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Fluidization of binary mixtures of sisal residue and sand: A new model for deriving the final fluidization velocity

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ABSTRACT

The influence of different factors on the fluidization of a binary mixture of sisal residue and sand was investigated. The particle sizes of the sand and sisal residue were varied from 0.2 to 0.8 mm and the biomass mass fractions from 2% to 9%. Some segregation was noted, and a significant relationship was found among the final fluidization velocity (U_{ff}), the biomass and sand sizes, and the biomass mass fraction. A novel model was developed for predicting U_{ff}, leading to an average discrepancy of 12.69% between the measured and predicted U_{ff} compared with the best match of 15.32% when using a model from a previous paper. The new model was applied to data from studies using other biomass and a broad range of particle characteristics. The average divergences from measured values when using the new model were 7.9% for corn cob and walnut shell, and 20.5% for sweet sorghum bagasse, tobacco residue, and soy hulls. These were superior to the values derived using other models. Our results confirm the accuracy of the model developed in this work and show that it represents a viable alternative way to calculate U_{ff} for a binary mixture of sand and biomass.

Introduction

Fluidized bed reactors have been widely applied in the gasification, pyrolysis, or combustion of a wide range of particulate biomass. This reactor type yields a product of uniform quality because its efficient heat and mass transfer minimizes any temperature variation and ensures complete mixing (Bridgewater, 2004; Jeong, Lee, Chang, & Jeong, 2016; Wang et al., 2016). However, biomass particles are difficult to fluidize because of their varied shapes, sizes, and densities. To improve fluidization and processing, a second solid material is often introduced. This is typically an inert material such as silica sand, alumina, or calcite (Cui & Grace, 2007).

The minimum velocity at which these binary mixtures fluidize is an important parameter in optimizing the performance of the bed and reaction kinetics and making efficient use of the fluidizing gas (Karmakar, Haldar, & Chatterjee, 2012; Oliveira, Cardoso, & Ataíde,2013). When a binary mixture remains homogeneous during fluidization, the minimum fluidization velocity is commonly used (Oliveira et al., 2013). However, when a binary mixture segregates during fluidization, a fluidization process occurs between the initial fluidization velocity U_{if} and the final fluidization velocity U_{ff}. In this case, a bed-fluidized condition is attained at the final fluidization velocity (Formisani & Girimonte, 2003). Some models have been developed to predict the final fluidization velocity (Formisani, Girimonte, & Vivacqua, 2011; Formisani, Girimonte, & Vivacqua,2013) but these were developed for mineral binary systems, and they require information regarding the minimum fluidization velocity of the pure components, the minimum fluidization porosity, the bed height, and the mass fraction of the lightest component.

The minimum fluidization velocity must be equal to or less than the final fluidization velocity and is dependent on the mixing/segregation pattern accompanying the fluidization process (Formisani & Girimonte, 2003). In this way, the minimum fluidization velocity is influenced by the same variables that influence the final fluidization velocity, i.e., it depends on the initial arrangement of the fixed bed, the composition of the initial segregated system, and a well-mixed bed and size or density ratio of its components (Formisani, Girimonte, & Longo, 2008a).

The minimum fluidization velocity depends on the properties of the particles and fluidizing gas, the diameter and geometry of the bed, and the design of the distributor, including its aspect ratio and geometry (Yang, 2003). It is also affected by particle segrega-

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Nomenclature

Ar^*	Archimedes number (modified)
d_{bio}	biomass particle size, mm
DCP	discrepancy, %
d_{eff}	particle size of binary mixture, mm
d_{sand}	sand particle size, mm
g	acceleration due to gravity, m/s^2
$Re_{mf}{}^*$	Reynolds number (modified)
U_{ff}	final fluidization velocity, m/s
U_{if}	initial fluidization velocity, m/s
U_{mf}	minimum fluidization velocity, m/s
w_{bio}	biomass mass fraction
w_{sand}	sand mass fraction
ρ_{bio}	biomass density, kg/m^3
ρ_{eff}	effective density of mixture, kg/m^3
ρ_{fluid}	density of fluidizing medium, kg/m^3
ρ_{sand}	sand density, kg/m^3
μ	dynamic viscosity of fluidizing gas, kg/(m·s)

tion, which in turn is determined by the densities and sizes of the biomass particles and inert components (Chiba, Chiba, Nienow, & Kobayashi, 1979; Cluet, Mauviel, Rogaume, Authier, & Delebarre, 2015; Larcher & Jenkins, 2013; Walker & Rollins,1998).

The fluidization velocity of a binary mixture has been studied under different operating conditions and with different biomass types. Some studies have derived the fluidization velocity of a binary mixture from its overall composition, particle density, and particle diameter, rather than measuring the fluidization velocity of each component separately (Aznar, Gracia-Gorria, & Corella, 1992). Rao and Bheemarasetti (2001) and Chok, Gorin, and Chua (2010) proposed a standard equation for calculating the minimum fluidization velocity of a biomass/sand mixture based on its effective density and particle diameter. Abdullah, Husain, and Pong (2003) studied the fluidization velocities of a range of biomass residues (sawdust, coal bottom ash, coconut shell, rice husk, and palm fiber) and concluded that the bulk density and voidage are the main determining factors of the fluidizing quality of a bed.

Zhong, Jin, Zhang, Wang, and Xiao (2008) proposed a general equation based on the individual particle sizes and densities and the composition of the mixture, and they used this to derive minimum fluidization velocities for sawdust, wheat stalk, and quartz sand. Their approach was based on an equation developed by Wen and Yu (1966), using a correlation with the sphericity coefficient (Si & Guo, 2008). When biomass materials such as rice husk, bagasse, and sawdust were fluidized with sand, the equations of Rao and Bheemarasetti (2001) and of Aznar et al. (1992) were found to predict the minimum fluidization velocities. However, differences remained between the theoretical values and the experimentally observed data.

Many papers have reported equations for modeling binary mixtures in gas–solid systems (Chiba et al., 1979; Chok et al., 2010; Clarke, Pugsley, & Hill, 2005; Cluet et al., 2015; Gauthier, Zerguerras, & Flamant, 1999; Noda, Uchida, Makino, & Kamo, 1986; Shao et al., 2013; Shao, Zhong, & Yu, 2016; Wen & Yu, 1966). However, no consensus has yet emerged on the best approach to predicting the minimum fluidization velocity of a biomass or mixture of biomass and inert particles (Paudel & Feng, 2013).

The goal of the present study was to investigate the key factors that influence the final fluidization velocity of a binary mixture of sisal residue and sand and to derive a model that best represents those variables. A relationship between the final fluidization velocity and the particle size and mass percentage of the biomass was derived from the interaction effects using the response-surface methodology (RSM). The prediction of final fluidization velocity was based on a review of the previous literature, and a novel algorithm was developed using dimensional analysis. The main contribution of this paper is a general mathematical model for calculating the final fluidization velocity of a binary mixture of sand and biomass.

Materials and methods

Sisal residue

The sisal plant (*Agave sisalana*, of the Agavaceae family) is rich in long fibers and is used in rope making (Fig. 1(a)). These fibers are the economic basis of sisal exploitation (Fig. 1(b)), yet the fiber yield is only 3–4% of the weight of the plant. Ways of adding value to the sisal residue are therefore needed to improve the economic performance of the sector. Sisal residue was chosen for use in the fluidized bed (Fig. 1(c)). This byproduct is formed by scraping sisal sheets to remove the fibers; it is normally either treated as organic waste or used as a low-nutritional-value animal feed (EMBRAPA, 2011; Laksesvela & Said, 1970).

Preparation and characterization of sisal residue and sand

The sisal residue was transported to the laboratory and stored in a refrigerator to prevent fermentation taking place. A portion of the residue was dried in an oven at 105 °C for 4 h to remove excess water, making it similar to the material used in the production of bio-oil (Bridgwater, 2012). After cooling to room temperature, the short sisal fibers were removed from the biomass, leaving dried slices. The water content was measured by Karl Fischer titration using a Metrohm 836 Titrando analytical system. The dried biomass contained 6.85 ± 0.59 wt% of moisture.

The values for gas (air) density (1.1839 kg/m^3 at 1 atm and 25 °C) and dynamic viscosity (1.85 × 10^{-5} kg/(m s) at 1 atm and 25 °C) were taken from existing literature (Incropera & Dewitt, 2001; Perry, Green, & Maloney, 1997).

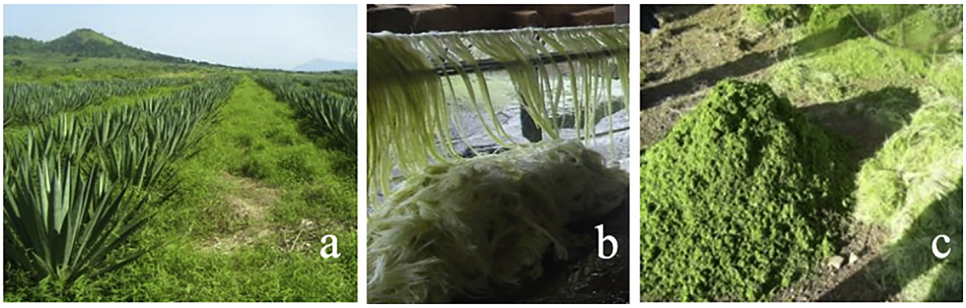

Fig. 1. Sisal plants and by-products: (a) sisal plantation, (b) sisal fibers, and (c) sisal residues.

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