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STUDY OF THE MINIMUM SPOUTING VELOCITY IN A DRAFT TUBE CONICAL SPOUTED BED

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STUDY OF THE MINIMUM SPOUTING VELOCITY IN A DRAFT-TUBE CONICAL SPOUTED BED

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Abstract. A study has been carried out on the hydrodynamics of conical spouted beds with a non-porous draft-tube. A hydrodynamic correlation has been proposed for calculating the minimum spouting velocity as a function of dimensionless moduli that take into account geometric factors, particle characteristics and operating conditions. A statistical analysis of the data obtained following a design of experiments shows that the inlet diameter, particle diameter and the height of the entrainment zone are the parameter of greater influence on the minimum spouting velocity.

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, the hydrodynamic parameters (minimum spouting velocity and operation pressure drop) are also functions of the type of draft-tube used.

In this paper, coarse particles have been used to carry out the hydrodynamic study of conical spouted beds. Despite coarse particles performed in a stable operation without using draft-tube, the hydrodynamic study has been carried out using non-porous draft-tubes in order to achieve a greater stability of the bed and lower values of the minimum spouting velocity and operation pressure drop.

EXPERIMENTAL

The experimental unit used is described in previous papers and allows for operating with contactors of different geometry (3, 4, 5, 25). 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. Three inlet diameters , D_0, have been used with each contactor: 0.03, 0.04 and 0.05 m. The dimensions of non-porous 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_0, 0.11, 0.14, 0.20, 0.25 and 0.30 m.

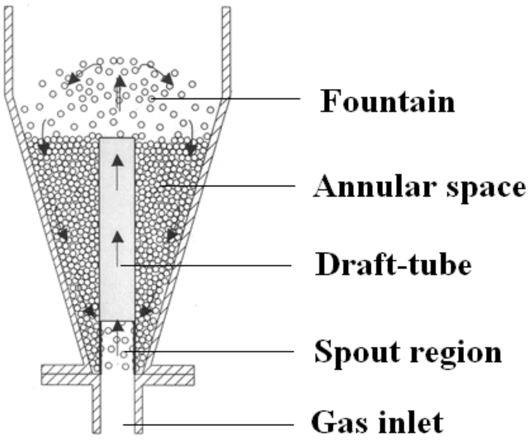

Figure 1. Zones in the conical spouted bed with draft-tube.

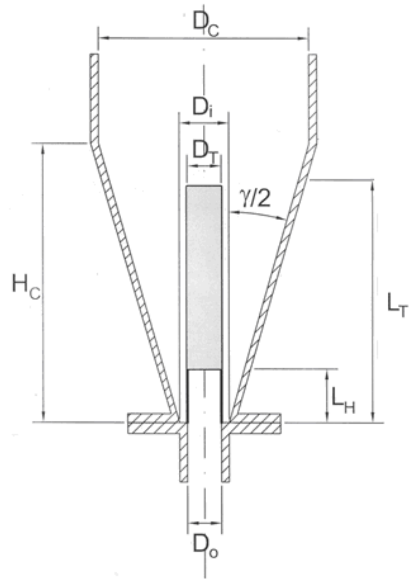

Figure 2. Geometric factors of the conical contactors with open-sided draft-tube.

The materials used for operation have been glass beads of different size (2 and 4 mm of diameter) and its density is 2358 kg m^{-3}.

Runs have been carried out by combining all these contactor variables, draft-tubes and glass beads of different size.

RESULTS

In order to illustrate the general characteristics of pressure drop evolution in the bed with air velocity from fixed bed to spouted bed, the results for two different systems are shown in Figure 3 and 4 as an example. From each system analysed, the performance of the spouted bed regime and the minimum spouting velocity (u_{ms}) may be determined.

Figure 3 and 4 show 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 to a value that remains constant for a wide range of air velocities.

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.

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.

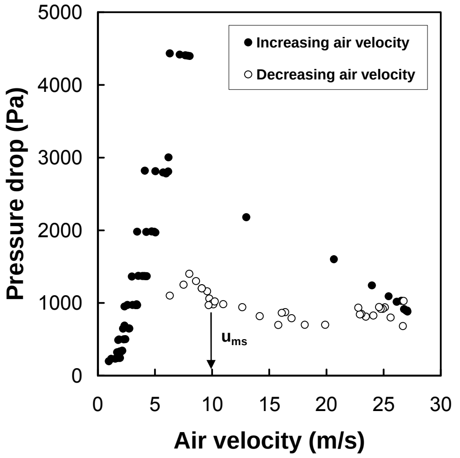

Figure 3. Pressure drop vs. air velocity d_p=0.002 m ; γ=28º; D_T=0.042 m; L_T=0.17 m; L_H=0.07 m; D_0=0.04 m; H_0=0.20 m.

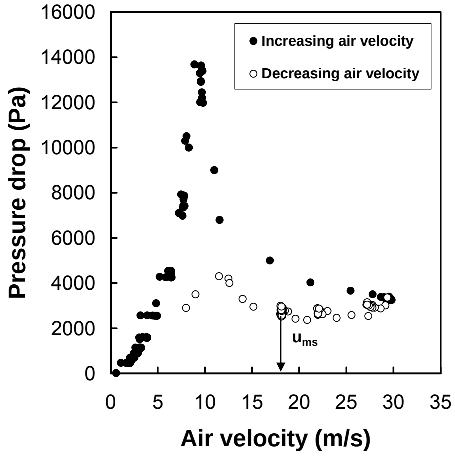

Figure 4. Pressure drop vs. air velocity d_p=0.004 m; γ=36º; D_T=0.053 m; L_T=0.17 m; L_H=0.15 m; D_0=0.04 m; H_0=0.20m

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

The experimental runs have been carried out following a design of experiments. Table 1 shows the factors and their levels used in all runs when non-porous draft-tubes have been used.

Runs have been carried out by combining the levels of all factors. For each system analyzed, the value of the minimum spouting velocity has been obtained.

In order to ascertain the influence of the different variables on the minimum spouting velocity, 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 (95% confidence interval) is as follows: $D_0 > d_p > L_H > H_0 > L_H x d_p > D_0 x H_0$.

Table 1. Factors and their levels.

FACTORS	LEVELS				
γ cone angle (degrees)	28	36	45		
D_0 inlet diameter (m)	0.03	0.04	0.05		
H_0 bed height (m)	0.11	0.14	0.20	0.25	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		

As is observed, inlet diameter is the parameter of greater influence. Moreover, particle diameter, height of the entrainment zone and stagnant bed height have also a great influence on this hydrodynamic parameter

The quantitative influence of the variables may be observed by plotting the minimum spouting velocity vs. the factors. As an example, Figures 5, 6, 7 and 8 show the change in minimum spouting velocity caused by a change in the level of these factors (inlet diameter, particle diameter, height of entrainment zone and stagnant bed height).

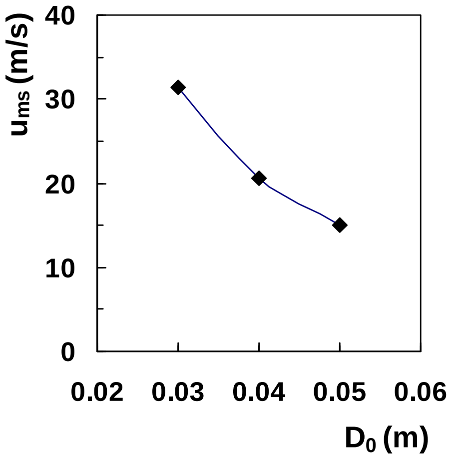

Figure 5. Influence of inlet diameter on the minimum spouting velocity.

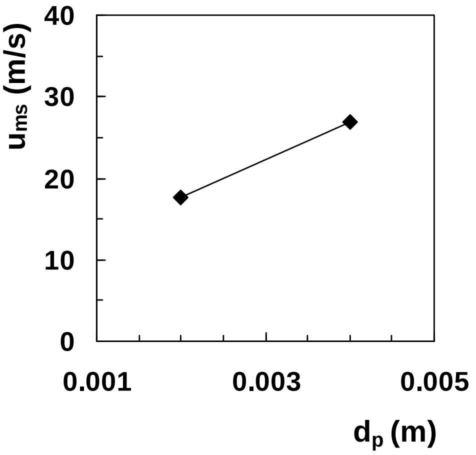

Figure 6. Influence of particle diameter on the minimum spouting velocity.

As is observed, a decrease in D_0, and an increase in d_p, L_H and in H_0 gives way to an increase in u_{ms}.

Based on dimensional and statistical analysis, a correlation has been proposed for the calculation of the minimum spouting velocity in conical spouted beds with draft-tube:

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

$$\left(\mathrm{Re}_0\right)_{ms} = 0.30\ Ar^{0.5}\left(\frac{H_0}{D_0}\right)^{1.2}\left(\frac{L_H}{D_0}\right)^{0.3} \tag{1}$$

The applicability ranges of these equations are: $4000<Ar<8000$, $2.2<(H_0/D_0)<10$, $0.7<(L_H/D_0)<5$.

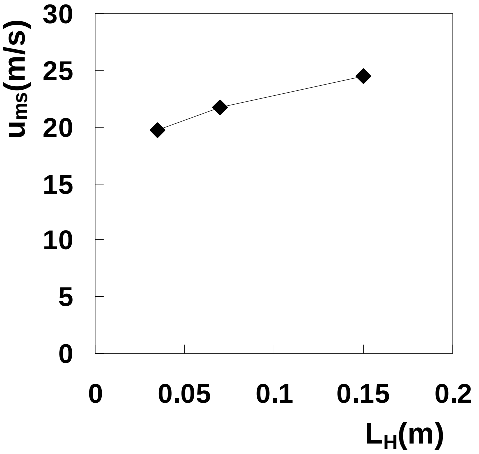

Figure 7. Influence of the height of entrainment zone on the minimum spouting velocity.

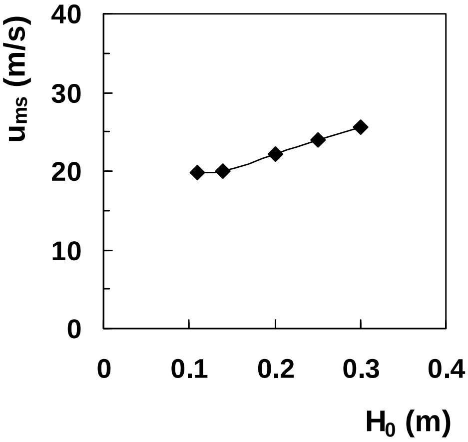

Figure 8. Influence of the height of stagnant bed on the minimum spouting velocity.

Regarding the performance of the spouted bed regime with non-porous draft-tube, the system is very stable, but the solid circulation rate (turbulence) is lower than in conical spouted beds without draft-tube. In previous papers (25, 26) a comparison has been carried out on the performance of with different draft-tubes (open-sided and non-porous draft-tubes). Although the air flowrate and operating pressure drop required with open-sided draft-tubes are higher than with non-porous draft-tubes, the solid circulation rate is higher with the former.

CONCLUSIONS

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 minimum spouting velocity are inlet diameter, particle diameter, height of the entrainment zone and stagnant bed height.

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NOTATION

Ar = Archimedes number, $gd_p^3\rho(\rho_s-\rho)/\mu^2$
D_0, D_T = gas inlet diameter and draft-tube diameter, m
d_p = particle diameter, mm
g = gravity constant, m s^{-2}
H_0 = 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 $m^{-1}s^{-1}$

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