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Minimum Spouting Velocity of Conical Spouted Beds Equipped with Draft Tubes of Different Configuration

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ABSTRACT: The hydrodynamics and the influence of the geometric and operating factors on the minimum spouting velocity have been studied in draft tube conical spouted beds with materials of different size and density. Two draft tube configurations have been used: nonporous and open-sided tubes. Based on an experimental design, the factors of greater influence have been extracted and the general correlations valid for fine and coarse materials have been proposed for predicting the minimum spouting velocity for each type of draft tube. A comparison of the velocities with and without a tube reveals that the nonporous draft tube requires the lowest minimum spouting velocity. Nevertheless, the solid circulation rate and the gas−solid contact efficiency of the open-sided draft tube outperform any other spouted bed configuration, especially for fine particles. Consequently, open-sided draft tubes allow stable operation with fine particles and high solid circulation rates in conical spouted beds.

1. INTRODUCTION

The spouted bed regime is an alternative contact method to fixed and fluidized beds. Different modifications of the original spouted bed (cylindrical with conical base) are proposed in the literature to improve its performance.[1,2]

Spouted beds with a fully conical geometry combine the features of cylindrical spouted beds (such as the capacity for handling coarse particles, small pressure drop, cyclic movement of the particles and so on) with those inherent to their geometry, such as stable operation in a wide range of gas flow rates.[3−5] The versatility of the gas flow rate allows handling particles of irregular texture, fine particles and those with a wide size distribution, as well as sticky solids, whose treatment is difficult using other gas−solid contact regimes.[6−10] Moreover, the dilute spouted bed can operate with short gas residence times (as low as milliseconds).[11,12]

There are three different zones in spouted beds, namely, spout, annulus, and fountain. Figure 1 shows these different zones in conical spouted beds provided with a nonporous draft tube.

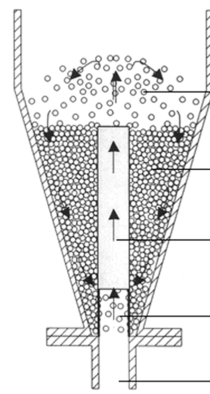

Figure 1. Zones in the conical spouted bed with a nonporous draft tube.

A crucial parameter that limits the scaling-up of spouted beds is the ratio between the inlet diameter and particle diameter. In fact, the inlet diameter should exceed 20−30 times the average particle diameter to achieve spouting status.[1,3] The insertion of a draft tube is the usual solution to this problem, being used for the first time by Buchanan and Wilson.[13] Nevertheless, a draft tube changes the hydrodynamics and solid circulation flow rate of spouted beds.[3,14] Thus, minimum spouting velocity, operating pressure drop, solid circulation pattern, particle cycle times, and gas distribution are influenced by the type of draft tube used. The performance of the contactor's lower conical section is different when a draft tube is used, and largely depends on bed geometry, draft tube diameter, length of the entrainment zone, and operating conditions.[14−28]

The use of a draft tube has the following advantages when operating with spouted beds:[14,22,29−36] greater flexibility, lower gas flow and pressure drop, solids of any size or nature may be treated, narrower residence time distribution, better control of solid circulation, a maximum spoutable bed height can be avoided, and higher bed stability is attained. Among the disadvantages, the following are worth mentioning: lower degree of mixing, complexity of design, risk of tube blockage, poorer gas−solid contact, lower heat and mass transfer, and longer recirculation time.

Consequently, the draft tube is an interesting option for optimizing the hydrodynamic performance of spouted beds, especially when scaling up, given that it is simple, economical and much more flexible.

Different draft tube configurations are reported in the literature: conventional nonporous draft tubes, porous draft tubes, and open-sided draft tubes. The latter have been developed in our research group for operating in conical spouted beds with fine particles, and they are especially suitable

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Table 1. Hydrodynamic Correlations for Calculating Minimum Spouting Velocity in Conical Spouted Beds Provided with Draft Tube

Author	Correlation
Kmiec[28]	$(Re_0)_{ms} = 0.0137Ar^{0.714}[V_r\phi/V_0]^{0.411}[D_g/D_0]^{-0.554}(\gamma)^{0.8}$ (1) where $\phi = [L_T - H_0/h_r]$
Altzibar et al.[38]	$(Re_0)_{ms} = 0.204Ar^{0.475}[H_0/D_0]^{1.24}[L_H/D_T]^{0.168}[\tan(\gamma/2)]^{-0.135}$ (2)
San Jose et al.[57]	$(Re_0)_{ms} = 0.126Ar^{0.5}[D_b/D_0]^{1.68}[\tan(\gamma/2)]^{-0.57}[H_0 - L_T/H_0]^{0.45} [D_i/(D_i - D_T)]^{0.17}$ (3) where $L_T = [H_0 - L_H]$

for a vigorous contact.[37,38] Thus, it has been observed that the minimum spouting velocity required and operating pressure drop are higher with open-sided tubes than nonporous and porous draft tubes for the same contactor geometry and operating conditions. Nevertheless, the regime is more vigorous and solid circulation is higher with this type of tube. Nagashima et al.[17] have recently developed porous and nonporous draft tubes of conical-cylindrical geometry, observing that gas−solid contact and solid circulation rate are considerably improved using the porous one.

Minimum spouting velocity (u_{ms}) is defined as the minimum air velocity required to maintain spouting regime. This velocity is a crucial variable, given that it determines other important operating parameters, such as residence time and, solid movement, among others. These parameters are decisive for the industrial applications of spouted beds and for a proper design, operation and scale-up of spouted bed reactors.[3,7,9,33,34,39,40] Unlike the minimum fluidization velocity, the minimum spouting velocity is not only a function of particle and fluid properties, but also a function of contactor geometry.

Although there are numerous correlations in the literature for calculating the minimum spouting velocity for plain cylindrical spouted beds[41−46] and conical spouted beds,[2,3,7,47−56] those considering the effect of draft tubes are very limited, and the velocity is usually calculated experimentally for the particular system used.

Table 1 shows the correlations developed in the literature for draft tube systems.[28,38,57] As observed, all of them include factors related to draft tube geometry, which indicates they significantly affect the minimum spouting velocity. Although it is widely accepted that the height of the entrainment zone is a highly significant parameter for the minimum spouting velocity,[28] it is important to note that eq 1 does not include this parameter. Nevertheless, these authors emphasize the significance of the difference between the upper end of the tube and the bed surface. Equation 2 was formulated in a previous paper to determine the minimum spouting velocity for nonporous draft tube conical spouted beds based on the factors of greater influence, with the height of the tube's entrainment zone being one such factor. Likewise, San José et al.[57] found the same trend in their study on nonporous draft tube conical spouted beds and, accordingly, the entrainment zone is included in the correlation (eq 3).

As noted, most of the papers dealing with the hydrodynamic study of draft tube conical spouted beds agree that the height of the entrainment zone is a significant factor for the minimum spouting velocity.[14,17,33,38,40,57,58] Thus, minimum spouting velocity increases as the height of the entrainment zone is increased because of the higher solid cross-flow from the annulus into the spout in the entrainment zone and the higher gas flow rate from the spout into the annulus. Several authors have observed that entrainment height is the parameter governing the solid cross-flow from the annulus into the spout and, consequently, the solid circulation rate.[14,17,21,30,33−36,38,59−62] Furthermore, this parameter also determines gas distribution in the contactor, given that longer entrainment zones give way to a higher diversion of the gas from the spout bottom into the annulus.[14,33,35,62]

Open-sided draft tubes have been used in previous studies for the drying of fine particles[37] and biomass,[63] but no systematic study has been carried out on the influence of their geometry on the minimum spouting velocity. Furthermore, studies on porous and nonporous draft tube conical spouted beds are very scarce.[37,38,57,63] Accordingly, this paper studies the influence of contactor and draft tube geometric factors in a wide range of operating conditions and particle characteristics. Nonporous draft tubes have been chosen in juxtaposition to their open-sided counterparts because the former are much more commonly used in the applications studied. Furthermore, the behavior of porous draft tubes has been reported to be halfway between open-sided and nonporous ones.

The runs have been carried out following an experimental design, providing a reliable data analysis and the identification of significant factors. Once the factors of greater influence have been identified, correlations have been developed for the calculation of the minimum spouting velocity for conical spouted beds with different types of draft tubes and particle sizes (fine and coarse particles).

2. EXPERIMENTAL SECTION

2.1. Equipment. The experimental unit has been described in previous papers.[38]

The blower supplies a maximum air flow rate of 300 N 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 50−300 m^3 h^{-1} and 0−100 m^3 h^{-1}. The blower supplies a constant flow rate, and the first mass flow-meter controls the air flowing into the contactor (in the 50−300 m^3 h^{-1} range) by operating a motor valve that reroutes the remaining air to the outside. When the flow required is lower than 50 m^3 h^{-1}, it passes through the first mass flow-meter, being regulated by the second one placed in series, which also operates another motor valve that adjusts the desired flow rate. The accuracy of this control is 0.5% of the flow rate measured.

The measurement of bed pressure drop is relayed to a differential pressure transducer (Siemens Teleperm), which quantifies these measurements within the 0−100% range. This transducer sends the 4−20 mA signal to a data logger (Ahlborn Almeno 2290−8), which is connected to a computer where the data are registered and processed by AMR-Control software. This software also registers and processes the air velocity data, providing continuous curves of pressure drop vs air velocity.

The experimental unit's main component is the contactor, Figure 2, which has a conical geometry. The unit allows

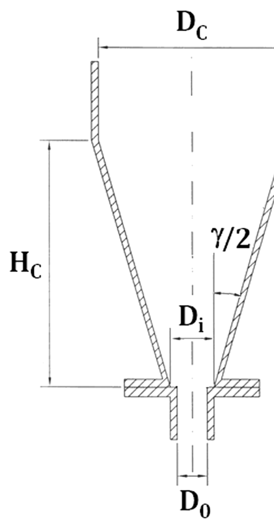

Figure 2. Geometric factors of the conical contactors.

operating with contactors of different geometry. Three conical contactors made of polymethyl methacrylate have been used. Figure 2 shows the geometric factors of these contactors. The dimensions of these contactors are: diameter of the upper cylindrical section, D_c, 0.36 m; contactor angle, γ, 28, 36, and 45°; height of the conical section, H_c, 0.60, 0.45, and 0.36 m; and base diameter, D_i, 0.068 m. The total height of the contactor (conical plus cylindrical sections) is 1.16 m. The gas inlet diameters used are, D_0, 0.03, 0.04, 0.05, and 0.06 m. The stagnant bed heights used are H_0, 0.14, 0.17, 0.20, 0.22, 0.25, 0.27, and 0.30 m.

These contactors allow fitting draft tubes at the inlet of the conical section. They are steel tubes of cylindrical shape (Figure 3), which are placed at the axis of the contactor. Two different configurations have been used: Open-sided draft tubes, Figure 3a, and nonporous draft tubes, Figure 3b. The nonporous draft tubes are conventional ones with three legs attaching them to the base of the contactor. Different nonporous tubes have been used in this hydrodynamic study, which differ in the height of the entrainment zone (distance between the gas inlet nozzle and the lower end of the tube), L_H, and the diameter of the tube, D_T. The length of these tubes is approximately equal to the bed height.

Open-sided draft tubes are tubes with part of their lateral face being open (different aperture ratios with three slots). Different open-sided tubes have been used varying the width of the faces (and therefore aperture ratio), W_H, and the diameter of the tube, D_T. The total length of the open-sided tubes is 0.50 m, which means they stand at least 0.20 m above the bed surface.

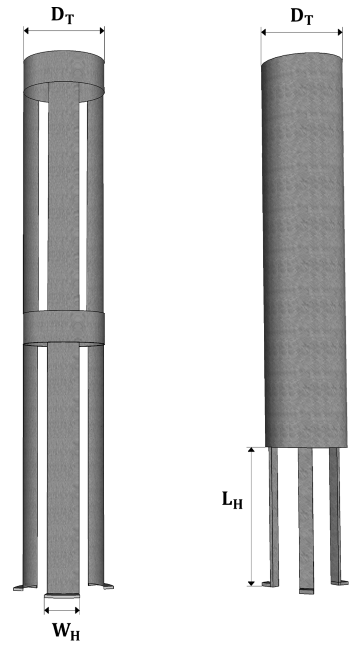

Figure 3. Draft tube configurations: (a) open-sided draft tube, (b) nonporous draft tube.

This length has been chosen according to previous experimentation with fine particles (smaller than 1 mm) in which lower and denser fountains were observed when the tube end was above the bed surface. In fact, the height above the bed must be at least 1/2−1/4 of the stagnant bed height. Accordingly, the height of the contactor required for operating with fine particles is much lower than when the upper end of the tube is flush with the bed surface.[37] It should be noted that this precaution is not required for operating with coarse particles. Table 2 shows the dimensions of the tubes used.

Table 2. Dimensions of the Non-Porous and Open-Sided Draft Tubes Used

draft tube	D_T, m	W_H, m (aperture ratio, %)	L_H, m
nonporous	0.028, 0.042, 0.053		0.03, 0.07, 0.15
open-sided	0.04, 0.05	0.010 (78), 0.018 (57), 0.025 (42)	

Furthermore, experiments have also been carried out without draft tubes to compare the results obtained with draft tubes.

2.2. Material. The following fine and coarse materials have been used in the study: building sand (with a wide particle size distribution and cuts with a narrow distribution), glass beads, and black peas.

Figure 4 shows the particle size distribution of the sand obtained by sieving (ISO 3310).

The average particle size (reciprocal mean diameter) has been calculated by means of the expression

$$\overline{d}_p = 1/[\sum (x_i/d_{pi})] \tag{4}$$

According to eq 4, the average size of the sand is 0.6 mm. This material is considered as fine (d_p <1 mm)[64] and corresponds to group B of the Geldart classification.[65,66]

To study the effect of particle diameter on the minimum spouting velocity with fine particles, two fractions of the sand

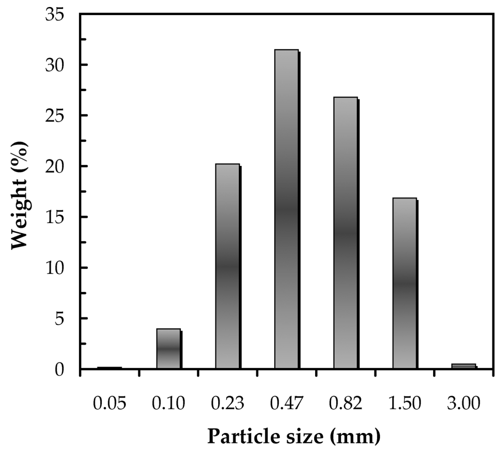

Figure 4. Particle size distribution of the sand.

with narrow size distributions have been used. The average particle sizes of the fractions are 0.4 and 0.85 mm.

Furthermore, the coarse materials used (d_p >1 mm) are glass beads of 2 and 4 mm particle diameter and black peas of 3.4 mm particle diameter, whose densities are 2400 kg m^{-3} and 1230 kg m^{-3}, respectively, with both corresponding to group D of the Geldart classification.

3. RESULTS

3.1. Design of Experiments. Experimental runs have been carried out following a design of experiments to ascertain the factors of greater influence on minimum spouting velocity and develop hydrodynamic correlations for the prediction of this velocity when different draft tube geometries and configurations are used. Furthermore, the design allows drawing conclusions on the effects contactor geometry, draft tube type and geometry and bed materials have on the hydrodynamics of draft tube conical spouted beds.

Tables 3 and 4 show the factors and their levels in the runs with nonporous and open-sided draft tubes.

Furthermore, runs have been carried out without draft tubes to compare the results with those obtained with different draft tubes, and check the validity of the correlations proposed for conical spouted beds. Nevertheless, when there is no draft tube, the ratio between inlet diameter and particle diameter must be lower than a given value (D_0/d_p < 20−30) for spout formation.[1,3] Accordingly, our experimental system can operate solely with glass beads and black peas (coarse particles). In this case, the following design of experiments has been followed (Table 5).

Experimental runs have been carried out by combining all these contactor geometries and draft tube configurations, that is, approximately 2000 runs involving nonporous draft tubes, 700 with open-sided tubes and 100 without a draft tube.

In each experimental run, the evolution of bed pressure drop with air velocity has been monitored from the fixed bed to the spouting regime. Prior to each run, and to obtain reproducible results, the bed has been expanded until the spouting state and then returned to the fixed state. Figures 5−8 show the results obtained in a given system for the evolution of pressure drop by increasing air flow rate until the spout is formed and by decreasing it to zero. This figure is used to determine minimum spouting velocity (u_{ms}), operating pressure drop (ΔP_S), and peak pressure drop (ΔP_M).

Table 3. Factors and Their Levels for the Systems with Non-Porous Tubes

factors			levels			
γ, cone angle (deg)			28	36	45	
D_0, inlet diameter (m)			0.03	0.04	0.05	0.06
H_0, bed height (m)			0.14	0.17	0.20	0.22
			0.25	0.27	0.30	
D_T, tube diameter (m)			0.028	0.042	0.053	
L_H, entrainment zone length (m)			0.035	0.07	0.15	
d_p, particle diameter (mm)						
	fine (sand)					
		whole sand	0.6			
		sand fractions	0.4	0.85		
	coarse					
		glass beads	2	4		
		black peas	3.4			

Table 4. Factors and Their Levels for the Systems with Open-Sided Tubes

factors			levels			
γ, cone angle (deg)			28	36	45	
D_0, inlet diameter (m)			0.03	0.04	0.05	0.06
H_0, bed height (m)			0.14	0.17	0.20	0.22
			0.25	0.27	0.30	
D_T, tube diameter (m)			0.042	0.053		
W_H, faces width (m)			0.01	0.018	0.025	
(*aperture ratio, %*)			(78)	(57)	(42)	
d_p, particle diameter (mm)						
	fine (sand)					
		whole sand	0.6			
		sand fractions	0.4	0.85		
	coarse					
		glass beads	2	4		
		black peas	3.4			

Table 5. Factors and Their Levels for Systems without Tubes

factors		levels			
γ, cone angle (deg)		28	36	45	
D_0, inlet diameter (m)		0.04	0.05		
H_0, bed height (m)		0.14	0.20	0.25	0.30
d_p, particle diameter (mm)					
	glass beads	2	4		
	black peas	3.4			

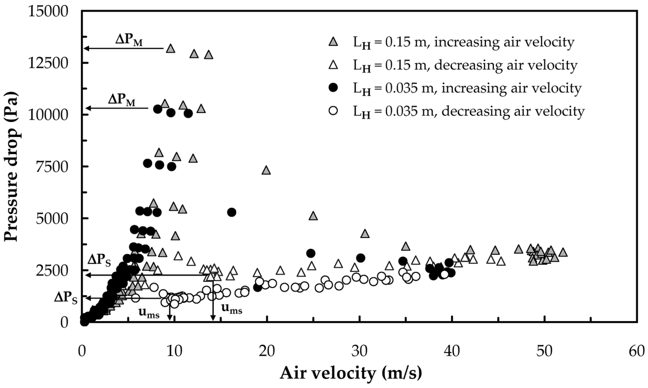

Figure 5. Evolution of the bed pressure drop with air velocity for different values of the height of the entrainment zone (L_H) when nonporous draft tubes are used. Experimental conditions: γ = 45°; D_0 = 0.04 m; H_0 = 0.27 m, D_T = 0.042 m; L_T = 0.27 m; d_p = 0.6 mm.

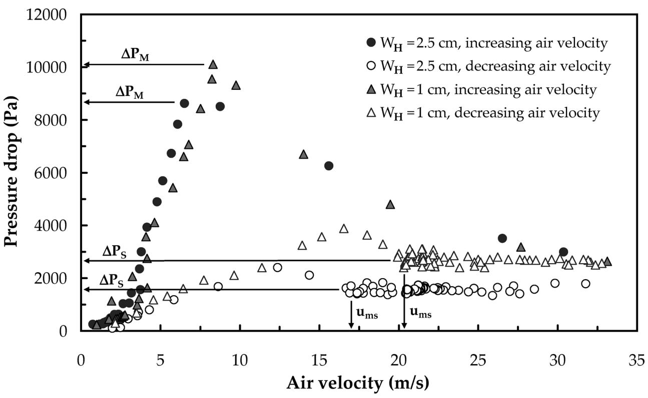

Figure 6. Evolution of the bed pressure drop with air velocity for different values of the width of the faces (and therefore aperture ratio) (W_H) when open-sided draft tubes are used. Experimental conditions: γ = 36°; D_0 = 0.04 m; H_0 = 0.20 m, D_T = 0.042 m; d_p = 2 mm.

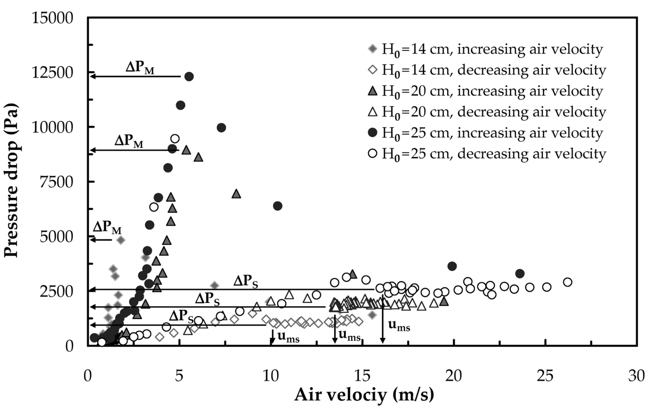

Figure 7. Evolution of the bed pressure drop with air velocity for different values of the bed height (H_0) when open-sided draft tubes are used. Experimental conditions: γ = 36°; D_0 = 0.04 m; D_T = 0.042 m; W_H = 2.5 cm; d_p = 0.6 mm.

Figures 5−8 show that the values of the minimum spouting velocity are highly dependent on the experimental system. The three hydrodynamic parameters increase in step with the height of the entrainment zone (L_H), aperture ratio (related to the width of the faces, W_H), bed height (H_0), and particle diameter (d_p).

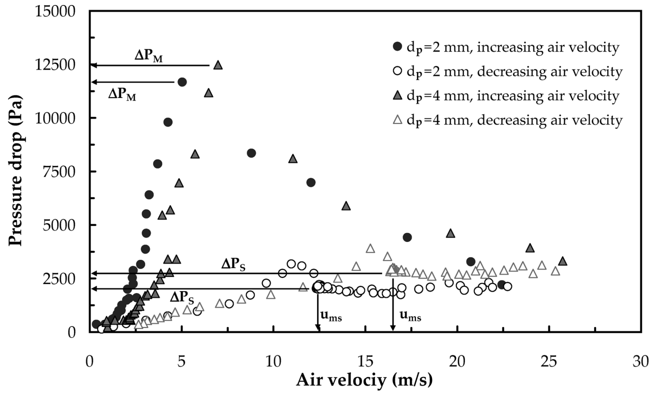

Figure 8. Evolution of the bed pressure drop with air velocity for different values of the particle diameter (d_p) when nonporous draft tubes are used. Experimental conditions: γ = 45°; D_0 = 0.04 m; H_0 = 0.25 m, D_T = 0.042 m; L_H = 0.15 m; L_T = 0.27 m.

A very pronounced hysteresis is noted, which is because the peak pressure drop is much higher than the operating pressure drop and, furthermore, a much higher velocity than the minimum one is required to break through the bed and open the spout. The hysteresis is more pronounced in conical spouted beds with a draft tube than under the same experimental conditions without a draft tube.[57] Other authors have also observed a pronounced hysteresis using nonporous draft tubes.[14,15,17]

The minimum spouting velocity (u_{ms}) is best obtained by decreasing air velocity from that corresponding to stable spouting to that of a fixed bed.[1,3] In our polymethyl methacrylate contactor, visual observation is the best way of determining the minimum spouting velocity. Furthermore, when the air flow rate is decreased from stable spouting, there is a slight increase in pressure drop immediately below the minimum spouting velocity.[3] The location of this state allows an accurate estimation of minimum spouting. Accordingly, transparent contactors and pressure drop monitoring allow observing bed performance and determining the minimum spouting velocity in all the experimental systems.

Most of the runs have been carried out twice and 50 corresponding to the more turbulent systems (basically involving small contactor angles and open-side tubes) have been repeated four times. Accordingly, average relative errors have been calculated, which amount to 8% for open-sided tubes and 7% for nonporous tubes.

3.2. Factors Influencing u_{ms}.

Prior to developing a hydrodynamic correlation, the factors of greater influence on the minimum spouting velocity must be ascertained, as they should appear in the correlation. Accordingly, an analysis of variance (ANOVA) has been carried out by means of a standard statistical package (SPSS 12.0). Given that two types of draft tubes have been used and each one has its own specific factors, they should be analyzed separately. The sole overall analysis that may be performed corresponds to the influence of draft tube type on the minimum spouting velocity, that is, whether the use of one or other draft tube affects minimum velocity.

The significance order of the factors analyzed when using the two types of draft tube and without a draft tube is shown in Table 6. The analysis has been conducted individually for the fine fractions (two sand fractions), coarse fractions (two glass bead sizes and black peas), and for the whole sand (fine particle

Table 6. Significance Order of Factors and Binary Interactions[a]

system	material	significance order
nonporous draft tubes	whole sand	$D_0 > L_H > H_0 > L_H x D_0 > D_0 x H_0 > \gamma$
	sand fractions	$d_p > D_0 > L_H > D_0 x d_p > D_0 x H_0$
	coarse particles	$D_0 > d_p > L_H > H_0 > L_H x d_p > D_0 x H_0$
open-sided draft tubes	whole sand	$\gamma > D_0 > W_H > H_0 > \gamma x D_0 > \gamma x W_H$
	sand fractions	$D_0 > d_p > H_0 > W_H > \gamma > D_0 x d_p$
	coarse particles	$d_p > D_0 > H_0 > D_0 x d_p > \gamma > H_0 x d_p$
without draft tubes	coarse particles	$d_p > D_0 > H_0 > \gamma > D_0 x d_p > H_0 x d_p$

[a]95% confidence interval.

distribution) to clearly identify the performance of the bed when different kinds of materials are used.

Table 6 shows that particle diameter significantly affects the minimum spouting velocity when both fine and coarse particles are used. As observed, when no draft tubes are used or with open-sided draft tubes with coarse particles, the three factors of greater influence on the minimum spouting velocity are the same: particle diameter (d_p), gas inlet diameter (D_0), and stagnant bed height (H_0). This result evidences the similarity between the two systems, that is, high aperture ratios of open-sided draft tubes (above 40%, Table 2) give way to a similar performance as when there is no draft tube.

The three factors of greater influence when nonporous draft tubes are used with coarse particles are as follows: gas inlet diameter (D_0), particle diameter (d_p), and the height of the entrainment zone (L_H). This means the stagnant bed height has a lower influence than in the other systems with no draft tube or open-sided draft tube. The explanation lies both in the bed partially supported by the tube around the spout and in the fact that solid cross-flow from the annulus into the spout is highly influenced by the height of the entrainment zone.[14−17,21,30,35,36,38,40,57,59,60,62] It should be noted that the minimum spouting velocity is directly related to the solid flow rate ascending in the spout and, therefore, to the solid cross-flow rate in the entrainment zone. Nevertheless, this study reveals that the solid cross-flow rate is not independent of stagnant bed height, although its influence is lower than that of the entrainment height.

An analysis of the data obtained with fine sand fractions reveals that the factors of greater influence are similar to those found with coarse particles. Thus, when nonporous draft tubes are used with fine particles, the factor of greater influence is particle diameter, followed by inlet diameter, whereas the reverse applies with coarse particles. A further aspect to be noted is that the width of the face (W_H) influences the minimum spouting with fine particles, but this is not the case with coarse particles.

The whole sand (unsieved) cannot be used without tube because no stable spouting is achieved. This material has been used with both types of tubes, but the influence of particle diameter cannot be ascertained because only one level is used (the average particle size). As observed in Table 6, the factors related to the contactor and draft tube are significant. Thus, the factors of greater influence in the case of nonporous draft tubes are inlet diameter, entrainment height, and stagnant bed height, with contactor angle being almost insignificant. Nevertheless, contactor angle is the more influential factor when open-sided tubes are used. A comparison of these data with those corresponding to coarse particles reveals that the influence of contactor angle is greater as particle size is smaller. This has been qualitatively observed in conical spouted beds without a draft tube.[3] Other factors affecting minimum spouting velocity in these systems (whole sand with open-sided tubes) are inlet diameter, width of the face (W_H) and stagnant bed height. The fact the factors related to draft tube geometry (L_H, W_H) are more influential when the whole sand is used must be related to bed segregation.[8] Thus, coarse particles in the annulus descend following trajectories close to the spout and, therefore, preferentially enter the spout and alter the minimum spouting velocity.

The quantitative influence of these factors on the minimum spouting velocity may be observed by plotting the values of this parameter vs factors. Figure 9 shows the change in minimum spouting velocity caused by the factor of greater influence (particle diameter) in the three types of systems studied.

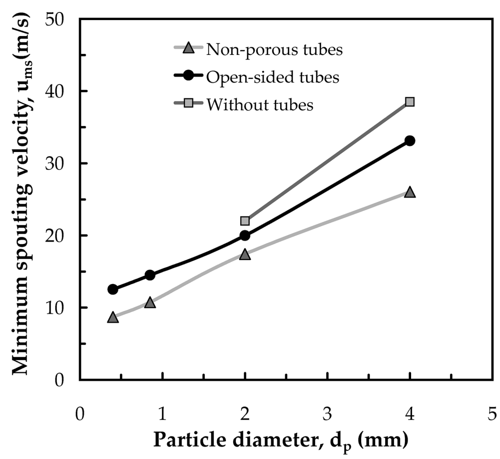

Figure 9. Influence of particle diameter on the minimum spouting velocity without tubes and when nonporous and open-sided tubes are used.

An increase in particle diameter gives way to a significant increase in minimum spouting velocity for the three systems studied. This trend is similar to that already observed qualitatively in a conical spouted bed without draft tubes operating with heavy particles[3,67] and in slot-rectangular spouted beds with draft plates.[33] The explanation lies in the smaller contact area of a bed containing coarse particles than a bed containing small particles (lower drag forces), and consequently the higher air velocity required to open the spout. Furthermore, there are significant differences between the values of the minimum spouting velocity corresponding to the three types of systems, with the lowest being those corresponding to the nonporous draft tube and the highest those without a tube. The change in minimum spouting velocity is more pronounced as particle diameter is larger, except for those systems with a nonporous draft tube, for which there is a similar trend in the whole range studied.

Figure 10 shows the change in minimum spouting velocity caused by the gas inlet diameter in the systems studied by operating with coarse particles (Figure 10a) and fine particles (Figure 10b).

Figure 10 shows that an increase in inlet diameter gives way to a pronounced decrease in minimum spouting velocity in all the systems and materials studied. This trend is similar to that qualitatively observed for conical spouted beds with a

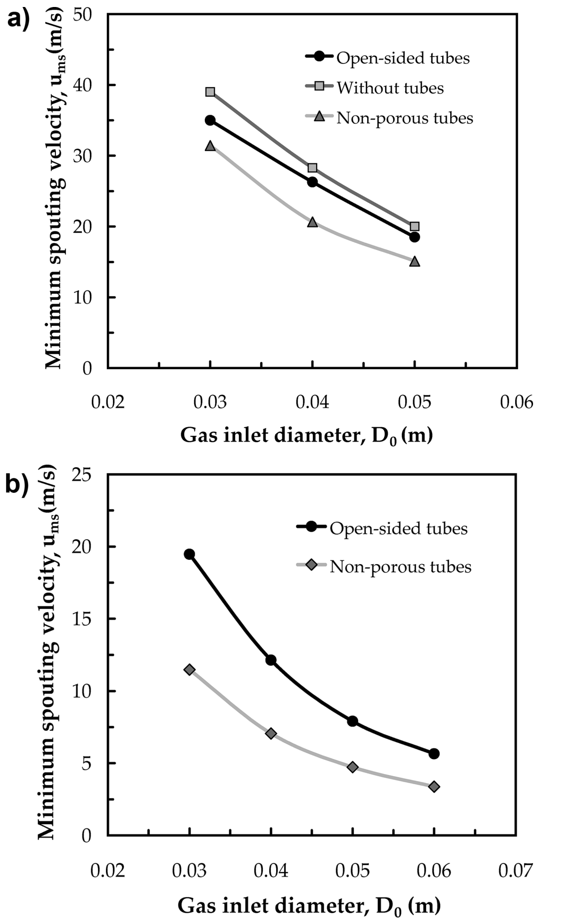

Figure 10. Influence of inlet diameter on the minimum spouting velocity: (a) coarse particles, (b) fine particles.

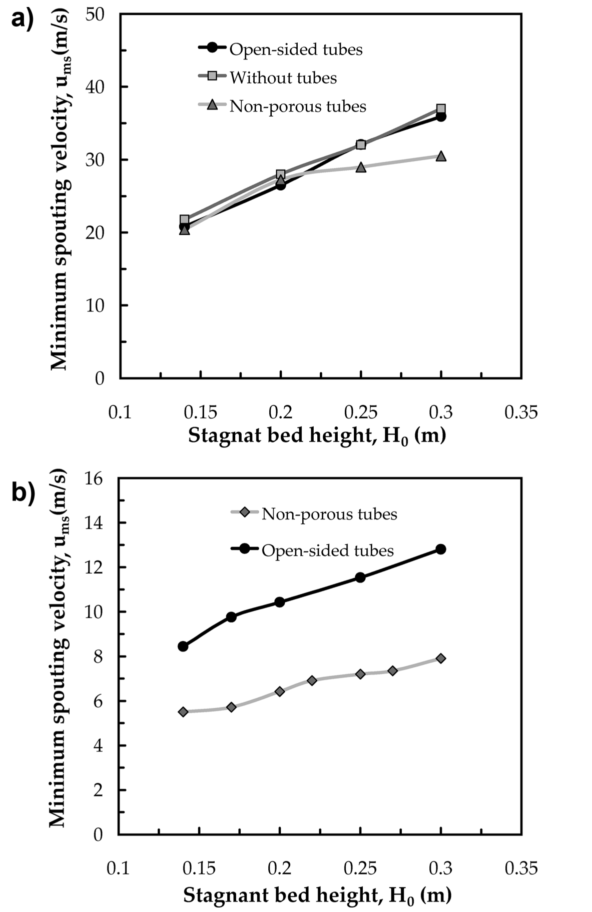

Figure 11. Influence of stagnant bed height on the minimum spouting velocity: (a) coarse particles, (b) fine particles.

nonporous draft tube[57] and without a tube.[68] It should be noted that although the minimum spouting velocity referred to the inlet diameter decreases, the inlet flow rate increases because of the increase in the inlet cross-sectional area.

Furthermore, the minimum spouting velocities required for coarse particles Figure 10a, are much higher than those required for fine particles, Figure 10b. A comparison between the values corresponding to the different systems reveals the same trends observed in Figure 9 for particle diameter, that is, the minimum spouting velocity for open-sided draft tube systems is higher than for nonporous draft tubes and lower than for systems without tubes.

Figure 11 shows the change in minimum spouting velocity caused by bed height in the systems studied by operating with coarse particles (Figure 11a) and fine particles (Figure 11b).

Figure 11 shows the values of minimum spouting velocity are much higher for coarse particles and increase as stagnant bed height is increased for all the systems and materials studied. This trend is similar to that reported in the literature for conical spouted beds with and without nonporous draft tubes.[3,52,57] A higher stagnant bed height means a higher amount of solids in the bed and, consequently, a higher air velocity is needed to open the spout.[40] Figure 11a shows that the values of the minimum spouting velocity for coarse particles are similar for plain spouted beds (without tubes) and open-sided tube systems for all stagnant bed heights.[3,52,54] Concerning bed height, this means the only role played by the open-sided tube is to stabilize the bed. In the case of nonporous tubes, stagnant bed height has a much lower influence when the other devices are used, Figure 11a, which has also been reported by San José et al.[57] for conical beds and Konduri et al.[69] for cylindrical beds. Furthermore, the minimum spouting velocity is approximately proportional to the square root of stagnant bed height, which is typical of cylindrical spouted beds.[41]

In the case of fine particles, Figure 11b, the trends are linear for both systems analyzed and, moreover, the influence of stagnant bed height with the open-sided tube is not as pronounced as with coarse particles (lower slope). It should be noted that no data are plotted for plain spouted beds (without tubes) because the bed is unstable with fine particles under these conditions.

Furthermore, Table 6 shows that contactor angle is the factor of greater influence on the minimum spouting velocity when an open-sided tube is used with the whole sand bed. The fact that contactor angle is only significant when the whole sand is treated, and not when fine fractions are treated, must be related to the lower permeability of a material with size distribution. Figure 12 shows the evolution of minimum spouting velocity as the level of this factor is changed.

The lower values of minimum spouting velocity correspond to an angle of 36°, and wider angles (45°) and narrower ones (28°) give way to higher values of this velocity. A wider angle (45°) means a greater amount of material in the bed (for the same bed height) and, consequently, a higher air velocity required to break through the bed and open the spout. A narrower angle (28°) means a lower amount of material in the

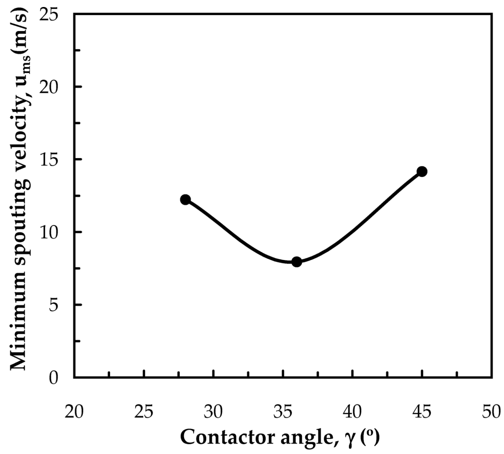

Figure 12. Influence of contactor angle on the minimum spouting velocity for open-sided draft tube systems operating with the whole sand bed (fine particles with size distribution).

bed, but the wall does not partially support the bed, and so a higher air velocity is required for minimum spouting. The contactor of 36° strikes a balance between these two aspects, and the lowest air velocity is required. A similar conclusion was obtained by Olazar et al.[3] for conical spouted beds without tubes.

To compare the results of fine particles with and without particle size distribution, Figure 13 shows the influence of the height of the entrainment zone on the minimum spouting velocity when nonporous draft tube systems are used.

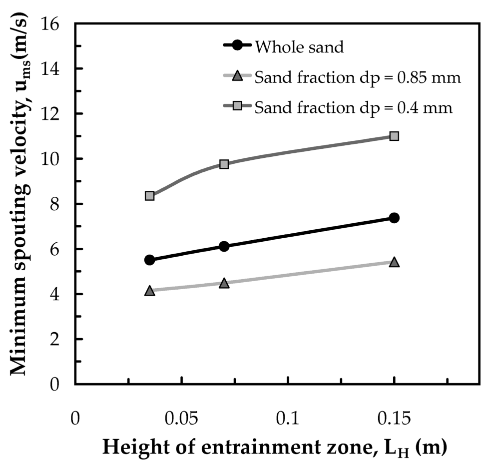

Figure 13. Influence of the entrainment zone height on the minimum spouting velocity for nonporous draft tube systems operating with fine particles (with and without size distribution).

As observed in Figure 13, an increase in the height of the entrainment zone gives way to a monotonous increase in the minimum spouting velocity.[14,17,33,40,57,58] This is explained by the higher solid-cross-flow from the annulus into the spout in the entrainment zone. Furthermore, the minimum spouting velocities of the whole sand are midway between those of the smaller and coarser sand fractions.

To compare the performance of fine materials (whole sand and narrow fractions) with open-sided and nonporous tubes, Figure 14 shows the evolution of minimum spouting velocity with inlet diameter. As observed, the performance of the whole whole sand is similar to the coarser fraction when the

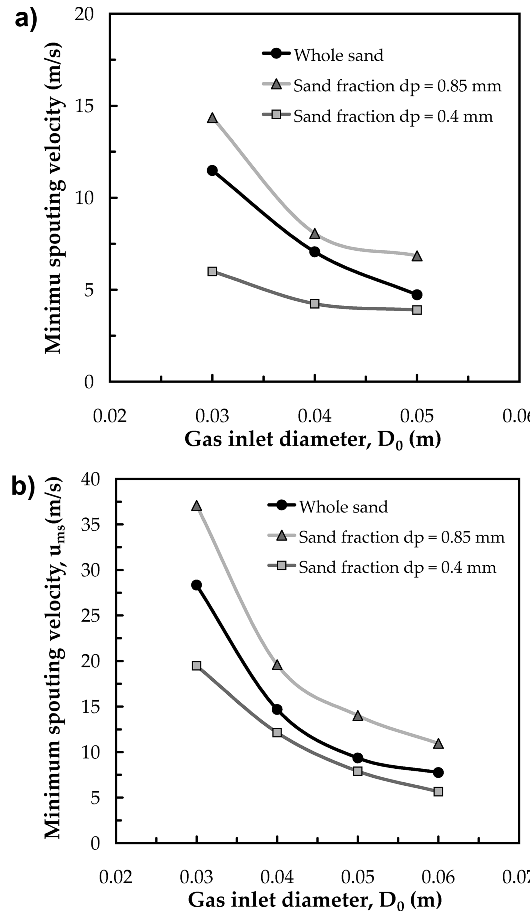

Figure 14. Influence of inlet diameter on the minimum spouting velocity when nonporous (a) and open-sided (b) draft tube systems are used with fine particles.

nonporous tube is used, Figure 14a, whereas it is similar to the finer fraction when the open-sided tube is used, Figure 14b. This is explained by the higher segregation in the former case. Thus, when the nonporous tube is used, the bigger particles descend preferentially along the outside of the tube and enter the spout at the bottom, whereas the bigger particles enter the spout along its whole length when open-sided tubes are used.

3.3. Hydrodynamic Correlations.

A hydrodynamic correlation was proposed in a previous paper for the minimum spouting velocity in nonporous draft tube conical spouted beds with fine particles.[38] The aim of this paper is to develop a more general correlation valid for nonporous draft tube conical spouted beds with fine and coarse particles in a wider range of operating conditions. Furthermore, the data obtained with open-sided draft tube conical spouted beds also allow establishing a reliable correlation for the design of these types of beds with fine and coarse particles.

As a starting point, the correlations in the literature for conical spouted beds with[28,38,57] and without[2,3,7,47−56] draft tubes have been tested, but the average relative errors between the experimental and the calculated data are in all cases above 50%. The lowest error corresponds to the correlation proposed by Olazar et al.,[3] eq 5, for plain conical spouted beds operating with coarse particles (d_p> 1 mm), which is explained by the suitable fit of a data fraction corresponding to open-sided tube systems with coarse particles.

$$Re_{msi} = 0.126Ar^{0.50}[D_b/D_i]^{1.68}[\tan(\gamma/2)]^{-0.57} \quad (5)$$

Figure 15 shows the quality of the fit between the experimental values and those calculated with eq 5 for the systems mentioned (regression coefficient $r^2 = 0.94$ and average relative error of 9%). Confidence intervals have been obtained by the Levenberg−Marquardt optimization algorithm for the parameters of best fit in eq 5, which are as follows for 95% confidence: 0.126 ± 0.025; 0.50 ± 0.09; 1.68 ± 0.34; −0.57 ± 0.11.

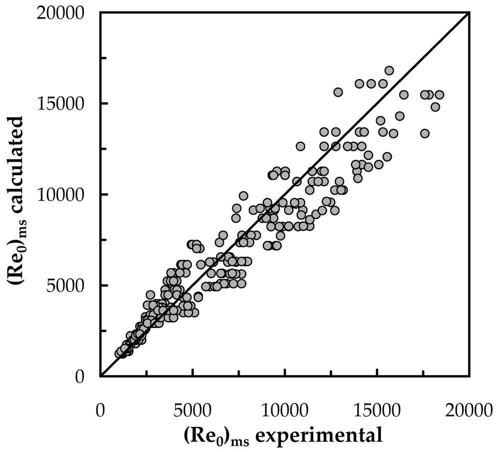

Figure 15. Comparison between the experimental data and those calculated using eq 5 for open-sided tube systems and coarse particles.

Nevertheless, eq 5 largely overestimates the minimum spouting velocity for open-sided tube systems with fine particles and for nonporous tube systems with both fine and coarse particles. The explanation lies in the nonconsideration of tube factors in the equation. Thus, the analysis of variance in Table 5 shows that the width of the faces (W_H) is a significant factor that should be considered in open-sided tubes, and the same applies to the height of the entrainment zone in nonporous tubes. Accordingly, equations have been proposed for conical spouted beds with an open-sided draft tube and a nonporous draft tube. Both are based on eq 5 by including the corresponding moduli related to the factor defining the tube. Thus, the equation for calculating the minimum spouting velocity in conical spouted beds with an open-sided draft tube includes the moduli in eq 5 plus one related to the aperture ratio, that is, open lateral area/total lateral area (A_0/A_T). A stepwise regression analysis has been carried out by maintaining the same parameters as those in eq 5 plus a new fitting parameter corresponding to the new modulus. A program written in Matlab and the subroutine *fminsearch* has been used for optimizing the error objective function, defined as the sum of the squared differences between experimental and calculated results.

The equation of best fit is as follows:

$$(Re_0)_{ms} = 0.126Ar^{0.50}[D_b/D_0]^{1.68}[\tan(\gamma/2)]^{-0.57} [A_0/A_T]^{0.30} \quad (6)$$

This equation contains the same moduli and parameters as eq 5 plus a new one corresponding to the aperture ratio.

Figure 16 shows the quality of the fit between the experimental values and those calculated with eq 6.

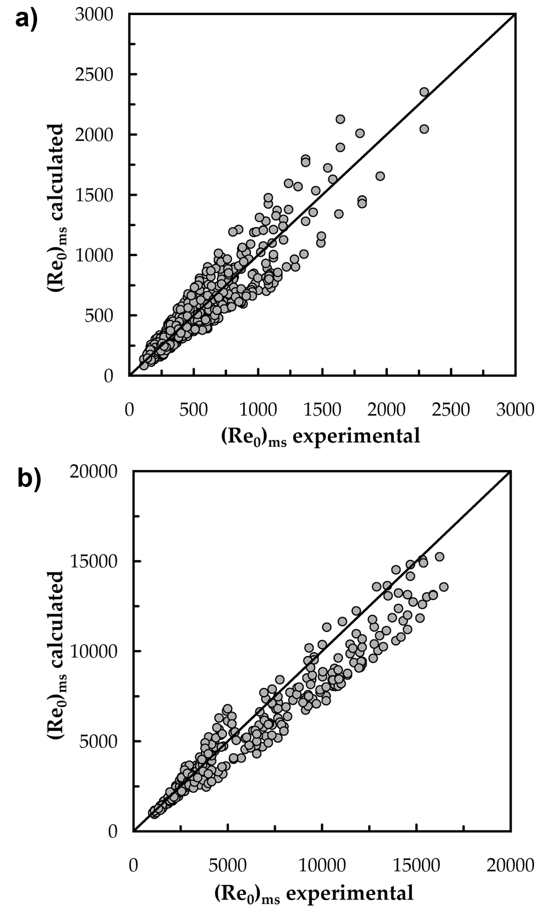

Figure 16. Comparison between the experimental values and those calculated using eq 6 for open-sided tube systems operating with fine (a) and coarse (b) particles.

The fit is adequate in both cases, although it is slightly better for coarse particles Thus, the regression coefficient is $r^2 = 0.89$ and the average relative error is 12% for coarse particles, whereas they are 0.84 and 18%, respectively, for fine particles. The 95% confidence intervals for the parameters of best fit are as follows: 0.126 ± 0.034; 0.50 ± 0.11; 1.68 ± 0.41; −0.57 ± 0.14; 0.30 ± 0.06.

Equation 6 is valid for the range of experimental parameters investigated, that is, the applicability ranges of this equation are $18500 < Ar < 5500000$, $2.20 < (D_b/D_0) < 10.35$, $28° < \gamma < 45°$, $0.42 < (A_0/A_T) < 0.78$.

Equation 6 is a generalization of eq 5, given that it is valid for calculating the minimum spouting velocity not only with open-sided draft tube systems but also without draft tubes. In fact, the aperture ratio of systems without a tube is 100%, and so the value of (A_0/A_T) modulus is unity, and eq 6 becomes eq 5.

Furthermore, a new correlation has been developed for nonporous systems based on dimensional and statistical analysis, and considering the factors of greater influence on the minimum spouting velocity for these systems. It should be noted that contactor angle has no influence on the minimum spouting velocity with nonporous draft tubes. The equation of best fit to the experimental data obtained using fine and coarse materials is as follows:

$$(Re_0)_{ms} = 0.25Ar^{0.5}[H_0/D_0]^{1.2}[L_H/D_0]^{0.3} \quad (7)$$

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The overall fitting of this equation is acceptable (regression coefficient r^2 = 0.86 and average relative error of 16%), although it slightly overestimates the minimum velocity for fine particles and slightly underestimates it for coarse particles. The 95% confidence intervals for the parameters of best fit are as follows: 0.25 ± 0.09; 0.50 ± 0.13; 1.20 ± 0.28; 0.30 ± 0.09

Equation 7 includes the following dimensionless moduli: the Archimedes modulus (Ar) accounting for gas and particle properties, the ratio between the stagnant bed height and the gas inlet diameter (H_0/D_0), and the ratio between the height of the entrainment zone and the gas inlet diameter (L_H/D_0).

It should be noted that, as observed in eqs 5 and 6, contactor angle influences the minimum spouting velocity when open-sided draft tubes are used. Nevertheless, the minimum spouting velocity does not depend on contactor angle when nonporous draft tubes are used, eq 7. This has been experimentally observed in the whole range of variables studied, except for a slight influence of the angle for high values of the entrainment zone. Nevertheless, these high values of the entrainment zone (compared to the whole length of the tube) may lead to bed instability, and operation is not recommended under these conditions. Consequently, the angle is irrelevant for the calculation of the minimum spouting velocity in conical beds with nonporous draft tubes.

The applicability ranges of the moduli are 18500 < Ar < 5500000, 2.3 < (H_0/D_0) < 10, 0.58 < (L_H/D_0) < 5.

3.4. Comparison between Plain and Draft Tube Conical Spouted Beds. Figure 17 shows the average values of the minimum spouting velocity obtained for the three types of systems analyzed, that is, the conical spouted bed with nonporous draft tube, with open-sided draft tube and without a tube.

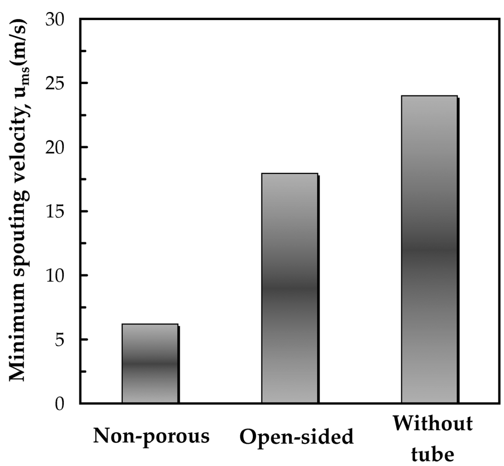

Figure 17. Average values of the minimum spouting velocity for different systems.

The minimum spouting velocity required for the systems without a draft tube is higher than for the systems with draft tubes.[14,17,33,34,58,70] The explanation lies in the gas and solid trajectories, which are very different in the three systems studied.

Comparing the systems with draft tubes, those with an open-sided draft tube require much higher values of minimum spouting velocity than those with a nonporous tube. In the systems with open-sided tubes (and also without a tube), the gas percolates from the spout into the annulus along the whole length of the spout, and the solid descending in the annulus enters the spout at any level in the bed.[71] Consequently, higher air velocity is required to open the spout and a higher solid circulation rate is produced.[38]

Regarding nonporous tube systems, a smaller fraction of the gas percolates from the spout into the annulus (in the draft tube entrainment zone) and most of the gas takes the direct route through the spout. Likewise, there is solid cross-flow only in the tube entrainment zone. Accordingly, the air velocity required to open the spout is much lower than in the other systems, and, consequently, the gas−solid contact and solid circulation rate are much poorer than in other systems.[14]

The values of the minimum spouting velocity for open-sided draft tube systems are midway between those for plain beds (without tubes) and nonporous draft tube systems, although they are much closer to plain beds, which is explained by the tube partially holding the bed. When the aperture ratio of the open-sided tube is close to 100%, the values of the minimum spouting velocity are similar for both systems. Likewise, when the aperture ratio is close to 0%, this device becomes a nonporous draft tube. The values of the minimum spouting velocity plotted in Figure 17 for the open-sided tube are the average of those corresponding to the three aperture ratios used (42, 58, and 78%), but the values for the higher aperture ratio (78%) are almost the same as those for plain beds (without tubes).

4. CONCLUSIONS

The experimental runs carried out in conical spouted beds provided with different types of draft tubes show that the hydrodynamics is different from plain spouted beds.

The results obtained based on an experimental design show that the minimum spouting velocity is influenced by the type of draft tube used and its geometry, by the contactor/particle factors, and by operating conditions.

A statistical analysis of the results shows that the factors of greater influence on the minimum spouting velocity for all systems (with and without tubes) and materials (coarse and fine) are particle diameter (d_p) and gas inlet diameter (D_0), followed by the factors of each type of tube (W_H, L_H) and bed height (H_0). In the case of open-sided tubes and sand with particle size distribution, contactor angle (γ) is the factor of greater influence.

The minimum spouting velocity has been found to increase with higher particle diameter, stagnant bed height, and the entrainment zone height of the nonporous tube, and with decrease in gas inlet diameter and the width of the face of the open-sided tube. In addition, the minimum spouting velocity has lower values for an angle of 36°, and a wider one (45°) and a narrower one (28°) give way to higher values of this velocity.

The hydrodynamic correlations in the literature for conical spouted beds cannot give satisfactory prediction results for the draft tube systems used here. Consequently, new correlations have been developed for nonporous and open-sided draft tube conical spouted beds, respectively, with fine and coarse particles in a wide range of operating conditions. These correlations are based on a previous correlation by including the corresponding moduli related to the factor defining the tube (aperture ratio of the open-sided tube and the entrainment zone height of the nonporous tube).

A comparison of the hydrodynamics of plain and draft tube conical spouted beds shows that draft tube systems require lower minimum spouting velocities with higher stability of the spouted bed regime. Plain spouted beds are adequate for bench scale, but draft tubes are necessary for stability on a larger scale.

Regarding draft tube conical spouted beds, the minimum spouting velocity of nonporous tube systems is much lower than of open-sided tube systems. However, open-sided tube systems perform much better with the advantage of allowing a higher solid circulation rate and better gas−solid contact because of a good aeration of the annulus.

Finally, draft tube conical spouted beds have proven to be a good system for operating with fine particles with a size distribution that causes stability problems in plain spouted beds.

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Notes

The authors declare no competing financial interest.

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■ NOTATION

A_0	Open lateral area of the tube, m^2
A_T	Total lateral area of the tube, m^2
Ar	Archimedes number, $gd_p^3\rho(\rho_s - \rho)\mu^{-2}$
d_p	Average particle diameter, m
d_{pi}	Average particle diameter of i fraction, m
D_0	Gas inlet diameter, m
D_b	Top diameter of the stagnant bed, m
D_C	Colum diameter, m
D_g	Diameter of the upper bed layer, m
D_i	Contactor base diameter, m
D_T	Diameter of the draft tube, m
H_0	Stagnant bed height, m
H_C	Height of the conical section, m
h_r	Height of the body of the nonporous draft tube, m
L_H	Height of the entrainment zone of the nonporous draft tube, m
L_T	Lenght of the draft tube, m
$(Re_0)_{ms}$	Reynolds number of minimum spouting, referred to D_0, $\rho u_{ms} d_p \mu^{-1}$
u_{ms}	Minimum spouting velocity at the inlet orifice, m s^{-1}
V_r	Volume of the draft tube, m^3
V_0	Volume of the static bed, m^3
W_H	Width of the face of the open-sided draft tube, m
ΔP_S	Operating pressure drop, Pa
ΔP_M	Peak pressure drop, Pa

Greek Letters

γ Cone angle, rad

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