



A new correlation for minimum spouting velocity for conical spouted beds operating with high density particles

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ABSTRACT

Hydrodynamics of conical spouted beds operating with high density particles was studied by means of measuring the minimum spouting velocity and analysis of pressure signals in time and frequency domains. Three different types of particles, zirconia ($d_p = 1$ mm; $\rho_p = 6050$ kg/m³), zirconia toughened alumina ($\rho_p = 3700$ kg/m³, $d_p = 1, 2$ and 2.4 mm) and glass beads ($\rho_p = 2460$ kg/m³, $d_p = 1$ and 2 mm) were used in the experiments. Experiments were performed in three small scale ($\gamma = 30^\circ, 45^\circ$ and 60°) and two large scale ($\gamma = 31^\circ$ and 66°) beds at different gas inlet diameters and static bed heights. It was found by the analysis of pressure signals that the pressure drop in the stable spouting bed increases with increasing bed size, static bed height, gas inlet diameter and density of particles, and decreasing particle size and cone angle. The minimum spouting velocity increases with increasing particle size, cone angle, static bed height and density of particles, and decreasing bed size and gas inlet diameter. Power spectral density of the pressure signals also revealed significant influence of the above mentioned parameters on the hydrodynamics of conical spouted beds. Based on the results of the experiments, a new correlation is proposed for prediction of the minimum spouting velocity in conical spouted beds operating within the density range of 2460 – 6050 kg/m³ particles. The average relative error and correlation coefficient of the proposed correlation was found to be 10.55% and 0.95 , respectively, which shows the potential of the proposed correlation for prediction of the minimum spouting velocity in conical spouted beds with high density particles.

1. Introduction

A conical spouted bed (CSB) is a cone filled with the processing materials. These gas-solid systems are proven to be effective means of contacting gas and solids and are used for various applications such as drying, coating and mixing [1–3]. The gas is injected into the bed through the inlet nozzle and a jet is emerged that throws the nearby particles up, which finally leads to a continuous circulation of particles inside the bed. Three distinct regions can be identified in a spouted bed: spout, annulus and fountain. The spout is referred to the central region of the bed above the gas inlet which can be identified by high upward velocities of gas and particles and very low particle concentration. In the annulus, on contrary, the solids hold-up is high (near the loosely packed condition), the particles move very slowly and the direction of flow is downward. In the fountain region, particles exit the spout and scatter above the annulus due to gravity.

Compared to conventional conical-cylindrical spouted beds, limited

studies have been performed to investigate the hydrodynamics of conical spouted beds [1,4]. Available studies in the literature on the hydrodynamics of conical spouted beds have mostly concentrated on the measurements of minimum spouting velocity (U_{ms}), bed pressure drop, velocity and concentration of particles [3–19]. Minimum spouting velocity is a fundamental parameter that is needed for the design and operation of conical spouted bed reactors. For this purpose, different minimum spouting velocity correlations, as listed in Table 1, have been proposed for conical spouted beds. The effects of various operating conditions and geometrical parameters on the minimum spouting velocity deduced from these correlations are summarized in Table 2. The accuracy of these correlations is limited to the diameter and density of particles used and also the range of operating conditions in which the experimental values were obtained. As can be seen in Table 1, majority of these correlations were developed for relatively light particles ($\rho_p < 3000$ kg/m³). Moreover, the only correlation developed for high density particles was proposed by Zhou et al. [19]. It should be noted

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Nomenclature		P_{xx}	averaged power spectrum, Pa ² /Hz
A	area, m ²	Re_{mso}	Reynolds number for minimum spouting velocity based on D_o , dimensionless
Ar	Archimedes number, dimensionless	R^2	correlation coefficient, dimensionless
D_c	column diameter, m	U_o	gas velocity, m/s
D_i	cone bottom diameter, mm	U_{ms}	minimum spouting velocity, m/s
D_o	gas inlet diameter, mm	x	normalized time-series signal
D_H	diameter of upper surface of bed, mm	\hat{x}	raw (non-normalized) time-series signal
d_p	particle diameter, mm	\bar{x}	average of the time-series signal
F	discrete Fourier transform	x_n	time-series signal in window n
f	frequency, Hz	<i>Greek symbols</i>	
g	gravitational acceleration, m/s ²	γ	cone angle, °
H_b	static bed height, mm	μ	gas viscosity, Pa s
H_c	height of the conical section, m	ρ	gas density, kg/m ³
j	unit imaginary number	ρ_p	particle density, kg/m ³
L	number of segments of the time-series	σ	standard deviation
m	number of data		
n	counter		
P_{xx}^i	power-spectrum estimate of each segment i , Pa ² /Hz		

Table 1
Correlations proposed for estimation of the minimum spouting velocity in conical spouted beds.

Authors	Correlation	Condition
Gorshtein and Mukhlenov [7]	$Re_{mso} = 0.174Ar^{0.5} \left(\frac{D_i}{D_o} \right)^{0.85} \left(\tan \left(\frac{\gamma}{2} \right) \right)^{-1.25}$	$980 \leq \rho_p \leq 2360 \text{ kg/m}^3$, $0.5 \leq d_p \leq 2.5 \text{ mm}$, $1 \leq D_o \leq 1.3 \text{ cm}$ and $12^\circ \leq \gamma \leq 60^\circ$
Gorshtein and Mukhlenov [8]	$Re_{mso} = 1.35Ar^{0.45} \left(\frac{H_b}{D_o} \right)^{1.25} \left(\tan \left(\frac{\gamma}{2} \right) \right)^{0.58}$	
Tsvik et al. [16]	$Re_{mso} = 0.4Ar^{0.52} \left(\frac{H_b}{D_o} \right)^{1.24} \left(\tan \left(\frac{\gamma}{2} \right) \right)^{0.42}$	$1650 \leq \rho_p \leq 1700 \text{ kg/m}^3$, $1.5 \leq d_p \leq 4 \text{ mm}$, $2 \leq D_o \leq 4.2 \text{ cm}$ and $20^\circ \leq \gamma \leq 50^\circ$
Mukhlenov and Gorshtein [12]	$Re_{mso} = 1.35Ar^{0.45} \left(\frac{D_H}{D_o} \right)^{1.25} \left(\tan \left(\frac{\gamma}{2} \right) \right)^{0.58}$	$980 \leq \rho_p \leq 2360 \text{ kg/m}^3$, $0.5 \leq d_p \leq 2.5 \text{ mm}$, $1 \leq D_o \leq 1.3 \text{ cm}$ and $12^\circ \leq \gamma \leq 60^\circ$
Wan-Fyong et al. [17]	$Re_{mso} = 1.24Re_t \left(\frac{H_b}{D_o} \right)^{0.82} \left(\tan \left(\frac{\gamma}{2} \right) \right)^{0.92}$	$450 \leq \rho_p \leq 1390 \text{ kg/m}^3$, $0.35 \leq d_p \leq 4 \text{ mm}$, $2.6 \leq D_o \leq 7.6 \text{ cm}$ and $10^\circ \leq \gamma \leq 70^\circ$
Kmiec [9]	$Re_{mso} = 0.0176Ar^{0.714} \left(\frac{H_b}{D_o} \right)^{1.535} \gamma^{0.714} z_{ms}^{2.21}$	$1300 \leq \rho_p \leq 2990 \text{ kg/m}^3$, $0.88 \leq d_p \leq 6.17 \text{ mm}$, $1.5 \leq D_o \leq 3.5 \text{ cm}$ and $24^\circ \leq \gamma \leq 60^\circ$
Markowski and Kaminski [10]	$Re_{mso} = 0.028Ar^{0.57} \left(\frac{H_b}{D_o} \right)^{0.48} \left(\frac{D_c}{D_o} \right)^{1.27}$	$1120 \leq \rho_p \leq 2380 \text{ kg/m}^3$, $3.41 \leq d_p \leq 10.35 \text{ mm}$, $1.8 \leq D_o \leq 5.6 \text{ cm}$ and $\gamma = 37^\circ$
Choi and Meisen [5]	$\frac{(U_{ms})_d}{\sqrt{2gH_b}} = 0.147 \left(\frac{\rho_p - \rho}{\rho} \right)^{0.477} \left(\frac{d_p}{D_c} \right)^{0.61} \left(\frac{H_b}{D_c} \right)^{0.508} \left(\frac{D_o}{D_c} \right)^{0.243}$	$1050 \leq \rho_p \leq 1090 \text{ kg/m}^3$, $2.16 \leq d_p \leq 2.8 \text{ mm}$, $21 \leq D_o \leq 35 \text{ mm}$ and $\gamma = 60^\circ$
Olazar et al. [14]	$Re_{mso} = 0.126Ar^{0.5} \left(\frac{D_H}{D_o} \right)^{1.68} \left(\tan \left(\frac{\gamma}{2} \right) \right)^{-0.57}$	$240 \leq \rho_p \leq 3520 \text{ kg/m}^3$, $1 \leq d_p \leq 25 \text{ mm}$, $3 \leq D_o \leq 6 \text{ cm}$ and $36^\circ \leq \gamma \leq 61^\circ$
Olazar et al. [13]	$Re_{mso} = 0.126Ar^{0.39} \left(\frac{D_H}{D_o} \right)^{1.68} \left(\tan \left(\frac{\gamma}{2} \right) \right)^{-0.57}$	$1250 \leq \rho_p \leq 2420 \text{ kg/m}^3$, $1 \leq d_p \leq 8 \text{ mm}$, $5 \leq D_o \leq 6 \text{ cm}$ and $\gamma \leq 150^\circ$
Zhou et al. [19]	$U_{ms} = 5.89 \times 10^6 d_p^{1.55} \left(\frac{H_b}{D_c} \right)^{1.59} \left(\tan \left(\frac{\gamma}{2} \right) \right)^{0.87}$	$\rho_p = 5890 \text{ kg/m}^3$, $0.3 \leq d_p \leq 0.65 \text{ mm}$, $D_o = 0.4 \text{ cm}$ and $45^\circ \leq \gamma \leq 75^\circ$

Table 2
Effects of operating and geometrical conditions on the minimum spouting velocity.

Parameter	Effect
Gas inlet diameter	Minimum spouting velocity decreases with increasing gas inlet diameter [7–10,12–14,16,17]
Static bed height	Minimum spouting velocity increases with increasing static bed height [5,8–10,16,17,19]
Particle size	Minimum spouting velocity increases with increasing particle size [5,7–10,12–14,16,17,19]
Particle density	Minimum spouting velocity increases with increasing particle density [5,7–10,12–14,16]
Cone angle	Contradictions are observed about the effect of bed cone angle on the U_{ms} in the proposed correlations. Gorshtein and Mukhlenov [7] and Olazar et al. [13] and [14] suggest decreasing the U_{ms} with increasing the cone angle, while Gorshtein and Mukhlenov [8], Tsvik et al. [16], Mukhlenov and Gorshtein [12], Wan-Fyong et al. [17], Kmiec [9] and Zhou et al. [19] stated that the minimum spouting velocity increases with increasing cone angle.

that this correlation was developed based on the data obtained using only one type of high density particles (zirconia, $\rho_p = 5890 \text{ kg/m}^3$) in a system with constant gas inlet diameter. Therefore, the experimental data set that the correlation is based on cannot adequately reflect the effects of the particle density and gas inlet diameter on U_{ms} .

Studies in the field of hydrodynamics of conical spouted beds also include the analyses based on bed pressure measurements [11,15,18,20–22]. Xu et al. [18] obtained pressure signals from two

different probes in conical and cylindrical regions of a spouted bed and evaluated standard deviation, skewness and power spectral density of the signals. They found that with increasing the gas velocity, the standard deviation increases with a jump at the minimum spouting velocity. They also detected the dominant frequency of the unstable and stable spouting in the range of 6–8 Hz and concluded that the dominant frequency depends on particle properties, gas velocity and bed geometry. Oliveira et al. [15] used different statistical and spectral

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