CHEMICAL ENGINEERING TRANSACTIONS

VOL. 74, 2019

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.cetjournal.it

Guest Editors: Sauro Pierucci, Jiří Jaromír Klemeš, Laura Piazza

ISBN 978-88-95608-71-6; **ISSN** 2283-9216

DOI: 10.3303/CET1974074

Experimental Analysis of a Rectangular Base Spouted Bed in Continuous Operation

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In this work, the pressure drops and characteristic velocities of a rectangular section spouted bed (RSB) used to fluidize sawdust particles which is a little used wet residue, are reported. The RSB considered was built in acrylic, with dimensions 1000 x 300 x 150 mm^3 and with an air intake opening of 14 by 150 mm^2. The conditions that allowed its continuous operation were sought and analyzed. In a first stage of the study, the fluid-dynamics of sawdust beds was characterized for particles with average sizes of 1.2, 1.7 and 2.4 mm, and with moisture content between 7 and 50 %, for sawdust loads of 400, 500 and 600 g. The characteristic parameters obtained experimentally were compared with predictions made with correlations from literature. In a second stage, a feeding system was installed on one of the walls of the RSB, consisting of a worm screw feeder provided with a variable velocity motor. On the opposite wall, an opening with a circular section of 5 cm in diameter was made to allow the solids to escape. In this unit, the conditions that allowed a stable operation for different feed rates and moisture content of the solids were determined, registering the bed height and the air flow rate. Stationary conditions were determined for sawdust feed rates between 18 and 45 kg/h and air velocities between 0.88 and 1.28 m/s, for the three particle sizes tested. Additionally, it was observed in experiences at room temperature (20 ºC), a decrease in the moisture content of the order of 10 % in 60-minute experiences, which exhibit the potential of the equipment to dry granular solids.

1. Introduction

Filter cakes, sawdust, and solid waste from water treatment plants are physically very different, but with a common characteristic: have a high moisture content, which must be reduced before continuing the next stage of their respective process and/or final disposal. When the solids are of low economic value, it is economically prohibitive to apply traditional drying technologies. Additionally, for all the solids above mentioned, the use of any fossil fuel produces emissions of CO2 adding to the greenhouse effect.

Enormous volumes of sawdust are produced by the forest industry, which can be used like raw material for the manufacture of pellets, boards, and briquettes, as well as in the processes of combustion and gasification of biomass. However, the sawdust obtained directly from a mill bears over 40% moisture content, which reduces its heating value and impairs its use in combustion chambers. In this sense, sawdust drying is fundamental for equipment size reduction, maintaining a suitable combustion temperature and diminishing the pollutant formation [Moreno et al, 2009; Reyes et al., 2008]. Thus, the search for efficient methods to dehydrate solids continues to be of major interest.

Convective drying kinetics are strongly favored by good contact between the wet solid and drying air, especially at elevated temperatures [Kudra and Mujumdar, 2009], although the energy cost presents a limitation for the use of high temperatures. Therefore, a reasonable choice is to optimize drying using air at a suitable velocity, at moderate temperatures. In the analysis of technologies that facilitate particle-fluid contact, fluidization is characterized by maximize fluid-particle contact [Kunii and Levenspiel, 1991; Sahoo & Sahoo, 2013], although solids with water content over 35%, present a very difficult fluidization [Grabowski et al., 1997]. The fluidized bed main disadvantage is its high pressure drop [Kunii and Levenspiel, 1991; Wan, 2008; Law & Mujumdar, 2015].

Paper Received: 22 July 2018; Revised: 25 October 2018; Accepted: 29 January 2019

Please cite this article as: Reyes A., Henriquez-Vargas L., Pailahueque N., Carvajal N., 2019, Experimental Analysis of a Rectangular Base Spouted Bed in Continuos Operation, Chemical Engineering Transactions, 74, 439-444 DOI:10.3303/CET1974074

In this regard, the spouted bed, which presents excellent fluid-particle contact with lower pressure drops, becomes a suitable alternative to dehydrate granular solids. An additional advantage is that the air stream impact in the mass of aggregated particles facilitates their separation and dehydration. Conventional Spouted Beds (CSB) have proven to be suitable for the drying of solids with a wide particle size distribution and irregular texture [Olazar et al., 2011; Tellabide et al, 2017].
Spouted bed technology is useful for drying solids that are sticky, have irregular texture and vary widely in particle size distribution [Olazar et al., 2011; Salikov et al., 2015]. In these driers there are a good solid mixing coupled with satisfactory gas-particle contact, which promote high interphase heat and mass transfer rates [Dotto et al., 2011]. Passos et al. (1994, 2011) indicate that the CSB, characterized by a conical-cylindrical column geometry, has its use for drying essentially limited to pilot-scale operation because of two disadvantages: **a**) The CSB dryer capacity is limited by the bed depth (h) and the column diameter (D) and **b**) The CSB dryer efficiency is restricted by the technique itself, as the gas flow rate is limited by the requirements of the spouting regime rather than those of heat and mass transfer. To facilitate scaling-up, Mujumdar (1984), promoted the concept of two-dimensional spouted beds (2DSBs), in which planar symmetry replaces axial symmetry. Two facing walls are completely vertical and parallel, whereas the other two are vertical with a sloping lower section so that the gas flow, which enters through an open slot at the bottom, diverges as it rises. The volumetric capacity of a 2DSB can be easily increased by extending the bed thickness [Chen, 2008]. Scaling-up can then be achieved by increasing the width and/or the thickness, with or without separating walls [Grace & Lim, 2011]. Passos et al. (2011), based on the results of Kalwar et al. (1991) and Wiriyaumpaiwong et al. (2006), concluded that 2DSB with draft plates ensure stable spouting.
Figure 1 shows the hydrodynamic evolution, starting from the static bed condition A and continuing with the increase in pressure drop with the fluid velocity until it reaches a maximum (ΔP_{Max} at B). With an additional increase of the gas velocity, the bed displays a moderate expansion and a corresponding decrease of pressure drop C due to the increase in bed porosity. Finally, an abrupt spouting leads to a sudden decrease of pressure drop that stabilizes at a nearly constant value D, which is maintained in all the operating range of gas rates. Decreasing the fluid velocity from the point D, the pressure drop remains constant down to the spout collapse E, which compacts the solid particles to some extent and the pressure drop increases again to F. The minimum spouting velocity (U_{ms}) is recorded at E. The whole system hydrodynamics is determined by ΔP_{Max}, U_{ms}, and the U/U_{ms} ratio chosen for a stable spouting (Rovero-2012; Curti, 2015).
In case of a bed of sufficient height the gas in the annulus may reach a superficial velocity close to the minimum fluidization velocity of the solids. In this case, the annulus could collapse into the spout, thus defining the maximum spoutable bed depth h_{Max}. [Mathur & Epstein, 1974]; which depends on vessel geometry, fluid and particle properties. The second fundamental parameter is given by the minimum rate of gas required to maintain the system spouting, the so-called minimum spouting velocity. This can be either determined by an experimental procedure or can be calculated by correlations [Rovero, 2012].
Stable spouting can be obtained by satisfying two hydrodynamic requirements: 1) the bed depth, h_s, must be lower than the h_{max} value, and 2) the gas flow rate must exceed U_{ms}. Several authors have adjusted expressions to predict U_{ms}, see equations 1 [Chen, Z.,2008] and 2 [Costa & Taranto, 2003], as function of the slot width (λ), column width(α), depth (β), bed porosity (ε)and particle diameter (dp). The maximum pressure drop, ΔP_{Max}, can be evaluated with equation 3, which comes from a force balance to the bed of particles.

$$U_{ms} = \sqrt{\frac{\pi}{2}}\left(\frac{d_p \lambda^{1/6}}{\alpha^{2/3}}\right)\sqrt{\frac{2gh_s(\rho_s-\rho_f)}{\rho_f}} \tag{1}$$

$$\frac{U_{ms}}{\sqrt{2gh_s}} = 3.0\left(\frac{\alpha}{\beta}\right)\left(\frac{\alpha}{d_p\phi}\right)^{-0.7}\left(\frac{h_s}{\alpha}\right)^{0.16}\left(\frac{(\rho_s-\rho_f)}{\rho_f}\right)^{0.23} \tag{2}$$

$$\Delta P_{max} = h_s \rho_s (1-\epsilon) \tag{3}$$

The spouted bed operation can be carried out discontinuously or continuously, depending on the requirements of the process [Curti, 2015]. In this study, the conditions in which it is possible to continuously operate a rectangular spouted bed are analyzed.

2. Experimental Procedure

The equipment used (Figure 2) is made of acrylic with 6 mm thick. It has a height of 1000 mm, a width of 300 mm and a depth of 150 mm. The passage of air is through a slot of 14x150 mm, located at the base of the main section, which also has walls that arise in the air intake slot and project at an angle of 60 ° upwards. The feed of solids is made using a worm screw, leaving the solids by overflow in the opposite wall.

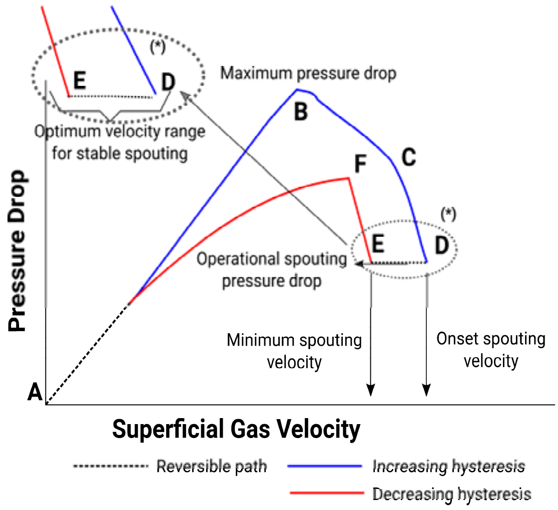

Figure 1. Spouting regime (Rovero, 2012)

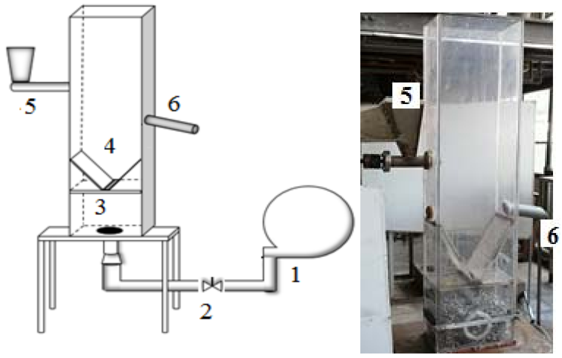

Figure 2. Rectangular section spouted bed.
Left: Sketch with feeding system 1. Blower, 2. Valve, 3. Slot, 4. Bed, 5. Hopper, 6 Solid discharge.
Right: Actual equipment.

3. Results and Discussions

The hydrodynamic parameters (U_{ms}, ΔP_{max}, h_S) were determined in duplicated batch experiences as a function of the solids loading (0.7 and 1.0 kg), for 3 sawdust particle sizes: 1.2, 1.7 and 2.4 mm for a moisture content of 7%. The continuous operation experiments were aimed to determine if steady state operation conditions could be achieved and how long does it take to reach them. As variables we considered two air velocities between 0.88 and 1.28 m/s and worm screw twist velocities (rotation frequency) 14.5 and 16 rpm, for the three sizes of particles and three moisture contents (20, 30 and 50 %).

Figure 3 presents the pressure drop as function of the air velocity for a sawdust load of 0.7 kg and a particle size of 1.7 mm. The shape of the curves is concordant with that described by Curti (2015). Starting from an initial static bed condition, as the gas flow increases, the pressure drop increases through the particle bed until reaching a maximum. Subsequently, as the air velocity continues to increase, it leads to a sudden decrease in pressure drop, the jet passed the surface of the bed, in this condition we find U_{ms}. Table 1 shows these experimental values and the prediction of correlations for U_{ms} and ΔP_{Max}. In equation 4 we adjusted the original numerical factor, corresponding to the group of design values, density of solid and air, considering the influence of d_p, h_s and slot width for 7% moisture content sawdust.

$$\frac{U_{ms}}{\sqrt{gh_s}} = 0.37\left(\frac{\lambda}{d_p}\right)^{-0.378}\left(\frac{h_s}{d_p}\right)^{0.264} \quad (4)$$

The experimental values of U_{ms} presented in Table 1 show that the minimum spouting velocity differs significantly with the predictions of correlations 1 and 2. These differences can be attributed to the fact that they are based on expressions adjusted initially for cylindrical beds. This motivated the adjustment for equation 3, valid for the system under study. The experimental values of ΔP_{Max} and those calculated with equation 4 showed good agreement, being consistent with Dogan et al. (2000) who indicated that the bed static height has influence in the pressure drop and not the particle diameter [Chen, 2008].

Table 1: Experimental and calculated U_{ms} and ΔP_{max} values for 7% moisture content.

Mass [kg]	d_p [mm]	U_{ms} Exp. m/s	Eq. 1 U_{ms} m/s	Eq. 1 % error	Eq. 2 U_{ms} m/s	Eq. 2 % error	Eq. 4 U_{ms} m/s	Eq. 4 % error	hs m	ΔP_{Max} Pascal Exp	ΔP_{Max} Pascal Eq. 3
0.7	2.4	0.96	0.87	10	1.33	28	1.11	10	0.24	355	357
	1.7	0.93	0.59	58	0.99	6	1.00	4	0.22	345	350
	1.2	0.88	0.39	124	0.72	22	0.91	1	0.20	320	334
1.0	2.4	0.99	0.93	6	1.47	33	0.98	2	0.28	429	464
	1.7	0.96	0.64	51	1.10	13	0.88	5	0.26	417	446
	1.2	0.90	0.43	108	0.82	10	0.79	10	0.24	387	426

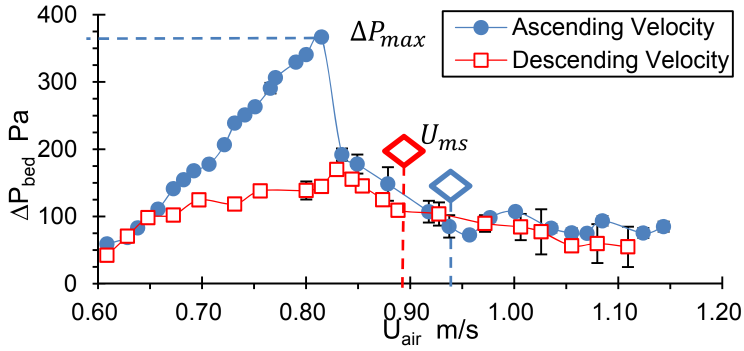

Figure 3. Pressure drop vs air velocity for 0.7 kg solid load with dp = 1.7 mm.

3.1 Continuous operation

Experimental runs had a duration of 60 min seeking the time necessary to reach stationary conditions for different particle sizes, air velocities and rotation frequencies (solid feed flow). The steady state was determined by plotting the discharged sawdust mass as a function of time, see figure 4, in which the first zone (red color) corresponds to the adaptation period, while the blue color corresponds to the stationary condition for which was observed that the level of solids was kept constant. Stationary conditions fluctuations are produced by the experimental procedure used to record the outlet sawdust mass. Table 2 shows steady state results for 7% moisture content sawdust. It can be seen that air velocity variations give for some particle diameters, variations in the feeding mass flow rate up to 50%, since that an increase in the air flow rate implies an increase in the bed height (with an increase in porosity), facilitating the discharge of solids. This effect was more pronounced for rotation frequency of 14.5 rpm and dp = 1.7 and 1.4 mm. The increase in particle size also caused an increase in the time needed to reach the steady state, because for a larger particle size, with the same air velocity, the lower the bed height, causing a decrease in the velocity with which the particles leave the equipment.

3.2 Effect of sawdust moisture content

In these tests, an air velocity was selected that allowed to keep the spout stable and at the same time to minimize the dead zones and the drag of solids to the outside. Sawdust moisture contents used were 20, 30 and 50%. The solid moisture content was determined at the beginning and end of each experimental run. Regarding the operational variables, the particle diameter, the feeding system rotation frequency and the sawdust moisture content were considered, estimating their effect on the stabilization time and the static bed height. Table 3 shows the results corresponding to the time necessary to reach stationary conditions for sawdust with moisture contents of 20, 30 and 50% respectively. Its last column corresponds to the variation of moisture content between the entry and exit of the solids after 1 h of operation. Although the operating temperature is low (20 ºC), a decrease in the moisture content of the solids was observed since the air relative humidity is less than 30%. It can be seen that both the moisture content and the particle diameter are not variables that affect significantly the stationary conditions. Whilst the rotation frequency significantly alters the operational scenarios as an increase from 14.5 to 16 rpm decreases in approximately a 50% the stabilization time almost invariably with the moisture content values of 20 and 30%. Particle agglomeration and formation of dead zones was observed with the moisture content increase as early as 30% difficulting the solid displacement to the slot, coexisting in several opportunities the fixed and spouted bed configuration. Regarding the rotation frequency, it can be inferred that the equipment has an identical behavior in relation to the stabilization time, regardless of the moisture content contained in the solid. On the contrary, for the feeding flow we can deduce that for moisture contents below 20%, the flow increased by 50%, varying between 0.005 and 0.01 kg/s, while at moisture contents between 20 and 50%, it showed a constant increase of 20%, i.e. at 14.5 rpm the value is constant at 0.008 kg/s, while for 16.0 rpm is 0.01 kg/s, regardless of the sawdust moisture content. It was observed that the rotation frequency of 16.0 rpm caused the most changes in the system. This is because a high rotation velocity contributes to minimize solid agglomerations, either due to moisture or size effects, as well as to improve drying performance.

Table 2: Results for 7% moisture content sawdust in stationary conditions.

dp [mm]	Rotation frequency rpm	Air Velocity m/s	Feed solid Kg/s	Stabilization time s
2.4	14.5	0.99	0.005	1020
		1.05	0.010	900
	16.0	0.98	0.010	540
		1.03	0.012	240
1.7	14.5	0.97	0.005	600
		1.06	0.010	480
	16.0	0.96	0.010	480
		1.06	0.010	180
1.2	14.5	0.95	0.010	420
		1.05	0.010	360
	16.0	0.94	0.010	300
		1.04	0.012	180

Table 3: Results for 20, 30 and 50% moisture content sawdust in stationary conditions.

Initial moisture %	dp [mm]	Rotation frequency rpm	Air velocity m/s	Bed Height m	Solid feed rate kg/s	Stabilization time s	Moisture diminished %
20	2.4	14.5	1.08	0.38	0.008	720	9
		16.0	1.04	0.39	0.010	360	12
	1.7	14.5	1.03	0.37	0.008	600	9
		16.0	0.98	0.38	0.010	300	11
	1.2	14.5	0.94	0.36	0.008	480	8
		16.0	0.88	0.37	0.010	180	12
30	2.4	14.5	1.22	0.37	0.008	840	9
		16.0	1.18	0.38	0.010	480	12
	1.7	14.5	1.08	0.36	0.008	600	10
		16.0	1.04	0.37	0.010	300	13
	1.2	14.5	0.98	0.35	0.008	600	9
		16.0	0.92	0.36	0.010	300	13
50	2.4	16.0	1.28	0.35	0.010	720	12
	1.7	16.0	1.21	0.34	0.010	600	10
	1.2	16.0	1.15	0.34	0.010	420	13

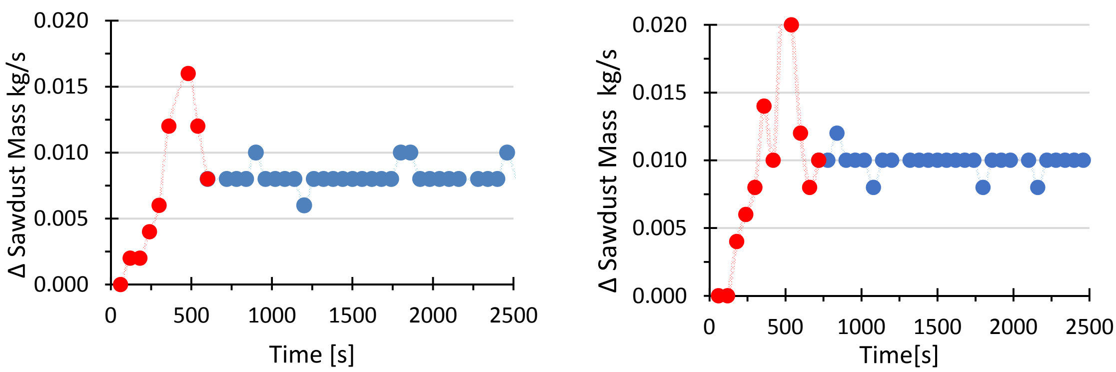

Figure 4. Evolution to steady state with 1 kg of solid load: Left rotation frequency 14.5 rpm, dp = 1.2 mm, 30 % moisture content; Right rotation frequency 16 rpm, dp = 2.4 mm, 50 % moisture content;

4. Conclusions

Variations of particle size and sawdust load did not significantly affect the minimum spouting velocity. The obtained experimental values showed deviations from those predicted by the correlations.
The maximum pressure drop has a strong dependence on the bed static height and weak or no dependence on the particle diameter. The stabilization time is not affected significantly by the moisture content and particle diameter. Whereas the air velocity and rotation frequency have a strong influence on it by facilitating the drying operation with the decrease in both agglomeration and dead zones. The rectangular spouted bed has the potential to perform sawdust drying, since even under ambient temperature conditions, a significant decrease in moisture content was registered.

Acknowledgments

The authors wish to thank the financial support of FONDECYT grant 1180028

Nomenclature

U_{ms}:	Minimum spouting velocity	m/s	h_s:	Static bed height	m	λ:	Slot width	m
ΔP_{Max}:	Maximum pressure drop	Pa	α:	Column width	m	ε:	Porosity	
dp:	Particle diameter	m	β:	Column depth	m	ρ:	Density	kg/m^3

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