ISSN 2176-5480

22nd International Congress of Mechanical Engineering (COBEM 2013)
November 3-7, 2013, Ribeirão Preto, SP, Brazil

EXPERIMENTAL STUDY OF SEGREGATION IN GRANULAR BINARY MIXTURES USING PRESSURE FLUCTUATIONS ANALYSIS IN A GAS-SOLID FLUIDIZED BED

Diego Andrés Rueda Ordóñez
Araí Augusta Bernárdez Pécora
University of Campinas, School of Mechanical Engineering
R. Mendeleyev, 200, 13083-860 - Campinas, SP, Brazil
diegorueda@fem.unicamp.br; arai@fem.unicamp.br

Emerson dos Reis
Federal Institute of Education, Science and Technology of São Paulo, Campus of São João da Boa Vista
13072-551 - São João da Boa Vista, SP, Brazil
emersonr@ifsp.edu.br

Abstract. *The segregation phenomenon is studied in the thermal science area involving applications of fluidized beds, as it affects the hydrodynamics and the efficiency of biomass combustion or drying processes. In the present work, pressure fluctuations analysis is used to study the fluidizing and segregation phenomena in beds containing granular binary mixtures with different sizes and densities. Pressure measurements have been made to characterize the dynamic behavior of fluidized beds and to find the segregation velocity range by using the standard deviation of pressure fluctuations. Two types of solid particles were used in this work: plastic and glass spheres. The experimental system consists of a column with 0.1m diameter and 2.5 m height equipped with a porous plate gas distributor. Measurements of pressure fluctuations in different gas superficial velocities allowed performing signal analysis in the time domain to study the fluidized bed dynamics behavior and consequently the segregation range for the binary mixture, the initial and final fluidizing velocities for the mixture. The results allowed identifying the segregation phenomena of initially mixed systems as the gas velocity correspondent to the maximum segregation rate.*

Keywords: *Fluidizing, pressure fluctuations, fast Fourier transform, binary mixtures, segregation of particles.*

1. INTRODUCTION

The use of biomass has the potential to mitigate the emission of greenhouse gases and reduce the volume of waste generated. Researchers around the world have verified the importance of studies in this area, which resulted in the development of technological processes involving the conversion of biomass for power generation, among which stand out combustion, pyrolysis and gasification (Lecker and Karlsson 1993)These technologies require often the use of fluidized beds that present numerous advantages: high heat transfer, uniform and easily controlled temperature, gas-solid contact and favorable possibility of using particles with very different properties (density, sphericity, size distribution). The efficiency of the processes involving fluidized bed requires a good mixture among the granular components of the bed. However, although the fluidizing contributes for the mixing of the components of the bed, segregation can be present, which is characterized by heterogeneous concentrations of particles in the bed. It is a phenomenon which appears when there is a difference in size and/or density into the mixture components. This allows changes in the hydrodynamics of the process and, once it is detected, the particles segregation phenomenon can be controlled by increasing the gas velocity.

One way to detect and study the mixing and the segregation phenomena that take place in fluidized systems is through the analysis of pressure fluctuations in different regions within the bed. Moreover, the evolution of the standard deviation of pressure fluctuations as a function of superficial gas velocity may be used as a method for determining the transition between fluidizing regimes.

According to Clark and Atkinson (1988), the most common way for studying hydrodynamics in fluidized bed is to use series of pressure taps in the wall of the bed column, since the measure of pressure fluctuations is a simple technique to control and monitor the fluidizing quality. This fact is attributed to a continuous variation of fluidizing behavior depending on gas velocity. Pressure fluctuations are a complex function which depends on the particle properties, gas distributor type, location of pressure sensor, and static height of the bed (Yates and Simons, 1994). The technique has been applied frequently to study the behavior of gas-solid systems by researchers as Puncochar *et al.* (1985), Johnsson *et al.* (2000),and Felipe and Rocha (2007)who diagnosed the behavior of the bed by analysis in the time domain or frequency, applying the fast Fourier transform (FFT) on signals of the pressure fluctuations in the plenum of a gas-fluidized bed equipment. The great advantage of this technique is the fact that it includes the effects of different phenomena occurring in fluidized beds as the turbulence of the flow due to the formation of gas bubbles, bubbles burst and passage around the pressure taps (Schouten and van den Bleek, 1998).

Puncochar *et al.* (1985) found that the standard deviation of pressure fluctuation is a linear function of the superficial gas velocity. Furthermore, they determined that the standard deviation becomes equal to zero when the gas superficial velocity is equal to the minimum fluidizing velocity.

The hydrodynamics behavior of fluidized beds containing binary mixtures is strongly influenced by the particles properties Chiba *et al*., 1979, Formisani *et al*., 2008. A strong tendency to segregation occurs when there is a significant difference in size and/or density of the particles, causing partial or total separation between the components of the fluidized bed (Kwant *et al*., 1995).

Regarding binary mixtures, it has been defined the gas superficial velocity at which the fine particles or lighter ones begin to fluidize, as the onset or initial fluidizing velocity (U_{if}). The velocity at which the larger/heavier particles begin to fluidize was defined as the total or complete fluidizing velocity (U_{tf}).

The most of cited authors agreed in attributing the occurrence of stratification of particles during fluidizing of a binary system to the action of bubbles flow through the bed. This interpretation was first proposed by Rowe *et al*., 1972. Studies by Formisani *et al.*(2001) and Formisani *et al.* (2008) showed that the range of gas superficial velocity between the beginning of the fluidizing (U_{if}) and complete fluidizing of the mixture (U_{tf}) reflects the segregation pattern in the bed containing binary mixtures. Thus, it is expected that variables that affect the dynamics of segregation phenomenon are the same that affect the minimum fluidizing velocity.

Analysis of the fluidizing phenomenon involving binary mixtures due to difference in size and/or density of the particles of mixtures was performed by Kondukow and Sosna (1965), and Formisani *et al.* (2008). The authors showed the importance of defining the minimum fluidizing velocity in mixtures, since erroneous conclusions about the influence of system variables in their behavior can occur depending on how it is defined. Results obtained by these researchers demonstrated the existence of a gap between the initial fluidizing velocity and the complete fluidizing velocity of the mixture.

This paper presents the experimental study of the segregation phenomenon, by determining the standard deviation of pressure fluctuations, which will be analyzed in the time domain, to study the dynamic behavior of fluidized beds composed by binary mixtures presenting different sizes and densities. Results from this study contribute to the development of an appropriate methodology to identify the bands of superficial gas velocity where the segregation phenomenon occurs.

2. MATERIALS AND METHODS

2.1 Solid particles

The choice of solids was made according the following criteria: (i) materials with the same diameter and different specific mass, (ii) materials with different diameters and different densities, (iii) materials which allow comparison of results with others from literature; and, (iv) material availability. Two types of solid particulates were chosen: two sizes of glass microspheres and one size of plastic microspheres whose properties are shown in Tab.1, which were determined experimentally by screening (to obtain the particle diameter, (d_p), by pycnometry (to obtain the particle density, ρ_p), by measuring the weight and volume of the loosely packed bed (to obtain the bulk density, ρ_b). The bed porosity at the minimum fluidizing condition was obtained by Eq. (1) from ρ_b and ρ_p data.

$$\varepsilon_{mf} = 1 - \frac{\rho_b}{\rho_p} \tag{1}$$

The minimum fluidizing velocity of each studied particles (U_{mf}) was determined experimentally from pressure fluctuation measurements as a function of gas superficial velocity (U_o). The particle terminal velocity (U_t) was calculated by the empirical correlation of Haider and Levenspiel (1989).

Table1. Physical properties of the solid particles.

Particles	d_p **(μm)**	ρ_p **(Kg/m^3)**	ρ_b **(Kg/m^3)**	ε_{mf} **(-)**	**Geldart classification (1973)**	U_{mf} **(m/s)**	U_t **(m/s)**
glass1	477	2628	1591	0.394	B	0.301	4.14
glass2	959	2492	1587	0.363	D	0.603	6.71
plastic	971	1016	625	0.384	B	0.296	4.09

Tests were performed with three different compositions of the binary mixture. All of them containing 5 %wt of the component of smaller diameter and/or density (i.e., mixtures containing 5% of the component tending to float). This ratio was chosen as it is a common composition in processes involving combustion, gasification and pyrolysis of solid

ISSN 2176-5480

fuels, where the combustible material is about 5 wt% (or less) of the bed material which consists mainly of inert material (Basu, 2006; Olasar *et al*., 2008, Amutio *et al*., 2012).

The studied mixtures are described as:

- Mixture1 (glass1-glass2): Composed by the same material but different particle diameters.
- Mixture2 (plastic-glass2): Composed by different materials but same particle diameters.
- Mixture3 (plastic-glass1): Composed by different materials and different particle diameters.

Table 2 shows the mass fraction of each component in the mixtures tested as the weight of the bed material

Table 2. Composition of the studied binary mixtures.

Particles	**Composition**		***Mass of the bed material (kg)***
	5 wt%	95 wt%	
Mixture1	glass1	glass2	1.87
Mixture2	plastic	glass2	1.74
Mixture3	plastic	glass1	1.74

2.2 Experimental set-up

The experimental system is shown in Fig. 1. Airflow was generated in a roots compressor (1) which was firstly controlled by the bypass valve (2) by setting the relative airflow pressure at about 0.25 bar at the orifice plate flowmeter. A globe valve (3) and a ball valve (4) control the air flow to the plenum (5) of the main column or riser (6). The flow temperature was measured by a J thermocouple (7), and its volumetric flow rate by an orifice plate (8) built according to ASME MFC-14M-2003 code coupled to a differential pressure transducer (9) and (10). The gas flow enters in the plenum and crosses a porous distributor plate (11) reaching the riser which presents 0.10 m of internal diameter and 2.5 m of height, until the Lapple cyclone (12) where the solid particles elutriated by the gas flow were collected and stored in a hopper (13). Pressure fluctuation signals from transducers (14) were acquired by the data acquisition system (15) and the computer (16). Images from the bed of particles were also acquired by (17).

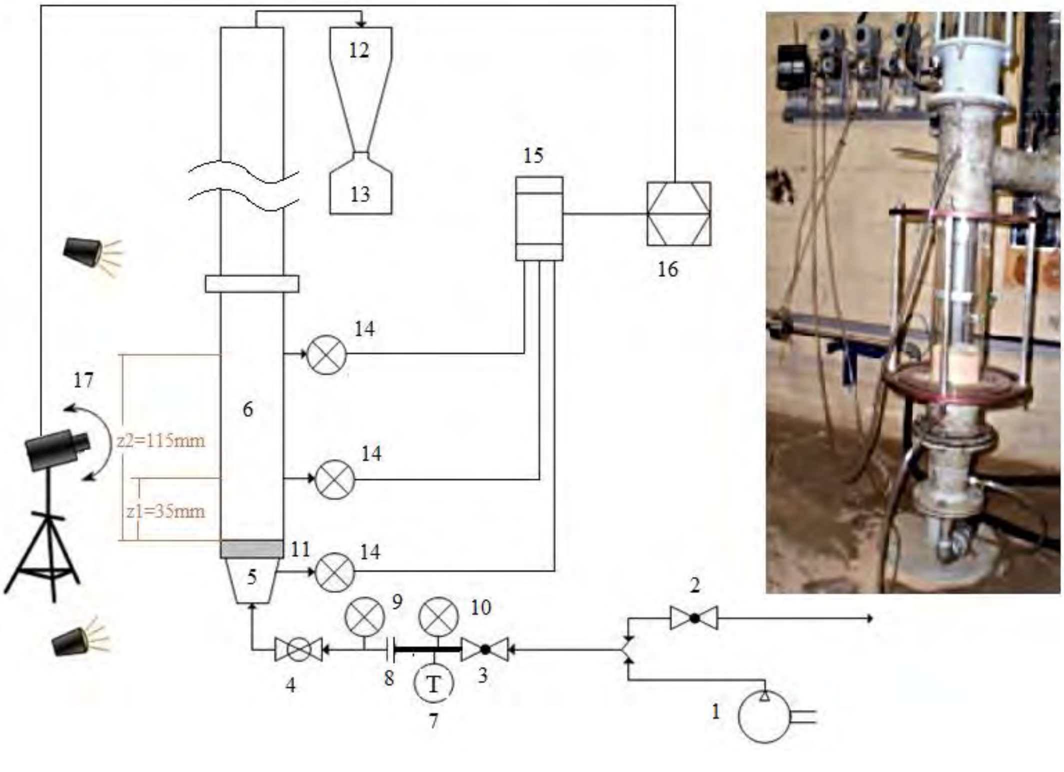


Figure 1. Schematic diagram and image of the experimental set-up:
(1) roots compressor, (2) bypass valve, (3) inlet valve, (4) airflow control valve, (5) plenum, (6) riser, (7) J type thermocouple, (8) orifice plate flowmeter, (9) and (10) differential pressure transducers, (11) distributor plate, (12) Lapple cyclone, (13) hopper, (14) pressure transducers for acquiring pressure fluctuation signals, (15) data acquisition system, (16) computer, (17) image acquisition system.

Pressure fluctuations in the plenum are measured by three pressure transducer: one located at plenum (P_{plenum}), model Smar LD301-D2, 0-50 kPa measuring range, 100 ms response time, ± 0.04 % of full scale accuracy), one located 0.035 m (z_1) above the gas distributor (P_{z1}), model Smar LD301-D2) and the third one located 0.115 m (z_2) above the gas distributor at the riser wall (P_{z2}), model Rosemount 3051, 0-200 kPa measuring range 100 ms response time, ±0.10% of full scale accuracy). These last two transducers were installed in order to verify changes in pressure fluctuations in the axial direction of the bed due to the particles segregation inside the bed.

The data acquisition system (15) in the Fig. 1, consists of three parts: data acquisition board from National Instruments, model NI USB 6255, a microcomputer (16) and the software Matlab 7.0 installed for data acquisition and analysis. The function of this system is basically to capture the voltage signal from the pressure transducers, convert it to digital data format and save these signals into a file for later analysis. An image system (17) showed in Fig. 1, was used to take pictures of the gas-solid flow (model OLYMPUSSP-800UZ). It gave additional information for identifying the gas velocities where the initial and complete fluidizing velocities occur, as discussed before.

2.3 Methodology

Solid materials are introduced inside the riser by the top of the column. The first material introduced was the one performing 95 wt% of the bed weight.

Studies of the hydrodynamics of binary mixtures must consider how the material was inserted in the bed. In this research we used the method applied by Formisani *et al.* (2001), in which the materials in the bed were initially segregated. Materials of smaller and/or lighter particles were inserted first, forming a layer on the bottom of the bed. Particles larger in size or density were placed after, forming an upper layer of the bed. In addition, researches on particle segregation has concentrated mainly on the aspect of the phenomenon of mixing, especially by Rowe *et al.* (1972), Yang and Keairns (1982), which identified two separate layers, one of material with tendency to float and other to sink.

Tests were carried out at room temperature and pressure. The height of the bed was kept constant and equal to 0.15m. After the addition of the material in the bed, gas was injected into the system until the bubbling fluidized bed regime was reached and the bed material was well mixed. From this point a gradual reduction of the gas flow was conducted, until the fixed bed regime was restored.

This procedure was repeated three times for each different bed material (mixtures 1 to 3) inside the bed, performing a total of nine tests, in order to verify the reproducibility of the results.

The bed pressure drop (ΔP_b) was measured for several gas superficial velocities (U_o) and these data were obtained from the relative value of P_{plenum} and distributor pressure drop measurements of the gas distributor ($\Delta P_{distributor}$) as shown in Eq. (2).

$$\Delta P_b = P_{plenum} - \Delta P_{distributor} \tag{2}$$

Tests were performed by acquiring pressure signals at sampling rate of 200 Hz during 50 s performing10000 pressure samples by each pressure transducer connected to the riser (P_{plenum}, P_{z1} *and* P_{z2}) for each tested superficial velocity of the gas flow. This sampling rate is according to recommendation of Wilkinson (1995) regarding the minimum number of data required to obtain a reliable estimation of the standard deviation of pressure measurements (σ_P).

Pictures of the bed were taken for several superficial gas velocities from the bubbling bed to the fixed bed regime.

Time analyses of pressure measurements were performed in the time domain in order to determine the standard deviation of pressure fluctuations as a function of superficial gas velocity, according to proposed by Puncochar *et al.* (1985).

All pressure signal were firstly normalized to remove the signal mean value $\bar{P}$. The methodology used in the analysis consisted initially of a collection of N points of relative pressure in the plenum and in the bed at heights z_1 and z_2 above the distributor plate.

After collecting the pressure signals from the bed, the mean value was extracted up aiming to eliminate the constant pressure level of the bed. This procedure corresponds to a mean centering of the "centering on mean”, which consists of subtracting the mean of a vector ($\bar{P}$) to each element of this vector, which is given by Eq. (3) as proposed by Lopes (2004).

$$PN_k = P_k - \bar{P} \tag{3}$$

Where, PN_k is the normalized pressure or mean centering pressure for k signal; P_k is the gauge pressure for k signal; $\bar{P}$ is the mean value regarding the 10000 gauge pressures collected by each transducer at each studied superficial gas velocity [Eq. (4)].

$$\bar{P} = \frac{1}{N}\sum_{k=1}^{N} P_k \tag{4}$$

An example of the signal can be seen in Fig. 2(a) for P_{plenum} measurements and in Fig. 2(b) for PN_{plenum}.

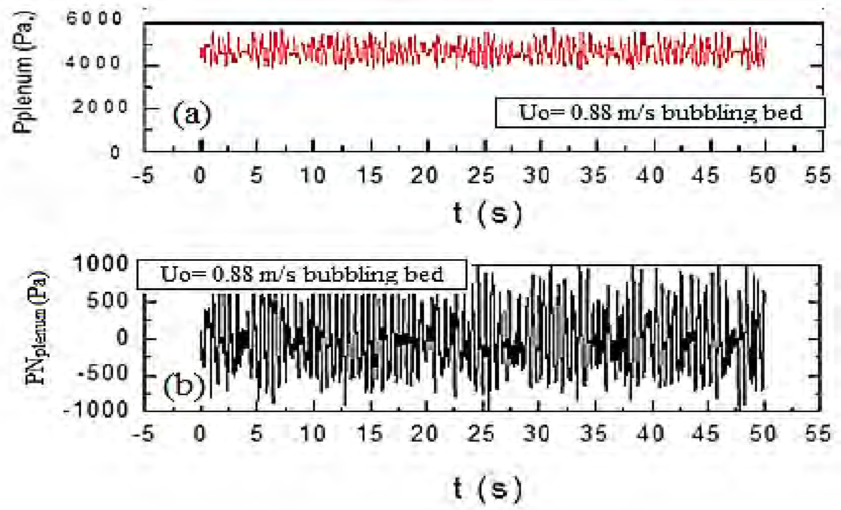


Figure 2. Signal of gauge pressure in the plenum, (P_{plenum}) for (a) gauge pressure signals, (b) mean centering pressure signals.

The standard deviation of pressure fluctuations (σP) was calculated by Eq. (5) and Eq. (6) to observe the behavior of measured signals collected for each tested superficial gas velocity.

$$\sigma P = \sqrt{\frac{1}{N-1}\sum_{k=1}^{N}(PN_k - \overline{PN})^2} \tag{5}$$

$$\overline{PN} = \frac{1}{N}\sum_{k=1}^{N} PN_k \tag{6}$$

Figure 3 shows the influence of the superficial gas velocity on the bed pressure drop (ΔP_b) and on the standard deviation of pressure fluctuations measured at plenum (σP_{plenum}) regarding a preliminary test made using the binary mixture 3 inside the bed.

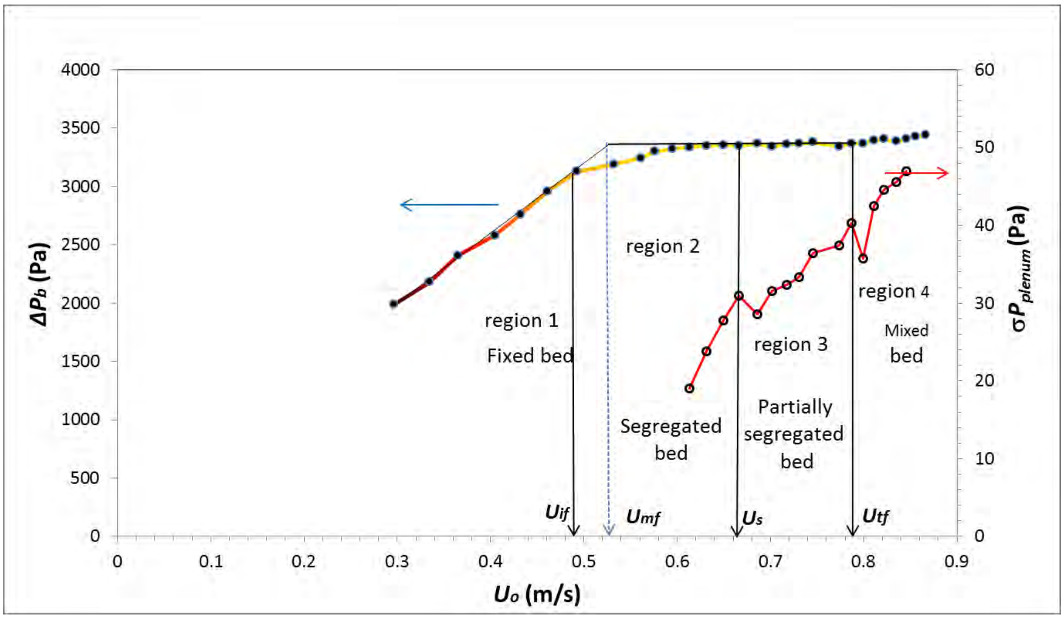


Figure 3. Bed pressure drop and standard deviation of pressure measurements as a function of superficial gas velocity (mixture 3).

On the standard deviation (σP_{z1}) curve showed in Fig. 3, the total fluidizing velocity (U_{tf}) and the gas velocity in which the maximum segregation occurs (U_S) were identified by the more pronounced deflections or peaks observed (Fig. 2).

The minimum fluidizing velocity (U_{mf}) was determined on the bed pressure drop (ΔP_b) curve by the intersection of the fitted straight lines for fixed bed and bubbling bed regimes, as shown in Fig. 3.

The initial fluidizing velocity (U_{if}) was identified by the point where the pressure signals acquired in the fixed bed regime deviates from the straight line fitted for this region.

Figure 3 was divided into four distinct regions: fixed bed (region 1), segregated bed (region 2), partially segregated bed (region 3), and well-mixed bed (region 4). The fluidizing velocities U_{tf}, U_S *and* U_{if} were considered as the transition velocities between these regions. These velocities were obtained for pressure fluctuations data collected by the transducers located at plenum, position z_1 and position z_2 at the riser.

3. RESULTS AND DISCUSSIONS

Figure 4 shows the bed pressure drop and the standard deviation of pressure measurements at plenum, obtained using mixtures 1 to 3 inside the bed. The minimum fluidizing velocity for each mixture was identified from ΔP_b curves while the identification of U_{if}, U_{tf} and U_S were made from σP_{plenum} curves as discussed before (item 2.3).

The comparison of the curves correspondent to each material [Fig. 4 (a), (b) and (c)] show that similar behavior occurred for mixtures 1 and 3 while mixture 2 (plastic-glass2) presents an U_s less evident as several peaks between U_{tf} and U_S were detected This fact is attributed to the Geldart D type behavior of the bed material, which is composed by particles presenting 959 μm (glass2) and 971 μm (plastic).

Figure 4 shows the four gas-solid regions identified in preliminary tests, as presented in Fig. 3. The transition velocities U_{if}, U_{mf} , U_S and U_{tf} are also indicated in Fig. 4.

The superficial gas velocity range depends on the particle properties, mainly particle diameter and particle density, which explains the lowest U_o range for tests involving mixture 3 as it contains the smallest particle (glass1) and the lightest particle (plastic).

The bed pressure drop curves in Fig. 4 shows a typical behavior of binary mixtures which is characterized by a smooth transition between the fixed bed and fluidized bed regimes. As expected, mixture 1 presented the highest U_{mf} value, followed by mixture 2. The lowest U_{mf} was obtained for the plastic-glass1 mixture (mixture 3) as it is composed by 95 wt% of the smallest material.

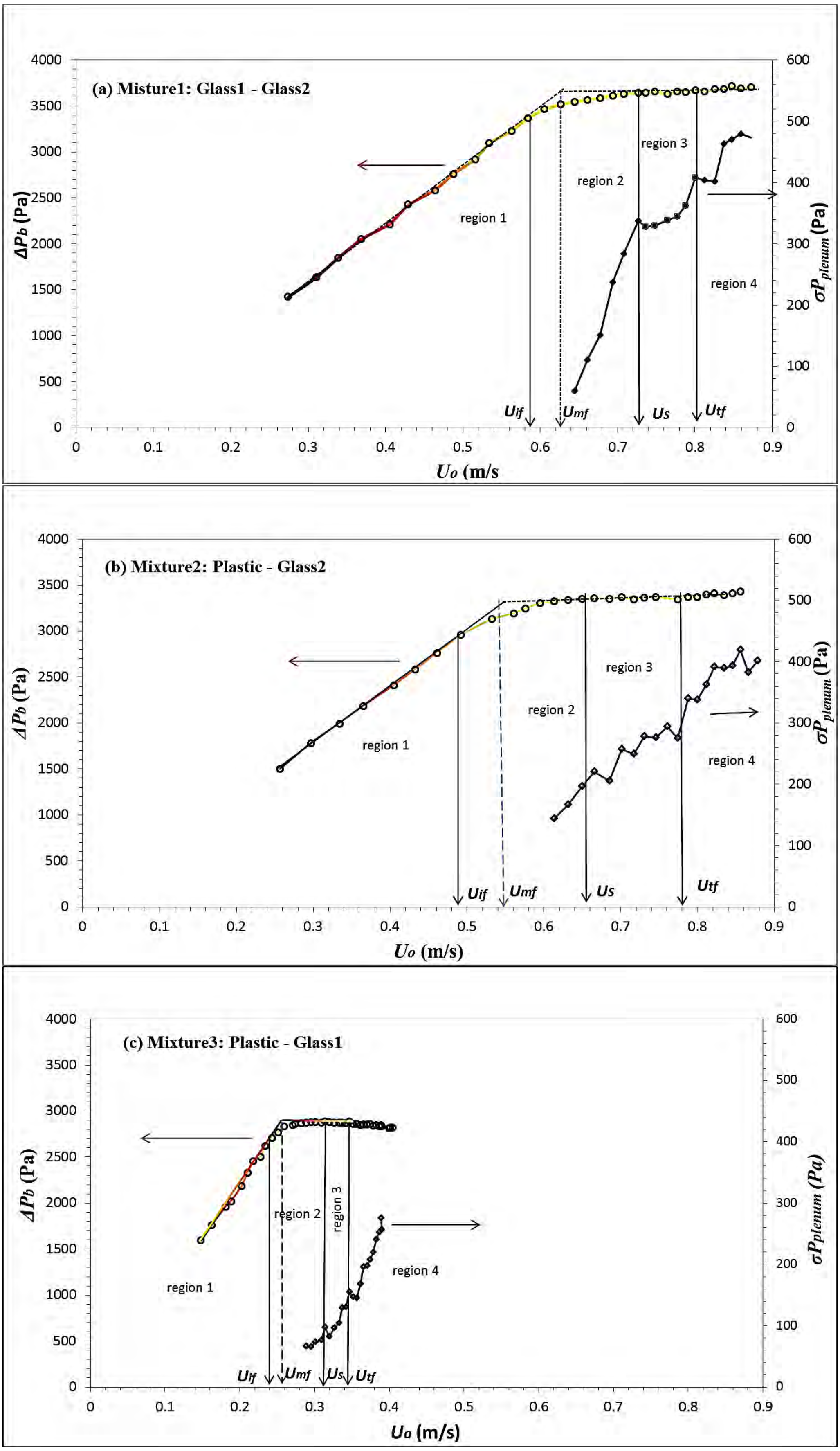
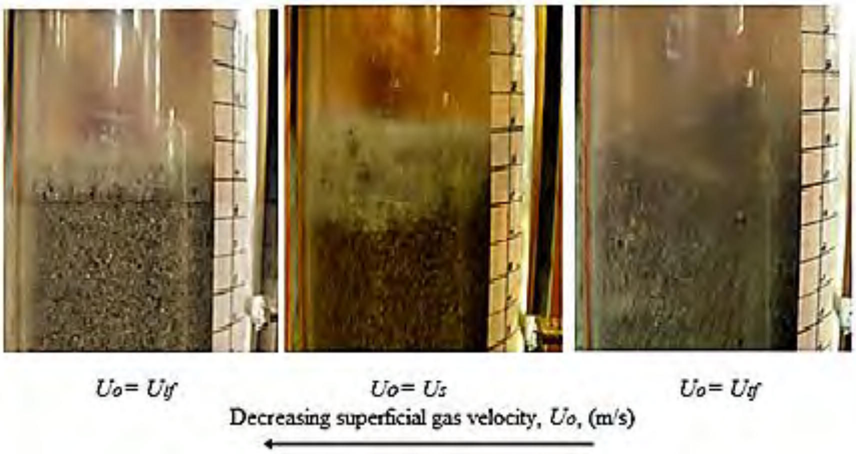
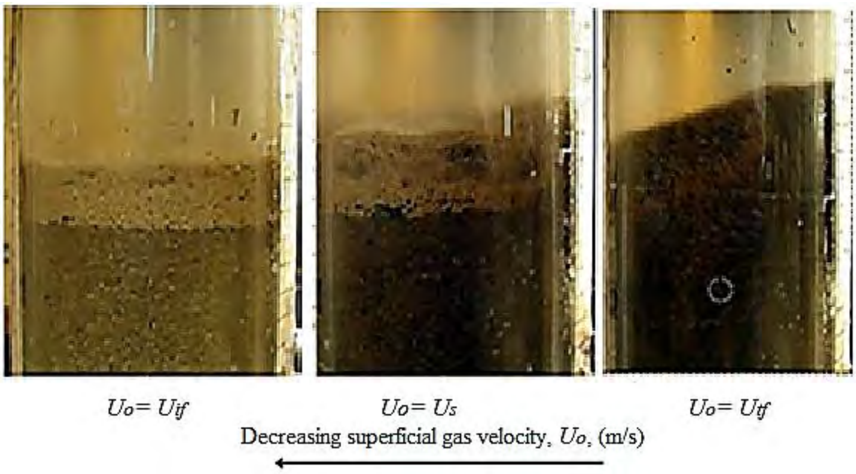


Figure 4. Bed pressure drop and standard deviation of pressure fluctuations at σP_{plenum} as a function of U_o, for mixtures 1 to 3.

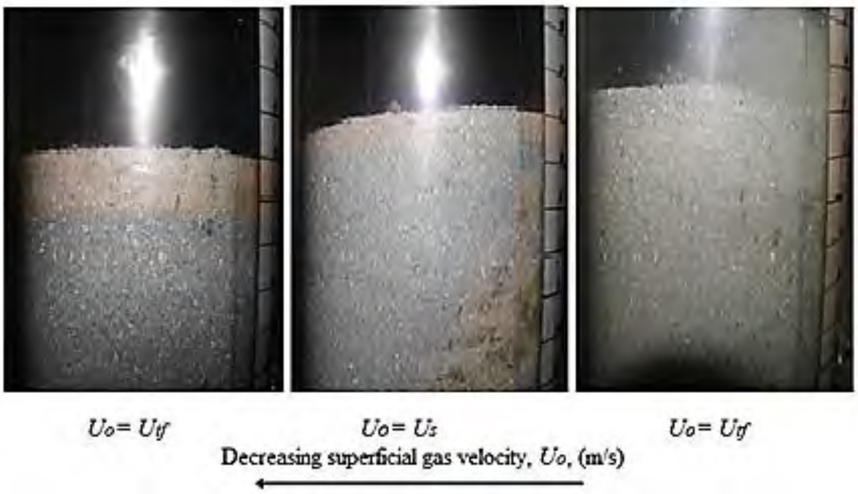
Images of the bed at the moment in which the transition velocities U_{if}, U_S and U_{tf} were detected are showed in Fig. 5.



(a) Mixture1: glass1-glass2



(b) Mixture2: plastic-glass2



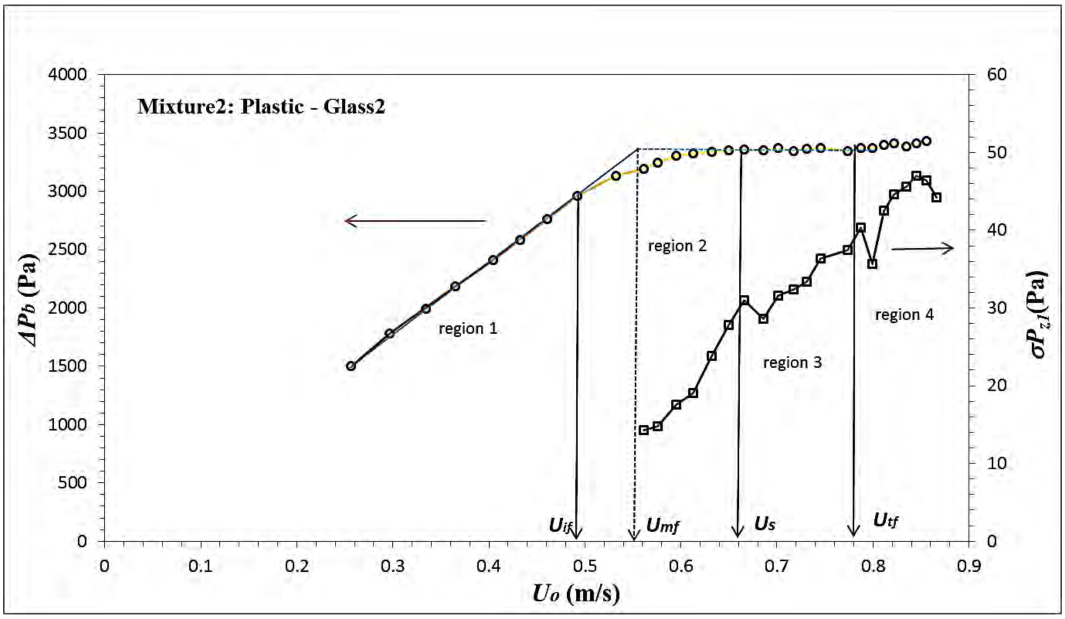
(c) Mixture3: plastic-glass1

Figure 5. Images of bed at transition velocities U_{if}, U_S and U_{tf}, for (a) mixture 1, (b) mixture 2 and (c) mixture 3.

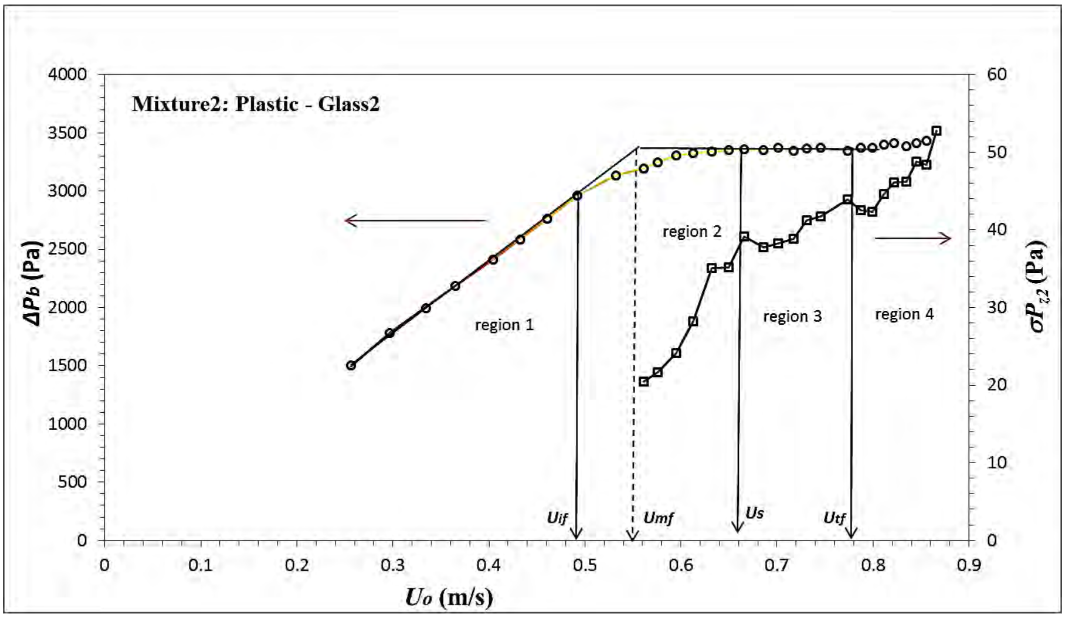
The reduction of the superficial gas velocity (Fig. 5), considering an initially mixed system, shows that around a gas velocity equal to U_{tf}, the segregation process begins. A clearer separation between the two materials, with the smallest or lightest particle at the top, is observed at gas velocities U_s and U_{if}. These materials, called floatsam by Rowe et al. (1972), are glass1 particles for mixture 1 and plastic particles for mixture 2 and 3. Visual observations show that the segregation process reaches a maximum velocity at U_s. At this velocity the segregation process is fast and bubbles can be seen carrying the floatsam particles upward, in the wake region.

As soon as the gas velocity is reduced to U_{if}, the fixed bed regime is reached and the segregation process finishes. The bed is clearly segregated at this point as showed in Fig. 5.

Pressure measurements at positions z_1 and z_2 for mixture 3 (plastic-glass1) inside the riser are shown in Fig. 6. Similar figures were obtained for all tests using mixtures 1 and 2. Figure 6 also shows the bed pressure drop measurements taken at plenum.



(a) Standard deviation from pressure signals at z_1



(b) Standard deviation from pressure signals at z_2

Figure 6. Bed pressure drop and standard deviation of pressure measurements as a function of superficial gas velocity for mixture 2, (a) σP_{z1} (0.0.35 m above distributor plate), (b) σP_{z2} (0.115 m above distributor plate).

The transition velocities are also indicated in Fig. 6 showing that these parameters can also be found from these pressure locations, even though small values of σP were observed. Additionally, it can be noticed that the transition velocities are better visualized from data collected at z_1 than at z_2 as the peaks are higher.

Table 3 shows the results for U_{if}, U_S *and* U_{tf}, from pressure measurements at plenum, z_1 and z_2 regarding all performed tests (three repetitions for each mixture). The results of U_{mf} from bed pressure drop curves are also showed in this table.

Table 3.Values of superficial velocities corresponding to U_{if}, U_{tf}, U_S and U_{mf}.

Bed material	Test	Transducer	U_{if} (m/s)	U_S (m/s)	U_{tf} (m/s)	U_{mf} (m/s) (plenum)
Mixture1: glass1-glass2	1	*Pz1*	0.58	0.73	0.8	0.62
		Pz2	0.59	0.73	0.8	
		Pplenum	0.59	0.74	0.81	
	2	*Pz1*	0.59	0.71	0.8	0.62
		Pz2	0.59	0.73	0.81	
		Pplenum	0.58	0.72	0.8	
	3	*Pz1*	0.58	0.72	0.81	0.63
		Pz2	0.59	0.73	0.81	
		Pplenum	0.58	0.73	0.8	
		Mean value	**0.59**	**0.73**	**0.80**	**0.62**
Mixture2: plastic-glass2	1	*Pz1*	0.48	0.66	0.78	0.56
		Pz2	0.48	0.67	0.78	
		Pplenum	0.48	0.66	0.78	
	2	*Pz1*	0.49	0.66	0.77	0.56
		Pz2	0.48	0.66	0.78	
		Pplenum	0.49	0.67	0.78	
	3	*Pz1*	0.48	0.66	0.78	0.57
		Pz2	0.49	0.66	0.77	
		Pplenum	0.48	0.67	0.77	
		Mean value	**0.48**	**0.66**	**0.78**	**0.56**
Mixture3: plastic-glass1	1	*Pz1*	0.26	0.31	0.34	0.27
		Pz2	0.28	0.32	0.34	
		Pplenum	0.27	0.32	0.35	
	2	*Pz1*	0.27	0.32	0.34	0.28
		Pz2	0.27	0.31	0.34	
		Pplenum	0.26	0.32	0.34	
	3	*Pz1*	0.27	0.31	0.35	0.28
		Pz2	0.27	0.32	0.35	
		Pplenum	0.26	0.31	0.34	
		Mean value	**0.27**	**0.32**	**0.34**	**0.28**

The analysis of Tab. 3 shows a good reproducibility of the results obtained for each tested operational condition.

Table 4 shows the mean values of the transition velocities for each studied mixture as the ratio between each transition velocity and U_{mf}.

Table 4. Transition velocities, mean values for mixtures 1 to 3.

Bed material	$\bar{U}_{if}$ (m/s)	$\bar{U}_S$ (m/s)	$\bar{U}_{tf}$ (m/s)	$\bar{U}_{mf}$ (m/s)	$\bar{U}_{if}/\bar{U}_{mf}$	$\bar{U}_S/\bar{U}_{mf}$	$\bar{U}_{tf}/\bar{U}_{mf}$
Mixture 1	0.59	0.73	0.80	0.62	0.94	1.17	1.29
Mixture 2	0.48	0.66	0.78	0.56	0.86	1.18	1.38
Mixture 3	0.27	0.32	0.34	0.28	0.97	1.14	1.24

A maximum deviation from the mean regarding each minimum fluidizing velocity result equal to 2.4%. Also, U_{if}, Us and U_{tf} results, obtained from σP_{plenum}, σP_{z1} and σP_{z2} data, presented a maximum deviation from the mean value for each velocity, equal to 4.6%. These percentages were calculated by Eq. (7).

$$\Delta U_i = \frac{(U_i - \bar{U}_i)}{\bar{U}_i}.100 \tag{7}$$

In this equation, U_i is the gas velocity (U_{mf}, U_{if}, Us or U_{tf}) and $\bar{U}_i$ is the mean velocity ($\bar{U}_{\mathrm{mf}}$, $\bar{U}_{if}$, $\bar{U}_s$ or $\bar{U}_{tf}$).

Results show that the initial fluidizing velocity obtained for mixture 3 is very close to its minimum fluidizing velocity, which was expected as both materials present similar U_{mf} as shown in Tab. 1. Otherwise, differences among densities and sizes of the particles in the bed caused the segregation phenomena.

Values of the ratio between the complete fluidizing velocity and the minimum fluidizing velocity around 1.3 were found for mixtures 1 and 3. Mixture 2 composed by large particles presented a high value of U_{tf}/U_{mf} ratio (equal to 1,38) showing that the segregation range increases with the increment on the particle diameter of the jetsam material.

Addition of fine particles inside the bed helps the fluidizing process and reduces the segregation velocity range as they can fit into the voids between the large particles. This behavior could be verified by comparing results from mixture 1 (glass1-glass2) and mixture 3 (plastic-glass2).

Additionally, results of $\bar{U}_S/\bar{U}_{mf}$ from Table 4, shows that the gas velocity in which the transition between a segregated bed and a partially segregated bed occurs is around 1.2 U_{mf} for all the tested mixtures. This operational condition indicates the superficial gas velocity in which the separation of the mixture components inside the bed is more intense.

4. CONCLUSIONS

Pressure fluctuations analysis in the time domain allowed the identification of the initial (U_{if}) and total (U_{tf}) fluidizing velocities as the gas velocity in which a faster segregation process occur (U_S).

Pressure measurements can be done at the plenum or at different locations in the riser above the distributor plate to obtain the transition velocities U_{if}, U_S and U_{tf}.

Four zones in the fluidizing process of the bed were identified for beds containing binary mixtures: (1) fixed bed; (2) segregated bed; (3) partially segregated bed; and (4) well-mixed bed.

The gas velocity in which the maximum segregation occurs is around 1.2 U_{mf} for all the tested mixtures.

The addition of fine particles inside the bed helps the fluidizing process and reduces the segregation velocity range as they can fit into the voids between the large particles.

5. ACKNOWLEDGEMENTS

The authors thank the financial support provided by Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES) from Brazil for the scholarship received by D. A. Rueda-Ordóñez.

6. REFERENCES

Amutio, M., Lopez, G., Artetxe, M., Elordi, G., Olazar, M., Bilbao, J., 2012.“Influence of temperature on biomass pyrolysis in a conical spouted bed reactor”. Resources, Conservation and Recycling. Vol. 59, p. 23–31.

Chiba, S., Chiba, T., Nienow A. W., Kobayashi H, 1979. “The minimum fluidization velocity_ bed expansion and pressure-drop profile of binary particle mixtures”. Powder Technology, Vol. 22, p. 255 – 269.

Clark, N. N, Atkinson, C. M., 1988. “Amplitude reduction and phase lag in fluidized-bed pressure Measurements”. Chemical Engineering Science, Vol. 43, p. 1547-1557.

Felipe, C. A., Rocha, S. C, 2007. "Prediction of Minimum Fluidizing Velocity of Gas-Solid Fluidized Bed by Pressure Fluctuation Measurements – Analysis of the Standard Deviation Methodology". Powder Technology, Vol.174, p. 104-113.

Formisani, B., De Cristofaro, G., Girimonte, R., 2001. "A fundamental approach to the phenomenology of fluidizing of size segregating binary mixtures of solids". Chemical Engineering Science. Vol. 56, p. 109-119.

Formisani, B., Girimonte, R., Longo, T., 2008. "The fluidizing process of binary mixtures of solids: Development of the approach based on the fluidizing velocity interval". Powder Technology. Vol. 185, p. 97 – 108.

Haider, A., Levenspiel, O. 1989. "Drag coefficient and terminal velocity of spherical and non-spherical particles". Powder Technology. Vol. 58, p. 63 – 70.

Johnsson, F., Zijerveld, R. C., Schouten, J. C., Van Den Bleek, C. M., Leckner, B., 2000. "Characterization of fluidizing regimes by time-series analysis of pressure fluctuation" International Journal of Multiphase Flow, Vol. 26, p. 663-715.

Yang, W. C. M., Kearns, D. L., 1982. "Rate of particle separation in a gas fluidized bed". Ind. Eng. Chem. Fundamentals J." Vol. 21, p. 228-235.

Kwant G., Prins W., van Swaaij, W. P. M., 1995. "Particle mixing and segregation in a binary solids floating fluidized bed".Powder Technology. Vol. 3, No. 82, p. 279-291.

Leckner B., Karlsson M., 1993. "Emission from circulating fluidized bed combustion of mixtures of wood and coal", in: Rubow, L., Commonwealth, G. (Eds.), Proceeding of 1993 International Conference on Fluidized Bed Combustion. American Society of Mechanical Engineers, New York, 109-115.

Lopes, N. E. C., Moris, V. A. S.,Taranto, O. P. 2009. "Analysis of spouted bed pressure fluctuations during particle coating". Chemical engineering and processing: process intensification. Vol. 48, p. 1129-1134

Olazar, M., Gartzen, L., Arabiourrutia, M.,Elordi, G.,Aguado, R., Bilbao, J., 2008. "Kinetic modeling of tyre pyrolysis in a conical spouted bed reactor". Journal of Analytical and Applied Pyrolysis. Vol. 81. No. 1, p. 127-132.

Puncochar, M., Drahos, J., Cermak, J., Selucky, K., 1985. "Evaluation of minimum fluidizing velocity in gas fluidized bed from pressure fluctuations". Chemical Engineering Communications. Vol. 35, p. 81-87.

Rowe, P. N., Nienow, A. W., Agbim, A. J., 1972. "A preliminary quantitative study of particle segregation in gas fluidized beds – Binary system of near spherical particles". Trans. Instn. Chem. Engrs. Vol. 52, p. 324-333.

Schouten, J. C., van Den Bleek, C. M., 1998. "Monitoring the quality of fluidizing using the short-term predictability of pressure fluctuations". AIChE Journal. Vol. 44, p. 48-60.

Sosna, M. K., Kondukov, N. B., 1968. " Criterion and formula for calculating the fluidizing velocity of a polydisperse bed". Inzhenerno Fizicheskii Zhurnal. Vol. 15, No. 1, p. 73-78.

Wilkinson, D., 1995. "Determination of minimum fluidizing velocity by pressure fluctuation measurement" The Canadian Journal of Chemical Engineering. Vol. 73, p. 562-565.

Yates, J. G., Simons, S. J. R. 1994. "Experimental methods in fluidizing research". International Journal Multiphase Flow. Vol. 20, p. 297–330.

7. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.