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# Correlation of the Minimum Spouting Velocity for the Design of Open-Sided Draft Tube Conical Spouted Beds for the Treatment of Fine Materials

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# CORRELATION OF THE MINIMUM SPOUTING VELOCITY FOR THE DESIGN OF OPEN-SIDED DRAFT TUBE CONICAL SPOUTED BEDS FOR THE TREATMENT OF FINE MATERIALS

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**ABSTRACT** - The hydrodynamics of conical spouted beds provided with open-sided draft tubes have been studied for the treatment of fine particles. A correlation has been proposed for the calculation of the minimum spouting velocity as a function of dimensionless moduli that take into account the geometric factors of the contactor and the draft tube, particle characteristics and operating conditions.

## INTRODUCTION

The spouted bed regime is an alternative contact method to fixed and fluidized beds. The conventional spouted bed contactor is a cylindrical contactor which has a conical base. This conventional spouted bed has limitations for operation with deep beds and solids that are coarse, sticky and have a wide size distribution.

Different modifications of the original spouted bed (cylindrical with conical base) are proposed in the literature with the aim of improving its performance. These modifications mainly concern the geometry of the contactor and/or the gas inlet to the bed. Given the advanced knowledge of their hydrodynamics and applications, the spouted beds of rectangular section, also with rectangular gas inlet (Freitas and Dogan (1), Dogan et al (2)), the conical spouted beds (Olazar et al (3,4,5), San José et al (6), Povrenovic et al (7), Al-Jabari et al (8), Bi et al (9)), and the spout-fluid beds (Nagarkatti and Chaterjee (10), Sutanto et al (11), Zhao et al (12), Passos and Mujumdar (13), Ye et al (14,15)), which combine the advantages of the spouted bed and of the bubbling fluidized bed, are worth mentioning.

Spouted beds with fully conical geometry combine the features of the 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 (Olazar et al (3,16), San José et al (6)). This versatility in the gas flow-rate allows handling particles of irregular texture, fine particles and those with a wide size distribution and sticky solids, whose treatment is difficult using other gas-solid contact regimes (Olazar et al (5,17,18), Bilbao et al (19)). Moreover, operation can be carried out with short gas residence times (as low as milliseconds) in the dilute spouted bed (Olazar et al (20,21)).

A crucial parameter that limits scaling up of spouted beds is the ratio between the gas inlet diameter and particle diameter. In fact, the inlet diameter should be smaller than 20-30 times the average particle diameter in order to achieve spouting status. The use of a draft tube is the usual solution to this problem. Nevertheless, solid circulation, particle cycle time, gas distribution and so on, are governed by the space between the bottom of the bed and the draft-tube, Moreover, minimum spouting velocity and operation pressure drop depend also on the type of draft tube used.

A study has been carried out in this paper on the hydrodynamics of conical spouted beds with open-sided draft tubes. The main aim is to obtain a correlation for the determination of the minimum spouting velocity when fine particles are used. In a previous paper (Altzibar et al. (22)), correlations have been determined for the design of conical spouted beds provided with non-porous draft tubes, and their performance has been compared with that of an open-sided draft tube. A detailed study is carried out in this paper using open-sided draft tubes of different diameter and aperture ratio in order to establish a reliable correlation for the design of conical spouted beds provided with this type of tube.

## EXPERIMENTAL

The experimental unit used is described in previous papers and allows for operating with contactors of different geometry (Olazar et al (3,4), San José et al (6), Altzibar et al. (22)). The blower supplies a maximum air flow-rate of 300 $m^3$ $h^{-1}$ at a pressure of 1500 mm of water column. The flow-rate is measured by means of two mass flow-meters in the ranges 50-300 $m^3$ $h^{-1}$ and 0-100 $m^3$ $h^{-1}$, both being controlled by computer. The blower supplies a constant flow-rate and the first mass flow-meter controls the air flow that enters the contactor (in the range 50-300 $m^3$ $h^{-1}$) by acting on a motor valve that reroutes the remaining air to the outside. When the flow required is lower than 50 $m^3$ $h^{-1}$, it crosses the first mass flow meter and is regulated by the second one placed in series, which also acts on another motor valve that regulates the desired flow-rate. The accuracy of this control is 0.5% of the measured flow-rate.

The measurement of the bed pressure drop is sent 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 (Alhborn Almeno 2290-8), which is connected to a computer where the data are registered and processed by means of the software AMR-Control. This software also registers and processes the air velocity data, which allows for the acquisition of continuous curves of pressure drop vs. air velocity.

There are three different zones in the conical spouted bed with draft tube, namely, spout, annulus and fountain. Figure 1 shows these different zones.

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: column diameter, $D_c$, 0.36 m; contactor angle, γ, 28, 36 and 45º; height of the conical section, $H_c$, 0.60, 0.45 and 0.36 m; gas inlet diameter, $D_0$, 0.03, 0.04, 0.05 and 0.06 m. The stagnant bed heights used are, $H_0$, 0.14, 0.20, 0.25 and 0.30 m.

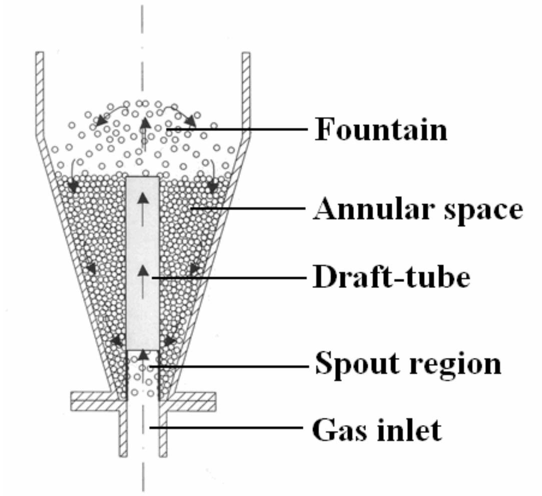


**Figure 1.** Zones in the conical spouted bed with draft tube.

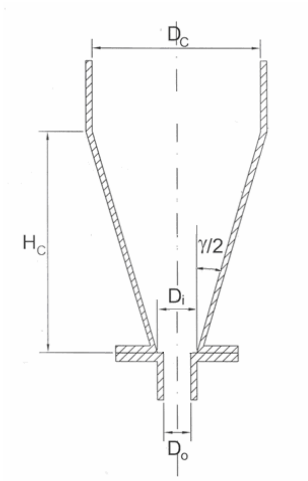


**Figure 2.** Geometric factors of the conical contactors.

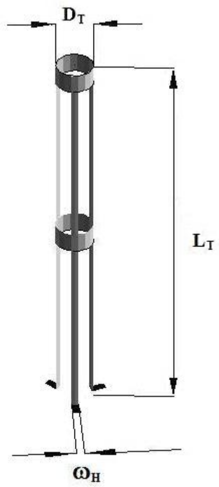


**Figure 3.** Scheme of the open-sided draft tube.

Furthermore, three open-sided draft tubes have been used. The scheme and geometric factors of the open-sided draft tube are shown in Figure 3. These tubes are of different aperture ratios with three slots. The widths of the faces on the open-sided tubes, $\omega_H$, are 0.025, 0.018 and 0.010 m, which mean 57, 65 and 78% of open area (aperture ratio) in the tubes. The diameters of the tubes, $D_T$, are 0.04 and 0.05 m. Moreover, the total length of the open-sided tubes is 0.50 m, which means they stand about 0.20 m above the bed surface. This length has been chosen according to previous experimentation 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 2/3 of the stagnant bed height.

Runs have been carried out by combining all these contactor and draft tubes variables.

The material used is building sand**.** Figure 4 shows the particle size distribution obtained by sieving (ISO 3310).

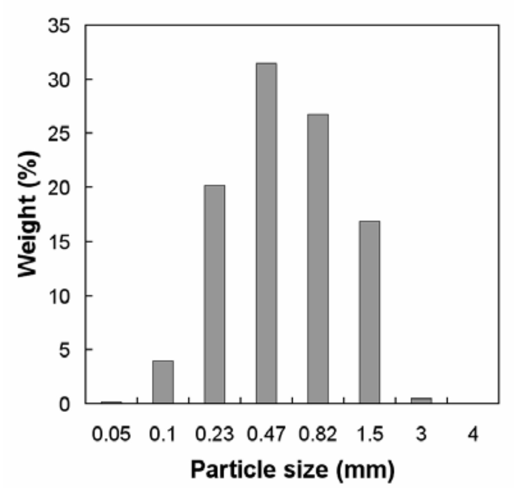


**Figure 4.** Particle size distribution of the sand.

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

$$\overline{d_p} = 1 \Big/ \left[ \sum \left( x_i / d_{p_i} \right) \right] \tag{1}$$

The average size of the sand obtained using eq.(1) is 0.71 mm and the density of the sand is 2358 kg $m^{-3}$.

In addition, different fractions of this material have also been used in order to establish a more reliable correlation. The mean diameters of these fractions are 0.4 and 0.9 mm, respectively.

## RESULTS AND DISCUSSION

In order to illustrate the general characteristics of pressure drop evolution in the bed with air velocity, the results for two different systems are shown in Figure 5 as an example. The operating conditions are the same for the two systems and only the value of the width of the faces ($\omega_H$) is varied.

Figure 5 shows for the two systems that, at first, as air velocity is increased, pressure drop increases to a maximum value. Subsequent to the maximum value, a further increase in air velocity gives way to the fountain and pressure drop decreases. In order to define more precisely the minimum spouting velocity, air velocity is then decreased and the values of operating pressure drop are monitored.

A very pronounced hysteresis is noticed, which is due to the fact that peak pressure drop is much higher than operating pressure drop and, furthermore, a much higher velocity than the minimum one is required to break the bed and open the spout.

Figure 5 shows that the values of minimum spouting velocity, operating pressure drop and peak pressure drop are highly dependent on the system configuration. As observed, the values of the minimum spouting velocity, operating pressure drop and peak pressure drop increase as the width of the faces is decreased (or as aperture ratio is increased).

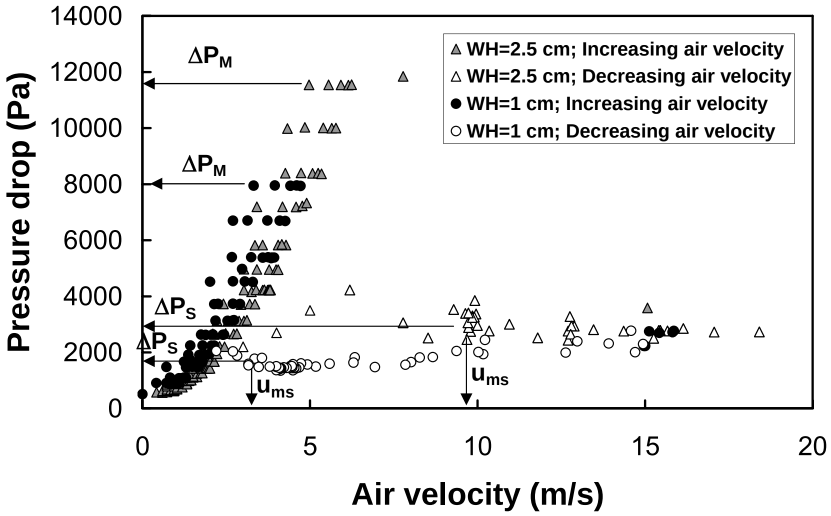


**Figure 5.** Evolution of the bed pressure drop with air velocity for different values of the widths of the faces ($\omega_H$) when non-porous draft tubes are used. Experimental conditions: $\gamma$=36º; $D_0$=0.04 m; $H_0$=0.25 m, $D_T$=0.042 m.

These higher values are due to the higher solid-cross flow from the annulus into the spout along the whole length of the spout. Moreover, it is clearly observed that the solid flow rate increases with the aperture ratio.

From these plots, the minimum spouting velocity has been determined for a wide range of systems.

In order to ascertain the influence of the different factors on the minimum spouting velocity, an analysis of variance (ANOVA) of the data obtained following a design of experiments has been carried out by means of a standard statistical program (SPSS 13.0).

The results show that the parameters of greater influence on the minimum spouting velocity, ordered by their significance, are the contactor angle ($\gamma$), gas inlet diameter ($D_0$) and width of the faces on the open-sided tubes ($\omega_H$), respectively.

The quantitative influence of the variables may be observed by plotting the different responses vs. factors. Figure 6 shows the change in minimum spouting velocity caused by the factors of greater influence (contactor angle, a; gas inlet diameter, b; width of the faces, c).

Figure 6a shows that the minimum spouting velocity goes through a minimum with contactor angle. Thus, it decreases as contactor angle is increased from 28 to 36 degrees and then increases with this factor. Regarding the gas inlet diameter (Figure 6b), an increase in this factor ($D_0$) gives way to a sharp decrease in the minimum spouting velocity. The same happens when the width of the faces is increased (Figure 6c), but in a much less pronounced way.

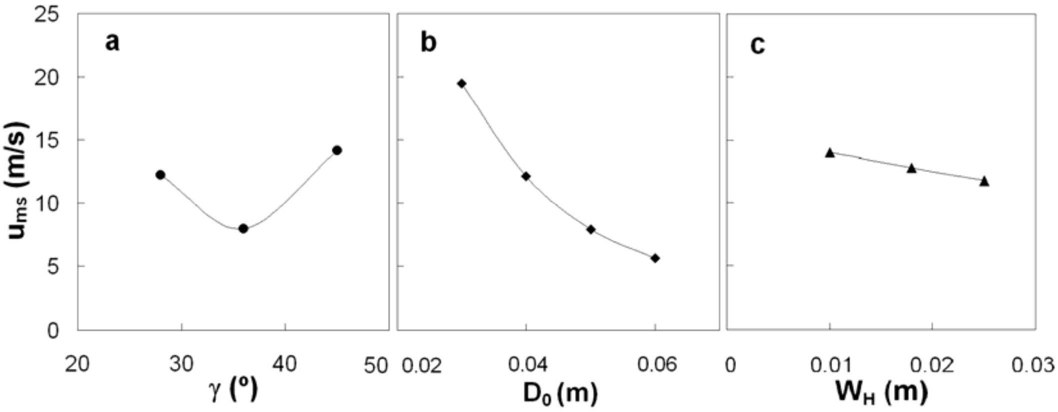


**Figure 6.** Influence of the contactor angle, the gas inlet diameter and the width of the faces on the minimum spouting velocity.

Based on dimensional and statistical analysis, a hydrodynamic correlation for the calculation of the minimum spouting velocity in open-sided draft tube conical spouted beds has been determined as a function of dimensionless moduli that take into account the geometric factors of the contactor and the draft tube, particle characteristics and operating conditions. The hydrodynamic correlation previously obtained by our research group for conical spouted beds without draft tubes (Olazar et al. (3)) has been taken as a starting point, and a dimensionless modulus related to the aperture ratio of open-sided draft tubes has been introduced. The correlation determined is the following:

$$(\mathrm{Re}_0)_{ms} = 0.126 \cdot \mathrm{Ar}^{0.5} \cdot \left(\frac{D_b}{D_0}\right)^{1.68} \cdot \left[\tan\left(\frac{\gamma}{2}\right)\right]^{-0.57} \cdot \left(\frac{A_0}{A_T}\right)^{0.32} \quad (2)$$

This equation is valid for calculating the minimum spouting velocity of stable beds in conical spouted beds with open-sided draft tubes (regression coefficient $r^2$= 0.87, and maximum relative error below 8%) in the range of contactor geometries and operating conditions studied.

## CONCLUSIONS

The hydrodynamic study of conical spouted beds provided with open-sided draft tubes have been carried out operating with fine particles. The evolution of bed pressure drop with air velocity has been studied in a wide range of conditions.

A very pronounced hysteresis, much higher than in conventional conical spouted beds, is obtained in the evolution of pressure drop with air velocity.

Hydrodynamics of conical spouted beds with open-sided draft tube is influenced by the geometric factors of the contactor and draft tube, and operating conditions.

The parameters of greater influence on the minimum spouting velocity are the contactor angle, the gas inlet diameter and the width of the faces.

The value of the minimum spouting velocity increases as the width of the faces of the tube and the gas inlet diameter are decreased.

Based on a wide range of experimental results and taken as a reference the hydrodynamic correlation previously obtained for plain conical spouted beds, a new correlation has been proposed for predicting the minimum spouting velocity in open-sided draft tube conical spouted beds.

## ACKNOWLEDGMENT

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## NOTATION

| | | |
|---|---|---|
| $A_0$ | [m$^2$] | external area of the tube, empty |
| $A_T$ | [m$^2$] | external area of the tube, full |
| Ar | [-] | Archimedes number, $gd_p^3\rho(\rho_s-\rho)\mu^{-2}$ |
| $d_p$ | [mm] | average particle diameter |
| $d_{pi}$ | [mm] | average particle diameter of i fraction |
| $D_c$ | [m] | column diameter |
| $D_o$ | [m] | gas inlet diameter |
| $D_T$ | [m] | draft-tube diameter |
| g | [m s$^{-2}$] | acceleration of gravity |
| $H_c$ | [m] | height of the conical section |
| $H_o$ | [m] | stagnant bed height |
| $L_T$ | [m] | length of the tube |
| $(Re_0)_{ms}$ | [-] | Reynolds number of minimum spouting, per unit area of inlet section, $\rho u_{ms}d_p\mu^{-1}$ |
| $u_{ms}$ | [m s$^{-1}$] | minimum spouting velocity at the inlet orifice |
| $\gamma$ | [deg] | included angle of the cone |
| $\Delta P_S$ | [Pa] | operating pressure drop |
| $\Delta P_M$ | [Pa] | peak pressure drop |
| $\mu$ | [kg m$^{-1}$s$^{-1}$] | viscosity of the gas |
| $\omega_H$ | [m] | width of the face of the tube |
| $\rho$ | [kg m$^{-3}$] | density of the gas |
| $\rho_b$ | [kg m$^{-3}$] | bed density |
| $\rho_s$ | [kg m$^{-3}$] | density of the particle |

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