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Particle Cycle Times in Draft Tube Conical Spouted Beds

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A hydrodynamic study of conical spouted beds equipped with draft tube has been carried out for glass beads. Runs have been carried out in conical spouted beds of different geometry according to a factorial design of experiments. The purpose of this design has been to study the effect on particle cycle times and solid circulation rate of the following: the insertion of a draft tube, draft tube configuration, and the different factors of the contactor and particle system. Particle cycle times (average, maximum, and minimum) have been measured in draft tube conical spouted beds for different geometric factors of the contactor (angle and gas inlet diameter), draft tubes (diameter, height of the entrainment zone, and width of the faces) and under different operating conditions. It can be concluded that the hydrodynamics of conical spouted beds with draft tube is influenced by the geometric factors of the draft tube, contactor and operating conditions.

1. Introduction

The outstanding advantage of the spouted bed technique in drying, coating, etc. lies in its ability to treat granular products that are too coarse for fluidized beds (Ando et al., 2002). Thus, the spouted bed regime is an alternative contact method to fixed and fluidized beds that is especially interesting when this regimes have limitations imposed either by the physical characteristics of the solid or by the gas residence time (Olazar et al., 1992). Different modifications of the original spouted bed (cylindrical with conical base) are proposed in the literature with the aim of improving its performance (Epstein and Grace, 2011).

Due to their excellent performance, conical spouted beds are widely used in several applications, such as drying (Berghel et al., 2008), coating (da Rosa and Rocha, 2010), gasification (Salam and Bhattacharya, 2006), combustion (Konduri and Altwicker, 1999) and pyrolysis (López et al., 2010).

Spouted beds with fully conical geometry combine the features of cylindrical spouted beds with those inherent to their geometry, such as stable operation in a wide range of gas flowrates (Olazar et al., 1999). This versatility in the gas flowrate allows handling particles of irregular texture, fine and light particles, and those with a wide size distribution, as well as sticky solids, whose treatment is difficult using other gas-solid contact regimes (Olazar et al., 2004).

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 no more than 20-30 times larger than 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 rate, particle cycle time, gas distribution, minimum spouting velocity, and operating pressure drop are influenced by the type of draft tube used.

The use of a draft tube causes changes in the hydrodynamics and solid circulation rate of spouted beds. The performance of the lower conical section of the contactor is different when the draft tube is used, and largely depends on the bed geometry, draft tube diameter, length of the entrainment zone, and operating conditions (Nagashima et al., 2009).

Different draft tube configurations are reported in the literature: conventional nonporous draft tubes, porous draft tubes, and open-sided draft tubes. The latter have been developed by our research group (Olazar et al., 2012) and they are especially suitable for vigorous contact. Recently, Nagashima et al. (2009) have developed porous and nonporous draft tubes with a conical-cylindrical geometry.

Previous works (Altzibar et al., 2008) show that open-sided draft tubes perform much better than conventional non-porous tubes for drying, and the solid circulation rate (turbulence) is much higher with open-sided draft tubes, which is due to the solid cross-flow from the annulus into the spout at any level in the bed, although their operating pressure drop and air flowrate required are higher. Furthermore, open-

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sided draft tubes allow for an optimum gas distribution in the bed, and consequently, open-sided draft tubes are the best option for drying processes (Olazar et al., 2012).
Particle cycle time is defined as the time that the particle takes to travel from the top of the annulus downward and back again to its starting point. Since the proportion of time spent by a particle in the spout is insignificant compared with that spent in the annulus, particle cycle times can be deduced from solid flow patterns in the annulus (Epstein and Grace, 2011).
Knowledge of particle cycle time is very useful to ascertain the bases of the spouted bed technique. Furthermore, information on this parameter and particle trajectories is essential for spouted bed applications, given that the average cycle time regulates energy and mass transfer, and influences chemical reactions (Makibar et al., 2011).
There are three different zones in the conical spouted bed with conventional draft tube, the central core is termed a spout, the surrounding annular region is termed the annulus, and the solids above the bed surface entrained by the spout and then raining down on the annulus are designated as the fountain. Figure 1a shows these different zones.
The main aim of this work is to gather information about particle cycle times in conical spouted beds provided with different internal devices and without devices. Based on this information, the factors of greater influence on particle cycle time and solid circulation rate are determined and their effect is quantified.

2. Experimental

Runs have been carried out in a unit described in previous papers (Altzibar et al., 2009). The unit allows operating with contactors of different geometry. These contactors are made of polymethyl methacrylate and have a conical geometry. Figure 1b shows the geometric factors of these contactors. The column diameter and the base diameter are the same for the different angles used, D_c, 0.36 m and D_i, 0.068 m, respectively. The height of the conical section, H_c, is 0.60, 0.45 and 0.36 m for the angles (γ) of 28, 36 and 45º, respectively. The gas inlet diameters used are, D_0, 0.04 and 0.05 m.

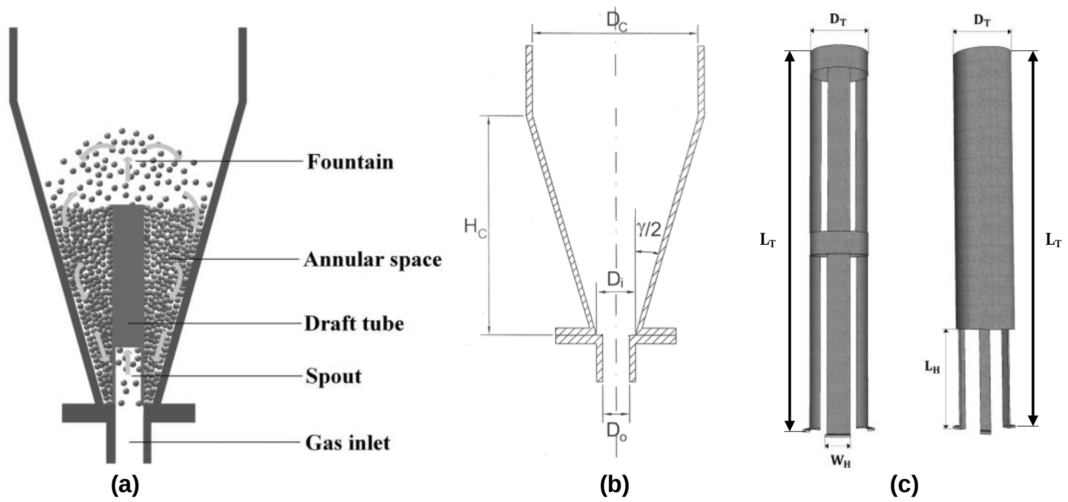

Figure 1: a) Zones in the conical spouted bed with conventional non-porous draft tube, b) geometric factors of conical spouted bed contactors and c) open-sided draft tube configuration and non-porous draft tube configuration.

Two types of draft tubes have been used: open-sided draft tubes and non-porous draft tubes. Figure 1c presents a scheme of both types of internal devices. The dimensions of the open-sided draft tube are as follows: length of the tube L_T= 0.5 m; width of the faces W_H= 0.01, 0.018 and 0.025 m (which mean aperture ratios of 78, 57 and 42% respectively); diameter of the tube D_T= 0.04 and 0.05 m. The dimensions of the non-porous draf tube are: length of the tube L_T= 0.27 m; height of entrainment zone (distance between the gas inlet nozzle and bottom of the draft tube) L_H= 0.07 and 0.15 m; diameter of the tube D_T= 0.04 and 0.05 m.
The material used for operation is glass beads of different size, which belong to group D of Geldart classification. The density of the glass beads is 2,420 kg m^{-3} and the particle diameter used are 0.004 and 0.006 m. The stagnant bed heights (H_0) used are 0.17 and 0.27 m.

3. Results

3.1 Design of experiment

In order to study the effect of the insertion of a draft tube, draft tube configuration, and the different factors of the contactor and particle system on particle cycle times and solid circulation rate, runs have been carried out by combining all these factors corresponding to the contactors (γ, D_0), draft tubes (W_H, L_H), materials (d_p) and operating conditions (H_0) according to a experimental design. To avoid instability problems, the runs with draft tube have been performed with the gas inlet diameter equal to that of the draft tube.

Furthermore, runs have been carried out without using a draft tube in order to ascertain the hydrodynamic differences between draft tube conical spouted beds and plain conical spouted beds.

Approximately 65 experimental runs have been carried using nonporous draft tubes, 60 with open-sided tubes and 12 without a draft tube.

In each experimental run, solid cycle times have been measured by monitoring a marked (painted) particle of the same material, with visual observation in the fountain through the transparent wall. Thus, the painted particle is deposited on the surface of the annulus zone and the time the particle takes to reappear in the fountain, i.e., to complete a cycle, is measured successively. After a significant number of measurements have been made, an average cycle time is determined.

The minimum cycle time is determined as the lowest value of the cycle times measured, and the maximum cycle time is measured by dropping the particle onto the bed adjacent to the wall and measuring the time required to reach the bottom of the contactor following the wall (Becker, 1961). All these measurements have been made operating under stable spouted bed regime ($u = 1.15 x u_{ms}$).

Particle cycle times (minimum, maximum and average) have been determined in each of the runs carried out according to the design of the experiments. Thus, at least thirty cycle times have been measured in each system in order to determine the average cycle time. To visualize the distribution of the random cycle times measured, histograms are plotted for each one and the average cycle time is obtained. Figure 2 shows the distribution of cycle times for a given system provided with a non-porous draft tube.

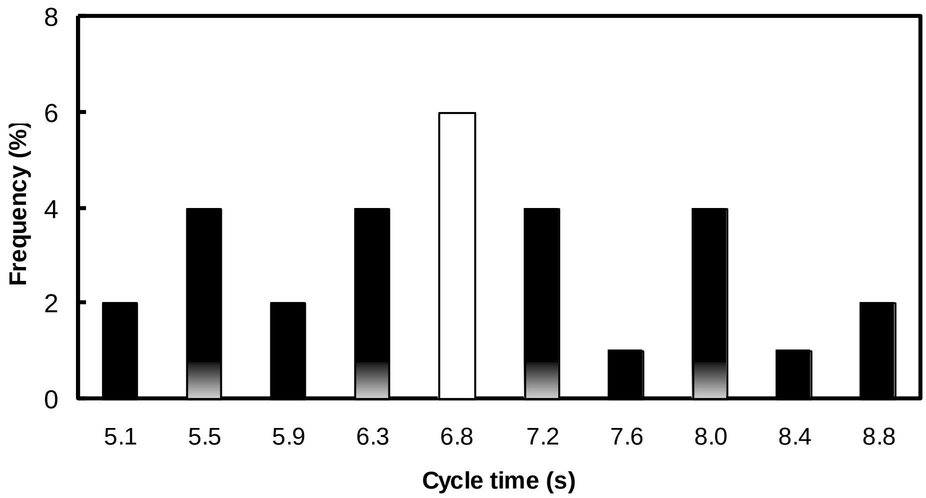

Figure 2: Cycle time distribution for a given system. Experimental conditions: γ, 28º; L_H, 0.15 m; D_T, 0.05 m; D_0, 0.04 m; H_0, 0.27 m; d_p, 0.006 m; material, glass beads.

Once the average cycle time ($\bar{t_c}$) has been obtained and, given that the bed mass in each experiment is known, the solid circulation rate is calculated as the ratio of the bed mass and the average solid cycle time. Accordingly, the solid circulation rate (W_s) is defined as the solid mass that is ascending through the spout and descending through the annulus per time unit. The knowledge of this parameter is essential to determine the amount of solids that can be treated, and consequently, the volume of the contactor.

3.2 Experimental results

Figures 3 and 4 shows typical trends observed in the experimental runs carried out, for given systems as an example.

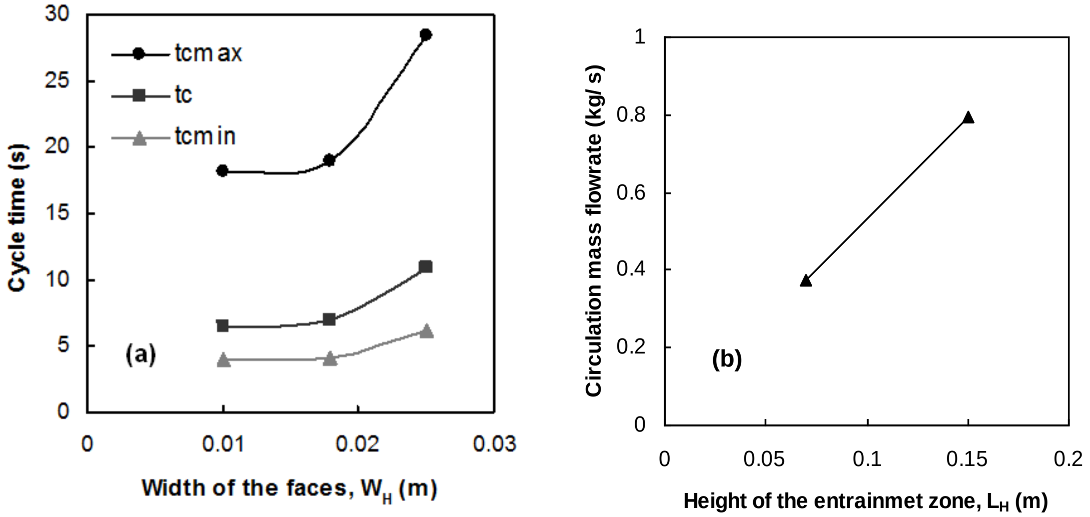

Figure 3: a) Influence of the width of the faces of open-sided tubes on the average, maximum, and minimum cycle times. Experimental conditions: γ, 36º; D_T, 0.04 m; D_0, 0.05 m; H_0, 0.27 m; d_p, 0.006 m; material, glass beads, b) Influence of the height of the entrainment zone of non-porous tubes on the solid circulation mass flowrate. Experimental conditions: γ, 28º; D_T, 0.04 m; D_0, 0.04 m; H_0, 0.17 m; d_p, 0.004 m; material, glass beads.

Figure 3a shows that an increase in the width of the faces (aperture ratio of the tube is decreased) increases the three particle cycle times, especially the maximum cycle time. This trend is explained by the lower aperture ratio when the width of the faces is increased, which causes fewer particles to enter the spout through the open side of the tube and, therefore, the average particle trajectory is longer and solid circulation is lower.

Figure 3b shows the effect of the height of the entrainment zone on the solid circulation rate. The height of the entrainment zone is the parameter that controls the solid-cross flow from the annulus into the spout in the entrainment zone, and so the solid circulation rate (Altzibar et al., 2009). As is observed in Figure 3, an increase in the height of the entrainment zone causes an increase in the solid circulation rate. Similar conclusions were obtained by Luo et al., 2004. This is explained by a larger fraction of particles entering the spout when the entrainment zone is higher, which gives way to higher solid circulation rate (Makibar et al., 2012). Furthermore, the air flowrate required for stable spouting is also higher as the entrainment zone is longer. Consequently, more air diverts from the spout into the annulus at the bottom of the bed, thereby contributing to a more vigorous solid circulation in the whole bed.

To gain an overall view of the effect caused by the use or not of different draft tubes, Figure 4a shows the average values of the cycle times for the three types of systems studied under the whole range of conditions studied. As shown in Figure 4a, the experimental systems with the lower average cycle time are those without a draft tube (Zhao et al., 2006). Open-sided tubes have intermediate average cycle times, and non-porous ones are the systems with the highest values. The decrease in cycle time is closely related to the vigorousness of the system, which is higher in systems without a tube, given that they require a much higher air flowrate for spouting. Nevertheless, instability is greater without a tube, and this is a serious drawback for scaling up. An open-sided draft tube stabilizes the bed, although the cycle time is slightly higher. Non-porous tubes give way to the highest values of average cycle time due to the poor vigorousness of the system caused by the small amount of solid cross-flow from the annulus into the spout (only in the entrainment zone), and the small air fraction diverting into the annulus, given that most of the air fraction rises through the spout (Wang et al., 2010). Consequently, the air flowrate required for spouting is much smaller, the amount of solids circulating in the contactor is lower, and the gas-solid contact is poorer, but this system is more stable than any other one (Altzibar et al., 2009). Furthermore, the values of the average cycle time for open-sided tubes are closer to those without a tube than to those with non-porous tubes. This is explained by the rather high aperture ratios of the open-sided tubes used (42, 57, and 78%). In fact, the higher value of aperture ratio used provides cycle times similar to those without a tube, with the advantage of greater stability.

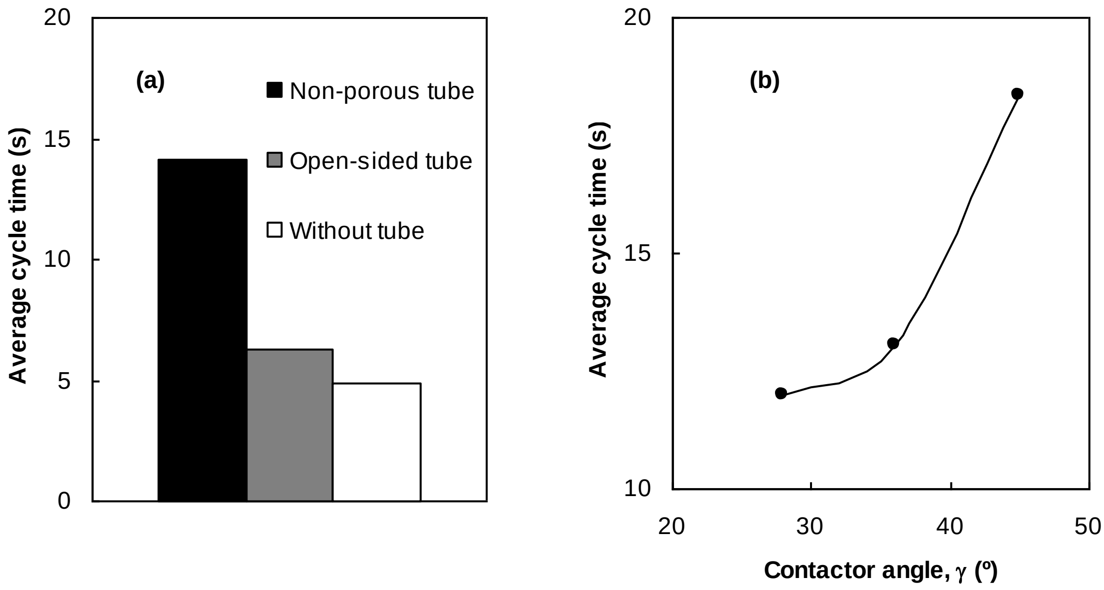

Figure 4: a) Overall average cycle times for the three systems studied, b) Influence of contactor angle of non-porous tubes on the average cycle time. Experimental conditions: L_H, 0.07 m; D_T, 0.05 m; D_0, 0.05 m; H_0, 0.27 m; d_p, 0.006 m; material, glass beads

As shown in Figure 4b, as the angle of the contactor is greater, the average cycle time is longer. This is explained by the higher amount of solid in the bed for the same stagnant bed height (which is 70% higher in the 45º contactor than in the 28º contactor) and by the longer particle trajectories (those descending near the wall) in the contactor with the higher angle. Therefore, operation with low contactor angles has a positive effect on solid circulation rate. Thus, higher contactor wall slope enhances solid circulation due to the increase in particle descending velocity in the annulus.

4. Conclusions

A hydrodynamic study of conical spouted beds equipped with different types of draft tube (open-sided and non-porous tubes) and without tubes has been carried out for glass beads. Particle cycle times (average, maximum, and minimum) have been measured in draft tube conical spouted beds for different geometric factors of the contactor (angle and gas inlet diameter), draft tubes (diameter, height of the entrainment zone, and width of the faces) and under different operating conditions.

The results obtained based on an experimental design show that particle cycle times (average, maximum, and minimum) and solid circulation rates are influenced by both the type of draft tube used and its geometry.

Regarding geometric factor of the contactor, as the angle of the contactor is greater, the average cycle time is longer. About draft tubes factors, an increase in the width of the faces (aperture ratio of the tube is decreased) increases the three particle cycle times and when the height of the entrainment zone is higher the solid circulation rate is higher.

The experimental systems concluded that non-porous ones are the systems with the highest average cycle times, then, open-sided tubes have intermediate values and the lower average cycle time are those without a draft tube.

The desired cycle times of the particles can be obtained for the conical spouted bed by choosing the suitable configuration of both the bed and the draft tube.

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