

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

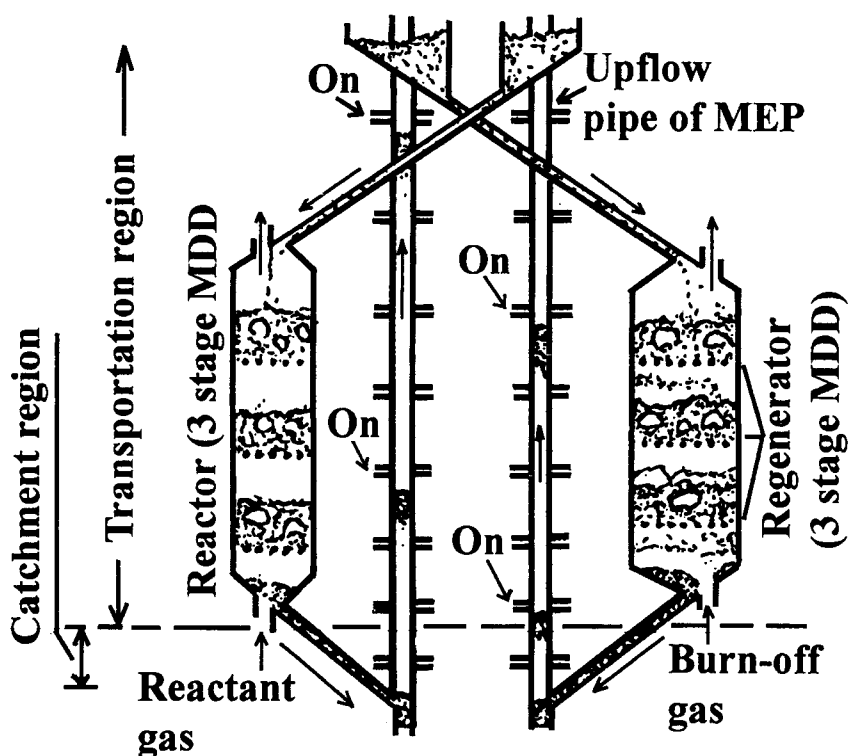


Fig. 59: Particle recirculation system proposed by Wallace et al. (1991) without pneumatic or hydraulic elements.

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

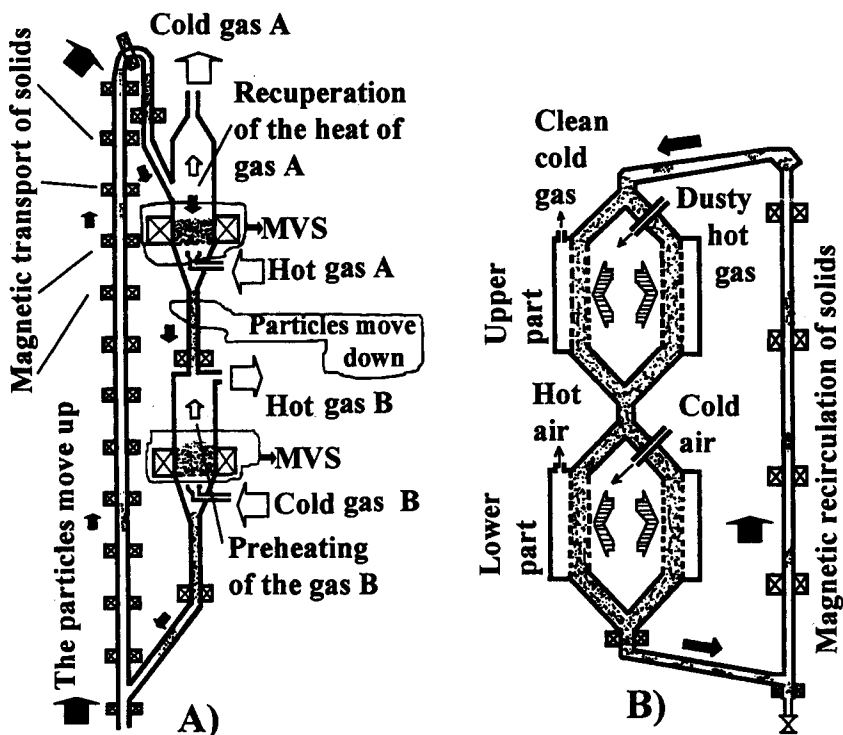


Fig. 60: Heat exchangers based on magnetic elevators of solids.

- 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 $L_{\text{transport}}$ is

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

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

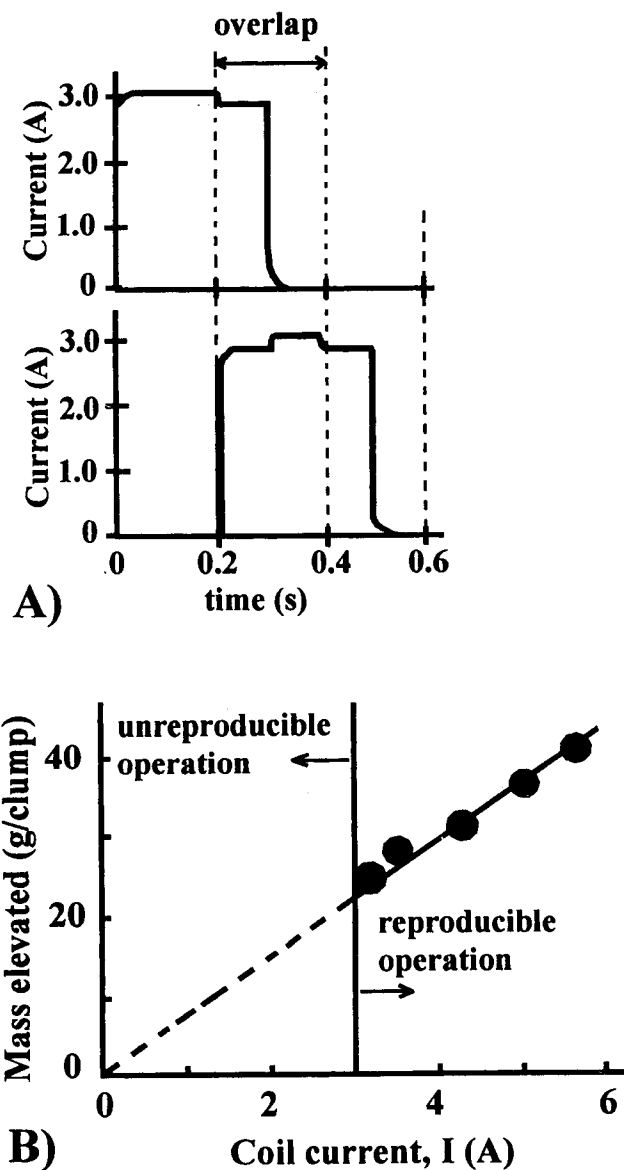


Fig. 61: Magnetization pulse parameters creating reproducible particle mass elevation. From Wallace et al. (1991)

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

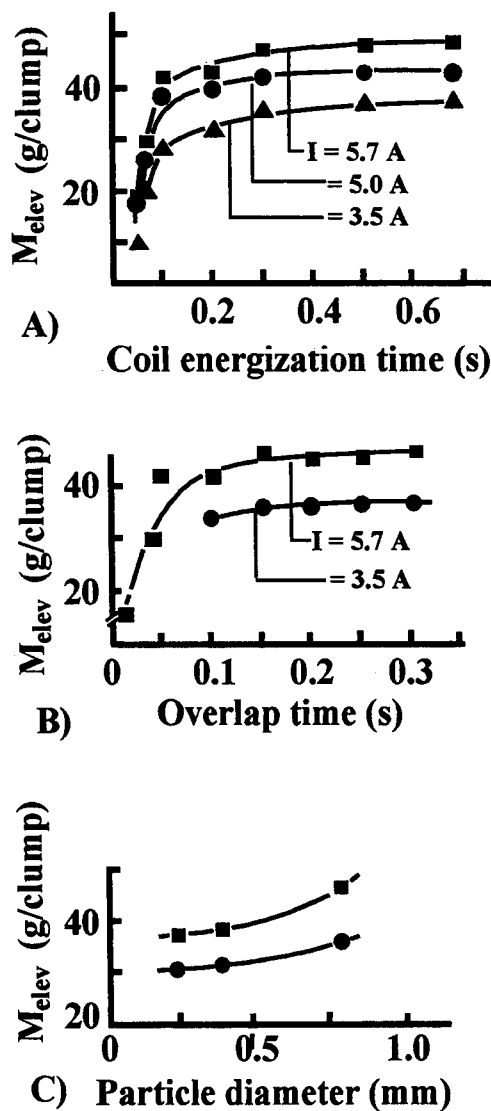


Fig. 62: Efficiency of the transport process as a function of the magnetization condition and the particle properties. From Wallace et al. (1991)

- 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.

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

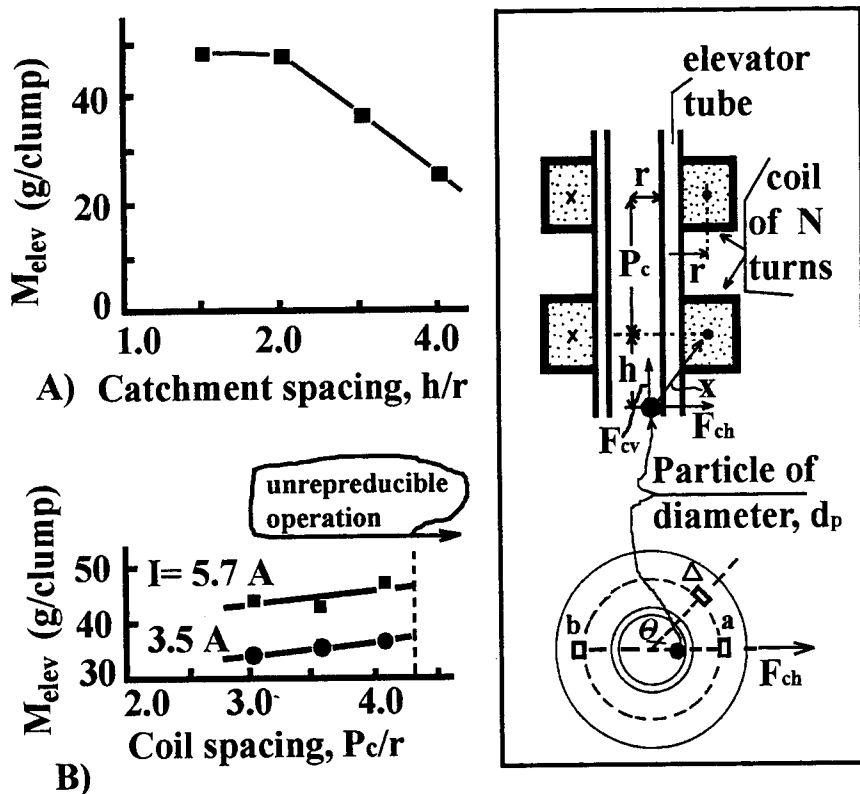


Fig. 63: Experimental adjustment of the elevator design expressed through the coil spacing of both regions of the transportation tube. From Wallace et al. (1991).

- 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 $F_{ponderomotive} \sim H grad H \sim H^2 \sim I^2$ (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.