03-015

Fluidization of wet fine sands in a conical spouted bed

Aitor Pablos Castro[1]; Jorge Vicente Peñalosa[2]; Javier Izquierdo Navarro[1]; Roberto Aguado Zárraga[1]; Martín Olazar Aurrecoechea[1]

[1]Euskal Herriko Unibertsitatea/Universidad del Pais Vasco (UPV/EHU); [2]Novattia Desarrollos S.L.

Fluidization of wet solids has been studied in a conical spouted bed with open-sided draft- tube and confinement system, being the design parameters the optimal obtained in a previous hydrodynamic study. This research is framed in the joint project of Catalytic Process & Waste Valorization Research group, (University of the Basque Country, UPV/EHU) and Novattia Desarrollos Ltd., technology development company, with the objective of designing a new dryer for fine and ultrafine sand based on spouted bed technology.

Several tests have been carried out using two strategies to moisten the bed: (a) loading sand with homogeneous moisture, testing moisture values of 15, 10, 5, 4, 3, 2 and 1% d.b.), and (b) mixing tests, in which sand with a a moisture of 15% d.b. was added to a dry bed, achieving moisture values after mixing of 4.5, 3.9, 3.1, 2.1 and 1.2% b.s.

The most important result of the study has been to determine that the maximum moisture for the bed to be fluidizable is 2% d.b.

Keywords: Conical spouted bed; fine sand; ultrafine sand; wet bedo; hydrodynamics

Fluidización de arena fina húmeda en un spouted bed cónico

Se ha estudiado la fluidización de los sólidos húmedos en un spouted bed cónico equipado con un draft-tube con apertura lateral yun confinador de fuente, utilizando los parámetros óptimos de diseño (diámetro den entrada, ángulo de cono, diámetro del draft-tube...) obtenidos en un estudio hidrodinámico previo. Esta investigación se enmarca en el proyecto conjunto de Investigación del grupo Procesos Catalíticos y Valorización de Residuos (UPV / EHU) y Novattia Desarrollos S.L, empresa de desarrollo tecnológico, con el objetivo de diseñar un nuevo secadero para arenas fina y ultrafina basada en la tecnología de spouted bed.

Se han realizado varios ensayos utilizando dos estrategias para humedecer el lecho: a) Carga de arena con humedad homogénea, ensayando valores de humedad de 15, 10, 5, 4, 3, 2 y 1% b.s.), y b) pruebas de mezclado en las que se partía de un lecho seco al que se le añadía arena al 15% b.s. para conseguir unos valores de humedad tras la mezcla de 4.5, 3.9, 3.1, 2.1 y 1.2% b.s.

El resultado más importante de las pruebas ha sido determinar la humedad máxima para que el lecho sea fluidizable es un 2% b.s.

Palabras clave: *Spouted bed cónico; arena fina; Arena ultrafina; lecho húmedo; hidrodinámica*

Correspondencia: Aitor Pablos Castro. Facultad de Ciencia y Tecnología. Universidad del Pais Vasco. C/ Sarriena s/n Leioa. Bizkaia. España.

Agradecimientos: Este trabajo ha sido llevado a cabo con el apoyo financiero de la Universidad del País Vasco (UPV / EHU) (Proyecto US / 12-13) y con la colaboración de Novattia Desarrollos ltd. Empresa.

Aitor Pablos está agradecido por beca doctoral de la Universidad del País Vasco.

1. Introduction

Drying of solids is an important and sometimes critical operation in several industries, such as chemical, mining, construction, food, pharmaceutical or agricultural industry. Many granular products require drying for subsequent packaging or for relatively long storage periods. Excess of moisture can be removed by mechanical methods (sedimentation, filtration and centrifugation). However, the most complete removal of moisture is obtained by the evaporation and removal of the formed vapours, namely, thermal drying, either using a gase stream or without the assistance of gas to remove the vapour (Knoule, 1968).

Drying occurs when the material liquid is vaporized by supplying heat to the wet feedstock. Heat can be supplied by convection (direct dryers), conduction (contact or indirect dryers), radiation or volumetrically by placing the wet material in a microwave or in a radio frequency electromagnetic field. Over 85 percent of industrial dryers are direct dryers with hot air or combustion gases as the drying medium and over 99 percent of the applications involve removal of water. In all cases the heat must diffuse in the solid mainly by conduction. The liquid must travel to the interfase of the material before it is transported by the carrier gas (or vacuum application in non-convective dryers).

The spouted bed is a fluid-particle contact technique that has been successfully applied to systems where fluidization has yielded unsatisfactory results, especially when particle size exceeds 1 mm.

Although the range of humidity and operating conditions of spouted bed dryers at the laboratory and commercial level is very broad, in all cases a thermal jump between the air inlet temperature and the bed temperature is observed. This characteristic, attributable to the countercurrent contact of the air in the spout with the solid descending the annular zone, is one of its great advantages for its use in the drying of thermo-sensitive materials, since with conventional dryers it must be used lower temperatures to prevent thermal deterioration.

Among the advantages of the spouted bed for drying are:

- Intense particle movement: Good particle mixing prevents localized overheating and ensures the homogeneous moisture content of the product.
- The particle recirculation movement ensures that during the residence time the drying particles contact the incoming hot air at regular intervals. The velocity of this recirculating particle motion can be adjusted as required by varying the operating parameters, such as gas velocity and bed height; varying geometric parameters, such as the size of the gas inlet nozzle; or with the use of an internal transport screw and internal elements such as draft-plate or draft-tube.
- The residence time of the particles can be changed and regulated within very broad limits, for example by changing bed height or using elements such as draft-plates or draft-tubes.
- In order to dry materials with bonded moisture (eg plastics), tangential air inlet and an internal transport screw are highly recommended, since the volumetric gas velocity can be adjusted as required by the drying process independently of the gas velocity required for the movement of particles.

Based on the extensive results obtained on spouted bed techniques by the Institute of Chemical Engineering and Process Research at Kaposvár University, it is established that with an optimized design and an adequate selection of operational parameters this technology lends itself to a wide range of applications in various industries, such as the drying of granular, pasty or pulpy materials with a wide range of possible particle sizes

(Pallai, Szentmarjay, & Mujumdar, 2007). In addition, spouted beds are especially suitable for the drying of heat-sensitive materials, such as seeds, food products, pharmaceuticals and synthetic products, in one or two stages.

One of the fields in which the spouted bed can make a significant advance in the state of technology is the drying of pasty materials and suspensions. These types of currents are used in many processes of the chemical and food industry. They are for example involved in the manufacture of foodstuffs, intermediate organic products, pigments, pharmaceuticals, inorganic sales and the like. The drying of these streams is a complex process for which only partial solutions have been proposed. In many cases, local overheating or crusting make it impossible to supply a good quality product, so that to obtain uniform size, disintegration or crushing is often necessary after the drying process. In some applications spray drying is applicable, but this technology is intensive in energy costs and initial investment.

Because of the wide variety of applications, the drying of pastes and suspensions represents a challenge for spouted bed technology, where numerous works have demonstrated the ability of the spout bed to process this type of feed (Arsenijević, Grbavcić, & Garić-Grulović, 2004; Benelli, Souza, & Oliveira, 2013; Corrêa, Freire, Corrêa, & Freire, 2004; Grbavčić, Arsenijević, & Garić-Grulović, 2000; Kudra & Bartczak, 1989; Mujumdar, 2000; Oliveira & Passos, 1997; Pallai-Varsányi, Tóth, & Gyenis, 2007; Reger, Romankov, & Rashkovskaya, 1976; Schneider & Bridgwater, 1988; Souza & Oliveira, 2005, 2009; Spitzner & Freire, 1998; Spitzner, & Freire, 1998; Szentmarjay & Pallai, 1989). Indeed, the high moisture content of pastes and suspensions means that the optimum drying technology is that guarantees an excellent transfer of heat and mass. Spouted bed dryers with an inert bed provide good conditions for this purpose, since the drying process is carried out on a wide and continuously renewed surface, in a thin layer formed on the surface of inert particles and with intensive contact between the wet material and the drying agent. Inert particles form the fluidized bed (Grbavčić et al., 2000) or spouted bed (Reger et al., 1976) which act as an auxiliary phase, and the suspension is fed to the moving or circulating bed, which provides a large surface for the contact. The wet solid distributed over the wide surface of the inert particles forms a thin layer in which a very short drying process takes place. Due to the friction of the inert particles, the dry thin layer wears away from the surface, and then the fine product is entrained by the air stream and collected in cyclones and / or bag filters.

To prevent the of the bed movement reduction due to the possible agglomeration of inert particles spouted bed dryers with vertical screw conveyors are used, in which the characteristic movement of the material is assured by the action of the conveyor. This type of dryer has been successfully used for the continuous drying of materials of high moisture content (Kudra & Bartczak, 1989; Pallai et al., 2007). In this case, diluted pulps, pulps or suspensions are introduced onto the bed of inert particles circulating through the inner conveyor screw. In this way, an almost homogeneous coating is formed in the form of a film on the surface of the inert particles, whose optimum thickness is 2 to 4 times higher than the primary particle size of the material to be dried. Since the inert particles provide a large contact surface, the heat transfer and mass drying processes are short even with a relatively low wet bulb temperature (Szentmarjay, Pallai, & Regényi, 1996).

In the drying of granular materials, which represent another field of application where the spouted bed has great potential, the optimal parameters are determined on the basis of their chemical composition, physical properties and potential use. For example, the drying of corn and oats to be used to produce feed for livestock can be used at temperatures higher than those used when these grains are planted, because excessive heating can damage the germination capacity. Some seeds require working at temperatures below 30-35 °C. Additionally the quality of the dried product is determined by the drying rate (which as mentioned may cause alterations in the shape and texture of the particle), the temperature and the flow rate of the drying agent, mainly in the initial period.

These conditions make the spouted bed a widely used technology in the drying of this type of material, since this gas-solid contact regime guarantees a remarkable temperature difference between the incoming air and the bed. Numerous examples of the drying of biomass and agricultural products can be found in the Bibliography which has led to the development of a wide range of different dryers based on spouted bed technology (Ando et al., 2002; Becker & Sallans, 1961; Berghel & Renström, 2004, 2014; Bezerra, Amante, de Oliveira, Rodrigues, & da Silva, 2013; Bie, Srzednicki, & Fletcher, 2013; Chhinnan, Bakshi, & Singh, 1978; Chielle, Bertuol, Meili, Tanabe, & Dotto, 2016; Cui & Grace, 2008; Duarte et al., 2004; Filho, Barrozo, Limaverde, & Ataide, 1998; Jumah, Mujumdar, & Raghavan, 1996; Kfuri & Freitas, 2005; Kundu, Datta, & Chatterjee, 2001; Liu et al., 2010; Martins, Reis, Ferreira, & Teixeira, 2011; Martins et al., 2011; Mathur & Gishler, 1955; Nguyen & Price, 2007; M. Olazar, Lopez, Altzibar, Amutio, & Bilbao, 2012; Renström, 2008; Zuritz & Singh, 1982).

The drying of granular materials in spouted bed has been achieved with different geometries of the contactor, but undoubtedly the one of greater industrial application, and consequently the best characterized in terms of fluid dynamics, has been the cylindrical geometry with conical base close to 60º. In these studies, initiated with the classic books of Leva (1959) and Zabrodsky (1967), the movement of the solid-gas system is studied and reliable empirical correlations have been developed for the calculation of properties such as the minimum speed of spouting, maximum head loss or bed expansion.

However, this conventional configuration of the spouted bed has a limited use due to two serious drawbacks that restrict its application on a large scale:

- The capacity is limited by a maximum bed height and column diameter, above which the characteristic central jet is no longer stable. The diameter is usually limited to 1 m to avoid dead zones inside the particle bed.
- The gas flow is conditioned by the requirements of the spouting regime rather than by the heat transfer and mass requirements, so the efficiency of the process is conditioned by hydrodynamics.

Reviewing the literature, it can be seen that different modifications of the original spouted bed (cylindrical with a conical base) have been proposed to improve its performance. These modifications mainly concern the geometry of the contactor and/or the gas inlet to the bed. Given the advanced knowledge of their hydrodynamics and applications, the following should be mentioned: spouted beds of rectangular section (Dogan, Freitas, Lim, Grace, & Luo, 2000; Freitas, Dogan, Lim, Grace, & Luo, 2000; Wiriyaumpaiwong, Soponronnarit, & Prachayawarakorn, 2003), also with rectangular gas inlet conical spouted beds(Al-Jabari, Van De Ven, & Weber, 1996; Bacelos, Neto, Silveira, & Freire, 2005; Bi, Macchi, Chaouki, & Legros, 1997; M. Olazar, San, Aguayo, Arandes, & Bilbao, 1993b, p. 1998; M. Olazar et al., 1993b; M. Olazar, San, Zabala, & Bilbao, 1994; Povrenovié, Hadžismajlovié, Grbavčić, Vuković, & Littman, 1992; San José, Olazar, Peñas, Arandes, & Bilbao, 1995), and spout-fluid beds (Nagarkatti & Chatterjee, 1974; Sutanto, Epstein, & Grace, 1985; Vuković, Hadžismajlović, Grbavćić, Garić, & Littman, 1984). The latter combine the advantages of both spouted beds and bubbling fluidized beds.

Spouted beds with fully conical geometry combine the features of the cylindrical spouted beds (such as the capacity for handling coarse particles, a small pressure drop, the cyclical movement of the particles and so on)with those inherent to their geometry, such as their capacity for stable operation in a wide range of gas flow rates (M. Olazar et al., 1994; Martin Olazar, San, Aguayo, Arandes, & Bilbao, 1992; Martin Olazar, San José, Aguado, Gaisán, & Bilbao, 1999). This versatility in the gas flow rate allows for the handling of particles of irregular texture, both fine particles and those with a wide size distribution, and sticky solids, whose treatment is difficult using other gas-solid contact regimes (Aguado, Olazar, Gaisán, Prieto, & Bilbao, 2003; M. Olazar, San, Aguayo, Arandes, & Bilbao, 1993a; San Jose, Olazar, Penas, & Bilbao, 1994). Moreover, operations in the dilute spouted bed can be carried out using short gas residence times (as low as milliseconds) (M. Olazar, Arandes, Zabala, Aguayo, & Bilbao, 1997; M. Olazar et al., 1993a, 1994).

Conical spouted beds have low segregation (Martin Olazar, San, Penas, Aguayo, & Bilbao, 1993a, 1993b), which allows for the handling of particles with a wide size distribution while experiencing no stability problems. This is an interesting quality for both physical operations, such as drying, and chemical operations, such as waste material pyrolysis, carried out to improve the product distribution and, consequently, to increase their commercial interest (Martin Olazar, Aguado, Bilbao, & Barona, 2000; Martin Olazar, Aguado, San José, & Bilbao, 2001).

A crucial parameter that limits the scaling-up of spouted beds is the ratio between inlet diameter and particle diameter. In fact, the inlet diameter should be no more 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 operating pressure drop are also functions of the type of draft tube used.

A conventional spouted bed with draft tube has proven to be an efficient dryer of simple construction (Costa, Cardoso, & Passos, 2001; Freitas & Freire, 2001; Kfuri & Freitas, 2005), providing a large interface area for gas and solid contact, high heat and mass transfer coefficients, and high production rates. Moreover, the use of a porous draft tube allows for gas percolation to the annular zone (Costa et al., 2001). Nevertheless, large beds in cylindrical contactors (flat or conical bottom) record low particle circulation rates.

In an earlier work of the research group (Altzibar et al., 2008), it was demonstrated the feasibility of conical spouted bed technology applied to the drying of these kind of materials. It was verified that a non-negligible amount of wet sand can be added to a dry sand bed which is homogeneously distributed rapidly without substantially altering the cyclic movement of the particles characteristic of this type of beds and without the generation of instability. However, no studies have been carried out to study the wet bed fluidization. The aim of this paper is to delve into this area, characterizing the wet bed fluidization and the fluidization of dry beds to which sand is incorporated in various proportions.

This research is framed in the joint project of Catalytic Process & Waste Valorization Research group, (University of the Basque Country, UPV/EHU) and Novattia Desarrollos Ltd., technology development company, with the objective of designing a new dryer for fine and ultrafine sands based on spouted bed technology. NOVATTIA Ltd. is a company created in 2010 with the aim of becoming a centre that perform R & D projects that have concrete and viable industrial applications in close collaboration with research centres and universities.

2. Methodology

The equipment used is a contactor (Figure 1a). It consists in a poly(methyl metacrylate) (PMMA) vessel with a height of 1.16 m, D_c= 0.36 m, D_0= 0.068 m and γ= 0.628 rad (36º). The contactor has the possibility to be used with different gas inlet diameters (D_i) and allows including draft-tubes (Figure 1b) at its inlet. In the study D_i=0.05 m has been used, together with a draft tube with 0.5 m of length (H_T), 0.054 m of diameter (D_T) and an aperture ratio of 60%. Moreover, the contactor has a confinement system that consists in a PMMA pipe of 0.2 m diameter and 0.6 m length, having the upper end closed (Figure 1c). All equipment is coupled to an air blower, and particles dragged by the air out of the contactor are retained with a bag filter.

The material used in the study is fine sand with a wide particle size distribution between 0 and 800 μm which a 50% of particles of Geldart's group B, a 49% of group A and a 1% of group C (Figure 2).

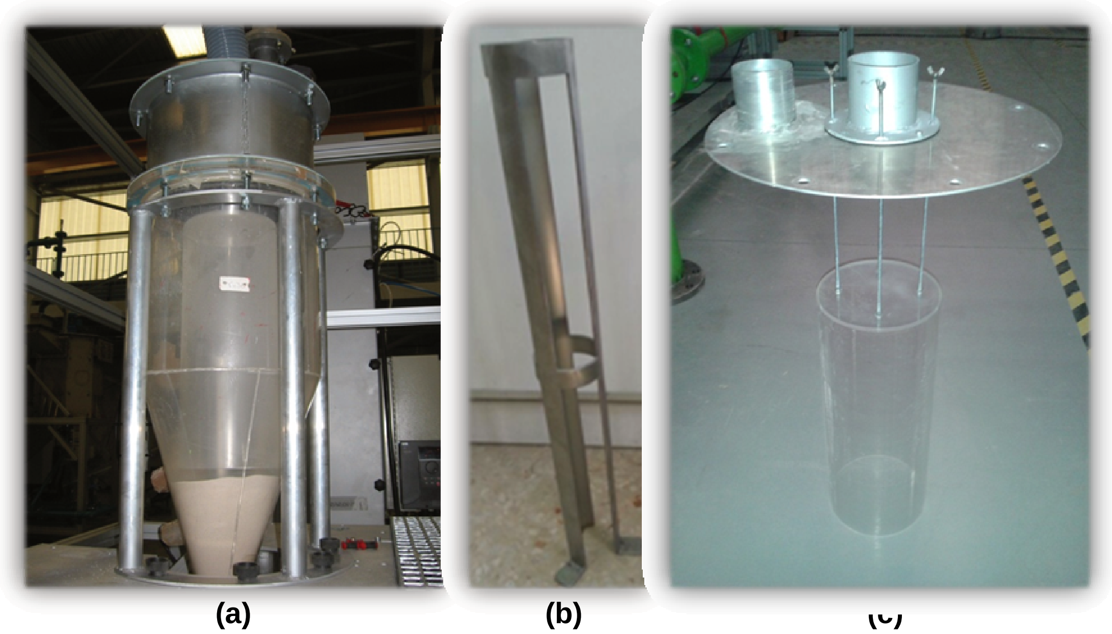


Figure 1: Different images for a) the entire contactor, b) the draft-tube and c) the confinement system used in the study.

Different experiments have been carried out to study the fluiddynamics of the sand, since the behaviour of the material is remarkably dependent of moisture content. Several tests have been performed using a single bed height of 0.25 m and testing two strategies for wetting the bed: a) Loading sand with homogeneous moisture, testing moisture values of 15, 10, 5, 4, 3, 2 and 1% w/w d.b.), and b) mixing experiments in which sand at 15% w/w d.b. was added to an initial dry bed to achieve moisture values after mixing of 4.5, 3.9, 3.1, 2.1 and 1.2% w/w d.b.

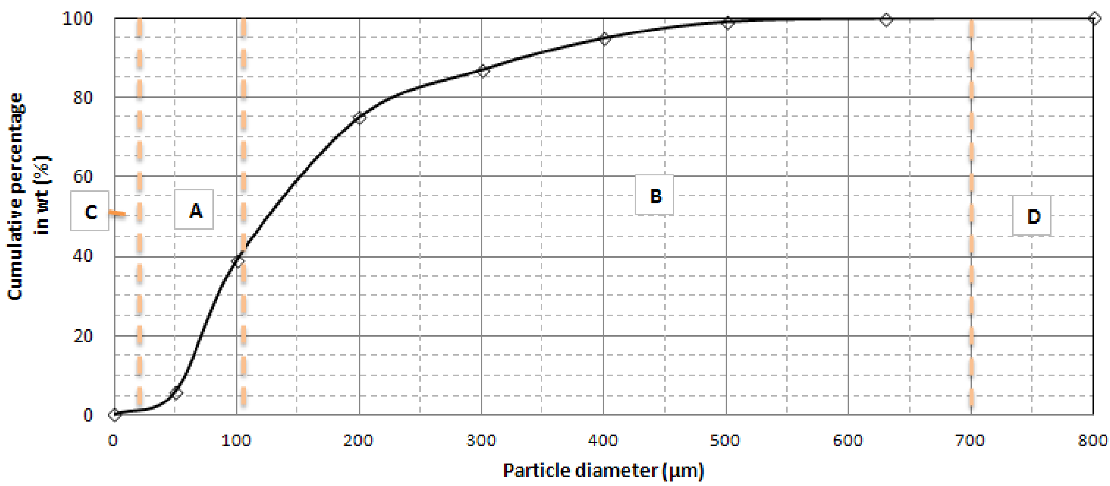


Figure 2: Cumulative percentage of the mass collected on the screens and separation by Geldart's groups for a) Type I sand and b) Type II sand.

3. Results

In experiments with an externally wetted bed, it was found that at a moisture content of more than 2% w/w d.b. is not possible to achieve a proper fluidization, with the characteristic gas and solid movement. Due to the interparticular cohesive forces, the sand grains are held together forming a compact block and the air creates a tubular hole or cavity that crosses the bed, becoming the preferential path of the gas and preventing good circulation of the solid (Figure 3). When it was working with a bed with a moisture content of 2% d.b., although in the first few seconds there are some instability symptoms, the bed rapidly tends to reach the characteristic gas and solid flow conditions of the spouted beds. Finally, working below this value it has been found that the operation of the plant is identical to that achieved with a totally dry bed. Based on this observation, 2% d.b. is established as the limit value for the batch and continuous drying.

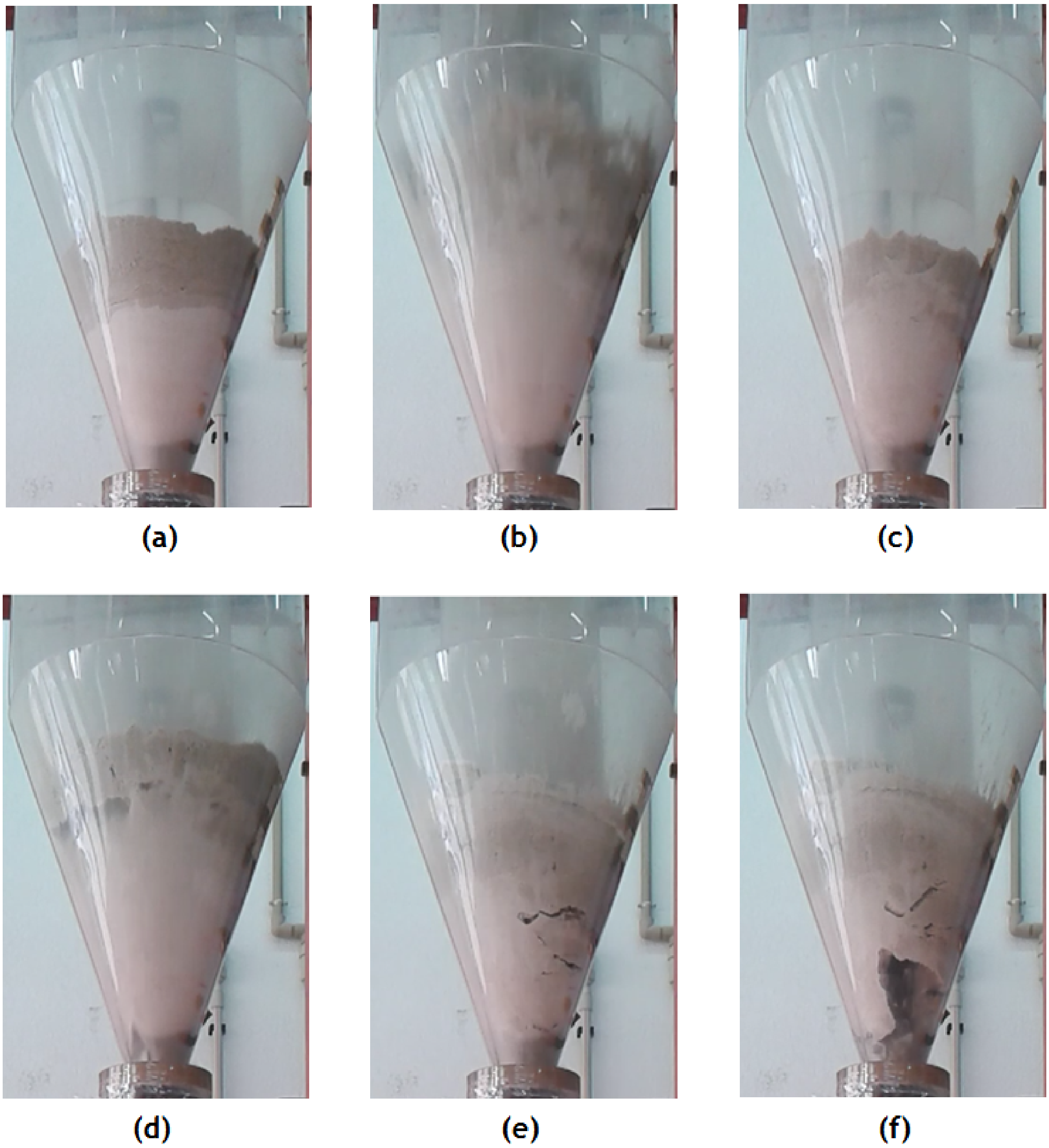
Figure 3: Image of the cavity open when the wet sand is stuck on the walls of the contactor (x_L= 10% d.b.)

In experiments in which wet sand is added to a dry bed it was observed that, as in the previous case, when the moisture of the resulting mixture is greater than 2% d. b. the final result is the same, i.e., static bed with tubular cavity through which the air crosses, Figure 4. However, the process to arrive at this situation is different; in this case it is observed a previous process of mixing with clear symptoms of instability, that results in the collapse of the bed and the formation of the preferential gas path.

As noted, the initially static bed (a) has a lower layer of dry sand and an upper layer of wet sand which prevents movement of the whole bed, thus it is generated a much greater pressure loss than the conventional for the rupture of the bed. When the necessary pressure is reached at the base of the contactor, the bed undergoes a first rupture (b) and returns to fixed bed regime with the sand partially mixed (c). As the flow increases further, the bed undergoes a second rupture and its expansion is clearly seen (d). In this situation, some of the sand has adhered to the walls, the bed is quite mixed but not completely homogeneous and the first signs of the formation of the tubular cavity are observed (e). The dry particles of the lower layer ascend through the spout and settle on top of the upper layers, without a downward circulation in the annular zone, whereby they finally form a preferential path which prevents good contact between the air and the bed (f).

This process occurs only when the resultant mixture between the dry bed and added wet sand has a moisture content higher than 2% d. b. In fact, in an experiment performed with a bed moisture after mixing of 2.21% d.b., steps (a) - (c) are repeated, but after the second rupture there is a movement similar to that achieved with dry sand. In an experiment performed with a bed moisture after mixing of 1.20% d.b., the contactor achieves a good homogenization after the first bed rupture. In this case, fluidization similar to that obtained with dry bed is achieved.

Figure 4: Proceso de creación de la vía preferencial partiendo de un lecho con arena seca y arena húmeda al 15% en b.s. sin mezclar (5.0 kg arena seca, 2.5 kg de arena húmeda)



4. Conclusions

It is concluded that a humidity of more than 2% d.b. in the bed generates serious problems which hinder its fluidization because downward circulation by the annular zone is prevented. This value does not represent a limitation for the use of spouted bed technology applied to the drying of sands, since this value coincides with the minimum drying requirements common in the industry for this type of materials.

This fact is particularly relevant when two or more contactors are required in series. In that case, the first spouted bed should dry the material below 2% w/w d. b. and the next one must lower the moisture content to the required specification.

5. References

Aguado, R., Olazar, M., Gaisán, B., Prieto, R., & Bilbao, J. (2003). Kinetics of polystyrene pyrolysis in a conical spouted bed reactor. *Chemical Engineering Journal*, *92*(1–3), 91-99. https://doi.org/10.1016/S1385-8947(02)00119-5

Al-Jabari, M., Van De Ven, T. G. M., & Weber, M. E. (1996). Liquid spouting of pulp fibers in a conical vessel. *The Canadian Journal of Chemical Engineering*, *74*(6), 867-875. https://doi.org/10.1002/cjce.5450740608

Altzibar, H., Lopez, G., Alvarez, S., San Jose, M. J., Barona, A., & Olazar, M. (2008). A draft-tube conical spouted bed for drying fine particles. *Drying Technology*, *26*(3), 308-314. https://doi.org/10.1080/07373930801898018

Ando, S., Maki, T., Nakagawa, Y., Namiki, N., Emi, H., & Otani, Y. (2002). Analysis of the drying process of seed particles in a spouted bed with a draft tube. *Advanced Powder Technology*, *13*(1), 73-91. https://doi.org/10.1163/15685520252900965

Arsenijević, Z. L., Grbavcić, Z. B., & Garić-Grulović, R. V. (2004). Drying of suspensions in the draft tube spouted bed. *Canadian Journal of Chemical Engineering*, *82*(3), 450-464.

Bacelos, M. S., Neto, P. I. S., Silveira, A. M., & Freire, J. T. (2005). Analysis of Fluid Dynamics Behavior of Conical Spouted Bed in Presence of Pastes. *Drying Technology*, *23*(3), 427-453. https://doi.org/10.1081/DRT-200054116

Becker, H. A., & Sallans, H. R. (1961). Drying wheat in a spouted bed: on continuous moisture diffusion controlled drying of solid particles in a well-mixed isothermal bed. *Chemical Engineering Science*, *13*(3), 97-112. https://doi.org/10.1016/0009-2509(61)80001-8

Benelli, L., Souza, C. R. F., & Oliveira, W. P. (2013). Spouted bed performance on drying of an aromatic plant extract. *Powder Technology*, *239*(0), 59-71.

Berghel, J., & Renström, R. (2004). Controllability of product moisture content when nonscreened sawdust is dried in a spouted bed. *Drying Technology*, *22*(3), 507-519. https://doi.org/10.1081/DRT-120029996

Berghel, J., & Renström, R. (2014). An Experimental Study on the Influence of Using a Draft Tube in a Continuous Spouted Bed Dryer. *Drying Technology*, *32*(5), 519-527. https://doi.org/10.1080/07373937.2013.840648

Bezerra, C. V., Amante, E. R., de Oliveira, D. C., Rodrigues, A. M. C., & da Silva, L. H. M. (2013). Green banana (Musa cavendishii) flour obtained in spouted bed – Effect of drying on physico-chemical, functional and morphological characteristics of the starch. *Industrial Crops and Products*, *41*, 241-249. https://doi.org/10.1016/j.indcrop.2012.04.035

Bi, H. T., Macchi, A., Chaouki, J., & Legros, R. (1997). Minimum spouting velocity of conical spouted beds. *The Canadian Journal of Chemical Engineering*, *75*(2), 460-465. https://doi.org/10.1002/cjce.5450750221

Bie, W. B., Srzednicki, G., & Fletcher, D. F. (2013). Hydrodynamics modeling of corn drying in a triangular spouted bed dryer. *Acta Horticulturae*, *1011*, 169-178.

Chhinnan, M. S., Bakshi, A. S., & Singh, R. P. (1978). Study of high temperature drying of rice in a Spouted Bed. *Paper - American Society of Agricultural Engineers*.

Chielle, D. P., Bertuol, D. A., Meili, L., Tanabe, E. H., & Dotto, G. L. (2016). Spouted bed drying of papaya seeds for oil production. *LWT - Food Science and Technology*, *65*, 852-860. https://doi.org/10.1016/j.lwt.2015.09.022

Corrêa, N. A., Freire, F. B., Corrêa, R. G., & Freire, J. T. (2004). Industrial trials of paste drying in spouted beds under QDMC. *Drying Technology*, *22*(5), 1087-1105. https://doi.org/10.1081/DRT-120038581

Costa, E. F., Cardoso, M., & Passos, M. L. (2001). Simulation of drying suspensions in spout-fluid beds of inert particles. *Drying Technology*, *19*(8), 1975-2001. https://doi.org/10.1081/DRT-100107284

Cui, H., & Grace, J. R. (2008). Spouting of biomass particles: A review. *Bioresource Technology*, *99*(10), 4008-4020. https://doi.org/10.1016/j.biortech.2007.04.048

Dogan, O. M., Freitas, L. A. P., Lim, C. J., Grace, J. R., & Luo, B. (2000). Hydrodynamics and Stabilityof Slot-Rectangular Spouted Beds. Part I: Thin Bed. *Chemical Engineering Communications*, *181*(1), 225-242. https://doi.org/10.1080/00986440008912822

Duarte, C. R., Neto, J. L. V., Lisboa, M. H., Santana, R. C., Barrozo, M. A. S., & Murata, V. V. (2004). Experimental study and simulation of mass distribution of the covering layer of soybean seeds coated in a spouted bed. *Brazilian Journal of Chemical Engineering*, *21*(1), 59-67.

Filho, R. S. C., Barrozo, M. A. S., Limaverde, J. R., & Ataide, C. H. (1998). Use of a spouted bed in the fertilizer coating of soybean seeds. *Drying Technology*, *16*(9-10), 2049-2064.

Freitas, L. A. P., Dogan, O. M., Lim, C. J., Grace, J. R., & Luo, B. (2000). Hydrodynamics and Stability of Slot-Rectangular Spouted Beds Part Ii: Increasing Bed Thickness. *Chemical Engineering Communications*, *181*(1), 243-258. https://doi.org/10.1080/00986440008912823

Freitas, L. A. P., & Freire, J. T. (2001). Gas-to-particle heat transfer in the draft tube of a spouted bed. *Drying Technology*, *19*(6), 1065-1082. https://doi.org/10.1081/DRT-100104805

Grbavčić, Z. B., Arsenijević, Z. L., & Garić-Grulović, R. V. (2000). Drying of suspension and pastes in fluidized bed of inert particles. *Journal of the Serbian Chemical Society*, *65*(12), 963-974.

Jumah, R. Y., Mujumdar, A. S., & Raghavan, G. S. V. (1996). Batch Drying Kinetics of Cornin a Novel Rotating Jet Spouted bed. *Canadian Journal of Chemical Engineering*, *74*, 479-486.

Kfuri, C. R., & Freitas, L. A. P. (2005). A comparative study of spouted and spout-fluid beds for tablet coating. *Drying Technology*, *23*(12), 2369-2387. https://doi.org/10.1080/07373930500340452

Knoule, F. (1968). *El Secado*. Bilbao: Ediciones Urno.

Kudra, T., & Bartczak, Z. (1989). Drying of paste-like materials in screw-type spouted-bed and spin-flash dryers. *Drying Technology*, *7*(3), 583-597. https://doi.org/10.1080/07373938908916612

Kundu, K. M., Datta, A. B., & Chatterjee, P. K. (2001). Drying of Oilseeds. *Drying Technology*, *19*(2), 343-358. https://doi.org/10.1081/DRT-100102909

Leva, M. (1959). *Fluidization*. (I. McGraw Hill Book Co., Ed.). New York. Recuperado a partir de http://www.sciencedirect.com/science/article/pii/0016003259904995

Liu, W., Xie, X., Liu, J., Wang, L., Zhao, R., & Zhao, J. (2010). Co-spouting capabilities of mixture of coal with straw in rotating draft tube spouted bed. *Nongye Gongcheng Xuebao/Transactions of the Chinese Society of Agricultural Engineering*, *26*(7), 134-139. https://doi.org/10.3969/j.issn.1002-6819.2010.07.024

Martins, L. A. B., Reis, M. A., Ferreira, M. E., & Teixeira, J. C. (2011). Drying kinetics of solid biomass (Vol. 4, pp. 857-864). Presentado en ASME 2011 International Mechanical Engineering Congress and Exposition, IMECE 2011.

Mathur, K. B., & Gishler, P. E. (1955). A study of the application of the spouted bed technique to wheat drying. *Journal of Applied Chemistry*, *5*(11), 624-636. https://doi.org/10.1002/jctb.5010051106

Mujumdar, A. S. (2000). Dryers for particulate solids, slurries and sheet-form materials. En S. Devahastin (Ed.), *Mujumdar's Practical Guide to industrial Drying*. Montreal, Canadá: Exergex Corp.

Nagarkatti, A., & Chatterjee, A. (1974). Pressure and flow characteristics of a gas phase spout-fluid bed and the minimum spout-fluid condition. *The Canadian Journal of Chemical Engineering*, *52*(2), 185-195. https://doi.org/10.1002/cjce.5450520209

Nguyen, M.-H., & Price, W. E. (2007). Air-drying of banana: Influence of experimental parameters, slab thickness, banana maturity and harvesting season. *Journal of Food Engineering*, *79*(1), 200-207. https://doi.org/10.1016/j.jfoodeng.2006.01.063

Olazar, M., Arandes, J. M., Zabala, G., Aguayo, A. T., & Bilbao, J. (1997). Design and Operation of a Catalytic Polymerization Reactor in a Dilute Spouted Bed Regime. *Industrial and Engineering Chemistry Research*, *36*(5), 1637-1643.

Olazar, M., Lopez, G., Altzibar, H., Amutio, M., & Bilbao, J. (2012). Drying of Biomass in a Conical Spouted Bed with Different Types of Internal Devices. *Drying Technology*, *30*(2), 207-216. https://doi.org/10.1080/07373937.2011.633194

Olazar, M., San, J., Aguayo, A. T., Arandes, J. M., & Bilbao, J. (1993a). Design factors of conical spouted beds and jet spouted beds. *Industrial and Engineering Chemistry Research*, *32*(6), 1245-1250.

Olazar, M., San, J., Aguayo, A. T., Arandes, J. M., & Bilbao, J. (1993b). Pressure drop in conical spouted beds. *The Chemical Engineering Journal*, *51*(1), 53-60. https://doi.org/10.1016/0300-9467(93)80008-C

Olazar, M., San, J., Zabala, G., & Bilbao, J. (1994). New reactor in jet spouted bed regime for catalytic polymerizations. *Chemical Engineering Science*, *49*(24 PART A), 4579-4588. https://doi.org/10.1016/S0009-2509(05)80042-9

Olazar, Martin, Aguado, R., Bilbao, J., & Barona, A. (2000). Pyrolysis of sawdust in a conical spouted-bed reactor with a HZSM-5 catalyst. *AIChE Journal*, *46*(5), 1025-1033. https://doi.org/10.1002/aic.690460514

Olazar, Martin, Aguado, R., San José, M. J., & Bilbao, J. (2001). Kinetic study of fast pyrolysis of sawdust in a conical spouted bed reactor in the range 400–500 °C. *Journal of Chemical Technology & Biotechnology*, *76*(5), 469-476. https://doi.org/10.1002/jctb.409

Olazar, Martin, San, J., Aguayo, A. T., Arandes, J. M., & Bilbao, J. (1992). Stable operation conditions for gas-solid contact regimes in conical spouted beds. *Industrial and Engineering Chemistry Research*, *31*(7), 1784-1792.

Olazar, Martin, San, J., Penas, F. J., Aguayo, A. T., & Bilbao, J. (1993a). Stability and hydrodynamics of conical spouted beds with binary mixtures. *Industrial and Engineering Chemistry Research*, *32*(11), 2826-2834.

Olazar, Martin, San, J., Penas, F. J., Aguayo, A. T., & Bilbao, J. (1993b). Stability and hydrodynamics of conical spouted beds with binary mixtures. *Industrial and Engineering Chemistry Research*, *32*(11), 2826-2834.

Olazar, Martin, San José, Aguado, R., Gaisán, B., & Bilbao, J. (1999). Bed Voidage in Conical Sawdust Beds in the Transition Regime between Spouting and Jet Spouting. *Industrial & Engineering Chemistry Research*, *38*(10), 4120-4122. https://doi.org/10.1021/ie990228z

Oliveira, I. M., & Passos, M. L. (1997). Simulation of drying suspension in a conical spouted bed. *Drying Technology*, *15*(2), 593-604.

Pallai, E., Szentmarjay, T., & Mujumdar, A. S. (2007). Spouted Bed Drying. En A. S. Mujumdar (Ed.), *Handbook of Industrial Drying* (3.ª ed., pp. 363-384). New York: Taylor & Francis.

Pallai-Varsányi, E., Tóth, J., & Gyenis, J. (2007). Drying of suspensions and solutions on inert particle surface in mechanically spouted bed dryer. *China Particuology*, *5*(5), 337-344.

Povrenovié, D. S., Hadžismajlovié, D. E., Grbavčić, Ž. B., Vuković, D. V., & Littman, H. (1992). Minimum fluid flowrate, pressure drop and stability of a conical spouted bed. *The Canadian Journal of Chemical Engineering*, *70*(2), 216-222. https://doi.org/10.1002/cjce.5450700202

Reger, E. O., Romankov, P. G., & Rashkovskaya, N. B. (1976). Drying of Pastelike Materials in Spouted Beds with Inert Bodies, *40*(10), 2276.

Renström, R. (2008). Mean residence time and residence time distribution when sawdust is dried in continuous dryers. *Drying Technology*, *26*(12), 1457-1463. https://doi.org/10.1080/07373930802412066

San Jose, M. J., Olazar, M., Penas, F. J., & Bilbao, J. (1994). Segregation in Conical Spouted Beds with Binary and Ternary Mixtures of Equidensity Spherical Particles. *Industrial & Engineering Chemistry Research*, *33*(7), 1838-1844. https://doi.org/10.1021/ie00031a025

San José, M. J., Olazar, M., Peñas, F. J., Arandes, J. M., & Bilbao, J. (1995). Correlation for calculation of the gas dispersion coefficient in conical spouted beds. *Chemical Engineering Science*, *50*(13), 2161-2172.

Schneider, T., & Bridgwater, J. (1988). Drying of Solutions and Suspensions in Spouted Beds. En *Proceedings*. Paris, France.

Souza, C. R. F., & Oliveira, W. P. (2005). Spouted bed drying of Bauhinia forficata link extract: the effects of feed atomizer position and operating conditions on equipment performance and product properties. *Brazilian Journal of Chemical Engineering*, *22*(2), 239-247. https://doi.org/10.1590/S0104-66322005000200011

Souza, C. R. F., & Oliveira, W. P. (2009). Drying of herbal extract in a draft-tube spouted bed. *Canadian Journal of Chemical Engineering*, *87*(2), 279-288. https://doi.org/10.1002/cjce.20160

Spitzner, P. I., & Freire, J. T. (1998). Analysis of the Effect of Paste on the Behavior of a Spouted Bed with Inerts. En *Proceedings* (Vol. C, pp. 1936–1943). Thessaloniki-Halkidiki, Greece.

Spitzner, P. I., & Freire, J. T. (1998). Evaluation of Models on the Drying of Pastes in Spouted Beds with Inerts. En *Proceedings* (Vol. C, pp. 2009–2016). Thessaloniki-Halkidiki, Greece.

Sutanto, W., Epstein, N., & Grace, J. R. (1985). Hydrodynamics of spout-fluid beds. *Powder Technology*, *44*(3), 205-212. https://doi.org/10.1016/0032-5910(85)85001-4

Szentmarjay, T., & Pallai, E. (1989). Drying of suspensions in a modified spouted bed drier with an inert packing. *Drying Technology*, *7*(3), 523-536. https://doi.org/10.1080/07373938908916607

Szentmarjay, T., Pallai, E., & Regényi, Z. (1996). Short-Time Drying of Beatsensitwe, Biologically Active Pulps and Pastes. *Drying Technology*, *14*(9), 2091-2115. https://doi.org/10.1080/07373939608917197

Vuković, D. V., Hadžismajlović, D. E., Grbavćić, Ž. B., Garić, R. V., & Littman, H. (1984). Flow regimes for spout-fluid beds. *The Canadian Journal of Chemical Engineering*, *62*(6), 825-829. https://doi.org/10.1002/cjce.5450620613

Wiriyaumpaiwong, S., Soponronnarit, S., & Prachayawarakorn, S. (2003). Soybean Drying by Two-Dimensional Spouted Bed. *Drying Technology*, *21*(9), 1735-1757. https://doi.org/10.1081/DRT-120025506

Zabrodsky, S. S. (1967). Hydrodynamics and heat transfer in fluidized beds. *Aiche Journal*, *13*(2). Recuperado a partir de <Go to ISI>://WOS:A19679049900001

Zuritz, C. A., & Singh, R. P. (1982). Simulation of rough rice drying in a spouted-bed., ed., Washington, D.C., U.S.A., Hemisphere Publishing Corp., 1982, Section 8, 239-247.