This is the preprint manuscript of the article that appeared in final form in **Powder Technology** 37 : 597-608 (2020) which has been published in final form at https://doi.org/10.1016/j.powtec.2020.07.087.

Minimum spouting velocity of fine particles in fountain confined conical spouted beds

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Abstract

A novel internal device called fountain confiner has been developed, which stabilizes the system and allows operating with fine particles, even without any type of draft tube. Given the stability this device confers upon the system, lower minimum spouting velocities than in conventional systems are required, and therefore the correlations in the literature overestimate this hydrodynamic parameter. Accordingly, runs have been carried out using this novel device in order to study the hydrodynamics and the influence geometric and operating factors have on the minimum spouting velocity in fountain confined conical spouted beds, with and without draft tubes. The beds are made up of fine sand and sawdust particles. Based on an experimental design, it was ascertained that, although certain factors are influential in given configurations, those of greater influence in all the configurations are the solid properties, static bed height and gas inlet diameter. Therefore,

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new correlations have been proposed for predicting the minimum spouting velocity in each configuration.
Keywords:
minimum spouting velocity, fine particles, conical spouted bed, fountain confiner, hydrodynamics

1. Introduction

The spouted bed technology is well established for the treatment of coarse particles, for which unsatisfactory results are obtained with fluidized beds. Moreover, the versatility of the gas flow rate allows handling particles of irregular texture and those with a wide size distribution, as well as sticky solids, whose treatment is difficult using other gas-solid contact regimes [1, 2, 3]. These properties make the spouted bed an interesting gas-solid contact method and alternative to fluidized beds.

The gas is introduced through a single nozzle at the centre of a conical or flat base and penetrates the bed creating a central spout zone, a fountain above the spout and the annulus surrounding the spout. The gas passes upward through the spout, fountain and annulus, while the particles are conveyed up the fountain core and down the fountain periphery and annulus. The recirculation of particles between the spout and annulus is one of the more relevant features of spouted beds, which differs from fixed and fluidized beds.

In the past [4], the spouted bed was designed to treat coarse particles (size greater than 1 mm) or mixtures of particles of different size and/or density [1, 5, 6, 7]. This technology has been distinguished from the fluidized bed not only by its peculiar particle circulation, but also by its lower pressure drop and better contact between the two phases due to the counter-current movement of the solid (upwards in the spout and downwards in the annulus). Moreover, the cross-flow of the particles from the annulus into the annulus is one of the more important characteristics of this regime.

Unfortunately, the greatest limitation of this technology lies in its scaling up and industrial application. Therefore, operation with fine particles in stable regime is only possible at small or very small-scale units. Stable operation is only attained when the ratio between the gas inlet diameter and particle diameter, D_0/d_p, is smaller than $20 - 30$ times the particle diameter [8, 9]. Higher values of this ratio lead to slugging and highly unstable beds, with these phenomena occurring with either fine or coarse particles. In this situation, the gas expands through the whole bed in the form of a big bubble instead of ascending through a well-defined spout along the centre of the bed. This phenomenon is known as slugging (incipient, radial or axial) and is generally accepted as the main cause of instability in spouted beds, given that it alters the uniform and cyclic particle movement characteristic of these beds [10]. Therefore, it is not possible to operate stably with fine particles. Several authors managed to attain stable operation with fine particles [7, 11, 12, 13, 14, 15], but in all cases they used low values of the mentioned ratio or stabilized the system with internal tubes.

There are different variants of conventional spouted beds (conical [16], cylindrical [17], two-dimensional [18], slot-rectangular [19]), with each one having advantages and disadvantages, but none have solved the problem of scaling up. The usual solution to operate with fine particles is the insertion of a draft tube [12, 20, 21, 22, 23, 24, 25, 26], and nowadays different draft tube configurations have been reported in the literature, as are: conventional nonporous draft tubes, porous draft tubes and open-sided draft tubes. The latter have been developed by our research group [27] and is especially suitable for a vigorous contact.

Nonetheless, draft tubes modify the hydrodynamics and solid circulation flow rate of the system [26, 28], changing the minimum spouting velocity, operating pressure drop, solid circulation patterns, gas distribution and particle cycle times (time required for a solid to complete a full cycle, crossing all the zones in the spouted bed). Furthermore, this central tubes operating with fine particles leads to very high fountains, and therefore severe particle entrainment. In order to avoid these problems, low gas flow rates (close to the minimum spouting velocity) must be used, which means poor solid circulation flow rate or bed turbulence.

In view of these problems, the use of a fountain confiner is the best solution to treat fine particle beds. This device is a cylindrical tube with the upper outlet closed and has been successfully applied in gasification [29, 30]. It is placed above the bed and collects the particles from the spout, avoiding their entrainment [31, 32]. Moreover, the use of this device allows increasing the upper limit of the residence time of the gas and improves gas-solid contact in the bed.

In order to step further into the scaling up of this technology, knowledge of operating parameters is required, especially the minimum spouting velocity (the minimum air velocity required to maintain the spouting regime). This velocity is probably the most relevant one in spouted beds, as it determines other important hydrodynamics parameters, such as residence time and solid movement. These parameters are decisive for a proper design, operation and scale up of spouted bed contactors for industrial applications, such as drying [33], pyrolysis [34], pine sawdust combustion [35], coating [36] and steam gasification [37].

Several correlations have been proposed for calculating the minimum spouting velocity in conical spouted beds and the main ones are listed in Table 1, 2 and 3. They have been proposed for systems without fountain confiner and differing in geometric factors and particle features.

As observed, most of the correlations relate the properties of the two phases (fluid and solid) and the geometric factors of the beds and draft tubes. The most common way to relate the properties of the two phases is based on the Archimedes dimensionless modulus (Ar). Furthermore, the contactor geometric factors commonly included in the correlations are gas inlet diameter (D_0), static bed height (H_0) and contactor angle (γ). Nevertheless, in certain Equations (Eq 1, 4, 5, 6, 7), the static bed height is replaced with the bed surface diameter (D_b), which relates the three factors mentioned

Table 1: Hydrodynamic correlations for calculating the minimum spouting velocity in conical spouted beds of different configuration.

Author	Configuration	Correlation
Gorshtein and Mukhlenov [38]	Conical spouted bed	$$(Re_0)_{ms} = 0.174Ar^{0.5}\left(\frac{D_b}{D_0}\right)^{0.25} tan\left(\frac{\gamma}{2}\right)^{-1.25} \quad (1)$$
Tsvick et al. [39]	Conical spouted bed	$$(Re_0)_{ms} = 0.4Ar^{0.52}\left(\frac{H_0}{D_0}\right)^{1.24} tan\left(\frac{\gamma}{2}\right)^{0.42} \quad (2)$$
Markowski and Kaminski [40]	Conical spouted bed	$$(Re_0)_{ms} = 0.028Ar^{0.57}\left(\frac{H_0}{D_0}\right)^{0.48}\left(\frac{D_C}{D_0}\right)^{1.27} \quad (3)$$
Olazar et al. [9]	Conical spouted bed	$$(Re_0)_{ms} = 0.126Ar^{0.5}\left(\frac{D_b}{D_0}\right)^{1.68}\left(tan(\frac{\gamma}{2})\right)^{-0.57} \quad (4)$$
Olazar et al. [41]	Conical spouted bed	$$(Re_0)_{ms} = 0.126Ar^{0.39}\left(\frac{D_b}{D_0}\right)^{1.68}\left(tan(\frac{\gamma}{2})\right)^{-0.57} \quad (5)$$

Table 2: Continuation of Table 1.

Author	Configuration	Correlation
Saldarriaga et al. [42]	Conical spouted bed	$$(Re_0)_{ms} = 0.126 Ar^{0.5} \left(\frac{D_b}{D_0}\right)^{1.37} \left(tan(\frac{\gamma}{2})\right)^{-0.57} \quad (6)$$
Golsthan et al. [43]	Conical spouted bed	$$(Re_0)_{ms} = 0.0965 Ar^{0.67} \left(\frac{H_0}{D_0}\right)^{1.32} \left(tan(\frac{\gamma}{2})\right)^{0.76} \quad (7)$$
Altzibar et al. [20]	Open-sided draft tube conical spouted bed	$$(Re_0)_{ms} = 0.126 Ar^{0.5} \left(\frac{D_b}{D_0}\right)^{1.68} \left(tan(\frac{\gamma}{2})\right)^{-0.57} \left(\frac{A_0}{A_T}\right)^{0.3} \quad (8)$$
Saldarriaga et al. [42]	Open-sided draft tube conical spouted bed	$$(Re_0)_{ms} = 0.272 Ar^{0.5} \left(\frac{D_b}{D_0}\right)^{1.25} \left(tan(\frac{\gamma}{2})\right)^{-0.57} \left(\frac{A_0}{A_T}\right)^{0.3} \phi^{0.274} \quad (9)$$

(D_0, H_0 and γ) apart from the base diameter (D_i). Certain authors have also included the diameter of the column (D_C) [46, 47, 40, 48, 49] to predict the minimum spouting velocity (Eq 3). However, unlike cylindrical spouted beds, it does not make sense to use this parameter in conical spouted beds, since it remains constant for all the systems, and therefore does not affect

Table 3: Continuation of Table 2.

Author	Configuration	Correlation
San José et al. [44]	Nonporous draft tube conical spouted bed	$$(Re_0)_{ms} = 0.126Ar^{0.5}\left(\frac{D_b}{D_0}\right)^{1.68}\left(tan(\frac{\gamma}{2})\right)^{-0.57}\left(\frac{H_0-L_T}{H_0}\right)^{0.4}\left(\frac{D_i}{D_i-D_T}\right)^{0.17} \quad (10)$$
Kmiec et al. [45]	Nonporous draft tube conical spouted bed	$$(Re_0)_{ms} = 0.0137Ar^{0.71}\left(\frac{D_b}{D_0}\right)^{-0.55}\left(\frac{\varphi V_r}{V_0}\right)^{0.41}\gamma^{0.8} \quad (11)$$
Altzibar et al. [20]	Nonporous draft tube conical spouted bed	$$(Re_0)_{ms} = 0.25Ar^{0.5}\left(\frac{H_0}{D_0}\right)^{1.2}\left(\frac{L_H}{D_0}\right)^{0.3} \quad (12)$$
Saldarriaga et al. [20]	Nonporous draft tube conical spouted bed	$$(Re_0)_{ms} = 0.5Ar^{0.5}\left(\frac{H_0}{D_0}\right)^{1.7}\left(\frac{L_H}{D_0}\right)^{0.1}\phi^{0.54} \quad (13)$$

the minimum spouting velocity (the bed is loaded in the conical zone).

Furthermore, the correlations obtained for draft tube conical spouted beds also include factors related to the geometry of the draft tube, which is evidence that they significantly affect the minimum spouting velocity. In the case of open-sided draft tubes, only two correlations are found in the literature and both are from our research group [20, 42] (Eq 8 and 9). Both correlations include the dimensionless modulus A_0/A_T (open lateral area/total lateral area), since the draft tube aperture ratio affects the solid cross-flow from the annulus into the spout and the gas flow diversion from the spout into the annulus, at any level in the bed.

In the case of nonporous draft tubes, more correlations than for open-sided draft tubes have been published in the literature. In all cases (Eq 10, 11, 12 and 13) they include factors related to the geometry of the central tube (l_d, φ and L_H), or more precisely to the entrainment zone. Moreover, it is widely accepted that the height of the entrainment zone is a highly significant parameter for the minimum spouting velocity in these systems [45].

Most of the correlations listed in Table 1, 2 and 3 have been obtained based on the results for coarse particles differing in both particle diameter and solid density. Our research group has developed several correlations for calculating the minimum spouting velocity under different operation conditions. Thus, Olazar et al. [9] proposed Eq 4 using coarse particles ($d_p = 1 - 8\,mm$ particle diameter) in conical spouted beds covering a wide range of contactor angles ($28 - 45°$) and inlet diameters ($0.03 - 0.06\,m$). In fact, it is a widely recognized correlation in the literature for plain conical spouted beds. Nevertheless, given that this correlation does provide suitable predictions for fine particle systems, these authors developed Eq 5 [41]. This equation was obtained operating with fine particles ($d_p = 0.3 - 1.2\,mm$ particle diameter), but using very low values of gas inlet diameters ($3 - 12\,mm$) in order to conform the D_o/d_p ratio for stability, and therefore its validity for scaling up is questionable. Altzibar et al. [20] used both coarse (glass beads and black peas) and fine (sand) particles in conical spouted beds with different configurations, as are: without draft tubes, with open-sided tubes and with nonporous tubes. They observed that Eq 4 provided suitable predictions in the systems without draft tubes (coarse particles systems), but a few modifications were required for open-sided and nonporous systems, which are reflected in Eq 8 and 12. Saldarriaga et al. [42] used five different biomasses ($d_p = 0.76 - 2.33\,mm$ particle size) and, although they obtained suitable predictions using Eq 4, 8 and 12, they improved these correlations by modifying slightly the exponents of certain moduli and inserting the sphericity factor. Accordingly, they proposed Eq 6,9 and 13.

A previous study [10] has proven that the fountain confiner stabilizes beds of fine particles, or it also allows operating without any type of draft tube. Furthermore, in systems where both devices are combined, the minimum spouting velocity is reduced due to the stability conferred by the confiner upon the bed.

Therefore, the main aim of this paper is to ascertain the validity of the correlations in the literature for calculating the minimum spouting velocity in fountain confined conical spouted beds with fine particles. In case there is no valid correlation, modifications in those of best fit will be carried out.

Accordingly, runs have been carried out following an experimental design, which allowed obtaining reliable data for analysis and identifying significant factors.

2. MATERIAL AND METHODS

2.1. Equipment

As shown in Fig 1, the pilot plant consists of a blower, flowmeter, pressure drop gauge, contactor, filter and cyclone. The blower has a power of $5.5\,kW$ and supplies the air required for spouting the beds in the contactor. The gas flow rate is measured by means of a thermal mass flowmeter in the $0 - 600\,N\,m^3\,h^{-1}$ range. This flow meter is composed of a resistance and temperature sensor, which allow an accurate measurements at low flow rates. The blower supplies a constant flow rate, and the flow that enters in the contactor is controlled by acting on a motor valve that reroutes the remaining air to the outside, or changing the frequency of the blower motor when strict control is necessary. Pressure measurements are carried out by means of two pressure taps, which are connected to the contactor input and output. Moreover, a cyclone and a filter are connected in series in order to separate the solids dragged by the air. The cyclone separates the coarser particles from the air, whereas the filter traps the fine ones.

The main component of the experimental setup is the contactor, Fig 2a, and is of conical geometry. The unit allows operating with contactors of different geometry. Three conical contactors made of polyethylene terephthalate

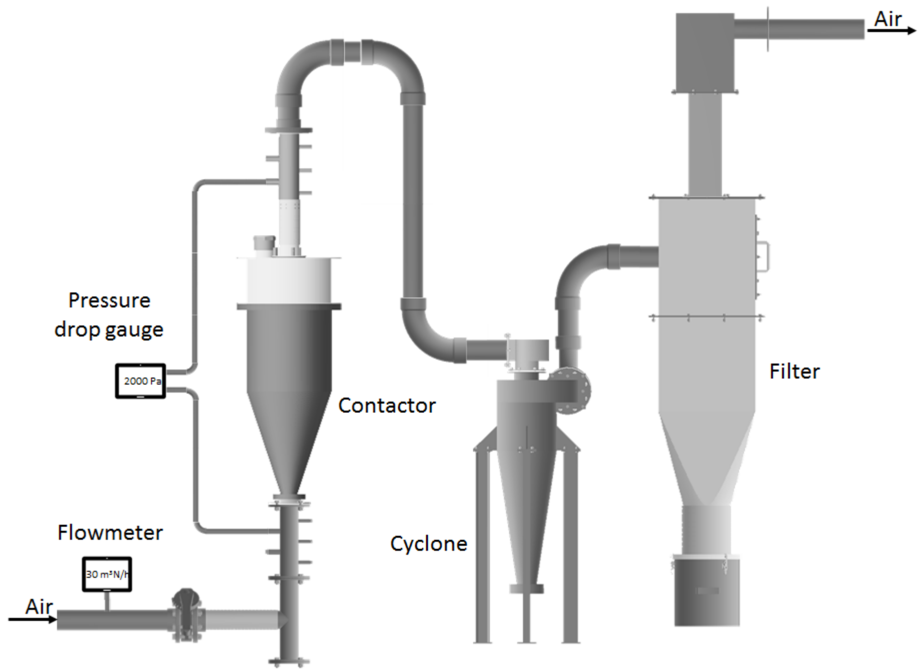


Figure 1: Diagrammatic representation of the pilot plant.

have been used. Fig 2a shows the geometric factors of these contactors, with their dimensions being as follows: column diameter, 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 gas inlet diameters, D_0, used are 0.03, 0.04 and $0.05\,m$. The static bed heights, H_0, used are 0.20 and $0.27\,m$.

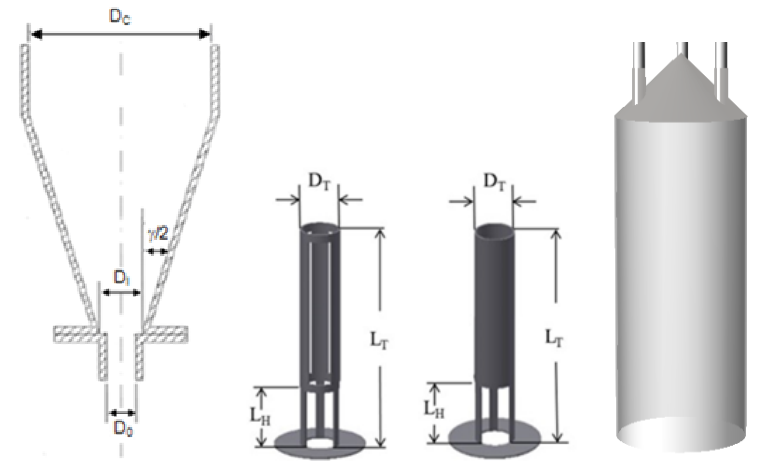
2.2. Draft tubes

These contactors allow fitting draft tubes at the inlet of the conical section. They are stainless steel tubes of cylindrical shape, which are located along the axis of the contactor and fixed at its bottom. Their performance has already been studied for sand, glass beds and different biomasses [50, 20, 42]. Two different types of draft tubes have been used in this study: open-sided and nonporous draft tubes. Figs 2b and 2c show a scheme of both types of internal devices.

In the case of the nonporous draft tubes, the main parameters governing hydrodynamics are the height of the entrainment zone (distance between the gas inlet nozzle and the lower end of the tube), L_H, and the tube diameter, D_T. The length of the tube is the same as the bed height, L_T, 0.20 and $0.27\,m$.

Furthermore, the open-sided draft tubes have part of their lateral surface area opened in order to allow solid cross-flow from the annulus into the spout and gas diversion from the spout into annulus along the whole length of the spout. Their main design parameters are the aperture ratio and the diameter of the tube, D_T. As in the case of nonporous draft tubes, their length is the same as bed height, L_T, 0.20 and $0.27\,m$.

As shown in Figs 2b and 2c both types of draft tubes are equipped with a flat base in which there is a hole of the same size as the tube diameter (D_T). Furthermore, there is an entrainment zone (L_H) in both types of draft tubes, which is $0.07\,m$ long for the open-sided tubes, but variable for nonporous draft tubes. In the case of the open-sided tubes, the solid may also enter the spout through the apertures along the tube.



(a) (b) (c) (d)

Figure 2: Geometric factors of the conical contactors (a), open-sided (b), nonporous draft tubes (c) and schematic representation of fountain confiner (d).

2.3. Fountain confiners

The fountain confiner (Fig 2d) is a cylindrical tube made of polyethylene terephthalate (for allowing visual observation) with the upper end closed to avoid gas and solid leaving the contactor through this device and force them to describe a downward trajectory. A stainless steel cone is coupled to the top of the fountain confiner to avoid the deposition of the solid on the device, i.e., the solids deposited on the cone slip and fall down onto the bed surface.

As observed in Fig 3a, this device is placed above the bed and confines the particles in the fountain (Fig 3b), avoiding their entrainment. This device forces both the fountain to adopt the shape of the confiner and the air to make a longer trajectory. Therefore, operation is possible at high values of the gas flow rate without loss of material in the bed and ensuring high solid circulation flow rates. Thus, it enhances the gas-solid contact.

Fig 3b shows the gas and solid trajectories in the fountain confined conical spouted bed. The solid trajectory is similar to that in conventional systems, but the fountain confiner changes the trajectory of the gas, given that once it has reached the top of the fountain (upper end of the confiner) it must descend and pass through the slot between the lower end of the device and the bed surface. This fact causes an additional contact between the gas and the solid in the fountain. Furthermore, this device avoids fine particle entrainment because the gas cannot drag the particles from the fountain directly to the outside of the contactor, i.e., the particles fall back onto the bed surface because gravity forces overcome drag ones.

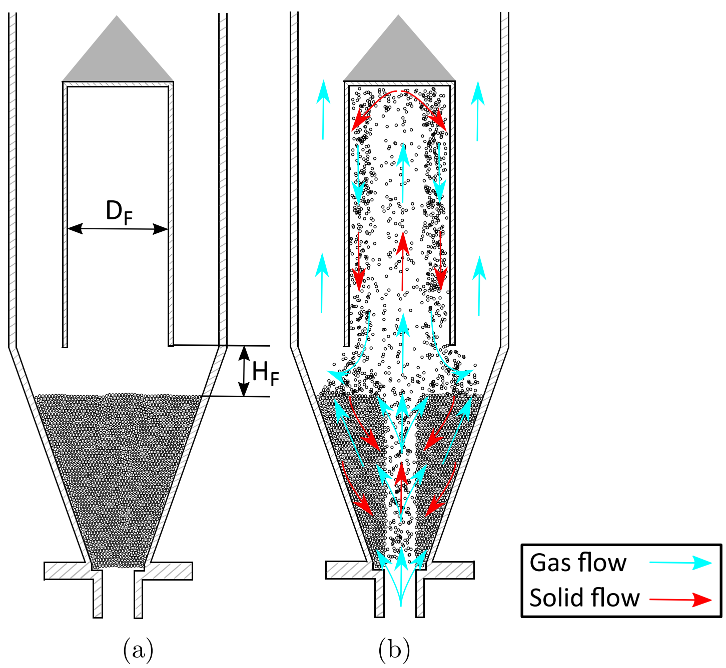


Figure 3: Fountain confiner location and its geometric factors (a), and gas and solid trajectories in the fountain confined conical spouted bed (b).

Two fountain confiners of different diameter (D_F) have been used. Thus, the diameters of the devices are 0.15 and 0.20 m.

2.4. Materials

Three types of siliceous sands and one of pine sawdust have been used, with their average particle sizes being: 0.050, 0.150 and 0.250 mm for the sand, and 0.250 mm for the sawdust. The particle size distributions, as well as the average particle sizes have been obtained by sieving in a CISA RP 200N sieve shaker using mesh sizes of 100, 200 and 300 μm, with the results being confirmed in a Mastersizer 2000 laser diffraction particle size analyser. The particle density for the sand is 2390 $kg\,m^3$ and for the sawdust 496 $kg\,m^3$, which have been determined in an Autopore 9220 mercury porosimeter from Micromeritics. Thus, the 50 μm sand fraction belongs to group A of Geldart classification and the other sand fractions belong to group B of Geldart classification [51]. The sawdust particles used correspond to Geldart group A.

3. RESULTS

The use of the confiner allows obtaining stable regimes with very fine particles without the need of draft tubes, since this device confines the fountain and avoids bed loosing. In addition, it improves the stability of the system with open-sided draft tubes, reducing the minimum spouting velocity and increasing the operational range. On the other hand, the joint use of the confiner and the nonporous central draft tube increases considerably the operational range, but does not lead to synergistic effects that decrease the minimum spouting velocity.

Accordingly, the validity of the correlations available in the bibliography should be checked and, in case their predictions are not suitable, modification should be carried out for the design and scale up of these fountain confined conical spouted beds. Therefore, runs have been carried out following a design of experiments to ascertain the factors of greater influence on the minimum spouting velocity and develop hydrodynamics correlations for the prediction of this velocity when different draft tube and fountain confiner geometries and configurations are used.

Tables 4, 5 and 6 show the factors and their levels used in the runs without draft tubes, with open-sided draft tubes and with nonporous draft tubes, respectively. It is well-known that stable operation without draft tube and fountain confiner is only attained when the ratio between inlet diameter and particle diameter (D_0/d_p) is below $20 - 30$. Nevertheless, preliminary experiments have proven that a fountain confiner allows increasing this ratio to even 1000. Furthermore, is should be noted that, although the fountain confiner is not required with coarse particles ($d_p > 1\,mm$), i.e., only the draft tube is enough to attain a stable spouting regime, it promotes additional contact between the two phases and may also avoid particle entrainment.

In each experimental run, the evolution of bed pressure drop with air velocity has been monitored from the fixed bed to the spouting regime. The

Table 4: Factors and their levels for systems without draft tubes.

Factors	Levels				
γ, contactor angle (°)	36	45			
D_0, gas inlet diameter (m)	0.03	0.04	0.05		
H_0, static bed height (m)	0.20	0.27			
d_p, particle diameter (μ m)					
Sand	50	150	250		
Sawdust	250				
D_F, confiner diameter (m)	0.15	0.20			
H_F, gap between bed surface and confiner (m)	0.02	0.04	0.06	0.08	0.10

Table 5: Factors and their levels for systems with open-sided draft tubes.

Factors	Levels				
γ, contactor angle (°)	28	36	45		
D_0, gas inlet diameter (m)	0.03	0.04	0.05		
H_0, static bed height (m)	0.20	0.27			
d_p, particle diameter (μ m)					
Sand	50	150	250		
Sawdust	250				
D_F, confiner diameter (m)	0.15	0.20			
H_F, gap between bed surface and confiner (m)	0.02	0.04	0.06	0.08	0.10
D_T, tube diameter (m)	0.04	0.05			
AR, aperture ratio (%)	78	57	42		

gas flow rate has then been decreased until zero to obtain the minimum spouting velocity.

Experimental runs have been carried out by combining different contac-

Table 6: Factors and their levels for systems with nonporous draft tubes.

Factors	**Levels**				
γ, contactor angle (°)	28	36	45		
D_0, gas inlet diameter (m)	0.03	0.04	0.05		
H_0, static bed height (m)	0.20	0.27			
d_p, particle diameter (μ m)					
Sand	50	150	250		
Sawdust	250				
D_F, confiner diameter (m)	0.15	0.20			
H_F, gap between bed surface and confiner (m)	0.02	0.04	0.06	0.08	0.10
D_T, tube diameter (m)	0.04	0.05			
L_H, height of the entrainment zone (m)	0.07	0.15			

tors, draft tubes and confiner geometries; that is, approximately 80 runs without a draft tube, 150 with open-sided draft tubes and 130 with non-porous draft tubes. All the runs have been repeated at least three times in order to decrease the relative error below 5%.

3.1. Significant factors in the minimum spouting velocity

In order to develop a correlation, the factors of greater influence and their effect on the minimum spouting velocity must be ascertained. Thus, an analysis of variance (ANOVA) has been carried out by means of a standard statistical package (SPSS 22.0). The use of a draft tube causes considerable changes in the hydrodynamics of the systems, and therefore in the minimum spouting velocity. Accordingly, the statistical analysis has been applied individually to each configuration with a 95% confidence interval.

The significance order of the factors analyzed when using different types of draft tubes and without draft tube is shown in Table 7. Firstly, sand and sawdust have been analyzed separately to clearly identify the performance of the beds when solids of different density are used. Subsequently, a joint statistical analysis of the two different solids was performed to analyze the influence of solid density on the minimum spouting velocity.

Table 7: Significance order of factors and binary interactions.

Configuration	**Material**	**Significance order**
Without draft tube	Sand	$H_0 >> H_0 * D_F > D_F > d_p > D_0$
	Sawdust	$D_0 > H_0 > \gamma > H_0 * D_0$
	Both materials	$H_0 > \rho_s > D_F * H_0 > H_0 * \rho_s$
Open-sided draft tube	Sand	$H_0 >> d_p > D_0 > D_T > D_0 * D_T > D_T * d_p$
	Sawdust	$H_0 > AR > \gamma > D_0 > D_T > D_F * H_0$
	Both materials	$\rho_s >> H_0 > d_p > D_0 > D_0 * \rho_s > AR$
Nonporous draft tube	Sand	$H_0 >> d_p > D_0 > \gamma > L_H > D_F$
	Sawdust	$H_0 > D_0 > D_T > \gamma > L_H > D_F * H_0$
	Both materials	$\rho_s > H_0 >> d_p > L_H > \gamma > D_T * d_p$

As shown in Table 7, solid density is the most influential factor on the minimum spouting velocity when all the results are jointly analysed. Furthermore, static bed height and gas inlet diameter are the geometric factors of the bed affecting the minimum spouting velocity in all configurations and materials.

As mentioned above, an individual analysis for each material shows that H_0 and D_0 are significant factors. Furthermore, Table 7 shows that particle diameter has also a great influence (even greater than inlet diameter) on the minimum spouting velocity. This is observed for sand, which is the material in which particle size was changed. It should be noted that contactor angle is significant in the beds of sawdust, but not in those of sand, which must be attributed to the low shape factor of the sawdust, which has an impact on the fluidity of this material along the inclined wall of the contactor.

Furthermore, Table 7 shows that the diameter of the confiner is a significant parameter in the systems without draft tube, especially in systems with sand. Nevertheless, when draft tubes are used together with the fountain confiner, its diameter is of low significance or even insignificant. This means that both the fountain confiner and the draft tube contribute to stabilizing the bed, and so have a similar effect on the minimum spouting velocity. Therefore, either one or the other contributes to decreasing the minimum spouting velocity but their joint use has a low synergistic effect on the minimum spouting velocity.

Concerning the effect of the geometric factors of the draft tubes on the minimum spouting velocity, Table 7 shows that both the aperture ratio and tube diameter are significant. Furthermore, the aperture ratio is of high significant in the irregular sawdust materials, which is explained by their low fluidity. Finally, in the systems in which nonporous draft tubes have been used, the height of the entrainment zone is a parameter of great influence on the minimum spouting velocity in both materials.

The quantitative influence of these factors may be observed by plotting the average values of the minimum spouting velocity for the different factor levels vs. the values of the factor levels. Fig 4 shows the change in minimum spouting velocity caused by solid density in the three configurations studied.

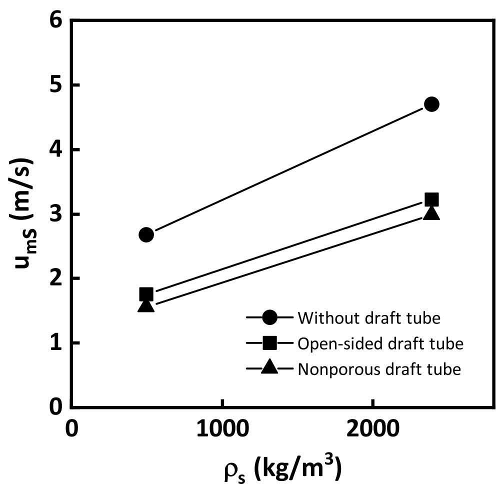


Figure 4: Influence of solid density on the minimum spouting velocity using different configurations.

As shown in Fig 4, an increase in solid density leads to a significant increase in the minimum spouting velocity for all the configurations studied. Given that an increase in solid density increases the gravitational force that the bed exerts on the gas, a higher gas flow rate or gas velocity is necessary to maintain the spouting regime. This trend is similar to that already observed by other authors with different materials [9, 20, 42] and very dense solids [43] in conical and cylindrical spouted beds [52]. Furthermore, systems without draft tube are the configurations with the highest minimum air velocity required to maintain the spouted bed regime. As shown in Fig 4, the use of a draft tube greatly reduces the minimum spouting velocity, with the systems with nonporous draft tube being those requiring the lowest air velocity (poorest gas-solid contact). In addition, the change in the minimum spouting velocity for an increase in solid density is more pronounced in the systems without draft tube.

Fig 5 shows the change in minimum spouting velocity caused by the static bed height in the three configurations studied with sand (Fig 5a) and sawdust (Fig 5b).

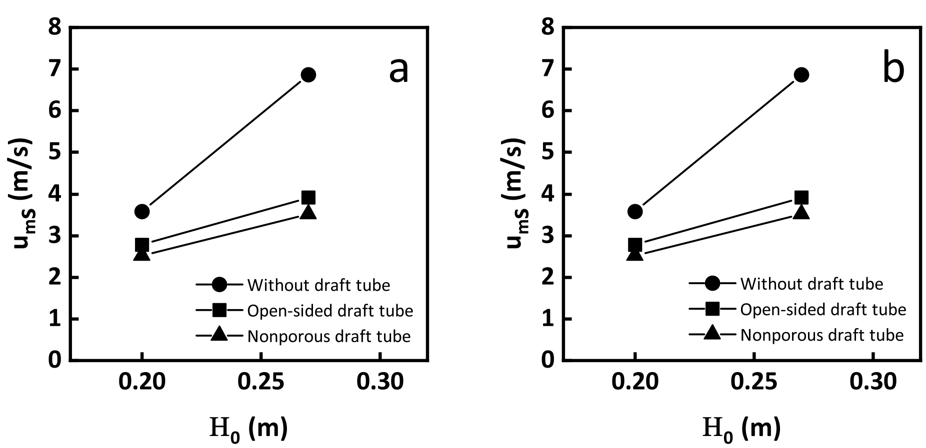


Figure 5: Influence of static bed height on the minimum spouting velocity using sand (a) and sawdust (b).

Fig 5 shows that an increase in the static bed height causes an increase in the minimum spouting velocity. This trend is similar to that observed for solid density (Fig 4), and is explained by the increase in the mass of solids contained in the bed. Similar trends have been reported by several authors for conical [9, 20, 42, 43, 44, 48], cylindrical [52, 53, 54, 55] and rectangular spouted beds [56].

As also observed in Fig 5, the minimum spouting velocities required for sand beds (Fig 5a) are higher than those for sawdust ones (Fig 5b) due to the higher solid density. Furthermore, the effect of the static bed height is greater in the systems without draft tube, since the slope of the corresponding lines in Figs 5a and 5b is higher. In addition, the velocity required to maintain the spouting regime is higher in the systems without draft tube. The effect of both draft tubes is similar, although the nonporous one leads to slightly lower velocities. Similar trends have been observed by Altzibar et al. [20] with coarse and fine particles without the fountain confiner.

Fig 6 shows the effect of gas inlet diameter on the minimum spouting velocity operated with sand (Fig 6a) and sawdust (Fig 6b).

As observed, an increase in the gas inlet diameter causes a decrease in the minimum spouting velocity in all systems and materials studied. The highest velocities correspond again to the systems without draft tube, whereas the lowest ones correspond to the nonporous draft tubes. Furthermore, Fig 6b shows that the type of draft tube has hardly any influence when the lighter solid (sawdust) is spouted. Similar trends have been reported in the literature for conical sand beds spouted with and without draft tubes [20, 43, 44]. Nevertheless, no clear trend has been reported for the sawdust [42]. It should be noted that opposite trends have been reported in the literature for cylin-

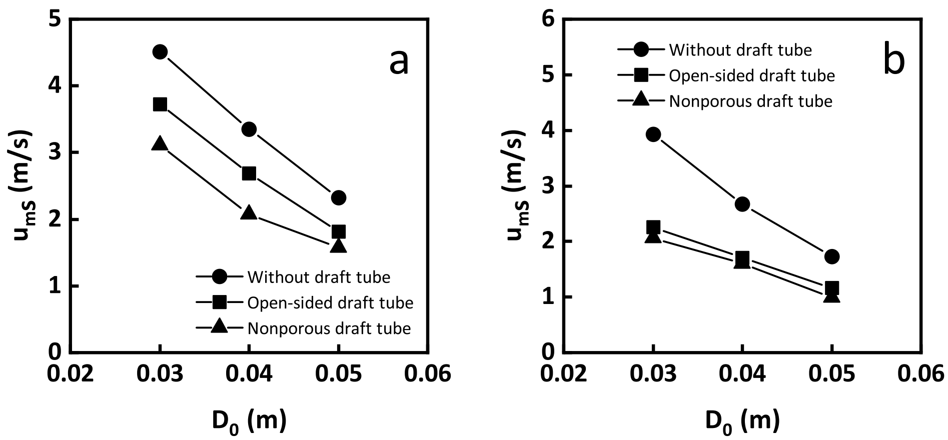


Figure 6: Influence of gas inlet diameter on the minimum spouting velocity using sand (a) and sawdust (b).

drical [53, 54], rectangular [56, 57] and spout-fluid [58] beds. A comparison of Fig 6a and 6b shows that the systems operated with sawdust require lower minimum spouting velocities.

As shown in Table 7, particle diameter is a very significant factor, and its quantitative influence is shown in Fig 7.

As shown in Fig 7, an increase in particle diameter leads to an increase in the minimum spouting velocity for the three configurations. The contact area between the fluid and the bed is greater when particle diameter decreases, so a lower air velocity is required to maintain spouting regime. Similar trends have been reported by different authors using conical [9, 20, 43, 59], cylindrical [52, 53] and rectangular spouted beds [56, 57]. As shown in Fig 7, there is a great difference between systems with and without draft tube, which is because the draft tube supports part of the bed, reducing the minimum

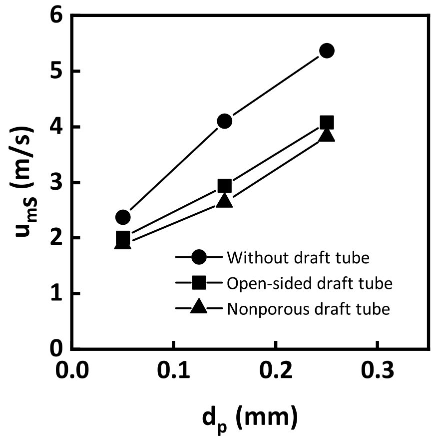


Figure 7: Influence of particle diameter on the minimum spouting velocity for sand beds operated with and without draft tubes.

spouting velocity.

As mentioned above, Table 7, contactor angle significantly affects the minimum spouting velocity when highly irregular particles, such as sawdust, are spouted. Fig 8 shows the evolution of the minimum spouting velocity as the level of this factor is changed.

Fig 8 shows that an increase in contactor angle causes a decrease in the minimum spouting velocity. A change in contactor angle causes two effects, on the one hand, a change in the inclination of the contactor wall and, on the other hand, a change in the mass of solids contained in the bed for a given static bed height. According to the former, the minimum spouting velocity increases when the cone angle is decreased, since the wall supporting effect is lower, but, according to the latter, the minimum spouting velocity decreases as the angle is decreased due to the lower amount of particles in the bed.

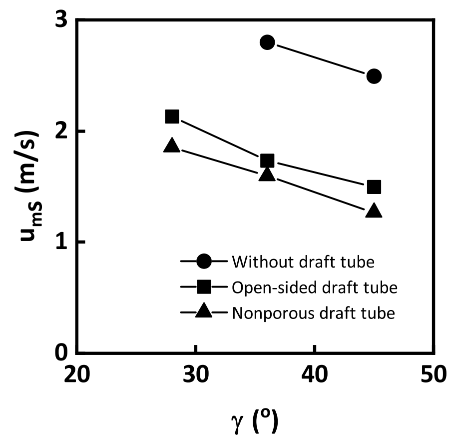


Figure 8: Influence of contactor angle on the minimum spouting velocity for systems with and without draft tubes operated with sawdust.

In our systems, the first effect prevails, and therefore the minimum spouting velocity decreases when the angle is increased. Saldarriaga et al. [42] found a similar trend operating with different types of biomasses, and Altzibar et al. [20] found an inverse peak for the contactor angle of 36 °. Opposite trends to this study have also been reported in the literature [43, 59]. As shown in Fig 8, the three configurations show the same trend, with the the systems without central tube being those requiring the highest minimum velocities and those with the nonporous draft tube the lowest ones. It is noteworthy that no stable spouting regime was attained when operating with the narrowest contactor (smallest angle) without any draft tube.

Other influential factors mentioned in Table 7 are as follows: Diameter of the fountain confiner (D_F) in the systems without draft tube, aperture ratio in those equipped with the open-sided draft tube and the height of the entrainment zone in those provided with the nonporous draft tube. Fig 9 shows the effect of these factors on the minimum spouting velocity.

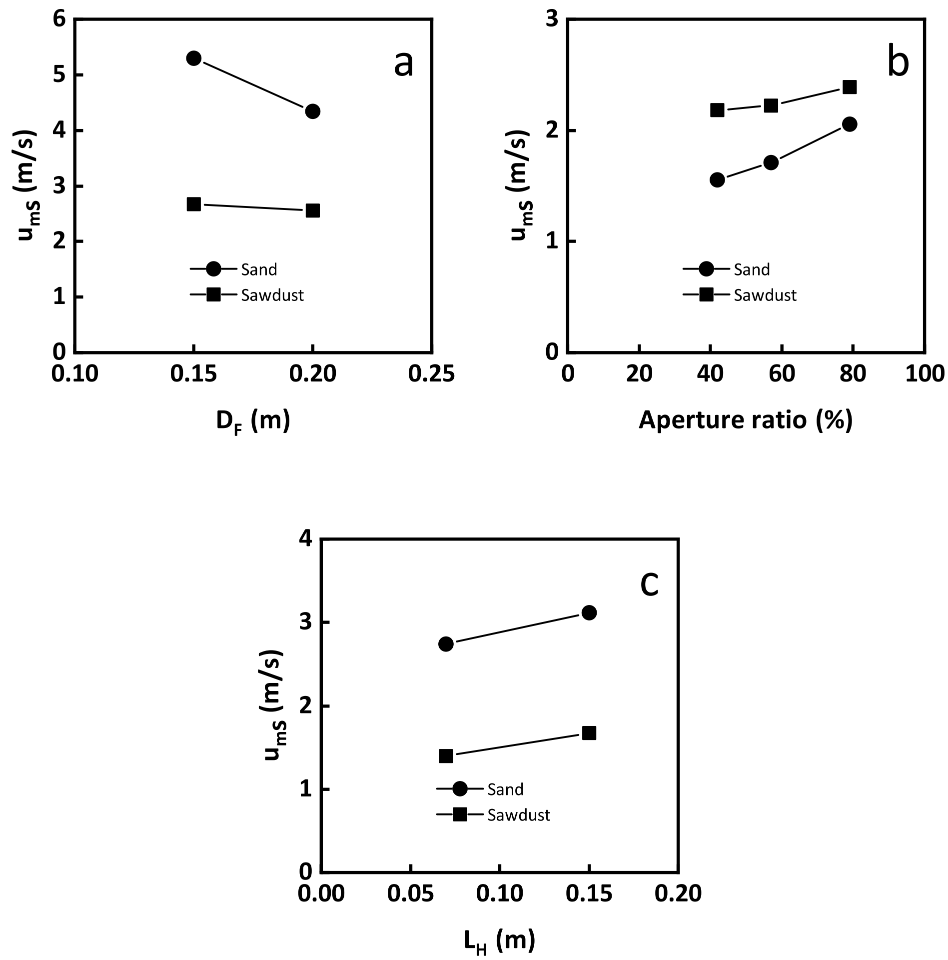


Figure 9: Influence of the confiner diameter in the systems without draft tube (a), aperture ratio in those equipped with the open-sided draft tube (b) and height of the entrainment zone in those with the nonporous draft tube (c) on the minimum spouting velocity.

As observed in Fig 9a, an increase in confiner diameter leads to a decrease in the minimum spouting velocity in sand beds, but has hardly any effect in sawdust beds. Thus, a greater diameter leads to a better fountain confinement, thereby stabilizing the system at lower gas velocities. Nevertheless, excessively large diameters are not recommended because they do not confine the fountain. Thus, Estiati et al. [32] observed that particle entrainment was reduced by increasing the diameter of the confiner, which in turn caused a reduction in air velocity and pressure drop.

Furthermore, the use of the draft tube favors the stability of the system, and therefore the diameter of the confiner is no longer an influential factor in the configurations with draft tube. Fig 9b shows that an increase in the aperture ratio leads to an increase in the minimum spouting velocity due to the lower bed supporting effect by the tube wall. Furthermore, a higher solid cross-flow from the annulus into the spout is attained, which leads to a better contact between the two phases. Therefore, this situation leads to a higher air velocity for spouting. Furthermore, Fig 9b shows that an increase in aperture ratio has a more pronounced effect on the lighter material.

Finally, Fig 9c shows that an increase in the height of the entrainment zone causes an increase in the minimum spouting velocity. In fact, this parameter governs the hydrodynamics of the system, since it delimits the entrance of the solids to the spout and the percolation of the gas through the annular zone. An increase in the entrainment height leads to a higher solid cross-flow from the annulus into the spout, and therefore higher air velocities are required to maintain the spouting regime. Fig 9c shows that this factor is of significant in both materials (considerable slope). Similar trends have been reported by several authors using conical [20, 44, 60], cylindrical [26, 61], spout-fluid [58] and slot-rectangular spouted beds [19].

3.2. Hydrodynamic correlations

As mentioned in previous papers [10, 31], the fountain confiner is an internal device that greatly enhances system stability, especially when fine particles are used without any draft tube. This device allows increasing the D_0/d_p ratio from 20-30 [9] to around 1000 [10]. In addition, it also provides stability to systems operating with fine particles and draft tubes, thus increasing operational range. Given that the minimum spouting velocity is an essential parameter for the design and scale up of these beds, correlations are required for its accurate estimation. Furthermore, they will also be a suitable tool for validating the minimum spouting velocities predicted based on CFD models.

As shown in Fig 5-9, the systems without draft tube are the ones requiring the highest minimum spouting velocity and the nonporous ones the lowest. In the systems without draft tube and with open-sided draft 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. The difference between these two configurations is that the open-sided draft tube partially supports the bed and reduces the access area of the solids from the annulus into the spout. Regarding nonporous tube systems, a smaller fraction of the gas percolates from the spout into the annulus (only at the entrainment zone), i.e., most of the gas takes the direct route through the spout. Likewise, there is solid cross-flow only in the entrainment zone.

The fountain confiner changes the hydrodynamics of the system, which is reflected in the results obtained for the minimum spouting velocity. In fact, these results are significantly lower than those predicted by any correlation in the literature for cylindrical, conical or slot rectangular spouted beds. Fig 10 shows the parity plots for the literature correlations of best fit. Each graph corresponds to a given configuration.

Although Eq 2, 5 and 12 are those of best fit, their predictions are rather poor, with their determination coefficients (r^2) being in the $0.60 - 070$ range and the average relative errors in the $30 - 50\%$ range.

As shown in Table 1, 2 and 3, Eq 2 includes solid properties (d_p and ρ_s, grouped within Ar), static bed height (H_0), gas inlet diameter (D_0) and contactor angle. All these factors, except contactor angle, have a great influence on the minimum spouting velocity in fountain confined conical spouted beds without draft tube. Furthermore, Fig 10a shows that the diameter of the confiner is also a very influential factor on the minimum spouting velocity. Accordingly, a new correlation has been proposed based on Eq 2, in which the modulus containing the contactor angle has been removed and two new moduli related to the confiner have been included.

A program written in Matlab and the subroutine *fminsearch* have been used for optimizing the error objective function, defined as the sum of the squared differences between experimental and calculated results. The Equa-

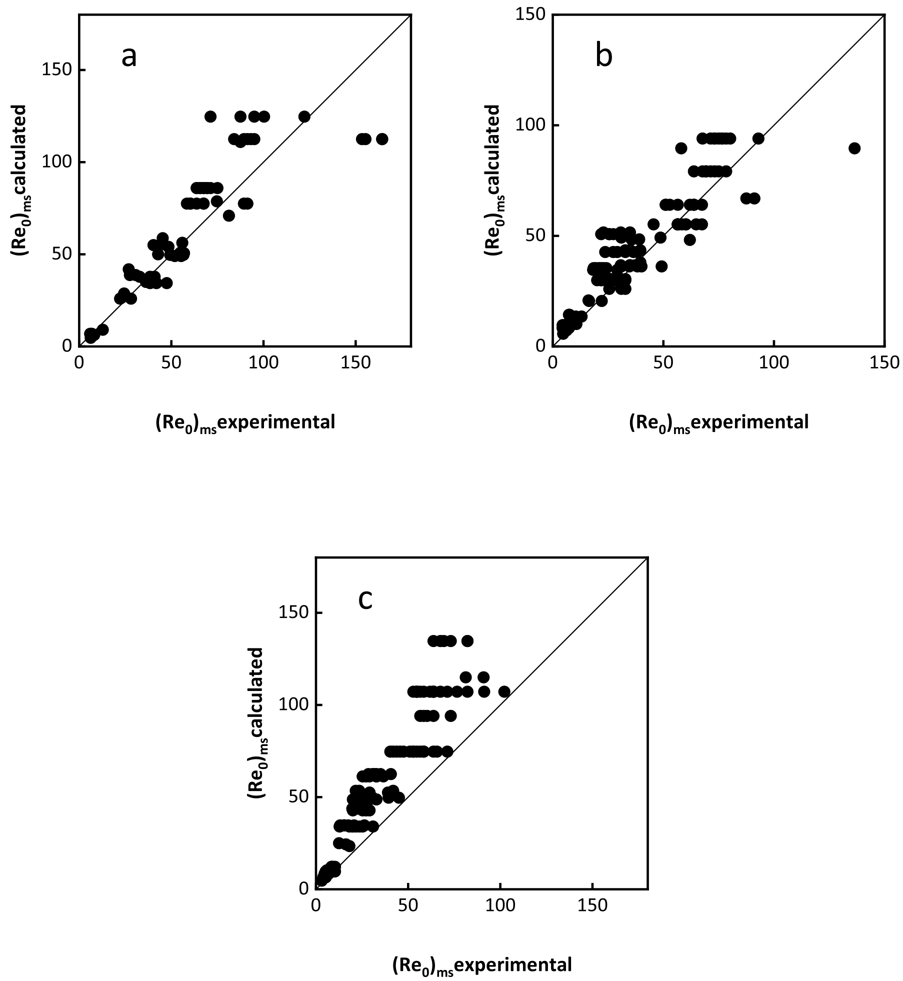


Figure 10: Comparison between the experimental data for systems without draft tube and those predicted using Eq 2 (a), experimental data for systems with open-sided draft tube and those predicted using Eq 5 (b) and experimental data for systems with nonporous draft tube and those predicted using Eq 12 (c).

tion of best fit is as follows:

$$(Re_0)_{ms} = 0.25Ar^{0.5}\left(\frac{H_0}{D_0}\right)^{1.15}\left(\frac{H_0}{D_F}\right)\left(\frac{H_F}{D_F}\right)^{0.04} \tag{14}$$

Fig 11 shows the quality of the fit between the experimental values and those calculated with Eq 14 for the fountain confined conical spouted beds without draft tube (regression coefficient $r^2 = 0.86$ and average relative error of 15%). It is noteworthy that H_0/D_F has been included in Eq 14 to account for the influence of the confiner diameter and H_F/D_F to reduce the stratification of the points.

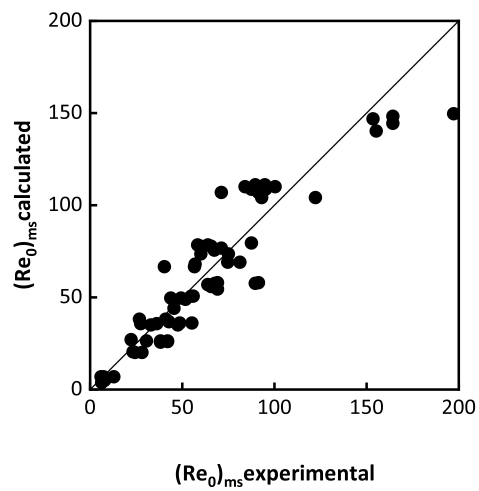


Figure 11: Comparison between the experimental data and those calculated using Eq 14 for the systems without draft tube.

The literature equation of best fit for the open-sided systems, Eq 5, includes the factors of greater significance found in this study, i.e., solid properties, static bed height and gas inlet diameter, which explains the reasonably good fit of this correlation. Furthermore, given that Eq 5 is well known in the literature for its accurate predictions for plain conical spouted beds, its fairly good predictions for open-sided tubes are evidence that these tubes contribute to stabilizing the bed, without significantly affecting hydrodynamics.

Furthermore, Eq 5 also includes the contactor angle ($\tan(\gamma/2)$), but the influence of this factor is not significant when the fountain confiner is used with these tubes. Accordingly, this modulus has been removed and two new ones have been included, i.e., one accounting for the open area of the draft tube (A_0/A_T), which, as shown in Table 7, is significant, and the other one for minimizing the stratification effect (H_F/D_F). The equation of best fit is as follows:

$$(Re_0)_{ms} = 0.43 Ar^{0.5} \left(\frac{H_0}{D_0}\right)^{0.9} \left(\frac{H_F}{D_F}\right)^{0.03} \left(\frac{A_0}{A_T}\right)^{0.2} \tag{15}$$

Fig 12 shows the quality of the fit between the experimental values and those calculated with Eq 15 for the fountained confined conical spouted beds equipped with open-sided draft tubes (regression coefficient $r^2 = 0.94$ and average relative error of 9%).

Finally, amongst the equations in the literature, Eq 12 is the one of best fit for the systems with nonporous draft tube. In this case, all the parameters and moduli in Eq 12 are significant factors in the minimum spouting velocity of the systems studied. Nevertheless, the values provided by this correlation are considerably higher than the experimental ones (Fig 9c). Therefore, a new correlation has been proposed by modifying Eq 12 and including the contactor angle, which was proven significant in these systems. The Equation

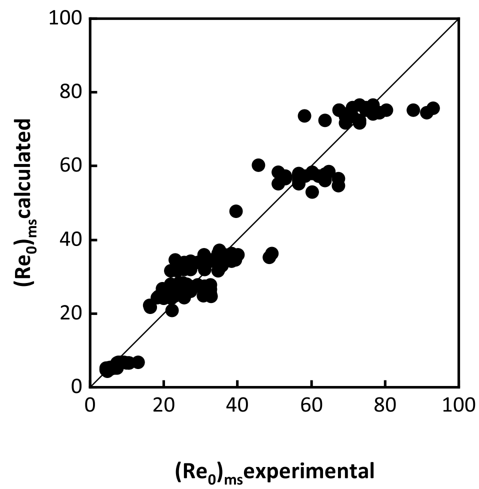


Figure 12: Comparison between the experimental values and those calculated using Eq 15 for the systems with the open-sided draft tube.

of best fit is as follows:

$$(Re_0)_{ms} = 0.23Ar^{0.5}\left(\frac{H_0}{D_0}\right)^{0.8}\left(\frac{L_H}{D_F}\right)^{0.05}\left(tan\frac{\gamma}{2}\right)^{-0.5} \tag{16}$$

Fig 13 shows the quality of the fit between the experimental values and those calculated with Eq 16 for the mentioned systems (regression coefficient $r^2 = 0.92$ and average relative error of 10%).

It is noteworthy that, unlike the previous configurations, the position of the fountain confiner (H_F) is not a significant factor on the minimum spouting velocity, i.e., no stratification effect is shown in Fig 13, and therefore there is no need to introduce it in the correlation.

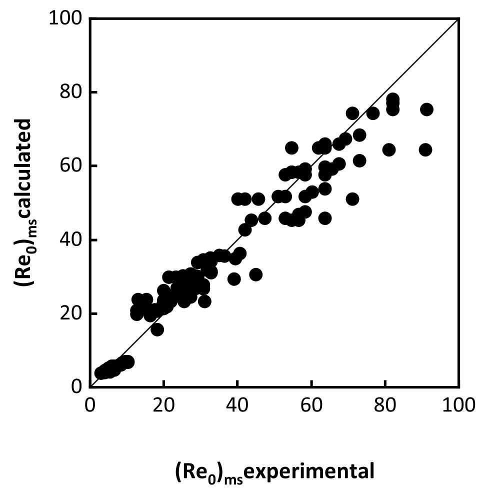


Figure 13: Comparison between the experimental values and those calculated using Eq 16 for the systems equipped with the nonporous draft tube.

4. CONCLUSIONS

The novel fountain confiner device has proven to stabilize beds made up of fine particles (Geldart group A and B) without any draft tube. This device is an essential element for the scaling up of the spouted bed technology at industrial level, since it allows attaining a spouting regime with both coarse and fine particles, without the limitations imposed by the bed inlet and/or the maximum spoutable bed height.

Furthermore, the fountain confiner partially changes the hydrodynamics of the spouted bed, since it modifies the trajectory of the gas in the fountain, enhancing the gas-solid contact in this zone. Therefore, the minimum spouting velocity is influenced by the geometry of the confiner, draft tube and contactor, the type of draft tube and the operating conditions.

A statistical analysis show that the factors of greatest influence on the minimum spouting velocity in all the configurations are solid properties (particle diameter, d_p, and solid density, ρ_s), static bed height (H_0) and gas inlet diameter (D_0). In addition to these factors, other ones affecting specific configurations are as follows: the diameter of the fountain confiner (D_F) in the systems without draft tube, the aperture ratio in the systems with open-sided draft tubes, and height of the entrainment zone (L_H) in those with nonporous draft tubes.

The hydrodynamic and statistical analyses allowed concluding that the minimum spouting velocity increases as solid density, particle diameter, static bed height, aperture ratio in open-sided draft tubes and entrainment height in the nonporous draft tubes are increased, and decreases as gas inlet diameter, contactor angle and the diameter of the fountain confiner are increased.

Furthermore, the results show that draft tubes stabilize any system and significantly reduce the minimum spouting velocity. Although the confiner ensures great stability, the systems without draft tube lead to the highest minimum spouting velocities and the narrowest operational ranges. The systems with nonporous draft tubes lead to the lowest minimum spouting velocities, but those with open-sided draft tubes allow better contact between the two phases and a more vigorous circulation of the solids due to better aeration in the annulus.

The validity of the correlations proposed in the literature for any type of spouted has been checked, but they overestimate the minimum spouting velocity for the systems equipped with fountain confiner. Therefore, different correlations have been proposed for each configuration used (without draft tube, with open-sided draft tube and with nonporous draft tube) based on the results in a wide range of operating conditions. The three proposed correlations contain the Archimedes (Ar) and H_0/D_0 dimensionless moduli. Furthermore, the correlation for the systems without draft tube includes the modulus H_0/D_F, those with open-sided draft tubes A_0/A_T and those with nonporous draft tubes L_H/D_F. Furthermore, in the correlations for systems without draft tube and open-sided draft tubes, the modulus H_F/D_F has been inserted to minimize the stratification effect.

Nomenclature

A_0	Open lateral area of the tube, m^2
A_T	Total lateral area of the tube, m^2
D_0	Gas inlet diameter, m
D_b	Top diameter of the static bed, m
D_C	Column diameter, m
D_F	Diameter of the fountain confiner, m

D_i Contactor base diameter, m

d_p Avarage particle diameter, mm

D_T Draft tube diameter, m

H_0 Static bed height, m

H_C Height of the conical section, m

H_F Distance between the bed surface and the lower end of the device, m

h_{r0} Distance between the top of the draft tube and the bottom of the spouted bed, m

L_H Height of the entrainment zone of the nonporous draft tube, m

L_T Height of the draft tube, m

u_{ms} Minimum spouting velocity, $m\, s^{-1}$

V_0 Volume of the static bed, m^3

V_r Volume of the draft tube, m^3

Re_{0ms} Reynolds number of minimum spouting based on D_0, $\rho\, u_{ms}\, d_p\, \mu^{-1}$

Greek letters

γ Contactor angle, $^\circ$

μ Viscosity of the gas, $kg\, m^{-1}\, s^{-1}$

ϕ Shape factor

ρ Density of the gas, $kg\,m^{-3}$

φ coefficient $\varphi = \left(\frac{h_{r0}-H_0}{L_T}\right)$

5. Acknowledgements

This work has received funding from Spain's Ministry of Economy and Competitiveness (CTQ2016-75535-R (AEI/FEDER, UE)). M. Tellabide thanks Spain's Ministry of Education, Culture and Sport for his Ph.D. grant (FPU14/05814). I. Estiati thanks the University of the Basque Country for her postgraduate grant (ESPDOC18/14).

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