

## FLUIDIZATION OF MIXTURES OF SAND AND WOOD BARK BIOMASS PARTICLES – AN EXPERIMENTAL STUDY

Guilherme A. Genehr, [ggenehr@gmail.com](mailto:ggenehr@gmail.com)

Hártur Kunzler Mainardi, [hartur.kunzler@gmail.com](mailto:hartur.kunzler@gmail.com)

Flávia S. F. Zinani, [fzinani@unisinós.br](mailto:fzinani@unisinós.br)

Maria L. S. Indrusiak, [mlsperb@unisinós.br](mailto:mlsperb@unisinós.br)

Mechanical Engineering Graduate Program, Universidade do Vale do Rio dos Sinos - UNISINOS, Av. Unisinós, 950, São Leopoldo, RS, Brazil.

**Abstract.** This work aims to characterize the fluid dynamic behavior of binary mixtures of biomass and sand, by determining the fluidization curves of these mixtures. The biomass investigated were eucalyptus bark (*Eucalyptus sp.*) and pine bark (*Pinus elliottii*). Experiments were performed in a bench scale reactor at UNISINOS, with internal diameter of 94 cm and 1.2 m high. The biomass samples had average particle sizes of 579.13  $\mu\text{m}$  (pine) and 537.50  $\mu\text{m}$  (eucalyptus) with densities of 1.271  $\text{g/cm}^3$  and 1.386  $\text{g/cm}^3$  respectively. The mixtures were made in proportions between 1.43% to 41.89% of biomass in mass. Fluidization curves were analyzed and initial ( $u_{fi}$ ), apparent ( $u_{fa}$ ) and complete ( $u_{fc}$ ) fluidization velocities were determined. The characteristic velocities were highly affected by the biomass concentration in the mixture and also by the kind of biomass, meaning that even for similar density and particle size, biomass morphology and composition are key features in the process of fluidization. The results showed that with the increase of the proportion of biomass characteristic velocities tend to increase, and that eucalyptus bark particles present the tendency to agglomerate and prevent an efficient fluidization.

**Keywords:** lignocellulosic biomass, fluidized bed, fluidization of binary mixtures.

### 1. INTRODUCTION

The increasing need for use of renewable resources for power generation has stimulated research using available biomass to replace fossil fuels, which in turn are finite and polluting. Biomass in Brazil is highly relevant in the electricity and transport sector (ethanol from biomass) and therefore studies in this direction are very important. It is estimated that in Brazil, the potential for cogeneration using biomass would be enough to meet half of the increase in energy demand over the next decade. (World Energy Council, 2013). Among all kinds of biomass, lignocellulosic biomass are a good choice as energy sources in thermal energy conversion, for their properties and availability. Lignocellulosic are obtained from farming, residuals of the wood, timber and paper industries.

One of the most efficient ways of converting biomass into electricity is fluidized bed combustion. Fluidized beds are widely used in industry, since it provides a fluidized mixture of particulate and fluid with high heat transfer rates and mass, as well as a good temperature homogeneity of the mixture. (Cremasco, 2012).

Due to the characteristics of some biomasses, which generally have random and irregular shapes, it becomes quite difficult to fluidize without the use of an inert material. Sand, alumina or calcite are usually employed as inert material. (Rao and Bheemarasetti, 2001).

Biomass and inert material characteristics, such as density, size and sphericity, directly affect fluidization, besides being essential information for design of fluidized beds. In addition to the properties of particulate, mixing ratios between particulate and inert material have influence on fluidization characteristics. According to Tannous and Lourenço (2015), lignocellulosic biomass particles have unique characteristics that influence their fluidization and models for inorganic particulate are not capable of predicting the fluidization behavior of such systems.

Thus, this work aims the physical characterization of biomass and inert material and the fluid dynamic behavior of their mixtures. Lignocellulosic biomass from eucalyptus barks (*Eucalyptus sp.*) and pine barks (*Pinus elliottii*) are common waste generated in the timber industry. Thus, in this study, we used these biomasses, provided by a MDP (medium density particles) panels industry, located in Montenegro-RS.

Many studies have been conducted to determine the minimum fluidization velocity of binary mixtures. Goosens et al., (1971), modified Wen e Yu (1966) equation, according to Eq. (1).

$$\frac{d_m u_{mf} \rho_g}{\mu} = \left[ 33.7^2 + 0.0408 \frac{d_m^3 \rho_g (\rho_m - \rho_g)}{\mu^2} \right]^{\frac{1}{2}} - 33.7 \quad (1)$$

where,  $d_m$  is the average size of the mixture,  $u_{mf}$  is the minimum fluidization velocity of the mixture,  $\rho_g$  is the density of the gas,  $\mu$  is the viscosity of the gas and  $\rho_m$  is the density of the mixture. The authors replaced the density of component

by the density of the mixture ( $\rho_m$ ) and the component particle size by the average size of the mixture ( $d_m$ ). They noted that the equation could be used for binary mixtures with different particle sizes and densities.

Paudel and Feng (2013) conducted experiments with binary mixtures of inert and biomass using sand, glass beads and alumina as inert components and shell nut and corn cob as biomass. The experiments used an acrylic tube as cold bed with internal diameter of 0.145 m and 1 m in height and air as fluidization media. The binary mixtures ranged from 10% to 90% by weight of biomass in the mixture with constant increment of 10% in biomass.

From the Ergun equation modified by Wen and Yu (1966), Eq. (1) and based on data generated by other authors and these experiments, Paudel and Feng (2013), proposed a new correlation, Eq. (2), to determine the minimum fluidization velocity of particles and homogenous mixtures of biomass and inert.

$$Re_{mf} = \left\{ 30.28^2 + \left[ 0.046(1 - X_b) + 0.108X_b^{1/2} \right] Ar \right\}^{1/2} - 30.28 \quad (2)$$

where  $X_b$  is the concentration in mass percentage of biomass,  $Re$  is the Reynolds number and  $Ar$  is the Archimedes number.

This study aims to characterize the fluid dynamics of fluidized beds composed of mixtures of lignocellulosic biomasses and sand by determining the fluidization curves, minimum fluidization velocity, bed expansion versus superficial gas velocity and bed porosity in minimum fluidization state.

## 2. MATERIAL AND METHODS

### 2.1 Characterization of materials

In this work, sand and two types of biomass were used (pine bark and eucalyptus bark). Biomass barks were chopped using a SEIBT brand mill, MGHS 270A model after drying the samples in an oven.

To determine the average particle sizes, particle size analysis was performed using a set of ISO 3310/1 standard sieves. After determining the mass fractions retained in sieves were then calculated the average diameters between the sieves and calculated the Sauter mean diameter ( $d_p$ ), defined by Eq. (3).

$$d_p = \left( \sum \frac{x_i}{d_{pi}} \right)^{-1} \quad (3)$$

where  $d_p$  is the Sauter mean diameter,  $x_i$  is the sample mass fraction retained in the sieve and  $d_{pi}$  is the average diameter between the sieves.

The density of materials were determined by pycnometry with helium gas, using a Micromeritics AccuPyc II 1340 equipment. The analysis is based on the variation of pressure and volume of helium between two chambers of calibrated volumes. A sample of known weight quantity is placed in the first reservoir and this is then pressurized with gas. After stabilization of the pressure in the first reservoir, the gas is released to another chamber, also of known volume. After stabilization of the pressure, the gas volume is measured again. The density of the sample is calculated by the variation of gas volume and mass of the sample.

The bulk density of each material was determined by placing a known mass quantity inside the bed. The height was then measured and calculated the volume occupied by it. By dividing the sample weight by the volume is obtained the bulk density. This procedure was repeated three times for each material.

Sand particles sphericity was determined from images obtained in a scanning electronic microscope (SEM). Using the software ImageJ 1.48v, the image was convert to binary where the overlapping or incomplete particles were then removed. The software identifies particle contour polygons and determine the greater inscribed diameter ( $d_{pi}$ ) and smaller circumscribed diameter ( $d_{ec}$ ) of each polygon. According to Massarani and Peçanha (1986), the sphericity of each polygon was determined, and then the average sphericity of the sand sample was determined. The sphericity of biomass was not determined since their shapes were quite fibrous. A summary containing the characteristics of the materials was organized in Tab. 1.

Table 1. Summary of characteristics of samples.

Sample	$d_p$ ( $\mu\text{m}$ )	$\rho_p$ ( $\text{g}/\text{cm}^3$ )	$\rho_{ap}$ ( $\text{g}/\text{cm}^3$ )	$\emptyset$
Sand	220.43±7.83	2.639±8.0×10 <sup>-4</sup>	1.598±0.022	0.74
Eucalyptus	537.50	1.386±5.5×10 <sup>-3</sup>	0.093±0.0026	-
Pine	579.13±2.30	1.271±1.1×10 <sup>-3</sup>	0.286±0.029	-

## 2.2 Fluidization bench

A test bench was designed to perform fluidization experiments. A schematic diagram of the fluidized bed is show in Fig. 1. The main part is the riser (04). It is where the particles are placed and fluidized. The riser was made of a plexiglass tube with internal diameter of 94 mm and wall thickness of 3 mm. At the bottom of the bed there is a distributor (05). It is from where the air flows to fluidize the particulate. It consisted of a cylindrical stainless steel tube, with a length of 100 mm and filled with marbles to homogenize the airflow. Compressed air was used as the fluidization agent. A flow meter (02) and a pressure indicator (01) were installed at the compressed air line. A differential pressure transducer (03) was employed to measure the pressure loss from the air distributor to the freeboard. The data was collected at a frequency of 1 Hz by a data logger (06).

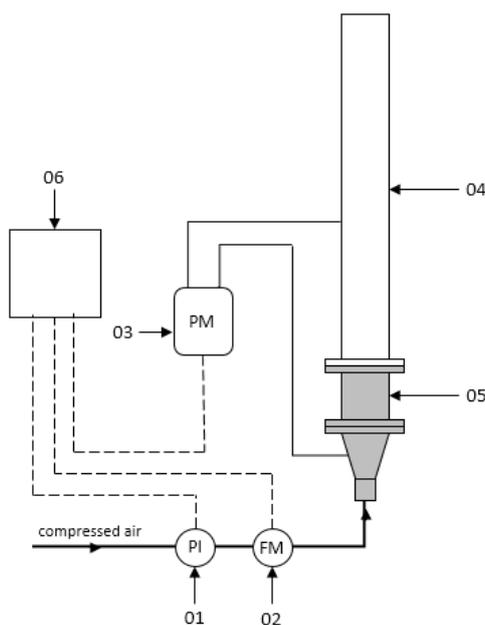


Figure 1. Fluidization bench schematic.

## 2.3 Experimental procedure

The fluidization experiments were performed with eucalyptus bark, pine bark, sand and binary mixtures of sand with biomass, with 20%, 30%, 40%, 60% and 80% of biomass on the total volume of the mixture. The experiments were evaluated quantitatively and qualitatively and recorded with images.

### 2.3.1 Determination of the fluidizing curves

The samples were placed in the bed and the airflow was increased as much as possible in order to mix the components. After approximately 10 seconds, the airflow was reduced to zero abruptly and then gradually increased to register the fluidization curve.

From the zero gas flow, the flow control valve is gradually opened until the gas reaches its maximum flow. Every 1 s the pressure differential was recorded by the data acquisition board. The opening of the flow control valve was performed quickly and slowly, but no difference in the curves were observed. Furthermore, fluidization curves (gas flow increase) and defluidization curves (gradual reduction of gas flow) were recorded.

### 2.3.2 Determination of the characteristic velocities

The characteristic velocities of the homogeneous samples and binary mixtures were determined using the pressure drop method from the graphics that relate fluid velocity and pressure drop in the bed. These velocities were identified according to the classification of Mourad et al., (1994):

- $u_{fi}$ , initial fluidization velocity. When the first movements of the particles occur.
- $u_{fa}$ , apparent fluidization velocity. Identified between the initial fluidization velocity of particles and segregation.
- $u_{fc}$ , complete fluidization velocity. It is where the biomass is completely supported by the airflow.

The minimum fluidization velocity or apparent fluidization velocity is determined by the intersection between the lines fitting the fixed bed region ( $\epsilon_{mf}$ ) and on constant pressure drop region after the fluidization.

### 3. RESULTS AND DISCUSSION

#### 3.1 Sand and eucalyptus mixtures curves

Figure 2 shows typical fluidization and defluidization curves for the mixtures of sand and eucalyptus bark pieces, with their characteristic velocities marked.

From the observation of the whole set of fluidization and defluidization curves, it was noted that the minimum fluidization velocity increased with increasing eucalyptus mass fraction in the mixture, but the pressure drop along the bed decreased. This behavior is due to the increase of preferential channels created by airflow. Eucalyptus has a very low bulk density, thus maintain voids between particles, facilitating the passage of the airflow. Thus, a higher velocity to start the fluidization is necessary, causing velocity increase without necessarily increasing the pressure drop. In fact, for mixtures with higher concentration of biomass, the pressure drop is lower because the bulk weight of the mixture is lower.

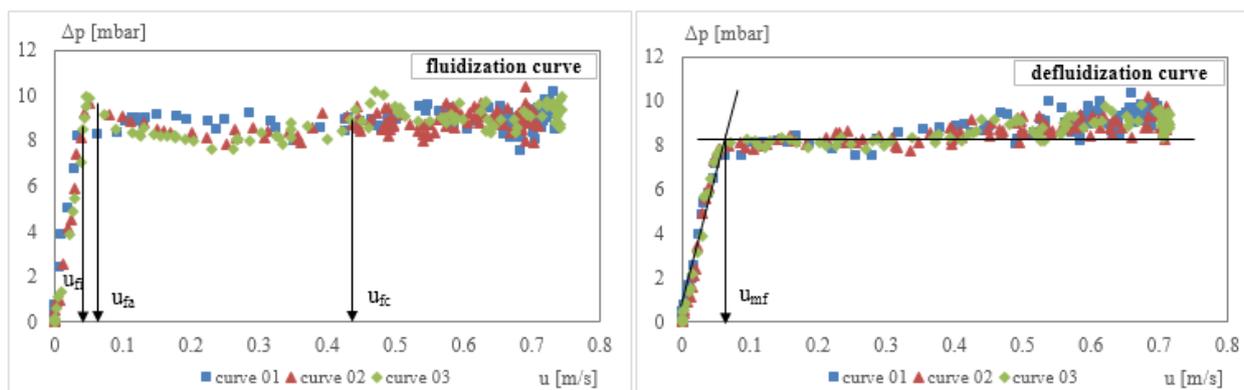


Figure 2. Fluidization and defluidization curves for sand and eucalyptus mixtures of 20% by volume of biomass.

For mixtures containing more than 8.07% by weight of eucalyptus, corresponding to mixtures with 60% and more by volume of biomass it was not possible to determine the fluidization curves. Biomass particles were so agglomerated that the process was unpractical. For mixture with 40% by volume of eucalyptus, the fluidization occurs, however due to the agglomeration of the biomass, preferential channels were formed and the bed of particles settled down. Therefore, after minimum apparent fluidization, the pressure drop decreases abruptly due to the channeling effect.

#### 3.2 Sand and pine mixtures curves

Figure 3 presents typical fluidization and defluidization curves of mixtures of sand with pine. Comparing the whole set of curves with those of mixtures of sand and eucalyptus bark, it was observed that the characteristic velocities were lower in mixtures of sand and pine, thus suggesting a better mixture between these two materials. This homogeneous characteristic was also observed in the pressure drop levels of these mixtures that are higher in relation to sand and eucalyptus.

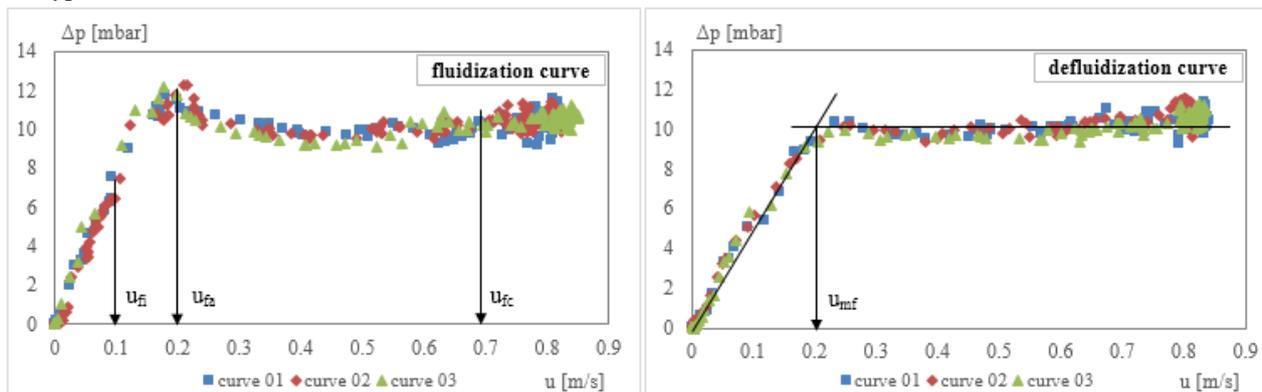


Figure 3. Fluidization and defluidization curves for sand and pine mixtures of 20% by volume of biomass.

Table 2 summarizes the characteristics velocities of sand and biomass mixtures.

Table 2. Characteristics velocities for mixtures of biomass with sand.

Component	$d_p$ [ $\mu\text{m}$ ]	Volume of biomass [%]	$\chi_b$ [%]	$u_{fi}$ [m/s]	$u_{fa}$ [m/s]	$u_{mf}$ [m/s]	$u_{fc}$ [m/s]
Sand	220.43	0%	0.00%	0.014	0.090	0.090	0.542
		20%	1.45%	0.040	0.072	0.072	0.449
Eucalyptus	537.50	30%	2.45%	0.063	0.142	0.156	0.512
		40%	3.85%	0.070	0.181	0.185	0.536
		60%	8.07%	-	-	-	-
		80%	18.96%	-	-	-	-
Pine	579.13	20%	4.12%	0.096	0.198	0.202	0.695
		30%	7.14%	0.085	0.178	0.180	0.728
		40%	10.68%	0.076	0.211	0.223	0.750
		60%	21.19%	0.071	0.274	0.308	0.765
		80%	41.89%	-	-	-	-

### 3.3 Effect of the type of biomass

In the case of sand and eucalyptus bark, there was considerable difference between the bulk density of these particles, being 1.598 g/cm<sup>3</sup> and 0.093 g/cm<sup>3</sup> respectively. Furthermore, eucalyptus particles have a shape close to rectangle and very fibrous, causing them to agglomerate. Therefore, when the volume fraction of eucalyptus becomes greater than 40%, channels are formed along the bed preventing its fluidization, as can be seen in Figure 4. It is also possible to observe that eucalyptus shows higher segregation making it more difficult to fluidize.



Figure 4. Preferential channels in the fluidization of eucalyptus bark pieces.

On the other hand, mixtures containing pine bark, which also has a bulk density (0.286 g/cm<sup>3</sup>) quite different of sand (1.598 g/cm<sup>3</sup>), have better behavior during fluidization. This difference probably occurs because the pine particles have a shape closer to spherical in relation to the eucalyptus particle. According to Nienow and Rowe (1976), the difference between the particle densities has more influence on the fluidization than the particle size.

Despite the better fluidization behavior of the pine, it is possible to observe a material segregation in Fig. 5. This segregation is associated with particle size of pine sample used, which has significant proportions of various sizes. Smaller and lighter particles segregate and remains in bed surface.



Figure 5. Segregation during fluidization of pine bark pieces.

### 3.4 Effect of biomass fraction

Figure 6 shows the behavior of the minimum fluidization velocity by increasing the mass concentration of biomass in the mixture.

With the increase of eucalyptus mass fraction, it is possible to observe an increase of minimum fluidization velocities. Due to the cohesive characteristic of eucalyptus biomass, a higher gas velocity is required, but over 3.85% of eucalyptus mass in the mixture that represents 40% in volume of biomass, it was impossible to achieve the fluidization state.

For mixtures of sand with 4.12% by weight of pine and sand with 3.85% by weight of eucalyptus, it is observed a very similar minimum fluidization velocity between the mixtures as shown in Fig. 6. It may be observed that for the smallest eucalyptus mass fraction, the minimum fluidization velocity was lower than that of sand, and that the results for  $u_{mf}$  were very similar when comparing biomass mass fractions. However, it is important to stress that in the fluidization of eucalyptus with sand, there was much segregation.

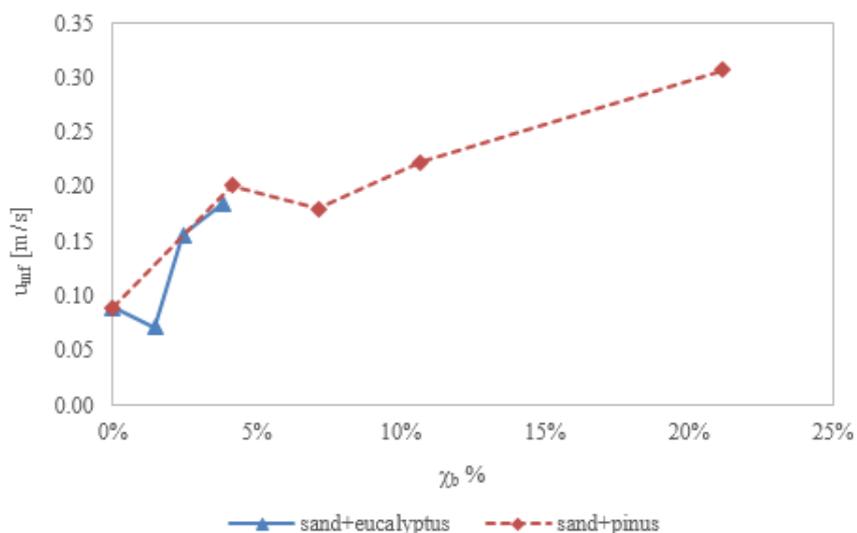


Figure 6. Biomass fraction influence on minimum fluidization velocities.

Figure 7 shows the evolution of characteristics velocities of mixtures of sand and biomass. The apparent and minimum fluidization velocities have an evolution with increasing mass of the biomass, but the complete fluidization velocity shows a decrease with increase of the mass of biomass on the mixtures of sand with eucalyptus, due to the segregation of

eucalyptus. The initial velocity increases with increasing of pine mass fraction in the mixture. This initial velocities increase is associated with the increased of pressure loss generated due to the homogeneity of the mixture of sand with pine.

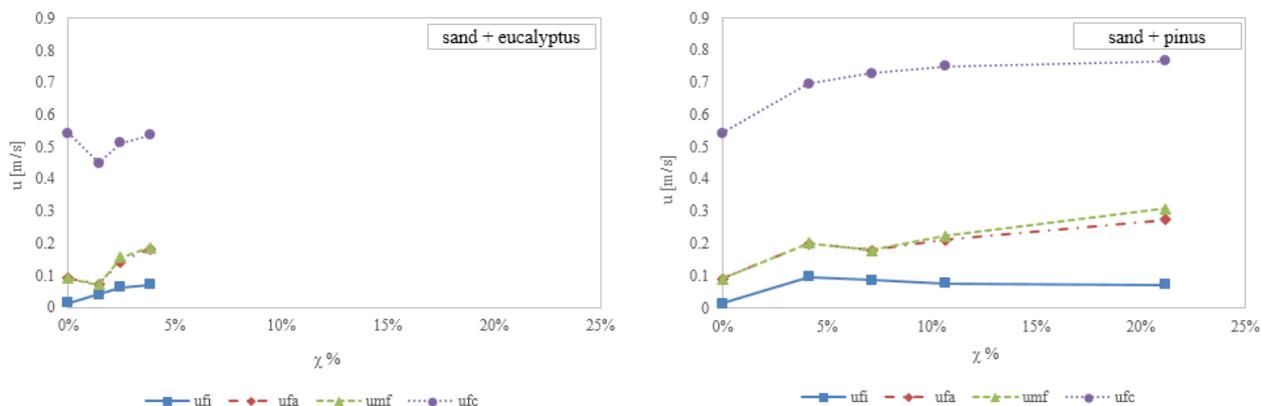


Figure 7. Characteristics velocities for eucalyptus mass fractions and sand and for pine mass fraction and sand.

## 5. CONCLUSIONS

From the results of this work the following conclusions are presented:

Due to the characteristics of eucalyptus and pine, it was not possible to obtain the fluidization curves of these individual biomasses. It is only possible to fluidize these materials when mixed to a more appropriate one, such as sand.

Eucalyptus characteristics influenced negatively in fluidization of the mixtures due to the cohesive characteristic, leading to agglomerations and the formation of preferential channels.

Mixtures of sand and pine had a superior quality for fluidization compared to eucalyptus, due to particle shape and bulk density, but for mixtures with a concentration higher than 21.19% by mass of biomass, that represents 60% by volume of biomass, it was not possible to achieve fluidization, due to segregation of materials.

## 6. ACKNOWLEDGEMENTS

The authors acknowledge the Brazilian agencies FAPERGS (Rio Grande do Sul State Research Foundation) (PqG, proc. 1957-2551/13-5), CNPq (National Counsel of Technological and Scientific Development) and CAPES (Coordination for the Improvement of Higher Education Personnel) (CAPES PNPd/2010) for financial support. The author F. Zinani is a grant holder of the CNPq (Process no. 308291/2014-0).

## 7. REFERENCES

- Cremasco, M. A., 2012. Operações unitárias em sistemas particulados e fluidomecânicos. São Paulo: Blucher. ISBN 978-85-212-0593-7.
- Goossens, W. R. A.; Dumont, G. L.; Spaepen, G. L., 1971. Fluidization of Binary Mixtures in the Laminar Flow Region. Chemical Engineering Progress Symposium Series, 67, 38-45.
- INTERNATIONAL ORGANIZATION FOR STANDARDIZATION (ISO) NM-ISO 3310-1 2010: Test sieves - Technical requirements and testing Part 1: Test sieves of metal wire cloth. 1st ed. Rio de Janeiro, 2010.
- Massarani, G.; Peçanha, R. P., 1986. Dimensão Característica e Forma de Partículas. CONGRESSO BRASILEIRO DE SISTEMAS PARTICULADOS, Campinas, 14, 312-313.
- Mourad, M.; Hemati, M.; Laguerie, C. Hydrodynamique d'un séchoir à lit fluidisé à flottation: Détermination des vitesses caractéristiques de fluidisation de mélanges de maïs et de sable. Powder Technology, 14 avril 1994. 45-54.
- National Institutes of Health (2010). ImageJ 1.48v [Software]. Bethesda, Maryland, MD, USA.
- Paudel, B.; Feng, Z.-G., 2013. Prediction of minimum fluidization velocity for binary mixtures of biomass and inert particles. Powder Technology, 237, 134-140.
- Rao, T. R.; Bheemarasetti, J. V. R. 2001. Minimum fluidization velocities of mixtures of biomass and sands. Energy, 26, 633-644.
- Rowe, P. N.; Nienow, A. W., 1976. Particle Mixing and Segregation in Gas Fluidized Beds. A Review. Powder Technology, 15, 141-147.

- Tannous, K.; Lourenço, J. B., 2015. Fluid Dynamic and Mixing Characteristics of Biomass Particles in Fluidized Beds. In: Tannous, K. Innovative Solutions in Fluid-Particle Systems and Renewable Energy Management. IGI Global, 2015. chap. 3, p. 54-91.
- Wen, C. Y.; Yu, Y. H., 1966. Mechanics of Fluidization. Chemical Engineering Progress Symposium Series, 62, 100-111.
- World Energy Council, 2013. World Energy Insight 2013. Daegu.

## **8. RESPONSIBILITY NOTICE**

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