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A NOVEL TECHNOLOGY TO SEGREGATE BINARY MIXTURES OF DIFFERENT DENSITY IN A CONICAL SPOUTED BED

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ABSTRACT
Radial and longitudinal segregation of beds consisting of binary mixtures of different density has been quantified in a conical spouted bed. Trajectories of heavier and lighter particles have been determined. The novel technology of conical spouted bed has a good performance to segregate beds consisting of particles of different density.

INTRODUCTION
Spouted beds technology of conical geometry has a good behaviour for treatment of solids of irregular texture, sticky, of a wide particle size distribution or density, due to the vigorous cyclic movement of particles (1). Segregation has been studied in the literature for cylindrical spouted beds of particles of equal density but different size (2-5), for mixtures of particles of equal size, but different densities (6-8), and for mixtures of both different particle size and density (9), and in conical spouted beds with binary and ternary mixtures of equidensity spherical particles (10-12) and recently in spout-fluid beds with beds of with equal density and different size (13), the same size and different density (14); (15), and in fluidized beds (15-21) and in tapered beds (22-23).

Spouted beds are divided into three zones, (24), each with specific flow behaviour: the annulus, the spout and the fountain. In conical spouted beds, the spout is the zone where particles move upwards; the fountain, the zone where solid distribution to the upper surface of the annulus happens, is divided into two zones: the core or particle ascending zone and the periphery or particle descending zone. The annulus is the zone where particles flow downwards and afterwards particles enter to the spout zone at every longitudinal position in the bed. The fountain is essential to the design of spouted bed contactor to separate particles of different size and/or density.

In order to separate materials with a density ratio of at least 3/1, in this paper, an experimental study of particle segregation has been carried out in beds consisting of binary mixtures of particles of different density and same size.

EXPERIMENTAL
The experimental unit designed at pilot plant scale, shown in Figure 1, consists basically of: a blower that supplies a maximum flow rate of 300 Nm^3h^{-1} at a

pressure of 15 kPa, and two high efficiency cyclones in order to collect fine particles. The flow rate is measured by means of two mass flowmeters controlled by a computer. The accuracy of this control is 0.5% of the measured flow rate.

A conical contactor of poly(methyl methacrylate), Figure 2, of angle, γ, 45º has been used. Gas inlet diameters have been D_o= 0.03, 0.04 and 0.05 m and the stagnant bed heights studied, H_o, are in the range between 0.05 and 0.30 m. Gas inlet flow rate has been at a 3% greater than minimum spouting rate.

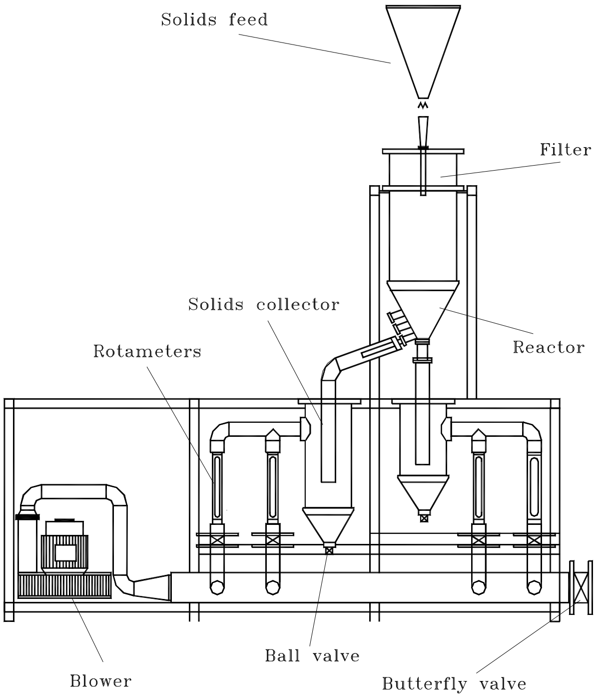

Figure 1. Experimental equipment

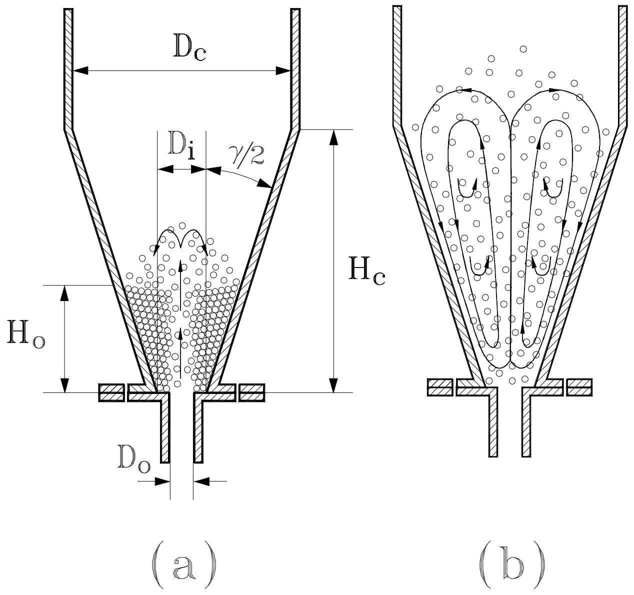

Figure 2. Geometric factors of the conical contactor and particle states in the spouted bed regime (a) and in the dilute spouted bed (jet spouted bed) regime (b).

The solids used have been binary mixtures of particles of different density: wood beads, glass beads, and ceramic beads whose properties, provided by the supplier, are set out in Table 1.

Table 1. Properties of the solid particles used

Material	**Particle diameter** d_p (mm)	**Density** ρ_s (kg/m^3)	**Shape** ϕ	**Bed voidage** ε_o	**Geldart classification**
Glass beads	3	2420	1	0.345	D
Ceramic beads	3	3520	1	0.351	D
Wood beads	3	560	1	0.367	D

Bed segregation has been quantified from the analysis of solid sampled at different bed levels in the bed, by means of a probe connected to a suction pump whose displacement is controlled by computer, Figure 3. The optimum sampling duration was estimated between 3 and 5 s, as shorter times give way to errors inherent in withdrawal of small amounts of sample. Longer times, corresponding to considerable quantities of sample with respect to the inventory, alter the bed composition. Each sampling is repeated three times at each position in the bed and the solids are returned to the contactor after each sampling.

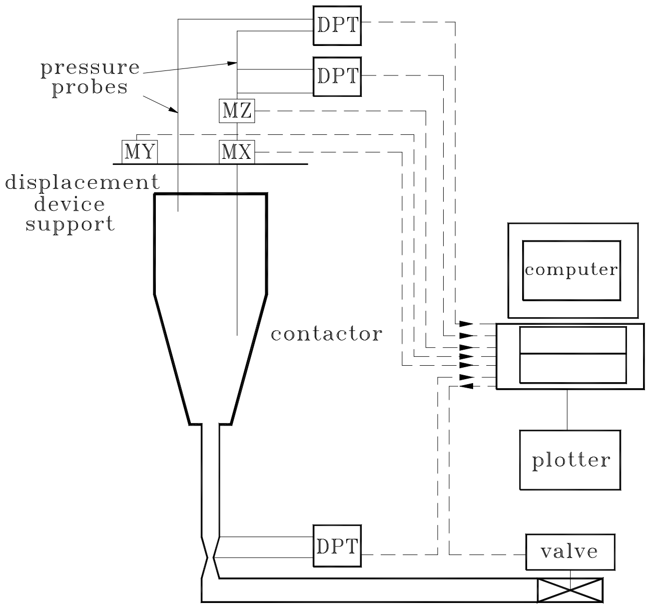

Figure 3. Schematic representation of the equipment and of the sampling device

Particle trajectories have been filmed by an image treatment system. The video equipment, Figure 4, has been described in detail in a previous paper (25) and is composed of a camera, a video recorder, a monitor, and the computer support needed for treatment of the data obtained.

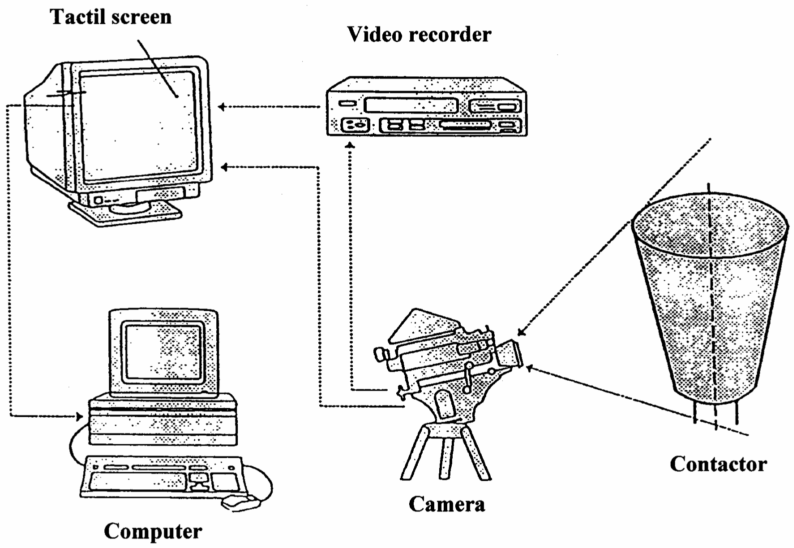

Figure 4. Scheme of the image treatment system.

RESULTS

The trajectories of the particles in the whole bed (spout, annular and fountain zones) are shown in Figure 5 for an experimental system taken as an example. The results correspond to a bed of a stagnant height of 0.18 m consisting of glass beads of particle diameter of 3 mm, in the conical contactor of angle 45°, a gas inlet diameter of 0.03 m, at gas velocity 1.02 times minimum spouting velocity. Greater spouting velocities would decrease separation and would improve mixing as reported by Rovero, (1983) (8) in conical based spouted beds, by Zhang et al. (2009) (13) in spout-fluid bed and by Gernon and Gilbertson (2012) (23) in tapered beds.

In all of the experimental systems studied, it is observed that in the spout zone, particles are ascending towards the axis at any bed level between the base and the level corresponding to the neck of the spout. Above the neck of the spout, particle trajectories are completely vertical within the whole spout. At the fountain core, particles tend to move away from the axis, to the interface fountain core-fountain periphery. At the fountain periphery, particles are distributed to the annular zone moving away from the axis towards the contactor wall all along the surface. In the annular zone the solid descends approaching the spout-annulus interface where there is solid cross-flow into the spout.

The fountain is essential in the design of spouted bed contactor to separate particles of mixtures. It has been observed that heavier particles tend to trace trajectories near the annular zone-spout zone interface. Whereas, lighter particles describe more ample trajectories nearer the contactor wall. It is obtained that control of inlet gas flow rate allows radial separation of particles.

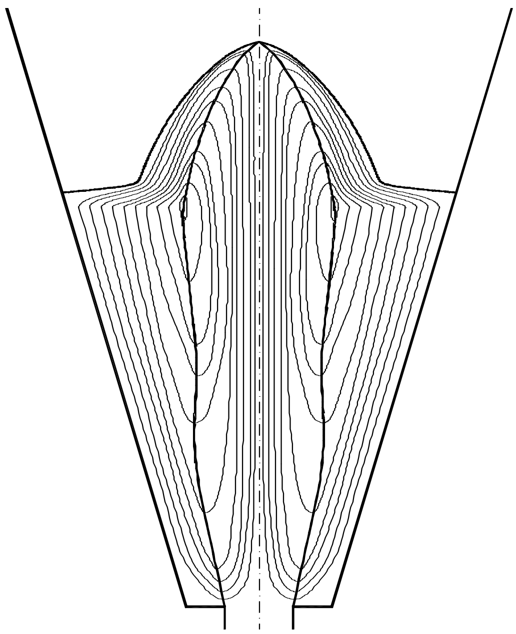

Figure 5. Solid trajectories in the whole bed. Experimental conditions: γ= 45°, D_o = 0.03 m, H_o= 0.18 m, glass beads of d_p = 3 mm, u= 1.02 u_{ms}.

In Figure 6, the weight fraction of the particles of greater density, X_B, at different radial and longitudinal positions of the bed has been plotted as an example of the results for a mixture with noticeable segregation (corresponding to beds consisting of binary mixtures of 50 wt% of glass beads and 50 wt% of wood beads of particle diameter d_p = 3 mm, (γ= 45 º; D_o= 0.04 m; H_o= 0.18 m).

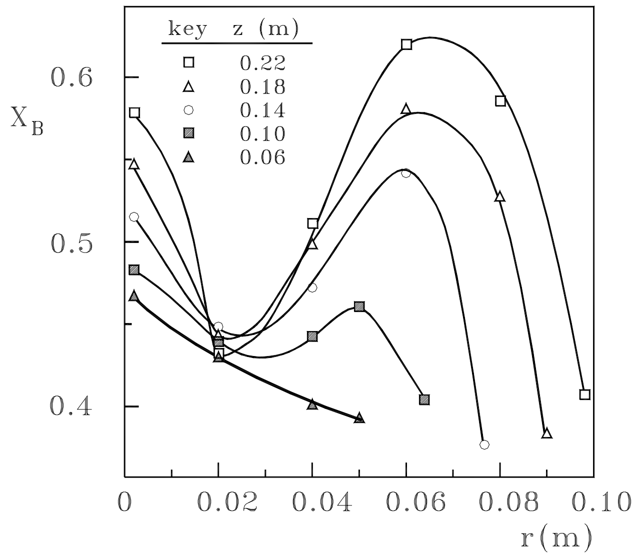

Figure 6. Weight fraction of the particles of greater density, X_B, at different radial and longitudinal position of the bed. System binary mixture (50 wt % of glass beads and wood beads of particle diameter d_p = 3 mm.

It is observed that for low bed levels, X_B passes thorough a minimum corresponding to the interface between the spout and annular zones. For higher bed levels as the radius increases over that corresponding to the spout, X_B passes through a maximum value corresponding to an intermediate position in the annular zone and subsequently decreases, reaching a new minimum value in the contactor wall. Besides, it is observed that the component of heavier size is in greater proportion in the upper part of the bed. This tendency is similar to that obtained with binary mixtures of particles of different size by San José et al. (1993) (26). These results agree with those reported by Piccinini et al. (1977) (6) for beds of particles of different density in conventional spouted beds.

The segregation has been quantified by using the mixing index calculated from the experimental values of weight fraction of particles of greater density in the upper volume half of the bed, $\left(\overline{X_B}\right)_u$ and the weight fraction in the whole bed, $\overline{X_B}$ (11) as a function of the geometric factors of the contactor, of bed composition and of air velocity.

$$M= \left(\overline{X_B}\right)_u / \overline{X_B} \qquad (1)$$

The experimental values of average weight fraction of the particles of greater density, $\left(\overline{X_B}\right)_z$, have been plotted in Figure 7, against the bed level as an example for a mixture corresponding a to bed consisting of binary mixtures of 50 wt % of glass beads and of 50 wt % wood beads of particle diameter d_p = 3 mm, (γ= 45º; D_o= 0.04 m; H_o= 0.24 m).

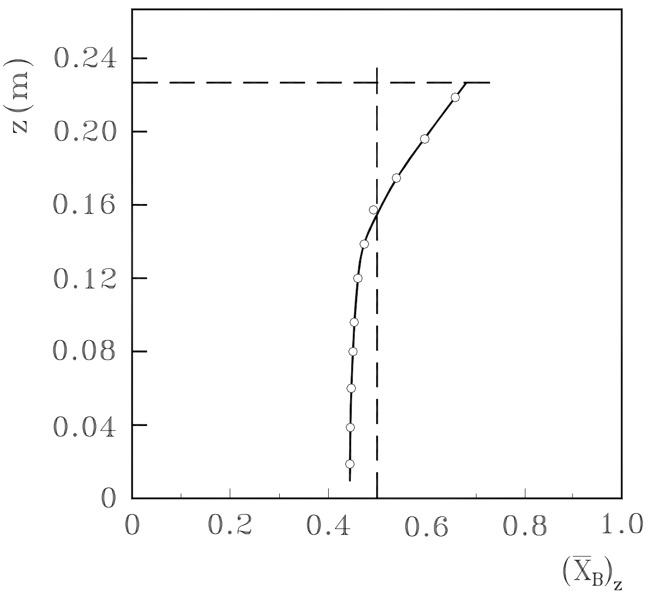

Figure 7. Average value of weight fraction of the particles of greater density, at different levels. System: binary mixture of 50 wt % of glass beads and of 50 wt % wood beads of particle diameter d_p = 3 mm, γ= 45º; D_o= 0.04 m; H_o= 0.24 m.

As it is observed, the heavier component is in greater proportion in the upper part of the bed, corresponding to weight fraction of these particles at each level, $\left(\overline{X_B}\right)_z$, greater than 0.5, whereas in the lower part of the bed, lighter particles are in greater proportion. This fact is due to the fact that heavy particles tend to follow shorter trajectories near the spout-annular interface than the lighter ones, which describe longer trajectories nearer the contactor wall and allows to segregate particles of different density.

CONCLUSIONS

In the spout zone, particles ascend through the spout zone and the fountain core, are distributed to the annular zone by the fountain periphery moving towards the contactor wall all along the surface and descend through the annular zone approaching the spout-annulus interface where solid cross to the spout.

The fountain is essential in the design of spouted bed contactor to separate particles of mixtures. Whereas, particles of greater density describe trajectories near the annular zone-spout zone interface, particles of smaller density trace more ample trajectories nearer the contactor wall. Besides, control of inlet gas flow rate allows to radial separation of particles.

The heavier component is in greater proportion at the top of the bed. In addition, at low bed levels, the weight fraction of particles of greater density, passes thorough a minimum corresponding to the interface between the spout and annular zones. At higher bed levels, for radial positions over the spout radius, the weight fraction of heavier particles passes through a maximum value corresponding to an intermediate position in the annular zone and subsequently decreases, achieving a new minimum value in the contactor wall.

Moreover, particle segregation increases as the difference of particles density is increased. Therefore, novel technology of spouted bed allows to segregate beds consisting of binary mixtures of particles of different density.

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NOTATION

A_f, H_f : amplitude and height of the fountain, respectively, m

D_c, D_i, D_o: diameter of the column, of the dryer bottom, of the bed inlet and of the gas inlet, respectively, m

d_p: particle diameter, m

H, H_c, H_o: height of the bed, of the conical section and of the stagnant bed, respectively, m

u, u_{ms}: velocity and minimum spouting velocity of the gas, respectively, m s^{-1}

X_B: weight fraction of the heavier particles

$\left(\overline{X_B}\right)_z$: average weight fraction of the heavier particles at z level

$\left(\overline{X_B}\right)_u$: average weight fraction of the heavier particles in the upper volume half of the bed

z : longitudinal coordinate, m

Greek Letters

ε_o: voidage of the static bed

ϕ: sphericity

γ: angle of the contactor, deg

ρ_s: density of the solid, kg m^{-3}

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KEY WORDS
Spouted beds, conical spouted beds, binary mixtures, binary mixtures of different density, particle trajectories, particle segregation, mixing index, separation technology, separation process, novel separation technology