Assessment of Homogenization Degree of Powder Mixing in a Cylinder Rotating Under Cascading Regime

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Abstract— The aim of this work is to evaluate the homogeneity degree of powder mixtures by studying axial and radial profiles, which are developed on a cylinder rotating under cascading regime, and two conditions of initial loaded distribution. The quantification of the internal composition of the mixture over time was obtained by solidification technique coupled to the image processing and analysis. Two sand types with similar properties, except for color, were mixed according to the experimental design. After, a binder was added to solidify sample when the mixing reaches homogeneity, and then it was sliced for taking pictures. The concentration and the homogeneity degree were calculated by statistical analysis based on the standard deviation using image processing and analysis. The fraction of orange particles in the radial zone of each slice is close to 0.5, while increasing the mixing time for both vertical and horizontal distributions, which is the desired value for a mixture having the same amount of two types of particles. The homogeneity degree in the radial profile of mixing with initial horizontal distribution is stabilized at about 30 seconds of operation for all the slices, but the region of radius 4 has lower value of RSD by continuous exchange of particles in this zone. On another hand, the homogeneity degree in the axial profile increases with increasing the mixing time; initially, the particle distribution is bimodal due to segregation of components and finalizing with unimodal particle distribution.

Keyword- Homogeneity degree, Cascading regime, Axial and radial profiles, Mixing

I. INTRODUCTION

The powder mixing is a very important process in the manufacture of glass, pharmaceuticals, processed food, ceramics, plastics, detergents, fertilizers, among others. Evidence of this is the world production that represents more than one billion pounds by year of products in way of granular and powder, which must be uniformly mixed to achieve the goals of quality [1]-[3]. Since many factors can affect the quality of mixing, it is crucial to monitor the internal distribution to establish the desired homogeneity point.

Many studies have expanded the area leading to the development of experimental techniques, and theories that analyze the flow behavior under different mixing regimes. In particular Ding et al. [4] presented theoretical models to calculate the rotation time of particle bed in the regimes of rolling and avalanche, and the transition between them. Likewise J. Mellman [5] developed simplified mathematical models that describe the behavior of transition between regimes.

There are different methods to analyze the evolution of the mixing process, divided into three categories. The first, emphasizes the use of tracers to follow the evolution of the mixed [6], [7], the second uses the online image analysis to follow the dynamics of the particles [8]-[11] and the third provides information on the internal structure of mixing through off-line analysis of samples [12]-[15].

Methods of particle bed solidification have been studied in different works [12]-[15] where image processing is used to analyze the composition internal of granular mixture. Wightman et al. [16] solidified the granular bed to characterize the structure of granular mixtures in a mixer with rocking. In this work used image analysis, providing an effective method for performing a detailed quantitative characterization. On the other hand, Obregon et al. [13] built a low shear mixing device consisting of a box with two moving walls and three static walls to study granular mixing. A fast digital camera with high resolution was used to take image during mixing process. After, particle bed was solidified and the entire slab was cut vertically in slices to analyze the composition internal under different periodic shear rate. Meanwhile, Dal Grande et al. [17] determined composition in granular mixtures through colorimetric imaging using a small scale drum mixer. After blending, the mixtures have been solidified and sliced to study the internal structure. The colorimetric analysis has been carried out on the interior of the granular bed. Its results have high accuracy and precision, and this method does not require a calibration curve and is therefore faster to implement and easier to generalize.

Many authors have studied the effect of different process variables [3], [18]-[20] on the mixing time. Some variables are: particle size, rotation speed of mixer, filling percentage, mixer diameter, number of baffles (paddles), repose angle, quantity ratio of each component. Other researchers [9], [20]-[22] have analyzed the powder flow behavior in diverse type of mixer, such as, high shear, rolling drum, the double-cone, the V-blender and tote-blender.

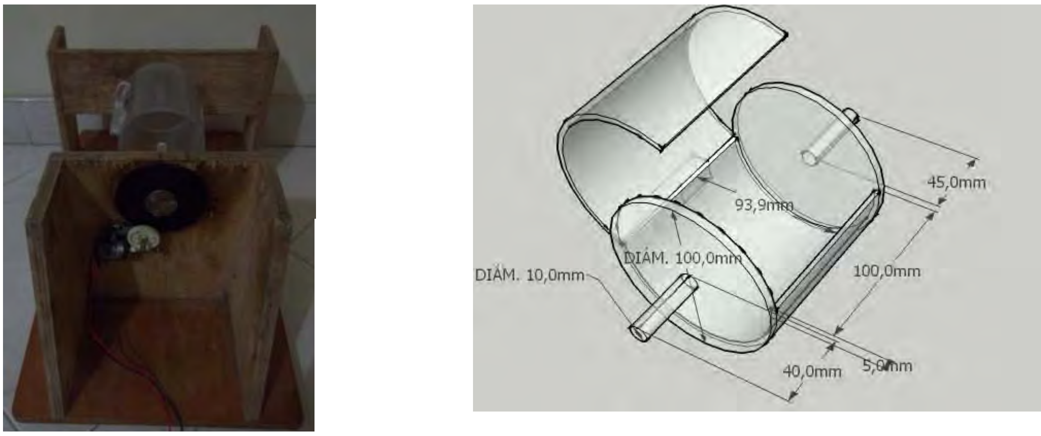
The objective of this work is to determine the composition and the homogenization degree of particle mixing in a rotating cylinder considering the axial and radial profiles developed under the cascading regime, and two initial distributions of the each component inside mixer.

II. MATERIALS AND METHODS

A. Experimental Equipment and Materials

Experiments were carried out in the cylindrical drum as shown in Fig. 1. The drum was constructed from acrylic and it has a length of 100 cm and diameter of 100 cm. It was powered by an electric motor of 12 volts and control of rotation rate was carried out by a pulse width modulator (PWM). All the tests were performed in the rolling and cascading regimes at 21.8 and 7.9 rpm, respectively, according to Froude number, which are common in many industrial applications [23].

The filling ratio of mixer corresponds to approximately 35%, based on previous research [24]. Two components were charged in the mixer by varying the initial distribution in two ways, a) two horizontal layers and b) two vertical layers, as shown in Fig. 2.



a) b)

Fig. 1. a) Top view of the mixer with its wooden support, and b) dimensions of mixer drum.

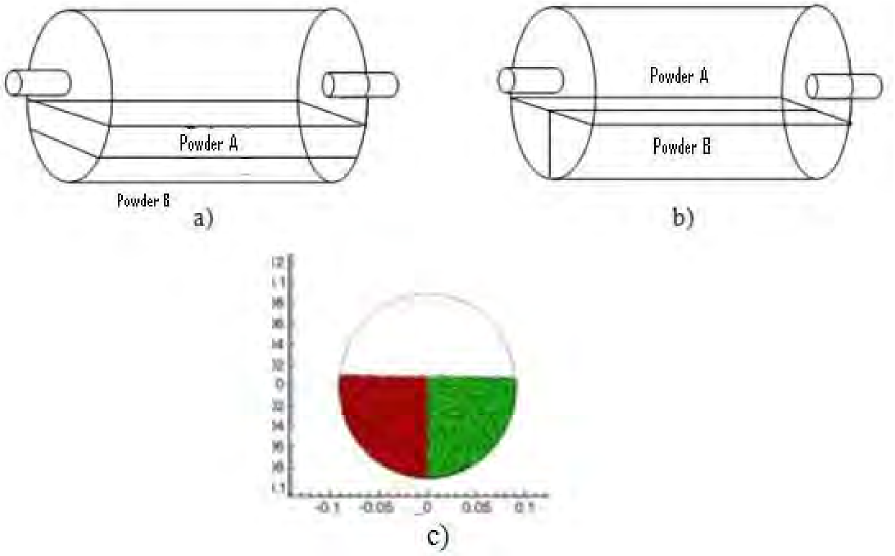


Fig. 2. Initial distributions of particles load, a) horizontal distribution and b) vertical distribution, and c) dimensions of each particle bed in the mixer.

The blue and red particles were obtained from granite stone and they are used for the mixing experiments; these particles could be identified adequately by means of a CCD camera. The particles of each color were sieved to choose particles of similar sizes retained by the mesh sieves of 325 and 270, and therefore to diminish segregation phenomenon by particle size during mixing.

The sampling times (2.8, 5.5, 13.7, 30.6 y 46.2 seconds) were determined by preliminary tests of the mixing profile, by calculating standard deviation of the surface concentration of the mixture at different time for both particle distributions, see Fig. 3.

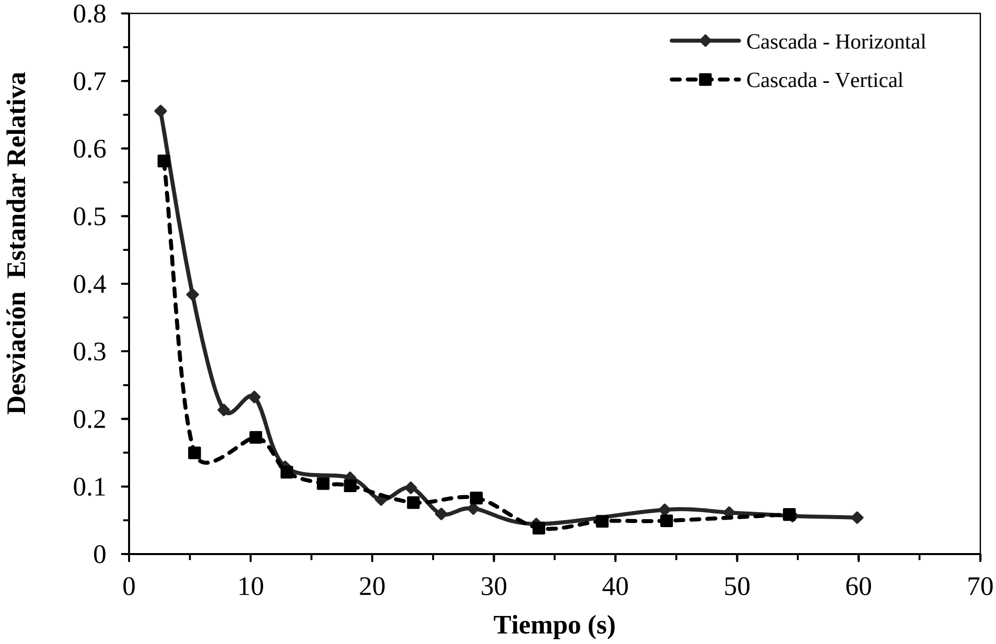


Fig. 3. Preliminary tests for analyzing the particle bed surface in cascading regime.

The cylindrical drum was longitudinally divided into two parts as indicated in Fig. 1b, and this allowed the loading and removal the particles from mixer after their solidification. Initially, the particles were loaded with two vertical layers (vertical distribution), according to Fig. 2b, with blue particles placed on the left and red one on the right. A solidification technique [15, 25, 13] was used to evaluate internal composition of particle mixture by using commercial gelatin as solidifier. After adding the gelatin is waited for eight hours to percolate through the entire bed, then, the mixture was refrigerated for about six hours at 2 degrees Celsius.

Finally the entire slab was cut vertically in 6 slices of thick 16.7 cm, as shown in Fig. 4. Pictures of each slice were taken quickly to study the distribution of particles in the vertical layers (y and z axes). The same procedure was done when particles were loaded in two horizontal layers, Fig. 2a.

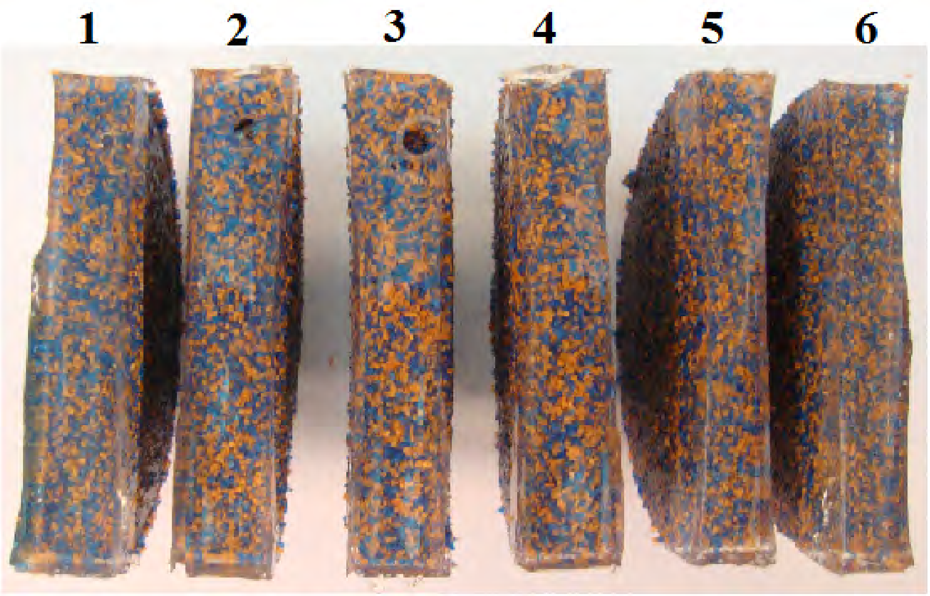


Fig. 4. Top view of the six axial slices of the solidified particle bed.

B. *Image Processing and Analysis for Determining Degree of Homogeneity*

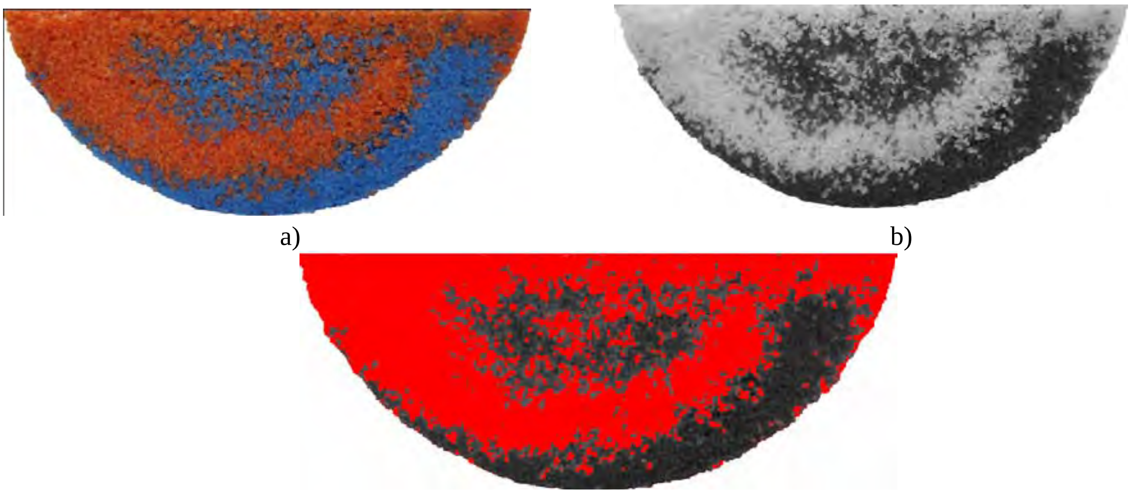
The images received by the CCD camera were converted to gray levels and binarized using IMAQ Vision Builder® of National Instruments, see Fig. 5. Also, Adobe Photoshop® CS2 software was used to cut images in radial and axial way, see Fig. 6.

The degree of homogeneity of the process was evaluated by construction of mixed curve as a function of the time. The relative standard deviation (RSD) was utilized (Equations 1 and 2) for the axial and radial analysis, to compare the degree of dispersion of average concentration for each image.

$$RSD = \frac{S}{\bar{C}} \tag{1}$$

$$S = \sqrt{\frac{\sum_{i=1}^{n}(C_i - \bar{C})^2}{n}} \tag{2}$$

where S is the standard deviation, $\bar{C}$ is the average concentration, C_i is the concentration of section i and n is the total number of samples.

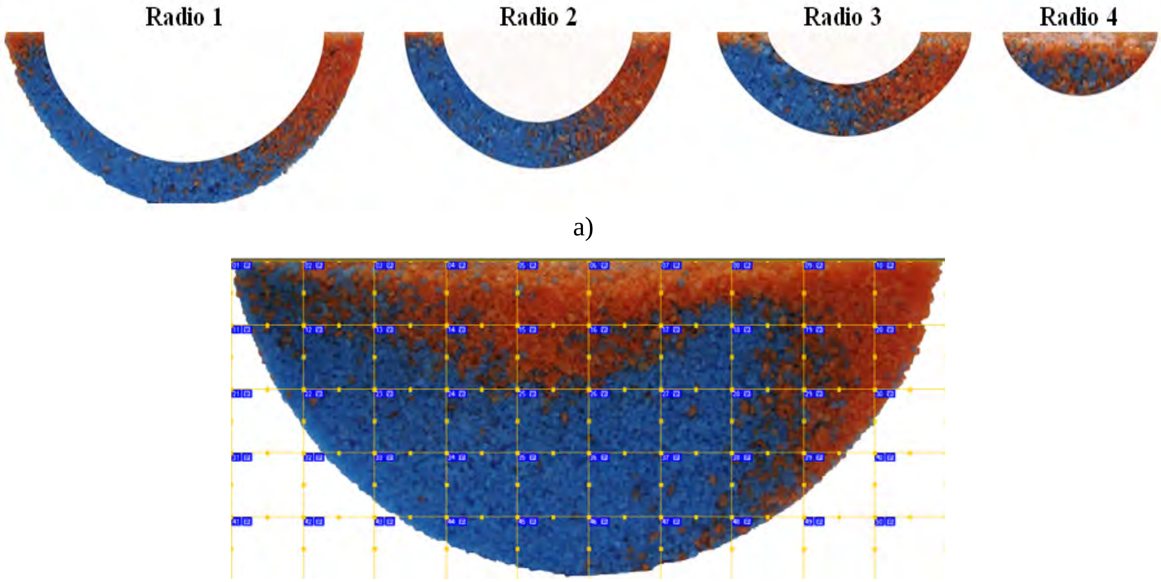

a) b)

c)

Fig. 5. Image processing IMAQ Vision Builder®: a) original image, b) grayscale image, c) binarized image

The radial analysis was carried out by dividing the image of a slab section (Fig. 5a) into four parts (radius), see Fig. 6a. Then, the concentration was determined in each radio as explained above.

The axial analysis was done by taking images of each slice and measuring its concentration. Each picture with a size of 3146 X 1253 pixels was partitioned into 50 sections of 314 X 251 pixels, Fig. 6b.



a)

b)

Fig. 6. a) Radial cuts of slab, and b) axial divisions of slab

III. RESULTS AND DISCUSSION

Figure 7 shows the variation of homogenization grade on the surface of the particles bed through relative standard deviation (RSD) as a function of mixing time for cascading regime with horizontal and vertical initial distributions of the components. For vertical initial distribution of components, the RSD decreases rapidly during the first 20 seconds and homogeneity is reached. However, a steady state of homogeneity is reached in approximately 40 seconds.

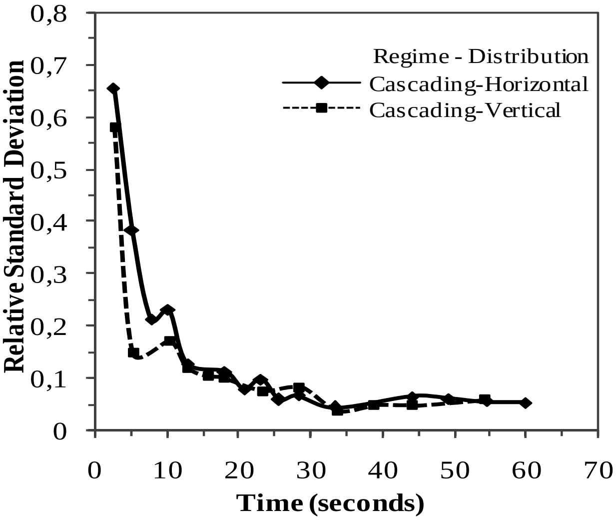


Fig. 7. Preliminary tests and analysis of the surface of the particles bed for cascading regime.

The sampling times, to stop the mixing process and by adding the solution in the mixture of particles were determined by analysis of the homogenization grade shown in Fig. 7. The chosen sampling times to analyze the inside particle beds, were: 2.79 s, 5.45 s, 13.71 s, 30.58 s and 46.19 s. According to the initial distribution of components along the mixer, it was assumed that there is symmetry with respect to the middle zone being perpendicular to the axis of rotation. Therefore, the axial slices: 1 and 6, 2 and 5, and 3 and 4 have similar concentration profiles as shown in Fig. 8. Based on the results observed in Fig. 8, three slices (1, 2 and 3) of the solidified particle bed were taken to study the axial and radial profiles, and to facilitate the images processing.

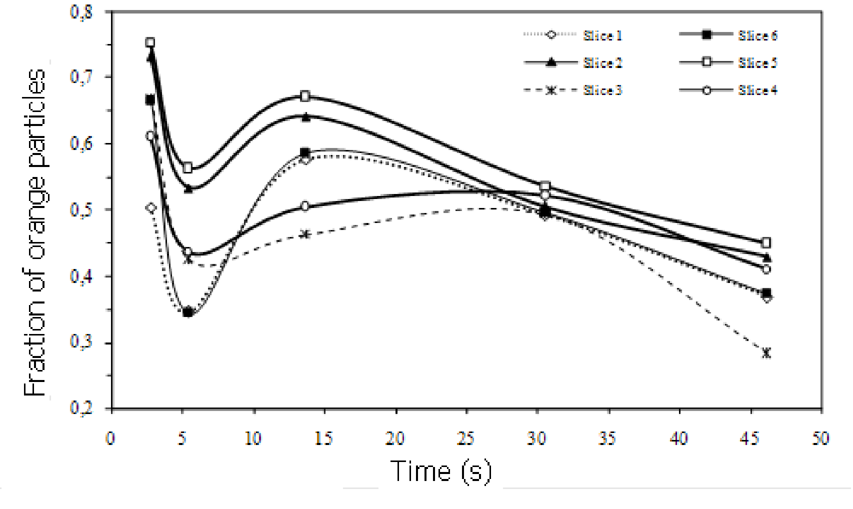
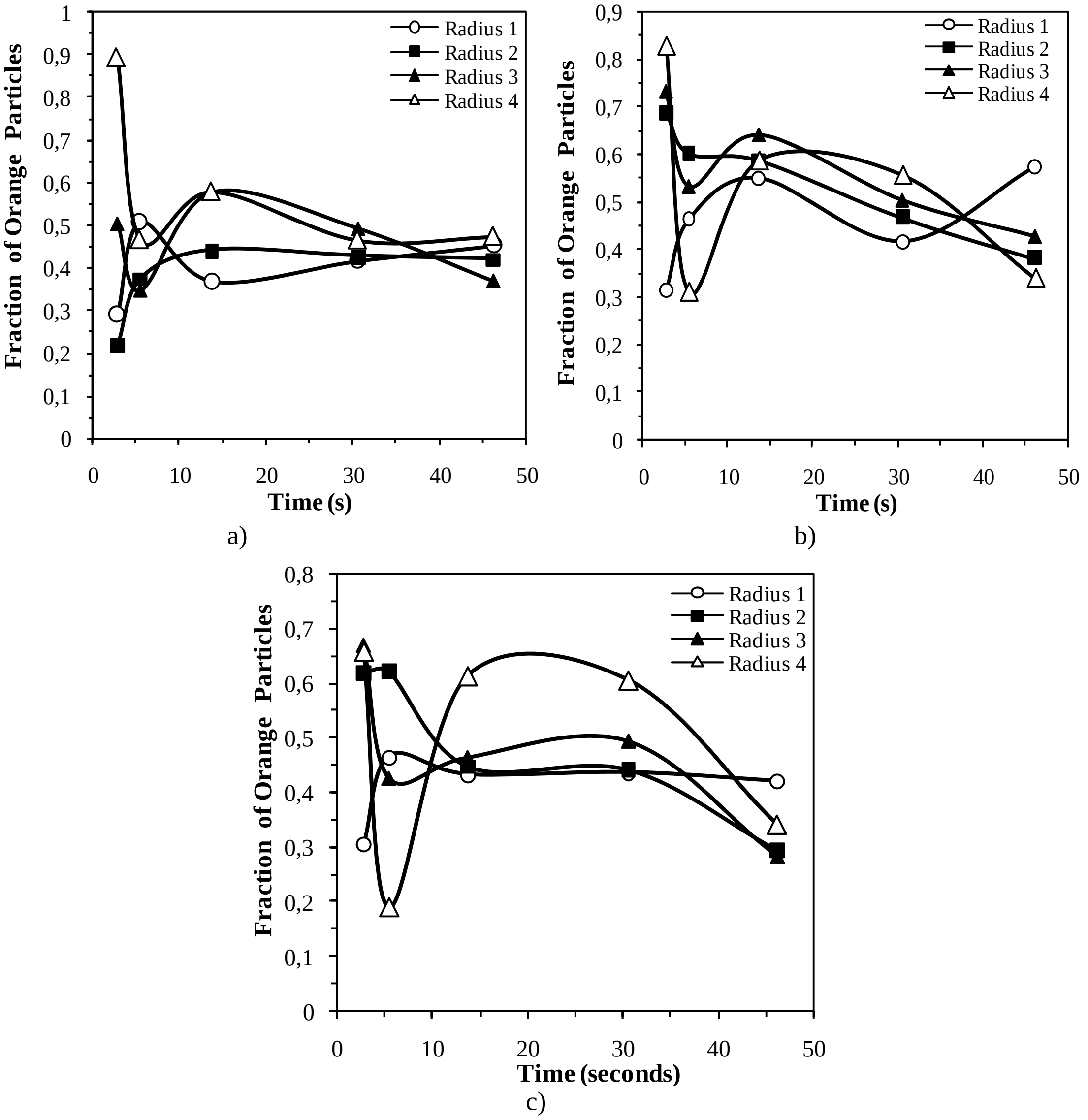


Fig. 8. Symmetry of the slices along the mixer in radius 3 for cascading regime.

C. *Analysis of the radial profile of mixture for cascading regime*

Figure 9 shows the radial profile of fraction of particles of each cross-section for cascade regime with horizontal distribution of components. The fraction of orange particles in the radial zone of each slice is close to 0.5, while increasing the mixing time, which is the desired value for a mixture having the same amount of two types of particles. Furthermore, the radial concentration profiles of slice 1 located at the end of the cylinder (Fig. 9a) presents a lesser fluctuation with respect to the other slices, because transport of particles does not occur through a cylinder wall side [26].

Radius 3 and 4 of each slice show substantial changes in the concentration profile over time, while radius 1 and 2, especially the first has a more stable behavior, in accordance with Sherrit [25]. Radius 1 and 2 are under the particle bed and near to the wall cylinder, and this area is called passive region, in which each particle is static with respect to the surrounding. Those particles rotate with the cylinder wall in a fixed radius without any opportunity for interaction between them, until they reach the top zone, known as active region. In this active region the particles flow rapidly and continuously due to the inclined surface of the bed, and then they mixed with other particles by random collisions. In the lower zone of the active region, the particles re-enter to the passive region to begin another cycle. In rolling regime, the active zone is characterized by flat surface with an angle of inclination to the horizontal plane known as dynamic angle of repose of the granular material. As mixer speed increases until the cascading regime, the surface is deformed due to increased centrifugal forces and increased acceleration and deceleration of the particles.



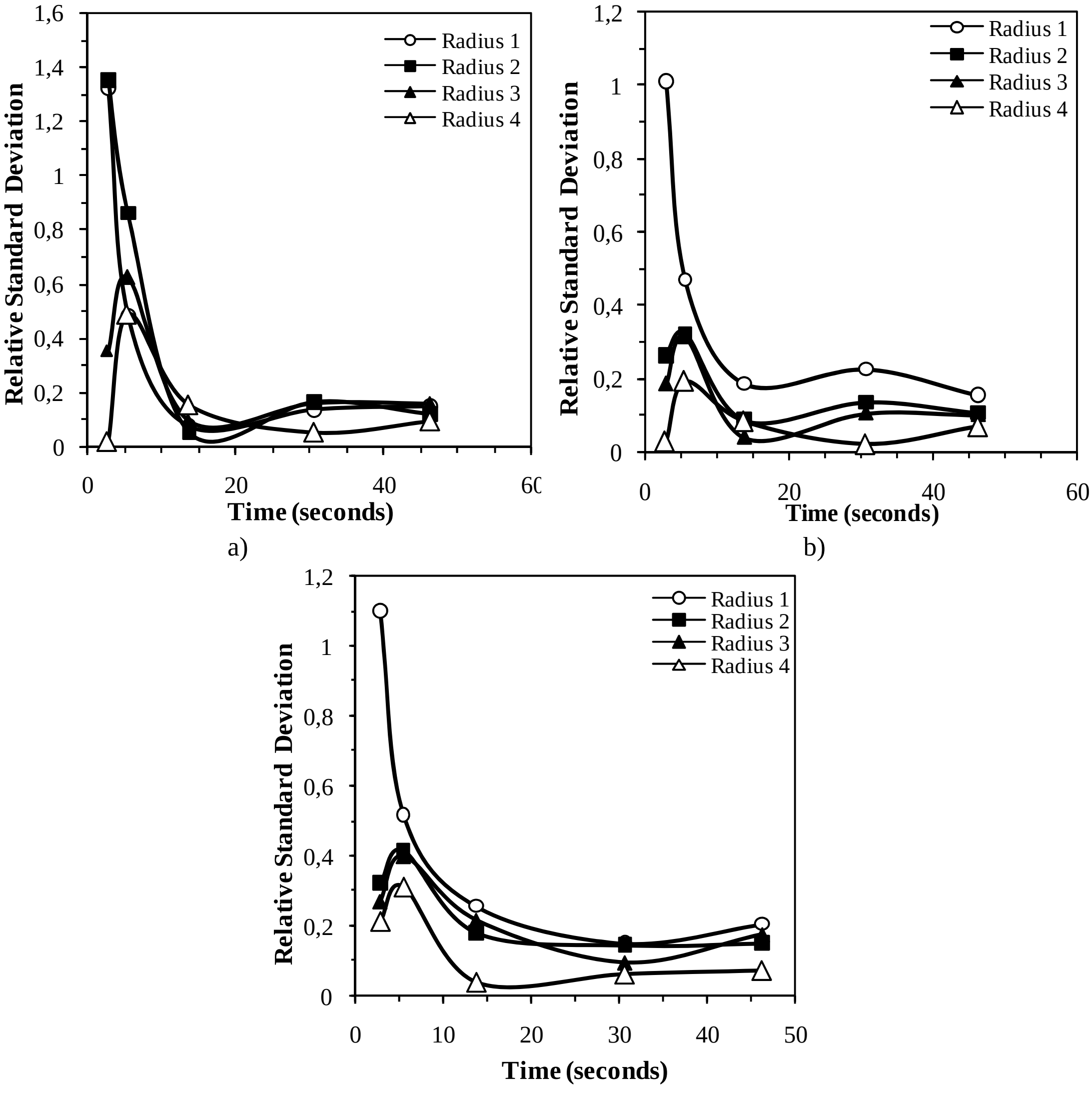
a)

b)

c)

Fig. 9. Concentration of the radial profile for cascading regime - horizontal distribution, a) Slice 1, b) Slice 2 and c) Slice 3.

The Figure 10 shows the homogeneity degree of mixing at cascading regimen with initial horizontal distribution. The homogeneity of mixing is stabilized at about 30 seconds of operation for all the slices, but the region of radius 4 has lower value of RSD by continuous exchange of particles in this zone. Moreover, the radius 1 has the highest deviation which tends to average 0.22, due to particle motion is restricted; the concentrations in the different sectors of the same radius are dispersed with respect to their average.



a)

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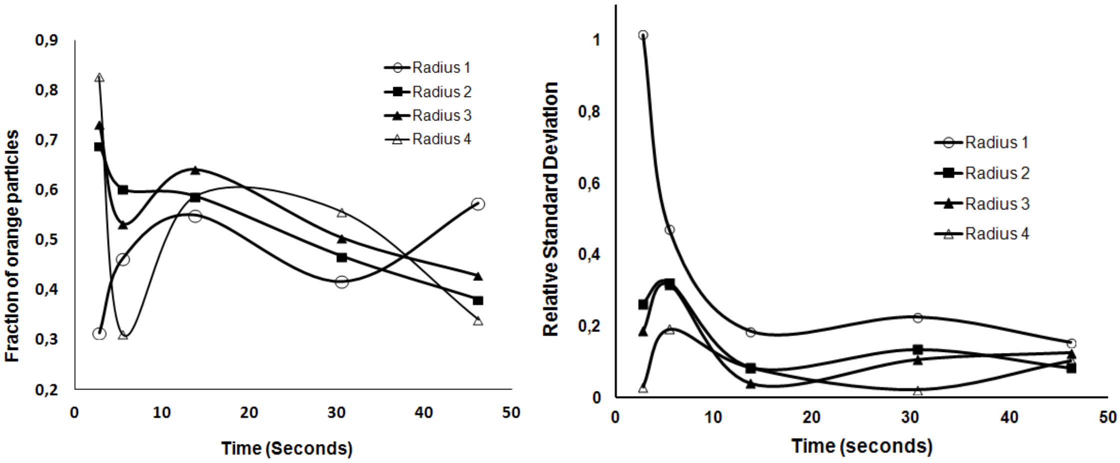
Fig. 10. Relative standard deviation of the radial profile for horizontal distribution: a) Slice 1, b) Slice 2 and c) Slice 3.

Figure 11a shows the concentration of the radial profile for cascading regime with vertical distribution, which indicates fraction of particles with an average of 0.486, while the horizontal distribution (Figure 9b) has an average value in all radius around 0.428. Therefore, the vertical distribution has lower dispersion than horizontal distribution (Figure 9b) by a closeness of the RSD between different radial zones. One possible explanation is that when increasing the interfacial area between the two components, only a small amount of movement is necessary to obtain efficient mixing [25].



a) b)

Fig. 11. a) Concentration of the radial profile for slice 2. b) RSD of the radial profile for slice 2 with cascading regime - vertical distribution.

Figure 12 shows the frequency curves for particle fraction of radius 3 for two initial distributions of each component at cascading regime. The horizontal distribution has an average value of 0.49. The dispersion of particle concentration of the horizontal distribution is lower than vertical distribution, indicating that the mixture can be considered highly homogeneous. The good mixing in the horizontal distribution is due to the high amount of particles passing through the active region.

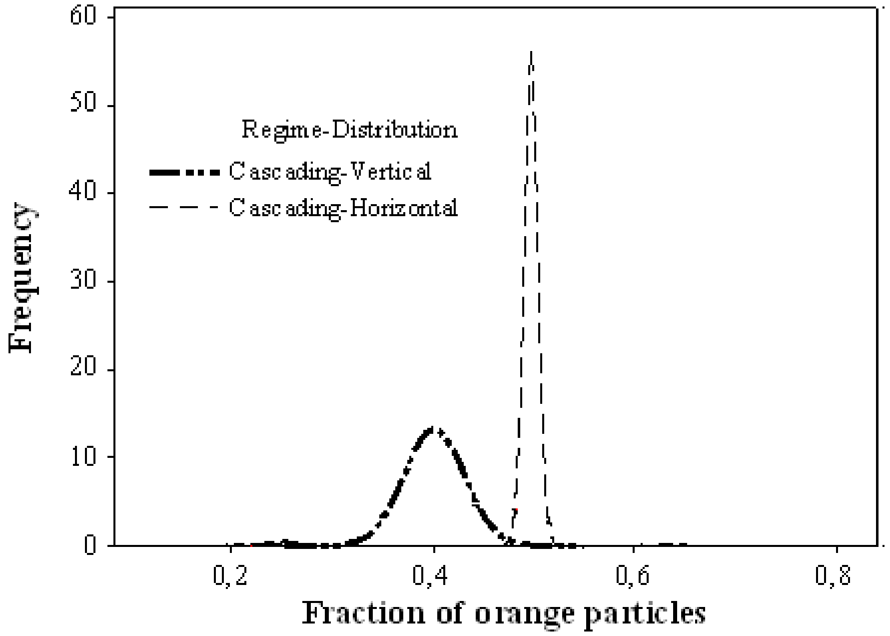
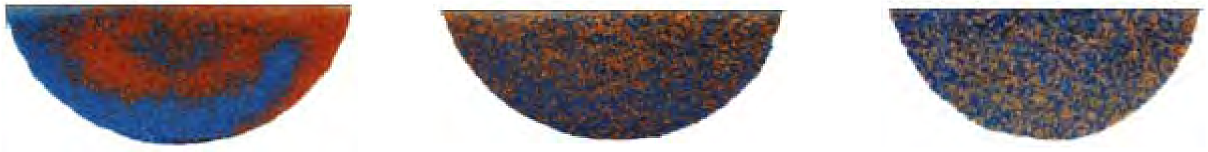


Fig. 12. Frequency curves of the concentration of radio 3 for each operating conditions.

D. *Analysis of the axial profile of Mixing for the Cascading Regime*

The mixing grade in the axial profile of particles was calculated by averaging the fraction of orange particles of six slices of particle bed (Fig. 4) in the time. Figure 13 shows the images of slice 1 in the time, which indicate the change of particle distribution, corresponding at 2,8, 13,7 y 46,2 seconds.



a) 2,8 s b) 13,7 s c) 46,2 s

Fig. 13. Images of slice 1 showing axial profile of particles at 2,8 s, 13,7 s y 46,2 s.

Figures 14, 15 and 16 show the frequency distribution of red particles of images shown in Fig. 13. The particle distribution at 2,79 s is bimodal due to segregation of components as indicated in Fig. 13a; while, the particle distributions at 13,7 and 46,2 s are unimodal, similar to the Gaussian. Although, the dispersion of particle in the 46,2 s (Fig. 16) is lower than in the 13,7 s (Fig. 15).

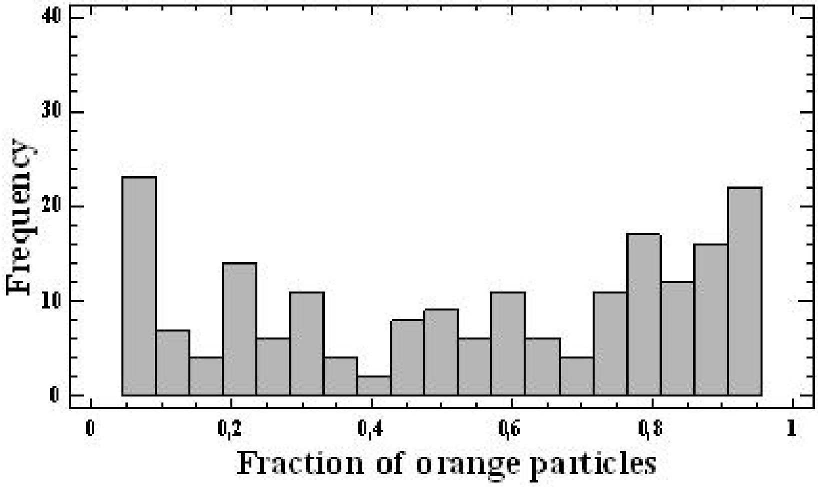


Fig. 14. Histogram of concentration for axial profile in cascading regime - horizontal distribution, 2,8 s

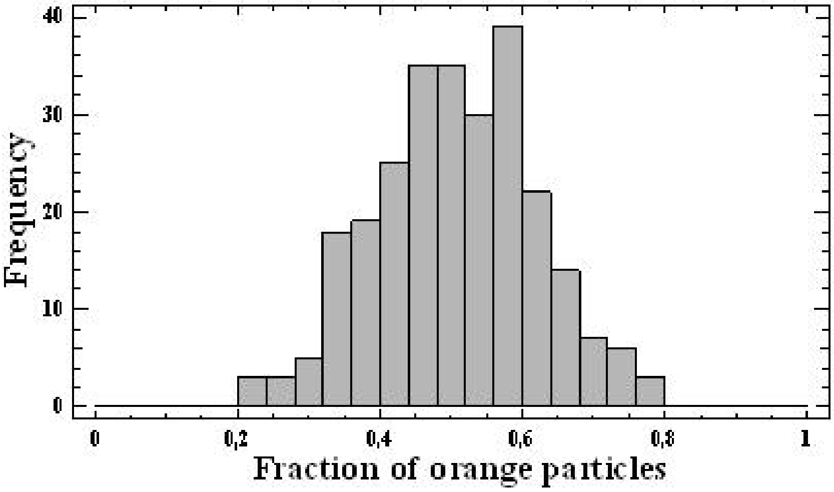


Fig. 15. Histogram of concentration for axial profile in cascading regime - horizontal distribution, 13,7 s

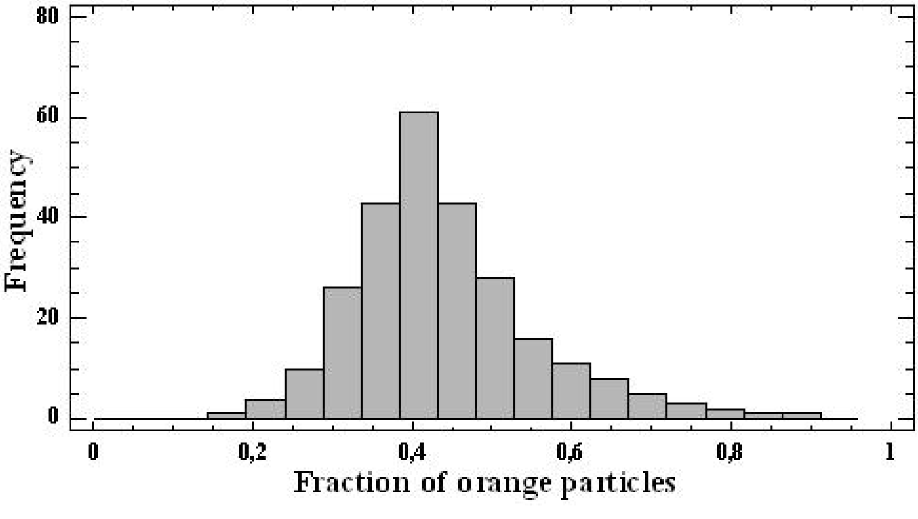


Fig. 16. Histogram of concentration for axial profile in cascading regime - horizontal distribution, 46,2 s

The homogenization grade of mixing follows a Gaussian phenomenon as observed in Fig. 17 for both particle distributions at 46,2 s. The dispersion of particle for vertical and horizontal distributions is low and similar between them; therefore, the mixtures have high homogenization grade.

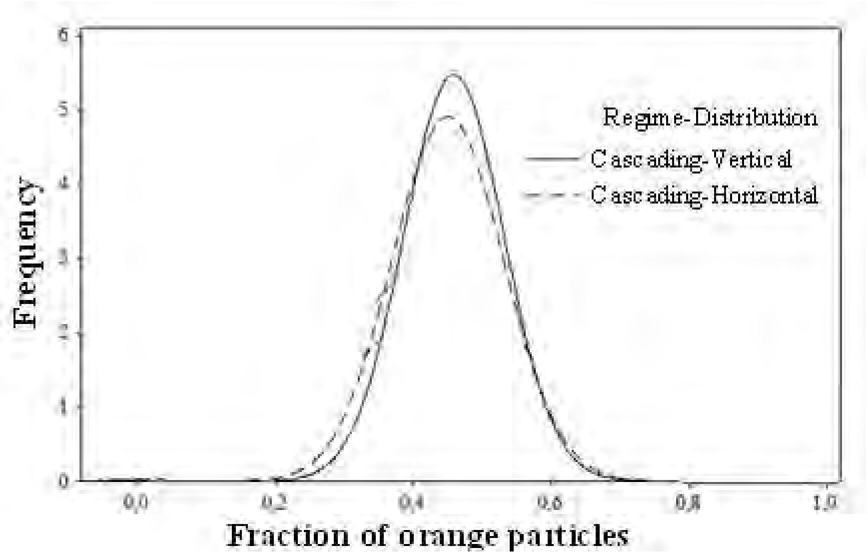


Fig. 17. Frequency distribution of concentration for vertical and horizontal distributions at 46,2 s.

IV. CONCLUSION

In this work was evaluated the composition and homogenization grade of the particle mixing in the cascading regime using as factors the vertical and horizontal distributions. From the results obtained, the following conclusions can be drawn: the homogenization degree is highest in internal radium for the radial profile, due to the highest number of random collisions of particles in the active zone. Also, the vertical distribution has lower dispersion than horizontal distribution by a closeness of the RSD between different radial zones, due to high interfacial area between two components in the vertical distribution, where a small amount of movement is necessary to obtain efficient mixing. On another hand, the particle distribution at initial time of mixing is bimodal due to segregation of components; while, the particle distribution at final time is unimodal, indicating highest homogenization, similar to the Gaussian. The image analysis and solidification technique permit to study the internal composition of the mixing bed, which can be beneficial to a very wide range of industries like pharmaceuticals, metallurgy, ceramics, polymers and food processing.

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