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HYDRODYNAMIC ASPECTS AND CORRELATIONS FOR THE DESIGN OF DRAFT-TUBE CONICAL SPOUTED BEDS

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ABSTRACT

A study has been carried out on the hydrodynamics of conical spouted beds with draft tube. Correlations have been proposed for calculating minimum spouting velocity, operating pressure drop and peak pressure drop as functions of dimensionless module that take into account geometric factors, particle characteristics and operating conditions.

INTRODUCTION

Different modifications of the original spouted bed (cylindrical with conical base) are proposed in the literature in order to improve its performance. These modifications concern mainly the geometry of the contactor and/or gas inlet to the bed. Given the advanced knowledge of their hydrodynamics and applications, spouted beds of rectangular section, also with rectangular gas inlet (1, 2), conical spouted beds (3, 4, 5, 6, 7, 8, 9), and spout-fluid bed (10, 11, 12, 13, 14, 15, 16), 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 (3, 4, 17). This versatility in the gas flow-rate allows for 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 (6, 18, 19, 20, 21). Moreover, operation can be carried out with short gas residence times (as low as milliseconds) in the dilute spouted bed (22, 23).

Conical spouted beds have a low segregation, which allows for using catalysts in situ in these waste material pyrolysis reactions in order to improve the distribution of products and, consequently, to increase their commercial interest (23, 24). This property is also interesting for handling lime, without segregation in the retention of SO_x in the gasification of coal. Thus, solids (such as calcium oxide or dolomites) may be used in situ for adsorption or as reactants, in order to retain hydrochloric acid in the pyrolysis of PVC.

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 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 are also functions of the type of draft-tube used.

In this paper, a hydrodynamic study of a conical spouted bed provided with draft tube is carried out to verify its potential application in the handling of fine particles.

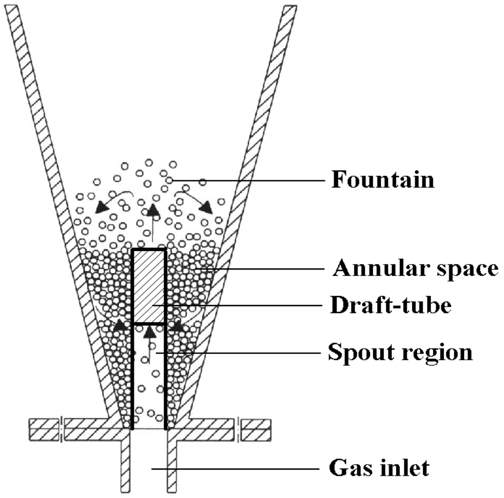
EXPERIMENTAL

The experimental unit used is described in previous papers and allows for operating with contactors of different geometry (3, 4, 5). The blower supplies a maximum air flow-rate of 300 $Nm^3 h^{-1}$ 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 AMR-Control software. 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 and of the draft tubes. The dimensions of these contactors are: 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; gas inlet diameter, D_o, 0.03, 0.04, 0.05 and 0.06 m. The dimensions of draft tubes are: length of the tube, L_T , 0.17, 0.22 and 0.27 m, height of entrainment zone (distance between the gas inlet nozzle and bottom of draft tube), L_H , 0.035, 0.07 and 0.15 m, diameter of the tube, D_T , 0.028, 0.042 and 0.053 m. The stagnant bed heights used are, H_o, 0.14, 0.17, 0.20, 0.22, 0.25 and 0.30 m.



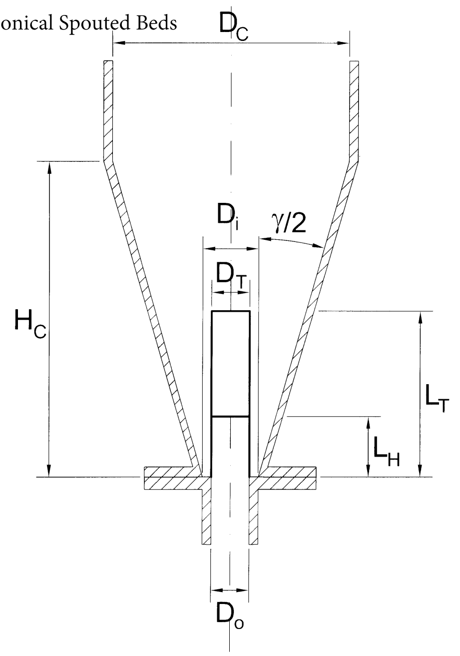


Figure 1. Zones in the conical spouted bed with draft tube.

Figure 2. Geometric factors of the conical contactors with draft tube.

The solid used is building sand. Table 1 shows the particle size distribution of this material.

Table 1. Particle size distribution of the sand.

Particle size (mm)	0.05	0.1	0.23	31.476	0.81	1.5	3	4	TOTAL
Weight (%)	0.172	3.974	20.210	31.476	26.793	16.852	0.489	0.034	100

Based on the values in Table 1, the average particle size (reciprocal mean diameter) has been calculated by means of the expression:

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

The average size of the sand obtained using eq (1) is 0.415 mm and its density is 2358 kg m^{-3}.

The runs have been carried out according to an experimental design in which the following factors have been taken into account: contactor angle, γ; height of entrainment, L_H; length of the tube, L_T; inlet diameter, D_o and stagnant bed height, H_o. The levels of these factors are the values mentioned above for these variables. The responses analysed are: minimum spouting velocity, u_{ms}, operation pressure drop, ΔP_S and peak pressure drop, ΔP_M.

3 RESULTS

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 3 and 4 as an example. It is observed that, at first, as air velocity is increased, pressure drop increases to a maximum value. Subsequent to the maximum value, when air velocity is increased, the fountain is created and pressure drop decreases. Subsequently, air velocity is decreased in order to obtain the values of operating pressure drop and minimum spouting velocity.

A very pronounced hysteresis is noteworthy, 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. Therefore, it is possible to obtain the values of peak pressure drop, operating pressure drop and minimum spouting velocity for each system.

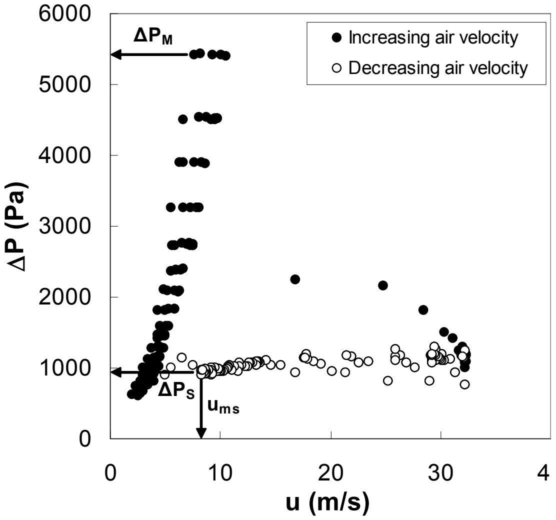


Figure 3. Pressure drop vs. air velocity γ=45°; D_T=0.028 m; L_T=0.17 m; L_H=0.035 m; D_o=0.03 m; H_o=0.17 m.

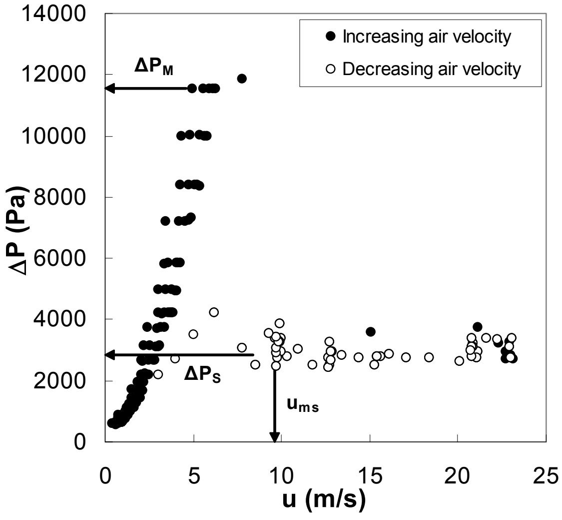


Figure 4. Pressure drop vs. air velocity γ=36°; D_T=0.053 m; L_T=0.27 m; L_H=0.15 m; D_o=0.05 m; H_o=0.27 m

Figures 3 and 4 show that the values of peak pressure drop, operation pressure drop and minimum spouting velocity are highly dependent on the nature of the system. From these plots, minimum spouting velocity, peak pressure drop and operation pressure drop have been determined for a wide range of systems.

The first step for the determination of the three properties is to loosen the bed. This precaution should be applied especially for reproducing peak pressure drop e. The determination of minimum spouting velocity should be carried out by decreasing air velocity from the state of stable spouting to fixed bed. In our poly-methylmethacrylate contactor, visual observation is the best way for determining this property. Nevertheless, when air is decreased from stable spouting, there is a slight increase in pressure immediately below minimum spouting velocity. This procedure is also valid for an accurate estimation of this property.

Spouting pressure drop remains constant for a wide range of air velocities (from minimum spouting velocity to two or three times this velocity). Consequently, this pressure is an average in this range. Again, the values of pressure corresponding to decreasing air velocity are more accurate for the determination of this property.

In order to ascertain the influence of the different values on the hydrodynamic parameters analysed (spouting velocity, peak pressure drop and operation pressure drop), an analysis of variance (ANOVA) has been carried out by means of a standard statistical program (SPSS 12.0). The significance order of the factors analysed is shown in Table 2. As is observed, inlet diameter is the parameter of greater influence on minimum spouting velocity. Moreover, stagnant bed height has no influence on this hydrodynamic parameter (in the range between 0.14 and 0.30 m). Nevertheless, this height is the factor of greater influence on peak pressure drop. The height of the entrainment zone is the variable of greater influence on operation pressure drop.

Table 2. Significance order of factors and interactions (95% confidence interval)

Hydrodynamic parameter	Significance order
u_{ms}	$D_o > D_T > L_H > \gamma \cdot D_T > \gamma$
ΔP_S	$L_H > D_T > H_o > \gamma > D_o$
ΔP_M	$H_o > D_T > \gamma > L_H > D_o > L_H \cdot D_T$

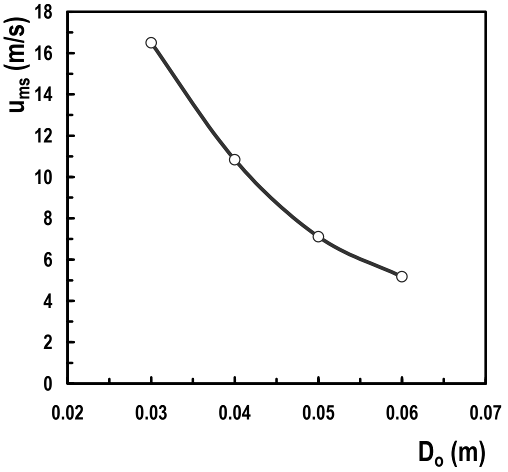
The quantitative influence of the variables may be observed by plotting the different responses vs. the factors. As an example, Figures 5 and Figure 6 show the change in minimum spouting velocity (Figure 5) and in operation pressure drop (Figure 6) caused by the factors of greater influence (inlet diameter and the height of the entrainment zone).

As is observed, an increase in D_o gives way to a decrease in u_{ms} and an increase in L_H gives way to an increase in ΔP_S. Moreover, the greater the levels of these factors, the smaller their influence.

Based on dimensional and statistical analysis, correlations required for the design of conical spouted beds with draft tube have been determined:

- Minimum spouting velocity (regression coefficient, r^2=0.96):

$$(\mathrm{Re}_o)_{ms} = 0.204\,\mathrm{Ar}^{0.475}\left(\frac{H_o}{D_o}\right)^{1.240}\left(\frac{L_H}{D_T}\right)^{0.168}\left(\tan\left(\frac{\gamma}{2}\right)\right)^{-0.135} \qquad (2)$$



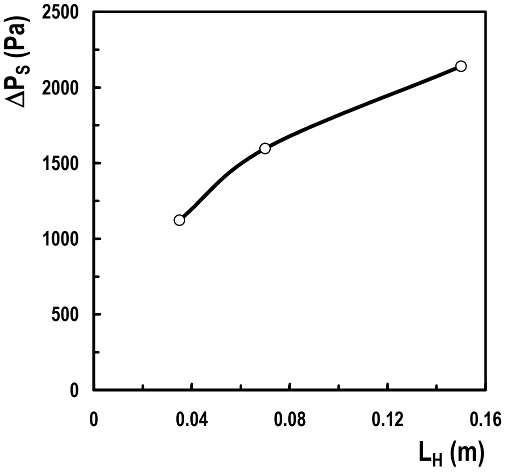


Figure 5. Influence of inlet diameter on minimum spouting velocity.

Figure 6. Influence of the height of the entrainment zone on operation pressure.

- Operation pressure drop (regression coefficient, $r^2=0.92$):

$$\frac{\Delta P_S}{H_o \rho_b g} = 0.212\left(\tan\left(\frac{\gamma}{2}\right)\right)^{-0.316}\left(\frac{H_o}{D_o}\right)^{-0.424}\left(1+\left(\frac{\Delta D}{D_o}\right)\right)^{-0.008}\left(\frac{L_H}{D_T}\right)^{0.393}\left(\mathrm{Re}_o\right)_{ms}^{\;0.170} \quad (3)$$

- Peak pressure drop (regression coefficient, $r^2=0.89$):

$$\frac{\Delta P_M}{\Delta P_S} = 1+97.3\left(\tan\left(\frac{\gamma}{2}\right)\right)^{1.470}\mathrm{Ar}^{-0.258}\left(\frac{L_H}{D_T}\right)^{-0.694}\left(\frac{H_o}{D_o}\right)^{0672} \quad (4)$$

The applicability ranges of these equations are: $4000<\mathrm{Ar}<8000$, $.67<(H_o/D_o)<10$, $28^o<\gamma<45^o$, $0.66<(L_H/D_T)<5.36$.

4 CONCLUSIONS

The hydrodynamics of conical spouted beds with draft tube is influenced by the geometric factors of the contactor and operating conditions.

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

The parameters of greater influence on the bed hydrodynamic variables analysed (minimum spouting velocity, peak pressure drop and operation pressure drop) are inlet diameter, height of the entrainment zone and stagnant bed height, respectively.

5 NOTATION

Ar = Archimedes number, $g d_p^3 \rho(\rho_s-\rho)/\mu^2$
D_o, D_T = gas inlet diameter and draft-tube diameter, m

d_p = particle diameter, mm
g = gravity constant, m s^{-2}
H_o = height of stagnant bed, m
L_T = length of the tube, m
L_H = height of entrainment zone, m
$(Re_o)_{ms}$ = Reynolds number of minimum spouting, $\rho u_{ms} d_p/\mu$
u, u_{ms} = fluid velocity and minimum spouting velocity through inlet orifice, m s^{-1}
γ = included angle of the cone, deg
ρ, ρ_s, ρ_b = density of the gas, particle and bed density, kg m^{-3}
μ = viscosity, kg $m^{-1}s^{-1}$
ΔD = Difference between the inlet diameter and draft-tube diameter, D_o-D_T, m
ΔP_S = operation pressure drop, Pa
ΔP_M = peak pressure drop, Pa

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7 REFERENCES

1. Freitas, L. A. P.; Dogan, O. M.; Lim, C. J.; Grace, J. R.; Luo, B. Hydrodynamics and Stability of Slot-Rectangular Spouted Beds. Part I: Thin Bed. Chem. Eng. Comm, vol. 181, 243-258, 2000.
2. Dogan, O. M.; Freitas, L. A. P.; Lim, C. J.; Grace, J. R.; Luo, B. Hydrodynamics and Stability of Slot-Rectangular Spouted Beds. Part II: Increasing Bed Thickness. Chem. Eng. Comm, vol. 181, 225-242, 2000.
3. Olazar, M.; San José, M. J.; Aguayo, A. T.; Arandes, J. M.; Bilbao, J. Stable Operation Conditions for Gas-Solid Contact Regimes in Conical Spouted Beds. Ind. Eng. Chem. Res., vol. 31, 1784-1791, 1992.
4. San José, M. J.; Olazar, M.; Aguayo, A. T.; Arandes, J. M.; Bilbao, J. Expansion of Spouted Beds in Conical Contactors. Chem. Eng. J., vol. 51, 45-52, 1993.
5. Olazar, M.; San José, M. J.; Aguayo, A. T.; Arandes, J. M.; Bilbao, J. Pressure Drop in Conical Spouted Beds. Chem. Eng. J., vol. 51, 53-60, 1993.
6. Olazar, M.; San José, M. J.; Llamosas, R.; Bilbao, J. Hydrodynamics of Sawdust and Mixtures of Wood Residues in Conical Spouted Beds. Ind. Eng. Chem. Res., vol. 33, 993-1000, 1994.
7. Povrenovic, D. S.; Hadzismajlovic, Dz. E.; Grbavcic, Z. B.; Vucovic, D. V.; Littman, H. Minimum Fluid Flowrate, Pressure Drop and Stability of a Conical Spouted Bed. Can. J. Chem. Eng., vol. 70, 216-222, 1992.
8. Al-Jabari, M.; Van de Ven, T. G. M.; Weber, M. E. Liquid Spouting of Pulp Fibers in a Conical Vessel. Can. J. Chem. Eng., vol. 74, 867-875, 1996.
9. Bi, H. T.; Macchi, A.; Chaouki, J.; Legros, R. Minimum Spouting Velocity of Conical Spouted Beds. Can. J. Chem. Eng., vol. 75, 460-465, 1997.
10. Nagarkatti, A.; Chaterjee, A. Pressure and Flow Characteristics of a Gas Phase Spout-Fluid Bed and the Minimum Spout-Fluid Condition. Can. J. Chem. Eng., vol. 52, 185-195, 1974.
11. Vukovic, D. V.; Hadzismajlovic, Dz. E., Grbavcic, Z. B.; Garic, R. V.; Littman, H. Flow Regimes for Spout-Fluid Beds. Can. J. Chem. Eng., vol. 62, 825-829, 1984.

12. Sutanto, W.; Epstein, N.; Grace, J. R. Hydrodynamics of Spout-Fluid Beds. Powder Technol., vol. 44, 205-212, 1985.
13. Zhao, J.; Lim, C. J.; Grace, J. R. Flow Regimes and Combustion Behaviour in Coal-Burning Spouted and Spout-Fluid Beds. Chem. Eng. Sci., vol. 42, 2865-2875, 1987.
14. Passos, M. L.; Mujumdar, A. S. Spouted and Spout-Fluidized Beds for Grain Drying. Drying Technol., vol. 7, 663-697, 1989.
15. Ye, B.; Lim, C. J.; Grace, J. R. Hydrodynamics of Spouted and Spout-Fluidized Beds at High Temperatures. Can. J. Chem. Eng., vol. 70, 840-847, 1992.
16. Ye, B.; Lim, C. J.; Grace, J. R. Spouted Bed and Spout-Fluid Bed Behaviour in a Column of Diameter 0.91 m. Can. J. Chem. Eng., vol. 70, 848-857, 1992.
17. Olazar, M.; San José, M. J.; Aguado, R.; Gaisán, B.; Bilbao, J. Bed Voidage in Conical Sawdust Beds in the Transition Regime between Spouting and Jet Spouting. Ind. Eng. Chem. Res., vol. 38, 4120-4122, 1999.
18. Olazar, M.; San José, M. J.; Cepeda, E.; Ortiz de Latierro, R.; Bilbao, J. Hydrodynamics of Fine Solids in Conical Spouted Beds. In *Fluidization VIII*; Large, J. F., Laguerie, C., Eds.; Engineering Foundation: New York; pp. 196-201, 1996.
19. Olazar, M.; San José, M. J.; Peñas, F. J.; Aguayo, A. T.; Bilbao, J. Stability and Hydrodynamics of Conical Spouted Beds with Binary Mixtures. Ind. Eng. Chem. Res., vol. 32, 2826-2834, 1993.
20. San José, Olazar, M.; M. J.; Peñas, F. J.; Bilbao, J. Segregation in Conical Spouted Beds with Binary and Tertiary Mixtures of Equidensity Spherical Particles. Ind. Eng. Chem. Res., vol. 33, 1838-1844, 1994.
21. Bilbao, J.; Olazar, M.; Romero, A.; Arandes, J. M. Design and Operation of a Jet Spouted Bed Reactor with Continuous Catalyst Feed in the Benzyl Alcohol Polymerization. Ind. Eng. Chem. Res., vol. 26, 1297-1304, 1987.
22. Bilbao J.; Olazar, M.; Arandes, J. M.; Romero, A Optimization of the Operation in a Reactor with Continuous Catalyst Circulation in the Gaseous Benzyl Alcohol Polymerization. Chem. Eng. Commun., vol. 75, 121-134, 1989.
23. Olazar, M.; Arandes, J. M.; Zabala, G.; Aguayo, A. T.; Bilbao, J. Design and Operation of a Catalytic Polymerization Reactor in a Dilute Spouted Bed Regime. Ind. Eng. Chem. Res., vol. 36, 1637-1643, 1997.
24. Olazar, M.; Aguado, R.; Barona, A.; Bilbao, J. Pyrolysis of Sawdust in a Conical Spouted Bed Reactor with a HZSM-5 Catalyst. AIChE J., vol. 46, 1025-1033, 2000.