Effect of the Entrainment Zone on the Solid Cross-flow in Conical Spouted Beds with a Draft Tube

María J. San José*, Sonia Alvarez, Francisco J. Peñas, Iris García

***Abstract*— In order to design the conical spouted beds with a non-porous draft tube, the solid cross-flow from the annular zone to the entrainment zone has been analyzed by carrying out the study with beds consisting of solids of different density and shape. Solid cross-flow has been determined from the variation of the solid circulation rate along the entrainment zone calculated by the experimental mass flow of particles determined by means of an optical fibre probe at a given longitudinal position at the entrainment zone. The effect of the height of the entrainment zone on solid flow as well as on solid cross-flow is analyzed.**

***Index Terms*— conical spouted beds, draft tube; solid circulation rate; solid cross-flow; solid flow rate**

I. Introduction

THE spouted bed technology in conical geometry of the contactor is very useful for applications where a vigorous movement of the solids is required, as happens in the handling of solids that are sticky, of irregular texture and with a wide particle size distribution [1-7]. Moreover, the conical spouted bed is successful for wastes treatment, especially biomass wastes, [3, 5-8] mainly because avoids the stickiness, particle segregation. This technology has been successfully proven for treatment of coarse and sticky particles with a wide particle size distribution and low segregation [1-2]; with great particle distribution with low segregation [4]; for biomass treatment [9-12], for cork wastes [13]; for sawdust and wood wastes [3] and for drying of sludge from paper industry [14].

The knowledge of solid flow pattern in spouted beds with a draft tube is of great interest for the design, scaled up and optimizing of this equipment, because solid trajectories should fit the requirements of the process carried out. A further interesting aspect in solid flow modelling combined with a model proposed for gas flow [15] is the solid cross-flow rate from the annular into the spout zone. The potential interest relies in knowing the adequate operating conditions for a given application, in which a defined solid trajectory in the contactor is required.

Aiming in widening applications of spouted beds, modifications such as the insertion of internal devices in the contactor have been developed in the literature. The use of a draft tube decreases gas flow [16]; uniformizes particle trajectories, narrows the frequency distribution of cycle times of particles and reduces energy consumption [17].

Several authors have determined the solid cross-flow in conventional spouted beds without a draft tube by means of a model applied into the spout in the lower conical section at the base of cylindrical beds [18]; by a mechanism of interparticle collisions at the interface [19] and by means of mass and momentum conservation equations in cylindrical spouted beds of flat bottom [17, 20]. There are some studies in the literary regarding to solid flow in spouted beds with a draft tube. Saadevandi and Turton [21] determined solid flow mass by using a computer-based video imaging technique in a semicircular semicircular spouted bed with a draft tube. Zhao et al. [22] calculated solid circulation rate from the particle velocity at the annular zone of cylindrical-conical spouted bed with a draft tube. Li et al. [23] determined solid circulation rate in a flat-based spouted bed with a draft tube by simulation with a Eulerian-Eulerian granular kinetic model.

In previous papers, the effect of the operating variables on the solid circulation rate along the spout and on the solid cross-flow from the annulus into the spout zone has been studied in conical spouted beds without draft tube with beds consisting of uniform beds of glass spheres of different particle diameter [24] and with beds consisting of solids of different density and shape [25] by means of mass conservation equation.

In this paper, the solid flow rate in conical spouted beds with a draft tube with beds consisting of solids of low density is calculated by the experimental mass flow of particles determined by means of an optical fibre probe at a given longitudinal position at the entrainment zone. From the experimental measurement of solid flow rate along the entrainment zone, the solid cross-flow rate from the annulus into the entrainment zone in conical spouted beds with a draft tube is determined. Furthermore, the effect of the height of the entrainment zone on solid flow and on solid cross-flow is analyzed.

II. Experimental

The experimental unit, Figure 1, designed at pilot plant

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scale [1] consists basically of a blower, two mass-flow meters for flow rate measurement, both controlled by computer, and probes for measurement of static and dynamic pressure connected to a computer.

Conical contactors made of PMMA (polymethylmethacrylate), Figure 2, have been used whose dimensions are shown in Table I. The draft tube, shown in Figure 2, is a cylindrical tube made of PMMA inserted centrally at the bottom of the contactor, locating the top of the draft tube at the same level that the upper bed surface [16-17], whose geometric factors are summarized in Table I. The thickness of the used draft tube has been chosen in order not to affect the hydrodynamics. The minimum value of the height of the entrainment zone has been determined experimentally for a viewpoint of the clogging of solid particles used and the length of the draft tube, l_d, has been calculated as $l_d = H_o - h_d$ [16]. Different tube lengths and entrainment zone heights have been used.

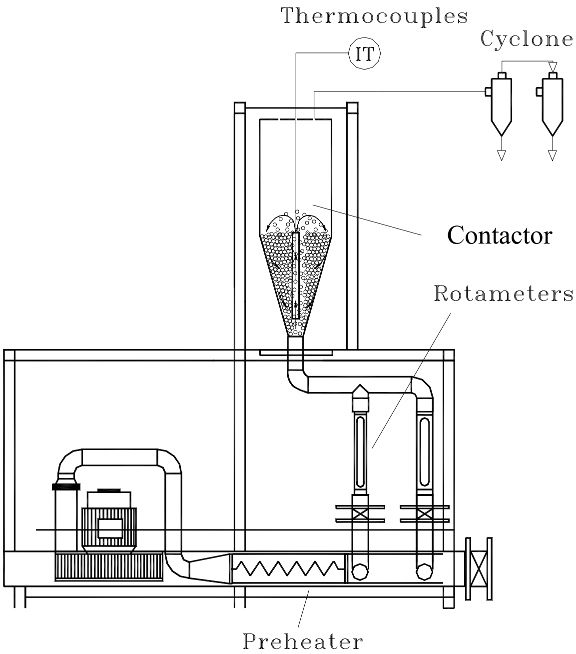

Fig. 1. Schematic diagram of the experimental unit.

TABLE I
GEOMETRIC FACTORS OF THE CONTACTOR AND OF THE DRAFT TUBE

Parameter	*Symbol*	*Value*
Conical contactor (PMMA)		
Column diameter	D_c (m)	0.36
Diameter of the contactor base	D_i (m)	0.06
Angle of the dryer base	γ (deg)	between 28 and 45
Height of the conical section,	H_c (m)	from 0.60 to 0.36 m
Gas inlet diameter	D_o (m)	0.03, 0.04 and 0.05
Draft tube (PMMA)		
Inside diameter	d_d (m)	0.03, 0.04 and 0.05
Thickness	t_d (m)	0.002
Height of the entrainment zone	h_d (m)	from 0.04 to 0.20
Length	l_d (m)	from 0.01 to 0.31
Draft tube to effective particle diameter ratio	d_d/d_e	between 5 and 50
Height of the entrainment zone to particle diameter ratio	h_d/d_e	≥ 10

The study has been carried out with beds consisting of materials of lower density: high-density polyethylene (HDPE), polypropylene (PP), and two types of polystyrene (PS), extruded and expanded. Table II shows the properties of the plastic materials, which have been used as supplied by Dow Chemical. The stagnant bed heights studied are between 0.05 and 0.35 m. The experimental study has been carried out at stable spouted bed regime at minimum spouting velocity, u_{ms}, and at velocities 20% and 30% above this value.

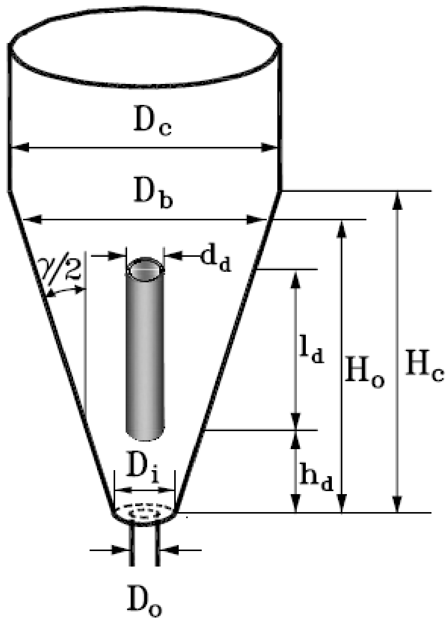

Fig. 2. Geometric factors of the conical contactor and of the draft tube.

TABLE II
PHYSICAL PROPERTIES OF THE SOLID PARTICLES

Solid properties				
Material	ρ_s *(kg/m³)*	d_p *(mm)*	ϕ	ε_o
Extruded PS	1030	3.5	0.80	0.36
		2.5	0.80	0.35
		1.5	0.80	0.34
HDPE	940	3.5	0.92	0.36
LDPE	923	3.5	0.95	0.34
PP	890	3.5	0.90	0.36
Expanded PS	65	3.5	0.95	0.32

The probe used for determining the geometry of the entrainment zone and for counting the number of ascending particles in the entrainment zone was described in previous papers [24-27] and consists of a casing of stainless steel which contains three optical fibres in parallel, Figure 3. The reflected light is collected in succession by the two fibres located at the extremes. A vertical displacement device positions the probe in front of the contactor hole, at the level at which the measurement is to be carried out. The probe is manually placed in the radial position in the bed, through holes made in the contactor wall (every 20 mm height). Grooves marked on the probe allow for setting the radial position in the bed within a maximum error of 1 mm. The interface between the entrainment zone and the annulus is delimited by the differences in the signals of the optical probe. When the tip of the probe is in the annulus, the signal is formed by wide peaks, corresponding to particles moving downward slowly, whereas in the entrainment zone the signal is formed by narrow and pronounced peaks

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corresponding to particles ascending at high velocity. These measurements have been carried out at 20 mm intervals of the bed level and at 2.5 mm intervals for radial positions of the probe with an experimental error of ±1.25 mm [27]. The high bed voidage (< 0.95) obtained in the entrainment zone allows for counting of the number of particles rising within a time range, given that each peak corresponds to one particle. Particles are identified with peaks in the signal of the optical fibre [24] and each measurement has been repeated five times at each position with the average relative error of ±2%.

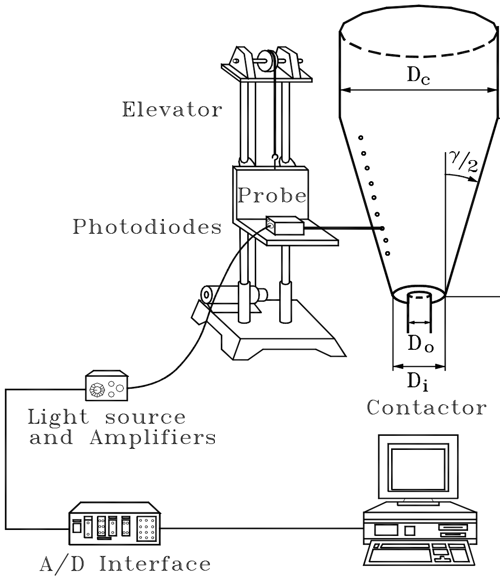

Fig. 3. Diagram of the equipment of optical fibre probe.

III. RESULTS

A. *Hydrodynamics of conical spouted beds with a draft tube*

The spouted bed regime in conical spouted beds with a non-porous draft tube is characterized by different regions: the spout, the draft, the annulus and the fountain. Particles move upwards in the spout and in the draft zones up to the fountain where are spread over the upper surface of the annulus, subsequently particles descend through the annulus up to the entrainment zone from which return to the spout zone. In spout and draft zones exists a gas-solid concurrent contact, whereas in the annular region around the draft tube a countercurrent contact occurs which improves both mass and heat transfer. Although this transfer is lower than in systems without a draft tube due to both gas and solids can not cross draft tube wall, the improvement in bed stability [16] and the energy-saving [17] overcomes this disadvantage.

An outline of the evolution of particle population in the different regimes is shown in Figure 4. Beginning in the fixed bed, Figure 4a, as gas velocity is increased stable spouted bed regime is obtained, Figure 4b, increasing gas velocity, both annular and spout zones become progressively confused (transition zone), Figure 4c, and increasing gas velocity jet spouting regime (dilute spouted bed) [28] is reached, Figure 4d.

B. *Solid cross at the spout zone*

The solid mass flow at a given longitudinal position in the entrainment zone, Q(z), has been calculated by means of the number of ascending particles counted by the optical fibre probe as:

$$Q(z) = \frac{1}{6}\pi d_p^3 \rho_S \iint_S n_z \, dS = \frac{1}{6}\pi d_p^3 \rho_S \int_0^{r_S} 2\pi n_z \, r \, dr \qquad (1)$$

where n_z is the number of ascending particles by unit time and unit surface at a given radial position in the spout.

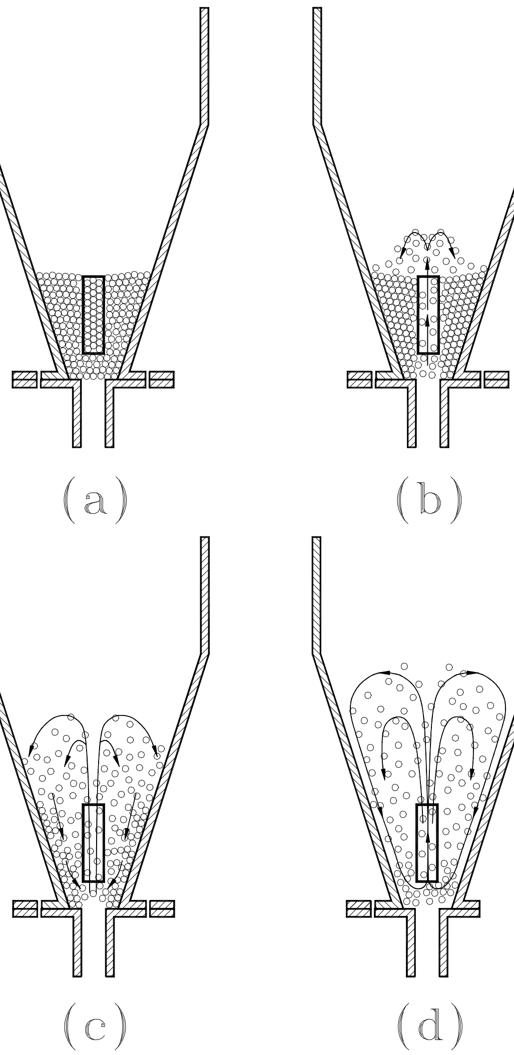

Fig. 4. Diagram of the equipment of optical fibre probe.

The values of Q(z) at different longitudinal positions have been calculated by solving of eq. (1) as the addition of the n_z values measured by means of the optical fibre at radial positions every 1 cm. At each bed level, the number of measurements depends on the diameter of the spout at this level.

The longitudinal profile of the solid flow in the entrainment zone is shown in Figure 5 for a system taken as an example (γ = 33º, D_o = 0.03 m, H_o = 0.15 m, u = u_{ms}, extruded PS of d_p = 3.5 mm, h_d = 0.05 m, l_d = 0.10 m, d_d = 0.04 m) together with the values reported by Zhao et al. [24] in a cylindrical-conical spouted bed with a draft tube. Taking into account that at a given bed level in the solid flow ascending through the entrainment zone is equal to the

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one descending through the annular zone, Figure 5 gives information on solid circulation throughout the entire bed.

From these results, it is determined that at the entrainment zone the solid flow rate increases from the contactor base with bed level below the draft tube and subsequently remains constant inside the non-porous draft tube due to the non solid cross-flow through the tube.

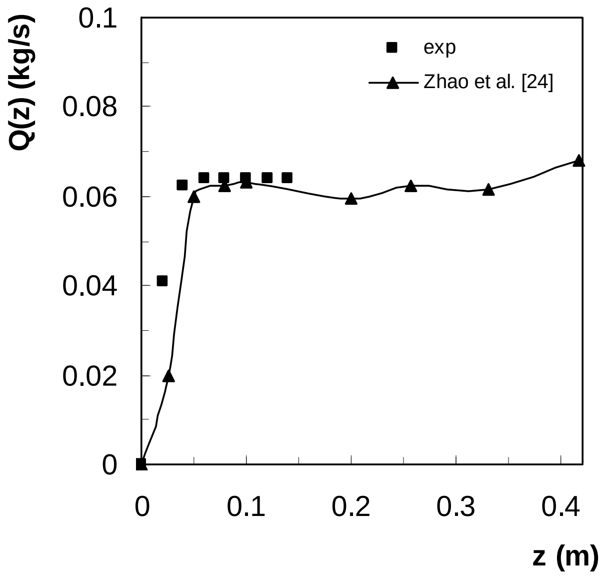

Fig. 5. Longitudinal profile of solid flow rate in the spout zone. Experimental system: γ = 33º, D_o = 0.03 m, H_o = 0.15 m, u = u_{ms}, h_d=0.05 m, l_d= 0.10 m, d_d = 0.04 m, extruded PS of d_p = 3.5 mm.

The effect of the height of the entrainment zone is shown in Figure 6, in which the solid flow at the entrainment zone is plotted for the experimental system γ = 33º, D_o = 0.03 m, H_o = 0.15 m, u = u_{ms}, LDPE d_p = 3.5 mm, d_d = 0.04 m, with different values of the height of the entrainment zone h_d = 0.04, 0.06 and 0.08 m and l_d = H_o - h_d. As can be seen in this Figure the increasing in the height of the entrainment zone gives way to an increasing in solid flow at the entrainment zone. The values of solid flow obtained in the experimental systems studied are consistent with the values of solid circulation rate reported by Saadevendi and Turton [23], by Zhao et al. [24] up to height corresponding to the conical section cylindrical-conical spouted bed with a draft tube and by Li et al. [25].

C. *Solid cross-flow at the entrainment zone*

The variation of the circulation rate along the entrainment zone, dQ(z)/dz, is due to the solid cross-flow from the annular zone into the entrainment zone through the interface.

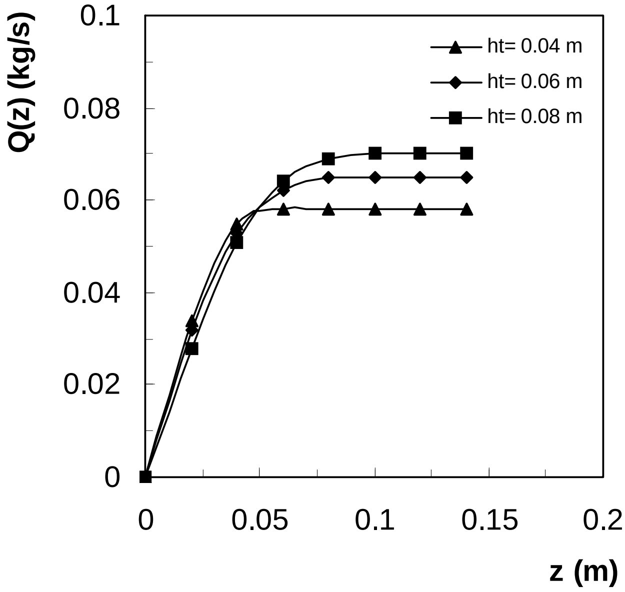

Fig. 6. Longitudinal profiles of solid flow rate in the spout zone. Experimental system: γ = 33º, D_o = 0.03 m, H_o = 0.15 m, u = u_{ms}, d_d = 0.04 m, h_d= 0.04, 0.06 and 0.08 m, l_d= H_o - h_d, LDPE of d_p = 3.5 mm.

In Figure 7 the longitudinal profile of the solid cross-flow rate from the annulus to the entrainment zone is plotted for a system taken as an example (γ = 33º, D_o = 0.03 m, H_o = 0.15 m, u = u_{ms}, extruded PS of, d_p = 3.5 mm, h_d = 0.05 m, l_d = 0.10 m, d_d = 0.04 m). As can be observed, solid cross-flow increases from zero value at the base of the contactor, subsequently passes through a maximum value and descends to zero value at the height corresponding to the lower edge of the draft tube.

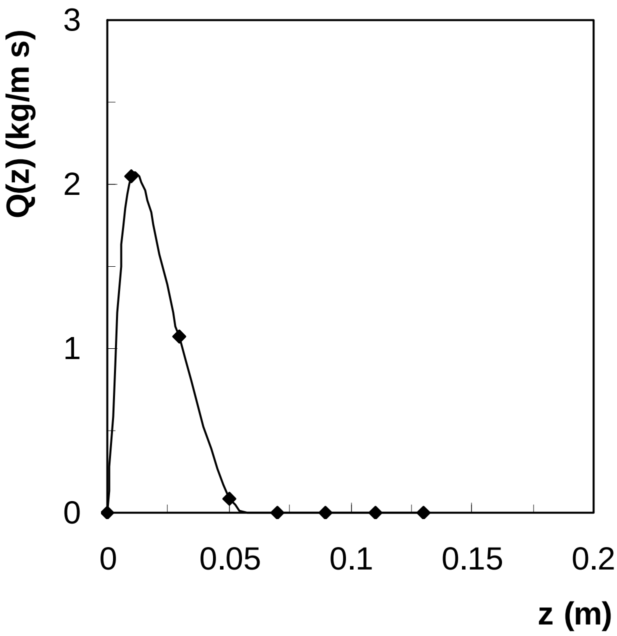

Fig. 7. Longitudinal profile of solid cross-flow. Experimental system: γ = 33º, D_o = 0.03 m, H_o = 0.15 m, u = u_{ms}, h_d=0.05 m, l_d= 0.10 m, d_d = 0.04 m, extruded PS d_p = 3.5 mm.

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Therefore, there is only one incorporation place whereas in conical spouted bed without draft tube solids crosses along the whole spout-annulus interface with two preferential incorporation zones near the contactor bottom and at an intermediate longitudinal position in the spout [19-20].

Figure 8 shows the effect of the height of the entrainment zone on the solid cross-flow from the annular zone to the entrainment zone, for the experimental system $\gamma = 33^o$, $D_o = 0.03$ m, $H_o = 0.15$ m, $u = u_{ms}$, LDPE $d_p = 3.5$ mm, $d_d = 0.04$ m, with different values of the height of the entrainment zone $h_d = 0.04$, 0.06 and 0.08 m and $l_d = H_o - h_d$. It is observed that although as the height of the entrainment zone is increased the value corresponding to the maximum solid cross-flow decreases, the zero value is reached at upper longitudinal positions.

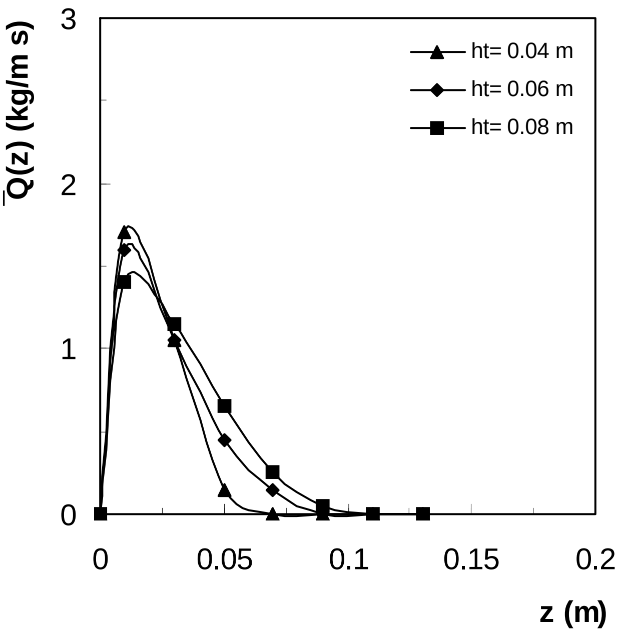

Fig. 8. Longitudinal profile of solid cross-flow. Experimental system: $\gamma = 33^o$, $D_o = 0.03$ m, $H_o = 0.15$ m, $u = u_{ms}$, h_d=0.05 m, l_d= 0.10 m, $d_d = 0.04$ m, extruded PS $d_p = 3.5$ mm.

IV. Conclusion

In conical spouted beds with a non-porous draft tube with uniform beds consisting of materials of different density the solid flow rate has been calculated from the counting of the particles in the entrainment zone by means of an optical fiber probe. This solid flow increases from zero value at the bottom of the contactor with the bed level at the entrainment zone below the draft tube and maintains constant inside the draft tube due to the lack of incorporation from the annular zone. An increasing in the height of the entrainment zone increases the solid flow at the entrainment zone. The values of solid flow obtained agree with those reported by Saadevendi and Turton [23], by Zhao et al. [24] and by Li et al. [25].

The solid cross-flow from the annulus into the entrainment zone, calculated as the variation of the solid flow along the entrainment zone, takes place only at the bed levels corresponding to the entrainment zone of the non-porous draft tube. Solid cross flow increases from zero at the contactor base, passes through a maximum and decreases up to the at the entrance to the draft tube. The increasing in the height of the entrainment zone decreases the maximum value, but enlarges the length of the curve.

These results of the solid cross-flow are of great utility for modelling applications of conical spouted beds with a draft tube with uniform beds consisting of solids of low density and different shape.

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Nomenclature

D_b, D_c, D_i, D_o,	upper diameter of the stagnant bed, of the column, of the bed base and of the gas inlet, respectively, m
d_d	diameter of the draft tube, m
d_e	effective distance between the two receiving fibres, mm
d_p	particle effective diameter and particle diameter, respectively, m
H, H_c, H_o	height of the contactor, of the conical section of the contactor, and of the stagnant bed, respectively, m
h_d	height of the entrainment zone, m
l_d	length of the draft tube, m
Q(z)	solid flow rate of the spout, kg s^{-1}
r, z	cylindrical coordinates, m
r_s	spout radius at level z, m
S	cross sectional area of the column, m^2
Greek Letters	
ε	bed voidage
γ	contactor angle, deg
ρ_s	density of solid, kg /m^3
υ_r, υ_z	components of particle velocity in the directions r and z, ms^{-1}

References

[1] M. Olazar, M. J. San José, A. T. Aguayo, J. M. Arandes, J. Bilbao, “Stable operation conditions for gas-solid contact regimes in conical spouted beds”, Ind. Eng. Chem. Res., vol. 31, pp. 1784-1791, 1992.

[2] M. Olazar, M. J. San José, F. J. Peñas, A. T. Aguayo, J. Bilbao, “The Stability and Hydrodynamics of Conical Spouted Beds with Binary Mixtures”, Ind. Eng. Chem. Res., vol. 32, 2826-2834, 1993.

[3] M. Olazar, M. J. San José, R. Llamosas, J. Bilbao, “Hydrodynamics of sawdust and mixtures of wood residues in conical spouted beds”, Ind. Eng. Chem. Res., vol. 33, pp. 993-1000, 1994.

[4] M. J. San José, M. Olazar, F. J. Peñas, J. Bilbao, “Segregation in Conical Spouted Beds with Binary and Tertiary Mixtures of Equidensity Spherical Particles”, Ind. Eng. Chem. Res., 33, 1838-1844, 1994.

[5] M. J. San José, S. Alvarez, R. Aguado, J. Bilbao, “Combustión de serrín y residuos agroforestales en lechos de borboteo cónicos (Conical Spouted Beds)”, Inf. Tecnol., vol. 13(2), pp. 127-131, 2002.

[6] M. Olazar, M.J. San José, and J. Bilbao Conical Spouted Beds. In Spouted and Spout-Fluid Beds. Fundamentals and Applications, Editors: Norman Epstein and John R. Grace. United Kingdon: Cambridge University Press, Chapter 5, 82-104, 2011.

ISBN: 978-988-19253-5-0
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

[7] M. J. San José, S. Alvarez, M. A. Izquierdo, A. Ortiz de Salazar, "Fluidodinámica de los lechos de borbor cónicos (spouted beds) para el tratamiento de residuos plásticos", Inf. Tecnol., vol. 13(5), pp. 21-24, 2002.
[8] M. J San José., S. Alvarez, A. Ortiz de Salazar, A. Morales, J. Bilbao "Treatment of Cork Wastes in a Conical Spouted Bed Reactor", Int. J. Chem. React. Eng., vol. 4, A15, pp. 1-7, 2006.
[9] M. Olazar, M. J. San José, J. Bilbao. Patent PE9700662, 1997.
[10] M. J San José, R. Aguado, S. Alvarez, M. Olazar. "Combustion of Sawdust and Agroforestal Wastes in Conical Spouted Beds". Inf. Tecnol., 13(2), 127-13, 2002.
[11] M.J San José., A. Ortíz de Salazar, S. Alvarez, M. Olazar. "Conical Spouted Beds for the Treatment of Coal". Inf. Tecnol., 13(2), 133-137, 2002.
[12] M.J. San José, S. Alvarez, A. Ortiz de Salazar, M. Olazar, J. Bilbao. "Operation Conditions in the Treatment of Biomass Wastes by Combustion in a Conical Spouted Bed" In: Science in Thermal and Chemical Biomass Conversion, Bridgwater, A.V., Boocock, D.G.B., Newbury Berks, UK: CPL press. vol. 1, pp. 228-236, 2006.
[13] M. J. San José, S. Alvarez, A. Ortiz de Salazar, A. Morales, J. Bilbao. "Treatment of Cork Wastes in a Conical Spouted Bed Reactor", Int. J. Chem. React. Eng., 4, A15, 1-7, 2006.
[14] M. J. San José, S. Alvarez, L.B. Lopez, M. Olazar, J. Bilbao. "Conical spouted beds contactors for drying of sludge from the paper industry". In: Drying 2010, Tsotsa E., Metzeger T., Peglow M., eds. Magdeburg: Docupoint GmbH, 1242-1248, 2010.
[15] M. J. San José, M. Olazar, F. J. Peñas, J. M. Arandes, J. Bilbao, "Correlation for calculation of the gas dispersion coefficient in conical spouted beds". Chem. Engng Sci., 50, 2161–2172, 1995.
[16] M. J. San José, S. Alvarez, A. Ortiz de Salazar, M. Olazar, J. Bilbao, "Operating Conditions of Conical Spouted Beds with a Draft Tube. Effect of the Diameter of the Draft Tube and of the Height of Entrainment Zone", Ind. Eng. Chem. Res., vol. 46, pp. 2877-2884, 2007.
[17] M. J. San José, S. Alvarez, F. J. Peñas, I. García. "Cycle Time in Draft Tube Conical Spouted Bed Dryer for Sludge from Paper Industry". Chem. Eng. Sci. Sci. 2013, http://dx.doi.org/10.1016/j.ces.2013.02.058.
[18] G. Volpicelli, G. Raso, L. Massimilla. "Gas and solid-flow in bidimensional spouted beds", in: Drinkenburg, A.A.H. (ed.). International Symposium on Fluidization, 123–133, 1967.
[19] G. A. Lefroy, J. F. Davidson. "The mechanics of spouted beds", Trans Inst Chem Engr, 47, 120–128, 1969.
[20] M. H. III Morgan, J. Y. Day, H. Littman. "Spout voidage distribution, stability and particle circulation rates in spouted beds of coarse particles", I. Theory, Chem Eng Sci, 40, 1367–1377, 1985.
[21] B. A. Saadevandi, R. Turton "Particle Velocity and Voidage Profiles in a Draft Tube Equipped Spouted-Fluidized Bed Coating Device," Chem. Eng. Commun. 191(10), 1379–1400 2004.
[22] X. L. Zhao, Q. Yao, S. Q. Li. Effect of draft tubes on particle velocity profiles in spouted beds", Chem. Eng. Technol., 7, 875-883, 2006.
[23] T. Li, Pougatch, M. Salcudeane, D. Grecov. "Numerical simulation of a spouted bed with a draft tube with and without liquid spray". Can. J. Chem. Eng., 87(2), 237-251, 2009.
[24] M. J. San José, M. Olazar, S. Alvarez, M. A. Izquierdo, J. Bilbao. "Solid cross-flow into the spout and particle trajectories in conical spouted beds", Chem. Eng. Sc., 53(20), 3561–3570, 1998.
[25] M. J. San José, S. Alvarez, A. Morales, M. Olazar, J. Bilbao. "Solid Cross-Flow into the Spout and Particle Trajectories in Conical Spouted Beds Consisting of Solids of Different Density and Shape", Chem. Eng. Res. Des., 84(6), 487–494, 2006.
[26] M. Olazar, M. J. San José, R. LLamosas, S. Alvarez, J. Bilbao. "Study of Local Properties in Conical Spouted Beds Using an Optical Fiber Probe". Ind. Eng. Chem. Res., 34, 4033-4039, 1995.
[27] M. J. San José, M. Olazar, S. Alvarez, A. Morales, J. Bilbao. "Spout and Fountain Geometry in Conical Spouted Beds Consisting of Solids of Varying Density", Ind. Eng. Chem. Res. 44, 193-200, 2005.
[28] M. J. San José, M. Olazar, A. T. Aguayo, J. M. Arandes, J. Bilbao. "Hydrodynamics Correlations of Conical Jet Spouted Beds". In: Fluidization VII, New York, 381-388, 1992.

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