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HIDRODYNAMICS AND OPERATIONAL PARAMETERS OF A CONTINUOUS MULTISTAGE VERTICAL FLUIDIZED BED SYSTEM

HIDRODINÁMICA Y PARÁMETROS DE OPERACIÓN DE UN SISTEMA DE LECHO FLUIDIZADO VERTICAL CONTINUO MULTIETAPA

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Abstract

A continuous vertical fluidized-bed dryer operates through a series of downcomers that transfer solids from an upper low-pressure stage to a lower high-pressure one. This work informs on the results testing a system of plastic particles of 0.009m diameter, 1090 kg/m^3 of density, and 0.94 of sphericity, under a counter-current airflow in two pressure stages. Each stage has 0.25m internal diameter Perspex tube and a height of 0.6m. Perspex tubes having 0.032 and 0.057m, internal diameter, fitted with a conic valve at the end of each one were used as downcomers in the experimental system. By using a 2^3 experimental factorial design, it was observed that the fact with the highest influence on the results was the length of bed/ diameter of bed (L/D). It was also found that the downcomer with the widest diameter showed the best behavior when operating with an L/D = 0.5 and an L/D =1, and gave a lower dragging risk as compared to the narrowest diameter.

Keywords: fluidization, fluidized-bed, continuous dryer, downcomer.

Resumen

Un secador de lecho fluidizado vertical continuo opera a través de una serie de vertederos que permiten la transferencia de sólidos desde una etapa superior de baja presión a una etapa inferior de alta presión. En este trabajo se presentan los resultados obtenidos utilizando como sistema de pruebas partículas plásticas de diámetro 0.009m, densidad 1090 kg/m^3 y esfericidad de 0.94, fluidizadas en contracorriente, utilizando dos etapas con presiones diferentes. Cada etapa se construyó en acrílico con un diámetro interno de 0.25m y una altura de 0.6m. El sistema de vertederos, consistió en tubos de acrílico de 0.032 y 0.057m de diámetro interno, con una válvula cónica en el extremo inferior de cada uno. Utilizando un diseño experimental factorial 2^3 se observó que la mayor influencia en los resultados la tuvo la relación longitud del lecho/ diámetro del lecho (L/D). También se encontró que el vertedero de mayor diámetro mostró el mejor comportamiento al operar con una L/D = 0.5 y una L/D= 1.0, presentando menor peligro de arrastre del material comparado con el vertedero de menor diámetro.

Palabras clave: fluidización, lecho fluidizado, secador continuo, vertedero.

1. Introduction

Fluidized bed is widely used for drying, cooling, agglomeration, granulation, and coating of particulate materials. A fluidized state is created by passing a gas through a bed of product under controlled fluid-velocity conditions. This process can be applied to a wide range of both heat-sensitive and non-heat sensitive materials such as chemicals, pharmaceuticals, biochemicals, polymers and food products. In the case of fluidized-bed drying (Davison *et al.,* 1988; Zank *et al.*, 2001; Tanfara *et al.*, 2002) it offers important advantages over other methods of drying particulate materials which size ranges between 50 and 5,000 microns. Some advantages of this process are easy material transport; high rates of heat exchange at high thermal efficiency which prevents overheating of particles. Powders, granules, agglomerates, and pellets can be processed using fluidized bed drying (Mujumdar and Devahastin, 2000).

Continuous operation of fluidized-bed dryers generates an extensive production of dried product. The design of this equipment depends on the characteristics of the material that will be dried. Additionally, continuous fluidized-bed dryers may

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be classified on the basis of the type of flow in the equipment such as perfect mixed, intermediate mixing or plug flow (Missen, 1999).

The perfect mixing behavior observed in solids along the continuous operation of fluidized-bed dryers results in low drying efficiencies, since the processed solids have a wide distribution of moisture content (Mujumdar and Devahastin, 2000; Grbavcic *et al.*, 2004; Reyes *et al.*, 2004). An alternative to narrow this distribution is the multistage operation (Reay, 1986; Davison *et al.*, 1988; Tanfara *et al.*, 2002) since the flow pattern of the solids tends to be less mixed as the number of stages increases, and at the limit, it approximates to a plug flow (Judd and Dixon, 1978; Sauer *et al.*, 1984). The continuous operation of a vertical multistage fluidized-bed dryer gives the additional advantage of higher dry air efficiency (Kunii and Levenspiel, 1991; Svend, 1997; Mujumdar and Devahastin, 2000).

However, the design of downcomers could limit the operation of the equipment (Pell and Dunson, 1999). A properly designed downcomer guarantees the flow of solids between stages without dragging them or clogging the tubes. A good flow of solids has been observed when the pressure drop in the downcomer approaches the pressure drop of the gas when going through the upper stage (Knowlton *et al.*, 1981; Sauer *et al.*, 1984; Pell and Dunson, 1999). In this way, the gas is homogeneously distributed in every stage between the surface of the distributor and the downcomer. In order to regulate the flow of air and solids through the downcomer tube, it is important to keep an adequate ratio of tube diameter to particle size (~6), and to have a valve or a reduction in the lower part of the tube that diminishes the air flow passing through it (Pell and Dunson, 1999; Zank *et al.*, 2001; Zhao *et al.*, 2004).

The present work analyzes the performance of downcomers in a vertical multistage bed-flow dryer, operating continuously at counter-flow, using plastic particles of a type D size according to Geldart (Kunii and Levenspiel, 1991; Svend, 1997; Grieco and Marmo, 2006). The parameters under study are: the diameter of the downcomer, the length/ diameter ratio of the bed, and the presence or absence of a valve at the lower end of the downcomer tube.

2. Experimental Methodology

2.1. Materials.

Polypropylene particles of 0.009m in diameter, density of 1090 kg/m^3, sphericity of 0.94 and minimum fluidizing velocity of 2.2 m/s were used in the experiment.

2.2. Experimental equipment.

Fig. 1 shows the experimental system used in the present study. It consists of two superimposed cylindrical stages made of Perspex, with continuous feeding and discharging in stage 1, as well as a non-circulating discharge of solids in stage 2. The amount of solids in stage 2 equals the amount of solids retained in stage 1. The tube that feeds stage 1 is under the same hydrodynamic conditions as a discharger located between two intermediate stages. Every stage has an internal diameter of 0.25m and a length of 0.6m. Stages are equipped with a distributing plate, which is a perforated aluminum plate with a free area of 25% and a differential manometer, which measures the pressure drop of air when passing through the stage. Air is fed into the system by a variable speed turbo fan, which has maximum flow capacity of 0.382 m^3/s at a discharge pressure of 87.9 kPa. A solid feeder is placed on top of the equipment and operates at a constant flow rate of 0.0012 kg/s.

Perspex tubes with internal diameters of 0.032 and 0.057m were used as downcomers. They had a conic valve at the bottom to regulate the airflow and to control the circulation of solids throughout the system. The distributing plate was placed at the same level as the downcomer, which also sets the height of the fluidized bed.
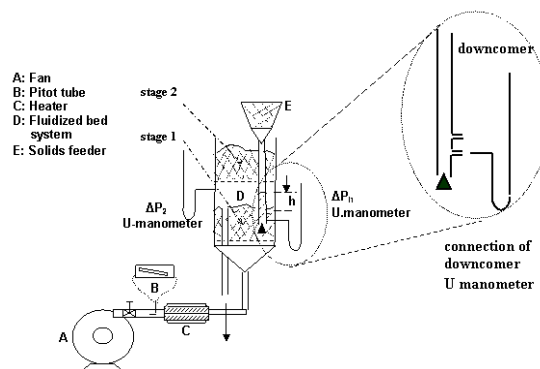

Fig. 1. Experimental set up used to measure the pressure drop.

2.3. Methodology.

Superficial airflow rates were measured in the downcomer tubes and in the main body of empty stage by means of digital anemometer (HTA4200 Digital Higrothermometer, Pacer Industries, Inc.). Particles were added into the system and the same measurements were taken. The pressure drop of the gas when passing through the downcomer, was also measured in stage 1 (ΔP_h), and the total pressure drop in stage 2 (ΔP_2).

Relative values of (ΔP_h) and (ΔP_2) may help to establish criterions to evaluate performance of the system. When $\Delta P_h = \Delta P_2$ solids move smoothly inside the downcomer pipe; air bubbles flow through the downcomer at relatively low velocities and circulation of material is optimum (recommended operating condition). When $\Delta P_h < \Delta P_2$, the air flow is poor and the circulation of the solids is significantly limited (not recommended operating condition). When $\Delta P_h > \Delta P_2$, airflow provokes the formation of

clumps of particles which are thrown towards the upper stage (not recommended operating conditions).

This hydrodynamic behavior was studied by measuring airflow rates and pressure drops in the discharger and the main body of the column, and observing the phenomena that took place inside the equipment. These evaluations were made at different downcomer diameters, different length/bed diameter ratios (L/D) and considering the presence or not of a valve at the end of the downcomer tube. Every experiment was carried out at room temperature. A factorial experimental 2^3 was designed. According to this design, the limits for the variability of each factor were calculated, as shown in Table 1.

Table 1. Variability of the experimental parameters as calculated with a 2^3 factorial design.

PARAMETER	LOWER LEVEL	UPPER LEVEL
DOWNCOMER DIAMETER (m)	0.032	0.057
VALVE AT THE END OF THE DOWNCOMER	NO	YES*
L/D RATIO	0.50	1.0

*80% free flow area determined by preliminary results.

3. Results and Discussion

Preliminary result, an 80% free area is needed at the end of the discharger, so that solids can slide through the tube for the upper level of the discharge valve diameter. The lower level corresponds to the removal of the accessory. The different downcomer diameters and the L/D ratio were established according to the dimensions of the column and the solid particles used in this study (Knowlton *et al.*, 1981; Davison *et al.*, 1988).

Table 2 presents the ranges of airflow rate (ΔU_o) that allowed a good circulation of solids through the system, as well as the critic airflow (U_A) that onsets particle dragging through the downcomer tube. Air flow diminishes when setting up a valve at the end of the downcomer. Presence of conical valve

generates an increment in superficial velocity of air at the bottom of the downcomer. This velocity decreases along the pipe. This phenomenon diminishes dragging of the solids, independently of the downcomer diameter and L/D ratio, and therefore increasing the operational capacity of the system. Size of the downcomer and the L/D ratio did not cause relevant differences in the operation of the system.

In Table 3, the mean heights (h) reached by particles into downcomers are shown for different operating conditions. It is noteworthy that for L/D = 1, h values are significantly higher than for L/D = 0.5 independently of diameter of downcomer and presence of conical valve. This may cause dragging of particles and blockage of downcomer (Kunii and Levenspiel, 1991; Pell and Dunson, 1999). Also, in Table 3, pressure drop values in the downcomer are shown along with those of the gas phase through second stage under normal fluidization conditions and close to critical fluidization (beginning of dragging). The higher the L/D ratio, the higher the pressure drops across the system. Tests 2, 3 7 and 8 meet the earlier established criterion for a good operation ($\Delta P_h = \Delta P_2$). On the other hand, operation for test 7, reached dragging conditions ($\Delta P_h > \Delta P_2$). In tests 3 and 8 vigorous slugging was observed due to increased air velocity into downcomer.

Table 2. Superficial air velocity in the column at various operating conditions

Test	d_V (m)	valve	L/D	ΔU_O range (m/s)	U_A (m/s)
1	0.032	no	0.5	2.3 → 4.0	4.2
2	0.057	no	0.5	2.8 → 3.4	4.1
3	0.032	yes	0.5	5.4 → 7.4	**
4	0.057	yes	0.5	3.5 → 6.5	**
5	0.032	no	1.0	2.9 → 3.4	4.4
6	0.057	no	1.0	2.6 → 3.9	4.2
7	0.032	yes	1.0	2.5 → 3.1	3.5
8	0.057	yes	1.0	4.4 → 6.8	**

** No dragging conditions into the downcomer were achieved.

Table 3. Hydrodynamic behavior of the downcomer, according to three experimental set ups: constant 7 ms^{-1} air flow rate, fluidization and critic conditions.

Test	d_V (m)	Valve	L/D	h (m)	ΔP_h (Pa)	ΔP_2 (Pa)	ΔP_h (Pa)	ΔP_2 (Pa)	Downcomer (hydrodynamic behavior)
					Normal fluidization conditions		Dragging conditions (critical)		
1	0.032	no	0.5	0.12	618	520	1030	637	SS → D
2	0.057	no	0.5	0.15	589	589	981	736	B → D
3	0.032	yes	0.5	0.18	608	608	883	706	B → S
4	0.057	yes	0.5	0.17	687	736	883	834	B → LS
5	0.032	no	1.0	0.25	1177	1324	1815	1275	S → D
6	0.057	no	1.0	0.26	1275	1324	1766	1373	B → D
7	0.032	yes	1.0	0.31	1226	1226	1766	1373	S → D
8	0.057	yes	1.0	0.26	1373	1373	1766	1373	B → SS

S: slugging; SS: Strong slugging; LS: low slugging; B: bubbling; D: dragging.

In test 1, where $\Delta P_h > \Delta P_2$, a strong flow of air prevails together with a strong slugging, even at normal operational conditions. On the other hand, in tests 5 and 6 ($\Delta P_h < \Delta P_2$) the pressure drop ratio inverts itself as the airflow rate increases, which favors dragging at the critical point. The best operating conditions of the system were found in test 4, when passing from bubbling to a low (soft) slugging of particles.

Figs. 2 and 3 show the values of pressure drops at the downcomer as a function of airflow rate. These values can also be observed in table 3. In every case, three well-delimited zones can be distinguished: low, intermediate and high airflow rate. The low rate zone (Uo < Umf) corresponds to the flow of gas through empty spaces left by the static solids. In the intermediate rate zone, bubbling (B) and slugging (S) are found and pressure drops remain relatively constant. In the last zone, dragging (D) of solids prevails together with an important decrease of pressure in the column ΔP_2 (see Table 3).
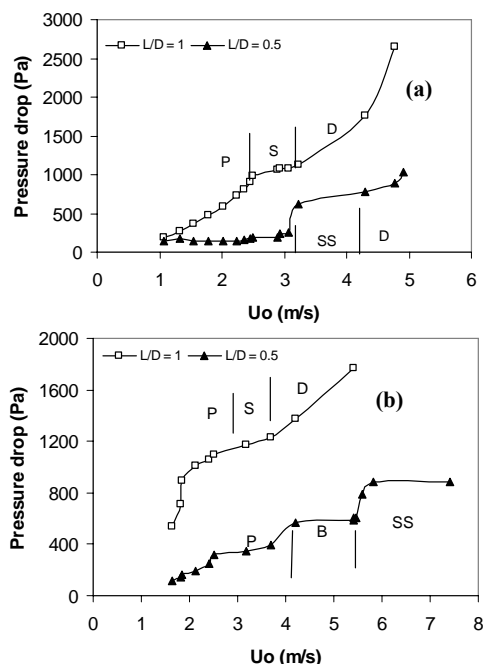

Fig. 2. Hydrodynamic behavior of the 0.032 m downcomer corresponding to L/D 1.0 and 0.5; (a) without valve, (b) with valve.

In the case of the 0.032m diameter downcomer, favorable conditions for solid dragging are found as the ratio L/D increases. However, the presence of the valve decreases this effect.

In the case of the downcomer with a diameter of 0.057m, a better behavior, regarding flow of particle in the downcomer tube, was observed respect to the 0.032 m diameter while maintaining a tendency towards dragging as the L/D ratio increases. As it may be seen in Fig. 3b, 0.057m diameter downcomer with valve can operate with

better condition than the 0.032m one (Fig. 2b) , even increasing the L/D to 1 where a strong slugging (SS) is observed.
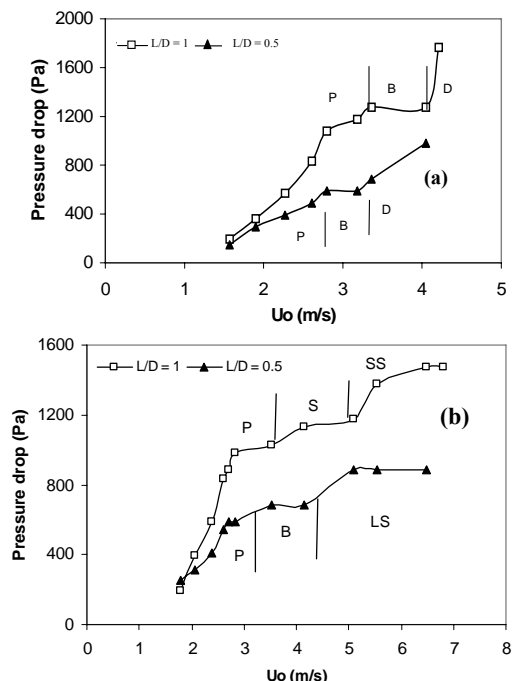

Fig. 3. Hydrodynamic behavior of the 0.057m downcomer internal diameter corresponding to L/D 1.0 and 0.5; (a) without valve, (b) with valve.

Conclusions

The presence of a conic valve at the end of the downcomer favors the operational conditions of the system, an increase of the local superficial air flow rate, which decreases as it goes inside the downcomer by decreasing the risks for dragging or clogging of the solids, independently of the downcomer diameter and L/D ratio, and therefore increasing the capacity of the system. However, the L/D ratio has a direct effect on the pressure drop through the system, which may affect the operational costs. For L/D equals 1.0, the height of the bed of particles retained into the downcomer is higher than for L/D of 0.5. The pressure drops at the downcomer is a function of airflow rate. In every case, three zones can be distinguished. A low rate zone (Uo < Umf) in which the flow of gas through empty spaces left by the static solids. An intermediate rate zone with existence of bubbling (B) and slugging (S), and pressure drops relatively constant. And in the last zone, the dragging (D) of solids prevails with an important decrease of pressure. The best operating conditions of the system were observed when passing from bubbling to a low (soft), but at the critical point of the operation, where $\Delta P_h > \Delta P_2$, dragging conditions were reached and a strong flow of air at the downcomer can produce a strong

slugging. The diameter of the downcomer affects the capacity of solid treatment and the risks for dragging.

Acknowledgment

Notation

d_v downcomer diameter (m).
D fluidized-bed diameter (m).
h height of the particles in the downcomer with respect to the level of the fluidized bed (m).
L height of the static bed (m).
ΔP_2 pressure drop through the second stage (kPa).
ΔP_h pressure drop in the downcomer (kPa).
U_A dragging velocity in the downcomer (m s^{-1}).
ΔU_O superficial air flow rate range (m s^{-1}).

References

Davison, J. F., Clift, R., and Harrison, D. (1988). *Fluidization*. (2nd ed.). Academic Press, New York.

Grbavcic, B. Z., Lj, A. Z. and Garic-Grulovic, V. R. (2004). Drying of slurries in fluidized bed of inert particles. *Drying Technology*, *22*(8), 1793-1812.

Grieco, E. and Marmo, L. (2006). Predicting the pressure drop across the solids flows rate control device of a circulating fluidized bed. *Powder Technology. 161*(2), 89-97.

Judd, M.R., Dixon, D.P. (1978). The flow of fine, dense solids down a vertical standpipe. *AIChE Symosium Series*, *74*(176), 38-44.

Knowlton, T. M., Aquino, Ch., Hiram, I. and Sishtla, Ch. (1981). Void-gas stripping in standpipes. *AIChE Symposium Ser*ies. *77*(207), 184-198.

Kunii D., and Levenspiel O. (1991). *Fluidization Engineering*. (2nd ed.). Butterworth-Weinemann, London.

Missen, R. W., Mims, Ch. A. and Saville, B.A. (1999). *Introduction to Chemical Reaction Engineering and Kinetics*. John Wiley and Sons Inc.

Mujumdar, A. S. and Devahastin, S. (2000). *Fluidized Bed Drying Technology. Mujumdar´s Practical Guide to Industrial Drying*. (Devahastin, S. ed.). Exergex Corp. Canada.

Pell, M. and Dunson, J. (1999). Gas-solid operation and equipment. In: *Perry's Chemical Engineers' Handbook*. (7th ed.). (Perry, R. H., Green, D. W., and Malone, J. O., eds.), Section 17, Pp. 1-14. Mc Graw-Hill, U.S.A.

Reay, D. (1986). *Fluid Bed Drying in Gas Fluidization Technology*. John Wiley & Sons Ltd. ed., USA,.

Reyes, A., Eckholt, M. and Alvarez, P.I. (2004). Drying and heat transfer characteristics for a novel fluidized bed dryer. *Drying Technology*, *22*(8), 1869-1895

Sauer, R.A., Chan, I.H. and Knowlton, T.M. (1984). The effect of system and geometrical parameters on the flow of class-B solids in overflows standpipes. *AIChE Symposium Series. 80*(234), 1-23.

Svend, H. (1997). Fluidized Bed Drying. In: *Handbook of Industrial Drying*. (Mujumdar, A. S., ed). Marcel Dekker. Inc. New York.

Tanfara, H., Pugsley, T. and Winters, C. (2002). Effect of particles size distribution on local voidage in a bench-scale conical fluidized bed dryer. *Drying Technology. 20*(6), 1273-1289.

Zank, J., Kind, M. and Schlünder, E. U. (2001). Particle growth in a continuously operated fluidized bed granulator. *Drying Technology. 19*(8), 1755-1772.

Zhao, L., Pan, Y., Li, J., Chen, G. and Mujumdar, A. S.(2004). Drying of a dilute suspension in a revolving flow fluidized bed of inert particles. *Drying Technology*, *22*(1&2), 363-376.