

Dynamic Parameters for Mixtures of Pillared Clay-Magnetic Particles in Fluidized Bed in Coaxial Magnetic Field

GABRIELA MUNTIANU^{1,3}, ALINA-VIOLETA URSU², GHOLAMREZA DJELVEH², GABRIELA ISOPENCU³, ALINA-MONICA MARES³, ILEANA DENISA NISTOR¹, COSMIN V. JINESCU^{4*}

¹"Vasile Alecsandri" University of Bacau, Department of Chemical and Food Engineering, 157 Marasesti Str., 600115, Bacau, Romania

²Clermont University, ENSCCF, Pascal Institute, GePEB axis, UMR CNRS 6602, 24 avenue des Landais, BP206, 63174, Aubière, Clermont Ferrand, France

³Politehnica University of Bucharest, Department of Chemical Engineering, 1-7 Polizu Str., 011061, Bucharest, Romania

⁴Politehnica University of Bucharest, Department of Equipments for Industrial Processes, 313 Splaiul Independentei, 060042, Bucharest, Romania

This study aims to investigate the dynamic parameters of pseudo homogenous mixtures of aluminum pillared clay and ferromagnetic steel particles (APC-FMS) in classic fluidization and in fluidization stabilized in coaxial magnetic field. For both dynamic conditions of fluidization the structure of the bed was important in order to enhance a quasi homogeneous structure and to prevent the segregation of the particles in the bed. The minimum fluidization velocity, the minimum pressure drop, the bed expansion height and the minimum bubbling velocity were determined for mixtures that contain 0.35, 0.55 and 0.75 mass fraction of magnetic particles. The optimal dynamic conditions were established in order to ensure a higher contact surface between the solid particles and the fluidization gas. This is useful in the mass transfer processes like adsorption of residual gases when the preservation of energy consumption is necessary.

Keywords: pillared clay, binary mixtures, fluidization, coaxial magnetic field

Fluidization in magnetic field of particle mixtures is a modern technique that combines classic fluidization with the particles exposing in a magnetic field for the use of that as additional technique to enhance/intensify operations of chemical processes (drying, adsorption, chemical and biochemical processes etc.) [1, 2].

Applying this technique assumes either use of mixtures of particles of adsorbent (high-porosity) with particles with magnetic properties [3] either use the particle of adsorbent with magnetically properties itself, like composites with silica or zeolite substrate and insertion of magnetic nanoparticles of iron oxide (Fe_3O_4 or $\delta\text{Fe}_2\text{O}_3$) [4-6]. The use of magnetically adsorbents in processes of adsorption involves increased costs as a result of the complexity of the synthesis processes but also linked to their regeneration.

The use of binary mixtures in adsorption process remains an interesting alternative from an economic point of view because it has the advantage of treating large flow of gas along with the conservation of the fluidized bed structure in magnetic field, with the condition of an optimal control of fluidization parameters.

Materials with magnetization capacity could be ferri- and ferromagnetic, these being the most used, but also para- and dia-magnetic [3]. Because of the magnetic properties they possess, they show a variety of industrial applications.

Concerning the dynamic parameters in classical fluidization bed (FB), the pressure drop and porosity of the bed have the same dimension for both the increasing fluidization agent flow, in the fluidized state, as well as for its de-fluidization state of the bed, at decreasing fluidization agent flow [7-9]. In assisted fluidization of the bed in the magnetic field (MFB – *magnetic field assisted fluidization*)

these phenomena may not be held, bed structure is influenced by the magnetic field; thus, the particles are placed along the magnetic field lines, and at the de-fluidization there has been a collapse of the particle bed, followed immediately by a significant decrease of pressure drop, lower than that measured at classical fluidization [10, 11].

Magnetic particles follow the magnetic field lines and respectively, in the co-axial magnetic field particles form preferential passages on the flow direction of the fluidization agent and, in transverse magnetic field shall be carried out layers of particles perpendicular to the flow direction of the fluidization agent direction [12-15]. Because of these phenomena, in typical process curves of pressure drop versus fluidization agent velocity, hysteresis appears between the two lines which describe the fluidization and de-fluidization state [7].

Under the effect of magnetic field the magnetizable particles are maintained in fixed position and after a fluidization cycle the final bed porosity is greater than the initial bed porosity [13, 16, 17]. Particle orientation in a pseudo-homogeneous mixture plays an important role in the conservation of the structure of magnetic stabilized fluidized bed, due to the absence of the gas bubbles and the bed structure irregularities (pistons, channeling). In the pseudo-homogeneous mixtures fluidization stabilized in coaxial magnetic field, gas bubbles delay to appear up to 5 times duration, compared with fluidization in transverse magnetic field. This shows that fluidization of particles in coaxial magnetic field are more stable than in transverse magnetic field [17-20].

The characteristic parameters of fluidized bed stabilized by magnetic field are represented by two specific velocities:

* email: cosmin.jinescu@yahoo.com

- minimum bed expansion velocity (U_{me}) or the velocity at which starts the bed expanding accompanied by the formation of several successive squeezed magnetic particles and corresponds to the incipient fluidization; this velocity is equated with minimum fluidization velocity in classical processes.

- minimum bubbling gas velocity or the gas velocity when the first gas bubbles appears, (U_{mb}), the destabilized structure of the bed being a result of the intense additional mixing of particles induced by gas bubbling.

In order to calculate the specific velocities in MFB the considered particular physical properties are magnetic field strength (H), susceptibility (χ) and magnetic permeability (μ_p), as well as general physical properties of the particles: particles diameter (d_p), the particles density (ρ_p) and viscosity of fluidization agent, (η).

The generalized equation for the calculation of minimum fluidization velocity has the form [7, 9, 32].

$$U_{mf} = \frac{\eta_g \left(\sqrt{C_1^2 + C_2 \cdot Ar} - C_1 \right)}{\rho_g \cdot d_p} \quad (1)$$

$$Ar = \frac{d_p^3 \cdot (\rho_p - \rho_g) \cdot \rho_g \cdot g}{\eta_g^2} \quad (2)$$

Parameter values used in the generalized equation, corresponding to the particular forms of the equation (1), are presented in table 1.

Table 1
 C_1 AND C_2 PARAMETERS VALUES

Authors [7]	C_1	C_2	Equation
Richardson (1971)	25.70	0.0365	(3)
Bourgeois and Grenier (1968)	25.46	0.0382	(4)
Saxena and Vogel (1977)	25.28	0.0571	(5)
Grace (1981)	27.20	0.0408	(6)

Minimum bubbling gas velocity is the velocity at which the bed is destabilizing and could be calculated using the following relation:

$$U_{mb} = U_{mf} + 0.0015 \cdot \left(\frac{v_g}{d_{p,FMS}} \right) \cdot Ar^{0.81} \cdot E_R^{0.59} \quad (7)$$

$$E_R = \frac{\frac{3}{2} \cdot \mu_b \cdot H^2}{d_{p,FMS} \cdot \rho_{p,FMS} \cdot g} \quad (8)$$

Magnetic permeability of the bed could be calculated on the basis of the relationship:

$$\mu_b = \varepsilon \cdot \mu_0 + (1 - \varepsilon) \cdot \mu_0 \cdot \exp(0.03 \cdot \mu_{FMS} \cdot H) \quad (9)$$

In the magnetic field assisted fluidization there are different regimes of fluidization arising out from the stability chart: fixed bed (FixB), provided by $U_g < U_{me}$, magnetic stabilized fluidized bed (MFB) provided by $U_{me} \leq U_g < U_{mb}$, magnetic fluidized bed with gas bubbles (MFBb), provided by $U_g > U_{mb}$ [15, 18-21, 33-35]. As mentioned in the literature [12, 14, 22-23], the operating parameters domain in MFB can be extended with increasing the mass fraction of magnetizable particles when the difference between U_{me} and U_{gb} increase too.

The main factors that influence the fluidization of a bi-component particles bed in magnetic field are: the solids mixtures properties (composition, diameter, density and shape), the fluidization agent velocity, the height of the bed and the coaxial magnetic field intensity [24- 26].

When mixtures of particles (magnetic and non-magnetic) are used in intensification of adsorption processes through stabilized magnetic fluidization technique, magnetic particles will be oriented on trajectories generated by the magnetic field and will cause the delay of the gas bubbles appearance into the fluidized bed. Non-magnetic particles will be encapsulated in structures generated by magnetic particle movement, its movement allowing permanent contact with the fluidization agent and, due to their surface properties and selective adsorption, there will be also an enhancement of the mass transfer [9, 28-31].

This paper describe the behaviour of a bed formed by a bi-component mixture of particles, consisting of solid ferromagnetic particles and particles of pillared clay, in coaxial magnetic fields assisted fluidization. The optimal dynamic parameters, in relation to the particular characteristics of materials used, geometrical criteria of the bed and magnetic field intensity were carried out.

Knowledge of dynamic conditions is essential for the implementation of magnetic stabilized fluidized bed technique in the retention of harmful gaseous pollutants.

Experimental part

Materials and methods

The study of dynamic parameters of cMFB (coaxial magnetic fluidized bed) of binary mixtures of magnetic and non - magnetic particles has been carried out in a laboratory pilot plant presented in figure 1.

The installation is composed of three main components: the fluidization column containing solid particles, the fluidization agent stream together with the measuring and automation devices and the generator of co-axial magnetic field. The fluidization column is of cylindrical shape, made of Pyrex glass, transparent, which allows the visualization of the particle bed, with internal diameter $D = 5$ m and height $H = 40$ cm. At the bottom of the fluidization column

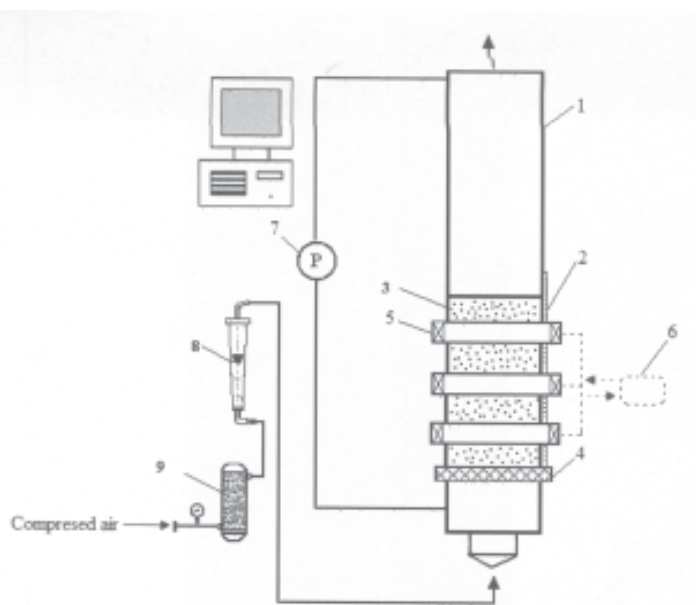


Fig. 1. Experimental laboratory plant

1 – fluidization column; 2 – scale; 3 – particles bed; 4 – porous plate; 5 –generators of electro-magnetic field (coils); 6 – electric power source; 7 – differential manometer; 8 – flow meter; 9 – air desiccators column

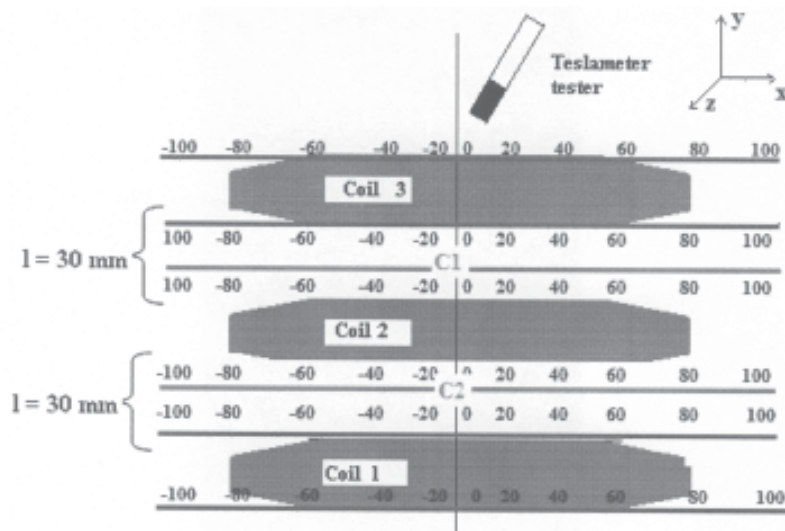


Fig. 2. Structure of the coaxial magnetic field generator

Particle type	Average diameter, d_p (10^{-3} , m)	Density, ρ_p ($kg \cdot m^{-3}$)
APC	0.35	973
	0.75	982
	1.50	1232
FMS	0.35	7450
	0.75	7500
	1.50	7500

Table 2
PHYSICAL PROPERTIES OF THE SOLID PARTICLES

is located a gas distributor as a porous plate which supports the solid particle bed and ensures a uniform distribution of the fluidization agent.

On the stream of the fluidization agent is placed a pressure regulator, a column with granular drierite particles for air drying and flow meters of type BROKS SHORATE GT 1024 and 1355 series, the fluidization agent (air) being supplied by a gas compression station.

The fluidization agent ascends in the fluidization column by the porous plate, rejoining the solid particles bed at different flow rate of gas and emerging at the top of the column. The pressure drop measuring in the bed was realized with a digital pressure gauge Keller PD type 33H which is connected to a computer via a transducer CONVERTER K-107 Keller.

The co-axial magnetic field generator is represented by three coils (electro-magnets) of cylindrical shape wrapping horizontally copper wires connected to a source of electrical current. The electro-magnetic field presents a spectrum composed of parallel lines to the fluidization agent flow direction and is uniform distributed in radial and axial fluidization column.

The three coils are located around the fluidization column, the distance between two coils on this configuration is 3 cm, on axial direction (fig. 2), in such a way that the magnetic field is uniform throughout its height.

In order to determine the homogeneity of the magnetic field measurements of the magnetic induction have been performed using a Tesla-meter MAGHET-PHYSIK FH 51 Gauss/Tesla-meter equipped with a test probe. Magnetic induction (B, mT) has been measured in the center C_1 and C_2 , axial and radial bean in 5 points, from a distance of 100 mm from the center at the currents intensity variation

($I = 1 \dots 5A$), corresponding with the values used in experimental determinations.

The homogeneous mixture bed is composed of: particles of pillared clay with aluminum positive ion (APC – aluminum pillared clay) prepared in the laboratory by chemical synthesis [28] (using a solution with molar ions ratio $OH^- / Al^{+3} = 2.2$ and for pillaring process it was considered the ratio of 12.5 mmol aluminum/gram clay, according the reaction stoichiometry and the stabilization of the obtained clay was made by calcinations at 400°C for 2 h) and, ferromagnetic steel particles (FMS) (Fe > 98.5 %) supplied by Wheelabrator (Allevard, France).

Average diameter of pure particles, d_p , was determined by particles sieving and the determination of the sizes distribution led to their split into three size classes: $d_p = 0.35 \cdot 10^{-3}$; $0.75 \cdot 10^{-3}$; $1.5 \cdot 10^{-3}$ m.

Bulk density of solid particles, ρ_p , has been determined by the volumetric method mass (mass measurement of a given volume of dry solids, placed in graduated cylinder by subsidence). Experimental values are given in table 2.

The physical properties of the particle mixtures APC-FMS use in the study of dynamics of fluidization bed in the presence or absence of magnetic field are presented in table 3.

Average mass diameter of the particle mixture APC-FMS, $d_{p,mix}$, was calculated by equation of weighed mass as following:

$$\bar{d}_{p,mix} = \left(\frac{x_{FMS}}{d_{p,FMS}} + \frac{1-x_{FMS}}{d_{p,APC}} \right)^{-1} \quad (10)$$

Average density of the mixture APC-FMS $\bar{\rho}_{p,mix}$, it has been calculated using the equation of weighted mass [29, 37-38]:

Mixture	Mass fraction (x_{MF})	Volumetric fraction ($x_{v,MF}$)	Average mixture diameter $\bar{d}_{p,mix}$ ($10^{-3}, m$)	Average mixture density $\bar{\rho}_{p,mix}$ (kg/m^3)
APC ($d_p = 0.75 \cdot 10^{-3} m$) + FMS ($d_p = 0.35 \cdot 10^{-3} m$)	0.35	0.0548	0.5357	1410.64
	0.55	0.1164	0.4605	1879.43
	0.75	0.2352	0.4038	2814.89

Table 3
PHYSICAL PROPERTIES OF MIXTURE
APC-FMS

$$\bar{\rho}_{p,mix} = \left(\frac{x_{FMS}}{\rho_{p,FMS}} + \frac{1-x_{FMS}}{\rho_{p,APC}} \right)^{-1} \quad (11)$$

Results and discussions

The main parameters varied in magnetic field assisted fluidization are: geometric ratio, L_0/D , solid particles diameter, d_p , mass fraction of ferromagnetic steel particles, x_{FMS} , and magnetic field intensity, H .

The dynamic parameters specific to the fluidized bed with/without coaxial magnetic field have been: the minimum fluidization velocity, U_{mf} , the minimum bed

expansion velocity, U_{me} , the minimum bubbling velocity, U_{mb} , the corresponding pressure drops and also the porosity of the fluidized bed, specific to each dynamic structure.

Dynamic parameters in FB of mono-component bed (aluminum pillared clay/ferromagnetic steel particles)

Experimental determinations were realized in order to select the optimum diameter of the magnetic and non-magnetic particles to obtain the binary mixture able to ensure the dynamic and adsorptive qualities.

In table 4 are presented experimental results for minimum fluidization velocity, $U_{mf,exp}$, and minimum

No. exp.	Particle type	$\bar{d}_p$ ($10^{-3} m$)	Experimental values			$U_{mf, calc.}$ ($m \cdot s^{-1}$)			
			L_0/D	$U_{mf, exp.}$ ($m \cdot s^{-1}$)	$\Delta P_{min, exp.}$ (Pa)	Eq.3	Eq.4	Eq.5	Eq.6
1.	APC	0.35	1	0.13	375	0.04	0.04	0.06	0.04
2.			2	0.17	770				
3.			3	0.19	1275				
4.		0.75	1	0.25	320	0.17	0.18	0.26	0.18
5.			2	0.28	740				
6.			3	0.28	1037.5				
7.		1.50	1	0.59	345	0.51	0.52	0.68	0.54
8.			2	0.68	862.5				
9.			3	0.76	1350				
10.	FMS	0.35	1	0.23	1587.2	0.30	0.31	0.45	0.31
11.			2	0.30	3925				
12.			3	0.30	5875				
13.		0.75	1	0.68	1562.5	0.85	0.88	1.15	0.90
14.			2	0.85	3675				
15.			3	1.02	5987.5				
16.		1.50	1	1.36	1550	1.53	1.58	1.98	1.62
17.			2	1.44	3700				
18.			3	1.44	5125				

Table 4
DYNAMIC PARAMETERS IN FB OF
MONO-COMPONENT BED

No. exp.	$\bar{d}_p$ ($10^{-3} m$)	L_0 / D	H (A/m)	U_{me} ($m \cdot s^{-1}$)	U_{mb} ($m \cdot s^{-1}$)	$U_{me,calc.}$ ($m \cdot s^{-1}$)	$U_{mb,calc.}$ ($m \cdot s^{-1}$)
1.	0.35	1	0	0.23	0.29	0.306	0.29
2.			8000	0.42	0.50		0.48
3.			15000	0.59	0.67		0.72
4.			20000	0.76	0.93		0.96
5.		2	0	0.30	0.31		0.31
6.			8000	0.42	0.59		0.51
7.			15000	0.50	0.67		0.79
8.			20000	0.67	0.93		1.03
9.		3	0	0.30	0.38		0.38
10.			8000	0.59	0.67		0.50
11.			15000	0.67	0.76		0.78
12.			20000	0.76	0.84		1.02
13.	0.75	1	0	0.68	0.84	0.860	0.84
14.			8000	0.50	0.59		1.73
15.			15000	0.84	0.93		2.84
16.			20000	0.93	1.10		3.81
17.		2	0	0.85	0.93		0.93
18.			8000	0.67	0.84		1.81
19.			15000	0.93	1.10		2.93
20.			20000	1.18	1.27		3.89
21.		3	0	1.02	1.01		1.01
22.			8000	0.84	0.93		1.89
23.			15000	0.93	1.01		3.01
24.			20000	1.10	1.18		3.97

Table 5
DYNAMIC PARAMETERS OF
cMFB OF FERROMAGNETIC
PARTICLES

* cosmin.jinescu@yahoo.com

pressure drop, ΔP_{min} , obtained at different L_0 / D and respectively, the calculated values for minimum fluidization velocity $U_{mf,calc.}$ with different empirical equations from literature, for mono-component beds.

Experimental values of minimum fluidization velocity were compared with theoretical values calculated with the equations from literature [4]: Richardson, 1971 (3) and Bourgeois and Grenier, 1968 (4) - applied for the particles of spherical shape, and respectively by Saxena and Vogel, 1977, (5) and Grace 1981 (6) - for the particle other than spherical shape, as described in table 4.

It is found that experimental values for minimum fluidization velocity shows a deviation from the values calculated with relations submitted, in the range 0-70 %, the lowest errors related to the experimental data presents the values calculated by the eq. 3.

From classical fluidization tests of mono-component beds in the absence of magnetic field have been selected those particles of magnetic particle category and non-magnetic respectively, which show similar values of minimum fluidization velocities to incipient fluidization.

Dynamic parameters in cMFB of the ferromagnetic particles

Because particles with magnetic properties are responsible for the stabilized structure in magnetic field fluidized bed, a study of the behaviour of MFB composed only of ferromagnetic particles was imposed (table 5).

Dynamics of ferromagnetic particles in fluidized bed stabilized in magnetic field is different from classical fluidization, because at low velocities of fluidization agent operates mainly electromagnetic field, but with an increase in the agent fluidization velocity, its dynamic action acts on solid particles, as a function of magnetic field intensity (H). Ferromagnetic particles will be arrange after the lines of co-axial magnetic field, in the direction of gas flow and are held in position "quasi-fixed" for certain gas velocities.

In table 5 are presented the experimental results obtained for minimum bed expansion velocity, U_{me} , and minimum bubbling velocity, U_{mb} , at fluidization in magnetic field, at different heights of bed (L_0 / D) and field intensities (H), for magnetic particle.

Analyzing the behaviour of ferromagnetic particles as a function of their mass fraction in cMFB and respectively, the values of the minimum bed expansion velocity and minimum bubbling, it is found that maximum range of stability of ferromagnetic particles in magnetic stabilized fluidized bed is reach for a mass fraction: $x_{FMS}=0.75$ [16]. From the experimental data analysis and in agreement with the literature data [1, 7, 29] is highlighted that the bed is held in a steady state starting with magnetic field intensity of 8000 A/m and for geometric ratio $L_0 / D=2$.

Thus, for operating magnetic stabilized fluidized bed of ferromagnetic particle, it is recommended to use the bed heights greater than 10 cm, because regardless of the bed

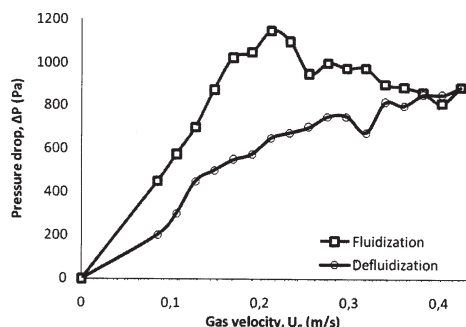


Fig. 3. Variation of the pressure drop as a function of gas velocity for a pseudo-homogeneous mixture bed with $x_{FMS} = 0.35$

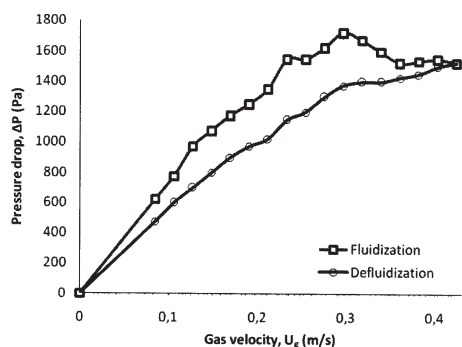


Fig. 4. Variation of the pressure drop as a function of gas velocity for a pseudo-homogeneous mixture bed with $x_{FMS} = 0.55$

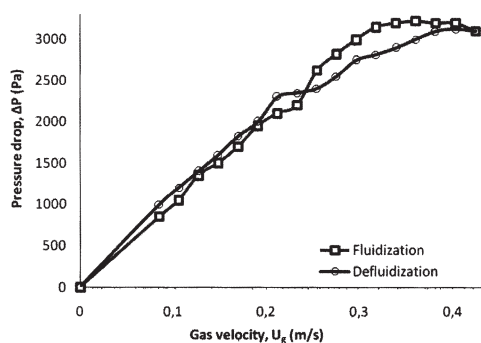


Fig. 5. Variation of the pressure drop as a function of gas velocity for a pseudo-homogeneous mixture bed with $x_{FMS} = 0.75$

configuration, the phenomena such as the gas bubbles, preferential channels, pistons, etc., delays to occur and that determine a good gas-solid particles surface contact.

Dynamic parameters for pseudo-homogeneous mixture in FB

Using the previous experimental results obtained for classical fluidization of mono-component beds of particles, for binary mixture formation have been selected pillared clay particle (APC) with the average diameter of $0.75 \cdot 10^{-3}$ m and minimum fluidization velocity $U_{mf} = 0.28 \text{ m} \cdot \text{s}^{-1}$ and ferromagnetic steel particles (FMS) with the average diameter of $0.35 \cdot 10^{-3}$ m and minimum fluidization velocity $U_{mf} = 0.30 \text{ m} \cdot \text{s}^{-1}$.

The selection criteria chosen for the mixtures design was the minimum fluidization velocity which assures a minimum of homogeneity of the bed. Experiments have been carried out while maintaining constant mass of APC to a value of 150 g and varying the quantity of ferromagnetic particles, which has led to changing mass fraction (table 3). Specific graphs used to characterize the fluidization state representing the evolution of the pressure drop as a function of gas velocity in a pseudo-homogeneous mixture,

with different mass fractions of magnetic particles are shown in figures 3, 4 and 5.

Experimentally it is found that with the increase of the fraction of ferromagnetic particles, the fluidized bed is more stable, highlighted by the hysteresis between the two curves of fluidization. This hysteresis represents a measure of the interparticular forces of beds and, hence of non-homogeneities from the bed structure [1, 36].

But, by improving bed structure, also the value of minimum pressure drop corresponding to the bed expansion increases 2.5 times corresponding to the 2 times increasing of the fraction of ferromagnetic particles in the bed. These results determine a substantial energy consumption for the transport of the fluidization agent through a particle bed whose weight increases of approximately 1.3 times for a mass fraction of ferromagnetic steel particles of 0.75.

Dynamic parameters in the cMFB of pseudo-homogeneous mixture

The variation of the dynamic parameters of cMFB (bed pressure drop, ΔP , versus gas velocity, U_g) as a function of the mixture composition (mass fraction of ferromagnetic steel particles, x_{FMS}) and of the magnetic field intensity (H), is shown in figures 6, 7 and 8.

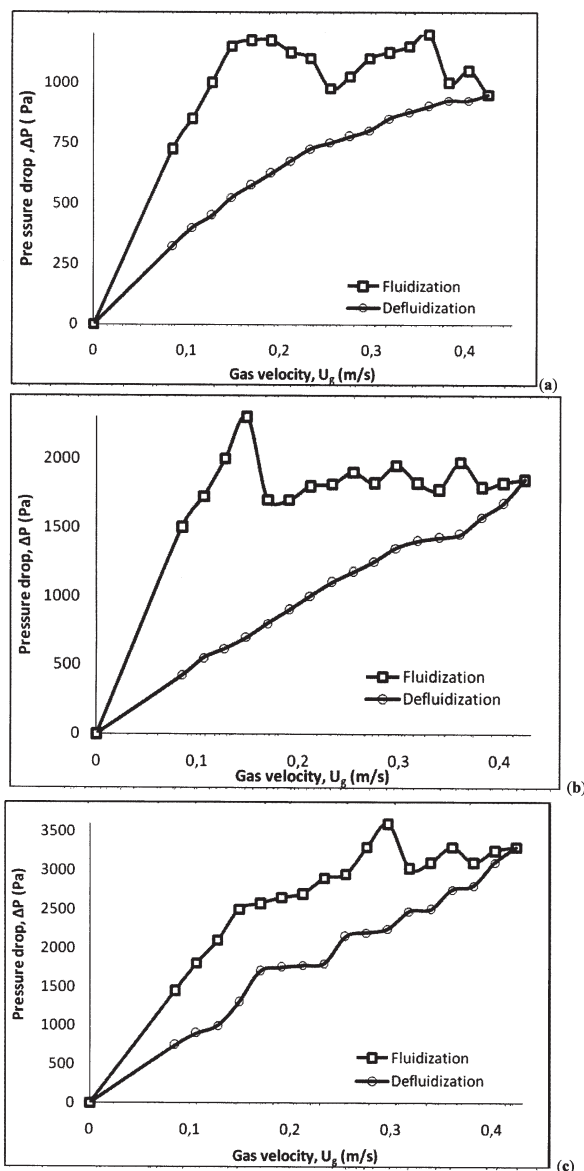


Fig. 6. Variation of the pressure drop as a function of gas velocity for a pseudo-homogeneous mixture bed at $H=8000 \text{ A/m}$, with (a) $x_{FMS} = 0.35$; (b) $x_{FMS} = 0.55$; (c) $x_{FMS} = 0.75$

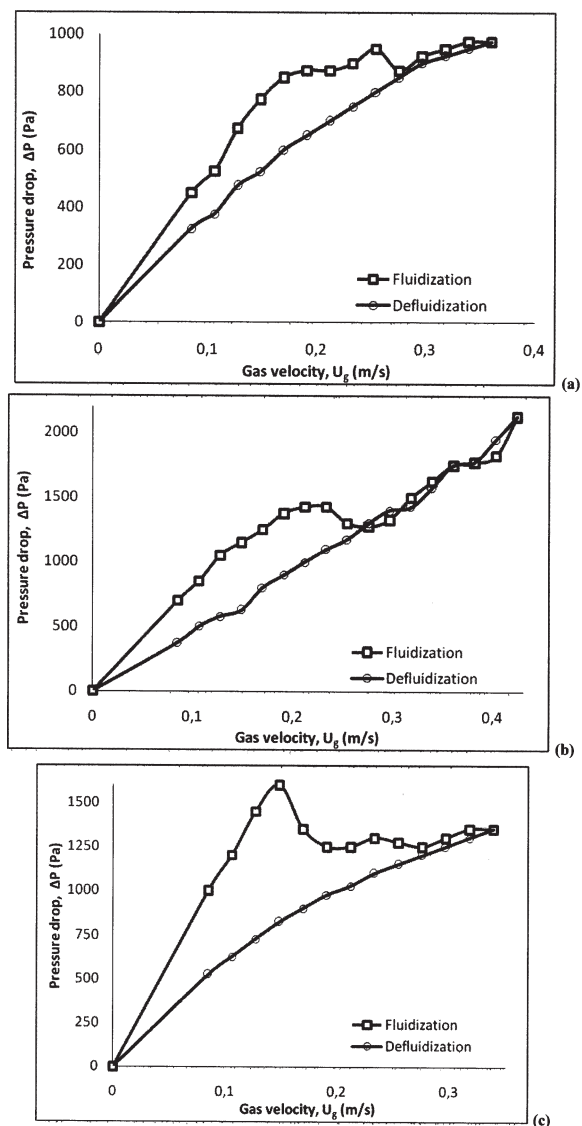


Fig. 7. Variation of the pressure drop as a function of gas velocity for a pseudo-homogeneous mixture bed at $H = 15000 \text{ A/m}$, with (a) $x_{\text{FMS}} = 0.35$; (b) $x_{\text{FMS}} = 0.55$; (c) $x_{\text{FMS}} = 0.75$

Analyzing the experimental results obtained in fluidization in co-axial magnetic field of a pseudo-homogeneous mixture of porous particle and ferromagnetic particles (introduced in different proportions), it was found that:

- at low values of magnetic field intensity, the structure of the bed - highlighted by the presence and shape of the hysteresis between the two fluidization curves - is similar to the fluidized bed structure obtained in classical conditions, but with an increase of 16% of the value of the minimum pressure drop corresponding to the bed expansion (for bed with 0.75 mass fraction of ferromagnetic steel particles), probably as a result of the increased electromagnetic forces between the ferromagnetic particles of the bed;

- with increasing of the applied magnetic field, the bed stability increase too, the structure of the bed becomes more homogeneous, by establishing the trajectories of the ferromagnetic particles on directions directed by the coaxial magnetic field lines. Thus, porous clay particles, which shown in FB a non-homogeneous structure of bed are engaged in a motion ordered by the ferromagnetic particles and the values of minimum pressure drop, corresponding to the bed expansion decline, once with the increasing of the magnetic field intensity, with approx

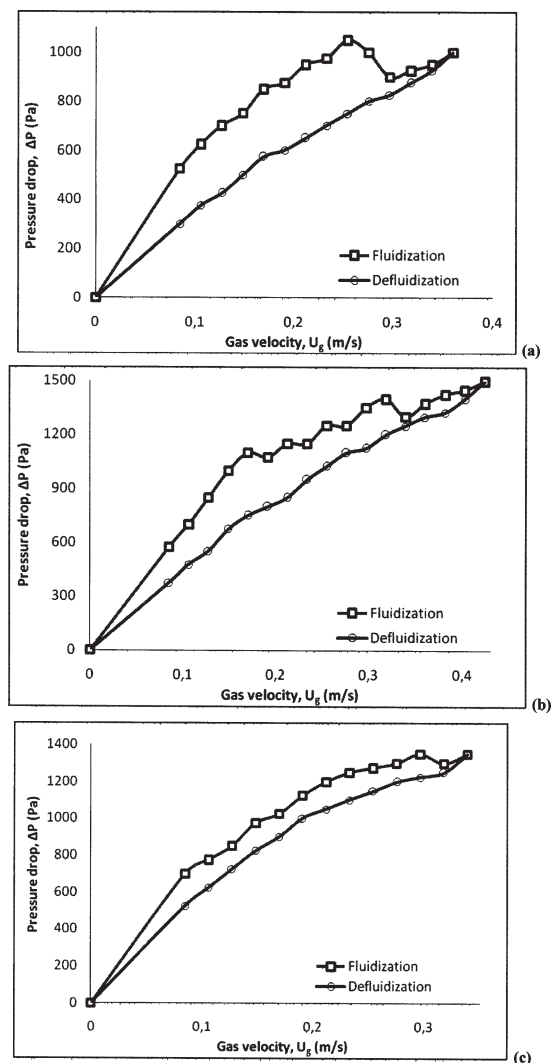


Fig. 8. Variation of the pressure drop as a function of gas velocity for a pseudo-homogeneous mixture bed at $H = 20000 \text{ A/m}$, with (a) $x_{\text{FMS}} = 0.35$; (b) $x_{\text{FMS}} = 0.55$; (c) $x_{\text{FMS}} = 0.75$

57% for $H = 15000 \text{ A/m}$ and, respectively, to approx. 65% for $H = 20000 \text{ A/m}$.

The minimum bed expansion velocity in cMFB records a decline of the values with the magnetic field applying, such as: at $H=8000 \text{ A/m}$, the velocity drops to 1.2 times, at $H=15000 \text{ A/m}$, the velocity value is reduced by 2 times, and at $H=20000 \text{ A/m}$, the velocity is reduced by 2.5 times against the minimum fluidization velocity in FB (pseudo-homogeneous mixture); at this value of magnetic field intensity, it can be considered that the status of light expansion can be installed immediately after the application of the magnetic field, because ferromagnetic particles, under the magnetic field action and due to electromagnetic forces installed in the bed, determine a state of mutual rejection. This can be highlighted also by the lower values of pressure loss in the bed, though its weight is significant.

Thus, in the case of cMFB for the bed with the mass fraction of ferromagnetic steel particles of 0.75 and bed height of approx. 10 cm (geometric ratio of $L_0/D = 2$), at an intensity of the magnetic field of 2000 A/m , the particles of clay are kept between ferromagnetic particles longer in easily expanded bed, the small distance between particles in bed, determining high flow velocities of the fluidization agent in the bed, intense mixing - by switching the flow direction and large contact surface. In these conditions, the most important goal of this study respectively the access of gaseous pollutants towards the clay particles

surface in cMFB, is achieved as a result of the dynamic conditions create and in which the transfers of impulse and the mass are substantially intensified.

Conclusions

The study of fluidization of pseudo-homogeneous mixtures in the co-axial magnetic field is important for the evaluation of the particle bed structure, with the objective to improve the contact between particles with high adsorption capacity and industrial waste gases with high level of polluting substances. In the absence of the co-axial magnetic field, as a function of gas velocity, the bed structure of pseudo-homogeneous mixture is corrupt due to the gas bubbles, pistons or channels formation which may be associated with partial or total segregation of the particles and can reduce the effectiveness of processes [26] like adsorption. The fluidization in co-axial magnetic field reduces those disadvantages and allows the optimization of the adsorption process by energy consumption reduction.

In this paper was established the optimum operating conditions of a cMFB as following:

- bed composition – it is recommended to use mixtures of particles which have a high content of ferromagnetic particles (0.75 mass fraction ferromagnetic steel particles in the mixture);

- bed geometry - refers to the height of the particle layer, which must be included in areas of electromagnetic field, and it is recommended a geometric ratio $L_0 / D=2$;

- magnetic field intensity - it is recommended a value of $H = 20000 \text{ A/m}$ in order to obtain homogeneous structures of the fluidized bed.

The adsorption capacity developed by aluminum pillared clay [39, 40] together with the special dynamic characteristics of the fluidized bed of pseudo-homogeneous mixtures in co-axial magnetic field presented in this paper can be useful to design high performance gas pollutants adsorption equipment. Another study that treats adsorption of ammonia on pillared clays in coaxial magnetic field assisted fluidized bed is under reviewing.

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Symbol	Measure	U.M.
$\underline{d}$	diameter	m
$\bar{d}$	average diameter	m
D	column diameter	m
g	gravitational acceleration	$\text{m} \cdot \text{s}^{-2}$
H	magnetic field intensity	$\text{A} \cdot \text{m}^{-1}$
L	bed height	m
U	velocity	$\text{m} \cdot \text{s}^{-1}$
x	mass fraction	-
Greek letters		
η	dynamic viscosity	$\text{Pa} \cdot \text{s}$
ρ	density	$\text{kg} \cdot \text{m}^{-3}$
$\bar{\rho}$	average density	$\text{kg} \cdot \text{m}^{-3}$
ν	inematic viscosity	$\text{m}^2 \cdot \text{s}^{-1}$
μ	magnetic permeability	$\text{H} \cdot \text{m}^{-1}$
ε	bed porosity	-
χ	magnetic susceptibility	-
ΔP	pressure drop	Pa

Index and exponents

0	vacuum	-
mix	mixture of particles	-
b	bed	-
APC	aluminum pillared clay	-
exp	experimental value	-
g	gas	-
FMS	ferromagnetic steel particles	-
me	minimum bed expansion	-
mb	minimum bubbling	-
mf	minimum fluidization	-
min	value corresponding to minimum	-
fluidization		-
p	particle	-
v	volumetric	-

Criteria

Ar	Arhimede number
E_R	dimensionless number that determine the ratio of the potential-energy densities

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