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A new segregation index for solid multicomponent mixtures

Mauricio M. Coletto [a,b,*], Daniele L. Marchisio [a], Antonello A. Barresi [a]

[a] Dip. Scienza Applicata e Tecnologia, Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Turin, Italy
[b] Departamento de Química, Universidad Nacional del Sur, Av. Alem 1253, B8000CPB Bahía Blanca, Argentina

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ABSTRACT

Several indices can be found in the literature in order to quantify the mixing degree of two component mixtures in fluidized beds, but none of them is actually capable of describing how a specific component of the mixture is distributed. Many of these indices may be influenced by the experimental procedure used for evaluating the mixture, such as the number of vacuumed layers, or equivalently the layer thickness, since the solids distribution is generally measured in layers (or at most in cells) and not in a continuous way along the bed. In the present work, a novel set of indices for studying segregation is proposed: the Three Thirds Segregation Indices Set, is developed allowing the characterization of not only the segregation level, but also the segregation pattern of a specific component of interest. The set is also compared, tested and validated with other existing indices (M index by Rowe et al. (1972) and "s" index by Goldscmidt et al. (2003)), and experimentally verified. As a result of these tests, it is found that M and "s" indices do not allow the comparison of experiments performed with different numbers of layers, and they do not distinguish different segregation profiles leading to some mistakes when in the proximity to the extreme cases (Full Central or Full Bottom segregation). On the opposite, the new set of indices turns out to be independent on the number of layers, and to minimize experimental errors or the discrepancies caused by applying different experimental procedures.

1. Introduction

Mixtures of solids are widely used in the process industry (such as food, petrochemical, or cement industries). According to the process characteristics and the desired final product, mixing can be carried out in different types of devices, such as mixers or fluidized beds. However, as solids mixtures are usually composed of particles differing in density and/or size, they may segregate or do not mix properly.

During the 1960s and 1970s a considerable number of indices were developed in order to quantify and characterize the mixing or segregation of a binary mixture and the performance of different types of mixers, such as the static mixer, the conical rotating mixer, the ribbon mixer, or the twin shell mixer, used mainly in the cement industry. As the evaluation of the mixture quality in these devices is performed by sampling, many of these indices were based on statistics; perfectly ordered, randomly mixed, or totally segregated mixture are then generally considered as limit cases [1–4].

Mixing performances are also important in other types of devices, such as fluidized beds or spout-fluid beds, often employed in the process industry, as chemical reactors or dryers; the atmospheric lyophilization of food by immersion in adsorbent material is an example of a complex binary mixture for which segregation can impair dramatically performances. In the fluidized bed air is passed through a perforated plate, while in the spout-fluid bed air is injected by means of a main injector (like a spouted bed) and lateral injectors, conferring a better mixing performance to the apparatus.

Many segregation or mixing indices were also developed specifically for characterizing mixing and segregation in fluidized beds, and some of them are based on statistical concepts similarly to those used for mixers. Di Renzo et al. [5] applied the *Mixing Index* proposed by Lacey [6], involving the variance of the concentration distribution in the particle system, to analyze segregation in a binary system of particles with different density and equal size. Zhang et al. [7] utilized the "Shannon entropy", which is also based on statistics, as indicator of the mixing performance evaluating the dynamics of mixing and the effect of time and particle density. Barghi et al. [8] proposed a mixing index based on collisions between aluminum tracer particles and the probes, assuming that the collisional frequency is proportional to the concentration of particles in a given bed height. Methods to predict the segregation behaviour of a mixture from the particle and fluid physical properties have also been proposed: Escudié et al. [9] used a "reduced bulk density" (taking into account particles and fluid densities) as indicator of the segregation degree in a liquid fluidized bed.

* Corresponding author at: Departamento de Química, Universidad Nacional del Sur, Av. Alem 1253, B8000CPB Bahía Blanca, Argentina.
E-mail addresses: mauricio.coletto@polito.it, mcoletto85@gmail.com (M.M. Coletto).

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Among the segregation indices, one of the most widely used is the M mixing index proposed by Rowe et al. [10], based on jetsam fractions in the upper part (X_J) and the whole of the bed ($\overline{X}_J$):

$$M = \frac{X_J}{\overline{X}_J} \tag{1}$$

This index can be applied as long as the jetsam and flotsam are clearly identified, bottom segregation is preponderantly dominant, and jetsam concentration and particle size are such that eventually one layer whose concentration is around 100% may be found. Thus, $M = 1$ corresponds to perfect mixing, whereas $M = 0$ means complete segregation.

In addition, Wu and Baeyens [11] reviewed predictive equations for this index, and for mixture minimum fluidization velocity calculation available in literature, and proposed a new equation for predicting M mixing index based on their experimental results.

On the other hand, Goldschmidt et al. [12] developed a segregation index suitable for digital image analysis of segregation in fluidized beds, the "s" index, which takes into account the composition along all the bed of both components of a binary mixture, and normalizes it considering a theoretical maximum segregation degree of the mixture. The mathematical formulation of the index is the following:

$$s = \frac{S-1}{S_{\max}-1} \tag{2}$$

where S is the ratio of an average layer height of small particles to the same quantity calculated for large particles,

$$S = \frac{\langle h_{\mathrm{small}} \rangle}{\langle h_{\mathrm{large}} \rangle} \tag{3}$$

and $S_{\max}$ represents the theoretical maximum degree of segregation,

$$S_{\max} = \frac{2-x_{\mathrm{small}}}{1-x_{\mathrm{small}}} \tag{4}$$

where x_{small} is the overall mass fraction of small particles in the bed.

Moreover, in their work the authors used particles of two different sizes colored according to their diameter. Therefore, after taking images during the fluidization and dividing the generated pictures in cells, they analyzed the color distribution, and calculated the solid volume fractions in each cell from the total area of pixels identified as particles in each cell. Thus, the numerator and denominator of Eq. (3) were calculated as follows:

$$\langle h_{\mathrm{large}} \rangle = \frac{\sum_k x_{\mathrm{large}} \alpha_{\mathrm{large},k} h_k V_k}{\sum_k x_{\mathrm{large}} \alpha_{\mathrm{large},k} V_k} \tag{5}$$

$$\langle h_{\mathrm{small}} \rangle = \frac{\sum_k x_{\mathrm{small}} \alpha_{\mathrm{small},k} h_k V_k}{\sum_k x_{\mathrm{small}} \alpha_{\mathrm{small},k} V_k} \tag{6}$$

where $\alpha_{\mathrm{large},k}$ or $\alpha_{\mathrm{small},k}$ is the total volume fraction of small or large diameter particles in the cell (depending on the case), x_{large} or x_{small} is the overall mass fraction of large or small particles in the bed, and h_k and V_k represent, respectively, the height of the center of the cell k from the air distributor and the cell volume.

Therefore, a value of 1 for the "s" index corresponds to a completely segregated system, whereas $s = 0$ means perfect mixing. This index can be also extended to ternary mixtures as done by Olaofe et al. [13] for mixtures composed of glass particles of equal density and different diameter.

Despite several indices were proposed by different authors in order to quantify the segregation level or mixing of a binary mixture in a fluidized bed, none of them is actually able to describe how a specific component of the mixture is distributed along the bed. In other words, sometimes it is important not only to know how much the binary system differs from the uniformity, but also the distribution of a certain component of interest.

On the other hand, proposed indices are generally influenced by the experimental procedure used for evaluating the mixture, such as the number of vacuumed layers (or the layer thickness), since the solids distribution is measured in layers (or at most in cells) and not in a continuous way along the bed. Consequently, it might be difficult to compare experiments done with non-equal number of layers and in fluidized beds of different size, and generally to compare results presented by different authors.

As it was mentioned above, the previously proposed segregation indices do not describe the shape of the segregation profile. In addition, according to the results of the theoretical tests hereafter described, they sometimes do not give completely accurate results, in particular when central segregation is present or the number of experimental layers varies even for the same segregation pattern.

Therefore, the main scope of the present work is to develop an appropriate segregation index which allows the comparison among different experiments independently of the equipment details and the experimental procedure used. It will be tested both with simulated and experimental cases and evaluated in comparison with other existing indices (M and "s").

2. The new segregation index

A new set of indices is proposed, based on the measure of the distribution of the material of interest along the bed and the segregation level; this differs from previous indices which use only one quantity to evaluate the segregation. This set is denominated Three Thirds Segregation Set of Indices (TTSIS), and is defined as:

$$TTSIS = [p_{\mathrm{I}}, p_{\mathrm{M}}, p_{\mathrm{S}}]_{\aleph_2} \tag{7}$$

where p_{I} is the Bottom Third Indicator, p_{M} is the Middle Third Indicator, p_{S} is the Top Third Indicator, and $\aleph_2$ is the Segregation Level. Defining $F_q(h^*)$, the accumulated mass of material of interest "q", as a function of the dimensionless bed height from the bottom (h^*), these three indicators are calculated as follows:

$$p_{\mathrm{I}} = \frac{F_{\mathrm{q}}\left(\frac{1}{3}\right)}{m_{\mathrm{qT}}} \tag{8}$$

$$p_{\mathrm{M}} = \frac{F_{\mathrm{q}}\left(\frac{2}{3}\right) - F_{\mathrm{q}}\left(\frac{1}{3}\right)}{m_{\mathrm{qT}}} \tag{9}$$

$$p_{\mathrm{S}} = \frac{m_{\mathrm{qT}} - F_{\mathrm{q}}\left(\frac{2}{3}\right)}{m_{\mathrm{qT}}} \tag{10}$$

and

$$\aleph_2 = \max(p_{\mathrm{I}}, p_{\mathrm{M}}, p_{\mathrm{S}}) - \min(p_{\mathrm{I}}, p_{\mathrm{M}}, p_{\mathrm{S}}) \tag{11}$$

where m_{qT} is the total mass of the material of interest in the bed.

Table 1
TTSIS extreme values.

p_{I}	p_{M}	p_{S}	$\aleph_2$	Meaning
0.33	0.33	0.33	0.00	Pure uniform distribution
0.00	0.00	1.00	1.00	Full top segregation
0.00	1.00	0.00	1.00	Full central segregation
1.00	0.00	0.00	1.00	Full bottom segregation
0.50	0.00	0.50	0.50	Pure V-segregation