale applications of magnetic field fluidization that are similar to the non-magnetic contacting devices. However, the use of an external magnetic field presents new problems to be solved. The discussion developed here follows the scheme drawn in Part 1 (Hristov, 2002), that allows elucidation of the

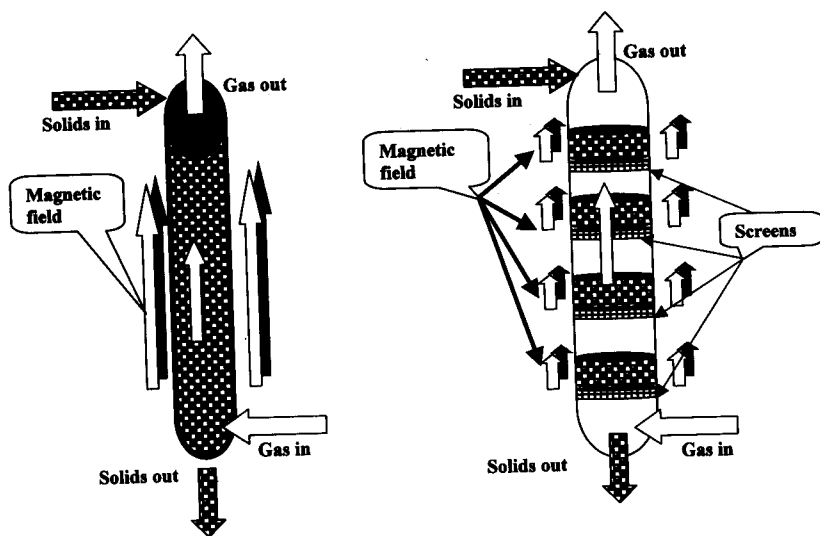


Fig. 1: Moving magnetizable beds – Basic idea (Present author's schematic presentation)

A. Dense beds.

B. Low-particle concentration beds (or multi-stage beds).

new problems based on the fundamental background developed in the previous reviews. Hereinafter, for the sake of simplicity, the previous parts of the series, included in the reference list as Hristov (2002, 2003a and 2003b), will be referred to as Part 1, Part 2 and Part 3, respectively.

1.1. Background and principle trends

The schematic presentation in Fig. 1 classifies the devices under consideration of two major groups:

- **Dense phase moving beds with a continuous solids throughput**

The Exxon group of Siegel and Coulaloglou (1984a; 1984b; 1985) developed these devices for purposes of hydrocarbon processing. This was a significant breakthrough in the technique of MFAF due to the creation of moving solids beds with continuous solids throughputs. The beds were successfully tested for gas chromatography separations (Siegel et al., 1985a, 1986) and various fluid-solids contacting processes (Coulaloglou and Siegel,

1981). The rheology and the relevant hydrodynamic problems of moving solids were investigated by Cheremisinoff et al. (1985) and Siegel et al. (1985b). The main idea was based on the well-known non-magnetic beds (Kunii and Levenspiel, 1989) and it received further impetus from the possibility to control the solids movement by external magnetic fields. The new element, e.g. the magnetic system used, did not affect the design of the downcomer.

- **Low-density moving beds (multistage fluidized beds)**

The second branch developed independently by the group of Jaraiz in Salamanca, Spain (Jaraiz, 1983; Jaraiz and Estevez, 1987) and Levenspiel and collaborators with the Oregon State University (Jaraiz et al., 1983; 1984a, 1984b), considers solids flow control by means of screens and external magnetic fields. Two devices were studied: magnetic distributor downcomers (**MDD**) and magnetic valves for solids (**MVS**). Each one of these has specific design and operating modes, so they will be discussed separately. However, the main idea is the applications of a *partition* created by a *screen* and an *external magnetic field* that *controls* the solids movements through the downcomer.

I.2. Review targets

I.2.1. Moving magnetizable beds – basic ideas

The principal targets to be analysed in the review are:

- **Bed design.** The efforts are oriented mainly towards the elucidation of the role of the new elements with respect to the basis offered by the non-magnetic devices. Further, special attention is paid to the magnetic system designs and their adequacies for efficient control of the solid phase mobility.
- **Operating modes.** The analysis is performed following the structure developed in Part 1. The principal operating modes, based on the type of magnetization and the fluid-solids interactions, are discussed.
- **Bed mechanics.** This is the major target of the discussion which is aimed at evaluation of the operating regimes and the possibilities of the fluid-solids contactors.
- **Bed rheology.** The rheology is considered as the principal element of the bed mechanics background. The concepts developed in Part 2 for batch - solids fluidized beds are applied here again.

- Design concepts of the magnetic systems employed in moving beds.
- Simple scaling and an attempt to generalize data through dimensional analysis.

1.2.2. Classification and structured approach

The actual place of the moving magnetically controlled beds among the other branches of MFA (Magnetic Field Assisted Fluidization) was illustrated in Fig. 13 of Part 1. The classification proposed (Fig. 2) in the

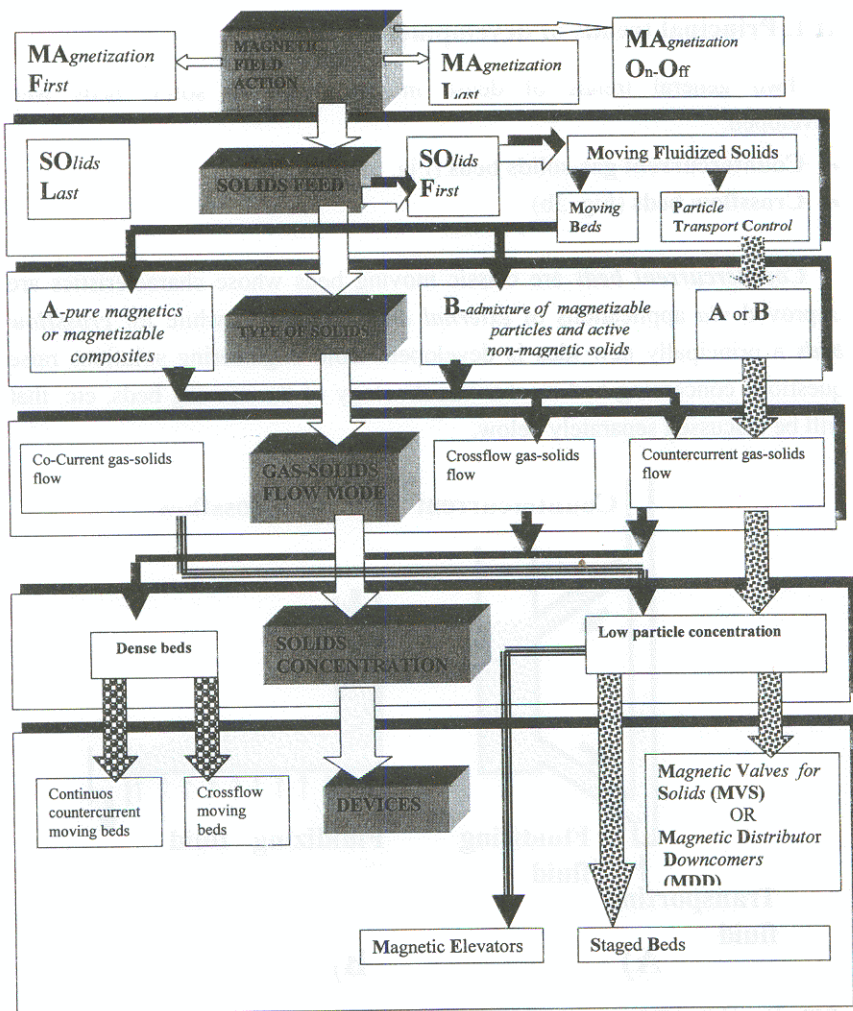


Fig. 2: A classification of the operating modes of the magnetic field assisted moving solids

present review follows the unified approach developed in Part 1. The schematic diagram considers moving solids beds *only* with respect to *magnetization modes* and *fluid-solids flow modes*. The discussion hereinafter follows the structure of this diagram.

II. DENSE MOVING FLUIDIZED BEDS WITH A CONTINUOUS SOLIDS THROUGHPUT

II.1. Principal trends of development

Two general trends of dense moving fluidized solids beds were developed:

- **Countercurrent gas-solids beds** (Fig. 3a)
- **Crossflow beds** (Fig. 3b)

Countercurrent beds are classic moving beds whose characteristics are improved *via* applications of *external magnetic fields*, while for **crossflow beds** a principally new idea is developed. Both engineering solutions raise questions concerning bed mechanics, rheology of the moving beds, etc. that will be discussed separately below.

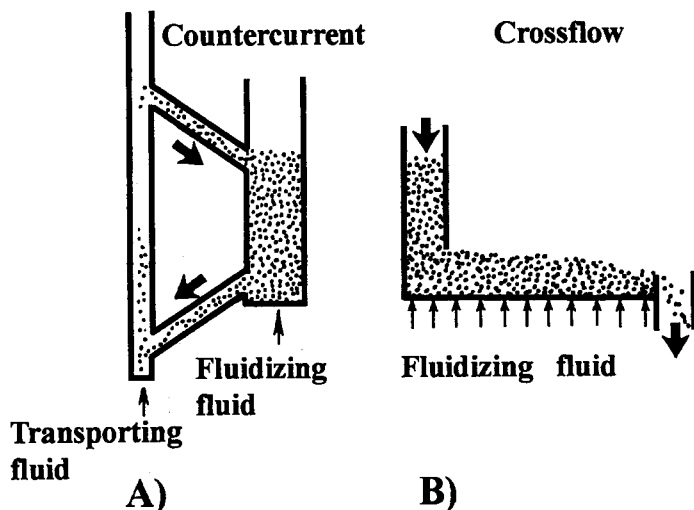


Fig. 3: Two dense moving MSBs. From Siegel and Coulaloglou (1984a).

- a. Countercurrent beds
- b. Crossflow beds

II.2. Continuous countercurrent moving beds

II.2. 1. Principal design and magnetization modes

Moving beds with continuous solids throughput were designed similarly to the well-known single-loop circulation systems. A new element is the magnetic system controlling the movement of the magnetizable solids through the downcomer section of the loop. Figure 4 shows a single-loop

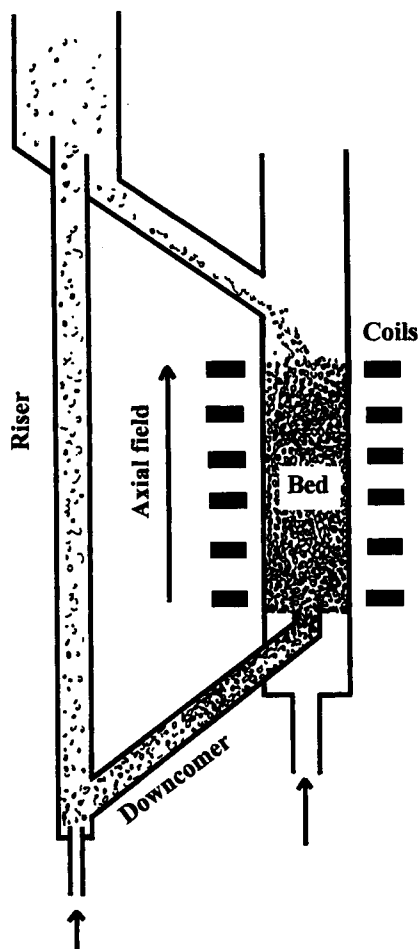


Fig. 4: Basic design of countercurrent magnetically stabilized beds in magnetic systems generating axial magnetic fields. Adapted from Coulaloglou and Siegel (1981). The present author introduced the labels.

magnetizable *countercurrent* gas-solid bed reported by Coulaloglou and Siegel (1981). In all devices investigated *axial magnetic fields* are applied. Thus, no new solutions concerning the bed magnetization are applied compared to those already known from batch-solids beds developed by the same research group – see Part 1.

The magnetization modes (i.e. fluidization “scenarios”) defined in Part I are also valid here, but should be considered with caution. The main reason is that the field acts over a limited part of the reactor downcomer. The solids entering the “*magnetization zone*” (a term introduced in this paper) arrange themselves in strings along the field lines. The entering solids flow is a two-phase system with negligible interparticle forces, so the fluid-particle conditions are the same as those in the *Magnetization LAST* mode. On the other hand, the solids flow mode is usually *solids LAST*, taking into account the *continuous action* of the external magnetic field. Therefore, following the established terminology of the operating modes and the possible combinations between them, the Countercurrent Moving MSB (CM-MSB) belongs to the *left branch* of the diagram shown in Fig. 2. Table 1 summarizes data concerning the principle operating conditions of CM-MSB investigated by different research groups.

II.2.2. Bed mechanics – cases of pure magnetic particles or composites

The solids charged into the downcomer are subjected to the simultaneous action of both the fluid flow and the external field. This was discussed in the previous parts of the series. In general, the transitions from fixed to stabilized beds corresponds to the first points where the solids pass from a static to a deformable state (i.e. the onset of bed flowability). For batch solids beds this is the velocity U_e at which bed body expansion starts.

The transition from fixed to flowing (movable) state was investigated by the Exxon group. As commented on earlier (Part I), these authors introduced and stuck to the term “transition velocity” U_T . They defined the point of breakdown of MSB, which in fact corresponds to the *fluidization onset*. So, taking into account the specificity of the moving solids beds, the term “transition velocity” will be used in the present review to denote the *onset of bed flowability*.

The macroscopic operating parameters that define the transition point are the *superficial gas velocity* and the *field intensity*. The results of Siegel and Coulaloglou (1984a) are demonstrated on Fig. 5. According to the authors

Table 1
Key data concerning magnetically stabilized beds with continuous solids throughputs – dense moving beds

Bed design	Bed design data	Solid particles	Magnetic field	Modes	Observations and Measured quantities	Reference
Single-loop system Fig. 4a	Plexiglas column Dc= 73.5 mm with a center discharge system	- Magnetite 177-250 μm $\rho_s = 5000 \text{ kg/m}^3$ - fluidized by air - Minimum bubbling velocity ($H=0$) $= 8.5 \text{ cm/s}$	- Axial (steady) - Two six-inch (4 inches high) bore magnets placed app. 10 cm apart. (Garrett system)*	- Solids $\blacktriangle$ FIRST - Magn. LAST $\blacktriangle$	- Bed height - Solids circulation rate - Transition locus $\blacktriangle$	Coulaloglou and Siegel (1981) (Example 1)
Single-loop system Fig. 3a	Plexiglas column Dc= 76.2 mm 30 cm height with a side discharge system	- Magnetite -60+80 U.S. Sieve (180-250 μm) $\clubsuit$ $\rho_s = 5000 \text{ kg/m}^3$ - fluidized by air	- Axial (steady) - Three solenoids (each 10 cm high and 15.2 I.D.) app. 10 cm apart. (Garrett system)*	- Solids $\blacktriangle$ FIRST - Magn. LAST $\blacktriangle$	- Bed height - Solids circulation rate - Transition locus $\blacktriangle$	Siegel and Coulaloglou (1984a)
Admixture moving beds (no loops)	Plexiglas column Dc= 38 mm 830 mm tall bed height 325-370 mm	- Mixture: Iron beads/sand - Iron beads, 150 μm $\rho_M = 7597 \text{ kg/m}^3$ - Sand, 360 μm $\rho_N = 2630 \text{ kg/m}^3$ $K_d = \frac{d_{PM}}{d_{PN}} = 0.416 \clubsuit$ $K_p = \frac{\rho_M}{\rho_N} = 2.888 \clubsuit$	- Axial 16 Helmholtz coils (Garrett system)* $H_{max} = 760 \text{ Oe}$ ($\approx 60724 \text{ A/m}$) $\clubsuit$	Solids FIRST Magn. LAST	- Solids concentration profiles - Particle segregation - Pressure pulsations	Shao and Kwauk (1991)

Labels: $\clubsuit$ - Defined by the present author. For details, see Part 1 (Hristov, 2002). $\clubsuit$ - present author calculations; $\blacktriangle$ -corresponding situations

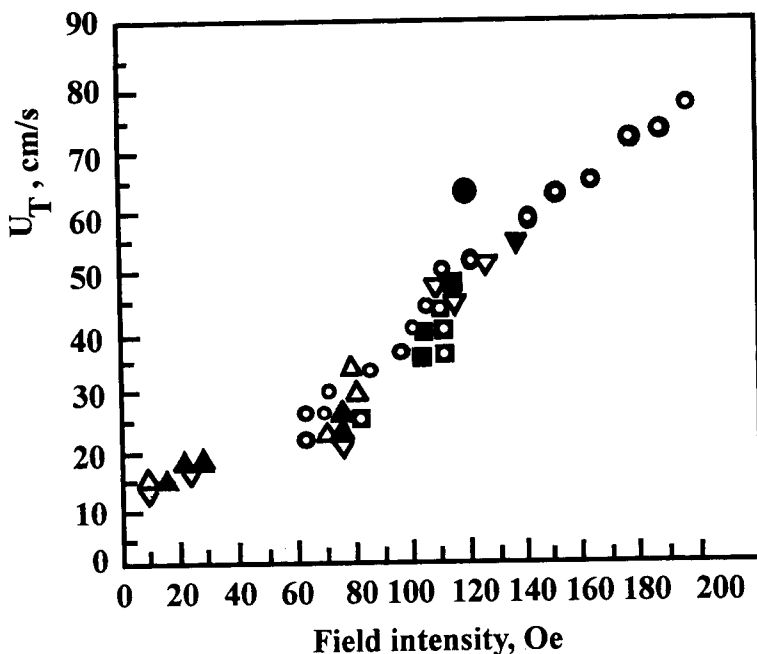


Fig. 5: Phase diagrams of moving beds showing the effect of the solids throughput (circulation) rate and the design of the solids discharge unit (see details in Table 1). Data of Coulaloglou and Siegel (1981) concerning air-magnetite beds and a side discharge unit (SDU) with the device illustrated in Fig. 4a (Fig. 3a is more informative). Labels: Particle flow (g/s): ○-0; ●- 5; △-10; ▲- 15; □-20; ■- 25; ▽- 30; ▼-35.

there are no significant differences between U_T determined in the batch or moving solids modes. Their technique for determining bed fluidity in the stabilized bed mode is based on determination of the velocity U_T . The transition point (Coulaloglou and Siegel, 1981) was determined visually by setting the velocity of the gas and increasing the magnetic field intensity until the bed was stabilized. The stabilization onset was detected visually at the moment of bubble "cessation" (disappearance). The gas velocities and the magnetic field intensities recorded in that manner form points of the transition locus separating the bubbling and the stabilized states.

The principal problem investigated in these studies is the solids discharge from the downcomer. Two discharge options were investigated: 1) centre

discharge of solids (annular discharge system) from the vessel bottom (see Fig. 4); 2) *side solids discharge* (see Fig. 3a). Coualoglou and Siegel (1981) pointed out that by using an annular discharge system the transition velocities were higher for circulating solids than for batch beds. According to them it might be speculated that the bed movement caused by solids circulation resulted in a more even distribution of the fluid flow.

The information about the transition tests (Coualoglou and Siegel, 1981; Siegel and Coualoglou, 1984a) indicates that they are performed in complete conformance to the *Magnetization LAST mode* (Hristov, 1998b; and Part1). According to the unified approach proposed in Part1, the points defining the minimum *freezing field intensities* form the transition locus ($H = H_{mfr}$) marking the transition from fluidized into the "frozen bed".

Solids flow experiments of Siegel and Coualoglou (1984a) demonstrated that the solids appear to move in a plug flow. The measurements of the solids linear velocity *near the wall* and the *calculated solids throughput* indicated essentially *plug flows* at relatively low solids throughput rates. This suggests that the solids velocity along the vessel wall is slightly lower than in the interior of the bed. The experiments also demonstrated higher actual solids throughputs than the calculated ones (Siegel and Coualoglou, 1984a).

Solids throughput rate is predetermined by the *preliminary setting* of the gas velocity depending on the type of the discharge orifice. Siegel and Coualoglou (1984a) comment that the bed fluidity (i.e. the flowability of the solids) in the stabilized regime decreases when the magnetic field is increased beyond the transition point. This information is illustrated by Fig. 6 (Siegel and Coualoglou, 1984a), but it is imprecise since the fluid velocity is unknown.

These results show no apparent effect of the solids circulation on the transition speeds for both the centre and the side discharge systems. In other words, the same high velocities for circulating beds can be reached as for batch beds if it is assumed that the applied magnetic field is the same. In addition, solids flow stops (last fluidity) in a way similar to that for batch bed systems of magnetite beyond an applied field of about 100 Oe (≈ 8000 A/m) (Siegel and Coualoglou, 1984a). The field intensity has no effect on the solids throughput in a bubbling regime. However, in a stabilized regime, further increase of the field intensity reduces the solids throughput rate once the field has increased sufficiently to stabilize the bed (i.e. *to freeze it*). In all the experiments of Siegel and Coualoglou (1984a) with magnetite particles

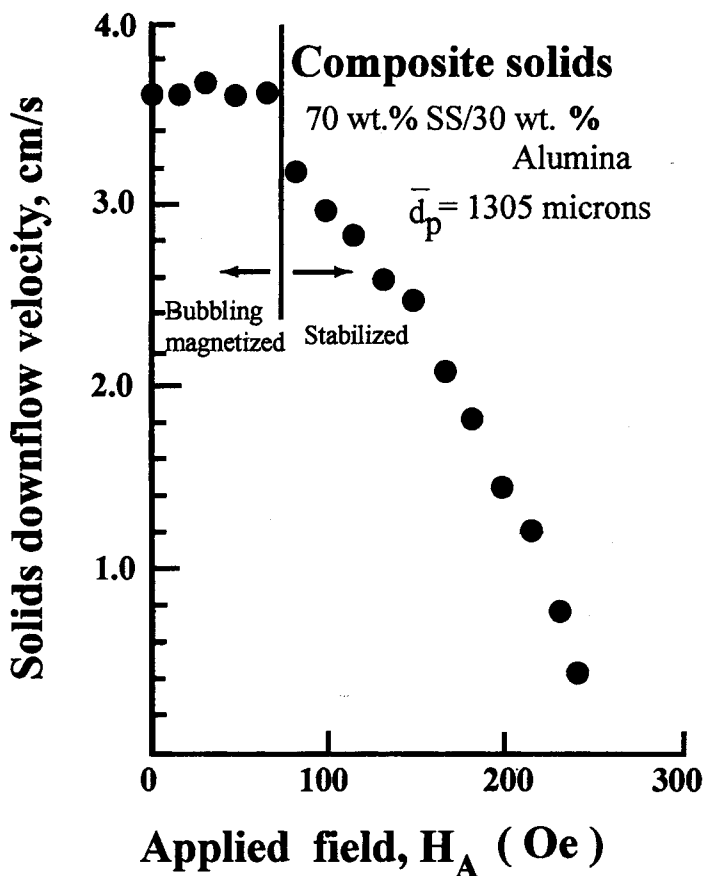


Fig. 6: Magnetic field effect on the solids throughput rate in a counter-current magnetically stabilized bed (Sieggell and Coulaloglou, 1984a). Composite solids (70 wt% stainless steel-30% alumina), $d_{pav} = 1305 \mu m$. No information about the gas velocity is available.

the field intensity was restricted by an upper value of about 250 Oe (≈ 19975 A/m).

The solids flow at a given magnetic field strength varies with the magnetization of the particles used (Coulaloglou and Sieggell, 1981). For example, G87RS nickel alloy composites (with a non-magnetic material) are *relatively fluid* at higher magnetic field strengths. On the other hand, particles such as iron and steel, unlike composites with non-magnetic materials, are able to *agglomerate* which leads to *stiffening* at fields exceeding 100 Oe (≈ 8000 A/m).

The poured angle of repose was used by the Exxon group (Coulaloglou and Siegel, 1981; Siegel and Coulaloglou, 1984a) to correlate the transition velocity. The experimental conditions were discussed as part of the rheological techniques applied to batch-fluidized solids in Part 2. Some data that explain the effect of the operating conditions on the angle of repose are shown in Fig. 7. The *low fluidity* can cause *flow stoppage* and bed “locking” with adverse effects on the smooth operation of MSB. Hence, *fluidity* is an important parameter for the rational design of MSB reactor systems.

According to Coulaloglou and Siegel (1989), the *flowability* is best characterized by the *solids flow resistance index* R_α that reflects the *relative* bed flowability (see comments in Part 2).

$$R_\alpha = \frac{\tan \beta}{\tan \beta_0} \quad (1)$$

At $R = 0$ the bed is fully fluidized and its fluidity is similar to that at $U = U_{mf0}$ and $H = 0$, while at $R = 1$ the bed fluidity is the same as that of a

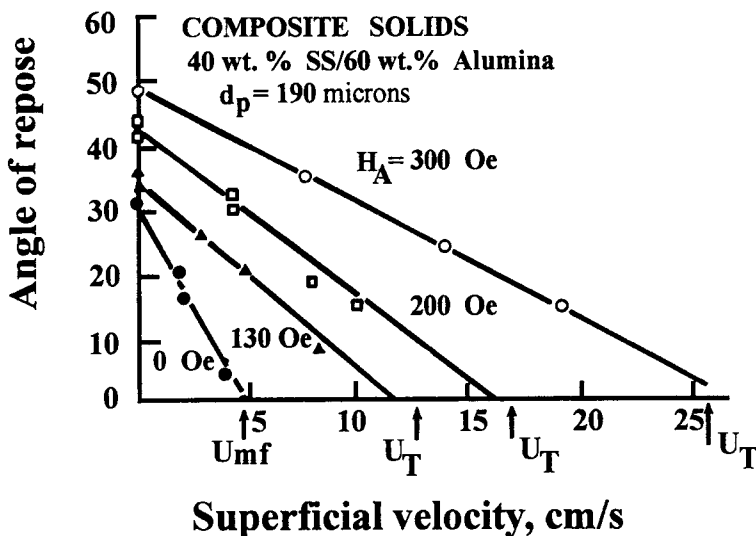


Fig. 7: Effect of the applied field and the superficial fluid velocity on the poured angle of repose. Adapted from Siegel and Coulaloglou, 1984a). Composite solids (40 wt% stainless steel-60% alumina), $d_{pav} = 190 \mu m$. Note: fixed height funnel experiments with a fixed base of the heap formed - see details in Part 2.

packed bed of solids. Thus, the range $0 < R < 1$ defines the regime of the stabilized bed. Experimental data of Coulaloglou and Siegel (1981) indicate that at superficial velocities beyond 50% of U_T the greater part of the bed could be considered as fully fluid (see also Fig. 41 of Part 2).

II.2.3. Bed mechanics -countercurrent-moving beds of admixtures

Magnetic stabilization of mixtures of magnetic and non-magnetic particles is an attractive field for investigation intensively studied mainly in the *batch solids mode* (Part 1 and Part 3). Shao and Kwauk (1991a) reported an interesting application of moving beds of iron/sand mixtures. The details of the experimental conditions are presented in Table 1 and the experimental set-up is illustrated in Fig. 8. The main efforts have been directed towards *particle mixing* and *particle concentration profiles* along the bed depth and the *pressure drop pulsations*.

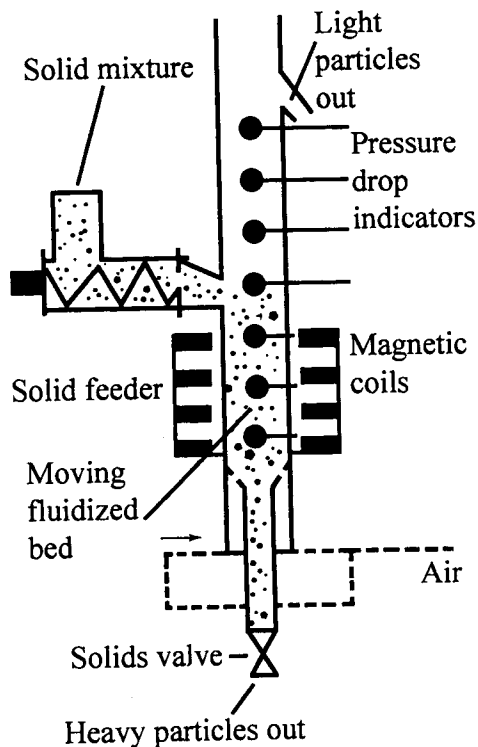


Fig. 8: Experimental set-up of Shao and Kwauk (1991).

Particle segregation was the main problem investigated by Shao and Kwauk (1991a). In the context of the present review the particle segregation onset could be considered also as the *mixture stability limit* under the simultaneous action of countercurrent gas flow and an external magnetic field. This viewpoint permits linking the results to those concerning batch beds (Part 1) where the main idea is *the mixture stability*.

Particle segregation was studied through the introduction of a segregation index N (Shao and Kwauk, 1991a)

$$N = \frac{S^*}{Z + \bar{X}_V^M} = 1 - \frac{\int_0^{\bar{Z}} X_V^M dZ}{\bar{Z} \int_0^1 X_V^M dZ} \quad (2)$$

with an expression approximating the axial distribution of the iron particles (Shao and Kwauk, (1991b)

$$X_V^M = a_0 + a_1 Z + a_2 Z^2 + a_3 Z^3 + a_4 Z^4 \quad (3)$$

Here, Z is the dimensionless bed height (measured height /bed height).

When $N = 0$ there is complete particle mixing, while at $N = 1$ the bed is completely segregated. The value of the segregation index could be calculated by using experimental data and Eqs. (2-3) and its graphical illustration is available in Fig. 9.

Shao and Kwauk (1991a) commented that the particle movement caused solely by the bubbles in a non-magnetized bed led to a “drift” displacement described by Rowe and Nienow (1976). As gas velocity was increased (or the particle density was decreased) the proportion of the “jetsam” in the upper region increased and mixing was improved (Fig. 10).

The effect of the solids throughput velocity U_{ST} on particle mixing was described by a set of differential equations (Shao and Kwauk, 1991b). The main assumption was that a dynamic equilibrium exists between the solids flux and the particle diffusion flux. This concept suggests buoyancy motions of the solids caused by the particle concentration and particle density.

$$\text{Upper bed: } \mu_{DM} \rho_M \frac{dX}{dZ} = +\sigma_M \left(\Delta\rho_{bm} - \Delta\rho_{bm}^* \right) X - U_{ST}^U \rho_{bm} \quad (4a)$$

$$\text{Lower bed: } \mu_{DM} \rho_M \frac{dX}{dZ} = -\sigma_M \left(\Delta\rho_{bm} - \Delta\rho_{bm}^0 \right) X - U_{ST}^B \rho_{bm} + F_m \quad (4b)$$

where

$$X = X_V^M (1 - \varepsilon); \quad Y = X_V^N (1 - \varepsilon) \quad (4c)$$

$$\rho_{bm} = \rho_M X + \rho_N Y \quad (4d)$$

Equations (4) are expressed here through the common symbols introduced in Part 1 and Part 2. The author did it for a better understanding of the links between batch and moving bed mechanics.

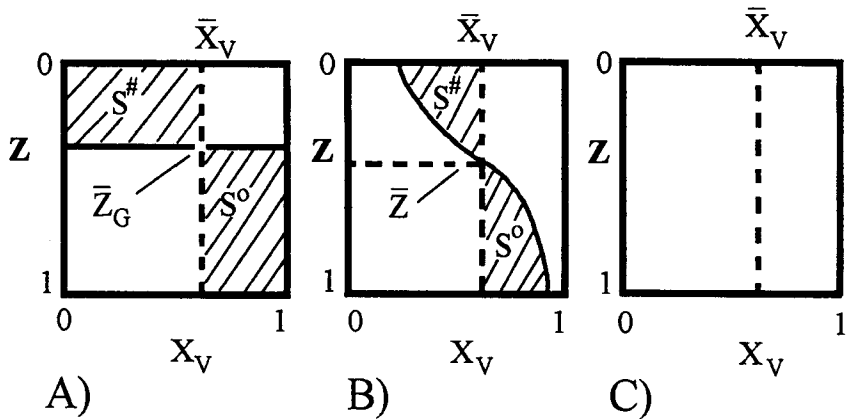


Fig. 9: Mixing/ segregation patterns of a binary particle mixture. From Shao and Kwauk (1991) (*original Fig. 2*). Comments by the present author in brackets.

- a) Complete segregation ($N = 1$). (There is no stabilized mixture bed. Two superposed layers of each particulate phase exist).
- b) Mixing-segregation equilibrium ($1 > N > 0$). (Moderate situation).
- c) Complete mixing ($N = 0$). (The best condition for bed stabilization)

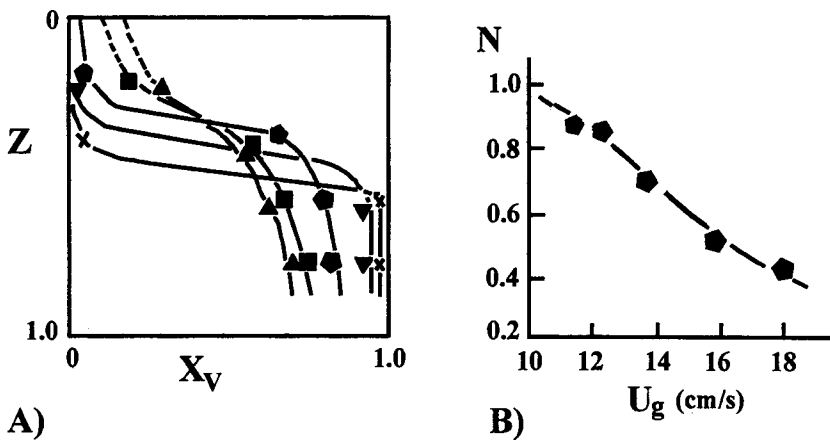


Fig. 10: Effect of the gas velocity on the segregation of particles at $U_{ST} = 0$. From Shao and Kwauk (1991). (original Fig. 3)

- a) The distribution of the volumetric concentration of the iron particles: ▲ - 18.01 ; ■ - 15.83; ● - 13.65; ▼ - 12.38; × - 11.46.
- b) Gas velocity versus the segregation index N . Labels, U_g (cm / s)

The increase in the solids throughput rate U_S enhances particle mixing (steeper curves in Fig. 11a) resulting in the reduction of both segregation gradients and segregation indices N (Fig. 11b). Therefore, the increased solids throughput rate permits easier bed stabilization, i.e. maintenance of an almost homogeneous distribution of the magnetizable particles over the entire bed. The increasing field intensity results in flatter iron particle concentration profiles (Fig. 12a) that indicate enhanced segregation or an increased value of the segregation index N (Fig. 12b).

The increase in the field intensity causes magnetic particle agglomeration (the photos are not shown here). As a result, magnetic aggregates and pockets filled mainly with sand particles are formed. The clusters (or, particle strings) and the pockets grow in size with the increase in field intensity. According to Shao and Kwauk (1991) the separation of strings and pockets from each other is easier than separation of non-aggregated iron particles. This is a macroscopic observation of the entire bed, while aggregate formation leads to segregation on a microscopic scale.

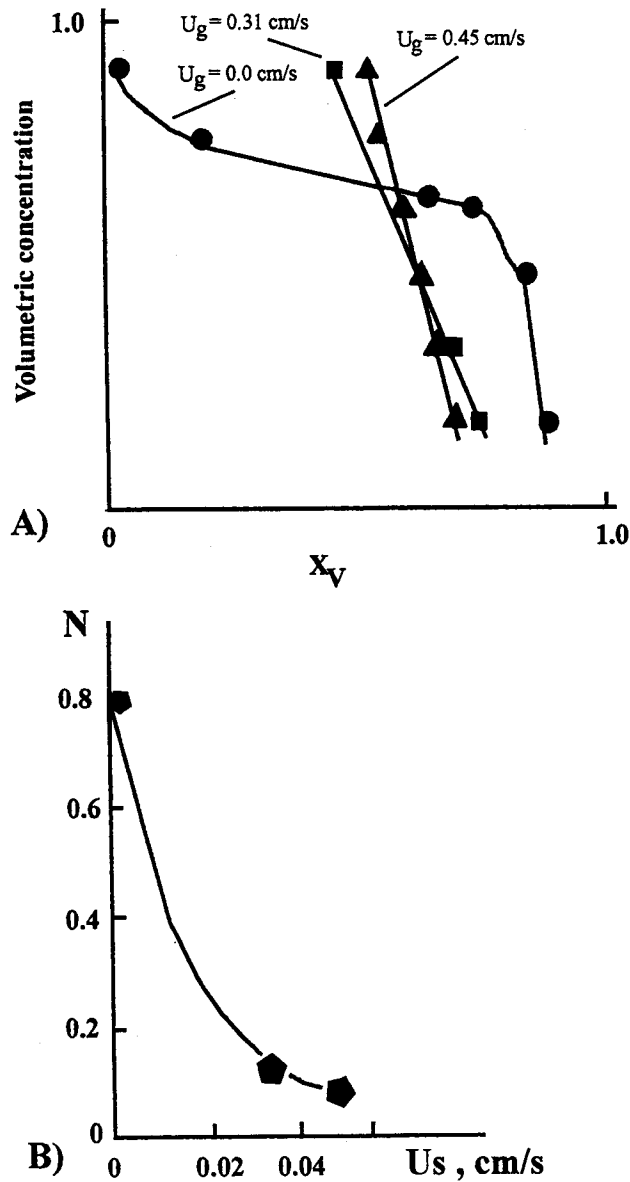
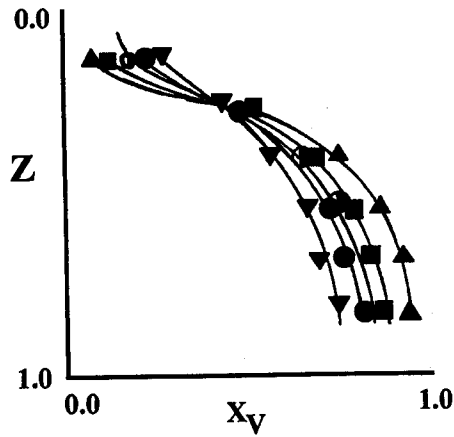
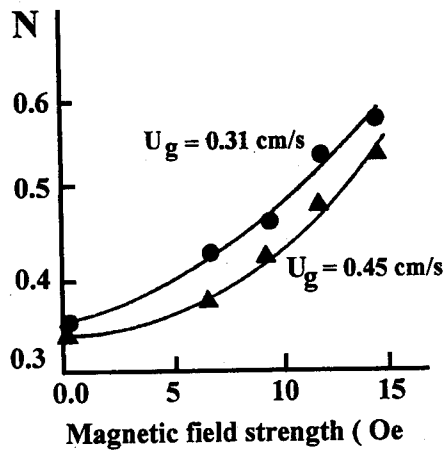


Fig. 11: Effect of solids flow rate U_s on particle segregation. From Shao and Kwauk (1991) (*original, Fig. 4*)

- The distribution of volumetric concentration of the iron particles at $U_s = 0.31$ m/s and $h_t = 370$ mm
- Solids moving rate U_s versus the segregation index N .



A)



B)

Fig. 12: Magnetic field effect on particle segregation. From Shao and Kwauk (1991) (*original Fig. 7*) (*The gas velocity is unknown.*)

- a) Volumetric concentration of iron particles at $U_{ST} = 0.031 \text{ m/s}$ and $h_t = 325 \text{ mm}$.
 Labels: Field intensity (Oe) : $\blacktriangledown$ -0; $\bullet$ -6.7; Φ -9.1; $\blacksquare$ - 11.6; $\blacktriangle$ -14;
- b) Magnetic field effect on the segregation index at two solids rates (*the gas velocity is unknown*)

Pressure pulsations and the bubble frequency in batch-solids beds were commented on in Part 1. According to Shao and Kwauk (1991) the increased field intensity reduces pressure fluctuations. Moreover, particle aggregation into elongated strings oriented parallel to gas flow decreases somewhat the pressure drop across the bed. According to these authors the reduction is equivalent to the gas velocity and /or solids rate reduction. From the point of view of magnetic stabilization, this suggests, consequently, the increased field intensity reduces both bubble motion and particle mixing. The result is *increased bed stability*, i.e. reduced particle segregation. The conclusion is based mainly on the behavior of batch beds of pure magnetic particles (see Part 1). The reason is that, unlike batch-solids beds of pure magnetic particles, pressure drop pulsations in stabilized mixture beds have not yet been studied.

11.2.4. Comments on continuous countercurrent moving beds

The data reviewed above are scarce. The only two sources available on moving beds (Coulaloglou and Siegel, 1981; Siegel and Coulaloglou, 1984a) report *identical* data with similar comments. However, some problems concerning the moving beds of mixtures could be formulated:

- The moving bed of mixtures studied by Shao and Kwauk (1991) is a unique investigation with no other papers on the problem published. As mentioned, unlike the case of batch solids beds no efforts were made with respect to the bed stabilization. Some observations reported by the above authors permit a redefinition of the results from the point of view of bed stabilization. Table 2 presents the results in parallel with comments that “translate” them into terms of stabilized beds.
- The bed behavior description resembles that reported by Hristov et al. (2000) and is discussed in Part 1. The formation of pockets filled with non-magnetic particles could be considered as a loss of bed “*total stability*” and transition into the state of “*global stability*”. The terminology for batch solids beds introduced by Chetty et al. (1991) permits clarification of the stability conditions for these moving mixtures (see the comments below). The diagrams in Fig. 10 do not allow easy estimation of the transition from total into global stability. Further, no data (gas velocity, field, solids throughput, etc) are available about the onset of magnetic aggregate formation and pocket filling with the non-magnetic phase.

Table 2
Principal advantages and characteristics of MSBs with continuous solids throughputs. Adapted from Coualoglou and Siegel (1981) with comments of the present author

Features and advantages	BATCH SOLIDS MODE (BSM)				CONTINUOUS SOLIDS THROUGHPUT MODE (CSTM)			Comments
	Fixed bed	Fluidized bed	MSB	Fixed bed (moving beds)	Fluidized bed	MSB		
Small particle size with low ΔP	no	yes	yes	no	moderate	yes		- The increase of bed depth of CSTM leads to higher-pressure drop, so multistage design is required. - The particle size is limited by the native fluidization behaviour. So, all the particles must be B particles of Geldart.
Gas bypassing	no	yes	no	no	yes	no		The gas bypassing is an disputable problem. However, the magnetic field minimizes the mixing due to bubbling and transforms the bubble into axial channels (see Part I) in axial fields mainly applied.
Particle entrainment	no	yes	no	no	yes	no		Generally avoided in MSB, that is a positive feature.
Particle mixing	no	yes	no	moderate	yes	no		The advantages with respect to the particle mixing are matters of arguments. Some processes, as heat transfer and drying require particle mixing and elimination of hot zones. MSB, generally suppress the particle mixing when a steady (or AC) continuous magnetization is applied. The particle mixing control needs On-Off magnetization.

II.3. Crossflow moving beds

II.3.1. Principal design

Crossflow fluidized beds, where solids flow in directions transverse to the ascending fluidizing fluids, are applied in different branches of the process industry. Some devices are shown in Fig. 13. They are characterized by a significant lateral mixing of the solids as well as common features of

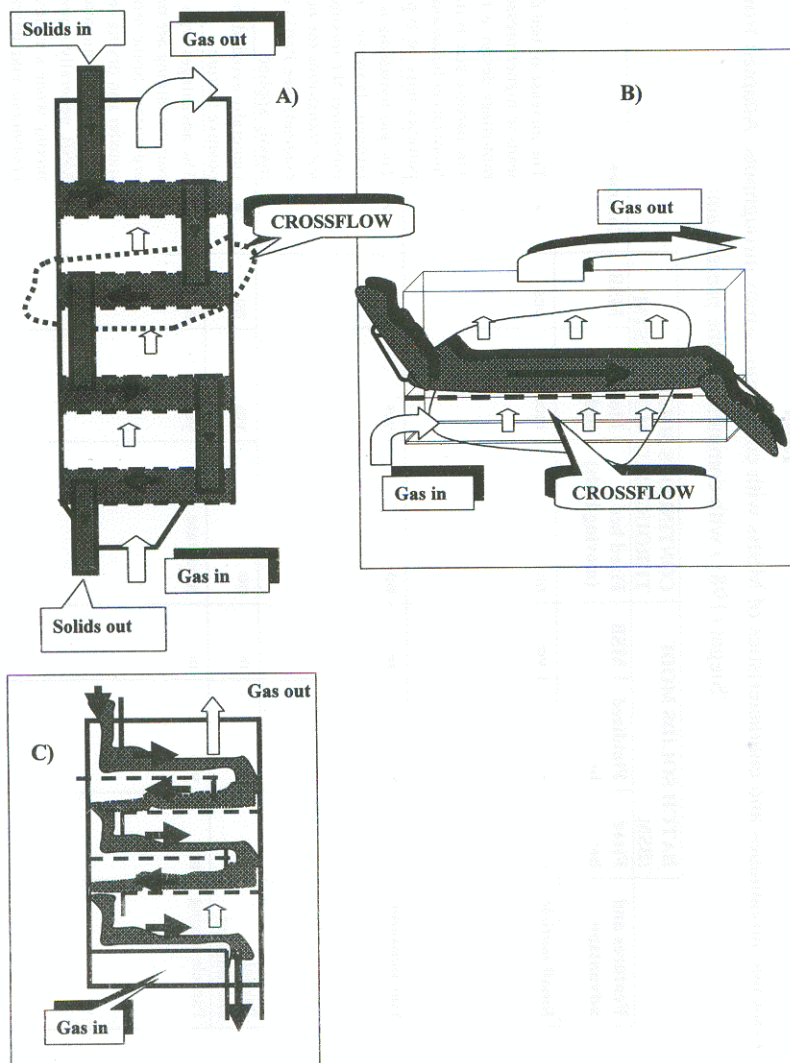


Fig. 13: Examples of nonmagnetic crossflow fluidized beds.

fluidized beds such as gas bypassing and vertical solids backmixing. The idea developed by Exxon (Siegel and Coulaloglou, 1984a, 1984b; Cheremisinoff et al., 1985) was provoked by the fact that the external magnetic field *can control* mobility of the solids, thus avoiding some *undesirable backmixing* specific to crossflow-fluidized beds. The main approach in these investigations is the same as in the studies on countercurrent stabilized beds.

The principal design suggested by Exxon was the same as that of the non-magnetic devices (see Fig. 3b), except for the external magnetic field around the channel. In all the studies the stabilizing field was oriented axially (parallel to both gas flow and column axis-see details in Table 3). This concept allowed building-up of a multistage fluidized bed with *general countercurrent* gas-solids flow and *specific (local) crossflow* on the contacting plates.

In contrast to the deep countercurrent beds, crossflow beds are shallow, which alters the gas-solids mechanics. Crossflow design requires a shorter magnetic system surrounding the bed compared to the longer magnetic systems around the deeper countercurrent beds. Thus crossflow design allows utilization of various magnetic systems (see examples shown in Part 1) creating magnetic field in different directions regarding both gas and fluid flows. The effects of such magnetic systems have not yet been investigated, so the discussion below focuses on beds controlled by axial fields as only reported in the literature.

II.3.2. Tilted channel crossflow MSB - operating conditions and macroscopic facts

The discussion addresses several problems: 1) Flowability conditions; 2). Field intensity effect; 3) Solids flow patterns; 4) Tilted channel bed depth control.

1) The flowability conditions of the solids in the crossflow mode were determined through a procedure similar to that employed with the countercurrent beds (see Fig. 5). This implies that the initial operating point is near to the transition locus that is followed by an increase in the field intensity up to flowability stop. This experimental procedure *determines* the field intensity range applicable to the particulate solids chosen. Siegel and Coulaloglou (1984b) performed the test under a *constant solids mass flow* rate controlled by a pneumatic transfer system similar to those countercurrent beds. Obviously, the solids throughput rate has an effect on the transition

Table 3
Crossflow MSB – Basic data about previous experiments

Bed design	Bed design data	Solid particles and Fluidizing gas	Magnetic field	Observations and Measured quantities	Reference
Tilted channel crossflow MSB	7.62 cm wide and 55 cm long channel unit made by Plexiglas	- Composite solids : > (40 wt% SS/60wt% Alumina) ♣ $\rho_s = 1000 \text{ kg/m}^3$ $d_p = 450 \mu\text{m}$ $d_p = 1050 \mu\text{m}$ > (70 wt% SS/30wt% Alumina) ♣ aluminum coated - Fluidized by air	- Axial (steady) - Four solenoids Each 90 cm I.D. and 16 cm high. 18 cm space between each magnet. - Total length of the magnetic system = 88 cm	- Bed height - Bed surface inclination - Distributor tilt effects - Solids throughput rate - Velocity profiles - Bed flowability - Effective bed viscosity	Siegel and Coualoglou (1984a) ♣ (1984b) ♣ Cheremisinoff et al. (1985) ♣
Carousel crossflow MSB	See the scheme on Fig. 22	- Composite solids : > 70 wt% SS/30wt% Alumina ♣ aluminum coated - Fluidized by air	- Axial (steady) $H_{\text{max}} = 234 \text{ Oe}$ $(\approx 18\,696 \text{ A/m})^*$ - Two Elliptical solenoids - Inside dimensions of 22cmx94.5 cm and 16 cm high. 15.5 cm space between the magnets. - Total length of the magnetic system = 88 cm	- Surface bed velocity profiles - Velocity profile across the bed depth	Siegel et al. (1985b) ♣ (1984b) ♣
Labels: * -calculated by the present author; ♣, ♠ - corresponding situations					

point.

2) **Field intensity** has no influence on the transition point, i.e. the transition locus remains unchanged (Fig. 14). Thus, the results repeat those reported for countercurrent beds. Siegel and Coulaloglou (1984a) also commented on the bed freezing at high field intensities without any support by quantitative data.

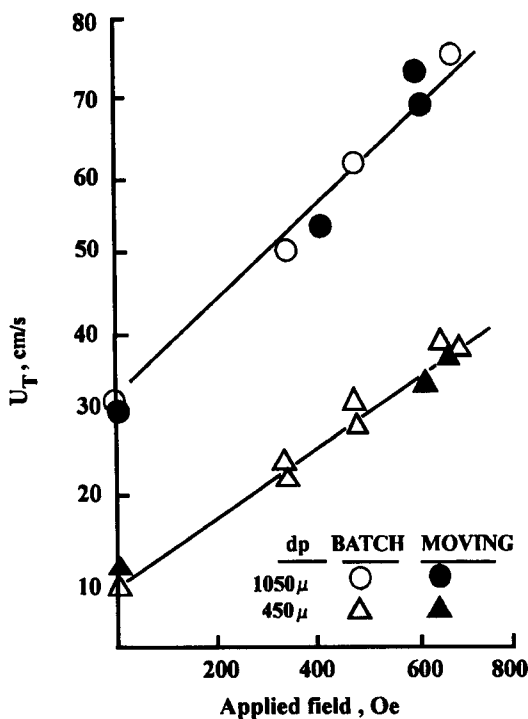


Fig. 14: Effect of the solids throughput on the transition in crossflow magnetically stabilized beds. According to Siegel and Coulaloglou (1984a).

3) **Solids flow patterns** observed by Siegel and Coulaloglou (1984a) in a crossflow MSB (three sizes of 40 wt. % stainless steel/60wt. % alumina) indicate that the velocity profiles almost correspond to a plug flow except for narrow layers (less than about 10% bed height) near the distributor. A comparison between calculated solids throughput rate and solids velocity measured through the vessel wall is illustrated in Fig. 15. The velocity profile shown in the inset of Fig. 15 is characteristic of Bingham plastic fluids with

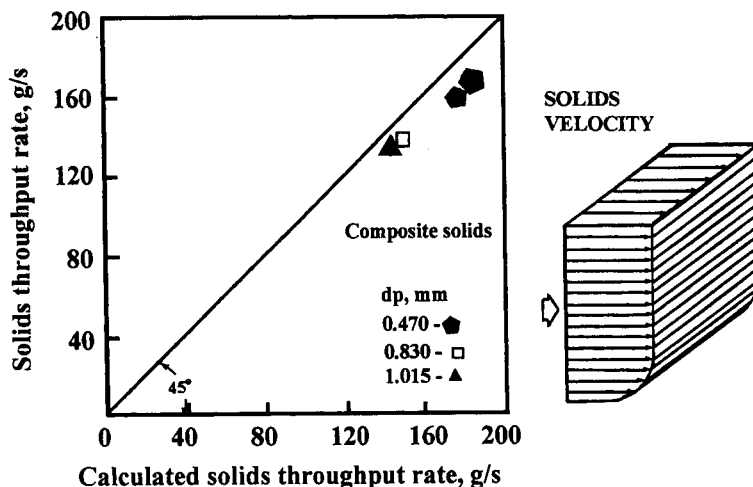
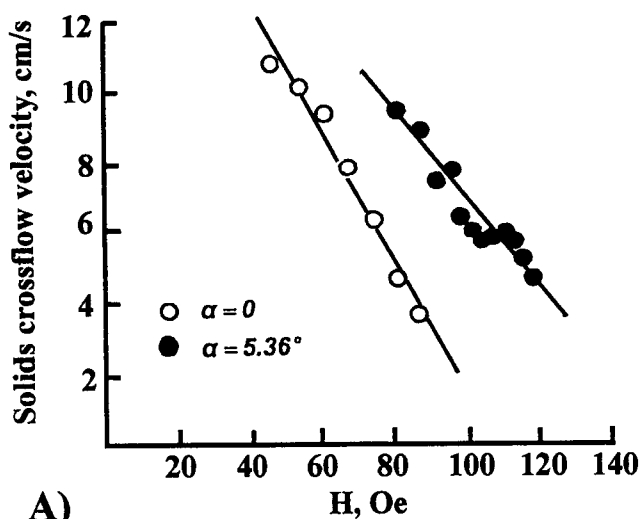


Fig. 15: Approach to plug flow of solids in cross-flow magnetically stabilized beds. From Siegel and Coulaloglou (1984a). Inset: Typical observed solids velocity profile.

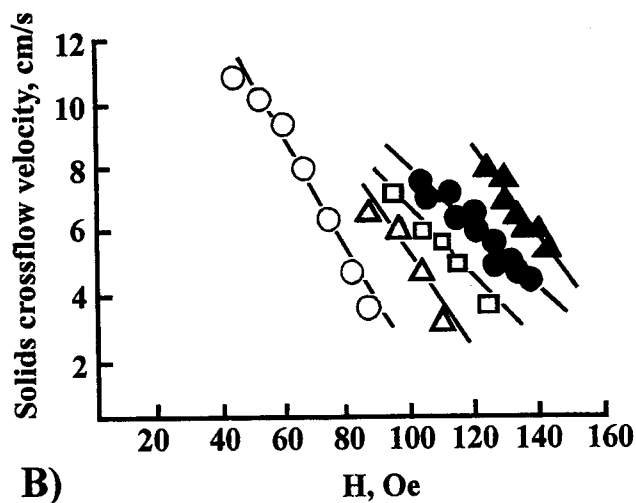
significant yield stresses, or of power law fluids indices approaching zero. The detailed bed mechanics will be discussed below.

The solids crossflow velocity, appearing to have a flat profile, is affected by several factors. The increased gas velocity increases the solids crossflow velocity (Fig. 16a) while the increased magnetic field intensity has the opposite effect (Fig. 16b). On the other hand, the distributor tilt angle has a significant effect on the solids velocity (Fig. 16b) since the increase in the distributor tilt reduces the field intensity effect. The latter fact could be considered as an increased contribution of gravity on solids flow, since flow in the channel is *gravity-driven*. In fact, the increase in bed tilt increases the driving gravity component parallel to the channel axis. This is a classic problem on gravity driven fluid flow along a surface found in textbooks on transport phenomena.

4) Tilted channel bed depth control. The highest flowability of cross-flow MSBs corresponds to the marginal area near the transition locus. An alternative measure of solids flowability is the inclination of the bed surface. High angles of solids flow can cause large differences in bed height. If the vessel is sufficiently long, this could be the cause of flow maldistributions. Distributors tilt of only 5.36° leads both to a substantial increase in solids flow and to a decrease in the solids flow angle (Figs. 16a).



A)



B)

Fig. 16: Solids crossflow velocity (i.e. solids throughput) as a function of the field intensity under different operating conditions

a) Effect of the distributor tilt angle. Siegel and Coulaloglou (1984a).

b) Effect of the superficial gas velocity. Siegel and Coulaloglou (1984a).

U , cm/s: $\circ$ - 103.5; $\triangle$ - 117; $\square$ - 130.6; $\bullet$ - 144.6; $\blacktriangle$ - 158.5.

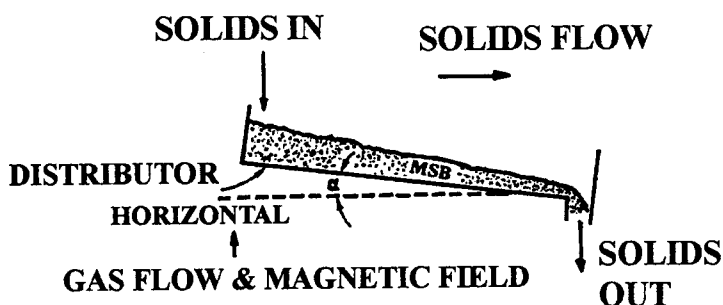


Fig. 17: *Tilted channel crossflow MSB* studied by Cheremisinoff et al. (1985).

Cheremisinoff et al. (1985) performed detailed experiments on fluid mechanics of tilted channel crossflow MSBs (see Fig. 17); for more details-see Table 3. The experiments identified the major parameters important to crossflow MSB operations. The device was designed to study continuous solids flow under a variety of conditions summarized in Table 4. The effects of the operating conditions on the bed tilt are formulated as follows:

- **Channel tilt.** Detailed experiments indicate that channel tilt affects dramatically bed depth (Fig. 18a). Increasing channel tilt reduces the depth.
- **Field intensity.** Increasing field intensity leads to thicker beds (Fig. 18c). The latter is a result of decreased particle mobility and increased aggregate-aggregate distances with stronger interparticle forces (see comments on the Magnetization LAST mode in Part 1).
- **Fluidizing flow rate.** Bed depth decreases as gas velocity increases (Fig. 18, b, d) due to the reduced drag at the distributor surface and the reduced effective bed viscosity (see below). As fluidization velocity approaches transition velocity, U_T , bed depth decreases (Fig. 18d). Both effects lead to faster movement of the bed along the channel.
- **Solids throughput.** Solids throughput practically does not affect the bed depth (Fig. 18b). Doubling of solids throughput increases the average bed depth (Fig. 18d) by only 10%.
- **Combined effects.** The combined effects of the operating parameters discussed above are:
 - **Bed depth decreases** as *channel tilt* and *gas velocity* increase (Fig. 18a, d). The effect of gas velocity is stronger.

Table 4
Detailed experiments in tilted channel crossflow MSB. According to Cheremisinoff et al. (1985b).

Bed design and operating conditions	Bed design data	Solid particles and Fluidizing gas	Magnetic field	Observations and Measurements
Channel geometry	7.67 cm wide and 65 cm long channel unit made by Plexiglas See the scheme on Fig. 20	- Composite solids : 70 wt% SS/30wt% Alumina aluminum coated - dp = -25 +50 U.S. sieve (average diameter $\approx 275\mu\text{m}$)["] $U_{mf0} = 22\text{cm/s}$ - Fluidized by air	- Axial (steady) parallel to the transverse axis of the channel $H_{\text{max}} = 234\text{ Oe}$ ($\approx 18\ 696\text{ A/m}$)[*] - Two solenoids connected in series	- Solids depth - Solids plug velocity - Effect of the ratio of operating to transition velocity - Velocity profiles - Effective bed viscosity - Shear stress
Channel inclination	0- 6°			
Aspect ratio: Average solids height to channel width measured	0.2 - 1.5			
Weir sizes	0.254 cm and 7.6 cm			
Ratio of operating to transition velocity	0.4-0.6 $\clubsuit$ 0.8 -1.5 $\heartsuit$			$\clubsuit$ majority of data taken $\heartsuit$ limited data taken

Labels: $\clubsuit$ -present author calculations $\heartsuit$ - corresponding situations

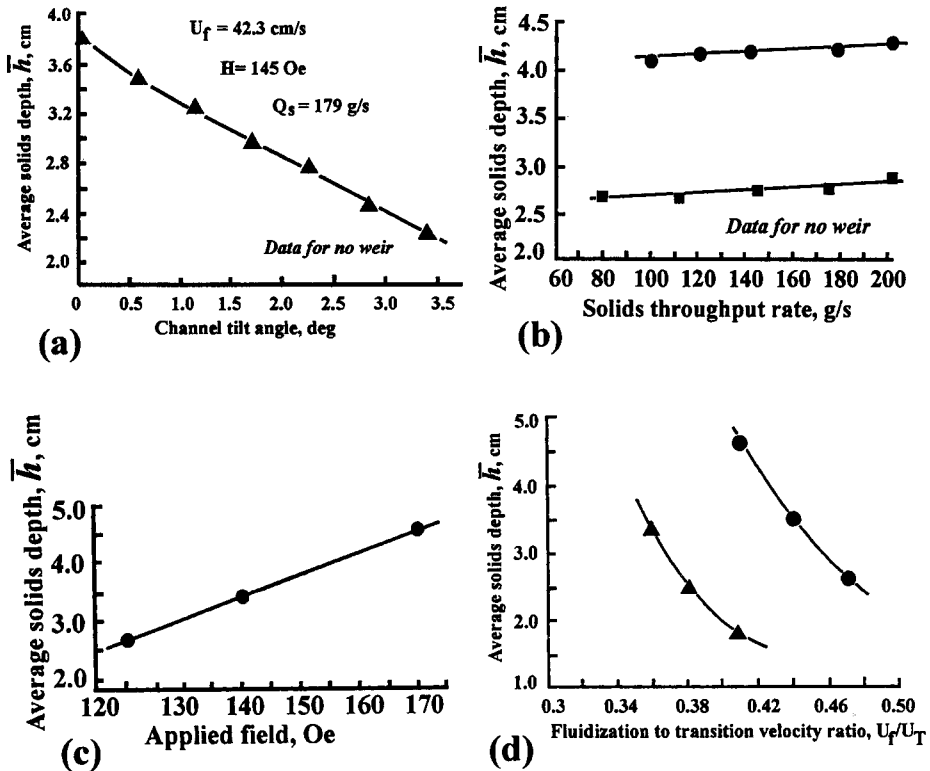


Fig. 18: Solids depth control in a *tilted channel* crossflow MSB. Adapted from Cheremisinoff et al.(1985).

- a) Effect of channel tilt angle on the average solids depth.
- b) Effect of solids throughput rate on the average solids depth.
- c) Effect of the applied magnetic field on the average solids depth.
- d) Effect of the ratio of the operating to the transition velocity on the average solids depth.

➤ **Bed depth increases** as *solids throughput* (Fig. 18a) and *field intensity* increase, if it assumed that both gas velocity and channel tilt (Fig.18b) remained unchanged. Field intensity affects stronger bed expansion while the solids throughput effect is weaker.

II. 3.3. Carousel crossflow MSB

The *tilted channel crossflow* MSB's design allows solids to be removed at one end of the vessel (channel) and pneumatically transported to a solids reservoir for controlled feed into the bed. The approach requires a lot of additional piping, gas compression costs, etc. Siegell et al. (1985b) proposed a solution avoiding many of these disadvantages. The solution has considered a crossflow MSB operating in a *carousel fashion*, without removing solids from the fluidization vessel. In such a configuration (Fig.19) solids circulate continuously in a closed horizontal loop. The horizontal movement of the fluidized solids was created by a huge amount of gas jets formed by 2001 round holes (0.00317 cm^2) drilled at an angle of 65° to the horizontal. The schematic carousel unit in Fig.19 has two types of turning sections: curricular (right section) and angled (left section) (more details about the carousel are summarized in Table 3).

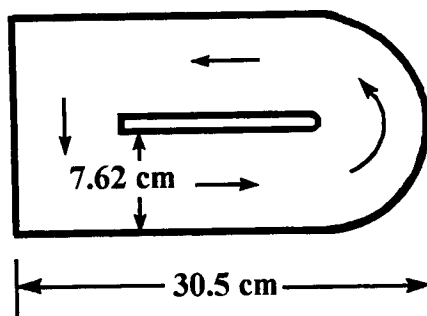


Fig. 19: Top view of carousel MSB experimental unit of Siegell et al. (1985b). The arrows denote the tilt directions of the distributor holes (the gas jets).

The main efforts were directed to studies both on *solids velocity profiles at the top bed surface* and on *bed depth control* through variations of the magnetic field intensity and the fluidizing gas velocity. The results are discussed below:

1) Magnetic field effect on top surface velocities. The experimental technique employed colored beads floating on a magnetized bed. The time needed to move them at a certain distance along the straight section of the carousel provided information about the bed surface velocity. The

experiments detected a near wall region where the solids remained stationary with parabolic velocity profiles (Fig. 20). This latter profile differs from the plug flow observed in tilted channel cross flow MSB. According to Siegel et al. (1985b), this might be attributed to the wall effects and the drag of the turning sections (in the corners) of the carousel. The stagnant layers of solids do not permit measurements of the vertical solids velocity profiles unlike the case of the tilted channel crossflow MSB.

2) Bed depth effects on top and vertical velocity profiles. Increasing bed depths leads to reduced top velocities. Taking into account that bed viscosity (see below) does not depend on bed depth, but is mainly affected by field intensity and gas flow rate, it might be suggested that the velocity profile is consistent with Poiseuille flow. Further experiments at different bed depths detected the highest velocity at the bed bottom near the distributor. Siegel et al. (1985b) suggested that changes in bed width might result in flattening of parabola profiles, relegating solids flow velocity variations to the order of the wall effects. Velocity measurements in both the lateral and the vertical directions clearly indicate that the solids have a complex two-dimensional velocity profile with a stagnant region in the lateral direction (across the channel width).

3) Gas velocity effects. Solids flow profiles obtained at a fixed field intensity but at different gas velocities demonstrate an effect that is opposed to that of variable field intensity. The physical meaning of this macroscopic observation is that both field and gas flow control bed fluidity within the marginal area around the transition locus. Decreasing bed fluidity (i.e. higher fields and lower gas velocities) results in flattening of velocity profiles (small velocity gradients). On the other hand, increasing solids fluidity leads to well defined parabolic velocity profiles (see Fig. 20).

II.3.4. Fluid flow models and rheology concept

The mathematical modelling of crossflow MSB has been developed in two papers only (Cheremisinoff et al., 1985 and Siegel et al., 1985b). Taking into account some specific features of both tilt channel and carousel devices, the models will be described separately. However, some common elements of the strategy and the assumptions forming the basis of the model build-up will be discussed at the beginning of the present section of the paper.

- **Tilted channel model.** The main suggestion of the model is that the bed is a homogeneous fluid flowing down through the channel as described by

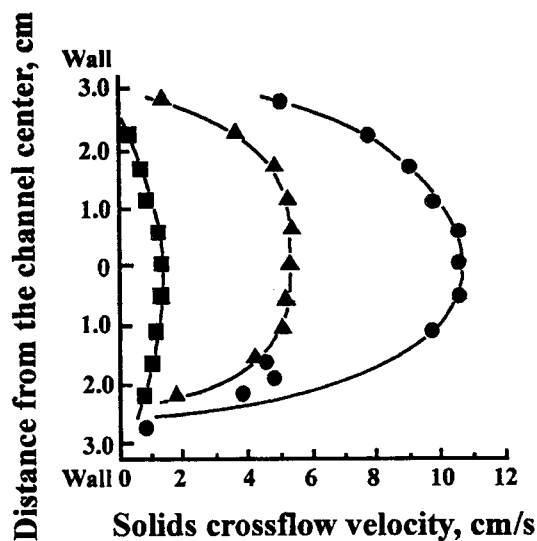
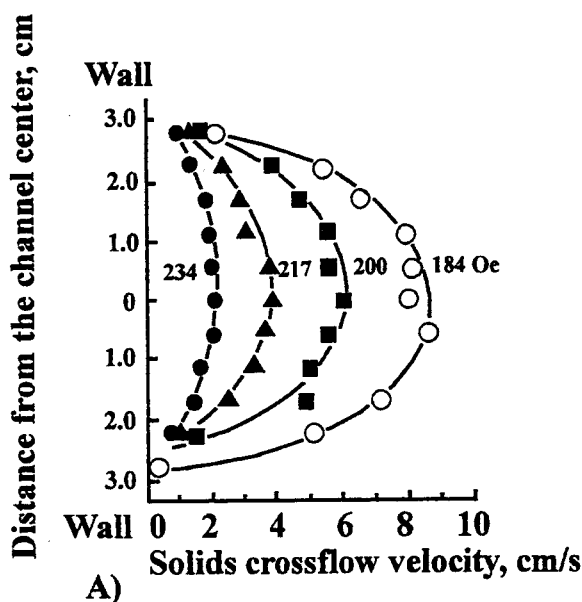


Fig. 20: Solids flow (top surface velocity) in a carousel crossflow MSB. From Siegel et al. (1985b).

a) Magnetic field effect on the top surface velocity.

b) Bed depth effect on the top surface velocity.

Dumped bed height, cm: ■ - 3; ▲ - 2.6; ● - 2.0.

the scheme in Fig. 21. If a steady state flow is assumed, the energy balance of the entire bed is

$$\Delta \left(\frac{U^2}{2\beta_c} \right) + \Delta (gy) + \int_1^2 v_0 dP + \sum_1^2 F + W_f = 0 \quad (5)$$

Further, since the fluid (incompressible flow) carries out no work, the last two terms ($\int_1^2 v_0 dP$ and W_f) vanish. Moreover, several assumptions were applied to Eq. (5):

- A) Solids flow through the channel is analogous to flow through a pipe.
- B) The model is *one-dimensional*
- C) Flow is *laminar*
- D) *Fluidized bed rheology is non-Newtonian.*
- E) The gas flow direction was assumed normal to the distributor, since negligible channel inclination is required for solids flow.
- F) No interfacial shear exists at the distributor-bed interface.

Application of assumptions A and B to Eq. (5) and approximating the longitudinal gradient of the friction losses, dF/dl , by the Darcy equation (assumption C), yields:

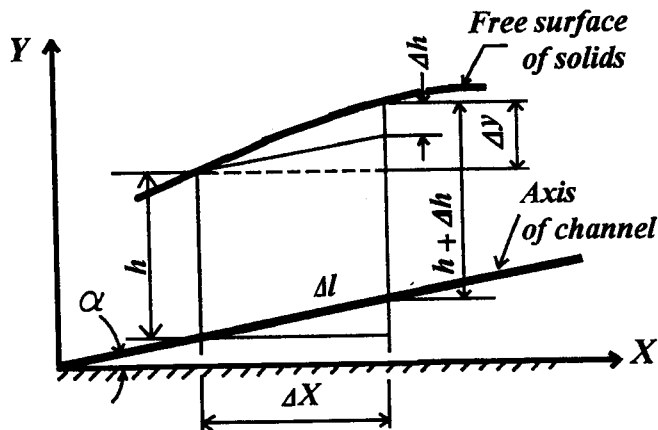


Fig. 21: Schematic of tilted channel cross flow model. Cheremisinoff et al. (1985).

$$\frac{U_{sm}}{\beta_c} \frac{dU_{sm}}{dl} + \rho g \left(\sin \alpha + \frac{dh}{dl} \right) + \frac{32\mu_e U_{sm}}{D_H^2 \rho} = 0 \quad (6)$$

The assumptions of continuity, together with the assumption E, lead to the following expression for the bed depth profile along the channel length.

$$\frac{dh}{dl} = \frac{-\left(\frac{32\mu_e U_{sm}}{\rho g D_H^2} + \sin \alpha \right)}{1 - \frac{(U_{sm})^2}{g \beta_c h}} \quad (7a)$$

where

$$U_{sm} = \frac{G_s}{\rho b h} \quad \text{and} \quad D_H = 4 \frac{b h}{b + 2h} \quad (7b)$$

The model assumes that a standard weir controls the channel discharge. This assumption permits extension of the classical theory of fluid flow over a weir. Application of the Francis equation (Zenz and Zenz, 1979) gives the free surface height at the discharge:

$$h_0 = \left[\frac{G^2}{b^2 g \rho (\rho_s - \rho_g)} \tan \Psi \right]^{\frac{1}{3}} \quad (8)$$

where Ψ is the angle of internal friction of the solids.

Cheremisinoff et al. (1985) have applied the value of h_0 as an initial input for integrating Eq. (7a) (via a second-order Runge-Kutta routine) from the solids discharge to the inlet.

- **Carousel crossflow MSB model** (Siegel et al., 1985). The model applied to this type of fluid-induced crossflow MSB begins with a simple equation of the rate of change of the horizontal gas momentum with the force applied to the bed as well as relation of the solids flow profile to the operating parameters. Siegel et al. (1985) considered a three-dimensional Poisson equation under the following assumptions:

1. The total force per cross-sectional area is the driving force.

2. The *apparent bed viscosity* is a function of the *solids velocity at the distributor*.

3. 3) *Velocity profiles* depend on the *solids velocities at the distributor*.

The following boundary conditions were assumed:

- No-slip conditions* at the side walls (*zero solids velocity*).
- Maximum solids velocity at the free surface (*zero velocity derivative*).
- Slip condition* at the distributor surface.

The following input variables were employed:

- Physical dimensions of the unit;
- Gas fluidization velocity, and
- Experimentally determined solids crossflow velocity at the symmetry axis of the top free surface

The model build-up follows several steps:

1) The change of gas momentum in carousel MSB is due to the fact that it *enters* the bed with a *horizontal velocity component* and leaves the bed *vertically* through the *free surface*. Thus, mass flow of the fluidizing gas and changing gas velocity are interrelated as follows:

$$\frac{M_g}{t} = Q_g = \rho_g U A \quad (9a)$$

$$\Delta U = U_0 \cos \alpha \quad (9b)$$

2) Equations (9) and $U_o = \frac{UA}{\sum A_o}$ give the total gas momentum change

per unit time

$$\frac{\rho_g A^2}{\sum A_o} U^2 \cos \alpha \equiv \left(\begin{array}{l} \text{the total horizontal force} \\ \text{exerted by the gas on the solids} \end{array} \right) \quad (10)$$

3) This yields a two-dimensional Poisson equation:

$$\mu_e \left(\frac{\partial U_s}{\partial y^2} + \frac{\partial U_s}{\partial x^2} \right) (bhl) = \frac{\rho_g A^2 U^2 \cos \alpha}{\sum A_o} \quad (11)$$

- **Rheology concept.** Bed rheology for the batch bed discussed in Part 2 focussed on the concept of the “*effective bed viscosity*”. In the case of crossflow MSB more information about the rheology of the flowing “*effective medium*” is needed both to explain the macroscopic phenomena and to provide a “*suitable closure*” of the bed model (see below).

Generally, the macroscopic results discussed above revealed that the bed flowability depends on the operating parameters and the solids properties (Cheremisinoff et al., 1985):

$$\text{Shear stress } \tau \propto \tau_y, \quad \eta \dot{\gamma} = f\left(Q_s, \alpha, \frac{U}{U_T}, H\right) \quad (12a)$$

$$\text{Effective viscosity } \mu_e \equiv \frac{\tau}{\dot{\gamma}}, \eta = f\left(Q_s, \alpha, \frac{U}{U_T}, H\right) \quad (12b)$$

The first three terms in the brackets of (12a, b) establish the *apparent*

$$\text{Channel shear rate } \dot{\gamma} \left(= 8 \frac{U_{sm}}{D_H}\right) \equiv f\left(\frac{U}{U_T}\right) \quad (12c)$$

with U / U_T most directly affecting the bed depth in the channel (i.e. the channel hydraulic radius – see Eq. (7b)).

Direct measurements of yield stresses, τ_y (affected mainly by the field intensity, H), and plastic viscosities, η , faced difficulties. The effective viscosity was calculated through the model of Eq. (7a). The integrating procedure was performed for values of μ_e that provided an averaged bed depth in agreement with the experimental values (averaged along the channel length) within 1%. Further, the *apparent channel shear rate* was assumed as $\dot{\gamma} \left(= 8 \frac{U_{sm}}{D_H}\right)$. This allowed the operating parameter μ_e (assumed as predicted through the integrating procedure) to be expressed as a function of $8 \frac{U_{sm}}{D_H}$ (see Fig. 22). The final results are expressed as a general power law relationship:

$$\mu_e = K \dot{\gamma}^{n-1} = K \left(8 \frac{U_{sm}}{D_H}\right)^{n-1} \quad (13)$$

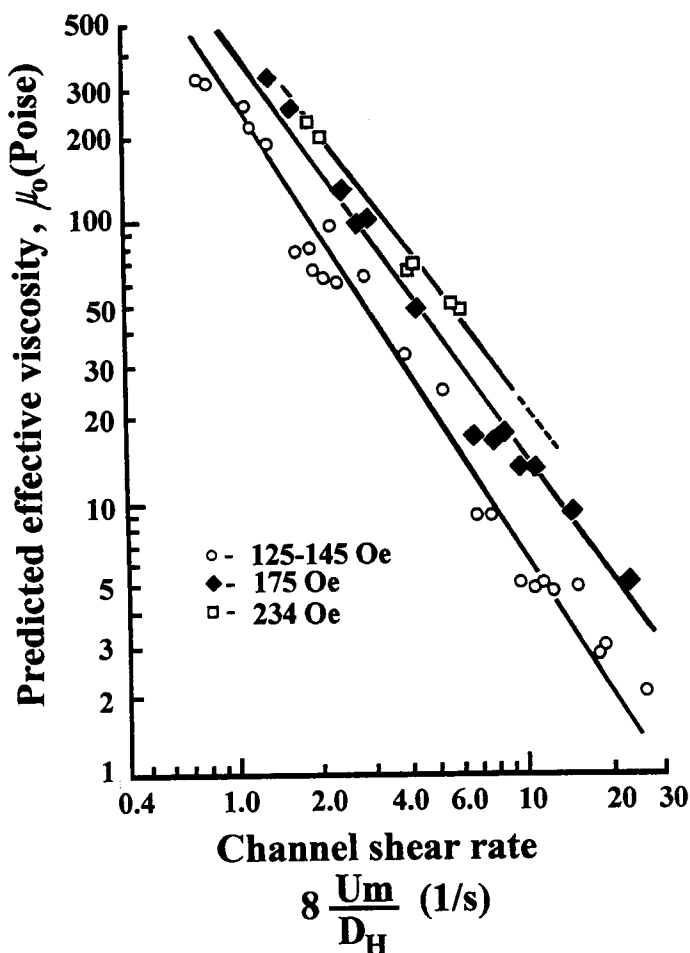


Fig. 22: Effect of the assumed channel shear rate on bed viscosity – predicted by the model (Eq. 7a). Cheremisinoff et al.(1985). The corresponding n values are available in Fig. 24 a

The power law (Eq. 13) does not explicitly state the *yield stress* value, but its form implies that the flow behavior is **assumed** to be that of a *pseudoplastic fluid* with a power-law index $n < 1$. The assumption of constant n and K yields an implicit yield shear stress through the effective bed viscosity

$$\mu_e = \frac{(\tau - \tau_y)}{\dot{\gamma}} = K \dot{\gamma}^{n-1} \quad (14)$$

The use of the effective bed viscosity was recognized as a sufficient approximation strictly describing only the steady-state flow (after the deformation onset). However, the two-phase flow onset requires a *yield stress* definition, i.e. the *minimum shear stress* has to be determined. Cheremisinoff et al. (1985) employed a macroscopic momentum balance of the wall shear stress

$$\tau = \frac{D_H}{4} \left(\rho_s g \sin \alpha - \frac{\Delta P}{l} \right) \quad (15)$$

The force balance (15) is the well-known definition of the hydraulic radius of ducts (see the excellent explanation of Frank-Kamenetskii (1969)). It allows the wall shear stress to be computed and plotted as a function of the channel shear rate (Fig. 23). The plots are characteristic of a pseudoplastic medium and their linear section slopes (see dashed extrapolating lines) define the effective viscosities at low and high shear rates. Moreover, the intercepts of the flow curves at low channel shear rates give the yield stress values that increase parallel to the increased field intensity. These results are consistent with the data of Lee (1983, 1991) for batch solids beds (see comments in Part 2).

Cheremisinoff et al. (1985) commented that MSB exhibited “shear thinning” behavior due to a decreased effective viscosity at increasing shear rates. It is clear that the power-law expression is strongly affected by the field intensity. However, the experimental results reported do not confirm this or, at least, they do not give quantitative data. Because of this, the present author digitalized the plots in Fig. 22 and the data provided values of the power index n shown in Fig. 24a. The same approach, applied to the data of Fig. 23, yielded the plot in Fig. 24b. These results confirm quantitatively that the beds in tilted channels really exhibit *shear thinning* behavior.

Siegell et al. (1985b) solved the Poisson equation (Eq. 11) numerically with two unknown variables: *bed viscosity* and *solids velocity* at the distributor. The integration was performed with data obtained from three experiments (see the bed depths in Fig. 25) at $U = 71 \text{ cm/s}$ and $H = 234 \text{ Oe} \approx 18696 \text{ A/m}$ assuming various bed viscosity values. The unique cross point of the curves gave bed viscosity $\approx 27 \text{ P}$ ($\approx 2.7 \text{ Pa.s}$), since it did not depend on the bed depth. No data concerning bed viscosity variations with field intensity were reported.

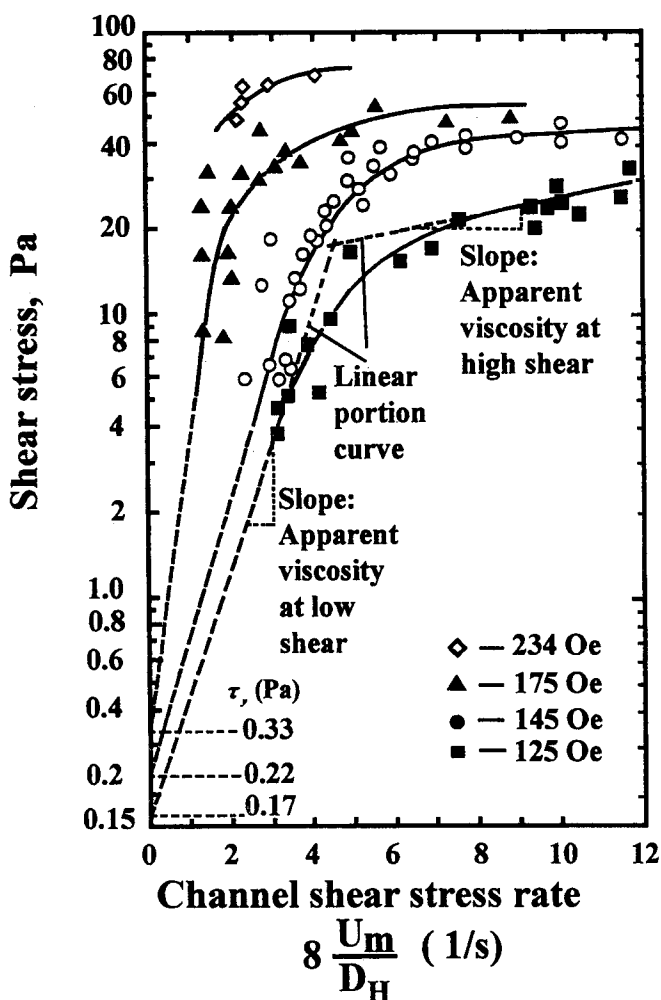


Fig. 23: Flow curves describing the rheology of tilted channel crossflow MSBs. Cheremisinoff et al. (1985).

❖ *Some remarks on the effective bed viscosity concept*

The models discussed above provide effective bed viscosity values and yield stresses through numerical solutions with adjustable coefficients. In fact, the procedure is an inverse problem solution, where the unknown

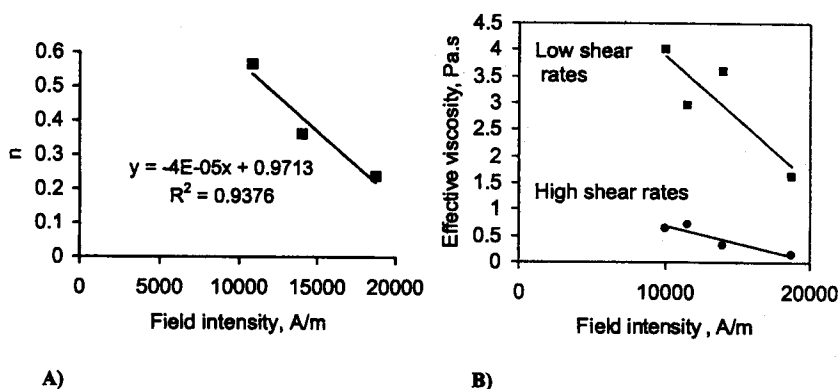


Fig. 24: Parameters of the models developed through some recalculations done in the present review.

- Variations of the power-law index with the applied field applied. Data source – Fig. 22
- Variations of the effective bed viscosity with the field intensity. Data source – Fig. 23

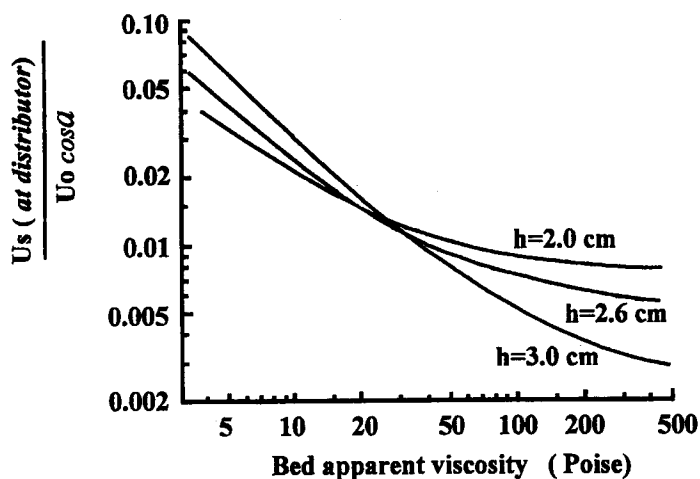


Fig. 25: Variations of the solids velocity at the bed bottom with the assumed bed viscosity in a carousel MSB. Sieggel et al. (1985b)

coefficients are looked for through minimization of the difference between the experimental and predicted values of the bed depth (at a predefined accuracy). Cheremisinoff et al. (1985) choose an accuracy of 1%. Similarly, Newton's definition of the viscosity $\tau = \mu\dot{\gamma}$ leads to the same approach through a procedure of a regression analysis performed by the least-squares method, for example. The methods used by Cheremisinoff et al. (1985) and Siegel et al. (1985b) are approximate and do not follow exactly the inverse problem theory (see Lawson and Hanson (1974) or Kirsch (1996)). The analysis employs a strong engineering intuitive approach using fluid flow analogies and scaling estimates. The results are qualitatively consistent with those established for batch solids beds (Lee, 1983, 1981). Some suggestions could be formulated as follows for further research:

- More detailed analysis on a microscopic scale of the particle-particle interaction in a magnetic field and particle size effects is necessary.
- More precise establishment of the fluid (gas) solids drag forces during the bed deformation should be performed.
- Development of a channel (or a pipe device) viscometers for gas-solids in an external magnetic field is needed (see further discussion, section V).

II.3.5. Model solutions

The model provided solutions for the bed depth longitudinal profile and velocity profiles in both crossflow devices discussed here. These solutions are discussed below

- **Bed depth longitudinal profile in a tilted channel crossflow MSB.** Siegel et al. (1985b) combined the expression (11) and the regression established slope of the lines in Fig. 22 to derive an equation with respect to the longitudinal gradient of bed depth.

$$\frac{dh}{dl} = \frac{\frac{2K}{\rho g C} \left(\frac{3n+1}{n} \right)^n U_{sm}^n + \sin \alpha}{1 - \frac{U_{sm}^2}{\beta_c g h}} \quad (16a)$$

$$\text{where } \beta_c = \frac{(2n+)(5n+3)}{3(3n+1)^2} \quad (16b)$$

$$C = \left(\frac{D_H}{2} \right)^{n+1} \quad (16c)$$

The predicted/extrapolated value of μ_e (see results on carousel MSB commented upon above) was used to predict the free surface profile $h = h(l)$ (see Fig. 25) under steady-state flow conditions (Fig. 26 and Table 5). Generally, the model cannot predict the potential flow instability near the weir.

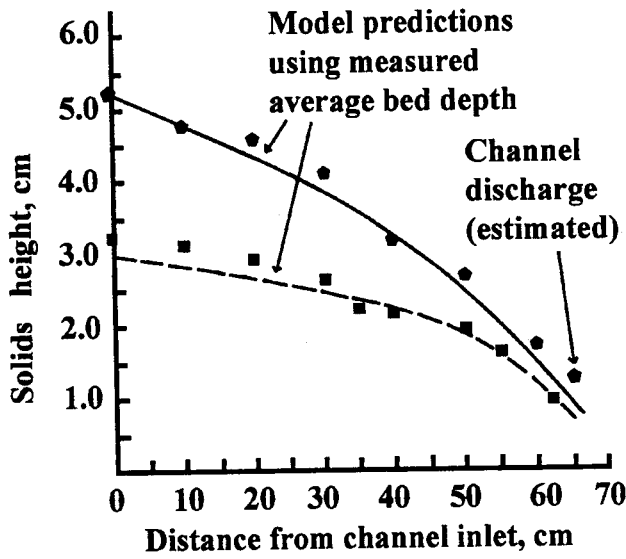


Fig. 26: Model predictions and experimental data. Cheremisinoff et al. (1985). The experimental conditions are summarized in Table 5.

Table 5
Detailed conditions of the experiments illustrated by Fig. 26.
Cheremisinoff et al. (1985)

Line & Symbol	H, Oe	α , deg	U, cm/s	Qs, g/s	U/U _T
— ○	145 (≈11 585 A/m)	0.56	42.3	110	0.52
- - - ●	145	2.81	42.3	114	0.51

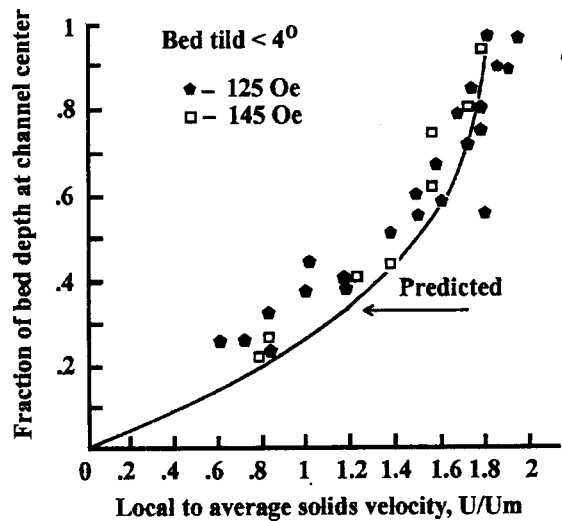
- **Vertical velocity profiles in a tilted channel MSB.** The power-law analogy assumed was employed to predict the vertical solids velocity profiles across the bed depth in a manner simulating power-law liquid flow in a tube

$$U = U_{sm} \left(\frac{3n+1}{n+1} \right) \left[1 - \left(1 - \frac{h}{h_{fb}} \right)^{\frac{n+1}{n}} \right] \quad (17)$$

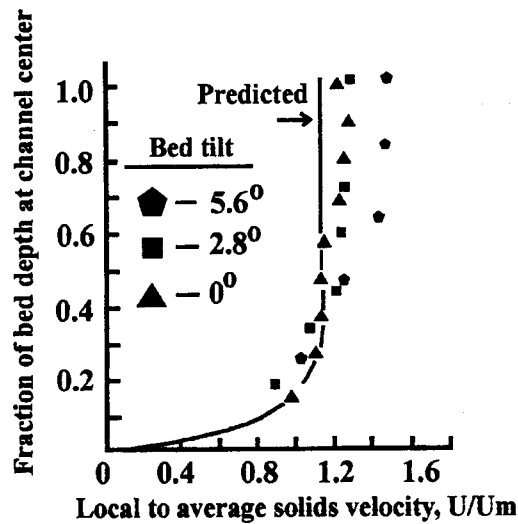
The solution assumes *no-slip conditions* at the channel walls and does not consider the flow inclination. The solutions and the measured solids velocity profiles are shown in Fig. 27 under conditions of two limit situations and for small bed tilt angles. The plots clearly indicate that at higher fields the velocity profiles approach plug flow. The authors attributed this to the increased bed viscosity (parallel to the increased field intensity) or, in other words, to the low values of the flow behavior index n . According to Cheremisinoff et al. (1985) at high field intensities (low solids rates) the controlling mechanism is the yield stress, while at rapidly moving beds it is the viscous flow behavior.

- **Solids velocity profiles in a carousel crossflow MSB.** The numerical solution of the Poisson equation (Eq.11) predicts a value of bed viscosity of 2.7 Pa.s (see Fig. 25). The results (not shown here) indicated a complex velocity profile that depends simultaneously on bed properties and gas velocity. No effects of the applied field intensities were reported.
- **Plug flow velocity (solids velocity) in tilted channel crossflow MSB.** If the above model is applied directly under the assumptions of a pseudoplastic fluid and linear stress distribution solids velocity should be presented by plug flow. However, Cheremisinoff et al. (1985) detected that the weir strongly affected the vertical solids velocity profiles. The flow over the weir yielded a non-linear velocity profile over more than 50 % of the entire bed depth. Moreover, the higher the solids discharge weir, the more the solids profile approached a plug flow.

A simple predictive procedure, assuming an analogy of bed flow as a liquid flow in a pipe (Cheremisinoff et al., 1985), gave a plug velocity approximation:



A)



B)

Fig. 27: Comparison of experimental data and model predictions for the solids free surface velocity. Cheremisinoff et al. (1985).

$$U_P = \frac{Q}{\rho A_H} \quad (18a)$$

where

$$A_H = \frac{\pi D_H^2}{4} \quad (18b)$$

The parity plot of the value of U_p defined by Eq. (18a) and the measured free surface velocity is presented in Fig. 28. According to Cheremisinoff et al. (1985) the plot clearly indicates that sufficient agreement exists at solids velocities less than 3 cm/s, i.e. for *slow-moving thick films*. With fast moving thin solids films the definition of U_p overestimates by as much as 60 % the free surface velocity.

Cheremisinoff et al. (1985) *recommended* Eq. (18) for estimation of solids free surface velocity of thick films. However, confusion occurs due to the hydraulic diameter D_H in Eq. (18b) to calculation of the bed cross area A_H . The definition of D_H is given by Eq. (15) as a **unique length scale** in ducts with complicated cross-sectional area. The force balance of the surface forces acting on an element of a flowing fluid of length l in a duct at $\alpha = 0$ yields

$$\tau = \frac{D_H}{4} \left(\frac{\Delta P}{L} \right) \quad (19a)$$

which at $\tau = \Delta P$ gives $l = \frac{D_H}{4}$. This is the *physical definition* of the hydraulic radius as a **length scale** of flow through the non-circular cross-sectional area of ducts. Generally, it can be expressed through simple algebra as (Denn, 1980):

$$D_H = 4 \frac{\text{wetted volume}}{\text{wetted surface}} \quad (19b)$$

which is practically the definition given by Eq. (7b)

This **length scale** could be employed **only** in *dimensionless groups*, such Reynolds number, or in the Darcy-Weisbach flow equation for *pressure drop*

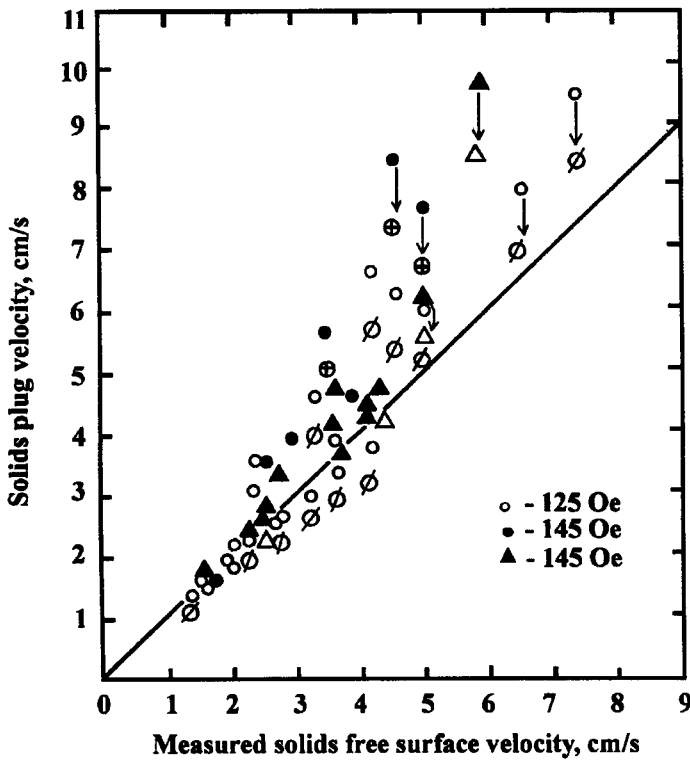


Fig. 28: A parity plot of a computer simulated velocity profile in a carousel MSB. Sieggel et al. (1985b). Symbols: $\circ$, $\bullet$, $\triangle$ – original work (calculations of Cheremisinoff); $\odot$, $\oplus$, $\blacktriangle$ – present work – corrected values – through Eq. (20)

calculation in pipes; uses of D_H for calculations of any areas are generally incorrect (Pnueli and Gutfinger, 1992 or Denn, 1980).

This short review of the hydraulic radius as a basic fluid flow length scale is reasonable since the commented results seem strange. Let us explain this correctly. Equation (7b) defines the *plug flow rate* (the superficial velocity), but not the mean solids velocity U_{sm} , as discussed by the authors. Both velocities coincide if the vertical velocity profile is *flat* and slip conditions at walls exist, *the basic assumption of the analysis is a non-slip condition*. However, the experimental results (see Fig. 27a) do not confirm the plug flow postulation. In order to obtain more accurate results some data in Fig. 28 are recalculated with a mean value of the bed depth of $h = 30$ mm. This value

was chosen as a mean value from the experiments carried out by Cheremisinoff et al., (1985), see Figs. 18 and 26, since there was *no information* in the original paper about the experimental conditions corresponding to the plotted data. The ratio of the cross-sectional areas calculated by the corrected approach and that of Cheremisinoff (Eq. 18b) is

$$\frac{U_p (A = b h)}{U_p (A_H)} = 0.885 \quad (20)$$

at $h = 30$ mm and a channel width of $b = 76.57$ mm.

The corrected values are plotted in the original figure with the corresponding symbols. The shift of the corrected values towards the parity line (see the arrows) indicates that the corrected approach works well. Thus, the overestimation (of about 60 %) of the model Eq. (18b) discussed by Cheremisinoff et al. (1985) is due to incorrect use of Eq. (18b). The corrected values indicate that at lower solids velocities the model prediction underestimates the experimental data, while at higher velocities it overestimates them. Therefore, the simple predictive procedure assuming pipe flow analogy gives physically adequate results as well as almost exact predictions at moderate solids velocities.

III. LOW-DENSITY MOVING FLUIDIZED BEDS (MULTISTAGE FLUIDIZED BEDS)

According to the classification in Fig. 2, the right branch of the structure corresponds to beds with *controlled non-continuous solids throughput*. The main idea emerged from the need to control solids mass flow through ducts (risers, downcomers or other transport lines). Since the beds consist of magnetizable particles, the devices should utilize magnetic field sources acting on solids. The devices developed by Jaraiz's group and Levenspiel (Jaraiz, 1983; Jaraiz and Estevez, 1987; Jaraiz et al., 1983; 1984a, 1984b) use combinations of screens and external magnetic fields.

The two types of devices developed, Magnetic Distributor Downcomers (**MDD**) and Magnetic Valves for Solids (**MVS**), have specific designs and operating modes, so they will be discussed separately.

This chapter of the review focuses on several points:

- Main ideas and trends in the development of **MVS** and **MDD**

- Principle designs of **MVS** and **MDD**
- Operating modes.
- Theories and scaling relationships.
- Experimental findings and correlations.

III.1. Main ideas and trends

Multistage fluidized beds are possible design solutions (see Fig. 13), but some difficulties hinder their development in practice. The main problems are due to:

- Channelling and gas bypass,
- Plug flow-up in downcomers,
- Blockages of the distributor screens and weirs, etc.

Nevertheless, if solids are magnetizable, opportunities exist to avoid some problems and to develop new multistage contacting devices. According to Jaraiz et al. (1983), the main questions that provoked studies of these aspects are:

- ❑ How to arrest the flow of a stream of flowing particles without use of mechanical barriers?
- ❑ How to control solids movement in fluidized beds by magnetic fields?
- ❑ How could this control create a distributor-downcomer for multistage beds, based on a magnetic field application?
- ❑ How to measure solids flow not only near the wall but also through the entire flowing mass using magnetic tracers?

In order to clarify the further discussion it is necessary to explain that the term “*low-density beds*” does not mean systems such as dusty gases and smokes. Separation devices utilizing magnetic fields to clean dusty gases such as precipitators, high-gradient separators, etc. are beyond the scope of the present discussion.

III.1.1. Fundamental principles of particle behavior in a magnetic field

Magnetic field actions on magnetizable particles were discussed under Fundamentals of Part I. Despite this, some specific phenomena occurring in low-density systems and forming the fundament of **MVS** and **MVD** will be reviewed here briefly.

An electric current generates a magnetic field that arranges the particles along the field lines. Such particle arrangements are true near the wire where the field generated is sufficiently strong to create

$$\text{Ponderomotive forces} \quad F_{PM} = k_1 H \frac{dB}{dr} \quad (21a)$$

and

$$\text{Particle-to-particle forces of attraction (magnetic Coulomb law)} \quad F_A = k_2 d_p^2 B^2 \quad (21b)$$

The main experiment (found in textbooks of physics) verifying this behaviour is the arrangement of iron filings on a sheet of paper through which a copper wire passes vertically. Further, field intensity decreases $\propto \frac{1}{r}$ (see below), so the field gradient and the ponderomotive forces decrease in an outward direction from the conductor. If the field is sufficiently strong the magnetic forces overcome the mechanical friction and the particles move (slide) toward the wire. On the other hand, if the magnetic forces are insufficient, the particles fall down (from the sheet) due to gravity or other mechanical forces.

The physical basis of the devices developed for low-density moving fluidized beds is formed by phenomena such as (Jaraiz et al. 1983):

- ❖ **Lining up of the particles** along the field lines.
- ❖ **Attraction of neighboring particles** (i.e. magnetic flocculation under Fundamentals of Part 1).
- ❖ **Magnetic lateral forces** oriented normally to the particle chain (string) curvature, i.e the Maxwell stress tensor forces (see Fundamentals of Part 1).

III.1.2.Principle designs and general considerations

The terms “**Magnetic Valve for Solids**” (MVS) and “**Magnetic Distributors-Downcomers**” (MDD) were introduced by Fitzgerald and Levenspiel (1984) for the devices schematically illustrated in Fig. 29. The main phenomenon employed by both devices is the *magnetic particle flocculation* that results in particle chain formation and chain attraction to the surface of the conductors when the current is turned on.

The turn on period of action of the current leads to solids flow stop,

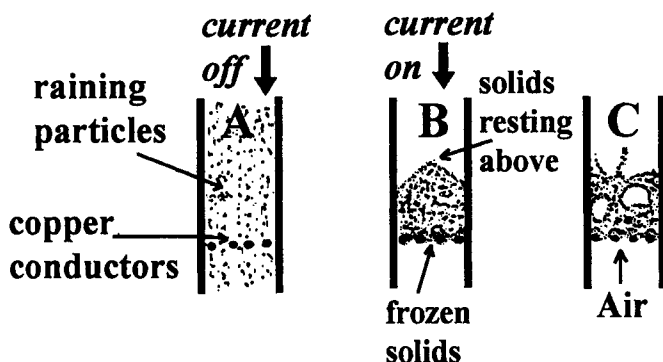


Fig. 29: Principal design of MVS and MDD. According to Jaraiz et al., 1983

- Freezing of raining particles around the wire when the current is turned on to create MVS
- The upflowing gas fluidizes the particle supported by the "frozen particle layer" and the device acts as a distributor-downcomer (c)

while the **turn off** period allows them to flow freely through the duct. Thus, by changing the duration of the two periods, it is possible to control the solid mass flux without any mechanical action, hence **magnetic valve for solids is created**. The latter implies gas flow that *does not form any upward particle motion*.

The particle-to-particle attraction decreases with increasing distance from the conductor, so the particles lying on the frozen layer are more movable than those near the wire. During the **turn on** period, the upward gas flow passes through the frozen particle layer like through a fluidized bed distributor. The continuously raining particles form a bed that is fluidized by the gas. The current **turn off** releases the particles down through the pipe. Therefore, there is an option of a **magnetic distributor-downcomer to be created**.

Generally, the adequate operation of the two devices depends on:

- **Solids concentration.** If particles are *sparsely distributed* (the case of **MVS**), very high currents are required to arrest them (the attractive forces depend on the distances between the particles (Coulomb's law). If current

intensity (the field strength) is low, some particles near the wire stop while others pass through, thus reducing the capturing efficiency that is never complete. On the other hand, in the case of **MDDs**, the *dense particle flow* needs low current intensities to form chains and to stop it.

- **Current strength.** The devices operate if current strengths can generate sufficient magnetic field intensities to produce particle aggregation and consequent bridging between the wires that form the partitions of **MVS** or **MDD**.
 - **Distance between the wires.** The distance between the wires, forming both the *sources of the magnetic field* and the *rigid skeleton* of the *magnetic partition*, strongly affects particle freezing and consequent phenomena. If, at a fixed current strength (during the **ON** period), the distance between two parallel wires (a mental experiment) increases, consequently, the field effect on the particles decreases. This leads to shorter particle chains and *insufficient bridge formations* between the wires, i.e. to *incomplete particle capture*. The opposite experiment – decrease in the distance between wires at a fixed current strength – leads to increased field intensity in the gap and consequently to easier particle aggregations and bridging. Thus, particle capturing and solids mass freezing are easier.
 - **Magnetic partition aperture.** The design of **MVS** and **MDD** utilizing superposition of a **screen** and a **magnetic field source** (see Fig. 30) based on particle flow stop due to chain formation with a size greater than the screen aperture.
- In general, the *controlling factor* of these devices is the *strength of the current* passing through the conductors.

The description of **MVS** and **MDD** clearly indicates that they operate according to the intermittent magnetization mode. According to the general nomenclature accepted in the review, this is the **ON-OFF** magnetization mode. From a physical point of view, the magnetic field **turn on** is followed by a series of consequent phenomena - particle aggregation, bridging, upper layer formation and fluidized bed growth occurring during the **ON** period. Therefore, the intermittent magnetization should have a sufficiently long **ON** period. Classification of the magnetization mode as **ON-OFF** is *based on a general principle*. Some phenomena during the **ON** period are the same as

those in the **Magnetization FIRST** mode, while others correspond to **Magnetization LAST** (at the onset of particle flow stoppage). So, from this point of view, precision of terminology is needed and such an attempt will be made in the review.

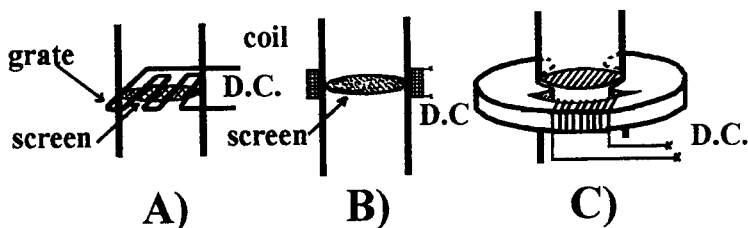


Fig. 30: Three main designs of MVS and MDD

- a) **Grate design** employing a current serpentine over a screen, both passing through the flow duct.
- b) **Collar design** with a short solenoid placed around the duct, while the screen remains in the flow channel.
- c) **Adjacent coil design** that uses the idea of the collar design, but with an iron yoke replacing the solenoid.

III.1.3. Potential applications

Potential applications of MVS and MDD will be discussed before the detailed analysis of their operational characteristics. The designs of these devices provide opportunities for new contactors, solids flow controllers, measuring devices, etc.

- **Gas-fine particles contactor.** Major problems emerging, when the conventional batch solids MSB is employed for reactions, are significant heat effects (discussed in Part 3 – Heat Transfer). The solution of Levenspiel and Kambholtz (Kambholtz, 1979; Levenspiel and Kambholtz, 1981) led to the application of an intermittent field with the **ON-OFF** magnetization mode. As commented, the main effect of that type of magnetization is avoidance of the axial temperature gradient in the bed by means of complete particle mixing without bubbles. According to Jaraiz et al. (1983), a potential problem is that *when the current is switched on*, the large bubbles (gas voids) may freeze in the bed, which results in *small extra deviations from plug flow*. These authors concluded

that both bubble size control and reduced gas bypassing could be achieved in devices consisting of several MVS at different levels, as shown in Fig. 31a, b.

- **Countercurrent moving bed contactors.** The possibility of creating countercurrent MSB in the continuous solids throughput mode was discussed earlier. The idea of developing countercurrent gas contactors based on MVS is shown in Fig. 31c. According to Jaraiz et al. (1983), the **ON-OFF** magnetization provides good solids flow control yielding a plug solids flow. However, the device in Fig. 31d can operate at relatively low gas velocities and minimum heat release.
- **Multistage fluidized bed contactors.** As mentioned, *the multistage fluidized beds are rarely used* due to lack of flexibility and the need of mechanical solids flow control. The latter problem is solved by a cross-flow MSB that is a version of continuous solids throughput contactors. **MDDs** arranged in a series along the channel form the device illustrated in Fig. 31d. Each stage of the bed is completely *independent of the pressure drop* value. This allows adjustment of safe and reliable behavior through proper timing of the magnetization current. Moreover, *plugging up* of the unit is impossible unlike the case with non-magnetic devices.

III.2. Theories of MVS and MDD

The designs discussed above need a more detailed description that would adequately present the basic phenomena taking place and their operational characteristics. This would enhance understanding of the engineering relationships derived for the device calculations.

Despite the fact that the three main types of MVS and MDD have specific characteristics, some phenomena taking place in the devices are common. The *theory employed* in the studies will be presented first and then the *operational characteristics* will be discussed. In the present section, some details discussed briefly earlier are adequately incorporated in the common description of the phenomena.

III.2.1. Qualitative theories of the devices

This section tries to explain, without any equations, the basic physical phenomenon that occurs in the devices. Moreover, the discussion elucidates the roles of principle design elements as grate, additional screens, external magnetic systems, etc. Two mental experiments are performed in order to define the *release current* as a key parameter controlling operations of MVS.

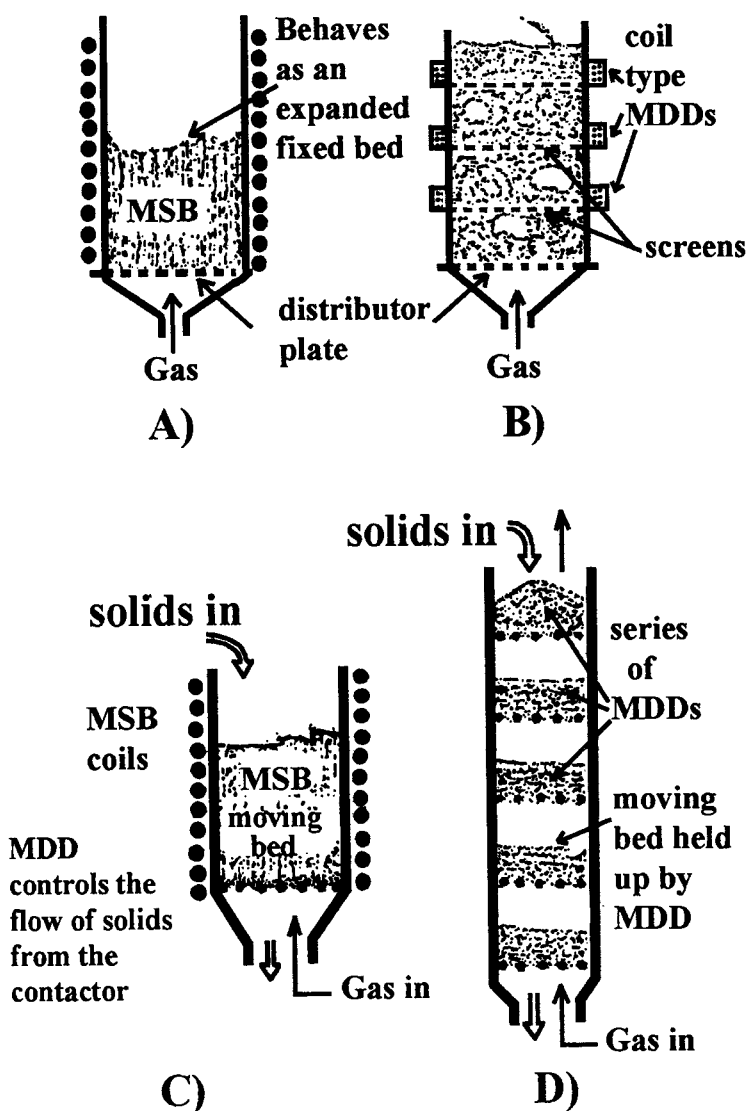


Fig. 31: Potential applications of MVS as improved contactors for fine solids. From Jaraiz et al. (1983).

- Conventional batch solids MSB with On-Off mode
- Series of MVS in a fluidized bed with intermittent magnetization currents
- Moving MSB (counter-current mode)
- Multistage moving beds controlled by a series of MVSS (counter-current mode).

III.2.1.1. Grate design task

- **Grate Design (GD) with a *conducting grate only*.** It is clear that magnetizable particles aggregate themselves in a magnetic field generated by electric current despite the design of the conductor. If there are no restrictions in the fluid surrounding the particles, such as buoyant forces, frictional forces due to fluid viscosity, etc., they will adhere to the conductor surface where field intensity is strongest. Thus, the particles raining towards the grate (Fig. 32a.) are attracted to its surface, rest on it, build up bridges (from bar to bar) and block the channel, which that leads to solids flow stoppage (Fig. 32b).
- **Grate Design (GD) with *additional screens*.** If a *non-magnetic screen* is placed just beneath the grate (Fig. 32c) an additional arresting effect occurs since the screen aperture is smaller than the particle aggregate sizes. However, if the *screen is magnetic*, it will distort field lines via *concentration of magnetic flux*, mainly through the screen bars. The latter become strong magnetic poles that attract the raining particles, thus forming the first layer that stops the solids flow (Fig. 32d).

III.2.1.2. MVS with magnetic systems outside the channel

In contrast to *grate design*, MVSs based on the *collar design (CD)* or the *external coil design (ECD)* do not employ electrical conductors protruding into the solids flow. Both designs utilize magnetic systems generating magnetic fields inside the channel. Thus, they resemble the classical MSBs with external magnetic systems. On the other hand, certain principle differences between MVS and MSB exist:

- The purpose of the magnetic system of MVS is **not magnetic stabilization**, but *solids flow stop* through the channel.
- The magnetic fields of MVS unlike those of MSB should *not be homogeneous*. They must *only create sufficient field gradients* inside the channel forming particle *aggregates with sizes greater than the screen aperture*.
- The screens of MVS *are permeable to solids flow* when the field is **switched off**. Two general options are possible:
 - i) The screen is *non-magnetic* and **blocks only the passage of particle aggregates** formed as a result of magnetic flocculation.
 - ii) The screen is *magnetic* and plays the role of a magnetic body that distorts magnetic field lines. Thus *centres of attraction* (magnetic poles) are formed for the raining magnetic particles. The attraction

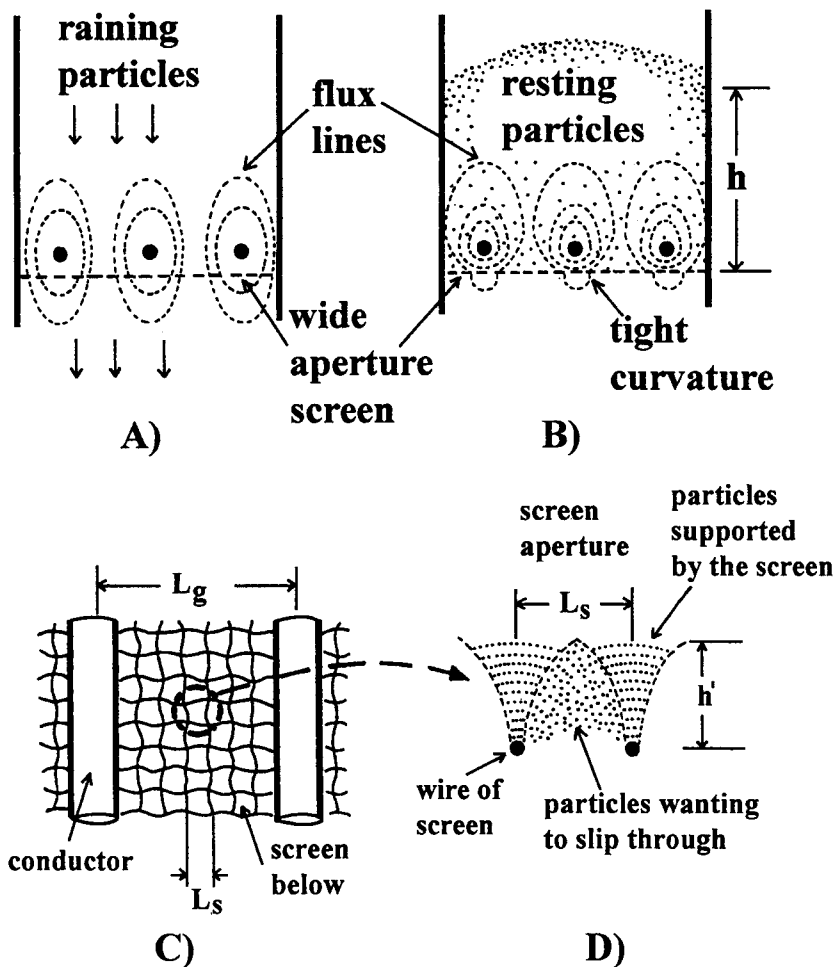


Fig. 32: Magnetic flux lines around the conductors forming a grate type MVS. From Jaraiz et al., 1984a)

- a) With free falling particles and non-magnetic conductors in the channel.
- b) With stopped particles and non-magnetic conductors in the channel.
- c) and d) Forces on particles ready to slide through the screen aperture.

leads to *particle flocculation* and *aggregate adherence* to the screen bars. Bridging between the bars may stop or may not stop solids flow. This depends on the field intensity generated between the bars.

III.2.1.3. Release current concept – two mental experiments

Particle flocculation and aggregate size growth depend on both particle magnetic properties and field intensity. This was discussed under Fundamentals of Part 1. Let us perform *two mental experiments* trying to elucidate MVS mechanics.

- **Experiment 1.** Let us assume a channel with free raining particles and a **switched-off** magnetic field. **Switching on** of the field and a slow increase in its strength (despite the type of the magnetic system) will lead to particle flocculation. At a certain field intensity particle aggregates will become greater than the aperture of partition (grate or screen) immersed in the channel, so solids flow will stop. The raining particles will build-up a growing particle bed that is supported by the first layer frozen by the partition. A further increase in field intensity will lead to deeper beds and to magnetic stabilization. The *minimum field intensity* that stops the solids flow through the grate (or the screen) can be named the minimum *holding intensity*.
- **Experiment 2.** Let us assume that no particles are *raining through the channel* and the field is **switched on** at a desired (sufficiently high) intensity. The start of solids flow will be followed by particle *aggregation* and no *solids will pass* through the partition. Obviously, the choice of the initial field intensity is a matter of argument and depends on the experience of the imaginary investigator. The continuously raining particles will form a bed supported by the first particle layer frozen by the partition. This phenomenon resembles that observed with Experiment 1. Now, let us start to decrease field intensity and detect the first particle detachment from the partition. At a certain field strength, particle leak starts and any further field intensity reduction will lead to growing particle mass flux through MVS. The *maximum field intensity* at which seepage of solids occurs is the *release intensity*.

Both experiments define the moment of the *solids flow stop*. Assuming that no hysteresis phenomena exist (keep in mind, **mechanical hysteresis**, not magnetic !), the minimum *holding intensity* and the *release intensity*

would coincide. Consider fluidization scenarios described in Part 1 *Experiment 1* corresponds to the *Magnetization LAST* mode, while *Experiment 2* is relevant to the *Magnetization FIRST* mode. In both experiments, the *minimum freezing field intensity* of the magnetic partitions is defined.

Further, an important element of the MVS design is the field non-homogeneity inside the channel. Therefore, *no representative field intensity could be defined* since its value varies with both vertical and lateral coordinates. The unique *representative parameter* that describes the operational characteristics of the devices is the **current strength I** . Although its value depends on the design of the particular device, it gives sufficient information about the characteristics of the valve. It should be kept in mind that the methodology employed with *Experiment 1* was applied to define the holding current I_h of magnetically semifluidized beds (Hristov, 1995, 1998a, Part 2). The groups that worked on MVS and MDD (Jaraiz et al., 1984a, Zang et al., 1984; Davis and Levenspiel, 1985) accepted the terminology corresponding to *Experiment 2* - **Release Intensity** and more precisely **Release Current I_r** . This terminology will be used hereinafter in the review.

III.2.2. Quantitative theories of the magnetic partitions of MVS

In contrast to the qualitative descriptions and analysis in the previous part, the quantitative theories of the devices employ basic physical laws and equations. This permits establishment of scaling relationships between *design parameters* of partitions and the *electric current as operating parameter*. The analysis starts with the simplest situation of a grate alone and gradually goes toward a most sophisticated design of MVS.

III.2.2.1. Grate design theory

Let us consider **current-carrying conductors only in the channel**. Particles subjected to a magnetic field generated by a flowing current I form a blanket of frozen magnetic particles (see Fig. 33a). Each particle is affected by four kinds of forces. If the outermost particle Y in the lateral direction that is most weakly held (see Fig. 33b) is considered these forces can be listed as follows:

- Forces of interaction, F_1 and F_2 , with their magnetic neighbors. These forces are equal but have opposite directions.
- Forces of attraction to the conductor F_C .
- Gravity forces F_g .

- Frictional resistance F_f , directly proportional to F_C and related to the coefficient of friction. This frictional resistance just overcomes the force of gravity F_g , since the particle is still being held in the blanket.

The force F_C is directly proportional to the magnetic susceptibility of the particle ($\propto$ to particle volume V_p) and to the product of the field intensity and its local gradient dH/dr (Jackson, 1962) (see also Part 1 and Eq. 21a here):

$$F_C = \frac{V_p (\bar{\mu} - 1) H}{2} \left(-\frac{dH}{dr} \right) \quad (22a)$$

For a straight conductor $H = \frac{I}{2\pi r} \Rightarrow -\frac{dH}{dr} = \frac{I}{2\pi r^2}$ (22b)

so $F_C = \frac{V_p (\bar{\mu} - 1)}{8} \frac{I^2}{\pi^2 r^3}$ (22c)

Thus, for the frictional force we have $F_f \propto F_C$, or $F_f = k' F_C$.

The **force balance for a particle** just held in place (at the critical release field intensity) means that $F_f = F_g = V_p \rho_s g$, so

$$I^2 = \frac{8\pi^2 \rho_s g}{k' (\bar{\mu} - 1)} r^3 \Rightarrow I_r = K_0 r^{\frac{3}{2}} \quad (23)$$

where $K_0 = \text{const.}$

The correct form of K_0 is $K_0 = \sqrt{\frac{8\pi^2 \rho_s g}{k' (\bar{\mu} - 1)}}$ unlike $\frac{8\pi^2 \rho_s g}{k' (\bar{\mu} - 1)}$ reported

by Yang et al. (1982).

The force balance developed above utilizes several simplifications. However, *the real facts are as follows*:

- The magnetic permeability is not constant.
- The outermost particle may have no balancing forces F_1 and F_2 due to the absence of neighboring particles below it.
- Equation (21b) is valid only for straight conductors.
- Finally, the proportional constant K_0 varies with particle shape, density and diameter.

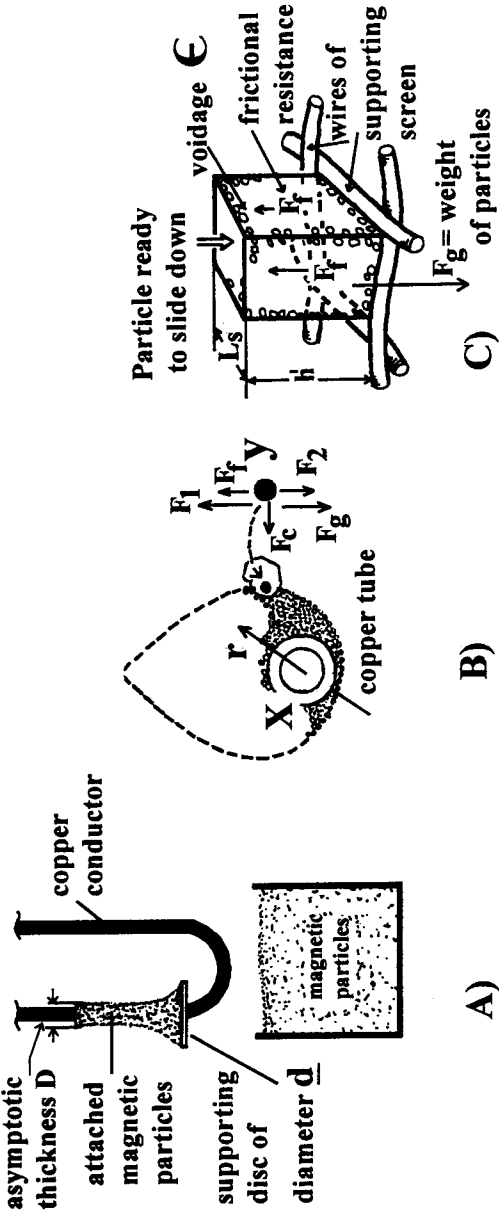


Fig. 33: Forces acting on a particle layer stopped by MVS:

- a) Simple experiment designed to determine the particle layer thickness on a vertical current-carrying wire. From Jaraiz et al. (1984a).
- b) **Grate design MVS.** Forces acting on a particle Y attracted by the blanket of particles surrounding the electric conductor. From Yang et al. (1982).
- c) **Collar design MVS.** Forces on particles ready to slide through a screen aperture. Zhang et al. (1984)

Let us assume the **grade spacing** L_g as a correlation length in the radial direction (from the conductor center), i.e. $r \sim L_g$. The final relationship (23) can be expressed as (Jaraiz et al., 1984a):

$$I_r = K'_0 L_g^{\frac{3}{2}} \quad (24)$$

The expression (24) gives a scaling relationship relating the operating parameter of the valve I_r and the design characteristic L_g .

A screen placed beneath the grate gives us a *new correlation length* in the radial direction expressed through the screen aperture L_s . The analysis considers a screen aperture much smaller than the grade spacing (see Fig. 32c), i.e. $L_s < L_g$. Current strength and particle characteristics (as commented above) determine the force balance. The simple model of the release current to the pertinent geometrical factors of MVS (Jaraiz et al., 1984a) considers a batch volume of particles at a typical aperture of the screen *in a closed valve position* (see Fig. 32b).

The **force balance** for particles tending to slide downwards (Jaraiz et al, 1984a) is:

$$\begin{aligned} F_{p,particle} &= \left(\begin{array}{c} \text{number of} \\ \text{pairs of facing} \\ \text{particles} \end{array} \right) \left(\begin{array}{c} \text{friction force} \\ \text{between pairs of} \\ \text{facing particles} \end{array} \right) \\ &= k_3 \left(\frac{4L_s h'}{d_p^2} \right) \left(\begin{array}{c} \text{horizontal component} \\ \text{of forces between} \\ \text{adjacent particles} \end{array} \right) \end{aligned} \quad (25a)$$

Taking into account the weight of sliding particles (see Fig. 32b), we have:

$$W_p = (\text{volume}) \left(\begin{array}{c} \text{bulk} \\ \text{density} \end{array} \right) = k_2 L_s^2 h' \quad (25b)$$

Combination between Eqs. (25a, b) yields the force just needed to hold the particle in place

$$F_{p,horizontal} = k_4 L_s d_p^2 = k_5 d_p^2 M^2 = k_5 d_p^2 \left(\frac{B}{\mu_o} - H \right)^2 \cos \theta = k_6 d_p^2 \left(\frac{B}{\mu_o} - H \right)^2 \quad (26)$$

where $F_p = k_5 d_p^2 M^2$ (Fink and Beaty, 1978), while k_5 depends on the magnetic properties of the particles.

Now, taking into account that $H = I/2\pi r$ and $B = \mu_e H$, Eq. (26) provides the current-*grate spacing* relationship

$$I^2 = \frac{4\pi^2 k_4}{k_6} \frac{r^2 L_s}{\left(\frac{\mu_e}{\mu_o} - 1 \right)^2} \quad (27)$$

At $r = \frac{L_g}{2}$ (the midpoint between the grate bars) and bearing in mind

that for most magnetic materials $\frac{\mu_e}{\mu} \gg 1$, the expression for I becomes

$$I = k_7 \frac{L_g \sqrt{L_s}}{\left(\frac{\mu_e}{\mu_o} \right)} = k_8 \frac{L_g \sqrt{L_s}}{\mu_e} \quad (28a)$$

The value of μ_e remains practically constant (see comments below), so

$$I = k_9 L_g \sqrt{L_s} \quad (28b)$$

When $L_s \rightarrow L_g$ and $L_s \approx L_g$, Eq. (28b) approaches Eq. (24) for a grate alone.

Jaraiz et al. (1984) considered magnetic saturation of the particle material at high field intensities, i.e. B is independent of both the field intensity H (see Part 1) and the radial co-ordinate r . Under these limiting conditions,

$\mu_e \sim \frac{1}{H} \sim \frac{r}{I}$ and Eq. (28) gives $L_s = L_{s,max} = \text{constant}$. This implies that at very high currents certain maximum screen spacing can be reached beyond which particles cannot be held despite the current applied. However, Jaraiz et al. (1984) discussed the B-H curve of iron as a typical particulate material at

field strengths where the *particle material is not magnetically saturated*.

III.2.2.2. Collar design theory

The *collar design of valves (CD MVS)* considers working current I_w higher than both the capturing current I_c and the release current I_r .

$$I_w > I_c > I_r$$

Particle flow stops when the frictional drag between the particles ready to slide through the aperture becomes equal to the weight of the suspended ones (see Fig. 33c)

$$F_f = F_g \quad (29)$$

$$\text{Thus } F_g = (1 - \varepsilon) \rho_s (L_s)^2 h' \quad (30a)$$

$$\begin{aligned} F_f &= k_1 \left(\frac{\text{number of facing}}{\text{pairs of particles}} \right) \left(\frac{\text{horizontal force}}{\text{between facing particles}} \right) \\ &= k_1 \left(\frac{4L_s h'}{d_p^2} \right) F_{p, \text{horizontal}} \end{aligned} \quad (30b)$$

The force acting on a particle in a magnetic field has two components:

- *Particle-to-particle* attractive force along the magnetic field line, and
- *Particle-to-conductor* attractive force normal to the magnetic field flux.

The expression (26) in the form $k_5 d_p^2 M^2$ gives $F_{p, \text{horizontal}}$ that represents the *particle-to-particle force*. The value of M depends on the conditions created by the field inside the channel.

Generally, all CD MVS devices employ short solenoids (see Fig. 34a). A principal characteristic of MVS is the field non-homogeneity that does not agree with the idea of magnetic stabilization (discussed in the previous parts of the review). Fields generated by the short solenoids of MVSs are similar to those employed by earlier investigator of MSB (see the discussion in Part 1). At any point of the channel axis (Winch, 1963; Zhang et al., 1984, and any physics textbook), the field intensity of the coil expressed through the release current I_r is:

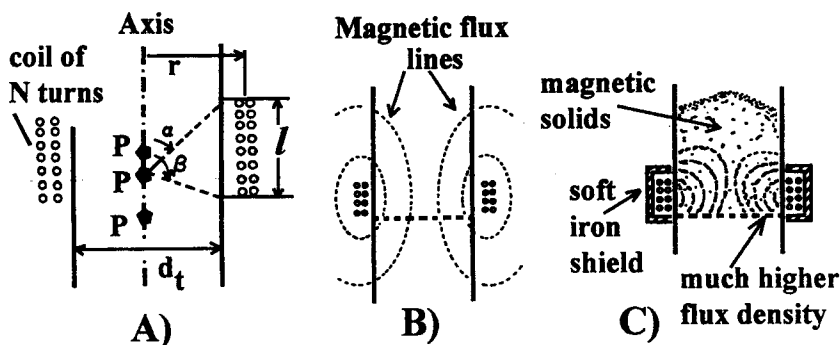


Fig. 34: Magnetic field of the short solenoid of a collar design MVS employed by Zhang et al. (1984).

- A sketch of the geometrical variable affecting the magnetic field intensity at the solenoid axis
- Magnetic field distribution with an empty tube.
- Magnetic field distribution with a packed bed of stopped particles.

$$H = N_w I_r \left(\frac{\cos \alpha - \cos \beta}{2l} \right) \quad (31a)$$

Here, the angles α and β and the length l are defined in Fig. 34a. At the solenoid center (the symmetry center P') the field intensity is

$$H = N_w I_r \frac{1}{\sqrt{4r^2 + l^2}} \quad (31b)$$

while at the solenoid bottom (point P'')

$$H = N_w I_r \frac{1}{\sqrt{4(r^2 + l^2)}} \quad (31c)$$

A particular situation considered by Zhang et al. (1984) is the location of the screen at the lower end of the coil. In this case field non-homogeneity is stronger in both the axial and the radial directions. At the same time ponderomotive forces attract the particles at that level towards the solenoid center counter to gravity forces. Expression of particle magnetization M as

$$M = \left(\frac{\mu_e}{\mu_o} - 1 \right) H \text{ permits Eq. (31c) to be solved with respect to } M$$

$$M = \left(\frac{\mu_e}{\mu_o} - 1 \right) \frac{N_w I_r}{\sqrt{4(r^2 + l^2)}} = \bar{\mu} \frac{N_w I_r}{\sqrt{4(r^2 + l^2)}} \quad (32)$$

Hence, the horizontal component of the **frictional force** is (see Eq. 26):

$$F_{p, \text{horizontal}} = k_s d_p^2 \left[\bar{\mu} \frac{N_w I_r}{\sqrt{4(r^2 + l^2)}} \right]^2 \quad (33)$$

The solution of (33) with respect to the ampere-turns ($N_w I_r$) (Zhang et al., 1984) yields:

$$N_w I_r = \left[\frac{k_3 \sqrt{\rho_s (1 - \varepsilon)}}{\bar{\mu}} \right] \left(\sqrt{r^2 + l^2} \right) \sqrt{L_s} \quad (34a)$$

$$\text{At } \bar{\mu} = \text{constant we have } N_w I_r \sim \left(\sqrt{r^2 + l^2} \right) \sqrt{L_s} \quad (34b)$$

Thus, at $l \ll r$ (short coil) the result is

$$N_w I_r \sim (\text{channel diameter}) \sqrt{\text{screen aperture}} . \quad (34c)$$

On the other hand, at magnetic saturation ($\bar{\mu} \sim \frac{1}{H}$) the maximum screen aperture can be defined as

$$L_s = L_{s, \text{max}} = \text{constant} \quad (35)$$

for any value of $\sqrt{r^2 + l^2}$. This implies a *maximum screen aperture* beyond which solids flow cannot be stopped. Equations (34a) and (35) refer to two extreme situations. First, if the perforated plate is replaced by a single orifice with a d_{or} , the screen equation (34b) could be modified as (Zhang et al., 1984)

$$N_w I_r \sim \left(\sqrt{r^2 + l^2} \right) \sqrt{d_{or}} \quad (36)$$

Second, at high magnetic field intensities, the expression (36) yields $d_{or} = \text{constant}$.

III.2.2.3. External coil design

The **external coil design (ECD)** of MVS was named because of the presence of a magnetic system containing iron elements (see Fig. 30c) that concentrate the magnetic field over a desired volume of the channel. The magnetization coil of such a system is placed on one of the arms of the iron yoke. Thus, there is no *direct contact between the coil and the flow channel wall* unlike collar designs of MVSs. This feature gives the name **external coil design (ECD)**.

The second and the most important feature of **ECD-MVS**, which generally distinguishes them from the other valves, is the *transverse field orientation*. The magnetic system is based on a C-shaped iron yoke with poles and a gap between them. The designs of **ECD** reported in the literature are shown in Fig. 35. The poles of the magnetic systems are faced slightly outside and on opposite sides of the vertical flow channel.

Generally, parallel-pole magnetic systems generate homogeneous fields over only 30 % of the gap volume (see comments in Part 1). This type of electromagnet design creates strong magnetic field gradients towards the poles (along the *normal vector* of the pole surface). A better solution is to build up an electromagnet with parallel flat poles, creating a homogeneous transverse field over a small volume of the gap. However, it has to be stressed that extension of the working volume towards the poles leads to strong field non-homogeneities that cannot be calculated analytically. Davis and Levenspiel (1985) performed an approximate analysis in order to establish *scaling* between the *release current* and the *screen spacing* as described below:

Ohm's law for a magnetic circuit may be expressed as

$$(\text{total flux}) = \frac{\text{driving force} = N_w I}{\text{reluctance of the magnetic circuit}}$$

$$\text{or} \quad \Phi_T = \frac{N_w I}{R_{MT}} = \frac{N_w I}{\sum_j R_{Mj}} \quad (37a)$$

$$\text{where} \quad R_{Mj} = \frac{\bar{L}_j}{\mu_o \mu_j A_j} \quad (37b)$$

is the reluctance of the circuit element j with a mean path length $\bar{L}_j$.

The magnetic field induction B , in the absence of a field fringing, is $B = \frac{\Phi}{w.h}$ (see Fig. 35a for the pole surface dimensions), which leads (through Eq. 37a) to

$$N_w I = B w h R_{MT} \quad (38)$$

Taking into account the three main elements of the magnetic circuit (magnetic core, particles within the channel and the gap formed by the channel wall), Eq. (38) can be expressed as

$$N_w I = B w h \left[\frac{\bar{L}_c}{\mu_o \mu_c w_c h} + \frac{\bar{L}_p}{\mu_o \mu_p w_p h} + \frac{\bar{L}_f}{\mu_o \mu_f w h} \right] \quad (39a)$$

where $\bar{L}_c, \bar{L}_p, \bar{L}_f$ are the mean paths of the magnetic flux through the magnetic core, the particle bed and the gap formed by the channel wall, respectively. μ_c, μ_p, μ_f are the mean magnetic permeabilities of sections of the magnetic circuit.

Simple rearrangements (and some algebra) lead to the main equation of Davis and Levenspiel (1985) that relates the ampere-turns $N_w I$ to the field induction B in the flow channel.

$$N_w I = B \left[\frac{w \bar{L}_c}{\mu_o \mu_c w_c} + \frac{s}{\mu_o \mu_p} + \bar{L}_f \left(\frac{1}{\mu_o \mu_f} - \frac{1}{\mu_o \mu_p} \right) \right] \quad (39b)$$

where $s = \bar{L}_p + \bar{L}_f$ is the pole face separation distance

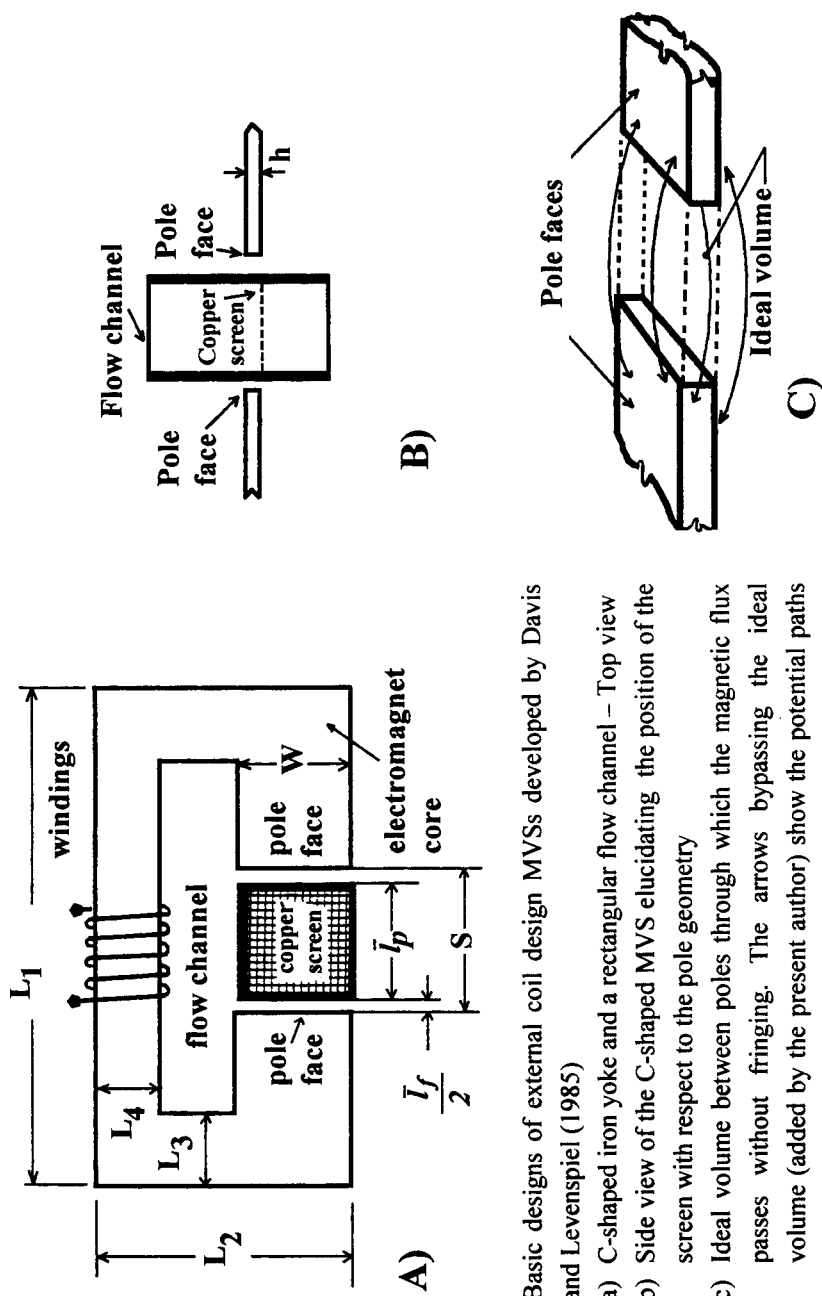


Fig. 35: Basic designs of external coil design MVSs developed by Davis and Levenspiel (1985)

- C-shaped iron yoke and a rectangular flow channel – Top view
- Side view of the C-shaped MVS elucidating the position of the screen with respect to the pole geometry
- Ideal volume between poles through which the magnetic flux passes without fringing. The arrows bypassing the ideal volume (added by the present author) show the potential paths of magnetic flux fringing not assumed in the design.

According to Davis and Levenspiel (1985), Eq. (39b) indicates that $N_w I$ is **independent** of the height of the electromagnet gap h and varies linearly with gap length s and pole width w . This is valid as long as the ratio $\bar{l}_c/w_c$ is kept constant. The analysis does not consider magnetic flux fringing or in other words magnetic flux bypass of the main paths of the magnetic circuits. Fringing represents alternative paths of the magnetic flux lines with minimum reluctances (see Fig. 35c).

III.2.2.4. Comments on the theories

The theories of MVS developed by Levenspiel's group give a tentative analysis of macroscopic phenomena. They are particularly focussed on estimations of *scaling relationships* between electric current partition spacings.

The main results (*scaling estimates*) that can be extracted from the theories are as follows:

- Release current $I_r \sim (L_g)^{\frac{3}{2}}$ for a single grate in the channel
and $I_r \sim L_g \sqrt{L_s}$ with a screen beneath the grate
- Release current $I_r \sim \sqrt{L_s}$ for a simple collar design with a screen
or $I_r \sim \sqrt{d_{or}}$ if a perforated plate replaces the screen

The above relationships disregard two important aspects: i) Magnetic field distortions by a particle bed accumulated on the non-magnetic screen; ii) Multi-gradient field generated inside the channel when the screen is magnetic. These complicated cases need to be tested experimentally on the basis of scaling relationships already established.

III.3. Operational characteristics of MVS and MDD in cases of pure magnetic particles

The title of this review section has been transferred directly from the paper of Yang et al. (1982). Thus the importance of the results reported in it is appreciated. The analysis that follows distinguishes *operational characteristics* from *mass transfer control* (section III.5). This approach allows more systematic presentation of the main ideas and easy comparison of the features of the devices investigated.

III.3.1. Holding (release) current of grate design MVS

Grate design MVS without screens, studied by Yang et al. (1982), was investigated in vertical channels (see Fig. 36) arranged with auxiliaries summarized in Table 6. The experiment was oriented to verify scaling relationships derived by the theory and the effects of iron screens that cannot be predicted by the theory.

Special tests were performed considering particle blanket formation on the surface of the copper conductors of the grate. The so-called “U-tube” experiments (see Fig. 33a) considered a U-shaped copper current-carrying conductor equipped with a disk-like platform. The U-shaped arm was placed in the empty vessel under a *current switch-off* condition. The vessel was filled with particles (soft iron material) and subsequently the *current was switched on*. After withdrawal of the arm, a particle blanket was formed (see the upper half of Fig. 33a). The asymptotic thickness of the blanket estimated as a function of the grate spacing (i.e. the disk diameter) exhibits a good fit with the prediction of Eq. (24) - see Fig. 37

Release current estimation was performed in accordance with the author’s *Mental Experiments* described above. Jaraiz et al. (1984a) decreased the current passing through the grate (as *Mental Experiment 1*) until particles started to fall from the grate. This experiment defines the *release current* I_r .

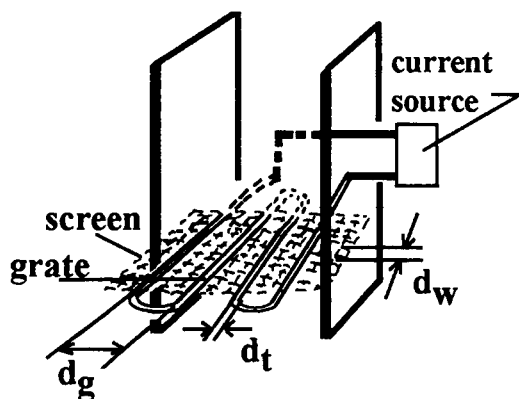


Fig. 36: Sketch of the experimental set-up employed for estimation of the operational characteristics of the grate design MVS. From Yang et al. (1982) and Fitzgerald and Levenspiel (1984). The design parameters are defined on the figure.

Table 6
Grate value variables (pure magnetic particles)

Valve Elements	Grate Design Parameter					References
Copper tubes	Spacing $\Rightarrow$ (Center to center distance, d_s)	13.0	19.5	25.4	31.7	Yang et al. (1982)
	o.d. of copper tubes, mm $\Rightarrow$	3.18	6.35	6.35	9.53	
Iron screens (~ 0.5mm wire diameter)	Aperture, d_w Code used	5.9 Screen 1	8.2 Screen 2	8.2 Screen 2	11.5 Screen 3	
Flow channel	Cylindrical tube	152 mm Pyrex tube				
Particles used	Soft iron particle d_p , mm	Average diameters, mm 0.14; 0.30; 0.69; 1.0; 1.4; 2.0				

Copper tubes	Spacing $\Rightarrow$ (Center to center distance, d_s)		12.7	19	25.4	Jaraiz et al. (1984a)
	o.d. of copper tubes, mm $\Rightarrow$	6.35				
Iron screens	Aperture, d_w Code used	3.3	6.4	8.5	-	
Particles used	Soft iron particle d_p , mm	0.24				

Further, with the *current off* and solids falling freely (as in *Mental Experiment 2*) the current was raised until the solids flow stopped. This step gave the *capturing current* I_c . The *working current* I_w was defined as a current slightly higher than I_c , satisfying the inequality $I_w > I_c > I_r$.

Three main effects on the holding (release) current were estimated experimentally (Yang et al., 1982):

1. Grate spacing effect.
2. Copper tube diameter.
3. Particle size effect
4. Iron screen effect.

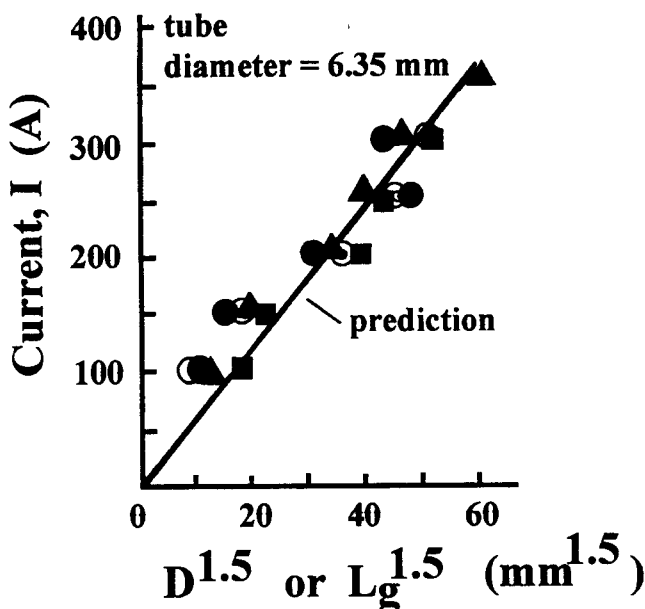


Fig. 37: Results from U-tube experiments for grate design MVS without screens. From Jaraiz et al. (1984a). See the experimental set-up in Fig.33a. Soft iron as particulate material used – present *author suggestion due to the absence of information in the original paper*. Labels: Disk diameter (mm): $\odot$ - 14; $\bullet$ - 20; $\blacksquare$ - 29; $\blacktriangle$ - 40. Solid line – Eq. 24.

- The **Grate Spacing** effect on the holding current through Eq. (23) is illustrated in Fig. 38a. The points indicate that at a lower grate spacing, Eqs. (23 and 24) ($I_r \sim d_g^{\frac{3}{2}}$) underestimate the values of I_r 5-10 %, while at larger d_g , the prediction overestimates it. Generally, an increase in grate spacing leads to higher values of holding currents, as predicted by theory.
- The **copper tube diameter** d_t has a similar effect on the values of I_h (Fig. 38b) due to easier bridging between grate bars. A larger tube diameter means weaker magnetic fields (see Eq. 22b) and higher holding currents. According to Yang et al. (1982), grate spacing is not an important factor, while tube diameter plays a distinct role. This can be argued since the

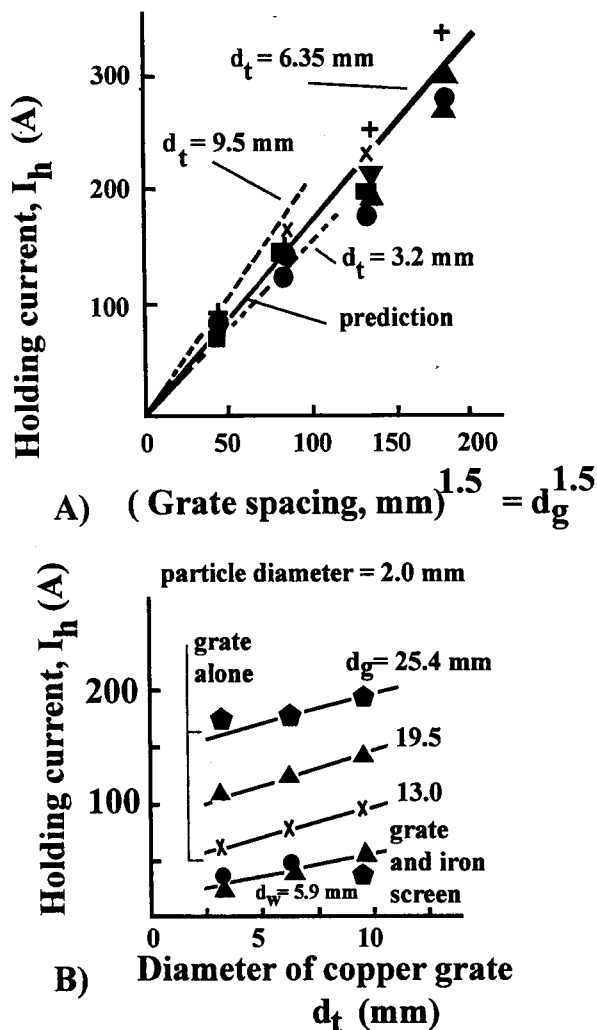


Fig. 38: Holding currents of the copper grate MVS. From Yang et al. (1982).

a) Parity plot of the predictions of Eq. (23) and experimental data.

Note: The symbol d_g is equivalent to L_g employed in the theoretical analysis. Labels, $d_p(\text{mm})$: $\times$ - 0.14; $+$ - 0.30; $\blacktriangle$ - 0.69; $\blacktriangledown$ - 1.0; $\blacksquare$ - 1.4; $\bullet$ - 2.0.

b) Effect of copper tube diameter d_t forming grate. The lower set of experimental points corresponds to an iron screen beneath the grate. (See Fig. 36 for better understanding of the geometry of MVS.)

plots in Fig. 38a indicate that a threefold increase in the grate spacing ($\sim d_g^{1.5}$) from 50 to 150 leads to a threefold increase in the holding current from 75 to 225 amperes. On the other hand, while the copper tube diameter varies from 2.5 to 10 mm (4 times), the holding current changes only by approximately 50%.

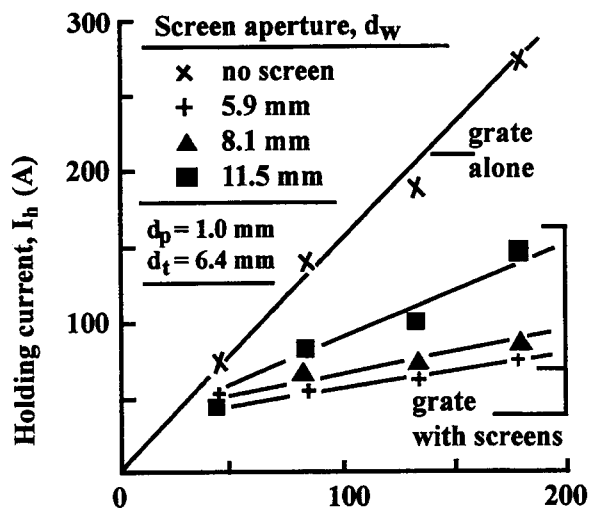
- The **particle size effect** is attributed mainly to the bridging phenomenon. With larger particle diameters bridging between grate bars is easier and the holding current is reduced (Fig. 38b). Hence, a, larger particle diameter, easier formation of a particle chain comparable to the grate spacing, easier blocking of the screen aperture.
- **Iron screens** placed below the grate act as magnetic field conductors that reduce the magnetic reluctance of the field flux. An important fact is that the screen bars distort the flux lines and form many *local field non-homogeneities*. The *strong local field gradients* pull particles towards the field non-homogeneities. Generally, the iron screens strongly reduce (by a factor of 2 to 3) holding current strengths with all other conditions unchanged (Fig. 39b). The particle size effect in the presence of iron screens has a more pronounced effect on bridging than in the presence of a grate alone. The screen aperture d_w is a less important design parameter (see Fig. 39c) when the particle diameter effect on the holding current is considered. However, in the presence of iron screens, only a twofold increase in screen aperture (Fig. 39a) leads to a reduction in the effect of grate spacing by a factor of 2-4 with respect to grate alone.

The attempt of Jaraiz et al. (1984a) to compare the theoretical predictions and experiments gives a relationship exhibiting a straight line $I_r \sim \sqrt{L_s}$ (see Fig. 39b). The exact data correlation is

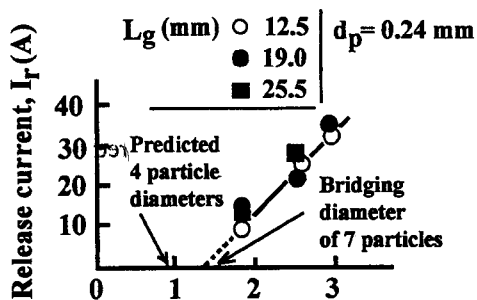
$$I_r = 630(\sqrt{L_s} - \sqrt{L_{so}}) \quad (40)$$

The intercept with the abscissa is $\sim 7d_p$, which is slightly higher than the predictions of Harmens (1963) of about $\sim 4d_p$. Thus, the orifice is likely to be blocked when its aperture is $\ll 4d_p$.

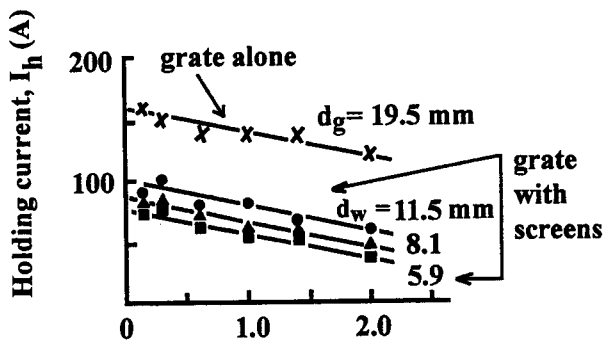
Jaraiz et al. (1984a) commented that $I_r = f(L_s)$ fitted the data linearly. This clearly indicates that something does not work well. Either the effect of L_s is not that predicted by the theory, or the experimental results are not



A) $(\text{Grate spacing, mm})^{1.5} = d_g^{1.5}$



B) $(\text{Aperture of screen})^{1.5}$



C)

Fig. 39: Holding currents for grate-design MVS with iron screens below.

- a) Holding current as a function of grate spacing – a parity plot of predictions of Eq. (23) and experimental data. From Yang et al. (1982) and Fitzgerald and Levenspiel (1984). Particle diameter, $d_p = 1.0 \text{ mm}$.
- b) Test of screen aperture prediction from theory (Jaraiz et al., 1984a).
- c) Simultaneous effect of particle diameter and iron screen aperture. From Yang et al. (1982). Particle diameter effect on holding currents. All runs with 1/4- in ($\sim 6.12 \text{ mm}$) copper tubes and a grate spacing $\sim 6.12 \text{ mm}$.

correct. Considering the simplicity of the experiments performed, there is no room for doubt about the experimental data. However, some critical comments about the theory might be made. The theory of Jaraiz et al. (1984a) presented earlier (see Eqs. 25 - 28) *does not consider any forces of attraction* between the magnetizable particles and the magnetic bars of the screen. The analysis *is truly valid for a non-magnetic screen only*. Complex fields generated by the magnetic screens need a more profound analysis than can be found in the textbooks of magnetic separation techniques (for example Karmazin and Karmazin, 1984). Such analysis of MVSs has not yet been developed.

- **Capture, Release and Working Currents.** These currents must satisfy the condition $I_w > I_c > I_r$, as discussed in the case of grate alone. The capture current is relevant to particle freezing, while the release current corresponds to particle leak through the valve. According to Jaraiz et al. (1984a), there are two reasons to expect that the capture current will be greater than the release current:
 - i) The capture current should hold the particles at the screen wires and stop any particle leak induced *by the kinetic energy of the raining particles*.
 - ii) The magnetic permeability of the raining particle flow is lower than that of the stopped particles. *This is obvious, since the raining particle concentration is lower than that of the bed on the screen. Moreover, the particles fall down as aggregates oriented parallel to the gas flow*

and the field lines. Such a system has a lower magnetic permeability than that of the concentrated particle body of the bed on the screen. For details, see Fundamentals of Part 1.

The data summarized in Table 7 (Table I of Jaraiz et al., 1984a) indicate that the difference between capture and release currents ($I_c > I_r$) increases significantly with reduction of screen apertures. Jaraiz et al. (1984) attributed this tendency to the phenomenon of bridging that occurs more frequently with small screen apertures. Thus, lower release currents are required for smaller apertures than for large screen openings.

Table 7
Operating currents of grate design MVS. Effects of grate spacing and screen aperture. From Jaraiz et al. (1984a)

Grate Spacing, mm ↓		Screen aperture ⇒	3.3 mm	6.4 mm	8.5 mm
12.7 mm	Currents, A	$I_r \Rightarrow$	10	26	33
		$I_c \Rightarrow$	22	37	43
		$I_w \Rightarrow$	26	40	45
19.0	Currents, A	$I_r \Rightarrow$	15	22	34
		$I_c \Rightarrow$	21	33	46
		$I_w \Rightarrow$	25	40	50
25.4	Currents, A	$I_r \Rightarrow$	11	27	34
		$I_c \Rightarrow$	24	40	57
		$I_w \Rightarrow$	25	50	70
The other operating conditions are available in Table 6					

III. 3.2. Holding currents of collar design MVS

The magnetic partition of collar design MVS consists of *two principal elements*: a **solenoid** outside the tube and a **screen** inside the channel. The possibility to change the screen position along the channel axis raises the question of optimal valve design. The presence of a non-magnetic screen (plastic or copper) does not affect the initial field distribution over the working volume of the valve. The only *magnetic element* under the working conditions is the *accumulated mass of magnetic particles* when the current is switched on. The use of magnetic screens significantly changes the field topology near the screen bars.

The developed theory (Zhang et al., 1984) (Eqs. (29) – (36)) was tested through a series of experiments focussed on:

- Field distribution inside MVS.
 - Iron screen position and aperture effects on holding currents.
 - One-hole orifice plates replacing the screens.
 - Non-magnetic screen effects.
 - Particle size effects.
 - Screen material effect.
 - Coil shield effect on field topology.
- **Field distribution - effects of the elements of the valve partition.** The experiments of Zhang et al. (1984) indicate field topology with a strong radial non-homogeneity (the pictures are not shown here). The experimental conditions used in mapping the field distribution are summarized in Table 8 (Table 2 of Zang et al., 1984). Effects of *three magnetic bodies* will be discussed based on these results:

First Body: *Soft iron shield of the solenoid.* The reduction in magnetic field fringing outside the channel through a *shield covering the solenoid* leads to increased field induction, B but does not affect field topology. The augmentation of magnetic field induction is about 35-40 %.

Second Body: *Magnetic screen.* An iron screen at the solenoid bottom leads to more uniform field distribution compared to the case where the screen is located in the solenoid symmetry plane. The

Table 8

Mapping conditions concerning the magnetic flux in a collar design MVS
(from Zhang et al., 1984).

Working Current, I_w	40 A
Diameter of the flow pipe	146 mm
Turns of the solenoid, N_w	22
Mean length of 4 layer solenoid*	34 mm
Shield thickness	2 mm
Distance between the tube axis and the solenoid center	84 mm
Solenoid dimensions (See Fig. 15)	40 mm height * internal diameter (unknown)

former distorts the field in a manner that increases field induction at the channel symmetry axis.

Third Body: Particle beds held by the screen. The particle bed stopped by the screen during the ON period of operation forms the third ferromagnetic body that affects the field of the solenoid. The field topology is more uniform compared to the case of an empty channel, since the particle bed closes the magnetic circuit and reduces its magnetic resistance. Shallow beds increase field induction in contrast to deeper ones (Zhang et al., 1984).

- **Effects of iron screen properties on the release current.** The iron screen position is the most important design parameter. Zhang et al. (1984) demonstrated (see the conditions in Table 9) that the release current increases slightly when the screen position varies between the symmetry plane and the bottom of the solenoid (see Fig. 40a). Alternatively, movement of the screen in the opposite direction results in higher release currents, approximately $I_r \sim (\text{screen position})^{-2}$. Both effects have simple physical explanations. In the first case the volume holding the raining particle is completely covered by the solenoid, so the entire volume inside the solenoid *works effectively*. In the second case there are two volumes:
 - i) *Volume emptied of magnetic materials* between the solenoid bottom and the screen.
 - ii) *Volume filled with raining particles* between the screen and the top of the solenoid.

Table 9

Collar valves. Experimental variables (pure magnetic particles)
(from Zhang et al., 1984).

Valve elements	Iron wire screens					References
Screen code	1	2	3	4	5	Zhang et al. (1984)
Screen wire diameter, d_s	0.7	0.8	1.0	1.2 ♣	1.6 ♣	
Screen aperture, L_s	6.4	8.5	12.0	6.4	12.8	
Particles used	Soft iron particles: > Porous iron, $d_p = 0.24$ mm; bulk density = 1390 kg/m ³ Solid iron, $d_p = 1.41; 1.0; 0.53$ mm					
Flow channel	Cylindrical tubes, inside diameters, mm		84 ; 146; 300; 554			
Note: ♣ - also made from copper						

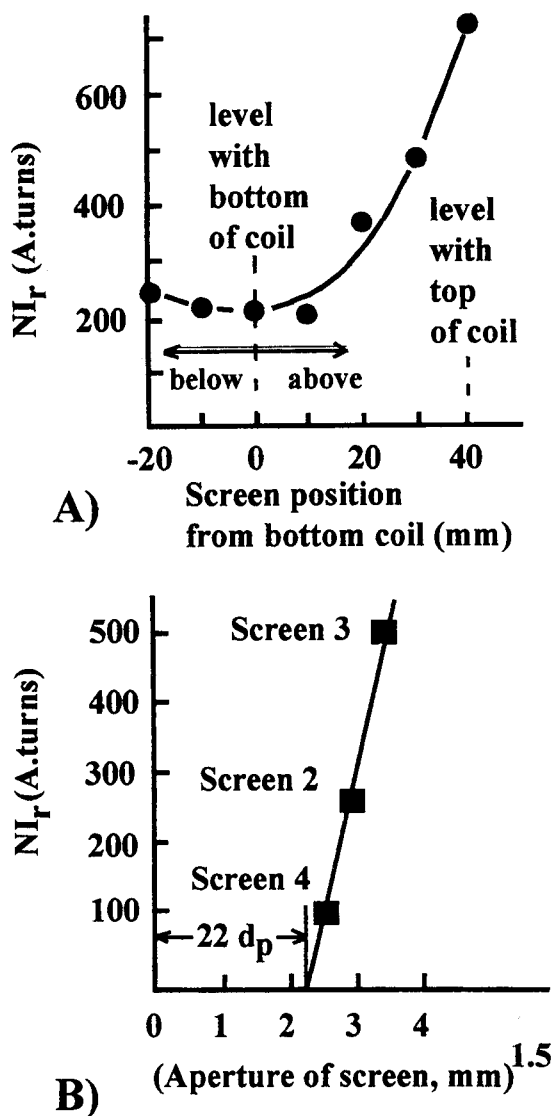


Fig. 40: Iron screen parameter effects on the release current of a collar design MVS. From Zhang et al. (1984).

- Screen position effect on the release current. Channel diameter+ 146 mm, screen No 1 (see Table 8, Table 1 of Zhang et al., 1984).
- Screen aperture effect of the release current (see details about the screens in Table 9).

The magnetic resistance of the circuit in the second case is greater since the magnetic resistances of both volumes are connected in series* along the field lines (*the field has axial symmetry). Therefore, the losses of magnetic energy are minimal if the screen is at the bottom level of the solenoid.

The other variations of screen parameters are related to the screen *bar diameter* and the screen *aperture*. It can be speculated that larger screen apertures would affect slightly the field topology while smaller ones would affect it strongly, supposing that all other conditions are the same. This might predict that larger screen apertures would require higher release currents. Figure 40b illustrates the practically established scaling relationship $I_r \sim \sqrt{L_s}$.

- **Replacement of the iron screen by a single-hole plate** is another aspect of the Levenspiel group studies. These investigations might look strange from the point of view of the data discussed above. However, they are oriented towards a very interesting problem that potentially exists, but could be encountered in some specific devices in the future. The problem could be formulated as: *How to create remote control of a particle flow through a single orifice, but without any mechanical devices.*

The single-hole plate replacing the screen in the internal volume of the solenoids faces problems similar to those of the tested screens. According to Eq. (36), we have $N_w I_r \sim \sqrt{d_{or}}$, so the straight lines in Fig. 41 confirm the theoretical predictions. The use of a single-hole orifice leads to the following new effects (see inset of Fig.41):

- ◆ Changes of the orifice position from the centre towards the channel wall (i.e. towards the solenoid windings) reduce the strengths of both the capturing and the release currents. This is because the orifice “moves” with current strength unchanged from the weakest (solenoid center) to the strongest field zone (the windings).
- ◆ A hysteresis effect of the current that controls the particle flow.
- **Particle size effects and bridging conditions.** The experimental results with collar design MVS resemble those of the grate-design device. Generally, an increase in particle diameter reduces the release current strengths. Some variations may occur in relation to the type of the iron screen (aperture or screen bar diameter) or to the orifice diameter of the plate-type partition. For screen-based collar type MVS, larger screen apertures result in a stronger release current (Zhang et al, 1984a).

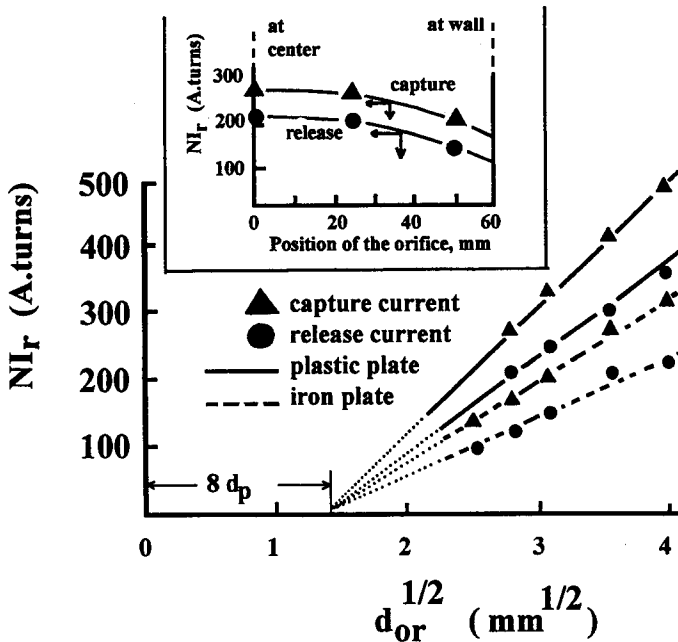


Fig. 41: Effect of the orifice parameters on the release current of a collar design MVS. From Zhang et al. (1984).

Main figure: The relationship between the orifice size and the release current of center-located single-hole plates and additional effects of the plate material. Channel diameter = 146 mm

Inset: Variations of the release current with the orifice position (adapted figure). Channel diameter = 146 mm, orifice diameter = 12.7 mm.

The relationships $N_w I_r \sim \sqrt{L_s}$ (see Fig. 40b) and $N_w I_r \sim \sqrt{d_{or}}$ fit well the experimental data with straight lines. Extrapolations to $N_w I_r = 0$ provide different bridging aggregate sizes, d_{br} . The common value of d_{br} in the case of single-hole plates (irrespective of their materials) is $d_{br} \approx 8d_p$, while for iron screen data it is $d_{br} \approx 22d_p$. In contrast to these results the experiments on mass flux control (see further) give $d_{br} \approx 15d_p$. Moreover, the extrapolated value for grate design MVS is about $d_{br} \approx 7d_p$ (see Fig. 39b), which is close to the extrapolation for single-hole plates. The differences in the extrapolated values are not explained in the original paper. Neither can they be explained from a physical point of view.

- **Effect of screen (plate) material and coil shield.** When the screen material is changed from iron to copper the value of the product $N_w I_r$ is increased (see data summarized in Table 10). Similar replacement of a single-hole iron plate with a plastic plate leads to a twofold increase in the release current (Fig. 41). Zhang et al.(1984a) attributed the latter to the fact that iron plates amplify and guide the magnetic flux.

Special experiments with a soft-iron shield and a 146 mm channel were performed to evaluate the shield's efficiency. A flow channel equipped with iron screen No 4 (see Table 10) and porous iron particles of $d_p = 0.24$ mm was tested under conditions created by a copper tube coil of turns varying from 6 to 22. The experiments demonstrated that without a shield $N_w I_r \cong 191$ A-turns, while the shield gave $N_w I_r \cong 105$ A-turns.

Table 10

Collar valves. Operating currents (for pure magnetic particles) as a function of screen material (from Zhang et al., 1984).

Operating current ↓	Screens				
		Iron		Copper	
	Screen code ⇒	4	5	4	5
$N_w I_r$ (release current), A-turns	88	246	422	805	
$N_w I_c$ (capture current), A-turns	136	328	528	909	
Particles used	Porous iron, $d_p = 0.24$ mm; bulk density = 1390 kg/m ³				
Flow channel	Cylindrical tube, mm (inside diameter)			146	

III.3.3. Holding (release) current of external coil design

The experimental program of Davis and Levenspiel (1985) addressed several factors affecting the operational characteristics of ECD MVS:

- **Effect of the core height**, i.e. the effect of the pole height that is equivalent to that of the solenoid height in cases of collar MVS.
- **Effect of the pole face separation**, i.e. the effect of the electromagnet gap and the channel.
- **Effect of the pole face width** related mainly to variations of the magnetic flux density through the channel.

Tests were performed with a rectangular flow channel and a copper screen of 6.35 mm mesh *positioned to line up with the lower edge* of the pole

faces. The experimental procedure corresponds to the Mental Experiment 1-*Magnetization FIRST* (current turn ON) and *Solids LAST* (subsequent solids flow). In all the experiments, beds of porous iron powder deeper than 150 mm were maintained. The experimental results and the regression equations obtained are summarized in Table 11. The equations (ECD-1 to ECD-3) are simple expressions for $N_w I_r$ as a function of the electromagnet gap dimensions. Davis and Levenspiel (1985) employed Eq. (ECD-2) as a basis to develop two predictive equations (see Table 11). These authors reported three illustrative examples with satisfactory results (not discussed here). Table 12 gives comparative information about the three types of MVS discussed in the present section of the paper.

Table 11

Experimental results and data correlations for ECD MVS studied by Davis and Levenspiel

Run	h, mm	s, mm	w, mm	$\frac{\bar{l}_c}{w_c}$	$N_w I_r$, Ampere-turns	Equation
1	25.4	200	200	12.5	720	$N_w I_r = 3.54(226 - h)$ (ECD-1)
1	52.4	200	200	12.5	600	
1	103.2	200	200	12.5	440	
2	25.4	105	305	8.2	315	$N_w I_r = 3.36s - 2.5$ (ECD-2) or $N_w I_r = 3.36s$
2	25.4	146	305	8.1	540	
2	25.4	205	305	7.9	689	
2	25.4	251	305	7.8	806	
2	25.4	292	305	7.7	991	
3	25.4	146	151	8.6	504	$N_w I_r = 1.89w + 42 + (1.47 \times 10^{13})w^{-5}$ (ECD-3)
3	25.4	146	179	8.5	468	
3	25.4	146	206	8.3	468	
3	25.4	146	230	8.3	486	
3	25.4	146	254	8.2	504	
3	25.4	146	270	8.1	558	
3	25.4	146	305	8.9	621	
$N_w I_r = 3.35 + 3.54(25.4 - h) + 1.89w + 1.47 \times 10^{13} w^{-5} - 582$						if $\frac{\bar{l}_c}{w_c} \cong \text{constant}$ (ECD-A)
$N_w I_r = 3.35 + 3.54(25.4 - h) + 0.233 \left(\frac{\bar{l}_c}{w_c} \right) w + 1.47 \times 10^{13} w^{-5} - 582$						if $\frac{\bar{l}_c}{w_c} \neq \text{constant}$ (ECD-B)

Table 12a
Comparative analysis MVs. Data extracted from various papers published by the group of Levenspiel.

MVS	Advantages with respect to:		Disadvantages with respect to:	
	Grate design	Collar design	Grate design	Collar design
External Coil Design (ECD)	• ECD has much simpler design than GD • The field generated in ECD is external to the channel • The coils does not require cooling • Easy removable from the flow channel	• May be used with rectangular and cylindrical channels	• ECD is much more massive • ECD is not suitable for MDD	• ECD is much more massive • ECD is not suitable for MDD • Permanent magnetism of the iron core • The design needs additional justifications

Table 12b
Comparative analysis MVs (continued). Data extracted from various papers published by the group of Levenspiel.

MVS	Advantages with respect to:		Disadvantages with respect to:	
	Grate design	External Coil Design	Grate design	Collar design
Grate design (GD)	• Operates with both magnetic and non-magnetic screens • The design is not massive • CD uses conductors immersed in the channel • GD can work without screens	• The design is not massive	• The current carrying conductors are subjected to abrasion • The grate tubes need water cooling	• The design does not allow easy movement of the valve along the channel • Needs high current strengths • The design does not allow easy movement of the valve along the channel • Needs high current strengths

Table 12c
Comparative analysis MVs (continued). Data extracted from various papers published by the group of Levenspiel.

MVS	Advantages with respect to:		Disadvantages with respect to:	
	Grate design	Collar design	Grate design	External Coil Design
Collar design (CD)	• More simple design • No abrasion of the current carrying elements • Works with perforated plates	• Easy design • Works with magnetic and non-magnetic screens	• More massive design	• Efficient only for cylindrical flow channels • The solenoids needs water cooling

III.3.4. Analysis of magnetization modes of MVS and relevant design details

The magnetization mode applied to MVS is an **On-Off** mode, as mentioned earlier. In contrast to batch-solids fluidized beds (Part 1 and Part 3 of the series), the effects of the magnetization parameters on the hydrodynamic behavior of MVSs were not investigated. Generally, the efforts were oriented towards mass flow control. Despite this, an attempt to summarize available data yielded Fig. 42 and Table 13. According to these, the frequency of the electric current varies between 0.5-1 Hz for both grate and collar design valves.

The current *frequency range* and the applied *magnetization mode* have to be related to the inductance of the “coil conductors” (grate or a collar). The electric inductive reactance of a wire coil is $X_L = 2\pi f L_{ind}$ (where the dimensions of X_L are Ω , Ohms; f - frequency, Hz and L_{ind} - inductance, H - see Pecht et al, 1993). When a DC voltage is applied to an R - L circuit (with an ohmic resistance, R , and an inductive reactance, X_L), a certain period of time, $t_{delay} = L_{ind} / R$, is required to charge the circuit. The *voltage pulses* applied to the conductors of the grate (or collar) are generally rectangular (see Table 14). However, the inductance of the conductors does not permit a “sudden jump” of the current, so the real form of the *current pulses* is trapezoidal, i.e there is a “time delay”. In the experiments of Jaraiz et al. (1984), this “time delay” has no effect on mass flow even for t_{closed} (e.g. $\tau_{on} \leq 0.2$ s), but when t_{open} increases (e.g. $\tau_{off} < 0.5$ s) its effects on mass flow becomes sensible (see the next chapter).

The increase in coil inductive reactance X_L reduces the frequency of the electric pulses that could charge the circuit and *vice versa* – if an increased frequency must be used, the coil inductance must be reduced. Moreover, the energy stored in the inductor and transferred to the magnetic solids is $W = (L_{ind} I^2 / 2)$, where $W (J)$; $L_{ind} (H)$; $I (A)$. Thus, any changes in the coils of the inductor are related to changes in its inductance. The information summarized in Table 14 “**translates**” the basic electrical knowledge to data relevant to the MVS devices discussed here. These comments on MVS are not to be found in the original literature sources, but data reported there allow us to formulate the conclusions in the last two columns of Table 14. The author suggests that the summary will enhance both understanding of the results reviewed and successful developments of future investigations. A short excursion through the electric engineering details could help us to

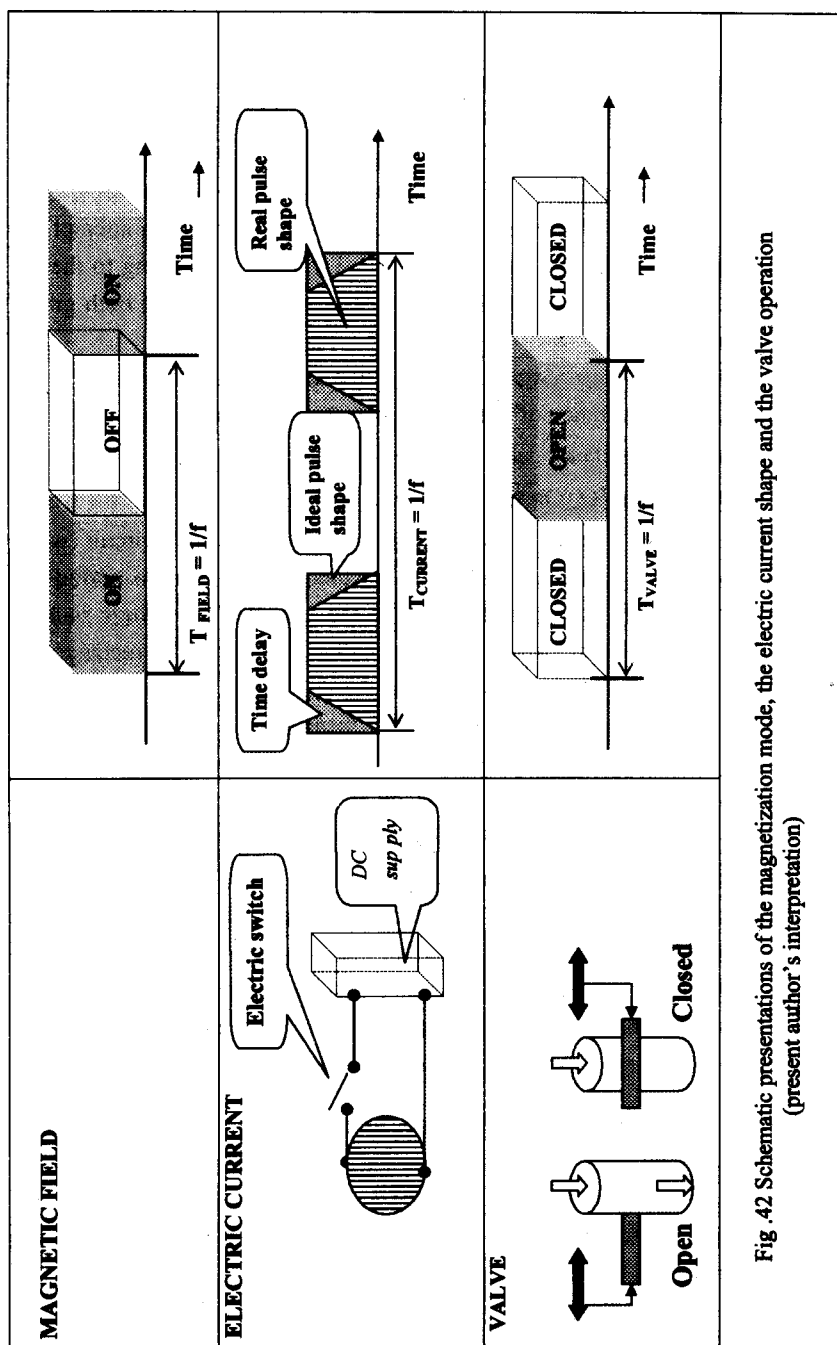


Table 13

On-Off magnetization of valves – data summarized from various sources

Reference ↓	MVS type ↓	Frequency f, Hz and Working current, I _w , A	τ_{on} , sec = t_{closed}	τ_{off} , sec = t_{open}	$\frac{\tau_{off}}{\tau_{on}}$ = $\frac{t_{open}}{t_{closed}}$	Data source	
						Original paper	Present work
Pure magnetic particles and composites							
Jaraiz et al. (1984a)	Grate design	f = 0.666 Hz ♣ I _w = 70 A	1	0.5	0.5 ♣	Fig. 10	Fig.37
		f = 0.5-0.9 Hz ♣ I _w = 70 A	0.5 - 1.5	0.6	12- 0.375 ♣	Fig. 11	
		f = 0.9 ♣ I _w = 34 A	0.5	0.6	1.2 ♣	Fig. 13	
		∅	??	0.1-2	∅	Fig. 12	Fig.45
Zhang et al. (1984)	Collar design	f = ∅ I _w = 16 A	??	0.3 1.0		Fig. 9	
		f = ∅ I _w = ??	??	0.2-2.0	∅	Fig.17	
			??	0.2-1.5	∅	Fig. 14	Fig.46
Mixtures of magnetic and non-magnetic particles							
Jaraiz et al. (1984a)	Grate design + mixtures iron-sand	f= 0.4 -1.42 Hz ♣ I _w = ??	0.5	0.2-2.0	0.4 - 4 ♣	Fig. 16	Fig.65a
Jaraiz et al. (1984a)	Grate design + mixtures iron-sand	f= 0.66 Hz ♣ I _w = ??	0.5	1	2 ♣	Fig. 17	Fig.65b
Zhang et al. (1984)	Collar design	∅	??	0.1-2.0	∅	Fig. 17	
Notes: ?? - no data available ; ∅ -impossible to calculate; ♣ - present author calculations							

comment on the next chapters concerning mass flow control characteristics of MVS and operational characteristics of MDD

III.3.5. Mass flow of solids

III.3.5.1. Grate design MVS

Yang et al. (1982) employed the analogy of solids discharge from a vertical pipe (Kunii and Levenspiel, 1969, 1991) to find a scaling relation with regard to *minimum grade spacing*:

$$(\text{discharge of solids}) \sim d_p^{-0.246}$$

Table 14

On-Off magnetization mode. Inductances of current carrying conductors. Effect of the design characteristics on the operational performance. "Translation" of basic electrical knowledge to parameters of the MVS devices relevant to their operational characteristics.

Changes in the inductance parameters ▲	Effects on the electric circuits ▲	Relevant changes of MVS design *	Effect on the operational characteristics of MVS *
1. The inductance is proportional to the square of the turns	• Increase the inductive reactance • Increase of the time constant • Reduction of the current amplitude at fixed DC voltage of the electric supply	• Increase of the number of the conductors forming the grade and decreasing of the grade spacing, L_g • Increase of the number of windings of the collar • Increase the length of the collar • Introduction of iron screen beneath the grade • Introduction of a shield of the collar • Decrease of the air gap between the windings (collar design) and the particle flow • Introduction of iron screen beneath the grade	• Increase of delay time • Effects on mass flow through the valve at shorter ON periods • Reduction of current amplitude that affects particle freezing on the conductors • Increase of delay time • Effects on mass flow through the valve at shorter ON periods • Reduction of current amplitude that reduces the amount of particles attracted at conductor surfaces.
2. The inductance increases as the winding length is increased.			
3. The inductance increases as the permeability of the core material increases			
4. The inductance increases with increase of the cross-sectional area of the core material			
5. Inductance is increased by inserting an iron core into the coil			
6. Shorted turns decrease the inductance, affect the frequency response, and increase the insertion losses.	• Decrease the inductive reactance • Decrease of the time constant • Increase of the current amplitude at a fixed DC voltage of the electric supply	• Decrease of the number of the conductors forming the grade and increasing of the grade spacing. • Removing iron screens from the channel • Increasing of the amount of non-magnetic particles in the flowing mixtures	• Decrease of delay time • Allows shorter ON periods, i.e. higher frequency of current switching • Allows higher current amplitudes • Low efficiency • High current intensities are required
7. Introduction of an air gap into a yoke reduces the inductance			
▲ - According to Pecht et al. (1993) ; * - Present author comments			

In this connection, when the current is *switched off*, i.e. the valve is open, both the grate and the screen beneath it are obstacles for particles raining in the channel. The *characteristic size of the opening* could be chosen as a *minimum* $[L_s, L_g]$. Screens with $L_s \ll L_g$ are usually reported in literature, so the *characteristic opening scale* is the screen aperture, i.e. $L \equiv L_s$. However, in the case of a grate alone we have $L \equiv L_g$. Jaraiz et al. (1984) employed the scaling relationship of Resnik (1966) for granular mass flow through orifices (at practically zero pressure drop) $G \sim \sqrt{L}$

in a slightly modified form
$$G \sim k_{10} (\sqrt{L} - \sqrt{L_0}) \quad (41a)$$

Jaraiz et al. (1984b) expressed (41a) as

$$G = A + B\sqrt{L_s} \quad (41b)$$

The experimental results for both moving and fluidized beds are shown in Fig. 43. With the iron screen there is more variation of the data, but in general, the linear fit is valid.

Eqs. (41) were discussed earlier (see Eq. 40) from the point of view of release current determination. The expressions suggest that the plots $G = f(\sqrt{L})$ will be straight lines that intercept the abscissa at the bridging points (see Fig. 41, commented on earlier). The extrapolations for moving beds (at $U=0$) give a bridging screen aperture equivalent to 12 particles (Fig. 43a, b). This estimate is greater than the value of 7 defined through experiments studying release currents (see Fig. 39b). On the other hand, the increase in gas velocity beyond the minimum fluidization point changes the minimum bridging aperture from 12 to 18 particles. According to Jaraiz et al. (1984b), the latter estimate is surprisingly high and could be attributed to:

- a) *Higher working currents* used with fluidized beds, resulting in *larger clumps* and particle aggregates;
 - b) *Additional frictional resistance* at the screen provided by the upflowing gas
- **Effects of Working Current and Bed Height.** According to the experiments of Jaraiz et al. (1984a) with moving beds (at $U=0$) working current I_w and bed depth do not affect mass flux through the valve. This was assumed as a confirmation of the results from non-magnetic

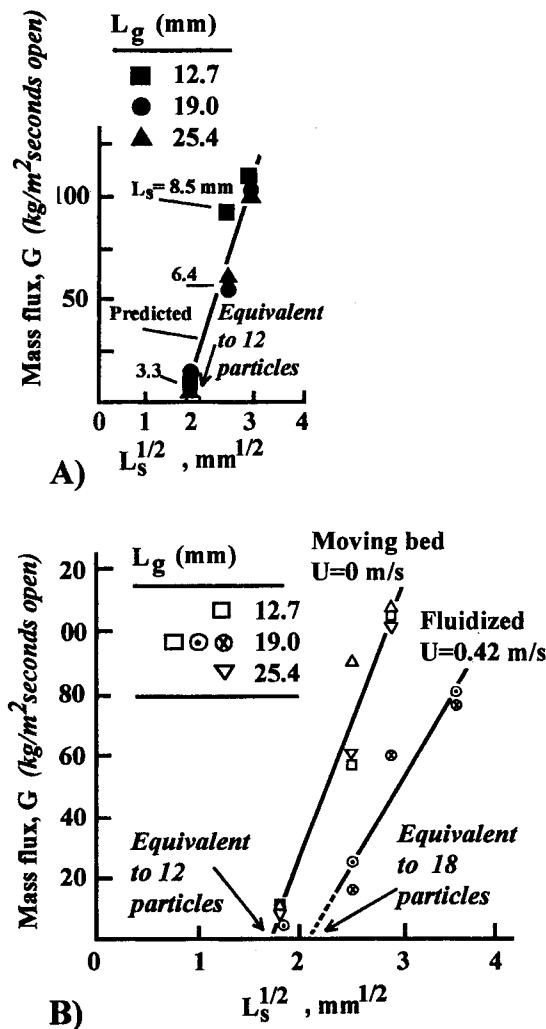


Fig. 43: The mass flux strongly depends on the screen aperture of grate-type MVS. The data fit well the predictions. The other conditions are available in Table 6 (grate variables).

- a) A test of the predictions for copper screens in the absence of air (moving bed). From Jaraiz et al. (1984a-Fig.14).
- b) A test of the predictions in the form of (41c) for moving and fluidized beds. From Jaraiz et al. (1984b-Fig.10). Additional effects of the screen materials are accounted for (one of the screens is made of iron). For solids: $U_{mfo} = 0.16 \text{ m/s}$; Valve operation: $t_{open} = 1.0 \text{ s}$; $t_{closed} = 0.5 \text{ s}$

experiments (Harmens, 1963) on granular solids flow through orifices. Hence, the flow regime was determined as *height-independent* beyond a certain minimum bed depth and as *current-independent* at moderate working currents.

Solids flux *independence* was not discussed in detail in the original literature sources. Still, some additional comments on the subject could be developed here since the facts are interrelated. The basic Eq. (41a) relates the force of attraction F_C , the current strength I , and the radial distance from the conductor centerline r . The field acts on the solids very close to the grate, thus affecting only a thin particle layer. Beyond a certain bed depth the effect of the distance r will be negligible, if the current strength remains constant, since $F_C \sim \frac{1}{r}$. From the same Eq. (41) it follows that with a fixed distance r the force scales as $F_C \sim I$. Both tendencies act in close proximity to the conductors and under certain conditions should compensate each other. Eqs. (41) *do not consider the effect of neighboring particles* and the fact that particle beds are also *magnetic flux conductors*. Moreover, the magnetic field tends to *minimize the length of the field lines*, i.e. the *fringing effect*, commented on earlier. Thus when a certain minimum bed depth is exceeded, practically the entire magnetic flux is collected inside the magnetizable solids. Therefore, all physical effects of magnetic field-particle interactions occur in the *near-field* of grate conductors. Particle bed built-up beyond a certain depth is not affected by the magnetic field generated by the horizontal inductors, if it is assumed that current strength remains unchanged. In contrast, a field intensity increase, i.e. increase of I_W , will compensate for the effect of $F_C \sim \frac{1}{r}$ and more particles will be strongly attracted to the magnetized parts of the bed, thus increasing its bed depth.

Both phenomena are related to *increased interparticle forces* leading to *low flowability* of solids and resulting in low *mass flux* through the valve. No cross-correlation of these results is reported in literature. Still, detailed data analysis allows us to suggest at $I_W < 80 \text{ A}$ and *bed depth* $\leq$ *channel diameter* (see Fig. 44) that no effects on mass flux can be detected.

- **Effect of the gas velocity on the mass flux of solids.** The effect of the upflowing gas velocity on mass flux is strongly related to the other operating parameters, such as the working current I_W , the screen aperture

L_s and the screen material. In general, an increase in gas velocity leads to a reduction in mass flux through the valve and to higher theoretical sizes of bridging orifices. The increase in both upward drag and increasing interparticle forces due to a higher I_w leads to a reduced mass flux through the valve (see Fig. 44), but beyond the minimum fluidization mass, fluxes reach saturation. Screens placed beneath the grate play the role of distributors for the fluidized bed formed above. At the same time they are serious obstacles to the flowing solids. Thus finer screens reduce mass flow flux. Mass flux is additionally reduced when particles are attracted by iron screen bars.

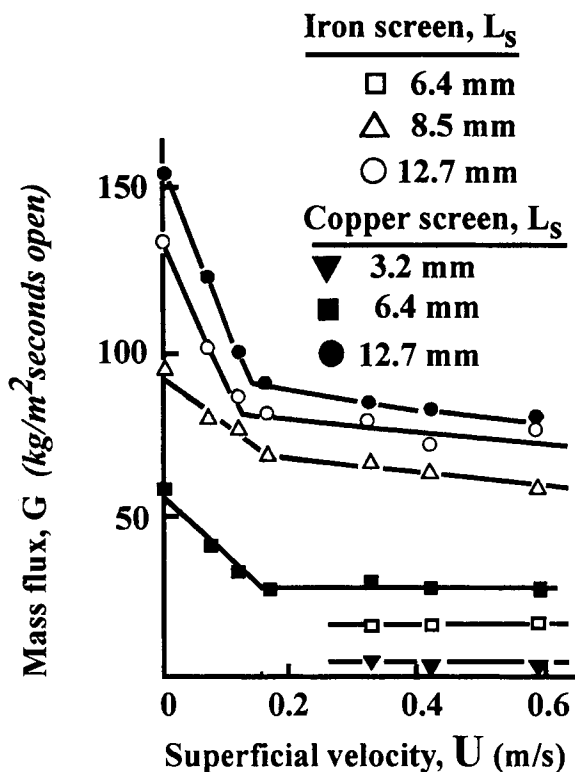


Fig. 44: Effect of the gas flow velocity on the mass flux through grate-type MVS. The mass flux exhibits saturation beyond the minimum fluidization velocity. However, the increased screen drag reduces the mass of solids passing through the valve. Grate spacing of $L_s = 19 \text{ mm}$. Magnetization pulse times: $t_{\text{open}} = 1.0 \text{ s}$, $t_{\text{open}} = 1.0 \text{ s}$. From Jaraiz et al. (1984b- Fig. 9)

- **Effect of On-Off pulse durations on solid mass flux.** The solids flow through the valve could be controlled through:
 - The length of the **OFF** period, i.e. the t_{open} time of the valve.
 - The length of the **ON** period, i.e. via the t_{closed} time of the valve.
 - The strength of the working current I_w with fixed **ON** and **OFF** periods.

The first two factors are practically equivalent, since at fixed current *switching frequency* the definition of an **ON** period undoubtedly defines the **OFF** period. The data presented in Fig. 45 show that mass flux is practically independent of the length of the magnetization periods except in cases of short **ON** or long **OFF** periods. Actually the plots indicate that if the **ON**

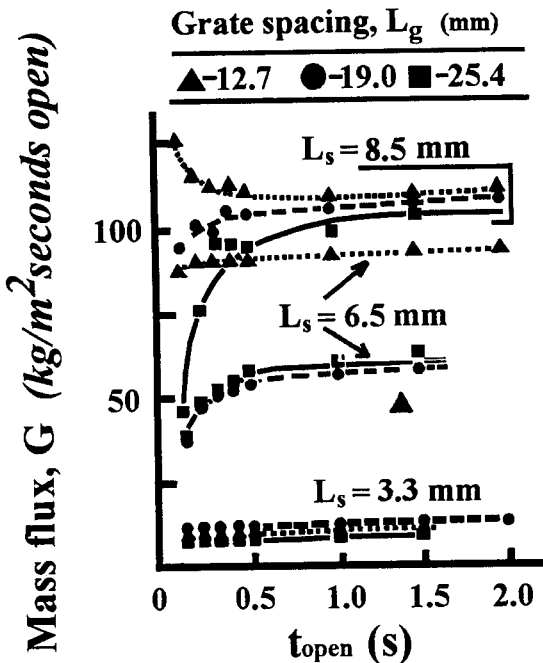


Fig. 45: Effect of the parameters of magnetization pulses on the mass flux through grate type MVS. From Jaraiz et al. (1984a). Effect of duration of valve “open period” on mass flux. The duration of the “closed period” is not available, but it could be suggested (on the basis of the other data published) that it is approximately 0.6 s.

period (t_{closed}) is shorter than 0.5 s solids flow starts to decrease. Data distributed in various plots can be summarized as follows:

- i) The region where solids flow is very sensitive to the magnetization mode corresponding to t_{open} (i.e. τ_{off}) less than 0.5 s (Fig. 45) and t_{closed} (τ_{on}) < 0.2 s. These critical values correspond to frequency $f_{critical} \approx 1.4$ Hz and the ratio $\frac{t_{closed}}{t_{open}} \leq 0.4$.
- ii) The boundary estimated in (i) should be assumed as approximate. In fact, data reported by Jaraiz et al. (1984a) give $f_{critical} = t_{open} + t_{closed} > 1.1$ Hz and a ratio $\frac{t_{closed}}{t_{open}} \approx 0.9$ (see Fig. 44). All experimental data concerning the effects of other operating parameters, i.e. current strength, screen aperture, grate spacing, bed depth, were reported at $f \geq 1.1$ Hz.
- iii) The results in Fig. 44 show that the application of finer screens (the lowest group of lines) practically *suppresses the effect* of magnetization pulse variations irrespective of grate spacing.

These comments are valid for the particular devices investigated. The absence of more detailed data does not allow us to draw more general conclusions. Still, in theory analysis and comparison of experiments could be easier if the following details were available:

- a) Data about the *inductance* of the valve *with or without particles*.
- b) Data about *frequencies* of the electric pulses applied.
- c) Data concerning the dynamic characteristics of flowing solids, i.e. *mass flux* through the screens in the absence of a magnetic field.

III.3.5.2. Collar design MVS

The characteristics of solids mass control with collar-type MVS have not been investigated at large, unlike those with grate-type devices. A collection of scarce data distributed in various sources permits systematic presentation of the information

1. **Effect of bed height on mass flux of solids.** The height of solids accumulated at the partition of the valve practically does not affect mass flow rate. A more detailed data analysis shows that the flux becomes *bed height-independent* when $h_b > D_{channel}$ and $h_b > 3(\text{solenoid length})$. Thus, the particles accumulated inside the solenoid affect only the solids leak through the screen. Only the *particles near the magnetic field source*

participate actively in the process. The effects are similar to those observed with grate-type devices.

2. **Effect of partition (screens and single-orifice plates).** Mass flux through the valve depends strongly on screen aperture when the open time is greater than 1 s. According to Zhang et al. (1984), this is due to the very short response time of the valve (less 1 sec.). No additional information was reported in the literature.
3. **Effect of magnetization pulse parameters.** Magnetization pulse parameter effects on mass flux control were not studied systematically. The only data available in Zhang et al. (1984) indicate that mass flux can be controlled effectively through t_{open} (see Fig. 46) . Simple data scaling (performed here through digitalization of plots) gives

$$\text{Mass flux} \sim (t_{open})^{\beta} \quad (42)$$

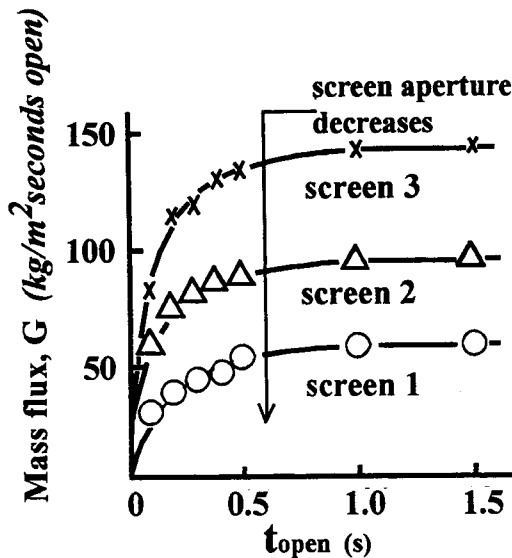


Fig. 46: Mass flux control by a collar-type device. Effects of the iron screen apertures. Adapted from Zhang et al. (1984). Combined effect of screen aperture and t_{open} pulse duration. The arrow indicates the decrease in screen aperture (added by the present author). For clarity of explanations, see also Table 9: Screen 3 – $L_s = 12 \text{ mm}$; Screen 2 – $L_s = 8.5 \text{ mm}$; Screen 1 – $L_s = 0.7 \text{ mm}$. Additional details: $D(\text{channel}) = 146 \text{ mm}$, $I_M = 15 \text{ A}$; Coil with $N = 22 \text{ turns}$.

The exponent for Screen 2 and Screen 3 is $\beta = 0.17$, while it is $\beta = 0.25$ for Screen 1. Both values are in the dimensions expressed in Fig. 46. More detailed scaling (analysis) will be performed under the next point.

4. **Simple scaling of the countercurrent velocity effect.** The air velocity effect was commented on shortly together with grate spacing determination in cases of grate type MVS. Collar-type MVSs demonstrate more non-linear dependence on air velocity (see Fig. 47). According to Jaraiz et al. (1984b), mass flow through the valve exhibits three flow regimes:

- a) Little or no air, $U > 0.1 \text{ m/s}$. Mass flux is high because particle drag is minimal.
- b) Intermediate regime, $0.1 < U < 0.25 \text{ m/s}$. Increased drag force combined with particle bridging practically stops solids flow

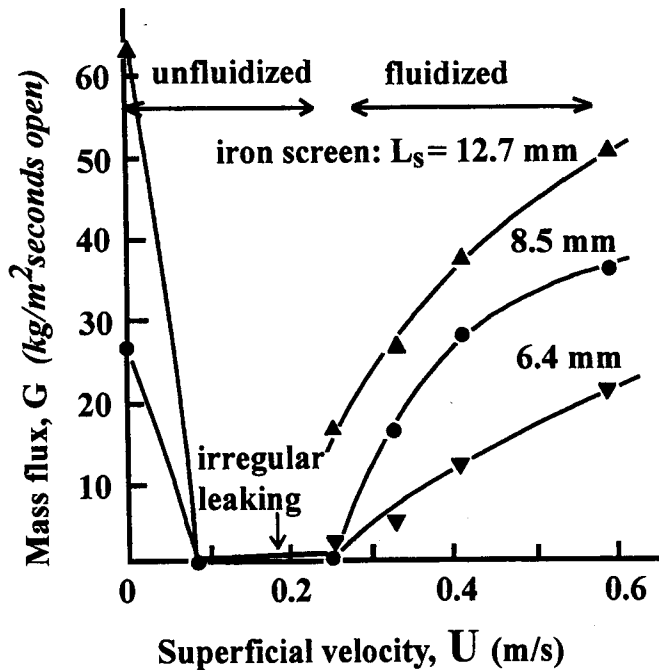


Fig. 47: Mass flux as a function of the superficial gas velocity of a collar-type MVS. Adapted from Jaraiz et al. (1984b). The experimental details are shown in the picture. Additional data: $I_W = 72 \text{ A}$;

$t_{\text{open}} = 1.0 \text{ s}$; $t_{\text{closed}} = 0.5 \text{ s}$.

- c) High air velocities $U > 0.25 \text{ m/s}$. Higher gas turbulence breaks up particle aggregates, which eliminates *bridging* and, consequently, leads to a *high mass flux* through the valve.

If the information from points (a) – (c) is generalized, two flow regimes can be defined (bearing in mind that in the absence of a field, $U_{mf} = 0.16 \text{ m/s}$ – see Fig. 47):

- a) Intermediate regime, at $\frac{U}{U_{mf}} < 0.625$, i.e. particles are fluidized neither in the absence of a field, nor under applied magnetization flux (*see the discussion in the next chapter concerning MDD*).
- b) Turbulent regime, at $\frac{U}{U_{mf}} > 1.56$

Simple scaling (performed here) leads to

$$\text{Mass flux} \sim \left(\frac{U}{U_{mf}} \right)^{\delta} \quad (43a)$$

where $\delta < 0$ at $\frac{U}{U_{mf}} \leq 0.625$ and $\delta \geq 0$ at $\frac{U}{U_{mf}} > 1.56$.

For the second range,

$$\delta \sim (\sqrt{L_s})^{-1.7} \text{ or } \delta \sim (L_s)^{-0.85}. \quad (43b)$$

Thus, mass flux could be scaled (under the assumption that $0.85 \approx 1.0$) as:

$$\delta \sim \frac{1}{L^{0.85}} \equiv \frac{1}{L} \quad (43c)$$

The latter gives

$$\text{Mass flux} \equiv \left(\frac{U}{U_{mf}} \right)^{\delta} \equiv (L_s)^{-2} \left(\frac{U}{U_{mf}} \right)^{\frac{1}{L_s}} \quad (43d)$$

The term $(L_s)^{-2}$ in (43c) denotes the slope of the curves in Fig. 47 and shows that screen aperture has a greater effect on mass flux than air velocity.

This particular scaling is valid for experimental conditions in which the duration of t_{open} does not affect mass flux. Combining the two scaling estimates (42 and 43), we have:

$$\text{Mass flux} \equiv \left(\frac{U}{U_{mf}} \right)^\delta \equiv (t_{open})^\beta (L_s)^{-2} \left(\frac{U}{U_{mf}} \right)^{\frac{1}{L_s}} \quad (44)$$

III.3.5.3. Some comments on external coil design MVS

This section does not contain data on mass flux control. It is included in the review for a more systematic presentation of the problems. Practically, these devices were investigated neither from the *hydrodynamic* nor from the *mass flow control* points of view. The only study concerning a magnetic circuit is that of Davis and Levenspiel (1985). It has not been followed by more detailed investigations.

The scope of the data published indicates that the grate-type devices are the principal objects of investigations. The other two designs were not studied systematically. No comments exist in the published papers, but this creates an extensive area for further investigations.

III.3.6. Exploratory results on MDD for pure magnetic particles (or composites)

Magnetic valves for solids (MVS) may be used as temporal distributors for fluidized beds. In this case MVS are transformed into magnetic distributor-downcomers (MDD). Figure 30 (at the beginning of the paper) illustrates the ideas developed by the Levenspiel group. The arrangement of a series of MVSs along the flowing channel leads to the formation of a multistage fluidized bed with distributors created on the MVS.

The main distinction between the two devices is the operating regime employed:

- The MVS controls only the mass flux of solids, whereas the behavior of the particle bed accumulated by the partition is of no interest, since the countercurrent gas flow is not sufficient to fluidize it.
- The MDD operates under conditions close to those of batch-fluidized beds. The countercurrent gas flow can fluidize the solids accumulated by the partition (grate, screen or a combination of them). Thus the operating gas velocity should be $u_0 > U_{mf}$.

➤ The magnetic field of the partition (grate, collar or external electromagnet) can control the behavior of fluidized solids, i.e. stabilize or freeze them. Hence, it may be expected that fluidized solids could exhibit the gross behavior of magnetically stabilized beds described in Part 1.

III.3.6.1. Qualitative behavior of MDD

The experimental findings, presented as phase diagrams, are summarized in Fig. 48. Both phase diagrams correspond to Magnetization FIRST and solids LAST modes. This implies a preliminary *turn-on* of the magnetic field of the MVS (at a sufficiently high value) followed by the start of particle raining flow towards the zone with a strong magnetic field. Thus, starting with a valve in the *closed* position, the field should freeze the particles in the vicinity of the grate or the screens.

With $U_0 < U_{mf}$ particles form a fixed bed, while a further increase in U_0 can cause fluidization with vigorous bubbling at $U_0 \gg U_{mf}$. Apparently, all these regimes and the transition states depend on combinations between magnetic field intensity (represented by current strength), particle properties and gas flow rate.

The phase diagrams indicate three definable main states, irrespective of the type of magnetic system used:

- ❑ **Open valve.** This state needs currents smaller than the release current I_r . The release current is practically independent of the superficial gas velocity.
- ❑ **Weeping valve.** This marginal state is bounded by the *release* and the *capture* currents. The width of the weeping valve zone (measured along the vertical axis) depends on the superficial gas velocity. Two specific sub-zones correspond to the fixed bed and the leaky fluidized bed. The “jump” at $U_0 = U_{mf}$ is specific of this regime.
- ❑ **Closed valve.** Currents beyond the capture current value create different bed regimes that depend on the type of the magnetic system used. Common elements are the stable first layer on the partition and the absence of particle leak. The zones of the phase diagrams that are bordered by capture current lines and the verticals $U_0 = U_{mf}$ have specific shapes, since capture currents increase with the increasing gas velocity.

The physical behavior of fluidized solids above the partition is similar to the Magnetization LAST mode observed with batch-solids beds (Part 1). The

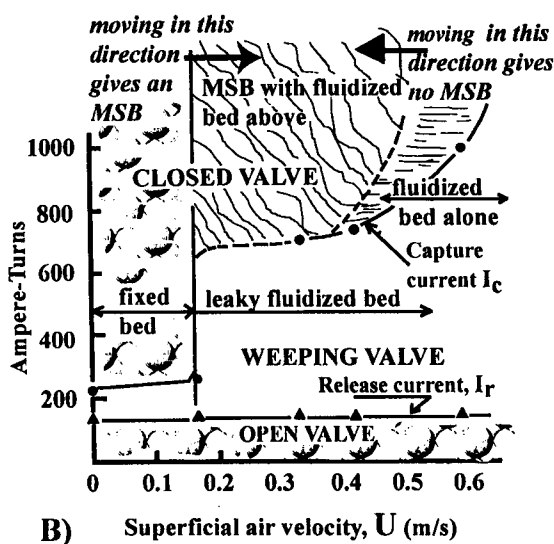
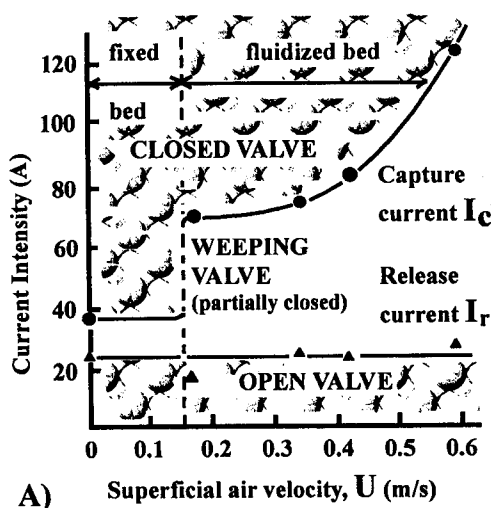


Fig. 48: Phase diagrams of MDD devices. Adapted from Jaraiz et al. (1984b)

a) Grate-type MDD (and MVS). Additional data: 6.4 mm water-cooled copper tubing for the grate, $L_g = 19\text{ mm}$, iron screen ($L_s = 6.4\text{ mm}$ with a wire of 0.7 mm).

b) Collar-type MDD (and MVS). Additional data: Channel diameter of 152 mm, iron screen ($L_s = 6.4\text{ mm}$ with a wire of 0.7 mm).

similarity is due to dominating inertia forces during the particle arrangement into a bed on the first frozen layer and the consequent formation of a fluidized section. This is summarized in Table 15.

However, there are differences in bed behavior that can be summarized as follows:

- i) Fields employed for batch solids beds are homogeneous, which results in homogeneous particle arrangements. Fields of MDDs are non-homogeneous. The particle strings orientation depends also on their location (position) inside the channel. This leads to channelling and vigorous bubbling.
- ii) Batch beds are entirely surrounded by magnetic systems, while MDDs can create beds deeper than the active zones of the solenoids employed.

Let us focus on the zones of the phase diagrams representing *closed valve states*. With the “weak” field of the grate-type valve no changes in bed behavior are expected, so the *fluidized bed* occupies the entire zone of the *closed valve* at $U_0 = U_{mf}$. On the other hand, the collar-type field is generated in a larger zone of space around the solenoid and this can affect gross bed behaviour. Because of this, the closed valve zone at $U_0 = U_{mf}$ could be divided into two areas. The stabilized bed occupies the left half of the zone and the arrows (Fig. 48b) correctly indicate its occurrence due to the expansion of the initial settled bed. This transition occurs when the action of the fluid drag begins to dominate over the stabilizing effect of the interparticle magnetic forces. A further increase in the gas flow leads to destruction of the MSB, thus causing fluidization (the marginal area in Fig. 48b). A consequent decrease in gas velocity does not transfer the particles into MSB due to the hysteresis of the magnetic fluidization. The occurring bed states resemble those of the Magnetization LAST mode and the backward (decreasing flow) pressure drop curve of Magnetization FIRST. Therefore, the right-side label in Fig. 48b correctly states the impossibility to reach MSB by a decreasing gas flow at fixed field (current) intensities. The state reached is a *fixed bed of particle strings* (aggregates) (see Part I and Hristov, 1998b).

III.3.6.2. Quantitative results

The pressure drop across the accumulated solids depends on several factors:

- Type of partition and field intensity generated along the bed axis
- Height and mass of stopped particles

Table 15
Comparative table of the characteristics of MDDs and batch-solids fluidized beds in axial fields with Magnetization LAST mode.

Common characteristics	Regimes	MDD		Batch-Solids Fluidization MSB-Magn. LAST in axial fields		Comments- present work	
		Grate specificity	Collar specificity	No-field effects		Common features	Differences
Particle leak	Fixed bed	Fixed bed at $u_o < U_{mf}$	Fixed at $u_o < U_{mf}$	Ordinary regimes: Fixed bed at $u_o < U_{mf0}$		No differences in the bed regimes	• The permeabilities of the supports
	Fluidized bed	Weakly fluidized bed on the grate at $u_o > U_{mf}$	Weakly fluidized bed on the screen at $u_o > U_{mf}$	Fluidized bed at $u_o > U_{mf0}$		No differences in the bed regimes (qualitatively). However, they are affected (quantitatively) by the solids mass flux and the permeability of the partition (grate or screen)	• Field topologies • The batch-solids beds are deeper and homogeneous • The height of the magnetic system
				Field effects on the particle motion			
Particle leak, but increased amount of particles rested on the partitions	Fixed bed	Fixed bed at $u_o < U_{mf}$	Fixed bed at $u_o < U_{mf}$	Fixed bed at $u_o < U_{mf0}$		No differences in the bed regimes and their sequences.	• The permeabilities of the supports
	Fluidized bed	Fluidized bed with particle aggregation on the grate at $u_o > U_{mf}$	Fluidized bed with particle aggregation on the screen at $u_o > U_{mf}$	Fluidized bed with particle strings at $u_o > U_{mf0}$ and $H \geq H_{cr}$		However, they are affected (quantitatively) by the solids mass flux and the permeability of the partition (grate or screen)	• Field topologies • Particle aggregate orientation • The batch beds are deeper • The MSD are more homogeneous
				Strong field effect on bed behaviour			
Particle flow stop	Fixed bed	Fixed bed at $u_o < U_{mf}$	Fixed bed at $u_o < U_{mf}$	Fixed bed at $u_o < U_{mf}$		No differences in the bed regimes and their sequences.	• The permeabilities of the supports
	Fluidized bed	Fluidized bed at $u_o > U_{mf}$	Fluidized bed at $u_o > U_{mf}$ and $I_r \leq I \leq I_c$	Fluidized bed at $u_o > U_{mf}$ and $H_{cr} \leq H \leq H_f$			• Field topologies • Particle aggregate orientation
	Frozen bed	Does not exist, except a narrow layer on the grate	Fixed bed at $u_o > U_{mf}$ and $I > I_c$	Fixed bed at $u_o > U_{mf}$ and $H \geq H_f$			• The batch beds are deeper and homogeneous

- Regime of aerated solids-fixed bed, fluidized bed, or frozen bed (i.e. MSB according to Levenspiel)

When a magnetic field is generated in close proximity to the screen, the picture of the field lines corresponds to grate-type distributors. In this case, the pressure drop-gas velocity curves resemble those of conventionally fluidized beds (Fig. 49). On the other hand, the type of bed support does not

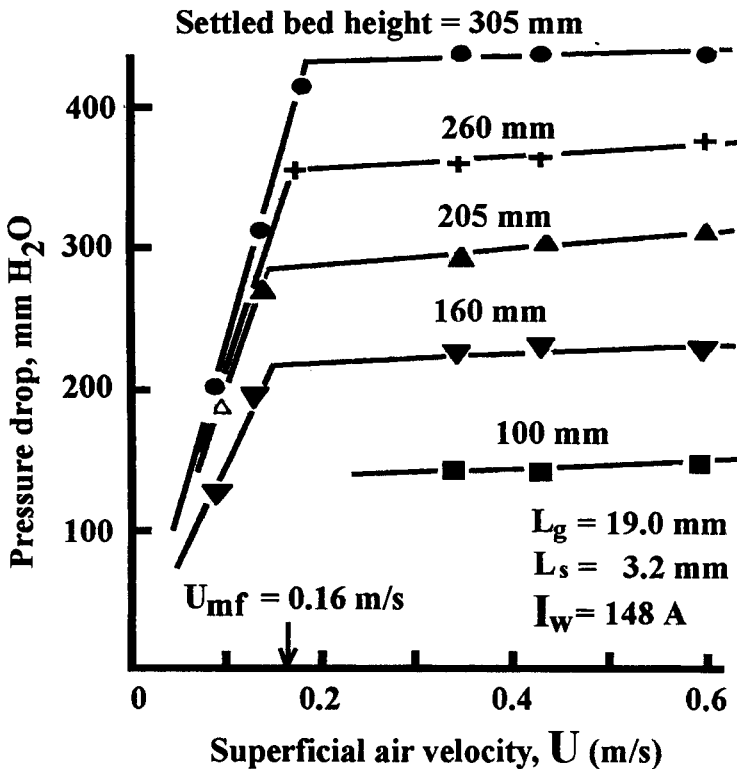


Fig. 49: Pressure drop across grate-design MDD. From Jaraiz et al. (1984b).

- Pressure drop at various depths of the particle bed accumulated at the partition (grate, $L_g = 19$ mm, copper screen, $L_s = 3.2$ mm) and working current $I_w = 148$ A.
- A more general presentation of the results concerning the pressure drop indicates that it is independent of both the screen properties and the working current strength.

depend on the variations of its building elements: *grate spacing, screens (iron or copper) and the working current strength*. This implies that the magnetic field *acts only on a thin frozen particle layer* at the bed bottom. The upper particle layers are fluidized “normally” according to Geldart (1973), i.e. with bubbling and are not affected by the field. Thus, the phase diagram of a grate-type MDD is a “simple” one and has two zones only – *fixed and fluidized*.

Collar-type MDDs (see data in Table 16) permit examinations of experimental conditions that have not been discussed or batch-solids MSB (Part 1). Jaraiz et al. (1984b) performed experiments (in accordance with the magnetization FIRST mode) concerning *bed depth effect on the overall behavior of the valve*. In fact, they studied the sensitive effect of the field generated by the solenoid on the overall bed behavior (Fig. 50). The following similarities between the well-known MSB behavior in homogeneous axial fields (Part 1) and MDDs can be noted:

- The fluidization curve of a collar-type MSB is smooth and *has no sharp transition from a fixed into a stabilized bed*.
- The pressure drop curves *do not exhibit plateaus*.
- The *breakdown of MSB* is sharp and the velocity at which it occurs *depends on the field intensity generated* (the working current strength)
- The *hysteresis* between the forward and backward curves *increases as the working current increased*.

Table 16

Studies on MDD operational characteristics - experimental conditions.
From Jaraiz et al. (1984b).

Common design parameters		
Flow channel	Cylindrical tube	152 mm Pyrex tube
Particles used	Soft porous iron particle d_p , mm d_p , mm	0.24 , bulk density = 1390 kg/m ³
Iron screens (~ 0.7 mm wire diameter)	Aperture,	6.4
	d_w -iron, mm	8.5
		12.7
Copper screens	Aperture,	3.2
	d_w -copper, mm	6.4
		12.7
Specific design parameters		
Valve type		
Grate	Spacing (Center to center distance, d_c)	19.0
	o.d. of copper tubes, mm	6.4
Collar	19 turns of 4.8 mm copper tubing and a soft iron shield. The height of the coil = 50 mm	

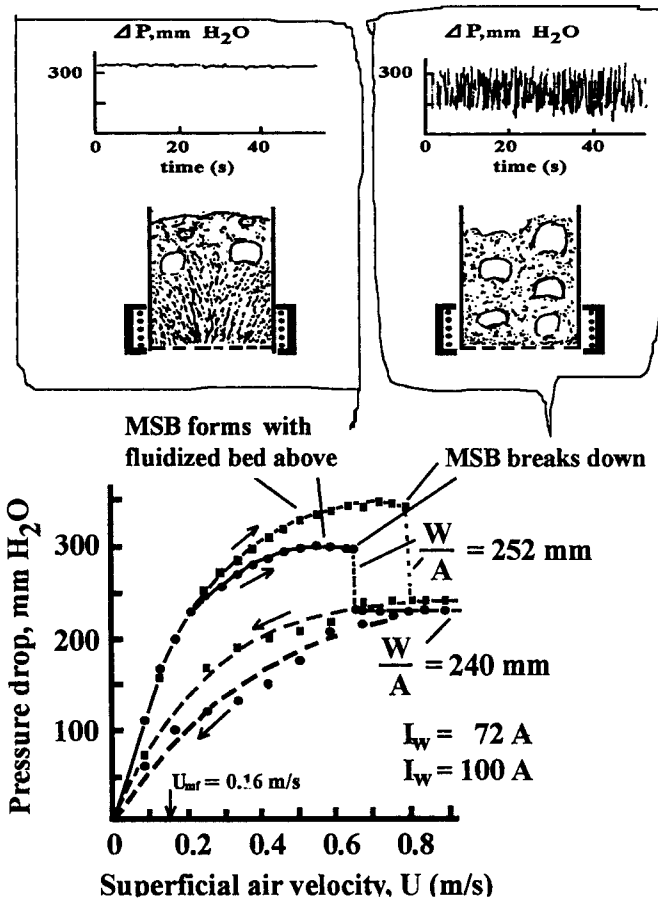


Fig. 50: Pressure drop curves for a collar-type MDD. From Jaraiz et al. (1984b). Behavior of a 180 mm deep particle bed ($\frac{h_b}{D_c} = 1.18$) at high working current magnetization. Additional data: 19 turns of the solenoid and an iron screen ($L_s = 6.4 \text{ mm}$).

However, shallow *beds* in MDDs exhibit greater ability to be stabilized than the deep ones, while in batch-solids MSB the deeper beds are more stable (Part I and Rosensweig, 1979) than shallow ones.

The variety of phenomena mentioned above is related to the sole fact that a very short solenoid with a nonhomogeneous field is used. The field acts at a short distance from the bed bottom. In fact, the bed remains stabilized until its top surface is subjected to a field intensity sufficient to create stable

interparticle forces. The increase in bed depth is equivalent to the decrease in field intensity at the position of the upper particle layers. Beyond a certain bed depth, the fluid drag dominates over the interparticle forces and solids become fluidized. Thus, the bed along the channel axis consists of a *stabilized bed* zone and a *fluidized (bubbling) bed* connected in series (see inset in Fig. 50). According to Jaraiz et al. (1984b), when the *settled bed height* (i.e. the initial fixed bed before fluidization) is greater than 6 coil heights (i.e. ~300 mm), *no stabilization is possible*.

In addition, the plots in Fig. 50 illustrate facts that should confirm some fundamental facts of magnetic stabilization discussed in Part 1. The two values of the W/A ratio in Fig. 50 are not due to bed weight changes but to additional interparticle forces and increased bed drag. The latter phenomenon results in high “overpressure” in the MSB regime when stronger working currents are applied.

III.3.6.3. Some comments on MDD

This closing part of the discussion on **MDD** addresses: (i) Features of MDDs that have determined their developments and (ii) Facts derived from both original papers and the present review:

1. Both grate-type and collar-type designs of **MDDs** require much higher currents when the bed is fluidized (Jaraiz et al., 1984b).
2. The collar design is attractive for applications since it does not require insertion of electric conductors into the channel (Jaraiz et al., 1984b).
3. Fluidized operations are usually exothermic; hence the formation of MSBs in collar-type **MDD** is not desirable. This is avoided by employing shorter solenoids, deep beds, low working current and large open times of the valve (Jaraiz et al., 1984b).
4. When a multistage bed is organized, movement of the solids from stage to stage should not be harmful. So a lower working current, not much higher than the release current, has to be used (Jaraiz et al., 1984b).

III.3.7. Exploratory results on MVSs and MDDs for mixtures of magnetic and non-magnetic particles

The magnetic field effect with Magnetization FIRST mode on the fluidization behavior of a mixture of magnetic and nonmagnetic particles was discussed in Part 1. Here, the study continues with regard to the specificities of **MVS** and **MDD** designs.

As in the case of batch-solids beds, the first problem to be discussed is the possibility to immobilize the mixture by induced magnetic forces. The magnetic field induces flocculation of the magnetic particles that form a skeleton entrapping the nonmagnetic ones (Part 1). This is the main mechanism of magnetic stabilization of magnetic-nonmagnetic mixtures. The conditions created by **MVS** and **MDD** are simpler than those in batch-solids beds. The only role of the partition, irrespective of its design (grate or collar), is to stop particle flow. Thus, the magnetic particles *have to block the partition aperture only*. Obviously, the blockage could consist of some sub-phenomena, such as magnetic skeleton formation and nonmagnetic solids entrapment.

The *release current* (i.e. the *minimum freezing field intensity*) close to the partition depends on the amount of magnetic particles in the flowing mixtures. The plots in Fig. 51 show that the decrease in magnetic particle content hinders blockage of the solids flow. The minimum amount of magnetic particles that requires adequate current intensities is about 5 mass-% for both grate-type and collar type valves.

The intermittent magnetization employed by **MVS** affects the flow of mixture solids if the magnetization **OFF** period (open valve) is sufficiently long. This implies that there is enough time for the destruction of the magnetic aggregates by friction and collisions with the nonmagnetic particles. If the **OFF** time is very short such a “relaxation” of the magnetic phase might not occur and relatively large aggregates would form and hinder the flow. The plots in Fig. 52 support this hypothesis. Sensitive effects on mass flow correspond to **OFF** periods of about 0.5 sec, similar to the case of pure magnetic solids. The same plots indicate that there is a sensitive effect of magnetic particle concentration on mass flux reduction at approximately 25 % (mass). At shorter **OFF** periods and pure magnetic flow (100 % iron), the solids are, in fact, *permanently magnetized*, which reduces their mobility through the partition. The comments of Jaraiz et al. (1984a) drew attention to the different fluidity of the iron and sand particles tested. The authors suggested that particles of similar geometries should have a *volumetric flux of the mixture independent of the mixture ratio*. They suggested that the ratio of the mass fluxes should agree with the density ratio

$$\frac{G_{\text{porous iron}}}{G_{\text{sand}}} = 1.1 \quad (45)$$

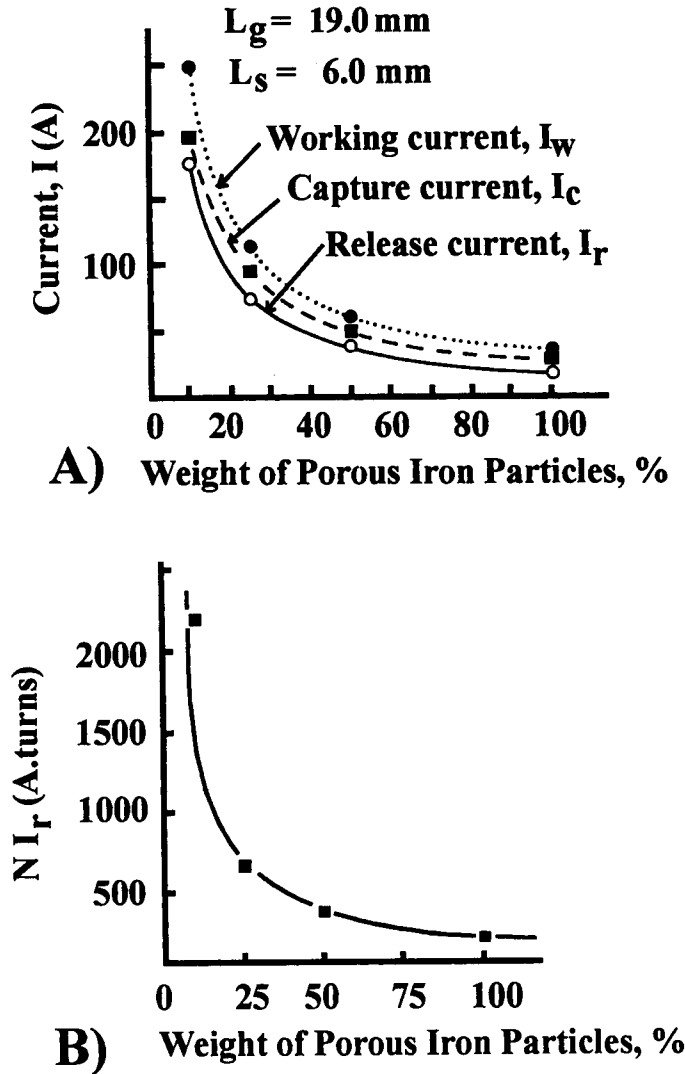


Fig. 51: Effect of the mass concentration of the magnetic particles on the critical currents of the valves:

- Grate-type MVS. From Jaraiz et al. 81984a)
- Collar-type MVS. Additional data: Channel diameter = 146 mm, Screen 1. From Zhang et al. (1984).

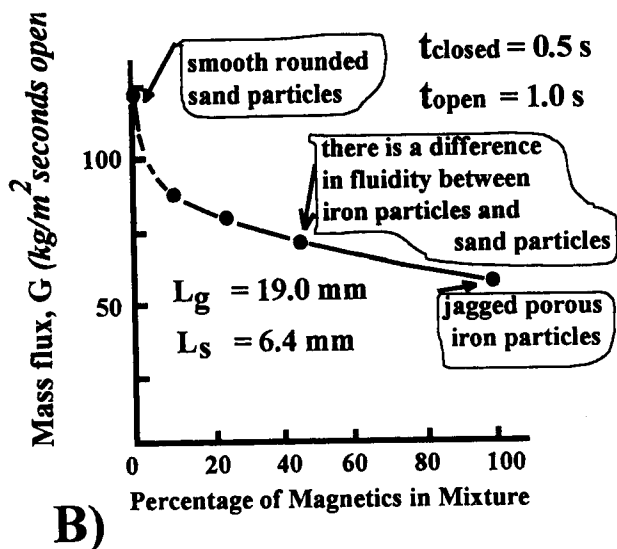
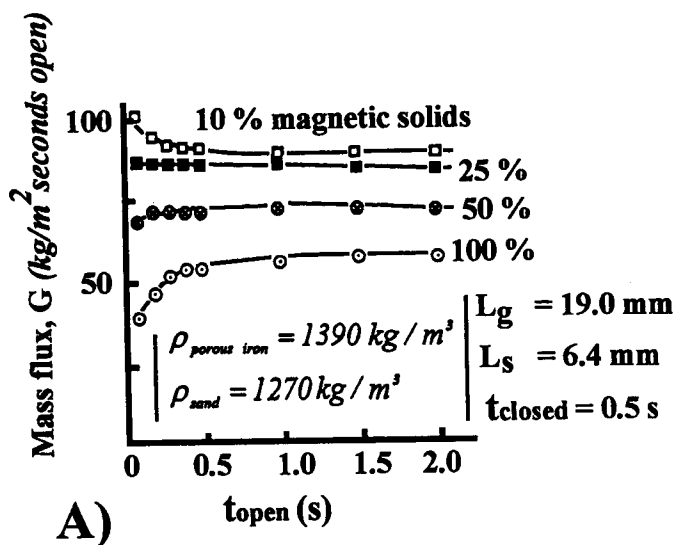


Fig. 52: Mass flux of admixtures through MVS

- Grate-type MVS. Effect of the t_{open} time on the mass flux at various concentrations (mass %) of the magnetic phase. From Jaraiz et al. (1984a).
- Collar-type MVS. Effect of the magnetic content (mass %) on the mass flux. From Zhang et al. (1984).

where $\rho_{\text{porous iron}} = 1390 \text{ kg/m}^3$; $\rho_{\text{sand}} = 1270 \text{ kg/m}^3$

However, the plot in Fig. 52b *does not confirm this suggestion*.

Lower concentrations of magnetic particles (10% only reported in the literature) lead to just the opposite effects – mass flow increases; no explanations were reported. This strange behavior could be explained by faster flow of the sand particles (Zhang et al., 1984). The authors suggest that both the acceleration and deceleration times of magnetic particles and sand in the mixture are less than 1 sec. No other experimental results have been published, so a more detailed analysis of these effects is difficult.

III.3.8. Energy demand

The energy consumption of an **MVS** (or **MVD**) is attributed to the ohmic resistance of the conductors (grade or collar design):

$$P_{\text{conductor}} = I^2 R_{\text{ohmic}} \quad (46)$$

With the grate-type device and continuous mode magnetization described by Yang et al. (1982) energy consumption is about $P = 30W$. The authors evaluated the additional hysteresis losses due to the presence of a magnetic material (particles) through the Steinmetz equation (Gilbert, 1941):

$$W_{\text{hyster}} = \eta (B_{\text{max}})^n \left[\frac{J}{\text{m}^3 \text{ of solids}} \right] \quad (47)$$

where W_{hyster} are the hysteresis losses per 1 cycle; for iron $\eta = 2.25 \times 10^{-11}$, while for steel $\eta = 3.75 \times 10^{-10}$, and B_{max} is the maximum field induction.

For the experiments performed by Yang et al. (1982), $\eta \approx 3 \times 10^{-11}$, $B_{\text{max}} \approx 1.5 \text{ We/m}^2$ and $n \approx 1.6 \div 1.7$. If the mean particle bed depth frozen in the tube (152 mm I.D) is assumed to be about 20 mm: $W_{\text{hyster}} \approx 6 \times 10^{-11} \text{ J/m}^3$. With *intermittent magnetization* the current is switched *twice ON-OFF* per period and the energy is

$$P_{\text{magnetic losses}} = W_{\text{hyster}} \left(\frac{\pi}{4} 0.15^2 \right) (0.02) \times 2 = 4 \times 10^{-4} \text{ W} \quad (48)$$

Thus , the total energy loss is $P_{total} = P_{conductor} + P_{magnetic \text{ losses}}$

There is little information about the design parameters and the relevant energy consumptions. For instance, Yang et al. (1982) commented that larger tube diameters created weaker field intensities at given r (centre-to-centre distance between the copper tube conductor and a particle). When iron screens of small apertures are employed, they significantly reduce the holding current. According to Yang et al. (1982), the grate spacing becomes important in cases of additional iron screens and also plays a distinct role in controlling energy consumption. For instance, a grate-type valve in a 6-in (≈ 146 mm) vertical tube with an iron screen placed beneath the tube conductors needs a current of about 50-100 A to stop the solids flow (or to be a distributor for a fluidized bed) . According to the same authors, power consumption was about 30 W.

III.4. Developments and some specific problems of MVS

III.4.1. Particle composites for MVS

The purpose of the magnetic valves is to create easily controllable gas-solid contactors. Special attention was paid by Cuellar and Jaraiz (1986) to the design of particle materials suitable for operation with MVS. These materials are summarized in Table 17. Alumina was chosen as a principal material of composite solids as it is the most commonly used catalyst support. Cuellar and Jaraiz (1986) oriented their study on particle properties toward applications in collar-type devices. Further, they used the concept of

Table 17

A summary of the experiments performed by Cuellar and Jaraiz (1986)

Particle material	Particle size	Composition	$\chi_p \mu_0, H m^{-1}$ $\times 10^3$	χ_p
Stainless steel	137 mm		9.62	7667
Magnetite			8.80	7006
Steel	100-200		7.03	5507
Magnetite-Alumina	Tyler mesh	30% Magnetite- 70 % Alumina	7.70	6130
Steel-Alumina		30% Steel - 70 % Alumina	6.42	5232
Iron-Alumina		30% Fe - 70 % Alumina	1.08	860
Composite preparation: According to Satterfield (1980):Drying of the wet past for 18 h ,then for 24 h at 110°C and finally for 24 h at 500°C				

Jaraiz and Estevez (1987) concerning a force acting on a single particle subjected to a magnetic field in a vacuum (μ_0) as:

$$\frac{F_p}{V_p} = \chi_p \mu_0 H_G \quad (49)$$

Here, F_p is the force on a particle with a volume V_p and a magnetic susceptibility χ_p .

The term H_G represents the product $H \text{ grad} H$. For a collar-type device (Cuellar and Jaraiz, 1986), the detailed expression is

$$H_G = I^2 \sum_{i=1}^m \frac{N^2}{4} \left(\frac{L+z}{\sqrt{X}} - \frac{z}{\sqrt{Y}} \right) \left(\frac{\sqrt{X} - (L+z)^2 \frac{1}{\sqrt{X}}}{X} - \frac{\sqrt{Y} - z^2 \frac{1}{\sqrt{Y}}}{Y} \right) \quad (50)$$

where $X = (L+z)^2 + r^2$, $Y = z^2 + r^2$, N is the number of turns of the coil, m is the number of the layers of the solenoid, L is the coil height, z is the distance between the coil and the particle and r is the radius of the i^{th} layer of the coil.

For a multilayered coil (Jaraiz and Estevez, 1987) and particle position at the coil symmetry axis (Eq. 50) we have:

$$H_{\text{applied}} = (NI) \frac{L}{2} \sum_{i=1}^m \frac{1}{\sqrt{L^2 + r^2}} \quad (51)$$

The simplified approach suggests F_p to be expressed as

$$F_p = \left(\begin{array}{l} \text{apparent weight} \\ \text{at current } I \end{array} \right) - \left(\begin{array}{l} \text{actual weight} \\ \text{in the absence of a field,} \\ \text{i.e. no current is passing} \end{array} \right) \quad (52)$$

This permits calculation of the term H_G according to Eqs. (50) and (52) as well as making it easy to determine χ_0 according to Eq. (50). The volume of the particles was determined from material density and particle mass.

The results presented in Fig. 53 are obtained with temperature variations

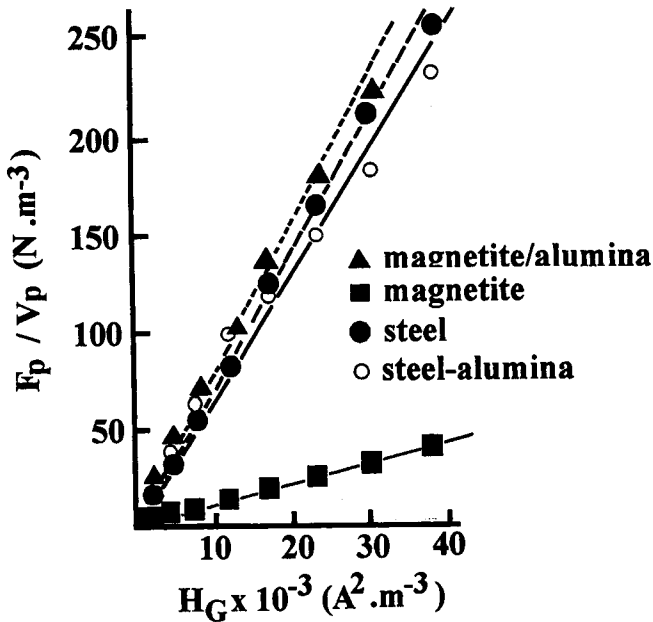


Fig. 53: Force on a single particle (per unit volume) as a function of the value of H_G . From Cuellar and Jaraiz (1986).

from the ambient up to 450°C, since in most applications high temperatures are used. As a result of these studies it becomes clear that the magnetic susceptibility was affected less than 2 % by temperature variations over the entire investigated range. The applied field was varied from 176 up to 1589 A/m. The magnetic susceptibilities are summarized in Table 17. The main conclusion drawn from these experiments is that the results obtained under ambient conditions are also valid for relatively high temperatures (approximately 450°C).

III.4.2. Design concepts developed in the University of Salamanca – critical analysis

Equation (49) is applicable when the magnetic susceptibility of the fluid is lower than that of the magnetic particles used. As commented previously, the collar-devices employ screens for solids flow control. Moreover, the analysis shows that for larger screen apertures, larger magnetic attractive forces (higher working currents) are needed. Consequently, if the value of F_p is calculated at a certain screen aperture, the desired value of H_G can be

defined and the complete valve can be designed.. This concept was employed to calculate the value of H_G at the symmetry axis of the pipe (see Fig. 54a, b). The magnetic field intensity at a point P of the central axis of the solenoid

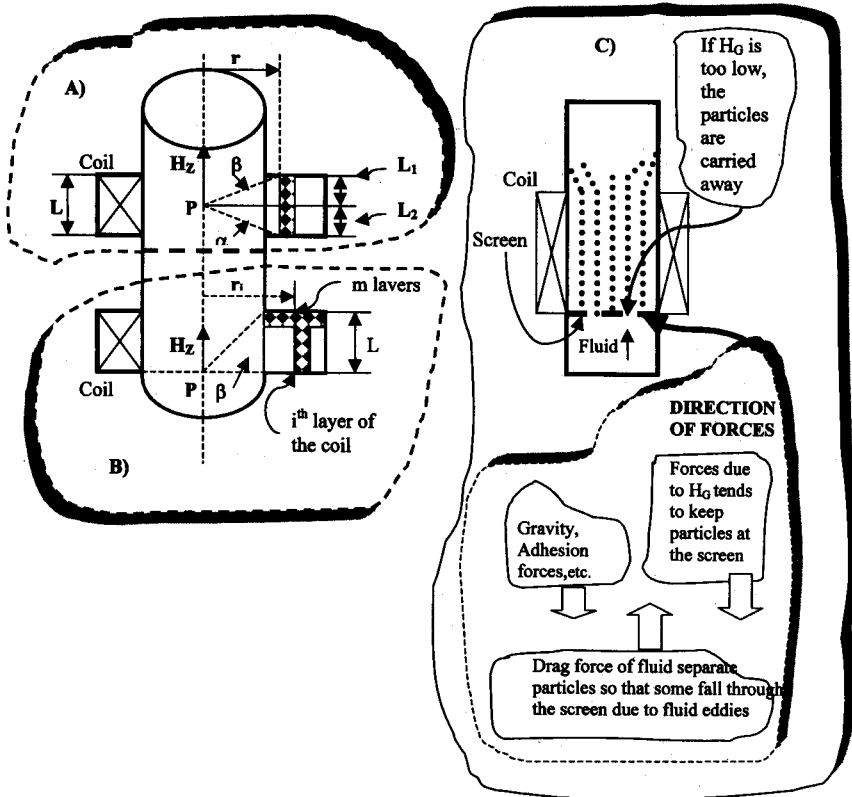


Fig. 54: Sketches of the co-ordinate system for field calculations and the physical model accepted by Jaraiz and Estevez (1987).

- Calculations when the point P is at the solenoid axis, but inside the solenoid.
- Calculations when the point P is at the bottom position of the screen.
- Physical model accepted.

Note: The figure collects two original drawings of Jaraiz and Estevez (1987). The present author, for clarity of explanation, redrew them electronically.

generated by only one layer of conductors (Fig. 54a), is

$$H_Z = \frac{NI}{2} (\sin \alpha + \sin \beta) \quad (53)$$

where

$$\sin \beta = \frac{L_2}{\sqrt{L_2^2 + r^2}} \text{ and } \sin \alpha = \frac{L_1}{\sqrt{L_1^2 + r^2}}$$

In the case of a multilayered coil, Eq. 53 takes the form of Eq. 51. Thus, the field gradient is (Estevez and Jaraiz, 1987):

$$\text{grad } H = (\text{Current factor})(\text{Geometry factor}) = I.F_{HG} \quad (54a)$$

so the final form of H_G is $H_G = I^2 F_{HG}$, where (after some algebraic manipulations)

$$F_{HG} = \frac{N^2}{4} \left[\sum_{i=1}^m \frac{L}{\sqrt{L^2 + r_i^2}} \right] \left[\sum_{i=1}^m \left(\frac{\sqrt{X_i} - L^2 \sqrt{X_i}}{X_i} - \frac{1}{r_i} \right) \right] \quad (54b)$$

where $X_i = L^2 + r_i^2$.

The term F_{HG} is a constant for a particular solenoid designed.

The physical model represented by Fig. 54c was developed as a simple force balance

$$\left[\begin{array}{l} \text{Drag force by} \\ \text{upflowing gas} \end{array} \right] = \left[\begin{array}{l} \text{Weight of} \\ \text{particles} \end{array} \right] + \left[\begin{array}{l} \text{Other forces} \\ \text{such as cohesion} \end{array} \right] + \left[\begin{array}{l} \text{Magnetic forces} \\ \text{on particles} \end{array} \right] \quad (55)$$

The basic hydrodynamic assumption of Estevez and Jaraiz (1987) is that of a laminar flow described by the Hagen-Poiseuille model for flow through the interparticle channels. Thus, the result is the Carman-Kozeny equation expressed as :

$$\frac{K\mu(1-\varepsilon)^2}{\varepsilon^3 d_p^2} U = \left\{ \left[(\rho_p - \rho_g)g + A_F \right] + (\chi_p \mu_0) H_G \right\} (1-\varepsilon) \quad (56a)$$

Here, A_F is a term representing additional forces, such as adhesion, while K is the Carman-Kozeny constant. Expressing H_G in the last term of (56a) as $H_G = I^2 F_{HG}$ we have

$$\frac{K\mu(1-\varepsilon)}{\varepsilon^3 d_p^2} U = \left[(\rho_p - \rho_g)g + A_F \right] + (\chi_p \mu_0) F_{HG} I^2 \quad (56b)$$

The solution of Eq. 56b with respect to I^2 gives

$$I_r^2 = -K_1 + K_2 U \quad (57a)$$

$$\text{where } K_1 = -\frac{[(\rho_p - \rho_g)g + A_F]}{\chi_p \mu_0 F_{HG}} \text{ and } K_2 = \frac{K\mu(1-\varepsilon)}{\chi_p \mu_0 F_{HG} d_p^2 \varepsilon^3} \quad (57b)$$

The expression (57a) implies that $I_r \sim U^{\frac{1}{2}}$, i.e. a linear relationship $I_r^2 \sim U$. The experimental plots in Fig. 55 fit satisfactorily $I_r^2 \sim U$, but some additional comments on the correctness of Eqs. (56) and (57) are required.

The plots in Fig. 55 indicate that the velocity range used in the experiments is from 0.4 up to 2 m/s (iron-alumina plot) and from 0.4 up to 1.2 m/s (iron and steel alumina plots). Taking into account air properties at ambient conditions and a mean particle diameter of 0.137 mm, the particle Reynolds number is $Re \approx 99.93 U$. This implies that the Reynolds number varies within the range $\approx 40 \div 200$, so the flow range is not truly laminar with $Re_p < 0.2$, where the Carman-Kozeny equation (56a) is applicable (see Cox and Clark, 1991). Moreover, the particle model arrangement as strings separated by channels suggests a loose bed structure rather than compact particle packing with a voidage of approximately $0.4 < \varepsilon < 0.5$ (Cox and Clark, 1991).

Let us perform a numerical experiment by replacing the Carman-Kozeny equation with its extreme counterpart the Burke-Plummer relationship (Cox and Clark, 1991):

$$\frac{\Delta P}{L} = 1.75 \frac{\rho_g}{d_p} \frac{1-\varepsilon}{\varepsilon^3} U^2 \quad (58a)$$

The result is:

$$I^2 = -K_1^{BP} + K_2^{BP} U^2 \quad (58b)$$

where $K_1^{BP} = K_1$ as established earlier (Eq. 57b), while

$$K_2^{BP} = 1.75 \left(\frac{\rho_g}{d_p} \right) \left(\frac{1}{\chi_p \mu_0} \right) \left(\frac{1}{\varepsilon^3} \right).$$

The expression (58b) suggests that $I_r \sim U$, but the plots in Fig. 55 (except data concerning steel-alumina composites) do not confirm this. However, conclusions should be drawn very cautiously since these plots are based on only three experimental points for each particulate material tested.

Foscolo et al. (1983) proposed an equation that covers the Reynolds number range of the experiments of Estevez and Jaraiz (1987):

$$\frac{\Delta P}{L} = \left(\frac{17}{\text{Re}} + 0.336 \right) \frac{\rho_g U^2}{d_p} (1 - \varepsilon) \varepsilon^{-4.8} \quad (59)$$

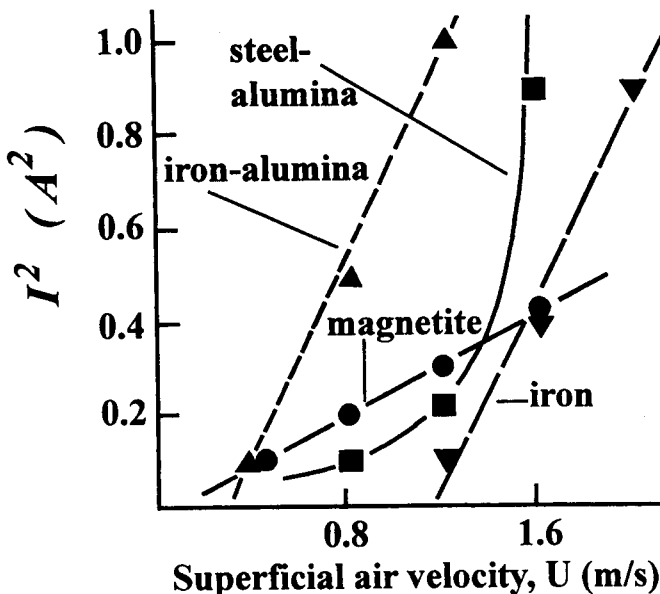


Fig. 55: The square of the release current as a function of the superficial gas velocity for various particles tested by Jaraiz and Estevez (1987).

valid for $500 > Re_p > 0.2$ (Cox and Clark, 1991).

This equation introduced on the left hand side of (56) (with some algebra) gives:

$$\left[\left(\frac{17\mu}{d_p^2} \right) U + \left(0.336 \frac{\rho_p}{d_p} \right) U^2 \right] (1-\varepsilon) \varepsilon^{-4.8} = \left\{ [(\rho_p - \rho_g)g + A_F] + (\chi_p \mu_0) H_G \right\} (1-\varepsilon) \quad (60)$$

Its solution for I is

$$I^2 = K_0 + K_1^{FGW} U + K_2^{FGW} U^2 \quad (61a)$$

The term

$$K_0 = - \frac{(\rho_p - \rho_g)g + A_F}{\chi_p \mu_0 F_{HG}} \quad (61b)$$

is equal to K_I derived by Estevez and Jaraiz (1987).

The two new terms (prefactors) are

$$K_1^{FGW} = \frac{17\mu}{d_p^2 \chi_p \mu_0 F_{HG}} \varepsilon^{-4.8} \quad (61c)$$

and

$$K_2^{FGW} = 0.336 \frac{\rho_g}{d_p \chi_p \mu_0 F_{HG}} \varepsilon^{-4.8}$$

It seems that the real relationship $I = f(u)$ is neither (57a) nor (61a). This simple numerical test with results summarized in Table 18 compares the three discussed equations. The calculations are performed at ambient conditions for the gas (air) and $d_p = 0.137 \text{ mm}$, and the values of $\chi_p \mu_0$ summarized in Table 18. The bed voidage is assumed to be about $\varepsilon = 0.5$ for clarity of explanations. Additionally, the term A_F is neglected because of its irrelevance with respect to the magnetic attractive forces. The calculations are performed only for two materials with known densities (magnetite = 5100 kg/m^3 and iron = 7100 kg/m^3). For the other materials (composites), the

Table 18

Comparative numerical experiment. Evaluation of the coefficients in the equations relating to I and U for beds in collar-type.

Particle material			Eq. (57)		Eq.(58b)		Eq.(61)		
	Velocity range, m/s		K_1 $\times 10^3$	K_2 $\times 10^3$	K_1^{BP} $\times 10^3$	K_2^{BP} $\times 10^3$	K_0 $\times 10^3$	K_1^{FGW} $\times 10^3$	K_2^{FGW} $\times 10^3$
	U_{min}	U_{max}							
Magnetite	0.4	1.6	3.02	3.278	3.02	43.8	3.02	3.006	5.94
Iron	1.2	0.984	5.271	3.283	5.271	43.8	5.27	3.767	7.445

densities are not available in the papers published.

The present author made a considerable effort to recover correct data concerning the solenoid employed by the Jaraiz group. It is a pity that such data were not reported in any of the papers published in by that group. A detailed study of these papers revealed that Estevez et al. (1991) published (in a small local journal) only data about the release currents in the form:

$$I^2 = E \cdot F_A \cdot J \quad (62a)$$

where

$$E = \frac{1}{V_p \chi_p \mu_0 P} \text{ and } J = \frac{g(\rho_p - \rho_g)}{\chi_p \mu_0 P} \quad (62b)$$

The symbol P denotes the coil geometry factor F_{HG} expressed by equations identical to Eq. (54b). The graphical treatment of the plots $I^2 = f(F_A)$ (not shown here) published by Estevez et al. (1991) provides an average value of $P = 1.8 \times 10^9$. The data in Table 18 were obtained using that value. This decision of the present author is based on published descriptions, namely by those of Jaraiz et al. who use one short solenoid in all of their studies.

Further graphical treatment of the curves shown in Fig. 55 yields slopes of the lines $1.230 \text{ A}^2/(m/s)$ for iron and $0.28 \text{ A}^2/(m/s)$ for magnetite, respectively. This seems strange, since the form of the coefficient K_2 (Eq. 57b) does not consider particle material density. Therefore, the slopes of the two lines (K_2) should be almost equal since the differences between the values of χ_p and μ_0 are insignificant (see Table 17). However, the graphs do not confirm this assumption

These comments were introduced into the text only to stress the fact that the simplified analysis *could lead to loss of information*. Correct publications of experimental conditions could help other investigators to understand the results. Unfortunately, incompletely described experimental conditions are typical of the earlier studies and generally of those performed in the 1980s (Part 1). Nevertheless the work carried out in the University of Salamanca and the personal contributions of Jaraiz to the reviewed topic are noteworthy.

Jaraiz and Estevez (1987) developed a simple scale-up methodology, based on the concepts for release current calculations. The main assumption is that the value of F_p does not depend on the size of the valve. Therefore, irrespective of the scale of MVS, we have

$$F_{p,min} = (V_p \chi_p \mu_0) H_{G,min} \quad (63)$$

where $H_{G,min}$ is the minimum field gradient sufficient to hold the particles on the screen bars. Thus, for two systems of different scales we have equal forces acting on the particles. It should be borne in mind that $H_G = I^2 F_{HG}$ Eq. (63) can be re-written as

$$F_{p,min} = \underbrace{\left[(V_p \chi_p \mu_0) I_1^2 F_{HG-1} \right]}_{\text{small scale-1}} = \underbrace{\left[(V_p \chi_p \mu_0) I_2^2 F_{HG-2} \right]}_{\text{large scale-2}} \quad (64)$$

Consequently, from Eq. (64) it follows that

$$\frac{I_2}{I_1} = \sqrt{\frac{F_{HG-1}}{F_{HG-2}}} \quad (65)$$

Additionally, Jaraiz and Estevez employed the scaling relationships between release current and screen aperture ($NI \sim \sqrt{L_s}$) developed by Zhang et al. (1984). Hence, for a term contributing to the screen aperture ratio we have

$$\frac{I_2}{I_1} = \sqrt{\frac{F_{HG-1}}{F_{HG-2}}} \sqrt{\frac{L_{s-2}}{L_{s-1}}} \quad (66)$$

Up to now, no papers concerning experimental verifications of this scale-up concept have yet been published.

III.4.3. Grate-type staged fluidized beds for countercurrent gas-solid contacting

An interesting development of MVS and MDD towards effective solids flow control was reported by Levien and Al-Zahrani (1991). The investigations were oriented to a grate-type valve (Fig. 56) in two basic

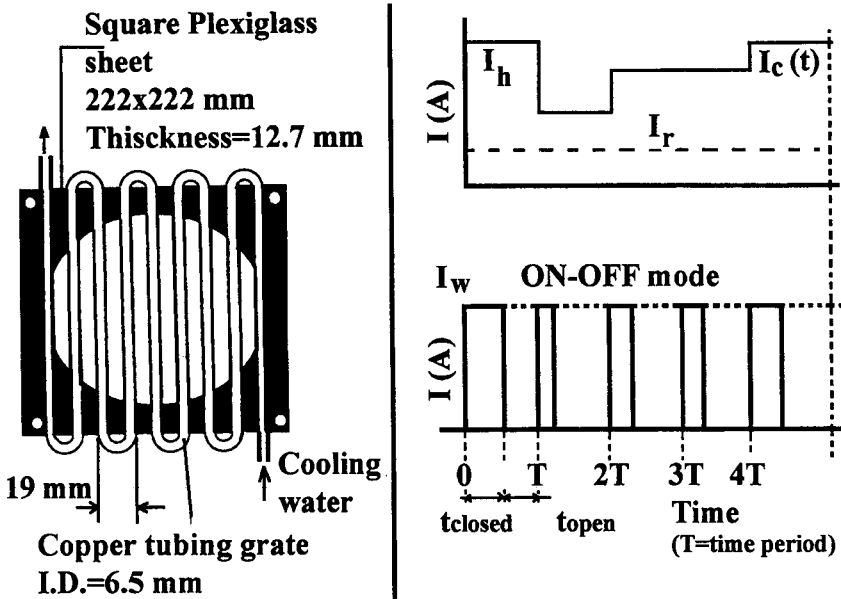


Fig. 56: Grate-type MDD investigated by Levien and Al-Zahrani (1991).

- Grate design
- Current magnetization modes

magnetization modes:

- Continuous current mode.** The electric current I_c is adjusted continuously at every sample time t_s .
- On-Off mode.** The current pulse amplitude is equal to I_w during the magnetization periods. The duration of the magnetization off period is t_{op} (open valve) and t_{cl} is the closed valve time. The study employed a *fixed frequency* magnetization, so that the period of magnetization was kept constant, i.e. $T = t_{op} + t_{cl}$. The manipulated variable was the ratio

$$f_{op} = \frac{t_{op}}{T} \quad (67)$$

The equipment was designed as a three-stage section (Fig. 57a). Specially designed auxiliaries were used so that solids recirculation and controlled feed at the top of the column were assured. The frequency of magnetization and the duration of t_{op} period were controlled by a data acquisition and a control system.

III.4.3.1. Single-stage behavior without feedback control

The experimental results of Levien and Al-Zahrani (1991) demonstrated that pressure drop data were proportional to particle hold-ups on a stage (within a range from 0 up to 6 kPa and a nominal velocity of 0.2 m/s). This relationship was employed as a *measured process output* in all the experiments and models. Particle flow rate was manipulated by changing the current I_c in a continuous mode or $f_{op}(I_{avg})$ according to the On-Off magnetization. Thus, available valve opening was controlled by variations of the actual magnetic field. Throughout the preliminary experiments it was established that not all particles were released from the grate tube during the off period of magnetization. Therefore, the formation of such a particle “coating” reduced the actual open area of the valve. According to Levien and Al-Zahrani (1991) the thickness (the outer radius) of the particle layer was strongly proportional to the values of I_c or f_{op} . This practically confirmed the earlier results of Jaraiz et al. (1984); remember the U-tube experiments in Fig. 33a.

An essential phenomenon reported by Levien and Al-Zahrani (1991) is *particle flow hysteresis* (Fig. 57b). First, with current I_{cap} or greater, the magnetic particles will be totally captured by the grate, so no leaks are possible down to I_h (Path A). Reducing the current to I_r (release current) will lead to an increased particle flow, following the path of line B. If the current is adjusted within the interval $I_h > I > I_r$, the flow rate remains on line B. Further reduction of the current ($I < I_r$) shifts the path to line C. The opposite manipulation - current increase from I_r to I_h and further up to I_{cap} follows path C and then line D, *but not path B*. Hysteresis is inherent to the continuous mode of magnetization. In the **ON-OFF** mode this can be easily avoided since the principal requirement is that the working current I_w be greater than I_{cap} .

The phase diagram in Fig. 57c presents three distinguished flow regimes detected visually. Here, the operating variables are the **OFF** period of magnetization (open fraction of the pulse) and the pulse period

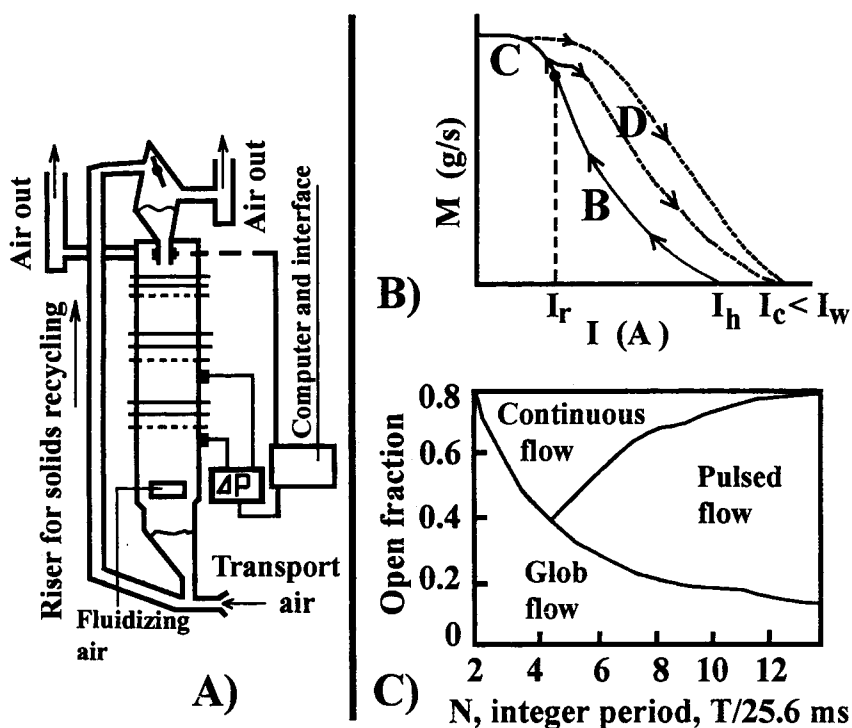


Fig. 57: Experimental set-up of Levien and Al-Zahrani (1991).

- Vertical column (150 mm, I.D.), a riser (19 mm I.D.), and the top feeder assure adequate flow control.
- Mass flow rate hysteresis and adjustment of the amplitudes of the current pulses.
- A phase diagram representing the available particle flow regime because of simultaneous manipulation of both the period of the magnetization pulsation and the open time of the valve. The period corresponds to $T = 128$ ms, so N is equal to 5.

$T = t_{open} + t_{closed}$. Obviously, the pulsing magnetic field averages the solids mass flow through the grate. The *glob flow* implies *sporadic particle leaks* at different locations of the cross-section of the channel in the form of “globs” or clumps. The diagram indicates that this unstable particle flow depends mainly on the magnetization pulse period, but not on the duration of t_{open} .

The *smooth flow* or the *continuous flow* (according to the terminology employed by Levien and Al-Zahrani, 1991) appears in a narrow area corresponding to very small closed times and moderate periods of pulsations. The *increase in the period* of the magnetization pulse or the *decrease in the duration* of t_{open} leads to *particle flow instability* with strong variations – between zero and maximum. These variations are specific to the *pulsation flow regime*.

As mentioned before, the pressure drop is a measure used to control particle hold-up on the grate. A single-step change of f_{op} leads to both positive and negative variations of the particle mass flow (Fig. 58a). The decrease in f_{op} gives the record a. It physically means that the increase in the closed time of the valve leads to accumulation of more particles on the grate. The step change in f_{op} in the opposite direction (record b) is related to a longer t_{open} and less particle masses stopped by the grate.

The mass flow through the valve expressed as a simple mass balance (Levien and Al-Zahrani (1991) is:

$$\frac{dM_0}{dt} = m_{in} - m_{out} \quad (68a)$$

or as averaged pressure drop ΔP_{avg}

$$\frac{\Delta P_{avg}}{dt} = \frac{m_{in} - m_{out}}{A_{CS} (1 - \varepsilon_s) \rho_s K_h} \quad (68b)$$

$$\text{where } M_0 = A_{CS} h_s (1 - \varepsilon_s) \rho_s \text{ and } h_s \approx K_h \Delta P_{avg} \quad (68c)$$

The general *pressure drop response* to changes in m_{in} and m_{out} is described by Eq. (68b). The value of m_{in} , for the top stage, can be accurately manipulated by the feeder, while m_{out} depends on the operating variables of the valve. This allows expression of the value of m_{out} as a function of the manipulated variable I_c (or f_{op}) in a simple form – see data fitting in Fig.58b.

$$m_{out} = K_1 I^2 - K_2 I + K_3 \quad (69)$$

where K_1 , K_2 and K_3 are positive constants that depend on valve design.

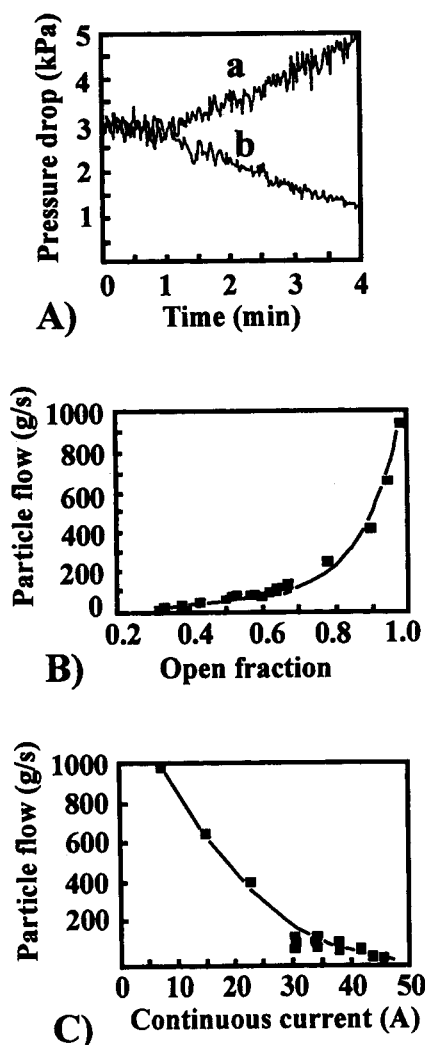


Fig. 58: Manipulations of the valve operation through the parameters of magnetization. From Levien and Al-Zahrani (1991).

- a) *On-Off mode*. Valve response (pressure drop ~ the mass of resting particles) to a single step change in f_{op} a) from 0.549 to 0.471 and b) from 0.549 to 0.627
- b) *On-Off mode*. Flow rate through MDD as a function of t_{open} . Solid line – Eq. 70
- c) *Continuous-current mode*. Flow rate through MDD as a function of the working current strength. Solid line – Eq. (71).

The variations of f_{op} are more appropriate for the control of m_{out} through the following expression used for simulations (see data fitting in Fig. 58b)

$$m_{out} = 54 + 950 f_{op}^{8.5} \quad (g/s) \quad (70)$$

The same approach to the continuous-current (continuous magnetization) mode yields a regression equation (see data fitting in Fig. 58c)

$$m_{out} = 0.73 I_c^2 - 64 I_c + 1430 \quad (g/s) \quad (71)$$

with $R^2 = 0.97$

III.4.3.2. Multistage behavior with a feedback control

The studies were oriented towards assessment of step set-point changes of:

- *particle amount on a stage and*
- *step disturbance in the feed rate to the column top feeder.*

Changes in gas flow were not found to be significant for the process control. The model of the instantaneous pressure drop signal was approximated through pressure fluctuations on a single stage (since Eq. 68b represents a time-averaged value) in the form:

$$\Delta P = \Delta P_{avg} + K_f \sin(\omega t) \quad (72a)$$

where

$$K_f = 0.47 \sqrt{\Delta P_{avg}} \quad \text{and} \quad \omega = 21.0 \Delta P_{avg}^{-0.4} \quad (72b)$$

The dynamic equations of a three-stage fluidized column were considered as a one-way interaction (see the structure of the matrix A_I) in the form:

$$\frac{\Delta P_{avg}}{dt} = \alpha A_1 m_0 + \alpha B_1 m_{feed} \quad (73a)$$

where

$$\alpha = \frac{1}{A_{CS} (1 - \varepsilon_s) \rho_s K_h} \quad (73b)$$

$$\text{and } \mathbf{A_I} = \begin{bmatrix} 1 & 0 & 0 \\ 1 & -1 & 0 \\ 0 & 1 & -1 \end{bmatrix} \text{ and } \mathbf{B_I} = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} \quad (73c)$$

$$\text{stage (1)} \quad \left. \frac{\Delta p_{avg}}{dt} \right|_1 \quad (73d)$$

$$\text{stage (2)} \quad \left. \frac{\Delta P_{avg}}{dt} = \frac{\Delta P_{avg}}{dt} \right|_2 \quad (73e)$$

$$\text{stage (3)} \quad \left. \frac{\Delta p_{avg}}{dt} \right|_3 \quad (73f)$$

Moreover, the mass flow rates at the stages are

$$m_{out}(1), \quad m_0 = m_{out}(2), \quad m_{out}(3) \quad (73g)$$

Mass flow control through **MDD** was not designed with open loop-gain, so conventional input-output analysis is not applicable. Independent controllers with logic-based decoupling design were used at each stage. This means that the pressure drop across each stage is constant when the derivatives in Eq. (73a) are zero, or when *the flow out* is equal to *the flow into* the stage.

The parameters required for a simple control scheme were selected as follows:

- controller gain K_c ,
- filter time τ_f ,
- constraints (lower and upper) of the manipulated variables and
- value of I_w in the On-Off mode.

A series of simulations were performed with controlled parameters (see Table 19).

Table 19

Tuned controlling parameters in the multistage experiments of Levien and Al-Zahrani (1991)

Parameter	Range	
	min	max
Continuous-current mode		
Controller gain K_c (A/kPa)	228 A/psia= 33 A/kPa	
Filter time , τ_f	1.8 sec	
Currents , $I_h = I_c$	22 A	47 A
On-Off mode		
Controller gain K_c (A/kPa)	- 0. 34 kPa ⁻¹ for T= 128 ms	
Filter time , τ_f	1.8 sec	
f_{op}	0.31 i.e. $t_{op} = 40\ ms \clubsuit$	1, i.e. $max\ t_{op} = T = 128\ ms$
Working current, I_w	148 A	
$\clubsuit$ zero rate of particles		

• **What magnetization mode has to be used?**

Levien and Al-Zahrani (1991) tried to analyze set-point experiments with both modes of magnetization with respect to the mass flow regimes observed. The main conclusions of the authors are:

- The set-point change in the *On-Off mode* leads to *more sluggish flow* compared to the *continuous mode of magnetization*. The formation of slugs is attributed to the strong particle magnetization: the average current intensity is 65 A. On the other hand, softer conditions are created in the continuous mode: the average current intensity is 35 A.
- In the *continuous current mode* the *top stage is more unstable* during the *set-point changes*, while the *On-Off mode* leads to more stable responses. The authors attribute the oscillatory behavior in the continuous mode to hysteresis of the mass flow (see earlier comments).
- Mass flow rate variations from 0 to 900 g/s reveal that with flow rates less than 300 g/s the continuous mode demands less energy (30 % lower average current) than the On-Off mode. However, for larger mass flows the On-Off mode needs a lower average current than the continuous mode. No further analysis was performed in the original study.
- There is a *frozen layer* near the grate tube irrespective of the type of

magnetization. In the On-Off mode the completely frozen particle layer falls through the grates during the open valve period t_{open} . According to Levien and Al-Zahrani (1991), this is an undesirable phenomenon when mixtures of magnetic and non-magnetic solids are used.

However, this statement is not supported by any experimental data published in the literature. No experimental data concerning mixtures are available in the literature, so this problem has not been investigated and further studies should address such operations.

- The *continuous mode compared to the On-Off one* allows *more efficient independent control* of the particle hold-up at any stage. Hence, changes in gas flow rate can be achieved resulting in *optimized aeration conditions* of staged fluidized beds.
- *Synchronization* of staged MDD eliminates upsets to lower stages if large leaks of the top stage occur.

The study of Levien and Al-Zahrani (1991) is a good example of the implementation of a *process engineering approach* to the fluidized bed control. In fact, this approach has not been applied in other studies on MSBs in either a batch-solids or a continuous flow mode. This fruitful methodology could be developed for future mass and heat transfer applications of MSBs irrespective of process design. The simplified model of stage dynamics developed by the authors exhibits flexibility, so future efforts should address to *dynamic models and simulations* of MSB of both *batch and multistage designs*.

IV. MAGNETIC ELEVATORS FOR PARTICLES

IV.1. Introductory comments and a motivation for this section

In the preface of the review series two types of fluidization with participation of an external magnetic field are defined:

- *Magnetic-field assisted fluidization (MFAF)*. The fluidization energy is introduced by the flowing fluid while the magnetic field affects mainly the interparticle interaction. This generally implies the application of “static” (steady) or time-variable fields homogeneous fields with relatively weak ponderomotive magnetic forces. **MFAF** is discussed in almost all reviews.

- *Magnetically driven fluidization (MDF). The fluid is relatively passive and no fluid drag forces create particle motions. The fluidization is caused by an external magnetic field. This type of fluidization suggests application of time-variable and space-variable fields generating strong ponderomotive magnetic forces, i.e. fields with strong gradients $gradH$.*
A special part dedicated to problems of **MDF** will be published at the end of the review series for a unity of review.

The present chapter addresses magnetic elevators. These devices occupy an intermediate position, between **MFAF** and **MDF**, but they have multistage beds discussed before. The groups of Jaraiz and Levenspiel developed these elevators parallel to **MVS** and **MDD**. Completeness of the explanation requires these devices to be analyzed and compared with those already discussed in the present paper.

IV.2. Main idea, basic concepts and configurations

The development of multistage magnetically controlled beds requires recirculation systems, similar to the continuous countercurrent beds discussed at the beginning of the paper. Generally, the recirculation systems are pneumatically designed risers. The main idea of the magnetic elevators of particles (**MEP**) is to replace the transporting gas by magnetic forces distributed along the recirculation leg of the contacting system. The abbreviation MEP was introduced by Wallace et al. (1991) and is also used in the present paper. The illustrations in Fig. 59 and 60 show two basic investigated ideas. The idea of Wallace considers a system without pneumatic leaks and energized only from electric sources, which might be an advantage in *zero and low-gravity applications*. On the other hand, more realistic *terrestrial applications* follow from the concepts of Jaraiz (1990), Macias-Machin and Henriquez (1997, 1998). Both devices are moving bed heat exchangers with *magnetically driven recirculations* of the solids.

According to the scheme of Wallace et al. (1991), the magnetic “riser” has two regions. In the *catchment region*, a small amount of particles is accumulated inside the first coil of the chain. Consequently, they aggregate and form an *annular clump* within the tube. The *clump* can be transported up as a *compact magnetic mass* by lifting forces created by the magnetic field of the upper coils. The elevator resembles a linear reluctance motor. The coils have to be *switched on* for short times, subsequently starting from the lowest

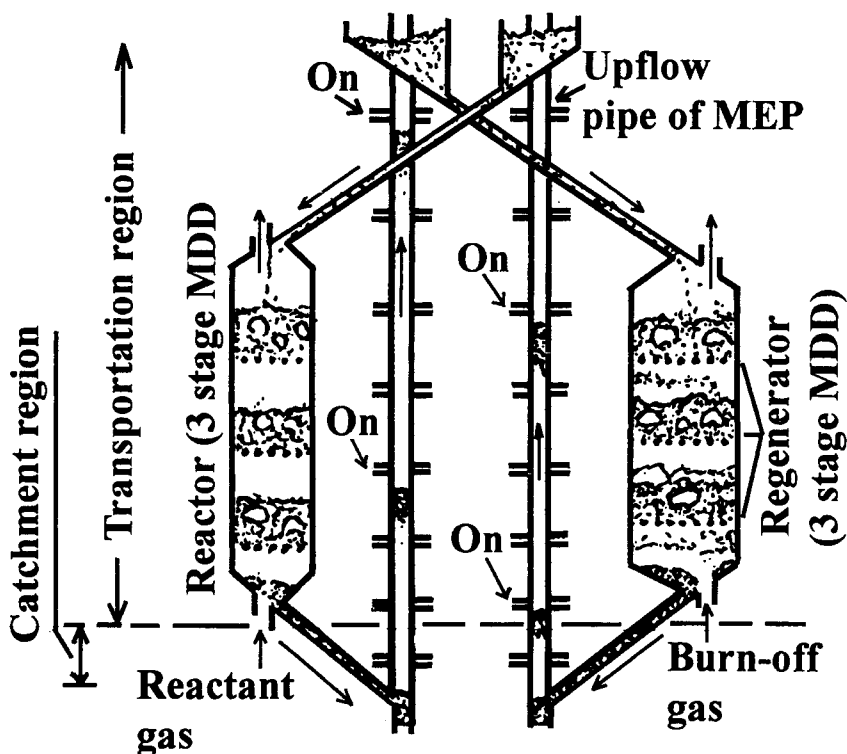


Fig. 59: Particle recirculation system proposed by Wallace et al. (1991) without pneumatic or hydraulic elements.

and finishing with the top coil and again from the bottom placed one. Considering the fields of two neighbouring coils, when the lower is *switched off* and the upper is *switched on*, there is a *pseudo-continuous* magnetic field zone that *runs upwards as a wave*. Besides, the overlapping of the neighbouring magnetic pulses is necessary since it leads to important consequent phenomena: i) the field intensity is strong enough to form a particle clump and ii) strong field gradients that to pull it up through the channel.

IV.3. Experimental tests

Wallace et al. (1991) tested the idea with a 1-in tube riser. The experimental details are summarized in Table 20. The main investigations

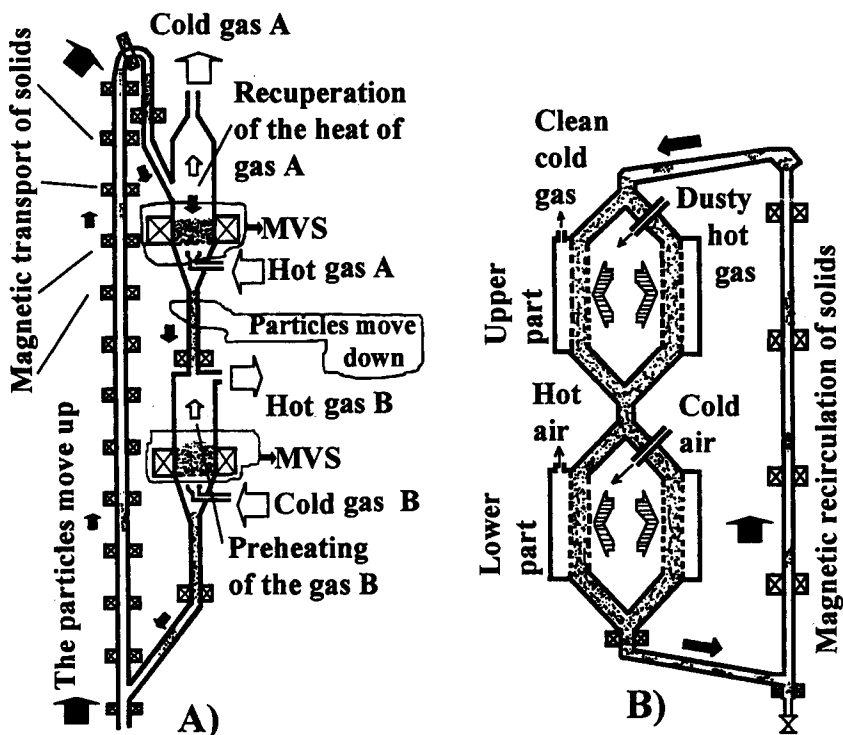


Fig. 60: Heat exchangers based on magnetic elevators of solids.

- a) Two-stage heat exchanger based on MVS with a magnetically-driven recirculation of particles. From Jaraiz (1990). The present author replaced all the Spanish labels with English texts.
- b) Heat exchanger developed by Macias-Machin and Henriquez (1997, 1998).

addressed:

- Minimum coil current required ;
- Energization "on" time;
- "Overlap" time between the adjacent coils;
- Effect of the coil spacing;
- Effect of the particle size.

Table 20
Experimental condition of Wallace et al. (1991).

Elevator elements	Main details	Comments	Data source of comments
Tube	1-in (25.4 mm)	No data about the length are available. I can suggest that the total length ≈ 762 mm	Original paper <i>Maximum coil pitch</i> x coils = $2 \times 25.4 \times 15 \approx 762$ mm
Coils 16 coils	700 turns 22 wire gauge 17 mH inductance 2.85 resistance	No data about the coil geometry are available	There is a conclusion that for the catchment region the coil length should be equal to the coil diameter ("square" design according to these authors)
Current	$3.5 \leq I \leq 5.7$ A	Personal computer controlled switches with free-wheeling diodes across the MEP coil for protection during the OFF period. Basic or Fortran codes	Original paper
Magnetic particles	Hydrogen-reduced sponge iron powder (Pyron Corp.-R12) True density = 7850 kg/m^3 Sponge form apparent density = 1300 kg/m^3 Purity = 97 % iron Currie point is about 770°C	No detailed granulometric data about are available. Tentative particle size, $0.25 \leq d_p \leq 0.75$	Fig. 62c here and Fig. 9 of the original work

The efficiency of the elevator was defined as

$$\eta = \frac{\text{gain in potential energy}}{\text{electrical energy input}} = \frac{\Delta E_p}{\Delta E_e} \quad (74a)$$

The potential energy gain of m mass of particles elevated to a height $L_{transport}$ is

$$\Delta E_p = mgL_{transport} \quad (74b)$$

while the electric gain is the total power ($P = U_e I$) introduced in n coils during the energization time, T_n , i.e.

$$\Delta E_e = \sum_{n=1}^{n=16} U_e^n I_n T_n \quad (74c)$$

The main energy losses of **MEP** are due to coil electrical resistance and mechanical friction (Wallace et al., 1991). The first loss could be minimized through an efficient coil design. On the other hand the short coil design employed leads to strong lateral gradients. The latter pull the particles towards the channel wall, thus increasing the dry Coulomb friction of the moving clump. For instance, if the *field is axial and homogeneous*, the field forces will compress the particle clump along the channel radius that leads to *minimum friction at the wall*. In the opposite case of a *transverse field*, the field will extend the particle mass along the radius and consequently *the friction at the wall will increase*. Fields generated by short coils hold intermediate positions, so the friction at the wall depends on the product $H \text{ grad } H$.

Both the current waveforms of two adjacent coils (Fig. 61a) and pulse magnitude have to create a sufficient vertical field gradient. The plot in Fig. 61b shows that, for the particular design, reproducible operations are available when $I > 3A$ during 0.3 s *ON-time* and the overlap time of the pulses is of about 0.1 s. The magnetic pulse parameters indicate that above threshold timing (from 0.1 to 0.2 s) the **MEP** efficiency, measured via the mass of particles elevated, reaches almost a *saturation level* (Fig. 62a). The magnitude of this saturation depends *only on the pulse magnitude* (current intensity). In this way, Wallace et al. (1991) confirmed the well-known

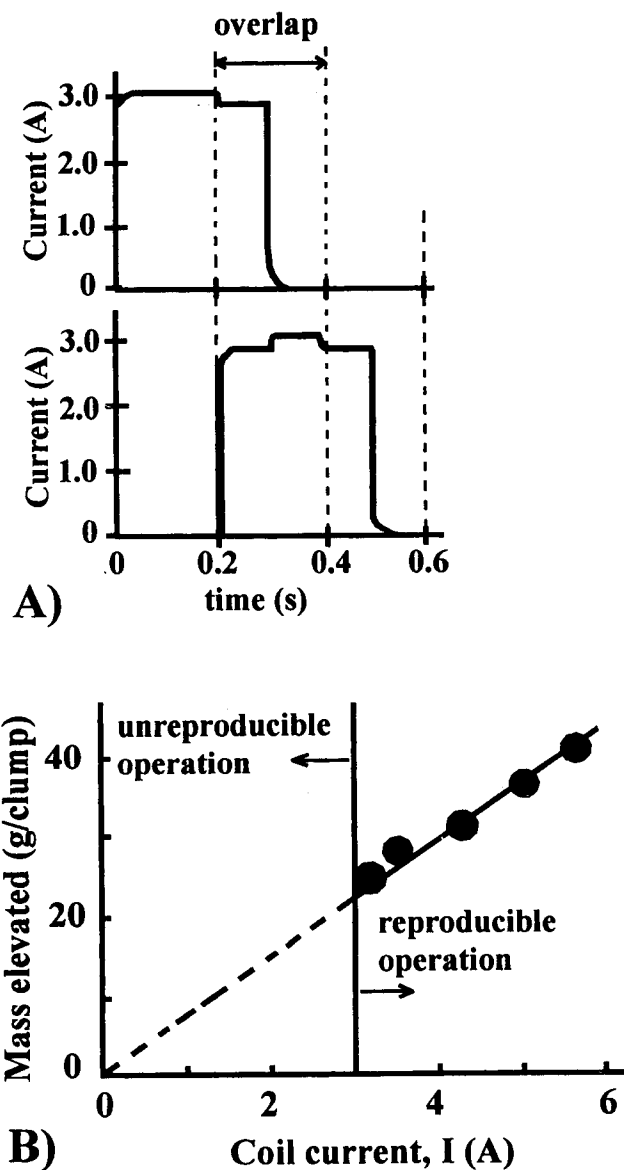


Fig. 61: Magnetization pulse parameters creating reproducible particle mass elevation. From Wallace et al. (1991)

- Current pulse shapes of two adjacent coils with a time overlap.
- Current magnitude effect on stable clump formation for 0.75mm particles.

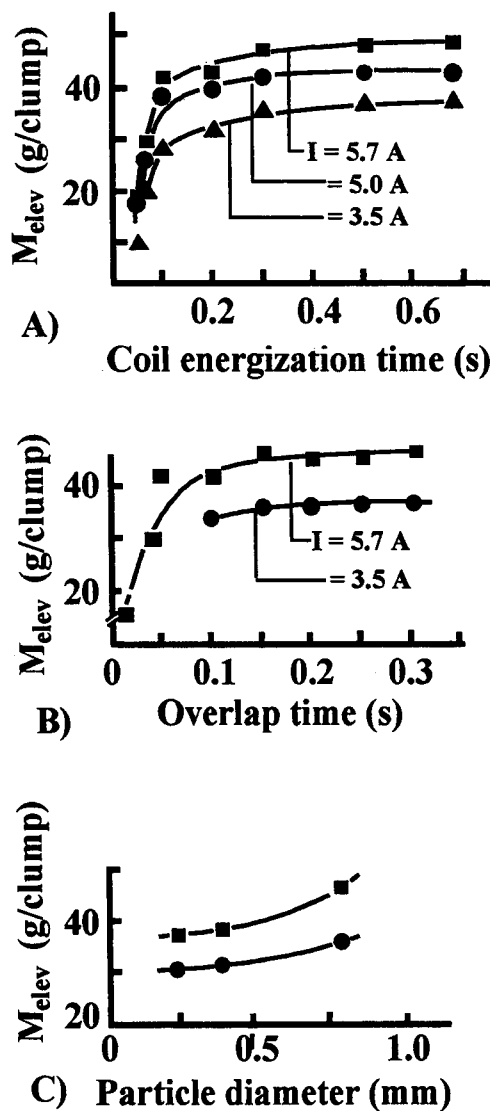


Fig. 62: Efficiency of the transport process as a function of the magnetization condition and the particle properties. From Wallace et al. (1991)

- Time pulse duration effect on the mass of elevated particles (for 0.75 mm particles).
- Overlap time effect on the mass of elevated particles (for 0.75mm particles).
- Particle size effect on the mass of elevated particles.

information from synchronous electric machines that the particle *travel time is independent* of the current magnitude. However, the *mass of particles* (the mass of the clump) attracted by the coils *depends on the current magnitude*. Variations of the overlap time leads to a similar behavior, i.e. there is a saturation zone (Fig. 62b) affected by the current magnitude only. A decrease in the overlap time (lower left corner of the graphs) leads to unstable particle clumps. Alternatively, movement towards the upper right corner of the graph implies extended overlaps of the magnetization pulses, maintaining clumps stable between the coils.

In general, the particle clump should not be affected by particle size. However, Fig. 62c shows that the mass of elevated particles increases as the particle size is increased. Wallace et al. (1991) did not explain this fact. However, the two lines in Fig. 62c are strongly related to the *particle flocculation* discussed in Part 1. At fixed field intensity, the “*flock size*” (i.e. the clump mass at certain particles sizes) depends on the particle diameter, but not on the particle mass. If we have two disperse systems (with two different particle sizes) the aggregates formed in them will be statistically identical – considering flock shapes and the number of particles aggregated. Nevertheless, the *aggregates* of the coarser system will be *larger and heavier*, since both particle volume and mass (e.g. the clump’s volume and mass) *scale to* $(d_p)^3$, which explains the results of Wallace et al. (1991).

IV.4. Design concepts

The design concepts of the elevator consider both the coil design and the coil arrangements along the vertical channel. The general requirement is to guarantee a *continuous clump formation* during its travel between two adjacent coils. This implies that along the “clump route” the field intensity should be maintained at a value that assures: i) clump formation; ii) clump maintenance and mechanical *stability* during the lift; iii) forces sufficient to create clump *vertical motion*. These requirements address two important geometrical factor of the elevator:

- 1) *Catchment spacing*.
- 2) *Coils pitch* – the vertical distance between the coil centres in the transportation region.

Effects of these factors are shown in Fig. 63. According to Wallace et al. (1991), catchment efficiency drops significantly if the particles that must be attracted are at a distance exceeding one tube diameter from the first catchment coil (Fig. 63a). After starting of the transportation process, the coil pitch could be increased to 2 tube diameters (Fig. 63b).

As stated earlier, the field forces acting on the particles (see Eq. (26) and Eq. (33)) are proportional to the generated field gradient as well as the particle magnetic properties (see Eq. (26) and Eq. (29)). Thus, expressing a relationship through the field induction, B (Wallace et al., 1991) we have:

$$\begin{array}{ll} \text{Particle-to-particle forces} & \\ \text{(clump formation)} & \Rightarrow F_p = K_1 d_p B^2 \end{array} \quad (75a)$$

and

$$\begin{array}{ll} \text{Particle-to-coil force} & \Rightarrow F_{coil} = K_2 H \frac{dB}{dx} \end{array} \quad (75b)$$

where K_1 and K_2 are prefactors.

The applications of Ampere's law (Eq. 31) to the design concept, illustrated in Fig. 63 (see the inset), gives for the **catchment region**

$$H_{axial} = \frac{NI}{2\pi x} = \frac{NI}{2\pi \sqrt{r^2 + h^2}} \quad (76a)$$

where x is the field axial co-ordinate of the coil, while for a coil element Δ , the field is

$$H_\theta = \frac{NI}{2\pi} \frac{1}{\sqrt{(2r - r \cos \theta)^2 + h^2}} \quad (76b)$$

The complete field determination implies integration around the complete coil, i.e.

$$H_{coil} \equiv \int_{\text{complete coil}} H_\theta \equiv \int_{0 < \theta < 360^\circ} H_\theta \quad (77)$$

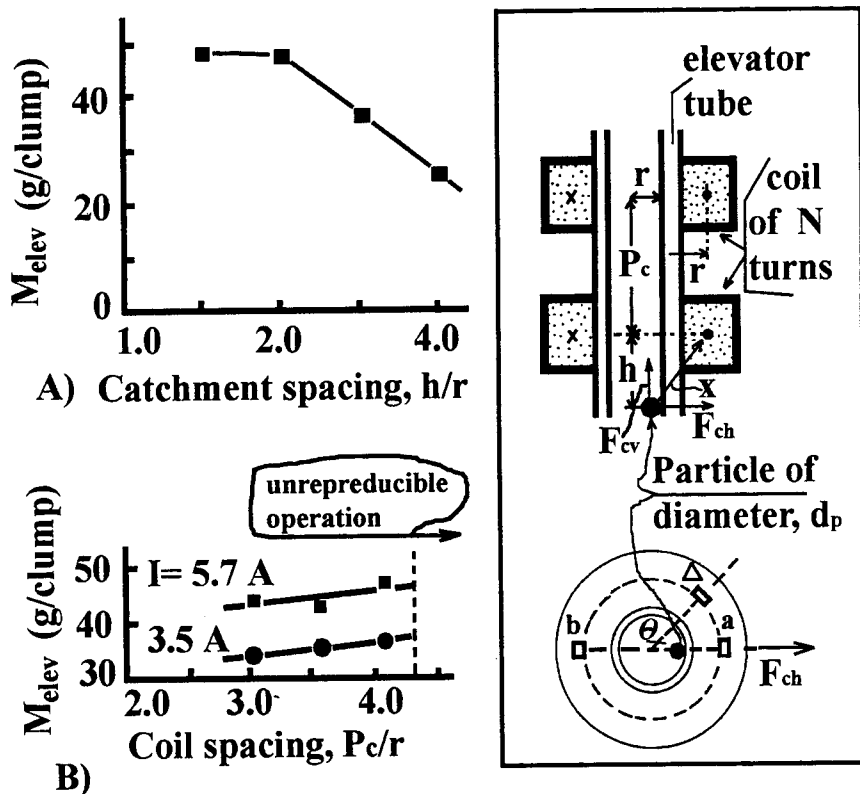


Fig. 63: Experimental adjustment of the elevator design expressed through the coil spacing of both regions of the transportation tube. From Wallace et al. (1991).

- Mass elevated as a function of the relative catchment spacing, h/r (see the definition of h and r in the Inset).
- Mass elevated as a function of the relative coil spacing in the transport region, expressed through the relative coil pitch, P_c/r (see Inset)

Inset: geometrical configuration of the MEP design.

The **transport sector** needs a more detailed analysis, but this is beyond the scope of the present review. Generally, the particle clump affects the coil inductance, L_{ind} and, consequently, its reluctance (a magnetic body inside a coil increases its inductance), so $L_{ind} \equiv L_{ind}(h)$. Thus the lifting force acting on a particular clump $F_{elevating}$ is (Wallace et al., 1991)

$$F_{elevating}(h) = \frac{1}{2} \frac{dL_{ind}(h)}{dh} I^2 \quad (78)$$

It should be kept in mind that $F_{ponderomotive} \sim HgradH \sim H^2 \sim I^2$ (Eq.75 and Ampere's law)

Jaraiz (1990) performed a detailed study in a similar way. His results can be outlined as follows:

- 1) The value of $H_G = \frac{1}{2} grad(H^2)$ and the consequent forces acting on the particles increase when the coil has *more layers* and *less wire turns per layer*. Thus, *shorter coils with larger external diameters* are more effective.
- 2) The impulse time decreases as the attracting force ($\sim I^2$) increases. The force-time product = (**Force**) x (**Time of impulse**) is relatively small, while the force is large. Jaraiz decided that the optimization problem based on the *force-time product* should be solved to define the *maximum lifting force*

This short section of the review closes the analysis of both the magnetic control and the transport of particles in ducts. The results are far from generalizations and more of them require detailed analysis. This offers a large area for further research concerning: different design concepts, scale-up analysis, simple dynamic models, etc.

V. DIMENSIONAL ANALYSIS AND SCALING APPLIED TO SOME PROBLEMS

A multitude of experimental data and correlations discussed in the preceding sections motivated this chapter of the paper. In fact, magnetically assisted fluidized beds have been objects of dimensional analysis and scaling. The use of dimensionless numbers is concentrated mainly on the particle Reynolds number in some hydrodynamics studies (see Part 1) or the Nusselt number in heat transfer processes (see Part 3) unlike the classical non-magnetic fluidization and the two-phase flow problems. Problems concerning model build-ups will be discussed in a separate part of the review series, but the following comments focus on two classical approaches of engineering dimensional analysis (Bridgman, 1951; Kline, 1965, Massey, 1971) that can be applied to moving MSB:

- Inspectional analysis of constitutive equations describing processes,
- Dimensional analysis in its classical “blind” form applied to complex processes without models.

Prior to discussion of the topic, we should explain why dimensional analysis was not applied in previous chapters with respect to the particular problems reviewed. The answer is straightforward. The tools of the dimensional analysis were not used in the original studies – this was the reason for the extensive particular correlations without any systematization. Moreover, the previous sections presented problems as developed by different research groups, irrespective of data arrangements and discussions following the point of view of the present author.

This section tries to extract more information existing in the original papers and to present it in a comprehensive form. In fact, it is an original study oriented towards systematization of information through the methods of dimensional analysis. The results commented on before are used *as raw data*. The only objectives of this study are: i) Forming a compact presentation of the results of moving MSBs. ii) Formulation of new problems.

V.1. Inspectional Analysis of Crossflow MSB

The inspectional analysis employed here follows the classical approach of nondimensionalization of the constitutive equations creating the model (Kline, 1965; Massey, 1971). Classical examples of that approach consider

fluid flows in pipes and channels (Denn, 1980; Pnueli and Gutfinger, 1992). In the case of moving MSBs, there are two problems that permit such an analysis: i) Tilted-channel crossflow MSB. ii) Carrousel cross flow MSB.

V.1.1. Inspectional analysis of tilted channel crossflow MSB model

The force balance presented by Eq. (6) considers one-dimensional gravity-driven flow with terms presenting both the bed thickness and the velocity profile along the channel axis. It is a relatively simple problem and the attention will be focussed on the fluidized bed longitudinal profile dh/dl – see Eq. (7). The first step is to define the characteristic scales. However, the process has no natural *characteristic velocity* or *characteristic length* in the vertical (y) direction – see Fig. 17 and Fig. 21. The model developed by Cheremisinoff et al. (1985) uses the bed hydraulic diameter D_H as a length scale. However, it is dependent parameter since it is a function of bed thickness, h through the relationship (7b) as in a classical problem of an *open channel flow*. Therefore, we look for velocity and length scales, U_0 and l_0 , that should be specified. Hence, we have two dimensional variables:

$$U^* = U_{sm}/U_0, \quad l^* = l/l_0 \quad (79)$$

Thus, Equation (7a) can be expressed in a dimensionless form as

$$\frac{dh}{dl} = - \frac{\frac{32}{\text{Re}_0} \left(\frac{L_0}{D_H} \right)^2 U^* + \sin \alpha}{1 - \frac{(U^*)^2}{\beta_c h^*} \frac{U_0^2}{gl_0}} \quad (80)$$

The *channel Reynolds number* $\text{Re}_0 = (\rho U_0 l_0 / \mu_e)$ is the dimensionless group controlling the process. The development of Eq. (80) requires some simple tricks: $h = h(l)$, so $dU/dl = (dU/dh)(dh/dl)$ and $dU/dh \equiv U/h$ (see the denominator of (7a)). The denominator of (80) shows how to define both the *velocity and length scale*: Setting the term U^2/gl_0 equal to unity we define the velocity scale as $U_0 = \sqrt{gL_0}$, so the dimensionless velocity is $U^* = U_0/\sqrt{gl_0}$, where $l_0 = L_0$ (channel length). The group $\sqrt{gL_0}$ is a typical velocity scale for gravity driven and buoyancy-dominated fluid

motions without defined momentum fluxes. Therefore, the dimensionless bed profile (80) is:

$$\frac{dh}{dl} = - \frac{\frac{32}{\text{Re}_0} \frac{1}{C_0} U^* + \sin \alpha}{1 - \frac{(U^*)^2}{\beta_c h^*}} \quad (81)$$

The prefactor $1/C_0 = (L_0/D_H)^2$ is a ratio of two length scales – a longitudinal macroscopic one and that describing the fluid flow through the particle bed. Besides, the product $\frac{32}{\text{Re}_0} \frac{1}{C_0}$ is the bed friction factor. Since for crossflow bed D_H varies along the channel (see Eqs. (15) and (19a), the friction factor depends on bed thickness.

Let us perform order-of-magnitude analysis and asymptotic scaling. Velocities (see Figs. 18a, b) in both the vertical and axial direction vary within the range of $(10\text{--}15) \cdot 10^{-2}$ m/s, while the bed thickness is approximately $(1\text{--}5) \cdot 10^{-2}$ m. The term β_c depends on bed rheology. The expression (16b) and the data derived here (see Fig. 24) indicate that

$$\beta_c = \frac{(2n+1)(5n+1)}{3(3n+1)^2} = 1.13 \div 1.3$$

where $0.5 \leq n \leq 5.5$. Thus, we can accept that $\beta_c \approx (1)$ facilitates the analysis. Hence, for *thick beds* (and *stronger fields*) in the channel entrance section, the denominator of (81) is $\left(1 - (U^*/h^*)U^*\right) \cong 1$, since the gradient $(U^*/h^*) \cong 0$ due to almost flat velocity profiles – see the profiles in Fig. 27, a, b. This permits us to express (81) (suggesting small variations of $1/C_0$) as:

$$\frac{dh^*}{dl^*} = - \frac{32}{\text{Re}_0} \frac{1}{C_0} U^* + \sin \alpha \quad (82a)$$

with the boundary condition $(h^*)_0 = (h_0/L_0)$ at $l^* = 1$ (at $l = L_0$) defined by both the weir and channel end. The solids mass flow rate defined by Eq. (8) permits the dimensionless bed depth profile to be expressed as a linear function

$$h^* = \left(\frac{32}{\text{Re}_0} \frac{1}{C_0} U^* + \sin \alpha \right) \left(1 - \frac{l}{L_0} \right) + (h^*)_0 \quad (82b)$$

The profiles plotted in Fig. 26 confirm the negative slope

$$-f(\text{Re}_0, U^*, \sin \alpha) = \frac{1}{L_0} \left(\frac{32}{\text{Re}_0} \frac{1}{C_0} U^* \right) \quad (82c)$$

- ❖ **An idea for an MSB viscometer.** Equations (82a, b) offer a possibility to create an open channel viscometer like those developed for non-Newtonian viscoelastic fluids (see Macosko, 1994). The idea considers measurements of bed depth (i.e. the walls should be transparent) at several positions along the channel. Equation (83a) can be presented as

$$h^* = \left(\frac{1}{\text{Re}_0} \right) A + B, \text{ where } A = \frac{32}{C_0} U^* \text{ and } B = \sin \alpha + h_0^* \quad (83)$$

Several measurements at fixed positions and subsequent regression analysis could provide values of $1/\text{Re}_0$ and bed effective viscosity as functions of macroscopic variables such as Q_s , U/U_T , $\sin \alpha$ and h_0 . Alternatively, it is possible to vary the angle α with subsequent measurements of h^* at fixed positions along the channel. In fact, this is a more general idea for a fluidized bed viscometer, since the field does not appear as an explicit controlling parameter in (82) and (83). The author hopes that colleagues will test this idea experimentally.

- **Comparison with the experimental data**

The average bed depth (along the channel) is

$$\bar{h} = \frac{1}{L_0} \int_0^{L_0} h(l) dl = \frac{1}{2} \left(\frac{32}{\text{Re}_0} \frac{1}{C_0} \frac{U}{\sqrt{gL_0}} + \sin \alpha \right) L_0 + \frac{h_0}{L_0} \quad (84a)$$

$$\text{i.e. } \bar{h} = f(\text{Re}_0^{-1}, U^*, \sin \alpha) \quad (84b)$$

The form (84b) allows simple dimensionless engineering correlations.

Two macroscopic factors that strongly affect the flow are not explicitly incorporated in the equations. These factors are *the field intensity* and the *gas fluidization velocity* and they control both the *effective bed viscosity* μ_e and *Reynolds number*. The increase in the channel Reynolds number implies that the effective viscosity μ_e decreases or the bed density increases if all other parameters remain unchanged. Bed-effective viscosity is a more important parameter than bed density.

The theoretical bed longitudinal profile and the experiments of Cheremisinoff et al. (1985) require a comparative analysis. Its main results can be outlined as follows:

- Equation (84a) defines a linear relationship between average bed height and the angle α (since at small values of α , $\sin \alpha \approx \alpha$), which is confirmed by the data in Figs. 18a,bd
- The dimensionless velocity $U^* = U/\sqrt{gL_0}$ is in fact a dimensionless solids throughput rate. The plots in Fig. (18b) exhibit a weak effect of U^* on practically linear profiles (Eqs. 84 predicts them). This fact could be attributed to the decreasing value of $C_\theta = (D_H/L_0)^2 = (1/L_0)^2 [4(bh/b+h)]^2$. With increasing bed velocity, the bed thickness should reach a maximum value defined by both the weir design and the solids throughput rate.
- Increasing the field intensity leads to a low mobility of the solids and a high effective viscosity μ_e . Assuming all other parameters unchanged, the average bed depth is a linear function of the effective viscosity, i.e.

$$\bar{h} \sim 1/\text{Re}_0 \sim \mu_e \equiv \mu_e (H, U/U_T) \quad (85)$$

Shear-thinning behavior (Cheremisinoff et al., 1985 and Fig. 24b here) exhibited by beds (i.e. so $\mu_e \sim 1/H$) is stronger at low shear rates (see also Fig. 23). At high shear stresses this effect is negligible (the lower plot in Fig. 24b). Despite the small disagreements between bed depth evolution and shear thinning behavior, the growing bed depth in Fig. 18c could be attributed to decreasing bed densities since at stronger fields the structure of beds becomes looser.

➤ Increasing gas velocity leads to increased particle mobility and compensates the field intensity effects (Fig. 18d). The latter implies a higher gas velocity and consequently lower bed viscosities, lower bed densities, higher Reynolds numbers *and thinner beds* (see also Fig. 18b).

• **Some problems emerging from the inspectional analysis**

The inspectional analysis identified some problems that will be outlined briefly:

➤ The inspectional analysis identifies the channel Reynolds number as a controlling dimensionless group. It includes the effective bed viscosity *depending on the experiments, so Re cannot be defined as an independent variable*. This indicates that an iterative numerical solution similar to that performed by Cheremisinoff et al. (1985) should be performed. A similar problem exists with Eq. (16a) where the nonlinear term (see Eq. 81) is:

$$\frac{2K}{\rho gC} \left(\frac{3n+1}{n} \right)^n U_{sm}^n \equiv \frac{32}{Re_0} \frac{1}{C_0} U^* \quad (86)$$

The nondimensionalization of the vertical velocity profile equation (Eq. 17) identifies the same dimensionless group. In this case Re includes effects of both the field intensity and the gas velocity through the ratio $(3n+1)/(n+1)$. The exponent $(n+1)/n$ complicates the problem too.

➤ The problem studied by Cheremisinoff et al. (1985) permits an alternative analysis based on falling film flow analogy. An axial field applied to channel flow is parallel to the gas velocity and the vertical channel walls. Thus, such a field compresses the bed inward the channel and extends it along the vertical axis (Part 1). This action decreases friction forces at the channel walls and increases friction at the distributor surface. These circumstances allow us *to omit the channel flow analogy* (the tube flow analogy too) and to apply the well-known analysis of *gravity driven film flow* along an inclined plate.

According to Pnueli and Gutfinger (1992), the steady state Bingham flow in one-dimensional form (following the scheme in Fig. 21) could be expressed as.

$$0 = \rho g \sin \alpha + \frac{\partial \tau_{yx}}{\partial y} \quad (87a)$$

Cross flow MSBs do not form steady state bed depths, so the correct force balance is

$$U \frac{\partial \rho U}{\partial x} = \rho g \sin \alpha + \frac{\partial \tau_{yx}}{\partial y} \quad (87b)$$

similarly to Eq. (6) developed by Cheremisinoff et al. (1985). A steady state equation (87a) yields:

$$(\rho g \sin \alpha) \delta = -\tau_0 + \mu \left(\frac{\partial U}{\partial y} \right) \text{ for } |\tau| > \tau_0 \quad (88)$$

$$\text{and } \frac{\partial U}{\partial y} = 0 \quad \text{for } 0 \leq \tau \leq \tau_0$$

Here, δ is the film flow thickness and $\tau_0 = \tau_y$ employed by Eq. (14). This permits the maximum thickness $\delta_{\max}$ to be obtained (for $\tau = \tau_0$ and $\partial U / \partial y = 0$)

$$\delta_{\max} = \frac{\tau_0}{\rho g \sin \alpha}. \quad (89)$$

Despite the fact that (88) is a *very strong simplification* of the problem, the value of $\delta_{\max}$ defined by (89) could be employed as a *length scale* in a direction transverse to the fluid flow. Some data concerning τ_0 , relevant to the experiments of Cheremisinoff et al. (1985) are available in Fig. 23. A detailed study via boundary layer analysis of a power-law fluid with L as longitudinal flow length scale (Pnueli and Gutfinger, 1992) yields

$$\text{Re} = \frac{L^n U^{2-n} \rho}{K} \quad (90)$$

Here, the viscosity is represented by $K \left| \frac{\partial}{\partial y} \left| \frac{\partial U}{\partial y} \right| \right|^n$. The last expression confirms again the value of the Reynolds number as a flow-controlling

parameter. It is a dependent parameter since it cannot be defined before the experiment due to the complex nature of the consistency index K and the exponent n . Both parameters are complex functions of gas velocity and field intensity. The engineering analysis needs clearer forms of dimensionless groups controlling solids behavior in a tilted channel crossflow MSB.

Non-dimensionalization of Eq. (87) with two length scales – longitudinal L and transverse $\delta_{\max}$ – provides two dimensionless groups: Reynolds and Froude numbers

$$\text{Re}(\delta_{\max}) = \frac{\rho U_0 \delta_{\max}}{\mu},$$

$$\text{Fr} = \frac{U_o^2}{gL}$$

Since the velocity scale is unknown, the classical way is to define the Galileo number in the specific form $\text{Ga} = \frac{\rho^2 \delta_{\max}^2}{\mu^2} gL$. If the steady state equation (87) is considered, there is only one length scale $\delta_{\max}$ and the Galileo number takes its classical form $\text{Ga} = \frac{\rho^2 \delta_{\max}^3}{\mu^2} g$. Formulation of the Galileo number permits us to look for correlations $\text{Re}(\delta) = f(\text{Ga})$ similar to those employed in free settling of particles. Such correlations have not yet been developed. Despite this, the above comments show the way how to do this in future investigations.

V.2. “Blind” dimensional analysis of crossflow and counter-current MSB

V.2. 1. Crossflow MSB (tilted channel and carrousel devices)

The term “blind” implies that the approach does not specify the complete number of the controlling factors and there are no models permitting non-dimensionalization (Langhaar, 1951, Bridgman, 1978, Isaacson and Isaacson, 1975). Despite this, the experimental data reviewed and the inspectional analyses performed above identify the variables (quantities) (following Sonin, 2001):

Independent quantities (in SI units):

Solids flow rate	Q_s	[kg/s]	MT^{-1}
Solids density	ρ_s	[kg/m ³]	ML^{-3}
Gravity acceleration	g	[m/s ²]	LT^{-2}
Channel length	L_0	[m]	L
Channel width	b	[m]	L
Field intensity	H	[A/m]	AL^{-1}
Gas velocity	U	[m/s]	LT^{-1}

and a **dependent quantity**: bed depth $[h] = L$

The use of [A/m] as a dimension of the magnetic field intensities gives rise to a complicated situation since physically the dimension of current [A] is a derived unit (electric charge per time) (Sonin, 2001). In order to avoid further complications and to arrange all the problems within the basic MLT units, the following rearrangement of the quantities is possible:

Independent quantities (in SI units):

Solids flow rate	Q_s	[kg/s]	MT^{-1}
Solids density	ρ_s	[kg/m ³]	ML^{-3}
Gravity acceleration	g	[m/s ²]	LT^{-2}
Channel length	L_0	[m]	L
Channel width	b	[m]	L
Dimensionless field intensity	H/M	[-]	1
Dimensionless gas velocity	U/U_T	[-]	1
Channel inclination	$\sin \alpha$	[-]	1

In addition, the dimensionless bed depth ($[h/L_0] = 1$) is introduced as a **dependent quantity defined by inspection**. This approach significantly simplifies further formation of dimensionless groups.

The following analysis will be written simply by inspection through omitting formal algebraic methods (Langhaar, 1951, Bridgman, 1978, Isaacson and Isaacson, 1975). The first four parameters form two independent dimensionless similarity parameters

$$\Pi_1 = \frac{Q_s}{\rho L_0^2 \sqrt{gL_0}} \quad \text{and} \quad \Pi_2 = \frac{b}{L_0} \quad (91a)$$

Simple manipulations of Π_1 and Π_2 form a unique independent dimensionless group

$$\Pi = \frac{\Pi_1}{\Pi_2} = \frac{Q_s}{\rho b L_0 \sqrt{gL_0}} \quad (91b)$$

Therefore, the dimensionless bed thickness could be expressed as

$$\frac{h}{L_0} = f \left(\frac{Q_s}{\rho b L_0 \sqrt{gL_0}}, \sin \alpha, \frac{H}{M_s}, \frac{U}{U_T} \right) = \left(\frac{Q_s}{\rho b L_0 \sqrt{gL_0}} \right)^{P_1} (\sin \alpha)^{P_2} \left(\frac{H}{M_s} \right)^{P_3} \left(\frac{U}{U_T} \right)^{P_4} \quad (92)$$

Unfortunately, the blind dimensional analysis does not specify the form of the function f . Further data treatment will not be performed here (there is a deficiency of data in the experiments reported by Cheremisinoff et al., 1985), but some physical facts will be discussed:

- Bed depth increases as the solids flow rate is increased, so concerning the denominator of $\Pi = const.$, the exponents P_1 should be relatively small and positive (Fig. 18b).
- The dimensionless field intensity (H/M_s) is relatively small (of the order of magnitude of $10^{-2} \div 10^{-3}$) for the materials employed in MSB at $H < 50$ kA/m (see Hristov, 1996, 1998b and Part 1). Thus, the exponent P_3 should be relatively high and positive.
- Both the channel inclination (through $\sin \alpha$) and fluidization velocity (through U/U_T) lead to a decrease in bed depth. Therefore, it might be expected that both exponents, P_2 and P_4 , will be negative.
- Therefore, the expressions (91)–(92) operate with macroscopic parameters only and avoid the problem due to the complex behavior of the bed viscosity. Additionally the denominator of (91) defines the scale of solids mass flow as $Q'_0 = \rho b L_0 \sqrt{gL_0}$.

V.2.2. Countercurrent MSB

The countercurrent MSBs (see II.2.) have several controlling parameters:

Independent quantities (in SI units):

Solids flow rate	Q_s	[kg/s]	MT^{-1}
Solids density	ρ_s	[kg/m ³]	ML^{-3}
Gravity acceleration	g	[m/s ²]	LT^{-2}
Column diameter	D	[m]	L
Bed depth	h_b	[m]	L

Dependent quantity:

Dimensionless gas velocity	U/U_T	[-]	1
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A simple approach like that in the case of crossflow MSB yields:

$$\Pi = \frac{Q_s}{\rho h_b D \sqrt{gD}} \quad (93a)$$

Incorporating the ratio $\frac{H}{Ms}$, defined by inspections, we have

$$\frac{U}{U_T} = f \left(\frac{Q_s}{\rho h_b D \sqrt{gD}}, \frac{H}{Ms} \right) \quad (93b)$$

The form of the function f is unknown. According to the experiments performed by Siegel and Coulaloglou (see Fig. 5) it is possible to keep Q_s and the bed depth h_b unchanged, so the RHS of (93) depends only on the dimensionless field intensity H/Ms . On the other hand, considering the flow throughput rate as a *controlled parameter* (see Fig. 6), this will change the positions of Π and the dimensionless velocity, so we have:

$$\Pi = f \left(\frac{U}{U_T}, \frac{H}{Ms} \right) \quad (94)$$

This case is relatively simple, since both ratios of the RHS in (94) are interrelated, i.e. $U/U_T = \phi(H/Ms)$ due to interparticle forces not considered by the applied dimensional analysis. The flow scale is $Q_0^* = \rho h_b D \sqrt{gD}$, similar to Q_0^* defined above. The functional relationship

$\phi (H/Ms)$ can be defined by batch fluidization experiments (see Fig. 5 and related comments).

Further, concerning both the fluid and the particle properties, it is possible to derive the particle Reynolds or Galileo (Archimedes) numbers. In this case, the left side of (93b) could be expressed as a ratio of the corresponding Reynolds numbers, while the function f should concern the particle Galileo (Archimedes) number, as discussed for crossflow MSBs. However, this approach is formalistic, because in a stabilized bed *there are no separate particles*, but continuously changing *particle aggregates*. A similar approach could be applied to a countercurrent bed of admixtures, but the data available do not allow a detailed analysis. This is a problem for future investigations.

V.3. Dimensional analysis for MVS and MDD

V.3.1. Release current estimation (an example of a grate-type MVS)

The large body of data published by the Jaraiz group employed mainly simple force balances and the Ampere's law. An attempt to build up correlations based on a blind dimensional analysis approach faces the following quantities controlling the process:

- particle diameter, d_p ; - grade spacing, L_g ; -screen aperture, L_s ;
- magnetic field intensity, H (i.e. the current intensity, I) and
- the gravity acceleration, g

The problem mixes *magnetic* and *mechanical* quantities that could cause misunderstandings when expressing quantities through basic units. Let us simplify the problem and create a problem description by mechanical quantities only, so the MLT system that is more familiar to chemical engineers will be used. This approach leads to new quantities that relate to grate-type MVS design:

- Force created by the magnetic field, F_M
- Force created by the gravity field, F_g
- Volume of particles stopped by the field action, V_M
- Volume of particles stopped in the presence of gravity only, V_g

Looking for homogeneity of physical equations (Sonin, 2001), we have:

$$\frac{F_M}{F_g} = f \left(\frac{V_M}{V_g} \right) \quad (95a)$$

However, the function f is unknown. Both classical mechanics (Newton's law, $F = ma$) and magnetic field theory ($F = mH\text{grad}H$) provide linear relationships between forces and masses (volumes, respectively). Thus, we can assume a linear function by analogy

$$\frac{F_M}{F_g} = K_{DA} \left(\frac{V_M}{V_g} \right) \quad (95b)$$

where K_{DA} is a coefficient of proportionality.

- **Grate alone in the channel.** Let us express both sides of (95b) in more detailed forms. Assuming an MVS with a grate alone (Eqs. 22-23), we have:

$$\frac{F_M}{F_g} \equiv \frac{V_p k_\mu H \text{grad} H}{V_p \rho g} \equiv \frac{V_p k_\mu (1/r) (1/r^2)}{V_p \rho g} \equiv \frac{k_\mu}{\rho g} \frac{1^2}{r^3} \quad (96a)$$

$$\frac{V_M}{V_g} \equiv \frac{\text{volume of the aggregates}}{\text{volume of particles resting on the bars}} \equiv \left(\frac{d_{\text{aggregate}}}{L_g} \right) \sim O(1) \quad (96b)$$

A combination of both expressions (96) through the relationship (95b) yields:

$$1^2 \equiv \frac{\rho g}{k_\mu} r^3 \quad (97a)$$

Assuming the maximum field action at $r = (L_g/2)$ (the centreline between two grate bars), we have

$$1^2 \equiv \frac{\rho g}{k_\mu} \left(\frac{L_g}{2} \right)^3 \Rightarrow 1 \sim (L_g)^{\frac{3}{2}} \quad (97b)$$

In fact, the result (97b) is the main scaling relationship of Yang et al. (1982) (see Eq. (23)) concerning grate alone in a channel. The analysis uses $(d_{\text{aggregate}}/L_g) \sim O(1)$ in order to facilitate the estimates as well as to

demonstrate a manner of thinking similar to that of Jaraiz et al. Nevertheless, if we want to consider the particle diameter effect, some scales should be taken into consideration, i.e.:

$$O(1) \sim \left(\frac{d_{\text{aggregate}}}{L_g} \right) \equiv \left(\frac{d_p}{L_g} \right) \equiv \frac{k_\mu}{\rho g} \frac{I^2}{r^3} \quad (98)$$

In addition, $L_g / d_{\text{aggregate}} \equiv L_g / d_p \sim O(1)$, so we have

$$I^2 \equiv \frac{\rho g}{k_\mu} \left(\frac{L_g}{d_p} \right) \left(\frac{L_g}{2} \right)^3 \Rightarrow I \sim (L_g)^2 \sqrt{d_p} \sim \sqrt{d_p L_g} (L_g)^{\frac{3}{2}} \quad (99)$$

The result (99) differs from the scaling estimations derived by Jaraiz. The introduction of the ratio (L_g/d_p) followed from the present author's experience with semifluidized beds (See Hristov, 1998 and Part 2).

- **Grate with a screen below.** Let us now introduce a screen beneath the grate ($L_s \leq L_g$). Therefore, the ratio L_s/L_g can be introduced by inspection. The ratio of volumes (96b) could be expressed as

$$\begin{aligned} \frac{V_M}{V_g} &\equiv \frac{\text{volume of aggregates}}{\left(\text{volume of particles resting on the bars} \right)} \\ &\quad \left(\text{of both the screen and the grate} \right) \\ &\equiv \underbrace{\left(\frac{d_{\text{aggregate}}}{L_g} \right)}_{O(1)} \left(\frac{L_s}{L_g} \right) \equiv O(1) \left(\frac{L_s}{L_g} \right) \end{aligned} \quad (100)$$

Equating the groups defined by (95a) and applying the employed technique to the expression of (97), we have

$$I^2 \equiv \frac{\rho g}{k_\mu} (L_g/2)^3 (L_s/L_g) \Rightarrow I \sim \sqrt{L_s} L_g \quad (101)$$

This is the main scaling relationship of Jaraiz et al. (1984a) for the release current (see Eq. 28b). The contribution of (L_s/d_p) (through Eq. (100) as in Eq. (98)) gives

$$I \sim \left(\frac{L_g}{d} \right) \sqrt{L_s} \quad (102)$$

The latter expression differs from the Jaraiz estimates.

As mentioned above, the derived scaling estimates differ slightly from those derived by Jaraiz. The main reason for this is the use of the ratio of the particle diameter to the aperture of the mechanical partitions of MVS (grate spacing or screen aperture). This ratio is physically relevant to the particle flocculation phenomenon. The magnetic field forms aggregates that are stopped by the partition. A large (L_s/d_p) or (L_g/d_p) ratio implies that larger aggregates should be created to stop the flow and, consequently, higher current strengths are required. The analysis of Jaraiz, discussed at large here, does **not consider particle flocculation effects**, but a **single particle** subjected to magnetic field action. This is the probable origin of disagreements between the theoretical predictions and the experiments concerning the bridging diameters of the partitions (see III.3.1).

V.3.2. Mass flux of solids (an example of a grate-type MVS)

The mass flux control analysis introduces new quantities, such as G_s ($\text{kg}/\text{m}^2\text{s}$) and the ratio $t_{\text{open}}/(t_{\text{open}} + t_{\text{closed}}) = t_{\text{open}}/T$. The latter dimensionless quantity follows directly from the problem inspection. Generally, the mass flux is a dependent variable and needs detailed analysis. Problem examination specifies the following quantities

Independent quantities (in SI units):

Solids density	ρ_s	$[\text{kg}/\text{m}^3]$	ML^{-3}
Gravity acceleration	g	$[\text{m}/\text{s}^2]$	LT^{-2}
Channel diameter	D	$[\text{m}]$	L
Screen aperture (or grate spacing)	L_s (or L_g)	$[\text{m}]$	L
Gas velocity	U_g	$[\text{m}/\text{s}]$	LT^{-1}

and a dependent quantity:

Solids flow rate	Q_s	[kg/s]	Ml^{-1}
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The quantity of Q_s was selected for easy data treatment and analysis. The field intensity expressed as A/m can be replaced by a simple ratio I_W/I_r introduced by inspection, thus unifying all the quantities within the MLT system. The value of I_W/I_r can be estimated from a preliminary analysis (see Eq. (99) developed above) of the process. In the absence of a counter-current gas velocity ($U_g = 0$), two dimensionless groups appear

$$\begin{aligned}\Pi_1 &= \frac{Q_s}{\rho(L_s)^2 \sqrt{gL_s}} \text{ and } \Pi_2 = \frac{D}{L_s} \Rightarrow \\ \Pi &= \frac{Q_s}{\rho(L_s D) \sqrt{gL_s}} = f\left(\frac{I_W}{I_r}, \frac{t_{open}}{T}\right)\end{aligned}\quad (103)$$

In contrast to this result, if the gas flow velocity U_g is taken into account we have

$$\Pi_1 = \frac{Q_s}{\rho(L_s)^2 \sqrt{gL_s}}, \quad \Pi_2 = \frac{D}{L_s} \quad \text{and} \quad \Pi_3 = \frac{U_0}{\sqrt{gL_s}} \quad (104)$$

Hence

$$\frac{Q_s}{\rho(L_s D) \sqrt{gL_s}} = f\left(\frac{I_W}{I_r}, \frac{t_{open}}{T}, \frac{U_0}{\sqrt{gL_s}}\right) \quad (105)$$

If the grate spacing is chosen as a controlling parameter, the new groups resemble (104), but L_s is replaced by L_g , which leads to:

$$\frac{Q_s}{\rho(L_s D) \sqrt{gL_g}} = f\left(\frac{I_W}{I_r}, \frac{t_{open}}{T}, \frac{U_0}{\sqrt{gL_g}}\right) \quad (106)$$

This example (V.3.2) really shows that the analysis is “blind”. If the particle diameter is selected as a controlling parameter instead of L_s (or L_g), this does not change the form of the groups derived, because it has the same

dimension (L). However, the absence of L_s (or L_g) in the list of controlling parameters indicates ignorance of the physics of the process modelled. Therefore, in cases of complex processes without constitutive equations (MVS and MDD are typical examples) deep knowledge of the physical process is required and, of course, some engineering intuition.

V.4. Remarks

The attempt to apply a dimensional analysis to some of the reviewed problems yields simple equations employing macroscopic values. Moreover, this analysis offers new problems that are not yet solved, but are attractive for future investigations. The main efforts are oriented towards exploration of the mechanical quantities in the derived equation. The magnetic field action is *smoothed* in order to present more clearly the main idea of the dimensional analysis.. However, two sub-areas of magnetic field assisted fluidization are not discussed here:

- the design and scale-up of magnetic systems, and
- the design of an electric circuit supplying pulses to magnetic systems.

These problems are beyond the scope of the present work, but they will be commented on in a special part of the review series. Nevertheless, we can decide that, at the present, an analysis of *mechanical quantities* only is *sufficient* for process description. This is valid only if the fields *supplied to fluidized systems* by magnetic systems of any scales are homogeneous. Some specific problems were commented in Fundamentals of Part 1, based on the approach of Montgomery (1969). The approach applied by Jaraiz and Estevez (1987) (see III.4.2.4) through scaling relationships incorporating together magnetic quantities and screen parameters (see Eqs. 63-66) is a methodology that forms a matter of argument.

The chemical engineering area has excellent examples of applications of dimensional analysis and scaling (Ruckenstein, 1987, 1998; Astarita, 1997, Molerus, 1998) to disperse systems that should be accepted as *guiding works* in magnetic field assisted fluidization.

The presented examples employed dimensional analysis with easy manual data treatments. This is done especially in order to explain: i) the main idea of selection of quantities, and ii) employment of physical knowledge accompanied by engineering intuition to derive scaling estimates. Obviously, systems that are more complex require applications of systematic algebraic

approaches (Isaacson and Isaacson, 1975). Recent development (Szirtesz, 1997) allows a more automatic evaluation (through computer codes with matrix algebra) of dimensional groups. Moreover, some recent developments in engineering tools, such as Order of Magnitude Scaling (Mendez, 1999, Mendez and Eagar, 1999), offer new possibilities that have not yet been applied to problems of fluidized beds. The author hopes that both the techniques and results of this section will motivate new systematic investigations providing, comprehensible presentations of results in MFAF.

VI. CLOSING COMMENTS

This paper is the last one in the series that is relevant to the hydrodynamics of gas-solids fluidized beds. The latest review went through many particular problems studied over a large period of time employing different investigation ideologies. The main message to the reader is that an approach based on fundamentals of mechanics and electricity can create a unified and comprehensive presentation. This is strongly relevant to dense moving beds (MB), usually discussed in the literature together with batch-solids beds. The arrangement of MB within a logical chain, including MVS, MDD and magnetic elevators, allows us to explain from a general point of view the common characteristics, ideas and problems that have to be solved. Besides, the text contains not only explanations of published results but also many comments, tests of ideas and critical points of views. Therefore, a special section named DISCUSSIONS is not necessary as a closing part of the article. Nevertheless, some ideas and general conclusions will be outlined briefly.

V.1. A backward glance: Status, problems and future trends in moving gas-fluidized beds

The status of the moving beds could be defined as a research area of sporadic and nonsystematic interests due to several reasons: i) Lack of systematic reviews so far. ii) Most of the studies (practically all of them) were published as “state of the art” without any systematization. This hindered the research interests of other investigators.

The present attempt to systematize the information identified some knowledge gaps and focussed the attention on potential problems. Some of them could be summarized as follows:

- **MSB with continuous solids throughput**

- Deep moving beds with continuous solids throughput require more detailed studies in order to meet requirements of mass and heat transfer problems associated with such devices.
- Continuous moving beds of magnetic/nonmagnetic mixtures form a specific branch with great potential for applications in heat/mass transfer operations and particle separation techniques. The work of Shao and Kwauk is the first example in that direction.
- Crossflow MSBs as *inclined channel* and *carousel* devices are attractive for both heat/mass transfer operations and mechanical separations. The EXXON group developed very nice chromatographic devices and particle/particle separators that will be commented in future special parts of the series.
- All variants of MSBs with continuous moving solids present several fundamental problems that require solutions :
 - Bed rheology** is a milestone of moving beds, since without knowledge of basic constitutive relationships it is not possible to build up successfully both prototypes (and large scale devices) and adequate mathematical models for computer simulations and design.
 - Mathematical modelling** is a problem that requires special comments. The two examples discussed here show only attempts to build up particular models, but not a systematic approach. Model backgrounds have to be created with deep understanding of bed mechanics, field effects on both the rheology and fluid-particle interaction. There is a strong deficiency of knowledge in this area.
- Moving beds were developed with axial fields only. However, the increase in scale of devices requires larger magnetic systems. Magnetic systems based on solenoids or short coils do not satisfy the engineering requirements of increasing column scales. Saddle coils (Part I) offer opportunities for large-scale applications, so both MB in a transverse field and scale-up problems are attractive areas of research.

VI.2. MSB with low-density solids flow – valves and relevant devices

Many problems of these devices were identified throughout the discussion. Several major points and future trends will be noted briefly:

- Both the analysis and the comparative studies performed here identify many disagreements between model predictions and experiments. The discussion clearly states where simplified calculations help in estimating scaling laws and where they do not agree with experiments. We hope that this will motivate further studies in that direction.
- The process engineering analysis applied to MVS and MDD is an attractive but undeveloped area of research. Moreover, such an approach is necessary for better applications of automatic control (feedback control, for example).
- Finally, beds moving against gravity, discussed here as Magnetic Elevators for Particles (MEP), offer a new trend for applications in both the terrestrial and space applications.

VI.3. Remarks on the methodologies of the reviewed investigations

The subjects reviewed in the present paper mainly provoke this special comment. The first feeling called to mind is that all studies are *state of the art* and no links to fundamental knowledge are available. A huge amount of particular formulae and scaling equations, linking an enormous quantity of variables, totally hinders formulations of main results and basic principles. Dimensional analysis performed in the section V cases is an example of a systematic presentation of experimental results. The approach is practically unexplored in the area of MFAF and we suggest that section V should provoke further studies.

VI.4. Some remarks on the review series ideology

The *study* arranged as Part 4 demonstrates that magnetic field-assisted fluidization is a multidisciplinary area that requires knowledge of various fundamental disciplines, such as electricity, magnetism, fluid dynamics, granular media mechanics, rheology, etc. The word “study” is used in a special sense in the previous sentence. The main idea in the already developing series of reviews is not only to collect data and comments, but to study problems from positions of fundamental disciplines of science. This approach allows arrangement of the accumulated results as a comprehensive source of knowledge facilitating further problem developments. The approach has two goals: i) Any young researcher could come across complete collections of facts collated from various papers that are very hard to find on his desk. ii) To stress the fact that MFAF requires a more complex background than is provided by classical Chemical Engineering Education. In

other words, each particular problem should be solved without any disregard of basic knowledge and results of the science.

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Last, but not least the efforts of my wife Dr. Violeta Dimitrova are appreciated. To this brilliant woman and scientist I owe the progress of my reviews.

LIST OF SYMBOLS

A	-	total cross-sectional area of the bed, m^2
A_{CS}	-	cross-sectional area of a multistage column, m^2
b	-	channel width, m
B	-	magnetic field induction, T
C	-	discharge coefficient (dimensionless).
D_c	-	column diameter, m
D_H	-	hydraulic diameter, m
d_{or}	-	orifice diameter, m
d_p	-	particle diameter, m
d_{pav}	-	average particle diameter, m
f	-	field frequency, Hz
f_{op}	-	a parameter defined by Eq. (67)
F	-	frictional losses of flow, $kg.m.s^{-2}$
F_{PM}	-	ponderomotive force, N

- F_A - particle-to-particle adhesion force, N
 F_C - force of attraction to the conductor, N
 F_f - friction force, N
 F_g - gravity force, N
 FIM = $\frac{\text{velocity of the breakdown of MSB}}{U_{mf} \text{ at } H=0}$ -a general definition
 FIM = $\frac{U_{e2}}{U_{mfo}}$ (Axial field) (Penchev and Hristov, 1990b)
 g - acceleration due to gravity, m/s^2
 G - magnetic permeability of the circuit ($G = 1/R_M$) (Eq. 39d), A/Wb
 G - mass flux (Eq. 45), $kg/m^2.s$
 G_s - solids mass throughput rate, kg/s
 G_g - gas mass flow rate, kg/s
 H - magnetic field intensity, A/m
 H_A - field intensity applied for magnetization, A/m
 H_{mfr} - minimum field intensity required to create a frozen bed in accordance with the Magn. LAST mode, A/m
 h - height of solid free surface normal to the channel bottom, m
 h_o - solids free surface at the discharge, m
 h_b - bed height, m
 h_{fb} - fluidized bed height (inclined channel crossflow $_{MSB}$)
 h_{bo} - initial bed height (before the fluidization onset), m
 h_s - height of settled particle bed in the valve, m
 h_t - total bed height (experiments of Shao and Kwauk, 1991), m
 I - electric current intensity (strength), A
 I_{avg} - time-averaged current, A
 I_h - holding current, A
 I_w - working current, A
 I_C - capture current, A
 I_r - release current, A
 $K_d = \frac{d_{pM}}{d_{pN}}$ a ratio of particle diameters in an admixture bed defined in Part I (Hristov, 2002a)
 $K_\rho = \frac{\rho_M}{\rho_N}$ a ratio of particle densities in an admixture bed defined in Part I (Hristov, 2000a)

K	-	fluid consistency index, $\text{g.s}^{n-2}.\text{cm}^{-1}$
K_h	-	proportionality constant, m/kPa (see Eq. 68c)
l	-	channel length, m
l_c	-	distance between the poles of external coil design MVS (Eq. 39)
L	-	length (see the adequate use in the equations), m
L_{ind}	-	inductance of the magnetic coil (the system generating the field), H (Henry)
L_s	-	screen aperture, m
L_g	-	grate spacing, m
dt	-	tube diameter (grate tube conductor), m
M	-	magnetization, A/m
M_s	-	magnetization at saturation, A/m
M_g	-	mass of gas, kg
M_0	-	mass of particle held on the stage, kg
N_w	-	number of windings of a coil
m_{in}	-	mass of the particle into the stage, kg/h
m_{ou}	-	mass of particle out of the stage, kg/h
$\mathbf{m}_0$	-	vector of mass flow rates of particles out of stages
N	-	segregation index defined by Eq. (2)
n	-	power-law index or flow behavior index (dimensionless) (Eq. 13)
ΔP	-	pressure drop, Pa
$\Delta P (\text{Umf})$	-	pressure drop at the fluidization onset, Pa
P	-	power dissipated (Eq. 46), W
Q	-	volumetric flow rate, m^3/s
r	-	radius (or a co-ordinate)
R_M	-	magnetic resistance, Wb/A . (Eq. 37)
R_{ohmic}	-	current carrying conductor resistance, Ohms
t	-	time, s
U	-	gas superficial velocity, m/s
U_e	-	gas velocity at the onset of batch-solids MSB (all field orientations except the axial one), m/s
U_{mf}	-	minimum fluidization velocity, m/s
U_0	-	orifice jet velocity, m/s
ΔU	-	change in gas velocity, m/s
U_{mfo}	-	minimum fluidization velocity in the absence of a magnetic field, m/s

U_{ST}	-	solids throughput velocity (superficial) at the transition point (Shao and Kwauk, 1991), m/s
U_p	-	plug velocity, m/s
U_s	-	solids throughput (superficial) velocity (experiments of Shao and Kwauk, 1991), m/s
U_{sm}	-	mean solids velocity through the channel, m/s
U_T	-	transition velocity in the case of batch fluidized beds, m/s
V	-	volume, m^3
V_p	-	particle volume, m^3
W	-	specific magnetic energy (see the context), J/m^3
W or W_p	-	weight of solids (bed) - see the context, kg
W_f	-	work done by the flowing solids, $kg.m^2/s^2$
w_c	-	air gap width, m (Eqs. 38-39)
x	-	axial coordinate
X_M^M	-	magnetic particle content, % mass
X_M^N	-	non-magnetic particle content, % mass
X_V^M	-	magnetic particles content, % vol.
X_V^N	-	non-magnetic particle content, % vol.
y	-	vertical coordinate
Z	-	bed depth (dimensional or dimensionless) or a coordinate in a bed (see the context), m

Greek Letters

α	-	angle of distributor tilt (tilted-channel crossflow MSB, see also Fig. 24), deg
β	-	angle of repose or angle of the field orientation, deg
β_0	-	angle of repose in absence of a field, deg
β_c	-	correction factor of kinetic energy term of Eq. 6
$\dot{\gamma}$	-	shear rate, s^{-1}
η	-	coefficient of plasticity, P
ε	-	porosity (dimensionless)
μ_e	-	effective bed viscosity, Pa.s
v_0	-	specific volume, m^3/kg
μ	-	fluid dynamic viscosity (see the context), Pa.s
μ	-	magnetic permeability (see the context), Wb/Am
$\bar{\mu}$	-	averaged magnetic permeability of the medium

μ_g	-	gas dynamic viscosity, Pa.s
Φ	-	magnetic flux, Wb
ρ_b	-	bed bulk density, kg/m ³
ρ_s	-	particle density, kg/m ³
ρ_f	-	fluid density, kg/m ³
ρ_g	-	gas density, kg/m ³
ρ_M	-	density of the magnetic particles, kg/m ³
ρ_N	-	density of the non-magnetic particles, kg/m ³
τ	-	shear stress, N/m ²
τ_y	-	yield stress, N/m ²
$\chi = \delta M / \delta H$	-	the tangent magnetic susceptibility
$\chi_0 = M / H$	-	the chord susceptibility
δ	-	scaling exponent
ψ	-	angle of internal friction of a granular medium, deg

Subscripts

b	-	bubbling or bulk, or bed (see the context)
e	-	effective
f	-	fluid
g	-	gas
M	-	magnetic
N	-	nonmagnetic
s	-	solids; staging; slugging (see the context)
t	-	tilting

Special symbols

$\propto$	-	<i>proportional to;</i>
O	-	<i>order of magnitude;</i>
$\approx$	-	<i>about equal;</i>
$\equiv$	-	identical (equivalent to)
$a \sim b$	-	a scale to b as well as
$\Rightarrow$	-	<i>it follows that</i> (implies)
$a \rightarrow b$	-	a approaches b
$ $	-	absolute value

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