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ОБЗОР ЭКСПЕРИМЕНТАЛЬНЫХ ИССЛЕДОВАНИЙ ГИДРОДИНАМИЧЕСКОГО ПОВЕДЕНИЯ ЧАСТИЦ БИОМАССЫ В КИПЯЩЕМ СЛОЕ

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Сокращение запасов и увеличение стоимости ископаемого топлива на фоне роста потребления энергии, ужесточения экологических стандартов и необходимость повышения уровня диверсификации энергетики побуждает человечество к более широкому использованию возобновляемых энергоресурсов, в том числе твердых видов топлива биологического происхождения. Потенциал использования биотоплива весьма значителен, так как энергетический эквивалент земного урожая биомассы на суше в несколько раз превышает общемировое потребление энергии. Применение биомассы в качестве возобновляемого топлива стало уже мировой реальностью в связи с развитием стратегий и технологий, которые жизнеспособны для превращения биомассы в энергию. Цель данной работы - представить обзор литературных источников по экспериментальным исследованиям, касающихся использования для этих целей аппаратов с кипящим слоем, принимающих во внимание их конструкции и масштабные переходы. Сначала представлена традиционная терминология, касающаяся твердых частиц и важных свойств частиц биомассы. Приведено краткое описание технологий конверсии биомассы и явлений, возникающих при ее псевдоожижении, с последующим объяснением различных экспериментальных техник. Обсуждены характеристические скорости (начальная, кажущаяся, сегрегационная и полная) для различных свойств биомассы и многочисленные эмпирические формулы для этих скоростей. Наконец, высказаны некоторые соображения о порозности кипящего слоя (кажущейся и полной) и расширения слоя. На основе литературного анализа достигнуто лучшее понимание явлений, возникающих при псевдоожижении биомассы. Однако необходимы дальнейшие исследования, чтобы осмыслить влияние характеристик биомассы на рабочие слои. Кроме того, более точные и обобщенные эмпирические корреляции должны быть получены, чтобы усовершенствовать эти технологии.

Ключевые слова: кипящий слой, характеристические скорости, техника эксперимента, смешивание, порозность, свойства биомассы, расширение слоя

EXPERIMENTAL STUDY OF FLUID DYNAMIC BEHAVIOR OF BIOMASS PARTICLES IN FLUIDIZED BEDS: A REVIEW

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Decease of natural resources and increase of price of fossil fuels at growing energy consumption, toughening of ecological standards and necessity of the increase of the level of energetics diversification motivates mankind to more wide usage of renewable energy resources including the solid fuel of biological origin. The potential of biofuel usage is rather considerable because the energy equivalent of the biomass harvest on the land exceeds the worldwide energy consumption several times as much. The biomass application as a renewable fuel is already a reality worldwide with the development of policies and technologies that turn viable the transformation of biomass into energy. The aims of this work is to present a literature experimental review on the studies concerning to the use of fluidized beds taking into account their design and scale-up. Initially, the usual solid particle terminology and some important biomass properties are presented. A brief description of conversion technologies and the fluidization phenomena are introduced, followed by an explanation of the different experimental techniques. The characteristic velocities (initial, apparent, of segregation, and complete) are discussed based on different biomass properties, as well as a number of empirical correlations for these velocities are described. Finally, some considerations are made about characteristic bed porosities (apparent and complete) and bed expansion. Based on the literature analysis, an improvement has been done on the understanding of the biomass fluidization phenomena, however, further research is needed to comprehend the effect of biomass characteristics on the bed operational parameters, besides more accurate and general correlations must be developed to improve these technologies.

Key words: fluidized bed, characteristic velocities, experimental technique, mixing, porosity, biomass properties, bed expansion

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INTRODUCTION

Sustainability is a watchword today. Several policies have been developed around the world associating the profit target with environmental impacts minimization and social commitment. Based on this context, various solutions have been presented into the energy domain and the use of biomass is one of the most prominent. The transformation of organic particulate waste into renewable fuels gives much of their value to materials that usually perishes without any profit and also promotes diversification of energy production.

According to the World Bioenergy Association (2017), the use of biomass as an energy source has been growing over the years. Its most recent evaluation (year 2014) shows that 10.4% of the energy supplied worldwide came from this raw material. Different technologies are under development to increase this percentage and to make the biomass to energy conversion more efficient. A number of them use fluidized bed as equipments for the reaction stages as well as other unit operations of the process.

The fluidized bed design and the success of the scale-up applying biomass depend strictly on the best operating conditions adopted. Then, this work aims to present a literature review and recommendations for readers in order to facilitate.

SOLID PARTICLE TERMINOLOGY

Geldart [1] proposed a dynamic classification for solid particles emphasizing particle and fluid properties. It is still very helpful to understand different behavior patterns in gas-solid systems. Four groups were defined according to the symbology: C, A, B and D. In the group C (e.g., cohesive) the particles are cohesive due their interparticle forces, as a result the particles of this group observed a strong tendency to agglomerate and requires additional activities to be fluidized. It can be improved with mechanical facilities or with the addition of a second solid. The group A (e.g., aeratable) includes particles in which interparticle forces are moderated and the fluidization starts before the minimum bubbling condition. In the group B (e.g., sand-like), the particles are fluidizable, interparticle forces are negligible and the fluidization starts at the same time of bubbles. The particles in the group D (e.g., millet) are spoutable, consequently large bubbles grow near the distributor crossing the bed like complete slugs.

Concerning the binary mixtures, Rowe et al. [2] defined a specific terminology differing the main particle properties of each component as heavy and light relating to density, small and big regarding to diameter as well as fluid and packed depending on its behavior into solid-gas fluidized bed systems. Heavier or bigger particles inclined to sink into the bed were called jetsam. In their turn, particles that tendency to float, in smaller size or lower density, were usually denominated as flotsam. During several years, this terminology has been applied for inert materials, e.g., corundum, glass, iron, polyethylene, polystyrene, steel, ceramic spheres, and sand [3-6], and currently for biomasses [7-10].

BIOMASS PROPERTIES

Biomasses are defined as organic materials of biological origin that have the potential to become energy, mainly thermal and electrical [11]. The physical properties of these materials (e.g., particle diameter, size distribution, shape, density, and moisture) affect on their fluid dynamic parameters. As noted in several studies [7,9,12-13], biomass does not fluidize or fluidize with low quality without the presence of an inert due to appearance of channeling and dead zones. Biomass particles may be processed independently or co-fed with other materials like coal, petroleum coke, sand or even other types of biomass.

The biomasses employed in general have a regionalist character and are generally chosen according to their availability in the origin country of the authors. **Wood (sawdust or ground)** was investigated by Clarke et al. [7], Tannous and Lourenço [9], Zhong et al. [12], Ramakers et al. [14], Si and Guo [15], Rao and Reddy [16], Karmakar et al. [17], and Pécora et al. [18]. Particle diameters studied were between 0.5 and 2 mm, but larger dimensions were also found on Cluet et al. [8] work with dowels (8 mm diameter x 25 mm length) and chips-like shape (5.5x4x57 mm and 2x4x29.5 mm). Particle densities varied between 364 kg/m³ and 564 kg/m³. Cluet et al. [8] verified the particle shape of 0.77 for dowels (cylindrical shape) and 0.50 for chip-like shape. Tannous and Lourenço [9] considered the particle shape of rectangular parallelepiped between 0.36 and 0.50. The **sugarcane bagasse** was studied by Karmakar et al. [17]; Perez et al. [10] and Pécora et al. [18], using particle diameters of 0.075 to 9.5 mm, particle densities varying between 465 kg/m³ and 953 kg/m³, and particle shape of 0.27 and 0.55.

Other types of biomass and its properties were found in the literature such as: **rice husk** [16-20] d_p =1.1-2.09 mm and ρ_p =988.76-1089 kg/m³. Higuchi and Tannous [20] reported that these particles have a prolate spheroid shape and present low sphericity (between 0.24 and 0.27); **cotton stalk** [12-13], d_p = 3.4-6.5 mm and ρ_p =365-385.3 kg/m³, long thin biomass and 0.73 of sphericity; **corn stalk** [12], d_p = 4 mm, ρ_p =274 kg/m³, long thin biomass as shape; **corn cob** [19,21-22], d_p =1040-1.080 mm, ρ_p =1080 kg/m³, and angular shape of 0.71; **palm pressed fiber** [23], d_p = 0.675 mm, ρ_p = 407.4 kg/m³; **palm kernel shell** [23], d_p = 1.425 mm and ρ_p = 398.7 kg/m³; **sweet sorghum bagasse** [24], d_p =0.125-0.850 mm and ρ_p = 871 kg/m³; **waste tobacco** [24], d_p =0.125-0.850 mm and ρ_p =727.10 kg/m³; **soybean hulls** [24], d_p =0.150-0.850 mm and ρ_p=1051.0 kg/m³; **coffee husk** [18], d_p =0.570 mm ρ_p=1361 kg/m³; **groundnut shell** [16], d_p=8.78 mm and ρ_p=680.4 kg/m³); **walnut shell** [21-22], d_p=0.856 mm; ρ_p =1200 kg/m³, angular sphericity; **tucumã fruit endocarp** [9,18], dp = 0.291 mm, 0.502 mm-2.017 mm, ρ_p = 1115-1195kg/m³, and high sphericity (0.81-0.89).

BIOMASS ENERGY CONVERSION TECHNOLOGIES

There are two major directions in the biomass conversion into energy. The first one is the thermochemical route, in which the material undergoes decomposition by means of pyrolysis, combustion or gasification being transformed into solid (biochar), liquid (bio-oil) and gaseous fuel (CH_4 and H_2). The second one is the biochemical route, in which the biomass decomposes in the digestion, fermentation, acid or enzymatic hydrolysis performed by microorganisms. In these cases, the fuels produced can be liquid and gaseous [11].

Fluidized beds are the main technology applied in the case of thermochemical conversion, mainly because of its developed surface of a gas-solid contact, high values of mass and heat transfer coefficients, uniform distribution of solids temperature due to particles movement, and the possibility of working with different types of particles [25]. This technology is also used in other stages of the biomass conversion process. For instance, in drying, in which occurs release of water and extractives of low molecular weight [26-28]. And also in the torrefaction as pretreatment [29-33], which can be considered a milder pyrolysis, alters the structure of the particles, releases oxygen compounds and makes a suitable feedstock for the decomposition reaction.

FLUIDIZATION PHENOMENA OF MIXTURES

Two representative cases of mixing and segregation phenomena in gas-fluidized beds between inert and biomass (different size and density of particles) were showed by Tannous and Lourenço [9]. Considering a fluidized bed initially well-mixed and decreasing gas velocity, it was observed partial segregation of particles, in which heavier and larger particles move to the bottom of the beds, followed by effective separation with stratification where lighter and smaller particles move to the top of the beds. Finally, in even lower velocities, all particles are fixed in their respective priority (lighter and smaller particles close to the bed's surface and heavier and larger close to the distributor). Such behaviours can be also influenced by increasing of mass fraction of biomass in the mixture.

The mixture and segregation regions of binary particles are differentiated by their characteristic fluidization velocities [9]. These superficial velocities of gas are presented on the figures 1 and 2. The initial fluidizing velocity U_{if}, corresponding to the beginning of the bed motion, predominantly with inert particles, without significant pressure fluctuations. Below this velocity, the pressure drop decreases linearly with the reduction of gas velocity; apparent fluidization velocity U_{af}, usually represented as the minimum fluidization velocity of the mixture and graphically identified by the intersection between fixed and fluidized states, as defined for homogeneous particles (U_{mf}). The segregation velocity U_S, corresponding to the totally defluidized zone on the upper/lower layer of the bed and characterizing the limit between the total and partial segregation states. The complete fluidization velocity U_{cf}, defined when the pressure drop is quite constant and equal to the apparent weight of bed per unit of cross-sectional area of the column and corresponding to complete suspension of the particles in the bed. Thus, four zones are defined characterized through the bubble types presenting the bed: fixed bed, total segregation, partial segregation and complete fluidization, respectively.

EXPERIMENTAL TECHNIQUES

For properly fluidized bed reactor design and scale-up, it is important to define precisely the physical properties of each component, the best mass proportions among the materials, and their fluid dynamics related to the velocity and porosity of mixture (biomass and inert). Most techniques presented in the literature for this purpose involve pressure measurement, since pressure transducers are low cost meters and easiness to monitor. Other evaluation forms should be developed and tested for a better analysis of the process. The following is a brief description of the most common techniques.

<u>Method 1 (Total pressure drop)</u>: Traditionally the pressure drop is specified as a function of superficial gas velocity [9]. This method is associated to the measuring of differential pressure between the base and the top of the bed and considering it as a function of the superficial gas velocity. The measurement is usually made with the decreasing gas velocity, starting from a completely mixed bed to the fixed bed state. Fig. 1 shows a schematic of this method identifying the fluidization characteristic velocities for binary particle mixtures. Various fluidization velocities are identified due to the complexity of interactions: initial (U_{if}), apparent (U_{af}), segregation (U_S) and complete (U_{fc}). Depending on the kinds of biomass particles, these determinations can be distinct, mainly referring to the segregation velocity (gray patterned area).

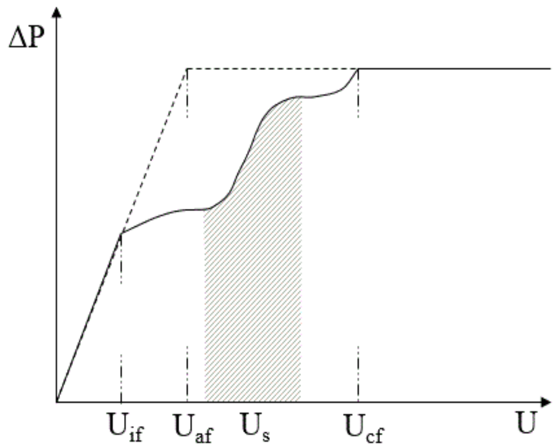

Fig. 1. Evolution of the total pressure drop of the bed as a function of the superficial gas velocity

Рис.1. Изменение полного перепада давления на слое в зависимости от расходной скорости газа

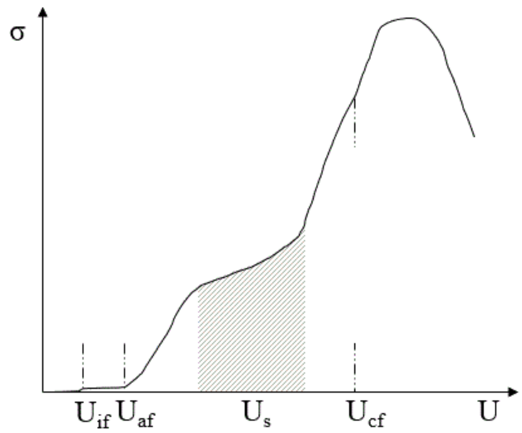

Fig. 2. Total standard deviation as a function of the superficial gas velocity

Рис.2. Изменение среднеквадратичного отклонения в зависимости от расходной скорости газа

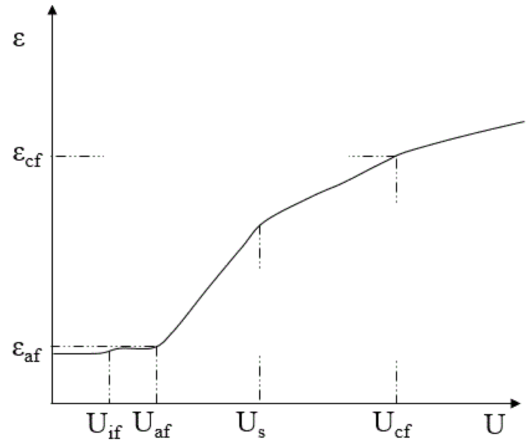

Fig. 3. Bed expansion as a function of superficial gas velocity

Рис.3. Расширение слоя в зависимости от расходной скорости газа

Method 2 (Total standard deviation of pressure fluctuation): The approach was proposed firstly by Punčochář, Drahoš, Čermák, and Selucký [34] for homogeneous particles, and later applied to polydispersed particles [35] and to binary mixtures [9]. In this case, the characteristic velocities are determined according to the inflections in the curve schematized in Fig. 2, corresponding to changes in the bubbling intensity of the bed. This means that the higher the intensity the greater the standard deviation until it reaches its complete mixing state.

Method 3 (Bed expansion): The method was defined by the ratio between the void volume and the total volume of the mixture of biomass and inert [9] as a function of superficial gas velocity. As shown in Fig. 3, the velocities are also mainly identified in the curve inflections. It is important to note that the U_{if} is not well-defined due to the low bed height, since the total bed is still complete mixed. In some cases it can be the same of U_{af} . The segregation velocity is not easily to identify because depending on the biomass type and bed arrangement. This methodology allows determining the apparent (ε_{af}) and complete (ε_{cf}) porosities, which are related to the apparent (U_{af}) and complete (U_{cf}) fluidization velocities, respectively.

Modern procedures such as the evaluation of the pressure fluctuation in the time domain and the power spectrum calculated by the Fast Fourier Transform (FFT) in the frequency domain can also be applied. However, they are frequently used for homogeneous particles [36], since the mechanism of interaction between heterogeneous particles in these procedures is still not well understood [4,37].

Method 4 (Pressure Fluctuation): Pressure fluctuations are irregular oscillations caused by the bubble movement within the bed during fluidization. The evaluation of these fluctuations allows a better understanding of the fluid dynamics states, consequently leading to the mechanism of mixing and segregation of the particles. The analysis is performed from the pressure fluctuation measurements by pressure transducers as a function of the analysis time, at a defined sampling rate (e.g., 200 Hz). A schematic example of this analysis (bubbling regime) can be seen in Fig. 4.

Method 5 (Power spectrum by Fast Fourier Transform): This methodology also uses the pressure fluctuation data as a function of time, however its evaluation is done by frequency domain (so-called the Fourier domain). The width, amplitude and frequency of these spectra (Fig. 5) can be related to the fluid dynamic behavior of the bed. For instance, it can indicate the formation of bubbles or slugs, which may be associated with presence of the complete mixtures.

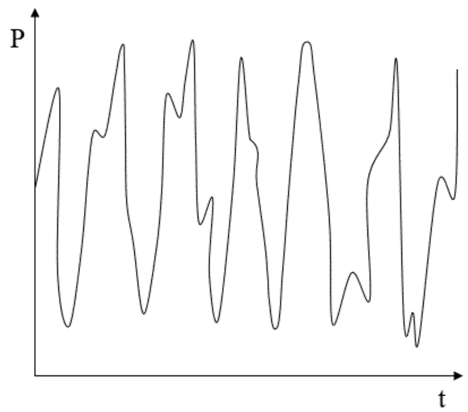

Fig. 4. Character of pressure fluctuation with time measured by a pressure transducer

Рис.4. Характер флуктуаций давления, измеренного преобразователем давления

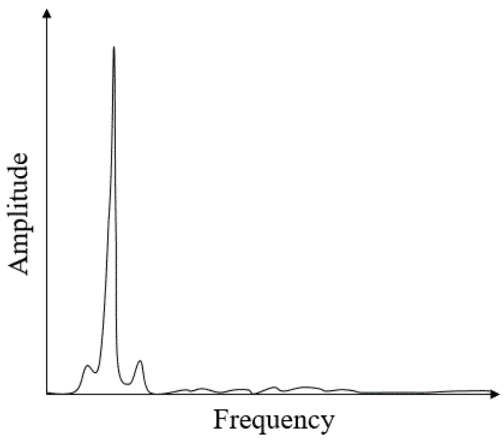

Fig. 5. Power spectrum by fast Fourier transform
Рис.5. Энергетический спектр по быстрому преобразованию Фурье

CHARACTERISTIC OF FLUIDIZATION VELOCITIES

The biomass size and density are commonly important parameters for understanding the fluid dynamics behavior of the materials and straightforward by biomass. However, for fluidized beds another relevant feature is the mass fraction ratio (χ) considering the biomass and inert material. Several studies from literature aim to evaluate these parameters in order to identify their influence on the characteristic velocities of mixing in different processes (e.g., drying, torrefaction, pyrolysis, combustion gasification). Tannous and Lourenço [9] discussed a broad bibliographic review and an update will be showed in this paper. On account of nomenclature divergences, the minimum fluidization velocity of mixtures (U_{mf}, $U_{mf,m}$) will be adopted as the apparent fluidization velocity (U_{af})

Influence of biomass/inert diameter ratio, D

Zhong et al. [12] analyzed the effect of the different inert diameters (sand d_p = 1.00 mm, continental flood basalt cinder d_p = 2.8 mm) on the mixture with mung beans (d_p = 3.2 mm). Besides, mixtures with three different sand diameters (d_p = 0.5-1.3 mm) with wood chip (d_p = 0.89 mm) was also studied. For the both biomasses, the increase of the apparent fluidization velocities (U_{af}) with the increase of the inert diameter was observed. In addition, when authors evaluated the mixture of cotton stalk (d_p = 3.0-6.5 mm) and two other inert (sand, CFB cinder and aluminum oxide, all with d_p = 1.0 mm), they verified a slight increase on the U_{af} with the increase of the biomass diameter.

Ramakers et al. [14] investigated the mixture of wood cylinders (6 mm diameter/ 9 mm length) with three different sands (d_p = 0.1-0.5 mm, 0.4-0.6 mm and 0.8-1.2 mm) and various biomass fraction in the range from 5 to 35wt % and also observed the increase on U_{af} with the inert diameter.

Kumoro et al. [19] evaluated the effect of particle diameter on corn cob (d_p = 1.040 mm) and rice husk (d_p = 1.560 mm) mixtures with two different sand samples (d_p = 0.241 mm and 0.350 mm). From the diameter ratios between materials (4.31-6.47 and 2.97-4.46, respectively), the authors verified that the apparent fluidization velocities (U_{af}) were lower for the mixtures with higher diameter ratio (smaller sand diameter), which was evaluated as more suitable for fluidization of these biomasses.

Tannous and Lourenço [9] studied the influence of three diameters of *Eucalyptus grandis* (d_p=0.508 mm, 0.986 mm, and 1.993 mm) and tucumã endocarp (d_p=0.502 mm, 1.017 mm, and 2.017 mm) and one sand diameter (d_p = 0.331 mm) considering the diameter ratios of 1.5, 3.0, and 6.0 for mass fraction ratios between 5 and 20 wt%. For the first biomass, the authors found that U_{if} kept quite constant, however U_{af}, U_s, and U_{cf} were increasing with diameter ratio. Concerning to the second biomass, U_{if} and U_{af} were quite constant, whereas U_s and U_{cf} were increasing with the diameter ratio.

Perez et al. [10] evaluated the arrangement of nine different diameters of sugarcane bagasse ($0.075<d_p<$ 9.500 mm) with sand (d_p = 0.225 mm) considering the biomass fractions between 2 wt% and 15 wt%. For biomass sizes smaller than sand, U_{af} remained practically constant, however for the larger ones, the U_{af} were increasing with increasing of diameter ratio ($0.33<D<42.2$).

Influence of biomass/inert fraction ratio, χ

Ramakers et al. [14] studied the mixture of wood cylinders (d_p=7.9 mm) and three sand diameters (fine, medium and coarse) varying the mass fraction from 5 wt% to 35 wt%. The authors verified an increase on the apparent fluidization velocity (U_{af}) with the increase on biomass fraction ratio, considering the best mixtures the ones with smaller inert diameter and mass fraction up to 10wt%. This work was in agreement with Si and Guo [15] for the mixture of sawdust (d_p = 0.70-1.20 mm) and wheat stalk (d_p = 0.80-1.30 mm) with sand (d_p = 0.255 mm) varying the biomass mass fraction from 20 wt% to 50 wt%; Zhong et al. [12] for the chip wood/sand mixtures with biomass mass fractions of 10-25wt% and cotton stalk/CFB cinder mixtures from 1 to 5wt%; Fauziah et al. [23] for the mixture of palm kernel shell (d_p = 1.425 mm) and sand (d_p = 0.288 mm) regarding the biomass mass fraction between 5 wt% and 30 wt%; Basu Paudel [21] for mixtures of walnut shells (d_p = 0.856 mm), corn cob (d_p = 1.040 mm) and sand (d_p = 0.241 mm) in biomass mass fractions varying from 0 to 100wt%; and Oliveira et al. [24] for different biomasses (0.125 mm $\le d_p \le$ 0.850 mm) and sand (0.212 mm $\le d_p \le$ 1.400 mm).

Furthermore, Karmakaret et al. [17] also observed the increase of de U_{af} with mass fractions on studying mixtures (2-15 wt%) of rice husk (d_p=1.100 mm), sugarcane bagasse (d_p=1.250 mm) and wood sawdust (d_p=0.530 mm) with two sizes of sand (d_p=0.230 mm and 0.300 mm). Perez et al. [10] are only in agreement with this observation, when the diameter was higher than 0.225 mm for the same fraction ratio. For lower diameters (up to 0.225 mm), the U_{af} decreased related to the mass fraction ratios.

On the other hand, Zhong et al. [12] verified that U_{af} remains almost the same with the raise of biomass mass fraction from 5wt% to 80wt% for the mung beans/sand mixtures. This velocity presents accentuated increase for the mass fractions between 5 wt% and 15 wt% followed by a slight increase between 15wt% and 80 wt%.

Tannous and Lourenço [9] studied different characteristic velocities, U_{if}, U_{af}, U_{cf} and segregation velocity (U_s), of mixtures using *Eucaliptus grandis* and tucumã endocarp and sand (inert material) with fraction ratios of 2.5 e 20.0 wt%. Concerning the eucalyptus/sand mixtures, all fluidization velocities increased with the increasing mass fraction ratios. It is noteworthy that, for the largest mass fraction and diameter ratios (D=3, χ=20 wt%, and D=6, χ=15-20 wt%), the beds were more expressive in the slugging regime promoting a fair increase of velocities. In this case, U_{if} and U_{af} were almost equal, and both velocities can be used as a reference for the segregation range. This rising is also evident for the other ranges, U_{cf}/U_{if} and U_{cf}/U_{af}, with exception of 15 wt% (D=3.0) and 20 wt% (D=3-6), where these ratios decreased due the low mixture quality and bed collapse observed at drop pressure measurements.

Considering the *tucumã*/sand mixtures, the U_{if} and U_{af} were practically the same for all fraction ratios. Moreover, for D=1.5, these velocities were slightly slower than the minimum fluidization velocity of sand, suggesting an increase of the apparent porosity of bed. The segregation and complete velocities increased progressively leading to a larger region of segregation (U_{cf}–U_{if}), up to 70%. In this region, it was observed a higher concentration of tucumã endocarp in the upper layer of the bed.

Fauziah et al. [23] also observed the increasing of complete fluidization velocity (U_{cf}) of the biomass mixtures of palm kernel shell with sand with the increasing in the mass fraction ratios varied between 5wt% and 30 wt%.

Correlations for determination of characteristic velocities

Empirical modeling to determine the characteristic velocities allows the evaluation of a binary biomass/inert mixtures without the need to perform experimental procedures, and consequently, the fluidized bed design and scale-up are feasible. Some empirical correlations for mixtures are summarized in Table. It can remark that the most of the equation profiles use Ar_{ef} and R_e numbers of mixtures defined as effective numbers. Si and Guo [15] and Kumoro et al. [19] introduced the sphericity parameter in different ways into the equations. Kumoro et al. [19] used the same effective density definition of Goossens et al. [38], but applied the effective diameter as a weight average, similar to Oliveira et al. [24].

Tannous and Lourenço [9], Pérez et al. [10] and Basu Paudel and Feng [22] used the effective density (ρ_{ef}) and diameter (d_{ef}) according to Goossens equation [38] for defining apparent fluidization velocity. The second authors also presented other definition as U_{if}, U_S, and U_{cf} as a function of Reynolds number. The segregation Reynolds number presented here is an adjustment of original equation because an error was identified.

Zhong et al. [12] were the only ones that presented the combination between d_{p1} as the particle diameter with smaller mass fraction of the mixture (biomass or inert material), x_1 and x_2 as the mass fractions of particles in the binary mixture with $x_1 < x_2$, and ρ_1 and ρ_2 as the densities of particles in the binary mixture. Reynolds number for all characteristic velocities (U_{if}, U_{af}, U_S, and U_{cf}) were calculated using the classical dimensional equation as $R_e = d_{p,ef} U \rho_g / \mu_g$.

CHARACTERISTIC OF FLUIDIZATION POROSITIES

The characteristic porosities, apparent (ε_{af}) and complete (ε_{cf}), is sparingly seen in the literature and a quite few empirical correlations were found. These porosities regard to the void volume at the beginning of the particles motion at the top of the bed at the apparent fluidization velocity (U_{af}), and when the total bed is suspended by the gas related at the complete fluidization velocity (U_{cf}). It is noteworthy that these porosities are important parameters not only on the mapping of the fluidization quality but also on the simulation of bed profiles using CFD (Computer Fluid Dynamics) methods.

Ramarkers et al. [14] studied the mixtures of wood/sand varying mass fractions (5 wt% to 35 wt%). The authors observed a decrease on ε_{af} with the increase biomass mass fraction up to 20 wt% for the fine sand (d_p = 0.10-0.50 mm) and, 5 wt% for the medium sand (d_p = 0.40-0.60 mm) and for the coarse sand (d_p = 0.80-1.20 μm, possibly due to the filling of bed voids with inert particles. Above these fractions, the porosity increased with the increase of mass fraction. The authors did not mention any analysis related to diameter ratios.

Table

Empirical Correlations for Fluidization Characteristic Velocities

***Таблица.* Эмпирические соотношения для характеристических скоростей кипящего слоя**

Reference	Correlation		Definition
Si e Guo [15]	$Re_{af} = \left(C_1^2 + C_2 Ar_{ef}\right)^{\frac{1}{2}} - C_1$	(1)	$C_1 = 25.65(\phi_b^{0.21}\ \phi_i^{0.15})$ $C_2 = 0.056(\phi_b^{-0.045}\ \phi_i^{0.025})$ for $0.084 < \phi < 0.482$ $Ar_{ef} = \frac{d_{p,ef}^3 \rho_g (\rho_{p,m} - \rho_g) g}{\mu_g^2}$
Zhong et al. [12]	$U_{af} = 1.45 * 10^{-3} \left[\frac{d_{p,ef}^2(\rho_{pe} - \rho_g)}{\mu_g}\left(\frac{\rho_{pe}}{\rho_g}\right)^{1.23}\right]^{0.363}$ for $\rho_{p,ef} > 1000$ kg/m^3 $U_{af} = 1.2 * 10^{-4} \left[\frac{d_{p,ef}^2(\rho_{pe} - \rho_g)}{\mu_g}\left(\frac{\rho_{pe}}{\rho_g}\right)^{1.23}\right]^{0.633}$ for $0 < \rho_{p,ef} < 1000$ kg/m^3	(2)	$d_{p,ef} = d_{p1}\left[\left(\frac{\rho_1}{\rho_2}\right)\left(\frac{d_{p,2}}{d_{p,1}}\right)\right]^{x_2/x_1}$ $\rho_{p,ef} = \frac{x_1\rho_1 + x_2\rho_2}{x_1 + x_2}$
Oliveira et al. [24]	$U_{af} = (1.17 * 10^{-4}) * \left[\frac{d_{p,ef}^2(\rho_{p,ef} - \rho_g) g}{\mu_g}\left(\frac{\rho_{p,ef}}{\rho_g}\right)^{1,23}\right]^{0,4916}$	(3)	$\rho_{p,ef} = x_b\rho_{p,b} + x_i\rho_{p,i}$ $d_{p,ef} = d_{p,i}\left[\left(\frac{\rho_{p,i}}{\rho_{p,b}}\right)\left(\frac{d_{p,b}}{d_{p,i}}\right)\right]^{x_{b/x_i}}$ for $x_i > x_b$
Basu Paudel and Feng [22]	$Re_{af} = \left\{30{,}28^2 + \left[0{,}046(1 - x_b) + 0{,}108 x_b^{1/2}\right] Ar_{ef}\right\}^{1/2} - 30{,}28$	(4)	$\rho_{p,ef} = \frac{\rho_{p,b}\rho_{p,i}}{x_i\rho_{p,b} + x_b\rho_{p,i}}$ $d_{p,ef} = \frac{x_b\rho_{p,i} + x_i\rho_{p,b}}{x_b\rho_{p,i}d_{p,i} + x_i\rho_{p,b}d_{p.b}} d_{p,i}d_{p.b}$ $Ar_{ef} = \frac{d_{p,ef}^3 \rho_g (\rho_{p,m} - \rho_g) g}{\mu_g^2}$ $Re = \frac{d_{p,ef} U \rho_g}{\mu_g}$
Tannous and Lourenço [9]	$Re_{if} = \left(15{,}8^2 + 0{,}019 Ar_{ef}\right)^{\frac{1}{2}} - 15{,}8$ valid for $0.2 < Re_{if} < 7$ and $400 < Ar_{ef} < 1.5\ 10^4$ $Re_{af} = \left(33{,}9^2 + 0{,}051 Ar_{ef}\right)^{\frac{1}{2}} - 33{,}9$ valid for $1.4 < Re_{af} < 14$ and $340 < Ar_{ef} < 2.1\ 10^4$ $Re_s = 0{,}0008 Ar_{ef}^{1{,}04}$ $2.7 < Re_S < 30$ and $340 < Ar_{ef} < 1.5\ 10^4$ $Re_{cf} = 0.0123 Ar_{ef}^{0.8086}$ valid for $1 < Re_{cf} < 52$ and $340 < Ar_{ef} < 1.5\ 10^4$	(5)	
Pérez et al [10]	$u_{af} = \frac{0.00002\ Ar_{ef}^{\ 1.7125} \mu_g}{d_{p,ef}\rho_g}$	(6)	
Kumoro et al. [19]	$Ar_{ef} = 1176\,(1 - x_2)\emptyset^2 Re_{af} + 22.432 x_2^{1/2} Re_{af}^2$	(7)	$\rho_{p,ef} = x_i\rho_{p,i} + x_b\rho_{p,b}$ $d_{p,ef} = \frac{x_b\rho_{p,i} + x_i\rho_{p,b}}{x_b\rho_{p,i}d_{p,i} + x_i\rho_{p,b}d_{p.b}} d_{p,i}d_{p.b}$ $\emptyset_m = \sum_{p=1}^{n}(x_p\emptyset_p)$

Note: b (biomass); ef (effective); i (inert material); m (solid mass); particle density (ρ_p); particle diameter (d_p); x (mass fraction).
Примечание: b (биомасса); ef (эффективность); i (инертный материал); m (твердая масса); плотность частиц (ρ_p); диаметр частиц (d_p); x (массовая доля).

Tannous and Lourenço [9] determined both characteristics porosities (ε_{af} and ε_{cf}) for the mixture of *Eucalyptus grandis*/sand and tucumã endorcarp/sand. In the first case, the increase on diameter ratio (1.5-6) led to the maximum increase of 19% on ε_{af} and 13% on ε_{cf}. The increasing of mass fractions (5 to 20 wt%) led to the increase of 41% for ε_{af} and 200% on ε_{cf}. Based on these results, authors concluded the mass fraction is more influenced than the diameter on the porosities of mixtures. In the second case, the effects of diameter and mass fraction ratios were fewer noticeable. The increasing of mass fraction (5-20 wt%) caused a increment of 16.2 wt% on ε_{af} and 10.8% on ε_{cf}. Besides, ε_{af} and ε_{cf} decreased 5.1% and increased 10.8 wt%, respectively, with the change on diameter ratio from 3.1 to 6.1. The only empirical correlations founded on the literature were developed by the present authors, according to Equations 8 (ε_{af}) and 9 (ε_{cf}) considered for each characteristic velocity (U_{af} and U_{cf}, respectively). In these equations Mv is the dimensional density number, $Mv = (\rho_{p,ef} - \rho_g)/\rho_g$, considering $\rho_{p,ef}$ and ρ_g as the effective and gas densities, respectively.

$$\varepsilon_{af} = 0.07 Re_{af}^{0.43} Ar_{ef}^{0.5} Mv^{-0.4} \qquad (8)$$

valid for $1.6 < Re_{af} < 18$; $3.1\ 10^3 < Ar_{ef} < 1.5\ 10^4$; $1.0\ 10^3 < Mv < 2.1\ 10^3$

$$\varepsilon_{cf} = 0.07 Re_{cf}^{0.4} Ar_{ef}^{0.5} Mv^{-0.4} \qquad (9)$$

valid for $10 < Re_{cf} < 52$; $3.7\ 10^3 < Ar_{ef} < 1.5\ 10^4$; $1.0\ 10^3 < Mv < 2.1\ 10^3$

BED EXPANSION

The bed expansion (ε) is the one of the most important parameter on the fluidized bed design. This parameter can be described as the ratio between the bed height in a particular velocity and the bed height at the U_{af}, or as the relation between the void volume observed in a particular velocity and the total volume of the bed. The effects of the mass fraction and diameter ratios of biomass/inert mixtures are also observed.

Rao and Reddy [16] analyzed the influence of different arrangements of pairs of biomass/sand in the expanded bed height. The biomasses evaluated was rice husk (d_p = 2.094 mm), sawdust (d_p = 0.578 mm) and groundnut shell (d_p = 0.878 mm) and, three diameters of sand (d_p = 0.440 mm, 0.660 mm and 0.930 mm). The mass fraction ratios biomass:sand employed were 1:13, 1:5 and 1:12, respectively. The authors concluded that the best mixtures were rice husk and sawdust using smaller inert diameter, and groundnut shells using medium inert diameter.

Basul Paudel [21] evaluated the mixtures of walnut shell (d_p = 0.856 mm) and corn cob d_p=1.040 mm) with sand considering biomass mass fraction of 30wt%. The bed expansion decreased with increasing of effective density, due to the bed weight. The author concluded that the particle density has greater influence on the bed expansion than particle diameter.

Tannous and Lourenço [9] studied the bed expansion for mixtures of *Eucalyptus gradis*/sand and tucumã endorcarp/sand and observed that it was more significant for the smallest diameter and the highest mass fraction ratios due to the facility in mixing through the growth of bubbles and the intensity burst at the bed surface. In relation to the diameter ratios (D) of 1.5 and 3.1, it showed more significant in the bed expansion than for D=6.0 for the *Eucalyptus grandis*/sand mixture. A rapid increase was observed between U_{if} (or U_{af}) and U_{cf} and after this last velocity, an abrupt rise was identified due to the presence of slugs. On the other hand, tucumã endorcarp/sand mixture showed less influence on the bed expansion, but accentuated values for D=1.5. Regarding to the mass fraction ratio, the authors verified for the first mixture that the increase on the mass fraction (5-20wt%) caused a large deviation on the bed expansion between U_{if} and U_{cf} and the most pronounced expansion decay for 20 wt%, while for U_{cf} higher than 0.8 m/s the curves overlapped. For the second mixture, small differences were observed on the bed expansion due to the mass fraction ratio adopted. These authors proposed an empirical correlation for the bed expansion (Equation 10), validate for $10 < Re < 60$, $3.1\ 10^3 < Ar_{ef} < 1.5\ 10^4$, and $1.0\ 10^3 < Mv < 2.1\ 10^3$.

$$\varepsilon = 0.067 Re^{0.43} Ar_{ef}^{-0.22} Mv^{-0.12} \qquad (10)$$

CONCLUSIONS

This work showed a large lack in the literature about the diversity of biomasses in order to understand the mechanisms of mixture and segregation in fluidized beds using on the biomass to energy conversion process. Biomasses showed different physical characteristics concerning the particle size, density, and shape, which can possibly lead to the difficulties founded on the researches on the identification of fluid dynamic parameters. Regarding to the fluid dynamic behavior, there is an agreement that the presence of an inert can easily lead to a best quality of fluidization. Characteristic velocities (U_{if}, U_{af}, U_s, and U_{cf}) and fluid dynamic states were not exactly defined, mainly because the authors in general focus only on the minimum fluidization condition, while the other velocities and regimes are also important to understand the phenomena. Different methodologies were developed to improve the determination of these conditions and must be well explored. Concerning the influence of mass fraction and diameter ratios, in general the velocities tend to increase with the increase of these parameters. Particles with smaller diameters, angular shape and lower mass fraction ratios seem to support better the fluidization due to the facility of mixture. Further research is needed with different biomass/inert arrangements to improve the knowledge of the fluidization phenomena and its modeling.

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