Solid Cycle Times of Chickpeas in Draft Tube Conical Spouted Beds

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The growing demand for alternative energy sources has furthered the interest on biomass over the last decades. Thus, a hydrodinamic study of conical spouted beds equipped with draft tube has been carried out for biomass, specifically, chickpeas. Runs have been carried out in conical spouted beds of different geometry following a design of experiments. Solid cycle times (average, maximum and minimum) and circulation mass flowrates 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 show that solid cycle times and circulation mass flowrates are highly dependent on the type of draft tube and contactor angle.

1. Introduction

The shortage of oil has increased the interest in alternative sources. Biomass represents one of the main renewable energy resources available.

The spouted bed regime is an alternative contact method that is especially interesting when conventional regimes have limitations imposed by the physical characteristics of the solid and by gas residence time (Olazar et al., 1992). Spouted beds are gas-particle contactors in which the gas is introduced through a single nozzle at the center of a conical or flat base. Spouted beds provide a means of good mixing and circulation for particles of relatively large size and wide size distribution. The spouted bed technique has been applied in many processes, such as drying (Altzibar et al., 2008), coating (da Rosa and Rocha, 2010) and pyrolysis (López et al., 2010).

Olazar et al. (1992) observed that the ratio of the gas inlet diameter to the particle diameter is the parameter restricting the scaling up of conical spouted beds. In fact, the inlet diameter should be smaller than 20-30 times the average particle diameter in order to avoid a slugging regime and achieve spouting status. Draft tubes are used to achieve stability out of this range, but they change the hydrodynamics and solid circulation rate of spouted beds. The lower conical section of the contactor performs differently when the draft tube is used and depends largely on the bed geometry, draft tube diameter, length of the entrainment zone, and operating conditions (Nagashima et al., 2009). Consequently, the draft tube is an interesting option for optimizing the hydrodynamic performance of spouted beds, especially when scaling up, given that is simple, of low cost, and greatly increases flexibility. 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 (Altzibar et al., 2009).

Apart from scaling-up, the insertion of an internal device is aimed at fulfilling other requirements. In the case of gas combustion, it improves combustor flexibility in terms of residence time control and bed stability (Konduri et al., 1995). For a biomass (rice husk) combustor, it improves the circulation and mixing and prevents stratification (Taib et al., 2001). The internal device allows attaining a stricter control of the gas residence time distribution. In the case of fine particle drying, the objective is to improve the contact between the gas and the solid (Altzibar et al., 2008).

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).

The few papers dealing with the solid circulation rate in draft tube spouted beds report the influence on particle circulation of operating and geometric variables, such as draft tube diameter, particle size, height of entrainment zone, contactor angle and gas velocity (Makibar et al., 2012).

Figure 1a shows a scheme of the conical spouted bed equipped with a conventional non-porous draft tube, in which three different regions are clearly differentiated, namely, spout, annulus, and fountain, each with its own specific flow behaviour. The spout is a central region where particles move upwards, as in a transported bed; the annulus is the surrounding area where particles move downwards, as in a moving bed (annulus); and, finally, there is a fountain region where particles complete their cycle. In this work, solid cycle times of chickpeas have been measured in draft tube conical spouted beds.

2. Experimental

The experimental unit used is described in previous papers (Altzibar et al., 2008). The study has been carried out using 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 45 °, respectively. The gas inlet diameters used are, D_0, 0.04 and 0.05 m.

Two different types of draft tubes have been used in the study, namely non-porous and open-sided draft tubes. Figure 1c presents a schematic representation of both types of internal devices.
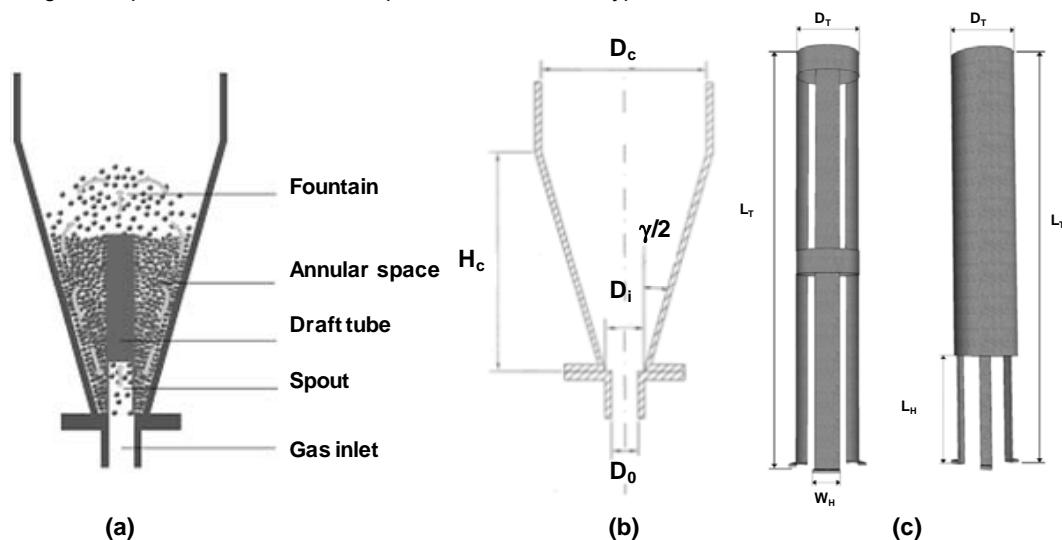

Figure 1: a) Zones in the conical spouted bed with conventional non-porous draft tube, b) geometric factors of conical spouted bed contactors and c) open-sided draft tube configuration and non-porous draft tube configuration

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). The dimensions of the non-porous draf tube are: length of the tube L_T= 0.17 and 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. The diameter of the tube used in both types of draft tube has been D_T= 0.04 and 0.05 m.

The material used in the study is chickpeas of 0.01 m of particle diameter, which density has been measured experimentally and has a value of 1210.9 kg m^{-3}. The stagnant bed heights (H_0) used are 0.14, 0.17 and 0.27 m.

3. Results

3.1 Design of experiment

Experimental runs have been carried out in conical spouted beds of different geometry following a design of experiments. The purpose of this design has been to study the effect on particle cycle times of the insertion of a draft tube, draft tube configuration and the different factors of the contactor and particle system.

In the experiments performed with the draft tube, preliminary experiments have shown that the gas inlet diameter (D_0) must be the same or slightly lower than that of the tube (D_T) in order to avoid instability problems.

In addition, runs have been carried out without any draft tube in order to compare them with those obtained with different draft tubes. Nevertheless, when there is no draft tube, the ratio between inlet diameter and particle diameter must be lower than a given value ($D_0/d_p < 20$-30) for spout formation (Olazar et al., 1992).

Experimental runs have been carried out by combining all contactor geometries and draft tube configurations that have been described in the experimental section, i.e., approximately 48 runs involving non-porous draft tubes, 72 open-sided tubes and 6 without draft tube.

Particle cycle times (minimum, maximum and average) 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 falls onto 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 ($\overline{t_c}$) is determined. Then, 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. Thereby, 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.

Thus, at least 100 cycle time have been measured in each system in order to have a representative sample for statistical inference.

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 ($u= 1.15 \times u_{ms}$). Accordingly all the systems studied are under the same hydrodinamic conditions (minimum particle motion).

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 an open-sided draft tube.
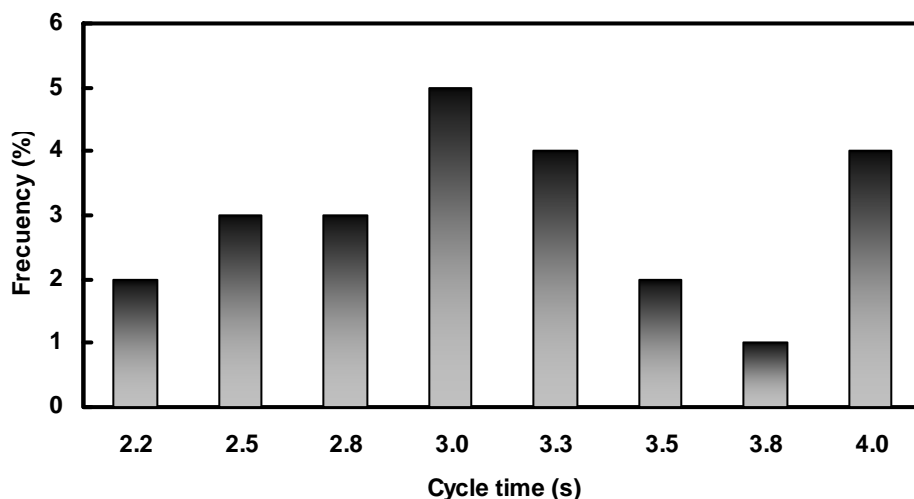

Figure 2: Cycle time distribution for a given system. Experimental conditions: γ, 28º; W_H, 0.01 m; D_T, 0.04 m; D_0, 0.04 m; H_0, 0.14 m; d_p, 0.01 m; material, chickpeas

3.2 Experimental results

The quantitative effect of the factors analyzed on the parameters studied may be observed by plotting the values for the response vs the factor levels, i.e., main effect plots. For this reason, in this section graphics have been performed with the experimental data.

The results show that the average cycle time is influenced by the type of draft tube used and the geometrical factors of the contactor. As it is observed in Figure 3a, as the angle of the contactor is greater, the average cycle time for the two systems 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 45 º contactor than in the 28 º contactor) and by the longer particle trajectories (those descending near the wall) in the contactor with the greater 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. These results are consistent with those obtained by Olazar et al. (1998) and Ijichi et al. (1998) in conical or conical-cylindrical spouted beds without a draft tube.

A comparison of the systems studied shows that open-sided tubes have shorter cycles times than non-porous tubes and also, the differences between the cycle times are smaller.
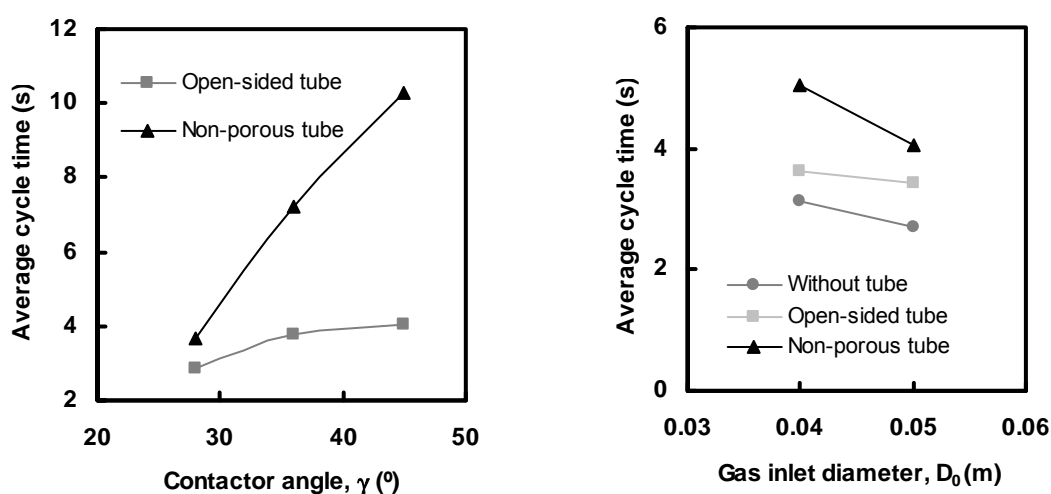

Figure 3: a) Influence of contactor angle on the average cycle time for the two systems studied. b) Influence of gas inlet diameter on the average cycle time for the three systems studied

Figure 3b shows that an increase in gas inlet diameter (and draft tube diameter at the same time) causes an increase in the solid circulation rate, and therefore a reduction in the average cycle time. In fact, a higher cross-sectional area of the spout caused by a greater inlet diameter gives way to an increase in gas flowrate in this zone and, therefore, to an increase in the solid flowrate ascending in the spout.

Figure 4a shows the maximum and the minimum values for the systems grouped according to the type of draft tube or to the operation without a tube. As observed, the average cycle time range is very different depending on the system used. Unlike conventional spouted beds, the widest range corresponds to the non-porous draft tube systems, whereas the open-sided draft tube systems and those without draft tube have much narrower ranges, with the latter ones having the narrowest ranges and shortest cycle times. The fact that non-porous tube systems have the widest ranges puts in evidence that, under the experimental conditions used in this work, the factors related to the non-porous tube have a greater influence on the average cycle time than those related to the open-sided draft tube. Thus, the particles in a conical spouted bed with a non-porous draft tube follow very different trajectories from the surface to the bottom. Besides, the trajectories of the particles that descend near the wall are much longer and their velocity is lower than those that descend near the draft tube. The difference in the length of the trajectories is not significant in conventional cylindrical beds, but it is significant in conical spouted beds, especially for high stagnant beds and wide angles. When conical spouted beds are fitted with an open-sided draft tube, the solids may enter the spout at any level, and this means that cycle times distributions are more uniform. Furthermore, the higher flowrate required for spouting gives way to a more vigorous bed, which contributes to shortening cycle times and rendering them more uniform. When there is no draft tube, the air flowrate required for spouting is even higher, and although the bed has greater

instability problems, cycle times are more uniform. Consequently, the desired particle cycle times can be obtained for a conical spouted bed by choosing the suitable configuration of the bed and draft tube.
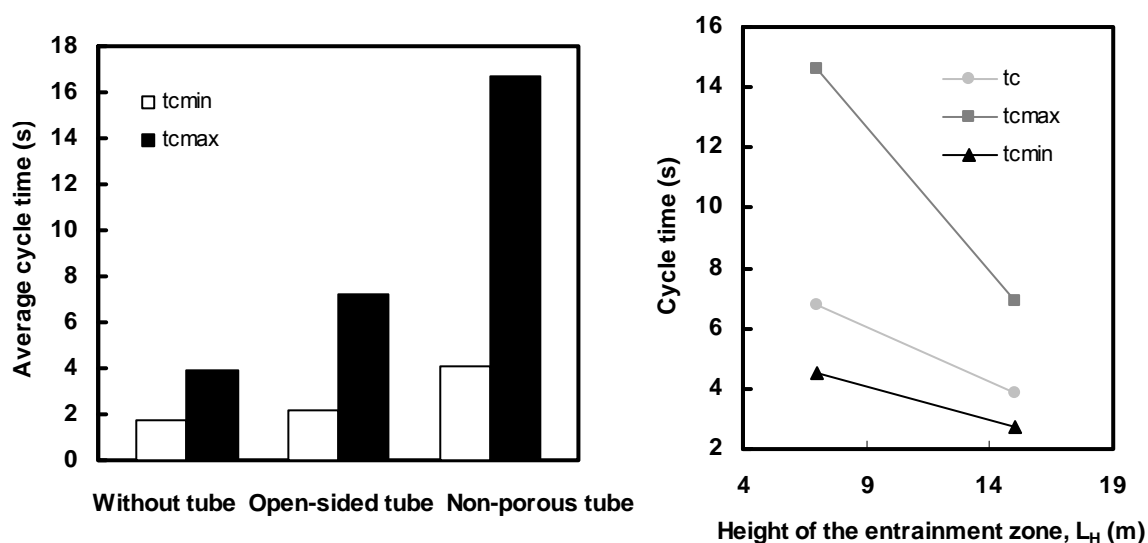

Figure 4: a) Average cycle time ranges for the three systems studied, b) Influence of the height of the entrainment zone of non-porous tubes on the average, maximum, and minimum cycle times

The height of the entrainment zone is the most influential parameter in operation with non-porous draft tubes (Olazar et al., 2012). This parameter governs the solids crossflow from the annulus into the spout; therefore, the higher the entrainment zone, the higher the circulation rate achieved (Altzibar et al., 2009). Furthermore, the gas flowrate through the annulus increases with an increase in the entrainment zone, and this also has a positive effect on the solids circulation rate (Wang et al., 2010). As shown in Figure 4b, when the entrainment zone is higher the three average cycle times are lower and more uniform (smaller differences). 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 and, consequently, a reduction in the average cycle times (Makibar et al., 2012).

Figure 4b also shows that the values of the maximum cycle time are approximately 3-fold higher than the values of the minimum cycle time. Several authors measured the maximum cycle times and proved that the maximum cycle time is severely affected by wall friction (He et al., 1994). Figure 4b also shows that the entrainment zone height has a greater impact on the maximum cycle time than on the minimum and average cycle times.

4. Conclusions

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

The experimental systems with the lowest cycle times are those without draft tubes, but they have more stability problems. Open-sided draft tubes register intermediate cycle times and non-porous ones are the systems with the highest solid cycle times. Furthermore, open-sided tube systems have better gas-solid contact than non-porous tube systems. Therefore, the cycle times desired for the particles can be obtained for the conical spouted bed by choosing the suitable configuration of both the bed and the draft tube.

The height of the entrainment zone is an effective factor for optimizing the solid circulation flowrate in draft tube conical spouted beds. Consequently, the solid circulation rate can be easily controlled by aerating the bed and adjusting the amount of solids entering the spout through the height of the entrainment zone, thereby giving the design flexibility.

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