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Fluid dynamic analysis for pyrolysis of macadamia shell in a conical spouted bed

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ABSTRACT

The pyrolysis is an important technology for generating energy from agro-industrial wastes. The processing of macadamia nut generates a lot of shell residues. In literature, the conical spouted bed has been pointed out as a promising air-solid contact system for pyrolysis process. Due to low density of biomass and their poor flowability, sand is added to improve the fluid-dynamic stability of the spouted bed. This research aims to experimentally investigate the fluid dynamics of a mixture of sand and macadamia shell in a conical spouted bed, with different mass fractions and static bed heights. The particles exhibited good circulation in the bed for mass fractions of 25 to 75%, with acceptable levels of segregation for pyrolysis process. Moreover, correlations have been proposed for the calculation of the minimum spouting air velocity and pressure drop in conical spouted beds made up of mixtures of macadamia shell and sand.

1. Introduction

Macadamia is known for producing a fruit (nuts), enclosed in very hard, woody shells. Macadamia nuts are extremely nutritious, with a high amount of beneficial fatty acids as well as calcium, iron and B vitamins. Macadamia shells are a by-product from macadamia nut processing [1]. For each ton of macadamia nut produced are generated 70 to 77% of shell residues. Thus, the disposal of the macadamia waste shells, as other agricultural residues [2], has created a serious problem for the processing industries. These residues have a lot of volatile material (>80%) and low ash content (<1%) [3]. In this context, macadamia shells can be seen as a promising option for use in biomass pyrolysis [4].

The spouted bed is an alternative technology for pyrolysis, because it is potentially more energy efficient than some reactors. The spouted bed was developed in 1954 by Gishler and Mathur as an alternative to fluidization for particulate solids too coarse for good fluidization [5]. Since then, due to its efficiency in contacting gases and coarser particles, this equipment has been successfully applied to a wide variety of processes such as drying, coating, granulation and mechanical extraction, among others applications [6–12].

In spouted bed, the cyclic moving of solid phase promotes an effective air-particle contact, producing a good mixing between phases involved and, consequently, high rates of heat and mass transfer [13]. In most of the early applications of spouted bed, particles with uniform density and narrow size distributions were generally used. However, for pyrolysis of biomass, an inert solid material should also be used for heating the biomass. Thus, for pyrolysis application, the spouted bed operates with a mixture of particles of different properties.

In general, due to low density of biomass and their poor flowability, sand is added, as an inert solid material, to improve the fluid-dynamic stability of the spouted bed [14]. Moreover, in pyrolysis applications, sand is the main material responsible for heating the biomass (particle-particle contact) [15]. Therefore in this spouted bed application two types of particles are present simultaneously.

The study of binary mixture in spouted bed can be found in several works of literature [16–24]. Most of these works involve mixtures of solids of different particle sizes, shapes and densities, making them subject to the particle segregation phenomenon. The segregation occurs mainly due to the difference in particle terminal velocities [16]. Particle segregation in spouted bed reactors can cause unstable spouting, or high temperature spots and hence, agglomeration of the biomass [24]. Despite the important contributions of these works involving the study of spouted bed with binary mixture [16–24], the applications of spouted beds in pyrolysis process with binary mixtures will encounter many challenges due to a lack of comprehensive understanding in the fluid-dynamics aspects related to the mixing and segregation of the sand and biomass.

In the literature there are several correlations for estimation of air velocity and pressure drop in the minimum spouting condition to mono-particle beds [25]. The correlations for minimum spouting velocity proposed by Saldarriaga et al. [26] takes into account the sphericity of particles, however, they are not applicable to binary mixtures. Paudel and Feng [27] and Asif [28] investigate the prediction of air velocity for binary mixtures using definitions of effective density and diameter, but in fluidized beds.

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Despite some studies related to the spouted bed pyrolysis reactors have been reported, the complexity of air-particle fluid dynamics is still the main challenge to be overcome before it be scaled up for commercial applications. Thus, additional investigations are needed to gain further insights into the fluid dynamics of spouted beds operating with particle mixtures, mainly for mixtures involving biomass particles and inert solid material.

The present work deals with the analysis of fluid dynamic behavior of a mixture of sand and macadamia shell in a conical spouted bed, with different mass fractions and static bed heights. The axial profile of particle segregation was also assessed. Moreover, correlations have been proposed for the calculation of the minimum spouting air velocity and pressure drop in conical spouted beds made up of mixtures of macadamia shell and sand.

2. Materials and methods

2.1. Characterization of particles

Macadamia nut shell used in the experiments came from São Mateus-ES, southeastern Brazil. The macadamia residue was first dried at 353 K for 24 h, then ground and sieved. Table 1 summarizes some mean physical properties of the sand and macadamia shell particles. The range of particle diameter was 2.36 mm–2.8 mm for the sand and 1.4 mm–1.7 mm for macadamia shell and the shape is spherical for both. Through of their properties, can be concluded that they belong to the group D of Geldart, having the ability to produce spouting regimes when subjected to the gas flow.

2.2. Experimental apparatus

The fluid dynamics tests were carried out in a semi-pilot scale conical spouted bed. The experimental setup is illustrated in Fig. 1. During the tests, air was supplied by an air compressor (2.0 hp). The pressure drop through the particle bed was measured using a pressure transducer (0–20 in WC). The signal was transmitted to a microcomputer by a data acquisition card and processed by LabVIEW™ software. Data were sampled for 1024 s at a sampling frequency of 1000 Hz, so that 1024 data points were recorded for each condition. The air velocity was measured by a thermo-anemometer (Kimo Instruments).

2.3. Experimental procedure

A 3^2 factorial experimental design, added with 2 central points, was performed to investigate the effects of mass fraction of macadamia shell (X_b) and stagnated bed height (H_o) on the fluid dynamics parameters. For the mass fraction of biomass, the following levels were chosen: 0.25; 0.50 and 0.75. For the stagnated bed height, were selected: 0.06; 0.08 and 0.10 m. The response variables analyzed were: minimum spouting air velocity (u_{ms}) and minimum spouting pressure drop ($-\Delta P_{ms}$).

The particles were weighed according to the mixture's composition, homogenized and added to the spouted bed until they reached the stagnated bed height of the respective test. The transition from a static bed to a spouted bed can be described by the characteristic curve, i.e., a plot of total pressure drop as a function of decreasing air velocity. The point at which the spout collapses defines the minimum spouting condition, i.e., minimum spouting air velocity (u_{ms}) and minimum spouting pressure drop ($-\Delta P_{ms}$).

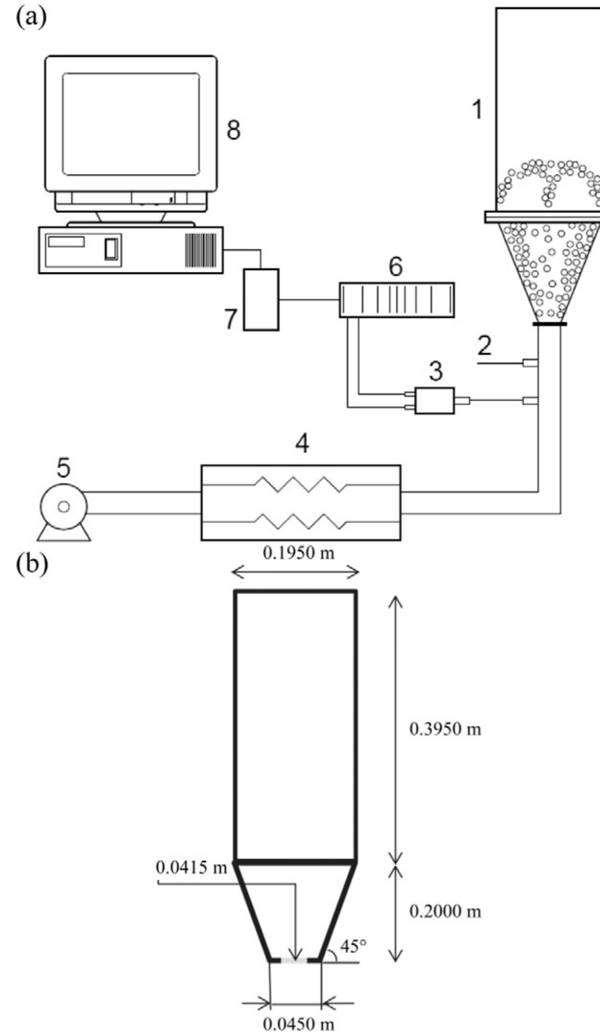

Fig. 1. Experimental apparatus. (a) Scheme of the experimental setup: 1 — conical spouted bed, 2 — thermocouple, 3 — pressure transducer, 4 — air heating system, 5 — blower, 6 — signal conditioner, 7 — data acquisition card, 8 — computer; (b) spouted bed geometry.

Table 1
Physical properties of materials.

Properties	Sand	Macadamia Shell
Density (ρ) [kg m^{-3}]	2624	1190
Voidage of monoparticle bed (ε) [−]	0.39	0.41
Diameter (d) [m]	2.58×10^{-3}	1.55×10^{-3}
Sphericity (Φ) [−]	0.76	0.72

2.4. Correlations for u_{ms} and $-\Delta P_{ms}$

In the present work, empirical equations to predicted minimum spouting air velocity (u_{ms}) and minimum spouting pressure drop

Table 2
Correlations for conical spouted bed operating with mono-particles.

Author	Correlation	Eq.
Minimum spouting air velocity (u_{ms})		
Markowski and Kaminski [29]	$\frac{\rho_f u_{ms} D_o}{\mu} = p_1 \left[\frac{d_{eff}^{\varepsilon} \rho_f (\rho_{eff} - \rho_f) g}{\mu^2}\right]^{p2} \left(\frac{H_o}{D_o}\right)^{p3} \left(\frac{D_c}{D_o}\right)^{p4}$	(1)
Tsvik et al. [30]	$\frac{\rho_f u_{ms} D_o}{\mu} = p1 \left[\frac{d_{eff}^{3} \rho_f (\rho_{eff} - \rho_f) g}{\mu^2}\right]^{p2} \left(\frac{H_o}{D_o}\right)^{p3} \left[\ ,\tan\left(\frac{\gamma}{2}\right)\right]^{0.42}$	(2)
Olazar et al. [31]	$\frac{\rho_f u_{ms} D_o}{\mu} = p1 \left[\frac{d_{eff}^{3} \rho_f (\rho_{eff} - \rho_f) g}{\mu^2}\right]^{p2} \left(\frac{D_b}{D_o}\right)^{p3} \left[\ ,\tan\left(\frac{\gamma}{2}\right)\right]^{-0.57}$	(3)
Nikolaev and Golubev [32]	$\frac{\rho_f u_{ms} D_o}{\mu} = p1 \left[\frac{d_{eff}^{3} \rho_f (\rho_{eff} - \rho_f) g}{\mu^2}\right]^{p2} \left(\frac{H_o}{D_c}\right)^{p3} \left(\frac{D_o}{D_c}\right)^{p4}$	(4)
Goltsiker [33]	$\frac{\rho_f u_{ms} D_o}{\mu} = p1 \left[\frac{d_{eff}^{3} \rho_f (\rho_{eff} - \rho_f) g}{\mu^2}\right]^{p2} \left(\frac{H_o}{D_o}\right)^{p3} \left(\frac{\rho_{eff}}{\rho_f}\right)^{p4}$	(5)
Minimum spouting pressure drop ($-\Delta P_{ms}$)		
Markowski and Kaminski [29]	$-\frac{\Delta P_{ms}}{\rho_f {u_{ms}}^2} = p1 \left(\frac{D_c}{H_o}\right)^{p2} \left(\frac{D_o}{H_o}\right)^{p3} \left(\frac{H_o}{d_{eff}}\right)^{p4}$	(6)
Olazar et al. [34]	$-\frac{\Delta P_{ms}}{\rho_{eff} g H_o} = \left(\frac{\rho_f u_{ms} D_o}{\mu}\right)^{p1} \left(\frac{H_o}{D_o}\right)^{p2} 1.20\left[\ ,\tan\left(\frac{\gamma}{2}\right)\right]^{-0.11}$	(7)