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Minimum spouting velocity for conical spouted beds of vegetable waste biomasses

Juan F. Saldarriaga, Roberto Aguado*, Haritz Altzibar, Aitor Atxutegi, Javier Bilbao, Martin Olazar

Department of Chemical Engineering, University of the Basque Country, Bilbao 644 - E48080, Spain

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ABSTRACT

Spouted beds are an interesting alternative for the treatment of biomass for energy purposes, given that the insertion of a draft-tube allows large-scale handling of solids with a wide range of sizes and diverse properties. The hydrodynamic correlations proposed in the literature have not been validated with particles of low density and shape factor. Therefore, a detailed experimental study has been conducted using five types of biomasses and different combinations of the contactor geometric factors. The correlations in the literature for plain conical spouted beds and for those provided with nonporous and open-sided draft-tubes have been taken as a starting point and, based on the experimental results, they have been modified in order to account for the properties of the solids. Two strategies have been considered in the methodology for modifying the coefficients in the literature correlations. Both are based on the introduction of coefficients one by one based on a hypothesis test. Accordingly, new correlations based on existing ones have been proposed, with the number of coefficients modified being minimum.

1. Introduction

Biomass is recovering part of the significance it had in the past as an energy source. Nowadays, it is the largest single renewable energy source, providing 10% of the global energy supply, and a strong increase is foreseen in bioenergy electricity supply for the year 2050. According to the forecasts, bioenergy would provide 3100 TWh of dispatchable and in many cases flexible electricity, meeting 7.5% of the world electricity demand [1]. These expectations are based on the renewable nature and abundance of biomass and the uniform distribution throughout the planet of feedstocks, including agricultural and forestry residues and wastes [2,3]. Accordingly, a worldwide growing interest has been aroused for developing efficient biomass thermal conversion technologies to combat climate change and provide the solutions for current energy crisis [4,5].

Spouted beds perform well in the treatment of coarse, sticky or highly irregular particles and, furthermore, operation with wide particle size distributions may be carried out without segregation problems [6]. These conditions are common in processes, such as drying, combustion and gasification of vegetable biomasses. The use of a conical geometry instead of the traditional cylindrical one allows operating stably in a wide range of gas flow rates [7]. Therefore, the conical spouted bed reactor is an alternative technology to the fluidized one, which performs well in the upgrading by thermochemical routes of wastes in general and vegetable biomass in particular [8–13].

The large-scale performance of this technology is limited by the ratio of the gas inlet diameter (D_o) to the particle diameter (d_p), which must be smaller than 20–30 in order to avoid slugging and achieve stable spouting status. The insertion of a draft-tube is the usual solution to this problem. Although this tube considerably modifies the hydrodynamic behaviour of the bed by affecting the solid circulation rate, particle cycle time, gas distribution, minimum spouting velocity and pressure drop [14–18], it provides clear advantages for steady state operation, such as greater flexibility and better control, higher bed stability, lower gas flow rate and pressure drop, the possibility of treating mixtures made up of solids of different nature and wide size distribution, narrower residence time distribution, better control of solid circulation and no maximum spoutable bed height [19–28].

Different draft-tube configurations have been used in the literature, namely, conventional nonporous draft-tubes, porous draft-tubes and open-sided draft-tubes, the latter especially suitable for vigorous contact. As proven in previous studies, operation with open-sided draft-tubes requires higher flow rates for achieving the spouting regime and the pressure drop generated is also higher than using nonporous draft-tubes, which gives way to a much more vigorous solid circulation in the bed.

Knowledge of the minimum spouting velocity is essential in the design and operation of these beds because it allows establishing

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* Corresponding author. Tel.: +34 946 015 394; fax: +34 946 013 500.
E-mail address: roberto.aguado@ehu.es (R. Aguado).

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Notation

ASRE	Average square relative error
A_0	Open lateral area of the tube, m^2
A_T	Total lateral area of the tube, m^2
Ar	Archimedes number, $gd_p{}^3\rho(\rho_s\text{-}\rho)\mu^{-2}$
d_p	Average particle diameter, m
d_{pi}	Average particle diameter of *i* fraction, m
D_o	Gas inlet diameter, m
D_b	Top diameter of the static bed, m
D_c	Colum diameter, m
D_i	Contactor base diameter, m
D_T	Diameter of the draft-tube, m
F	Fisher F distribution
H_c	Height of the conical section, m
H_o	Static bed height, m
H_t	Total height of the contactor, m
K	Proportionality constant
L_H	Height of the entrainment zone of the nonporous draft-tube, m
L_T	Length of the draft-tube, m
$(\mathrm{Re}_o)_{ms}$	Reynolds number of minimum spouting, referred to D_o, $\rho u_{ms} d_p \mu^{-1}$
SSR	Sum of square residuals
u_{ms}	Minimum spouting velocity measured at the inlet orifice D_o, m s^{-1}
V_r	Volume of the draft-tube, m^3
V_o	Volume of the static bed, m^3
W_H	Width of the face of the open-sided draft-tube, m
Greek Letters	
γ	Cone angle, rad
ϕ	shape factor
μ	Viscosity of the gas, kg m^{-1}s^{-1}
ρ	Density of the gas, kg m^{-3}
ρ_s	Density of the particle, kg m^{-3}
ρ_b	Bed density, kg m^{-3}

the operating velocity and determines other hydrodynamic parameter, such as pressure drop, residence time and solid circulation flow rate. Furthermore, whereas the minimum fluidization velocity is only a function of particle and fluid properties, the minimum spouting velocity, u_{ms}, is a function of fluid [29,30] and particle properties, and bed geometry.

Prior studies of our research team deal with the hydrodynamics of conical spouted beds made up of pine wood sawdust, shavings, chips and their binary and tertiary mixtures (Olazar et al., 1994) [54], which have the same density and sizes in the range from approximately 1–25 mm. Furthermore, [6,31–34] studied the effect of porous, nonporous and open sided draft-tube tubes on the hydrodynamics of conical spouted beds using beds made up of building sand, glass beads and black peas. Nevertheless, vegetable biomass includes a wide variety of materials with different properties, which in turn differ markedly from those usually handled and treated in other particulate processes, and therefore specific problems are encountered when subjecting to multiphase flow [35]. Thus, certain differences to be noted are those related to large mean particle sizes, wide size distributions, extreme shapes (including flakes, chips, fibers, slivers, splinters, stalks), pliability and flexibility, compressibility and general heterogeneity [36,37].

Therefore, although the correlations proposed in the literature and shown in Table 1 for plain conical spouted beds [38–44], conventional nonporous draft-tubes [31,34,45,46] and open-sided draft-tube systems [31] are a reasonable starting point, they require certain modifications in order to consider the specific properties of vegetable biomass.

The main aim of this paper is the scaling up of conical spouted beds for processing vegetable biomasses, for which reliable correlations are required to estimate the minimum spouting velocity. This aim has been approached following three steps: (1) hydrodynamic study of conical spouted beds made up of diverse vegetable biomasses from agro-forestry and industry, by operating without and with nonporous and open-sided draft-tubes, (2) modification of specific coefficients in the empirical correlations developed in the literature, and (3) rigorous statistical study in order to infer the need for including the usual dimensionless moduli in the literature correlations or new moduli to account for the effect of particle shape on the hydrodynamics.

2. Experimental

2.1. Equipment

The experimental unit has been described previously [7,31]. The blower supplies a maximum air flow of 300 m^3 h^{-1} at a pressure of 1500 mm of water column. The flow rate is measured by two computer controlled mass flow-meters in the ranges 0–100 and 50–300 m^3 h^{-1}.

The contactor, Fig. 1, is the main component of the experimental unit and is a conical vessel made of polymethyl methacrylate, whose dimensions are as follows: total height (conical plus cylindrical section), H_t, 1.16 m; diameter of the upper cylindrical section, D_c, 0.36 m; base diameter, D_i, 0.068 m. The unit allows operating with contactors of different cone angle, γ, with those used in this study being of 28, 33, 36 and 45°, whose conical section heights, H_c, are

Table 1
Hydrodynamic correlations for calculating the minimum spouting velocity in plain conical spouted beds, conventional nonporous draft-tubes and open-sided draft-tube systems.

Author	Correlation	Eq.	Draft-tube
Gorshtein and Mukhlenov[46]	$(\mathrm{Re}_o)_{ms} = 0.174Ar^{0.5}(D_b/D_o)^{0.85}(\tan(\gamma/2))^{-1.25}$	(1)	–
Nikolaev and Golubev[47]	$(\mathrm{Re}_o)_{ms} = 0.051Ar^{0.59}(D_o/D_c)^{0.1}(H_o/D_c)^{0.25}$	(2)	–
Goltsiker[48]	$(\mathrm{Re}_o)_{ms} = 0.73Ar^{0.14}(H_o/D_o)^{0.9}(\rho_s/\rho)^{0.47}$	(3)	–
Markowski and Kaminski[49]	$(\mathrm{Re}_o)_{ms} = 0.028Ar^{0.57}(D_c/D_o)^{1.27}(H_o/D_o)^{0.48}$	(4)	–
Choi and Meisen[50]	$(\mathrm{Re}_o)_{ms} = 0.147(2gH_o)^{0.5}H_o^{0.51}d_p^{0.61}D_o^{0.24}D_c^{-1.36}((\rho_s-\rho)/\rho)^{0.48}d_p\rho/\mu$	(5)	–
Tsvik et al.[51]	$(\mathrm{Re}_o)_{ms} = 0.4Ar^{0.52}(H_o/D_o)^{1.24}(\tan(\gamma/2))^{0.42}$	(6)	–
Olazar et al.[52]	$(\mathrm{Re}_o)_{ms} = 0.126Ar^{0.50}(D_b/D_o)^{1.68}(\tan(\gamma/2))^{-0.57}$	(7)	–
Altzibar et al.[39]	$(\mathrm{Re}_o)_{ms} = 0.204Ar^{0.475}(H_o/D_o)^{1.24}(L_H/D_T)^{0.168}(\tan(\gamma/2))^{-0.135}$	(8)	Nonporous
Altzibar et al.[40]	$(\mathrm{Re}_o)_{ms} = 0.25Ar^{0.50}(H_o/D_o)^{1.2}(L_H/D_o)^{0.3}$	(9)	Nonporous
San José et al.[53]	$(\mathrm{Re}_o)_{ms} = 0.126Ar^{0.5}(D_b/D_o)^{1.68}(\tan(\gamma/2))^{-0.57}(L_H/H_o)^{0.45}(D_i/(D_i-D_T))^{0.17}$	(10)	Nonporous
Kmiec et al.[54]	$(\mathrm{Re}_o)_{ms} = 0.0137Ar^{0.714}(V_r/V_o)^{0.411}(D_b/D_o)^{0.554}\gamma^{0.8}$ where $= \frac{L_T-H_o}{L_T-L_H}$	(11)	Nonporous
Altzibar et al.[40]	$(\mathrm{Re}_o)_{ms} = 0.126Ar^{0.5}(D_b/D_o)^{1.68}(\tan(\gamma/2))^{-0.57}(A_0/A_T)^{0.30}$	(12)	Open-sided