

# FEASIBILITY STUDY OF PARTICLE CLASSIFICATION IN FLUIDISED BEDS WITH INTERNAL BAFFLES

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## SUMMARY

In a fluidized bed in which the particles vary in size or density segregation can occur. Including horizontal sieve-like baffles in the bed can greatly increase the tendency of powders to segregate. This can make a fluidized bed particle classification process possible. In this article a feasibility study of such a process is presented.

Experiments were performed with a model system. It was found that the baffles increase the purity of both the 'flotsam' and the 'jetsam' fractions. The capacity of a fluidized bed particle classifier can be estimated using a mechanistic model, based on literature models. With such a model we found that the baffles are most effective in systems that tend to segregate but do actually hardly segregate without baffles. The use of fluidization gas by a fluid bed particle classifier is much smaller than that of a windsifter.

## INTRODUCTION

If the particles in a fluidized bed vary in size or density the particles can segregate; 'jetsam' particles tend to accumulate in the bottom of the bed and 'flotsam' particles in the top. Usually segregation is avoided as much as possible and making deliberate use of it seems unfeasible because the obtainable segregation is not very good. However it was found [1] that including horizontal sieve-like baffles in the bed can greatly increase the tendency of powders to segregate. This can make a fluidized bed particle classification process feasible, making a whole range of applications possible. Examples are separation of various recycled materials and *in situ* separation of granules from powder in fluidized bed granulation.

Advantages of the process compared to other classification processes are that a separation according to density is possible, the particles are not wetted, and the amount of gas used is much smaller than that in windsifting.

In this article a feasibility study of such a process is presented.

## LITERATURE SURVEY

In bubbling gas fluidized beds of mixtures of particles segregation can occur at gas velocities close to the minimum fluidization velocity. If it occurs, a segregated layer will be formed at the bottom of the bed. This layer will grow higher in time until it reaches a stationary height. Denser and larger particles tend to sink (jetsam) while less dense and smaller particles tend to float (flotsam). The density is the dominant driving force for segregation. However, if the densities differ only slightly, the size may determine the particles' behavior.

Segregation competes with mixing in the bed, and both involve the movement of particles relative to each other. The particle movement is thought to be caused solely by fluidization bubbles. Bubbles lift particles with them in their wake, which is compensated by a downward particle movement in the bulk. This is often called the 'circulation' [2]. Fluidization bubbles also cause a disturbance in the region surrounding them. Large-scale disturbances cause mixing of the bulk material, but the shear of the particles in the bed associated with these disturbances also enables particles to move relative to each other, causing segregation.

Little is known quantitatively about the effect of internal baffles on fluidized beds. Van Dijk et al. [3] used an X-ray technique to observe the effect of a baffle on bubbles. The bubbles were seen to lose (part of) their wake at the baffle. The effect of the baffles is thus to decrease the circulation rate. Bosma and Hoffmann [4] showed that baffles significantly increase segregation in a mixture of glass beads of 83 and 221  $\mu\text{m}$  average diameter. With baffles segregation even occurred at gas velocities above the minimum fluidization velocity of the jetsam component, which was never observed before for equal density mixtures.

## MODELLING

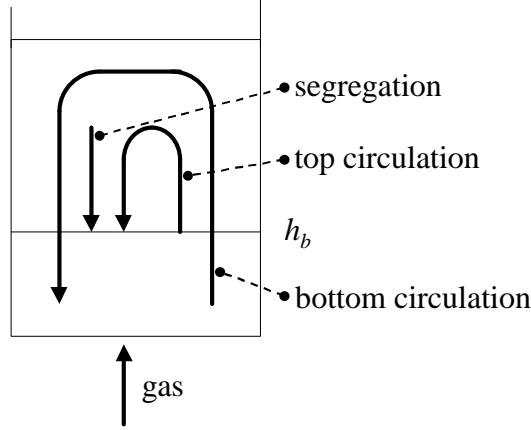
The extent of segregation can be estimated with several methods. An empirical approach uses the so-called 'mixing index'. This parameter was first introduced by Rowe *et al.* [5]. Nienow *et al.* [6] found an empirical equation for the mixing index using a large number of experimental results. Their expression includes the effects of particle size, shape, density and minimum fluidization velocity and the composition and bed height.

A mechanistic approach was introduced by Gibilaro and Rowe [2]. They used a two-phase theory in which it is assumed that the bed consists of a wake phase moving up with the bubbles and a bulk phase moving down. They took into account: *circulation* and *segregation* in the bulk phase due to disturbances caused by bubbles, material *exchange* between the bulk phase and the wake phase, and axial *dispersion* in the bulk phase. Gibilaro and Rowe found analytical solutions for some cases. Naimer *et al.* [7] and Hoffmann *et al.* [8] extended this approach by solving the model numerically. They used empirical equations for the parameters and made them dependent on the height. This model works satisfactory.

Our approach [4] is a simplification of the mechanistic approach mentioned above. It is aimed at having a good, and relatively simple, method to estimate the capacity of continuous baffled fluidized beds for powder classification, usable as a design tool. For that purpose we use the model concepts of Gibilaro and Rowe [2] with some simplifications. We emphasize that this represents an attempt at arriving at a first workable capacity model for the sort of systems we are looking at, and not an attempt at formulating globally valid model equations.

In our model we assume that both the top and the bottom layer have uniform compositions. For rough calculations such a model should be sufficient, also considering that the

experiments show that these assumptions are approximately true. Compared with the model concepts of Gibilaro and Rowe [2] this means that we neglect axial dispersion and exchange between the bubble and the wake. Our model differs from theirs in that we use different values for the parameters in the layers and we calculate not only the steady state but also the growth rate of the bottom layer. The steady state can be found by setting the growth rate to zero.



**Figure 1** the fluxes to and from the bottom layer in the simplified model

The model concept is schematically shown in the figure 1. Segregation and circulation are taken into account; the circulation is split into one due to bubbles originating in the bottom layer at the distributor plate and one due to bubbles originating in the top layer at, or just above, the boundary. A mass balance over the bottom layer gives:

$$\frac{dh_b}{dt}(x_b - x_t) = \mathbf{f}_{segr} + \mathbf{f}_{circ,b}(x_t - x_{w,b}) + \mathbf{f}_{circ,t}(x_t - x_{w,t}) \quad (1)$$

Here  $h_b$  is the height of the bottom layer, which is zero at the start of an experiment,  $x$  is the jetsam fraction, the  $\phi$ s are the fluxes to and from the bottom layer and the subscripts  $b$ ,  $t$  and  $w$  refer to bottom, top and wake respectively. Empirical equations are needed to quantify the fluxes and the bottom and wake compositions. These are presented elsewhere [4] but we will discuss two important aspects here: the effect of cohesivity and the effect of baffles.

Williams [9] mentions that in powder handling segregation is usually not a problem if all particles are smaller than 30  $\mu\text{m}$ . He also mentions that a small amount of moisture can prevent segregation. This indicates that particle cohesiveness can be a big problem for achieving segregation. Cohesive forces increase compared to gravitational forces with decreasing particle size; since in most empirical equations only the ratio of the particle sizes is included, these equations cannot account for an effect of cohesive forces on segregation. For relatively large particles there is probably indeed no effect of cohesive forces. For other particle sizes some effect is expected. Based on our results and those of others we found that assuming a linear relation between segregation flux and particle size gives satisfactory results. We used for the segregation flux:

$$\mathbf{f}_s = 0.6x(1+x)(u - u_{mf}) \frac{\Psi - 1}{1+x(\Psi - 1)} \frac{d_m}{163 \cdot 10^{-6}} \quad \text{for } d_m \leq 465 \cdot 10^{-6} \text{ m} \quad (2)$$

with:

$$\Psi = \frac{(rd^{1/3})_j}{(rd^{1/3})_f} \quad (3)$$

Here  $u$  is the gas velocity,  $u_{mf}$  is the minimum fluidization velocity of the mixture,  $\rho$  and  $d$  are the particle density and diameter and the subscripts  $m$ ,  $j$  and  $f$  refer to mean, jetsam and flotsam. We have defined the mean particle diameter as  $d_m \equiv x d_j + (1-x) d_f$ . The parameter  $\Psi$  represents the relative differences between the particles, causing segregation. The final division in equation 2 ( $d_m/163 \mu\text{m}$ ) represents the effect of particle cohesiveness.

The effect of the baffles was modeled by making the wake fraction of the bubbles dependent on the baffle spacing. In this way the circulation rate is affected. We used the following equation for the wake fraction:

$$f_w = \left( 1 - \exp\left(\frac{-\Delta}{\Delta_w}\right) \right) f_{w,eq} \quad (4)$$

Here  $\Delta$  is the baffle spacing,  $\Delta_w$  is a characteristic height and  $f_{w,eq}$  is the ‘normal’ or ‘equilibrium’ wake fraction. The idea behind the characteristic height is that bubbles lose their wakes at a baffle and that the rate of recollection of the wake is characterized by a certain height. We found satisfactory results by assuming:

$$\Delta_w = 0.00032 u^{-1.5} \quad (5)$$

The ‘normal’ wake fraction in equation 4 depends on the bubble size according to some empirical relation. In normal cases the bubble size can also be found with some empirical relation [4]. However the relevant bubble size is the size of the bubbles as they emerge from the jetsam layer and enter the flotsam layer. When the bottom layer is not fluidized the relation for the initial bubble size above a distributor plate according to Kato and Wen [10] can be used:

$$D_b = \frac{1.43}{g^{0.2}} \left( \frac{u - u_{mf,t}}{1000} \right)^{0.4} \quad (6)$$

When the bottom layer is fluidized we found that the best assumption for the bubble size is:

$$D_b = D_{b,b} \left( \frac{u - u_{mf,t}}{u - u_{mf,b}} \right)^{\frac{1}{3}} \quad (7)$$

where  $D_{b,b}$  is the size of the bubbles from the bottom circulation when they arrive at the boundary. This equation is not realistic at gas velocities just above the minimum fluidization velocity of the jetsam because then it predicts bubble sizes that are smaller than they would be if the boundary between the layers were a distributor plate. Therefore we take the initial bubble size above a porous plate distributor (eq. 6) as a minimum.

With the model and equations mentioned above we are finding quite good agreement with experiment for the particular system we did our experiments with, however, we stress the need for further work with other systems to formulate more generally valid model equations for fluidized bed particle classifiers.

## FEASIBILITY STUDY

In this section we investigate whether a fluidized bed particle classifier can function more effectively or more efficiently than other techniques.

Many parameters affect the capacity of a fluid bed separator, e.g. particle size and density. It is difficult to treat this problem in general terms and we chose to do calculations for some representative cases. These calculations were done with the model and equations introduced in the previous section. Instead of assuming a batch apparatus however in this case we assumed continuous operation. The calculations are done at a gas velocity that is equal to the

minimum fluidization velocity of the jetsam particles. At this gas velocity the bottom layer consists of almost pure jetsam (practically about 99%). The top layer still contains a fraction  $x_t$  of jetsam. The results are in presented table 1 and 2. The amount of fluidization gas used per kg jetsam product is given as well as de diameter a circular fluidized bed should have to produce 1 cubic meter of jetsam per hour.

mixture nr.	jetsam		flotsam		with baffles		
	$d$ [ $\mu\text{m}$ ]	$r$ [kg/L]	$d$ [ $\mu\text{m}$ ]	$r$ [kg/L]	$x_t$	[kg gas/ kg jetsam]	$D_{column}$ [m]
1	221	2.5	83	2.5	0.08	0.022	0.49
2	675	2.5	83	2.5	0.44	0.022	0.17
3	675	2.5	221	2.5	no segregation		
4	221	5	83	2.5	0.08	0.0045	0.19
5	221	10	83	2.5	0.15	0.0023	0.12
6	221	2.5	221	1	0.007	0.0083	0.25
7	221	5	221	1	0.013	0.0022	0.12
8	675	2.5	675	1	0.14	0.0074	0.084
9	675	5	675	1	0.11	0.0020	0.043
10	110	2.5	41	2.5	0.009	0.039	1.3
11	55	2.5	21	2.5	0.001	0.080	3.6
12	28	2.5	11	2.5	0.001	0.16	10

**Table 1** Estimations of the performance of a fluidized bed particle classifier with internal baffles (1 baffle per 4.3 mm) at a gas velocity equal to the minimum fluidization velocity of the jetsam particles.

mixture nr.	jetsam		flotsam		without baffles		
	$d$ [ $\mu\text{m}$ ]	$r$ [kg/L]	$d$ [ $\mu\text{m}$ ]	$r$ [kg/L]	$x_t$	[kg gas/ kg jetsam]	$D_{column}$ [m]
1	221	2.5	83	2.5	no segregation		
2	675	2.5	83	2.5	0.49	0.13	0.42
3	675	2.5	221	2.5	no segregation		
4	221	5	83	2.5	0.37	0.017	0.36
5	221	10	83	2.5	0.38	0.008	0.24
6	221	2.5	221	1	0.08	0.011	0.29
7	221	5	221	1	0.07	0.0032	0.14
8	675	2.5	675	1	0.17	0.0084	0.089
9	675	5	675	1	0.11	0.0021	0.043
10	110	2.5	41	2.5	0.41	0.18	2.7
11	55	2.5	21	2.5	0.26	0.15	5.0
12	28	2.5	11	2.5	0.15	0.21	12

**Table 2** Estimations of the performance of a fluidized bed particle classifier *without* internal baffles

It can be seen that the amount of gas needed for separation is in the order of tens of grams per kg of purified jetsam. This amount is much lower than that of a technique like windsifting, which uses amounts of gas in the order of kilograms per kg of purified jetsam. The calculated column diameters needed to purify 1 m<sup>3</sup> of jetsam per hour have a reasonable size, except when the particles are really small (cases 10-12).

Furthermore it can be noted that for the mixtures 1, 2, 4, 5 and 10 (with small particles) the use of the baffles gives a significant saving. For the mixtures with large particles (cases 6-9) the savings due to the use of baffles are small. For very small particles (cases 11 and 12) the savings due to the baffles are small. In general it can be concluded that savings due to the baffles are possible in cases where a tendency to segregate is present but not pronounced. For the small particles (cases 10-12) however these estimates should not be taken too serious because the calculations imply the assumption of good fluidizability. This suggests that for small particles the classification process is limited by the fluidizability of the mixture. For fluidizable particles (or free flowing mixtures) we can conclude that the usefulness of including baffles increases with decreasing particle size.

## DISCUSSION AND CONCLUSIONS

We have to emphasize the pioneering character of this work. The number of experiments available to validate the model is limited, especially considering the many variables that have an effect. Also the calculations are done for a continuous system while experiments were only done with batch systems; we have assumed that feeding and discharging do not have a significant effect on the performance. Therefore the results should be considered critically. Further work with other systems to formulate more generally valid model equations for fluidized bed particle classifiers is needed.

Despite that the following conclusions can be drawn:

- The experiments with glass beads show that the baffles increase segregation
- The capacity of a fluidized bed particle classifier can be estimated using a mechanistic model, based on literature models.
- The classification process seems feasible for many 'free flowing' mixtures,
- Since different size mixtures can easily be separated by sieving, the fluidized bed process is useful for classification of equal size different density mixtures.
- The baffles have the highest added value for mixtures with an intermediate tendency to segregate. If the mixture has (almost) no tendency to segregate the use of baffles will not give a useful segregation. On the other end, if the mixture segregates very easy, the baffles are not needed.

## ACKNOWLEDGEMENT

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