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Flow-regime transitions in fluidized beds of non-spherical particles

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ABSTRACT

Fluidized beds frequently involve non-spherical particles, especially if biomass is present. For spherical particles, numerous experimental investigations have been reported in the literature. In contrast, complex-shaped particles have received much less attention. There is a lack of understanding of how particle shape influences flow-regime transitions. In this study, differently shaped Geldart group D particles are experimentally examined. Bed height, pressure drop, and their respective fluctuations are analyzed. With increasing deviation of particle shape from spheres, differences in flow-regime transitions occur with a tendency for the bed to form channels instead of undergoing smooth fluidization. The correlations available in the literature for spherical particles are limited in their applicability when used to predict regime changes for complex-shaped particles. Hence, based on existing correlations, improvements are derived.

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Introduction

Fluidized beds are widely used in drying, combustion, and gasification processes as they possess favorable characteristics such as fast mixing, uniform temperature distribution, and good gas–solid contact (Basu, 2006; Grace, Avian, & Knowlton, 1997). With recent political developments toward CO_2 emission targets in the EU and similar worldwide initiatives, the importance of biomass in energy technology is growing steadily (Bilgili, 2012; Gustavsson, Borjesson, Johansson, & Svenningsson, 1995; Joelsson & Gustavsson, 2012). As biomass particles are often non-spherical, being instead long or flat in shape (Gil, Teruel, & Arauzo, 2014), particle shape becomes an important parameter.

In regard to the fluidization of complex-shaped particles, there is scant understanding of several aspects (Cui & Grace, 2007; Oliveira, Cardoso, & Ataíde, 2013). Currently there is only a little knowledge of the influence of particle properties like size and shape on the fluidization behavior. What is desired is not only an understanding of the onset of fluidization (Zhong, Jin, Zhang, Wang, & Xiao, 2008), but also insight into flow regime changes and its dependence on the fluid velocity. Such behavior has been fully investigated in the fluidization of spherical particles (Grace et al., 1997). To date, different flow regimes have been studied in fluidized beds (Jaiboon, Chalermsinsuwan, Mekasut, & Piumsomboon, 2013; Kage, Agari, Ogura, & Matsuno, 2000; Trnka, Vesely, Hartman, & Beran, 2000; Zijerveld, Johnsson, Marzocchella, Schouten, & Van Den Bleek, 1998) and more exhaustively in circulating fluidized beds (Chalermsinsuwan, Boonprasop, Nimmanterdwong, & Piumsomboon, 2014; Duan & Cong, 2013; Johnsson, Zijerveld, Schouten, Van Den Bleek, & Leckner, 2000; Kage et al., 2000; Zijerveld et al., 1998), focusing on spherical or nearly spherical particles like glass beads or sand. Moreover, absolute values and amplitude analysis of pressure and bed height, spectral analysis as well as visual observations, image analysis and solids distribution were considered (Zijerveld et al., 1998). Spherical particles pass through a fluid transition from a fixed to a fluidized bed at a minimum fluidization velocity U_{mf}. Above U_{mf} for Geldart A particles (Geldart, 1973), the bed expands uniformly with little pressure fluctuations present (Grace et al., 1997). An extensive list of correlations providing information on U_{mf} are provided (Suksankraisorn, Patumsawad, & Fungtammasan, 2001; Wu & Baeyens, 1991). At U_{mb}, bubbling fluidization starts with voids forming near the distributor plate leading to bubbles that grow by coalescing and rise to the surface. Significant irregular pressure fluctuations are present when bubble size increasing with gas velocity. For Geldart B and D particles U_{mb} is equivalent to U_{mf}. In the power spectral function obtained from fast Fourier transformation, three distinguished peaks can be identified for Geldart group A and B particles (Kage et al., 2000). Sedighikamal and Zarghami (2013) used a recurrence rate analysis of pressure fluctuations to characterize bubbling fluidization. When bubbles reach sizes similar to the column diameter, slugging is initiated at U_{ms}. The formation of slugging is dependent

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Nomenclature

A	surface area (m^2)
Ar	Archimedes number $Ar = \rho_g(\rho_p - \rho_g)\frac{d_p^3 g}{\mu_g^2}$
d	particle diameter (m)
d_V	equivalent volume sphere diameter $d_V = \left(\frac{6}{\pi}V_p\right)^{1/3}$ (m)
d_{SV}	equivalent surface volume diameter $d_{SV} = 6\frac{V_p}{A_p}$ (m)
D	column diameter (m)
f	frequency (Hz)
f_0, f_1	data points
F	shape factor $F = \frac{p}{q}$
g	gravitational acceleration (m/s^2)
h	height (m)
h_{mf}	bed height at minimum fluidization velocity (m)
h_s	static bed height (m)
H	expanded bed height (m)
K_T	correction factor for shape effects
l	length (m)
m	mass (kg)
n	index
N	total number of samples
p	elongation ratio $p = \frac{t}{w}$
p	pressure (Pa)
q	flatness ratio $q = \frac{w}{l}$
Re_{mf}	Reynolds number at minimum fluidization velocity $Re_{mf} = \frac{\rho_g U_{mf} d_p}{\mu_g}$
t	thickness (m)
U	superficial velocity (m/s)
U_b	bubbling velocity (m/s)
U_c	transition velocity, exploding bed to turbulent bed (m/s)
U_{CA}	dilute-phase transport velocity for circulating fluidized beds (m/s)
U_f	complete fluidization velocity (onset of active channel flow) (m/s)
U_{eb}	exploding bubble fluidization velocity (m/s)
U_k	transition velocity, intermediate turbulent to turbulent bed (m/s)
U_{mf}	minimum fluidization velocity (m/s)
U_{ms}	minimum slugging velocity (m/s)
U_{se}	fast fluidization velocity for circulating fluidized beds (m/s)
U_T	particle terminal velocity (m/s)
V	volume (m^3)
w	width (m)
x, x_0, x_1	data points
$\bar{x}$	mean value (Pa)

Greek symbols

ε	porosity
μ	dynamic viscosity (kg/(m s))
ρ	density (kg/m^3)
σ	standard deviation
ϕ	sphericity $\phi = \left(36\pi V_p^2/A_p^3\right)^{1/3}$

Subscripts

acf	active channel flow
eff	effective
g	gas
max	maximum
p	solid/particle
sph	spherical

on the vessel size and the fill level (Bi & Grace, 1995). The slugs rise and collapse regularly, leading to large and also regular pressure fluctuations (Grace et al., 1997). Power spectral density functions reveal just one peak whose frequency matches bubble generation and eruption (Kage et al., 2000). Satija and Fan (1985) identified differences in the slugging behavior of finer and coarse particles regarding the onset of slugging. McKain, Clark, and Ganser (1994) derived a correlation for the slug velocity. Singh and Roy (2008) and Padhi, Mohanty, Roy, and Sarangi (2014) addressed the influence of vessel geometry on slugging.

For low bed heights, instead of slugging, a single bubble bed regime or an exploding bubble regime can form (Zijerveld et al., 1998). The first is characterized by the presence of large bubbles whose sizes are comparable to the diameter of the vessel; slugging does not occur because of the limited bed height (Zijerveld et al., 1998). The latter is attributed to bubbles larger than those encountered during bubbling fluidization. Bubbles are exploding vigorously throwing particles into the free board (Zijerveld et al., 1998). For the definition of the onset of turbulent fluidization two definitions characterized by U_c and U_k are common (Yerushalmi & Cankurt, 1979). The turbulent fluidization is characterized by the gas velocity where either the standard deviation of the pressure fluctuations reaches a maximum at U_c or the standard deviation levels off at U_k. At U_c, bubble coalescence and break-up reach a dynamic balance with bubble break-up becoming predominant with further increasing gas velocity; at U_k, bubble break-up and coalescence have stabilized. Often the regime in between U_c and U_k is referred to as intermediate turbulent regime (Zijerveld et al., 1998). Cai, Jin, Yu, and Wang (1987) showed that the transition velocity to turbulent fluidization correlated well with the categories of the Geldart particle classification; additionally a suitable correlation was proposed. Recently, Dang, Gallucci, and van Sint Annaland (2014) investigated the onset of turbulent fluidization in micro structured fluidized beds. For Geldart Group B and D particles the leveling off of the standard deviation of the pressure fluctuations is often accompanied by the blow-out of bed particles (Zijerveld et al., 1998). Therefore, the transition of the flow regime into fast fluidization at U_{se} is often not observed for batch-operated gas–solid fluidized beds (Bi & Grace, 1995). In circulating fluidized beds, U_{se} can be reached and even exceeded leading to the transition into dilute-phase transport at U_{CA} (Basu, 2006; Grace et al., 1997).

For the less-known fluidization of non-spherical particles, the aspects studied have mainly been the onset of minimal fluidization and the behavior of binary mixtures of biomass and sand. Flow regime transitions are seldom considered. An exception is the investigation by Dimattia, Amyotte, and Hamdullahpur (1997) who analyzed the slugging fluidization of a variety of bed materials including coarse sand, long grain rice, red spring wheat, glass beads, pearl barley, and peas. All materials belonged to Geldart group D. Dimattia et al. (1997) derived a correlation for the onset of slugging and the slugging frequency. Rao and Bheemarasetti (2001) were the first to address mixtures of biomass and sand and derived an equation for the onset of minimum fluidization based on an effective particle diameter d_{eff} and an effective particle density ρ_{eff}. Dependent on the sphericity of particles ϕ, the hydrodynamics of large fluidized spherical and non-spherical particles under reduced pressure were investigated (Kozanoglu, Welti Chanes, García Cuautle, & Santos Jean, 2002). Based on the results, they derived a correlation for U_{mf}. A broad variety of aspects of the fluidization of biomass was discussed by Cui and Grace (2007) in the context of an extensive review. The onset of fluidization of complex-shaped particles was studied again (Liu, Zhang, Wang, & Hong, 2008). They were the first to propose a correlation for U_{mf} relying on the Zingg factor (Zingg, 1935) to account for the shape influence. Zhong et al. (2008) successfully extended correlations

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