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Correlations for calculating peak and spouting pressure drops in conical spouted beds of biomass

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ABSTRACT

A study has been carried out on the applicability of the correlations proposed in the literature for calculating peak and spouting pressure drops to biomass materials. These parameters are essential for estimating energy consumption in spouted beds and depend on the contactor geometry, operating conditions and the type of particles. Five biomass materials have been studied based on their suitability for energy production by combustion and their different size, density and shape factor. Both peak and spouting pressure drops increase as particle size and density are increased and shape factor is decreased. Correlations have been proposed based on those already reported in the literature for regular materials. The influence of particle size and density is more pronounced in these irregular biomass materials than in regular ones, especially in the peak pressure drop. Shape factor is also highly influential, which is reflected on the greater influence of the static bed height for irregular materials, especially for the spouting pressure drop.

1. Introduction

Use of biomass as a renewable energy source has gained increasing attention in recent years due to its much lower impact on climate change. Thus, nowadays it is the main source of renewable energy with a contribution of approximately 14% to the overall world consumption, which is of the same order as that of coal, 12%, and natural gas, 15% [1,2]. Furthermore, biomass has another advantage, such as availability, and the fact that it is carbon neutral, *i.e.*, the CO_2 released is that captured by the plant during its growing period. Biomass includes residues mainly from agriculture, forest and municipal waste collection [2].

Biomass is a suitable raw material for combustion due its low volatility and the reactivity of either the fuel itself or the char formed. Prior to use, its physical–chemical parameters should be determined, as are moisture content, volatile matter, fixed carbon and ashes, and the content of the three polymers making up the lignocellulosic materials (hemicellulose, cellulose and lignin), which condition its degradation kinetics [3,4].

The production of energy and biofuels from biomass is currently a very active research field, with the main conversion processes being combustion, gasification and pyrolysis. The conical spouted bed has proven to be especially suitable for these processes [5–8], given that this technology allows handling coarse particles ($d_p > 1\,mm$) [9] and those of irregular shape [10,11], as is the case of biomass materials.

Different modifications of the original spouted bed have been proposed in the literature with the aim of improving its hydrodynamic performance. These involve mainly the contactor geometry and the gas inlet section, with allow increasing their capacity for treating different types of solids, decreasing pressure drop, improving the cyclic circulation of the solids and operating in a stable way in a wide range of gas flow rates [9,12,13]. Thus, conical spouted beds allow operating in a dilute spouted bed regime with very short residence times (as low a milliseconds) [9,14–19].

Furthermore, according to Altzibar et al. [20], knowledge on pressure drop (both peak and operating ones) and minimum spouting velocity are essential for the design, operation and scaling up of these types of contactors. These are highly dependent on fluid and particle features and contactor geometry. The operating pressure in these contactors is considerably lower than in fluidized beds, which allows using blowers instead of compressors for air supply.

A detailed review of the correlations for calculating operating and peak pressure drops in conical spouted beds has been carried out by Olazar et al. [21]. These correlations are shown in Tables 1

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Nomenclature

ASRE	average square relative error
Ar	Archimedes number, $g\ d_p{}^3\ \rho(\rho_s-\rho)\mu^{-2}$
d_p	average particle diameter, m
D_o	gas inlet diameter, m
D_b	top diameter of the static bed, m
D_c	column diameter, m
D_i	contactor base diameter, m
F	Fisher F distribution
g	acceleration of gravity, m/s^2
H_o	static bed height, m
H_c	height of the conical section, m
K	proportionality constant
n	number of experimental data
Re_{msi}	Reynolds number for minimum spouting, referred to D_i, $\rho u_{ms} d_p \mu^{-1}$
SSR	sum of square residuals
u_{ms}	minimum spouting velocity measured at the inlet orifice D_o, m/s
V_r	volume of the draft-tube, m^3
V_o	volume of the static bed, m^3

Greek letters

γ	cone angle, rad
ϕ	sphericity
ε_o	fractional void volume of static bed
ρ	density of the gas, kg/m^3
ρ_b	bed density, kg/m^3
ρ_s	density of the particle, kg/m^3
ΔP_s	operating pressure drop, Pa
ΔP_M	peak pressure drop, Pa

and 2 and have been obtained using a wide range of particle sizes and even shape factors [16]. More recently, Saldarriaga et al. [10,11] have proven the excellent behavior of the conical spouted bed in the treatment of different types of irregular biomasses (wide particle size distribution and range of shape factors) with a high moisture content. Furthermore, previous papers by our research group have proven that the conical spouted bed is suitable for the drying and thermal processing of a wide variety of residues (biomass, plastics and sewage sludge) [3,7,16,21–24]. The hydrodynamics of the conical spouted beds differs significantly from that of the conventional ones (cylindrical with conical base). Therefore, the ranges of the hydrodynamic parameters required for stable spouting, *i.e.*, minimum spouting velocity, pressure drop and bed expansion, are also different [16,21,24].

This paper deals with the assessment of pressure drops in the treatment of different types of biomasses in a conical spouted bed. The aim is to account for the complex nature of these materials and the ranges of the geometric factors of the contactors, and delimit the conditions required for operating under stable regime. The correlations reported in the literature for these types of beds have been taken as the starting point [21] to propose new ones for peak and spouting pressure drops.

2. Experimental section

2.1. Physical–chemical properties of the biomasses

Five types of biomasses have been used based on their susceptibility for valorization by combustion and because they cover a wide range of biomass types for verifying the capability of the technology proposed for the treatment of materials that are difficult to handle with standard technologies. Furthermore, they are complementary for guaranteeing a regular supply not conditioned to seasonal changes for the implementation of a combustion plant. The types of biomasses used are as follows: residues from pine (*Pinus insignis)* wood industries, residues from food industries (rice husk and olive pit), herbaceous materials (*Rumex tianschanicus*), and posidonia (*Posidonia oceanica*), which is a seagrass species that is endemic to the Mediterranean Sea. Table 3 shows the main physical features of the biomasses studied.

The moisture content has been measured following ISO-589 standard and also using a halogen moisture analyzer (HR83, Mettler Toledo). Particle density has been measured by mercury porosimetry and the average particle size (mean reciprocal diameter) [28] according to the following expression:

$$\overline{d_p} = \frac{1}{\sum \frac{X_i}{d_{p_i}}} \tag{7}$$

where X_i values are the fractions obtained by sieving and those for d_{pi} are the corresponding average diameters.

As observed in Table 3, all the biomasses studied are highly irregular except the olive pit, which is more spherical than the other ones, with this fact having an influence on its hydrodynamic behavior, as has been observed in previous studies [22,30–34]. The solids bulk density or bed density, ρ_b, is the mass of biomass by volume unit in a loosely packed bed. It has been determined in a vessel whose diameter is at least 10 times higher than particle diameter and whose height is at least 10 times the vessel diameter. The measurement of shape factor, ϕ, for very irregular materials as those studied here is not straightforward and has been carried out based on the voidage of the loosely packed bed and the correlation by Brown and Richards [35].

Table 1
Hydrodynamic correlations for spouting pressure drop.

Authors	Correlations	Eq.
Gorshtein and Mukhlenov [25]	$\frac{-\Delta P_S}{H_0 \rho_b (1-\varepsilon_0) g} = 7.68(\tan(\gamma/2))^{0.2} (Re_{msi})^{-0.2} (\frac{H_o}{D_i})^{-0.33}$	(1)
Markowski and Kaminski [26]	$\frac{-\Delta P_S}{\rho u_{msi}^2} = 0.19(\frac{D_C}{H_o})^{0.56} (\frac{D_i}{H_o})^{2.39} (\frac{H_0}{d_p})^{2.35}$	(2)
Olazar et al. [16].	$\frac{-\Delta P_S}{H_0 \rho_s (1-\varepsilon_0) g} = 1.20(\tan(\gamma/2))^{-0.11} (Re_{msi})^{-0.06} (\frac{H_0}{D_i})^{0.08}$	(3)

Table 2
Hydrodynamic correlations for peak pressure drop.

Authors	Correlations	Eq.
Gelperin et al. [27]	$\frac{-\Delta P_M}{(H_o \rho_b g)} = 1 + 0.062(\frac{D_b}{D_i})^{2.54} ((\frac{D_b}{D_i}) - 1)(\tan(\gamma/2))^{-0.18}$	(4)
Gorshtein and Mukhlenov [25]	$\frac{-\Delta P_M}{\Delta P_S} = 1 + 6.65(\frac{H_o}{D_i})^{1.2} (\tan(\gamma/2))^{0.5} Ar^{0.2}$	(5)
Olazar et al. [16]	$\frac{-\Delta P_M}{\Delta P_S} = 1 + 0.116(\frac{H_o}{D_i})^{0.5} (\tan(\gamma/2))^{-0.8} Ar^{0.0125}$	(6)

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