Influence of the Fountain Confiner in a Conical Spouted Bed Dryer

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Abstract

The drying of fine sand particles (below 1 mm) has been studied in a conical spouted bed fitted with a draft tube in order to ascertain the performance of a new internal device to confine the fountain. Accordingly, batch runs have been carried out using three types of draft tubes, with confiner and without it under ambient conditions. Their performances have been compared in order to ascertain the optimum configuration. The results evidence that the systems with the confiner perform much better than those without it. Thus, the drying time decreases considerably and the pressure drop and air flow rate decrease slightly when the confiner is used. The drying performance of the open-sided draft tube is superior to any other configuration, i.e., the drying time required with this tube is the shortest. Nonporous draft tubes are the worst option due to their poor gas-solid contact. Porous draft tubes have an intermediate performance.

Keywords: drying; fountain confiner; conical spouted bed; open-sided draft tube; porous draft tube; nonporous draft tube.

1. INTRODUCTION

Drying is one of the most common operation in process industries, as most of the raw materials need to be dried and homogenized prior to use in subsequent chemical or physical operations. Furthermore, drying is one of the most energy consuming industrial operations. Accordingly, energy consumption must be optimized in the design process of the dryer, i.e., use of the minimum air flow rate with the best gas-solid contact. Rotary dryers are commonly used, but they have low efficiency and low heat and mass transfer rates. Spouted beds are an interesting alternative to overcome these shortcomings, as they are characterized by high heat and mass transfer rates leading to short residence times and compact design [1].

The advantage of the spouted bed technique for drying lies in its capacity for handling granular products that are too coarse to be readily fluidized [2,3]. Besides, spouted beds are suitable for operating with heat sensitive materials, such as foods, pharmaceuticals, and plastics due to their good heat transfer and isothermicity [4]. Spouted beds have been successfully applied to the drying of different solid materials, such as grain [5], sawdust [6], seeds [7], sludges [8] and inert materials [9,10]. Spouted bed dryers with inert particles have been commonly used to dry pastes and slurries [11,12]. The latest studies published on the drying in spouted beds involve the use of probiotic orange juice [13], skimmed milk [14] and agricultural grains [15].

Conical spouted beds have a low segregation [16], which allows handling particles with a wide size distribution without stability problems. This feature is very interesting for drying. Moreover, the high solid circulation rate in these conical beds results in a uniform moisture content and temperature in the bed, which improves the performance in drying processes [17].

Passos et al. [18] have demonstrated that the maximum capacity and efficiency of the spouted bed dryer were dependent on the geometry of the column and on the characteristics of the particle (size, appearance, porosity and density).

The humidity the solid must have at the end of the operation limits the drying time and the drying conditions required. Mostly, the content of the final humidity depends on the storage needs [19]. It is worth mentioning that the drying operation is a way of reducing product transport and storage cost [20].

The ratio between the inlet diameter and particle diameter limits the scaling up of spouted beds (the inlet diameter should be smaller than 20–30 times the particle diameter). To overcome this limitation, the use of a draft tube is a common as well as simple solution [21]. In fact, an internal device is the key for stable operation in a large-scale spouted bed and allows increasing the spoutable bed height and reducing bed pressure drop [22].

Conical spouted beds fitted with a draft tube have proven to be an efficient dryer of simple construction [23] providing a large interface area for gas-solid contact, high heat and mass transfer coefficients, and high production rates. The performance of the spouted bed (minimum spouting velocity, pressure drop, solid circulation, and so on) depends on the type of draft tube used. Moreover, the use of different types of draft tubes improves the versatility of the conical spouted bed in terms of gas flow rate, solid circulation, materials to be handled and so forth.

In previous papers [9,10], the performance of conical spouted beds fitted with three types of draft tubes was studied and their potential for the drying of sand particles was proven. Thus, batch runs were carried out using nonporous, porous, and open-sided draft tubes under ambient conditions and at different temperatures and their performance was compared.

The aim of this study is to analyse the potential of the fountain confiner for the drying of sand particles in a conical spouted bed fitted with different draft tubes. As described in a previous paper [24] the conical spouted bed with fountain confiner have many advantages, as is the good contact between the gas and the solid, which is a key parameter in the drying process. Accordingly, batch runs have been carried out in conical spouted beds fitted with three types of draft tubes, without a fountain confiner and with confiner under ambient conditions. Their performances have been compared in order to ascertain the optimum configuration for drying.

2. MATERIAL AND METHODS

2.1. Equipment

The pilot plant used in the runs has been described in previous paper [9] and is shown in Fig. 1.

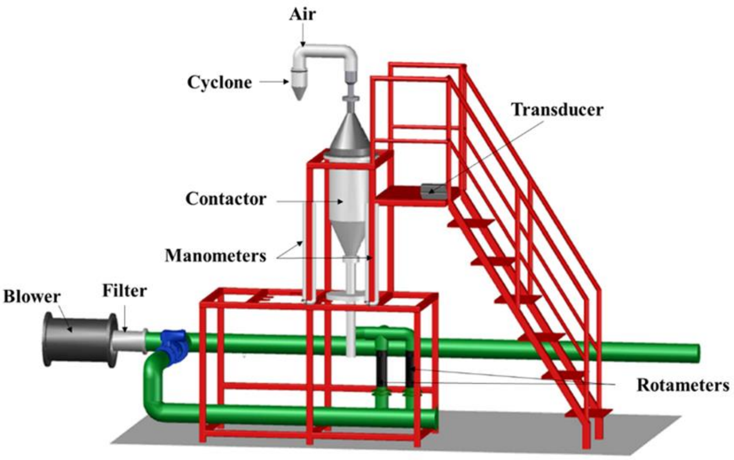


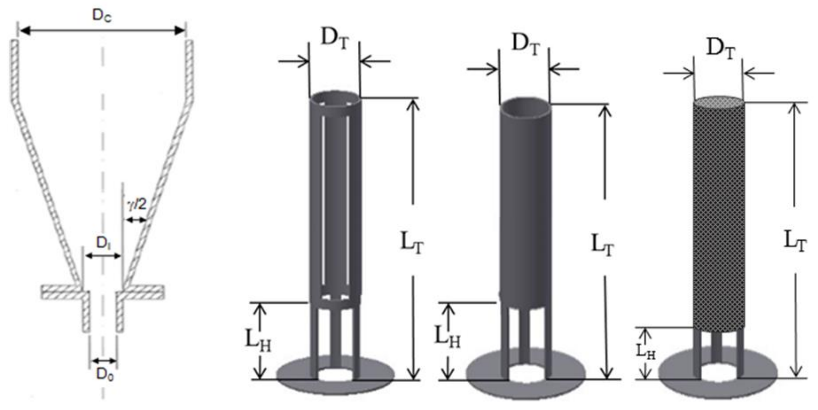
Fig. 1. Diagrammatic representation of the pilot plant.

The unit allows operating with contactors of different geometry, but in this study a contactor with a cone angle (γ) of 36º has been used, as it is the most versatile one and has already been studied in detail in a previous paper by our research group [9]. Furthermore, the values for the operating conditions have been established based on preliminary experimental runs.

Fig. 2 shows the contactor and draft tubes used. The contactor is made of polymethyl methacrylate and has a conical geometry. Fig. 2a shows the geometric factors of this contactor. The column diameter and the base diameter are D_c, 0.36 m and D_i, 0.068 m, respectively. The gas inlet diameter used is D_0= 0.04 m and the static bed height H_0=0.22 m.

2.2. Draft tubes

Six draft tubes of different configuration have been used, Fig. 2b, 2c and 2d: one porous, two nonporous (with different heights of the entrainment zone) and three open-sided (with different aperture ratios).



(a) **(b)** **(c)** **(d)**

Fig. 2. Geometric factors of the conical contactor (a), open-sided draft tube (b), nonporous draft tube (c) and porous draft tube (d).

The draft tubes are made of stainless steel and are placed along the axis of the contactor. They are fitted with a flat base to ensure perfect alignment along the axis, and so attain an optimum hydrodynamic performance. Their dimensions are as follows: length of the tube L_T= 0.22 m and aperture ratios (AR) of 42%, 57% and 79%.

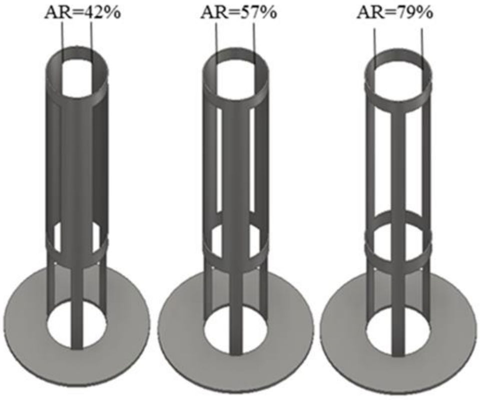


Fig. 3. Different aperture ratios (AR) of the open-sided draft tubes.

The dimensions of the nonporous draft tubes are: length of the tube L_T= 0.22 m and height of entrainment zone (distance between the gas inlet nozzle and the lower end of the draft tube) L_H= 0.07 and 0.15 m. The dimensions of the porous draft tube are the following: length of the tube L_T= 0.17 m and height of entrainment zone L_H= 0.02 m. The porous tube is made of a stainless steel screen. The diameter of all the tubes used is the same as the gas inlet diameter, D_T= 0.04 m.

2.3. Fountain confiner

The fountain confiner is a cylindrical tube made of polymethyl methacrylate with the upper outlet closed to avoid the exit of air and solid, Fig. 4. A stainless steel cone is attached to the top of the confiner to avoid solid deposition on the device; that is, the solids deposited on the cone slip and fall down onto the bed.

Fig. 4. Fountain confiner.

As observed in Fig. 5a, this device is placed at the upper section of the contactor (above the fountain) and traps the particles in the fountain, changes its shape (narrower and higher) and forces the air to make a longer trajectory, with its main effect being system stabilization. Fig. 5b shows the gas and solid trajectories in the conical spouted bed fitted with a nonporous draft tube. The trajectory of the solids is similar to that in the conventional systems, but the fountain confiner changes the trajectory of the gas, as once it has reached the top of the fountain (upper part of the confiner) it must descend and pass through the gap between the lower end of the device and the bed surface. This fact causes an additional contact between the gas and the solid in the fountain. Furthermore, this device avoids fine particle entrainment because the gas cannot drag the particles from the fountain directly to the outside of the contactor, i.e., the particles fall back onto the bed surface because gravity forces overcome drag forces.

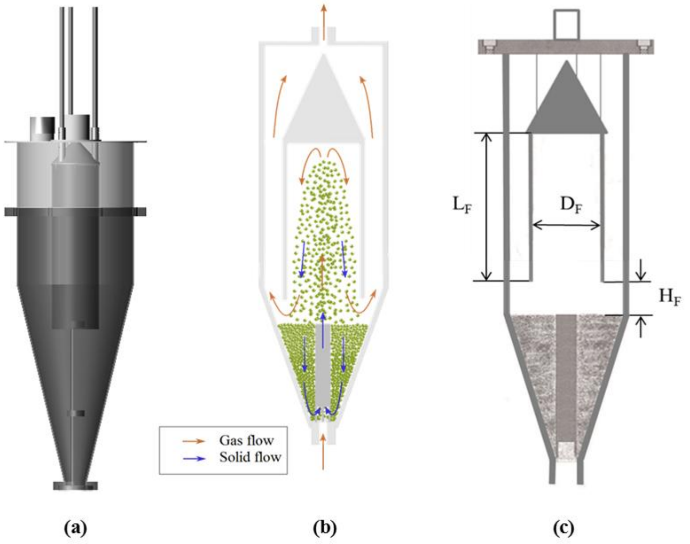


Fig. 5. Fountain confiner location (a), gas and solid trajectories in the conical spouted bed with a nonporous draft tube and (b) factors of the fountain confiner (c).

The dimensions of this device (Fig. 5 (c) are as follows: length of the fountain confiner L_F= 0.6 m, diameter of the fountain confiner D_F= 0.20 m and distance between the lower end of the fountain confiner and the bed surface H_F= 0.1 m. The dimensions of the fountain confiner have been chosen based on preliminary experimental runs [24].

2.4. Material

The material used for drying is building sand. The moisture content of the sand as received from the quarry is between 6 and 10%, and according to the product functional specification it should be dried to approximately 0.0005 kg of water/kg of dried solid for subsequent use.

The particle size distribution of the sand determined by sieving (ISO3310) is shown in Fig. 6.

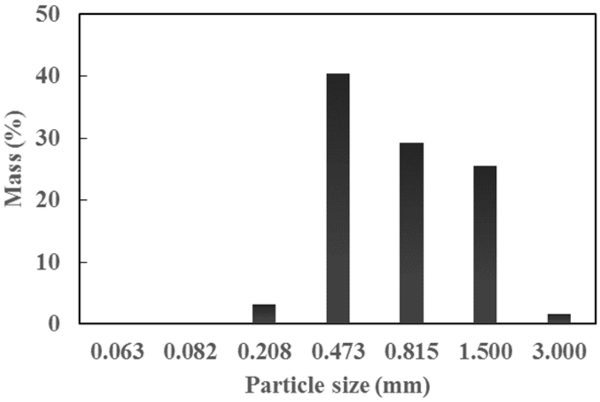


Fig. 6. Particle size distribution of the sand.

As observed in Fig. 6, the distribution is fairly wide. The average particle size (reciprocal mean diameter or volume surface mean diameter) has been calculated by means of the expression:

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

The average size of the sand based on the values in Fig. 6 and using Eq. (1) is 0.6 mm.

The real density of the sand and surface area, measured in a Micromeritics ASAP, are 2358 kg/m^3 and 65 m^2/kg, respectively. Therefore, the sand is a material corresponding to group B of Geldart classification [25].

The porous structure of the sand has been analysed by a Micromeritics AUTOPORE. The pore volume is 0.005 ml/g of sand, which indicates that it is of low porosity. Moreover, the analysis shows that the predominant pores are between 10 and 100 μm.

Runs have been carried out in batch mode using air at 25 ºC. Thus, pulses of 0.2 kg of wet sand were added to a bed containing 5 kg of dry sand.

3. RESULTS

The performance of the conical spouted bed fitted with different draft tubes has been analysed for the drying of sand particles. However, given that the main purpose is to assess the effect the fountain confiner has on the drying process, batch runs have been carried out in a draft tube conical spouted bed with and without fountain confiner, and their performance has been compared. Thus, throughout the batch drying run, the evolution of several parameters has been monitored, as are the air moisture content at the bed outlet, the pressure drop and the air flow rate with time.

The runs start when the wet sand pulse is injected and finish when the moisture content of the sand in the contactor is approximately 0.0005 kg of water/kg of dried solid. Given that the ambient temperature changed in the 22 ºC-25 ºC range, absolute humidity has been monitored (relative humidity is dependent on the temperature) for a more accurate comparison.

Preliminary runs have been carried out with different draft tubes to ascertain how much excess air above the minimum is required to operate using wet sand without bed collapse. The nonporous draft tube may operate at the minimum spouting velocity, but all the other types require higher velocities for stable operation. Thus, the porous one requires a flow rate 50% higher than the minimum one and the open-sided ones require as follows: 20% above the minimum one for the lowest aperture ratio, 40% for the intermediate one, and 60% for the highest one.

Once operating flow rates have been fixed, batch drying has been carried out. Fig. 7 shows the evolution of the air moisture content with time for the six different draft tubes. The runs have been carried out with fountain confiner (WC) and without confiner (WOC). Fig. 7a shows the results for the porous (PT) and nonporous drat tubes, with the latter differing in the height of entrainment zone, i.e., 7 cm (LH7) and 15 cm (LH15), respectively. Fig. 7b shows the results for the open-sided draft tubes with different aperture ratios (79%, 57% and 42%).

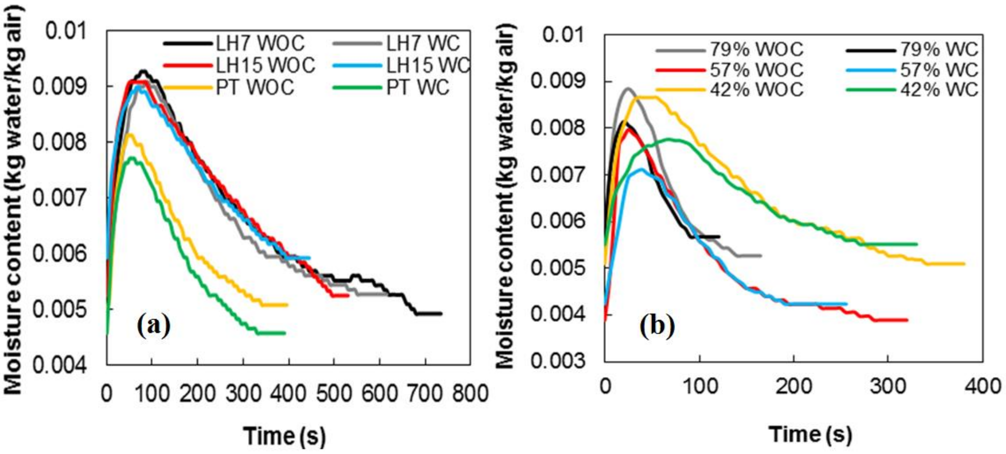


Fig. 7. Evolution of moisture content with drying time using nonporous and porous draft tubes (a) and open-sided draft tubes (b).

As observed in Fig. 7a, the heights of the moisture content peaks for the nonporous draft tubes are similar, either with the confiner or without it, and this value is close to that corresponding to saturation. Nevertheless, the peaks are considerably lower for the porous draft tube, i.e., considerably lower than those corresponding to saturation, which is explained by the higher air flow rates used. In the case of open-sided tubes, Fig. 7b, there is no clear relationship between the peaks and the aperture ratios and configurations (with or without confiner). In fact, an increase in aperture ratio leads to a more turbulent bed with a better distribution of the air flow, thereby moisture contact peak being close to saturation.

As observed in Fig. 7, in the systems with porous draft tube (PT) the drying time is very similar with or without confiner (within 3%), but in the other cases the drying time decreases (from 15 to 35%) using the fountain confiner. An explanation lies in the stability of the bed and the better contact between the gas and the solid when the bed is equipped with the confiner. Therefore, the beds with fountain confiner dry faster than those without it, and the one that dries fastest (around 100 s) among those studied is the configuration with the open-sided draft tube having 79% aperture ratio.

Fig. 7a shows that the drying time required using porous draft tubes (close to 400 s) is shorter than when nonporous ones (450-750 s) are used, which is attributed to the more vigorous circulation and wider fountain when the former are used. This is explained by the air percolating from the spout into the annulus, which leads to a better gas-solid contact [26]. This trend is consistent with the results reported by Altzibar et al., [9] on this bed's hydrodynamics.

As observed in Fig. 7a, regardless of using fountain confiner or not, as the height of the entrainment zone is increased from 7 to 15 cm, the drying time is 25% shorter. This trend is expected because the solid cross-flow from the annulus into the spout is higher when the height of entrainment zone is higher, which leads to a higher solid circulation rate [27,28]. Furthermore, 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 and so faster drying. Accordingly, as observed experimentally, when the height of the entrainment zone is higher the height of the fountain is lower.

Comparing the performance of the porous draft tube (Fig. 7a) with that of the three open-sided ones (Fig. 7b), the latter are more efficient dryers because the time required for drying is significantly shorter (from 400 s for porous tubes to 100 s for open-sided tubes with 79% aperture ratio). The explanation lies again in the much higher solid circulation rate, which in turn also helps air percolation into the annulus and so a better gas-solid contact [9].

Overall, Fig. 7 shows that the three open-sided draft tubes perform much better than the nonporous ones, i.e., the former require 100-400 s whereas the latter 450-750 s, which is again attributed to both gas percolation from the spout into the annulus and solid cross-flow from the annulus into the spout, which greatly enhance heat and the mass transfer rates. Thus, the gas-solid contact with nonporous draft tubes is not so good as with open-sided tubes, which was especially true in the annulus region where the gas flow rate is only a small fraction of that at the inlet [29]. This trend has also been observed in the literature for sawdust [30] and for drying sand at high temperature [10].

Fig. 7b shows that an increase in the aperture ratio decreases the drying time, from approximately 400 s for the tube with 42% aperture ratio to approximately 100 s for that with 79% aperture ratio. In fact, in the system with the largest aperture ratio, the amount of air that passes from the spout into the annulus is higher, which helps to increasing the solid flow rate, and therefore improving the gas-solid contact. This trend is consistent with that reported by Altzibar et al., [9] without fountain confiner, but in this case the differences are higher. Thus, that the drying capacity of the open-sided draft tubes is greater using a fountain confiner. In summary, the novel device is an excellent solution (simple and of low cost) to reduce drying time by up to 35%.

Fig. 8 shows the evolution of pressure drop with time for all the configurations studied. Thus, Fig. 8a compares the evolution for the systems with porous (PT) and nonporous draft tubes. The latter ones have been used with two different height of the entrainment zone: 7 cm (LH7) and 15 cm (LH15), respectively. Fig. 8b shows the results for the three open-sided draft tubes with different aperture ratio (79%, 57% and 42%). They have been used in spouted beds with fountain confiner (WC) and without it (WOC).

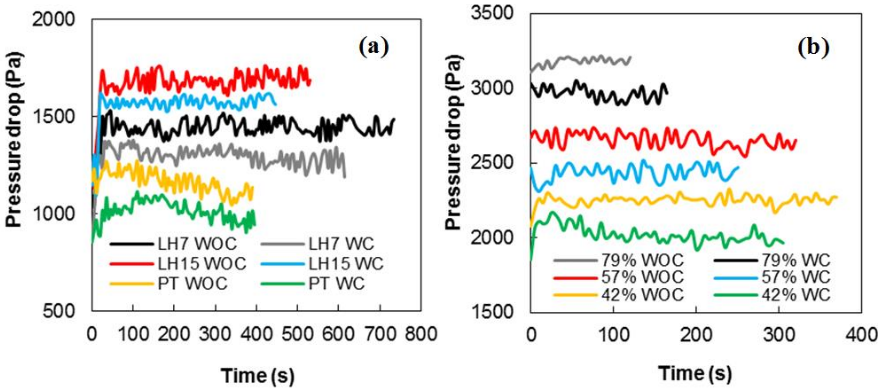


Fig. 8. Evolution of pressure drop with drying time in spouted beds equipped with nonporous and porous draft tubes and (a) and in beds with open-sided draft tubes (b).

As observed in Fig. 8, in most cases there is a short initial period in which pressure drop increases slightly with time, but it then remains constant until the end of the drying. This slight increase is related to the time required for the homogenization of the wet sand injected as a pulse.

Fig. 8a shows that the pressure drop of all the confined systems is between 5 and 20% lower than that of the systems without fountain confiner, since the confiner provides stability to the bed and so reduces the operating pressure drop. The lowest value of the pressure drop (around 1000 Pa) has been obtained using the porous draft tube and fountain confiner. It should be noted that this is due to the shorter entrainment height of this tube;

that is, 2 cm instead of the 7 or 15 cm of the nonporous draft tubes. Thus, a longer entrainment height allows a higher solid cross-flow rate from the annulus into the spout, and therefore a higher solid circulation flow rate [31]. As a result, higher pressure drop values are obtained [32]. Nevertheless, although the entrainment height of the porous tube is below one third of the nonporous one (2 cm vs. 7 or 15 cm), pressure drop is only slightly lower (approximately 1100 Pa vs. 1400 or 1700 Pa), which is because porous tubes allow air diversion from the spout into the annulus all over the spout all.

An interesting conclusion drawn by comparing Fig. 8a with 8b is that pressure drops for the open-sided draft tubes are approximately twice those for porous and nonporous draft tubes (an average of about 2600 vs. 1300 Pa). In fact, the open-sided draft tube enhances the solid circulation due to both better aeration of the annulus and higher solid cross-flow from the annulus into the spout through the tube slots (all over the spout length). Thus, the higher solid circulation characteristic of an open-sided draft tube causes a higher bed pressure drop due to the higher drag force exerted by the gas phase while conveying the particles in the spout [30]. This relationship between the solid circulation and the pressure drop has also been observed by other authors [21,33].

Furthermore, the aperture ratio has a great influence on the operating pressure drop, Fig. 8b. Thus, as this ratio is increased pressure drop increases significantly, from around 2000 Pa for the tube with a 42% aperture ratio to around 3000 Pa for that with a 79% ratio. The explanation for this trend lies again in the higher solid circulation flow rate for the higher aperture ratio. Summarizing, the confiner minimizes the pressure drop of all the configurations studied by at least 5%, which means significant energy saving.

Fig. 9 shows the evolution of the air flow rate with time for the systems analysed. Thus, Fig. 9a shows the evolution of the air flow rate with time for the systems with porous (PT) and nonporous draft tubes, with the latter ones differing in the height of the entrainment zone: 7 cm (LH7) and 15 cm (LH15), respectively. Fig. 9b shows the results for the three open-sided draft tubes with different aperture ratios (79%, 57% and 42%). The runs have been carried out using fountain confiner (WC) and without it (WOC).

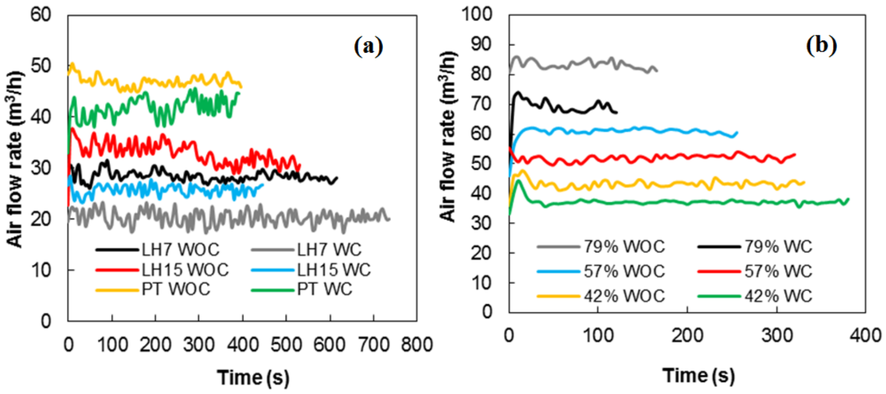


Fig. 9. Evolution of air flow rate with drying time using nonporous and porous draft tubes (a) and open-sided draft tubes (b).

As observed in Fig. 9, the average air flow rate hardly changes throughout drying. Furthermore, the air flow rate for all the configurations with the fountain confiner is between 10 and 30% lower than that for the configurations without it. As mentioned above, the fountain confiner stabilizes the system, and allows therefore attaining stable operation with a lower air velocity. The lowest value of the air flow rate (around 20 m^3/h) corresponds to the spouted bed fitted with the nonporous draft tube and fountain confiner. The highest values of Fig. 9a (approximately 45 m^3/h) correspond to the porous tube, either without confiner or with confiner, which is explained by the diversion (percolation) of the air along the whole length of the spout. Furthermore, as the entrainment zone of the nonporous tubes is increased from 7 to 15 cm (Fig. 9a), the air flow rate required for stable operation is 16% higher, which is explained by the higher solid circulation rate under these conditions, as reported by Ishikura et al. [10].

A comparison of Fig. 9a with Fig. 9b reveals that the configurations with open-sided draft tubes require the highest air flow rates. Furthermore, an increase in the aperture ratio leads to an increase in the air flow rate, from around 40 m^3/h for the tube with a 42% aperture ratio to around 80 m^3/h for that with a 79% ratio. Operation with the tube having 79% aperture ratio and without the confiner requires the highest flow rate (close to 85 m^3/h) of all the configurations analysed, which is attributed to the high solid cross-flow from the annulus into the spout and air diversion from the spout into the annulus all over the spout wall. This explains the shortest drying time required for this configuration.

The drying operation is a highly energy demanding process and the best gas-solid contact is achieved by using air flow rates close to the minimum for spouting. Accordingly, the confiner is a suitable device to improve the gas-solid contact, as it allows decreasing the minimum spouting air flow rate by at least 10%.

Previous studies have shown that scaling up of the conical spouted bed from laboratory to pilot plant [9,10] depends on the operating conditions (temperature, draft tube, and air excess above that corresponding to the minimum one) and cycle times. Furthermore, when both (operating conditions and cycle times) are of the same order, drying time does not change significantly when scaling up.

In this paper, we approached the drying process in a fountain confined conical spouted bed, which has clearly a better performance than without confiner. Furthermore, we expect the same as in the case without confiner will apply to these novel devices. Therefore, the information obtained in this paper will be directly applicable when scaling up. The only experimental parameter required at a larger scale is the cycle time.

4. CONCLUSIONS

The conical spouted bed is an interesting technology for drying fine particles due to its simple design and efficient operation. This contactor performs well fitted with a draft tube, as it is stable in a wide range of operating conditions. Runs have been carried out to assess whether the fountain confiner enhances the drying of fine sand particles (below 1 mm) in a conical spouted bed fitted with different draft tubes. The results evidence that the systems with the fountain confiner perform significantly better than the systems without it. This is explained by the highly stable operation and excellent gas-solid contact attained with this device. Accordingly, the drying time, pressure drop and air flow rate of all the configurations studied decrease with the fountain confiner by up to 35%, 20% and 30% respectively, which implies a considerable decrease in energy consumption.

The open-sided draft tubes provide the shortest drying time (around 100 s), whereas the porous draft tubes lead to the lowest value of pressure drop (around 1000 Pa) and the nonporous draft tubes to the lowest value of air flow rate (around 20 m^3/h).

Nonporous draft tubes are not the best option when the gas plays an active role, as in drying processes [29], because they lead to poor gas-solid contact and low solid circulation. Porous draft tubes perform better than the nonporous ones, as they allow lowering the drying time by 300 s and the pressure drop by 400 Pa less. However, the air flow rate required is almost twice that of the nonporous ones (around 25 vs. 45 m^3/h). Open-sided draft tubes perform even better than the porous ones, since the time required for drying is much shorter (an average of 300 vs. 400 s). The open-sided draft tube with the smallest aperture ratio (42%) records a similar drying time (around 400 s) as the porous draft tube with a slightly lower flow rate (close to 40 vs. 45 m^3/h), but significantly higher (double, specifically, 2100 vs. 1100 Pa) pressure drop.

It is noteworthy that the decrease in the drying time attained when using open-sided draft tubes instead of any other configuration is much more significant than the increase in pressure drop and air flow rate. Accordingly, the drying process is significantly improved by using open-sided draft tubes, and the optimum configuration among those studied for drying sand particles is a spouted bed fitted with the fountain confiner and the open-sided draft tube with 79% aperture ratio.

NOTATION

D_0	Gas inlet diameter, m
D_c	Colum diameter, m
D_F	Diameter of the fountain confiner, m

D_i	Contactor base diameter, m
D_T	Diameter of the draft tube, m
$\overline{d_p}$	Average particle diameter, mm
d_{pi}	Average particle diameter of an i fraction, mm
H_0	Static bed height, m
H_F	Distance between the lower end of the device and the bed surface, m
L_F	Height of the fountain confiner, m
L_H	Height of the entrainment zone of the nonporous draft tube, m
L_T	Length of the draft tube, m
x_i	Mass fraction of particles of size d_{pi}

Greek Letters

γ	Cone angle, rad

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REFERENCES

[1] V. Vanecek, R. Drbohlar, M. Markvard, Fluidized Bed Drying, Leonard Hi, 1965.

[2] M. Olazar, M.J. San Jose, A.T. Aguayo, J.M. Arandes, J. Bilbao, Design Factors of Conical Spouted Beds and Jet Spouted Beds, Ind. Eng. Chem. Res. 32 (1993) 1245–1250. doi:10.1021/ie00018a034.

[3] H. Cui, J.R. Grace, Spouting of biomass particles: A review, Bioresour. Technol. 99 (2008) 4008–4020. doi:10.1016/j.biortech.2007.04.048.

[4] L.A.P. Freitas, J.T. Freire, Heat transfer in a draft tube spouted bed with bottom solids feed, Powder Technol. 114 (2001) 152–162. doi:10.1016/S0032-5910(00)00305-3.

[5] M. Markowski, W. Sobieski, I. Konopka, M. Tanska, I. Białobrzewski, Drying characteristics of barley grain dried in a spouted-bed and combined IR-convection dryers, Dry. Technol. 25 (2007) 1621–1632. doi:10.1080/07373930701590715.

[6] J. Berghel, Drying Technology : An International Journal The Effect of Using a

Heating Tube in an Existing Spouted Bed Superheated Steam Dryer The Effect of Using a Heating Tube in an Existing Spouted Bed Superheated Steam Dryer, (2011) 37–41. doi:10.1080/07373937.2010.483030.

[7] W. Jittanit, G. Srzednicki, R.H. Driscoll, Comparison Between Fluidized Bed and Spouted Bed Drying for Seeds, Dry. Technol. 31 (2013) 52–56. doi:10.1080/07373937.2012.714827.

[8] M.J. San José, S. Alvarez, R. López, Drying of industrial sludge waste in a conical spouted bed dryer. Effect of air temperature and air velocity, Dry. Technol. 0 (2018) 1–11. doi:10.1080/07373937.2018.1441155.

[9] H. Altzibar, G. Lopez, S. Alvarez, M.J.S. Jose, A. Barona, M. Olazar, A draft-tube conical spouted bed for drying fine particles, Dry. Technol. 26 (2008) 308–314. doi:10.1080/07373930801898018.

[10] H. Altzibar, G. Lopez, M. Olazar, J. Bilbao, Effect of temperature on fine particle drying in a draft-tube conical spouted bed, Chem. Eng. Technol. 34 (2011) 1130–1135. doi:10.1002/ceat.201100032.

[11] R. Jumah, E. Al-Kteimat, A. Al-Hamad, E. Telfah, Constant and intermittent drying characteristics of olive cake, Dry. Technol. 25 (2007) 1417–1422. doi:10.1080/07373930701536668.

[12] L. Marmo, Low temperature drying of pomace in spout and spout-fluid beds, J. Food Eng. 79 (2007) 1179–1190. doi:10.1016/j.jfoodeng.2006.04.034.

[13] N.N. Alves, S. de Oliveira Sancho, A.R.A. da Silva, S. Desobry, J.M.C. da Costa, S. Rodrigues, Spouted bed as an efficient processing for probiotic orange juice drying, Food Res. Int. 101 (2017) 54–60. doi:10.1016/j.foodres.2017.08.052.

[14] M.T.B. Perazzini, F.B. Freire, M.C. Ferreira, J.T. Freire, Stability and performance of a spouted bed in drying skimmed milk: Influence of the cone

angle and air inlet device, Dry. Technol. 3937 (2017) 1–14. doi:10.1080/07373937.2017.1331240.

[15] S. Rajashekhara, D.V.R. Murthy, Drying of Agricultural Grains in a Multiple Porous Draft Tube Spouted Bed, Chem. Eng. Commun. 204 (2017) 942–950. doi:10.1080/00986445.2017.1328412.

[16] M.J. San Jose, M. Olazar, F.J. Penas, J. Bilbao, Segregation in conical spouted beds with binary and ternary mixtures of equidensity spherical particles, Ind. Eng. Chem. Res. 33 (1994) 1838–1844. doi:10.1021/ie00031a025.

[17] T. Swasdisevi, W. Tanthapanichakoon, T. Charinpanitkul, T. Kawaguchi, T. Tanaka, Y. Tsuji, Investigation of fluid and coarse-particle dynamics in a two-dimensional spouted bed, Chem. Eng. Technol. 27 (2004) 971–981. doi:10.1002/ceat.200401918.

[18] M.L. Passos, A.S. Mujumdar, G. Massarani, Scale-up of spouted bed dryers: Criteria and applications, Dry. Technol. 12 (1994) 351–391. doi:10.1080/07373939408959961.

[19] A.S. Mujumdar, Principles, Classification, and Selection of Dryers, in: Handb. Ind. Dry., Boca Raton, 2006.

[20] D. Krishnaiah, R. Nithyanandam, R. Sarbatly, A Critical Review on the Spray Drying of Fruit Extract: Effect of Additives on Physicochemical Properties, Crit. Rev. Food Sci. Nutr. 54 (2014) 449–473. doi:10.1080/10408398.2011.587038.

[21] H. Altzibar, G. Lopez, R. Aguado, S. Alvarez, M.J. San Jose, M. Olazar, Hydrodynamics of conical spouted beds using different types of internal devices, Chem. Eng. Technol. 32 (2009) 463–469. doi:10.1002/ceat.200800605.

[22] H. Nagashima, T. Ishikura, M. Ide, Flow regimes and vertical solids conveying in a spout-fluid bed with a draft tube, Can. J. Chem. Eng. 89 (2011) 264–273.

doi:10.1002/cjce.20403.

[23] C.R. Kfuri, L.A.P. Freitas, A comparative study of spouted and spout-fluid beds for tablet coating, Dry. Technol. 23 (2005) 2369–2387. doi:10.1080/07373930500340452.

[24] H. Altzibar, I. Estiati, G. Lopez, J.F. Saldarriaga, R. Aguado, J. Bilbao, M. Olazar, Fountain confined conical spouted beds, Powder Technol. 312 (2017) 334–346. doi:10.1016/j.powtec.2017.01.071.

[25] D. Geldart, Types of gas fluidization, Powder Technol. 7 (1973) 285–292. doi:10.1016/0032-5910(73)80037-3.

[26] J.K. Claflin, A.G. Fane, Spouting with a porous draft-tube, Can. J. Chem. Eng. 61 (1983) 356–363. doi:10.1002/cjce.5450610315.

[27] J.L. Vieira Neto, C.R. Duarte, V. V. Murata, M.A.S. Barrozo, Effect of a draft tube on the fluid dynamics of a spouted bed: Experimental and CFD studies, Dry. Technol. 26 (2008) 299–307. doi:10.1080/07373930801897994.

[28] J. Makibar, A.R. Fernandez-Akarregi, L. Diaz, G. Lopez, M. Olazar, Pilot scale conical spouted bed pyrolysis reactor: Draft tube selection and hydrodynamic performance, Powder Technol. 219 (2012) 49–58. doi:10.1016/j.powtec.2011.12.008.

[29] S. Wang, Y. Liu, Y. Liu, L. Wei, Q. Dong, C. Wang, Simulations of flow behavior of gas and particles in spouted bed with a porous draft tube, Powder Technol. 199 (2010) 238–247. doi:10.1016/j.powtec.2010.01.012.

[30] M. Olazar, G. Lopez, H. Altzibar, M. Amutio, J. Bilbao, Drying of Biomass in a Conical Spouted Bed with Different Types of Internal Devices, Dry. Technol. 30 (2012) 207–216. doi:Doi 10.1080/07373937.2011.633194.

[31] F.G. Cunha, K.G. Santos, C.H. Ataíde, N. Epstein, M.A.S. Barrozo, Annatto

powder production in a spouted bed: An experimental and CFD study, Ind. Eng. Chem. Res. 48 (2009) 976–982. doi:10.1021/ie801382d.

[32] B.L. Luo, C.J. Lim, L. a. P. Freitas, J.R. Grace, Flow characteristics in slot-rectangular spouted beds with draft plates, Can. J. Chem. Eng. 82 (2004) 83–88.

[33] T. Ishikura, H. Nagashima, M. Ide, Hydrodynamics of a spouted bed with a porous draft tube containing a small amount of finer particles, Powder Technol. 131 (2003) 56–65. doi:10.1016/S0032-5910(02)00321-2.