PERFORMANCE OF ZIGZAG CLASSIFIERS AT LOW PARTICLE CONCENTRATIONS:
A study of the Effect of Stage Geometry Variations

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Discussion by
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Presented below are a few of my observations from reading the subject paper by M. M. G. Senden.

THE SUPERFICIAL AIR VELOCITY

Readers unfamiliar with the term “superficial air velocity” would appreciate its full definition given in the paper. In view of the vital role played by $v_f$ throughout the paper, it appears to this discussor that additional effort to define $v_f$ in the List of Symbols is well justified.

AN ALTERNATIVE CHOICE OF THE CHANNEL GEOMETRY

In the case of zigzag air classifier of standard depth the channel depth $d_t$ is fixed by the section length $L_s$ and the angle between the sections $\alpha$. The channel width $W_c$ remains to be specified. The author chose the square-bottom configuration ($W_c = L_s = 20$ cm) for three air classifiers investigated in the paper. An alternative choice is to have $W_c$ inversely proportional to $\sin\alpha$, $0 < \alpha < 180$ degree. The latter choice yields an $\alpha$-independent relation between the volume rate of flow of air across a section and the mean air speed.

ON PARTICLE CONCENTRATIONS

It was stated in the paper that experiments were conducted at very low particle concentrations. It would be somewhat more satisfactory if a range of values of a measure characterizing particle-particle interactions, e.g., material loading in the conveying air stream were given for the experiments.

Furthermore, it seems that one would need to ascertain particle-particle interactions are indeed negligible at these apparently low concentrations. Or control must be exercised to ensure approximately the same degree of particle-particle interactions in experiments of a given type of material particles at different $v_f$ so data presented in Figs. 4 and 5 become more meaningful.

SOME REMARKS ON FIG. 4 AND 5

By definition, at $v_f/v_{fx}$ equal to unity $1-p_f$ (or $1-p_F$) has the value $x$. Data points in Figs. 4 and 5 should reflect this fact by converging into a neck in the neighborhood of $v_f/v_{fx} = 1$. However, such a neck is not evident at $v_f/v_{75} = 1$ in the $1-p_f$ plot.
for the 90-deg. zigzag air classifier of standard depth.

It is to be expected that the use of $\frac{\bar{V}_f}{\bar{V}_{fx}}$ provides a fairly good correlation of the $1-P_r$ and $1-P_f$ data for the particle types tested. In addition to the perfect correlation of all data at $\frac{\bar{V}_f}{\bar{V}_{fx}} = 1$, $1-P_r$ and $1-P_f$ increase rapidly to one when $\bar{V}_f$ is about 50 percent of $\bar{V}_{fx}$; and they approach their respective asymptotic values for large $\bar{V}_f$ if it is equal or greater than $2\bar{V}_{fx}$.

That $P_r$ does not exceed the value 0.5 even at large $\bar{V}_f$ for the 90-deg. zigzag air classifier of standard depth can be qualitatively explained. The normal impingement of an air stream to a plate will aerodynamicwise give a value of 0.5 to $P_{ro}$. Inclusion of the gravitational force, of course, causes $P_r$ to stay below 0.5 even at large $\bar{V}_f$.

ON THE ONE-STEP-MEMORY MODEL

As things stand in the paper, it appears to this discussor that Fig. 9 does not approve nor disapprove the one-step-memory model. The fact that the residence times of particles in the standard 90 deg. zigzag air classifier are considerably longer than those in the standard 120 deg. one gives only circumstantial support to the model.

It would be more conclusive if a check could be made on how exact Eq. (1) is jointly satisfied by experimentally determined efficiencies and theoretically deduced amplification factors.

Discussion by

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Resource recovery technology has in the past been almost totally dependent on the information borrowed from other fields. Mining and ore processing gave us the shredder; agricultural knowhow provided the fermentation techniques, air classification and color sorting; and chemical engineering contributed flotation, pyrolysis and other unit operations. Because of the immediate and pressing need for developing working resource recovery facilities, the engineering of these facilities has been for the most part a process of adopting and adapting existing technologies from related fields. Only recently has the science of resource recovery begun to catch up with the need for engineering applica-

The paper by Senden, in which only a small part of a much larger research effort is reported, represents a positive and much-needed start in the direction of developing a resource recovery engineering science. His and Professor Tel's efforts are to be applauded, for it is from such research ideas that new hardware and processing developments emerge.

In this discussion, we would like to contribute an additional bit of information to the analysis of air classifications. Since Senden's work involves low particle densities, it might be interesting to find how increased particle density within the classifier throat affects recovery.

Such experiments were recently conducted at Duke University by Mr. Richard Henrikson [1]. A feed consisting of square pieces of white plastic (the lights) and orange aluminum (the heavies) were introduced into a zig-zag classifier and multiple cameras used to record the number of particles of each type in the various stages of the classifier. Air flow rate was kept constant and the mass feed rate was varied. Figure 1 shows the behavior of the aluminum squares for six feed rates. The feed was introduced at stage 5 and had a downward momentum. Accordingly, the maximum concentration of aluminum is in stage 4 regardless of the feed rate. Some pieces are blown to higher stages; but they tend to fall back, thus resulting in a low concentration of aluminum in the air classifier overflow.

Conversely, the plastic squares are carried upwards and most of them exit with the overflow. As these aerodynamically light particles fly up into each successively higher stage, they have a higher and higher probability of continuing on to the next stage, and eventually exiting with the overflow. As the light particles travel upwards, the heavies have

![FIG. 1. PARTICLE CONCENTRATION (lb/ft³)](image-url)
already dropped off along the way, and as the number of stages increase upward, the probability of all particles attaining the next higher stage approaches 100 percent. This idea is developed mathematically by Henrikson [1].

Interestingly, it was determined that the stage of maximum particle concentration is the same for both the aluminum and plastic squares.

Finally, it might be interesting to evaluate the performance of a classifier using a simple equation developed by Worrell which allows a single-valued parameter for air classifier efficiency [2]:

\[
\text{Percent } E = \left( \frac{X_1}{X_0} \times \frac{Y_2}{Y_0} \right) \times 100
\]

where \(X_0\) and \(Y_0\) are the mass rates (or mass for a given sampling time) of components \(x\) (the lights) and \(y\) (the heavies) in the feed, \(X_1\) is component \(x\) in the overflow and \(Y_2\) is component \(y\) in the underflow. Using this expression, the efficiencies for 7 runs are as shown in Fig. 2. As the line is projected to zero feed rate, the efficiency of the classifier in separating single particles is established, thus defining the efficiency independent of feed rate. Efficiencies can thus be measured for various air flows and the optimum air flow determined [2]. Such analyses can become the basis for design and comparative evaluation.

\[
\text{FIG. 2. FEED RATE (lb/sec)}
\]

\[
\text{REFERENCES}
\]


Discussion by

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Dr. Senden and Prof. Tels' efforts in venturing into the field of air classification, and thereby trying to quantify the almost-unquantifiable, should be recognized with appreciation. We are familiar with the difficulties in attempting to order the great number of parameters into equations. Work of a similar, although now slightly diverging, nature is being carried out at Duke. We understand that this paper is only a beginning in air classifier research, and this discussion serves primarily to suggest future efforts.

Three broad questions come to mind: Does the exclusion of heavies from the discussion limit the analysis? Is the measure of efficiency arrived at by the author useful for classifier comparisons? Do the results for the 90 deg., 120 deg., and 150 deg. configurations suggest that the model does not apply to all three types of classifier? Each question is discussed below.

Even an air classifier whose job is to produce pure lights must concern itself with good recovery in the heavy fraction. The manner in which the classifier induces particles to fall must be examined, along with the manner in which it induces the rising of the light fraction. This brings up a twofold paradox: collisions and vortices.

**Collisions.** The collisions with downward facing walls which are seen by the author to prevent the response of rising particles to increase in air velocity for the 90 deg. classifier may be beneficial in inducing "flying" heavies to turn around. In this case, the same structural feature that may be beneficial to separation of heavies may be detrimental to the purity of the light fraction.

**Vortices.** The helium-filled soap bubble pictures demonstrate that vortices are present in the 90 deg. classifier, and not in the 120 deg. classifier. Perhaps vortices might entrain heavies and pull them from the rising stream to turn them around. If this is the case, the paradox would be repeated: the vortices beneficial to downward direction of heavies would contribute to air patterns detrimental to the separation of lights.

Thus, the exclusion of heavies from the discussion limits the understanding obtained of the separation mechanism.
In determining the separation effectiveness of a classifier, it is necessary to include the heavies, even if only the fraction of lights in the overflow is of interest. Doing otherwise restricts the discussion to "recovery," and ignores "purity."

**EXHIBIT I**

<table>
<thead>
<tr>
<th></th>
<th>LIGHTS</th>
<th>HEAVIES</th>
</tr>
</thead>
<tbody>
<tr>
<td>FEED</td>
<td>x₀</td>
<td>y₀</td>
</tr>
<tr>
<td>OVERFLOW</td>
<td>x₁</td>
<td>y₁</td>
</tr>
<tr>
<td>UNDERFLOW</td>
<td>x₃</td>
<td>y₃</td>
</tr>
</tbody>
</table>

Naming the variables as in Exhibit I, it can be seen that a ratio of

\[ R = \frac{x₁}{x₀} \]  (100)

gives 100 percent recovery in the overflow if \( x₁ = x₀ \). This ignores the possibility that \( y₁ \propto y₀ \); i.e., that the overflow is highly impure. Some indication must be given of the amount of heavies in the overflow. Worrel [1] suggests multiplying the light fraction recovery in the overflow by the heavy fraction recovery in the underflow:

\[ E (\text{percent}) = \left( \frac{x₁}{x₀} \cdot \frac{y₂}{y₀} \right) \]  (100).

In this manner, if the recovery of lights in the overflow is good, but impure, this will be reflected in a poor recovery of heavies in the underflow. Thus, excluding heavies from a discussion of air classifier efficiency renders efficiency parameters incomplete.

Further along the same line, the use of steepness of a probability curve to measure efficiency is confusing. The probabilities are defined as the tendency for the light particle to continue rising, or the heavy particle to continue falling, or some permutation of these possibilities. Graphing these probabilities as a function of airflow, and then examining the slope of the curve only gives a measure of the willingness of the particles to follow changes in air velocity: i.e., the extent to which the classifier geometry forces the particles to follow airflow. Isolating this part of Dr. Senden's paper, criteria of separation, or how well the classifier forces the particles to follow divergent paths, are not mentioned. Efficiency of the separation is not addressed.

Intuitively, a 90 deg. classifier should be a better separator than a 120 deg. classifier, as discussed above. From this thought follows a questioning of the philosophy behind the explanations given the model results. For example, the helium-filled soap bubbles in the 90 deg. and 120 deg. classifiers show entirely different airflow patterns: one with vortices, and one without. Furthermore, decreasing channel depth is shown to produce opposite results for the 90 deg. and 120 deg. classifiers. These results suggest two different mechanisms of operation. This does not change the validity of non-deterministic analysis, but the interpretation of the analysis, such as by the linking of the different classifiers on one graph, might have to be avoided until a theory allowing the mechanism of operation to proceed from one form of operation to another is evolved.

**REFERENCE**


**AUTHOR'S REPLY**

*To D. N. Fan*

Concerning D. N. Fan's comment on "An Alternative Choice of the Channel Geometry," we regret that we fail to see the advantage of D. N. Fan's proposal to couple the value of \( W_C \) to that of \( \alpha \). In experiment at very low particle concentration, channel width \( W_C \) can only affect the separations obtained in zigzag air classifiers when its value is chosen so low that interaction between the particles and the flat, vertical classifier walls is no longer negligible. We have used larger channel widths where \( W_C \) has no influence on the separation. While the volume rate of flow of air obviously has an economic significance, it does not affect the separation either as long as the average air velocity \( \overline{v_f} \) is kept constant. We therefore believe that D. N. Fan proposes to couple two quantities of which the channel width \( W_C \) is irrelevant to the separation.

Concerning D. N. Fan's comment on "On Particle Concentrations," we have stated in the paper that the experiments were carried out by repeatedly following the motions of one single particle in the column. This infinite dilution ensures the exclusion of particle - particle interactions.

Concerning D. N. Fan's comments on "Some Remarks on Figs. 4 and 5," the absence of a sharp neck in the neighborhood of \( \overline{v_f} \) is obviously explained by the fact that \( \overline{v_f} \) is determined from a set of experiments with a non zero spread. This causes the individual points in the figures to spread around the mean \( \overline{v_f} \).

Concerning D. N. Fan's comments on "On the
One-Step-Memory Model,” due to the space limitations we have not attempted to prove the validity of the one-step-memory model in the present article. The validity of this model has been proven in the below 2 publications [1, 2].

REFERENCES


To P. A. Vesilind

The contribution of Dr. Vesilind to our paper is of great value as it extends the insight information on the separation process in zig zag air classifiers to operation conditions involving higher particle loads.

The concentration gradients as given by Dr. Vesilind in a diagram are the complex result of the particle behavior at the individual stages, the number of stages and the location of the feedstage. In order to be able to discriminate between these various factors, a mathematical model as proposed by us will be very useful. In principle it enables the expansion of the experimental results to classifiers with a different number of stages and other location of the feedstage. Unfortunately, extra information is needed in addition to the concentration diagrams to be able to calculate internal mass flows that can form the basis from which the values of the transition probabilities can be established.

It is interesting to note that Dr. Vesilind’s suggestion that air classifier efficiencies are characterized independent of particle feed rate through extrapolating efficiency data to zero feed rate ultimately results in our method, where performance is actually measured at zero load. That we measure the behavior of single components separately is of no significance. At zero load no interaction between particles exists so that the particles of each single component must behave as if they were alone in the classifier.

To R. I. Stessel

We greatly appreciate the suggestions given by Stessel and we would like to comment on some of his statements.

In our opinion the discussion on the influence of wall collisions and vortices on the particle cannot be split into arguments concerning merely the “heavies” and aspects concerning merely the “lights”. In many cases the flying behavior of the various components to be separated are quite similar. Such mixtures are difficult to separate and our attention is especially dedicated to those kinds of mixtures. In that case both the heavies and the lights form a non-neglectable part of the rising and falling particle streams in the apparatus, especially around the feedstage.

Stessel’s statement that the rising motion of the “heavies” is better blocked in the 90 deg. zig zag air classifier is true. At the same time, however, the lights are blocked to about the same extent. A quite high air velocity is then required to reach a sufficient high recovery of the lights in the top. This is disadvantageous because of the high residence time of the particles due to the unfavorable ratio of \( p_r \) to \( p_f \) values. According to Fig. 9 of our article, the heavies will also pass through more stages than would be the case in a comparable situation in the 120 deg. zig zag air classifier unless both the \( p_r \) and \( p_f \)-value of the heavies are below 0.2. But in that case the differences in falling behavior of the lights and heavies would be quite large and good separation results would be obtained anyway.

Considering the fact that we studied the separation process over the full range of air velocities from which the percentage top product varies from 0 to 100 percent, we feel that we did not exclude “heavies”, or rather the formation of the falling particle streams, from our discussion. It should be recalled that our experiments were carried out at very low particle concentrations so that interaction between particles could not occur. When interaction between particles is excluded the performance of a classifier for separating mixtures can be calculated from individual experiments in which the behavior of single components is measured as a function of air velocity. The results of such calculations will obviously apply strictly at infinitely low concentrations of the mixtures only.

Some remarks of Stessel concern the definitions of separation sharpness and efficiency. He refers to the efficiency factor as defined by Worrel. The choice of a suitable way of describing the separation results obtained in any separation device is so fundamental, that quite a lot of attention has been paid to this aspect in general, especially in German literature. It should be pointed out that the component separation efficiency as given by Worrel, which is similar to a definition worked out by us [1] on the basis of a proposal by Rietema [2], is a com-
combination of the intrinsic separation performance of the classifier and the density distribution functions of the characteristic separation variable for the various components in the feed. In the case of air classifiers one can describe the intrinsic separation performance of the classifier by $\Phi (w)$, where $\Phi (w)$ is the fraction of particles with a fall velocity $w$ that end up in the bottom product stream. The characteristic separation variable is in that case the fall velocity $w$ and the density distribution function of $w$ for component $i$ in the feedstream can be indicated by $n_i (w)$. The relation between the component separation efficiency $E'$, defined by us as

$$E' = \left( \frac{x_2 - y_2}{x_0 - y_0} \right)$$

on the one hand and $\Phi (w)$ and the $n_i (w)$ on the other hand, has been derived by us quantitative [1]. A comparison of classifiers on the basis of any $E$-value should be carried out with care as variations in $n_i (w)$'s will influence the $E$-value, although the intrinsic separation performance of the classifier $\Phi (w)$ may remain the same.

In the process of attempting to define the separation performance correctly, we looked for a description of the intrinsic classifier performance. We used $\Phi (\bar{v_f})$ that gives the fraction of identical particles leaving at the bottom exit as function of the superficial air velocity $\bar{v_f}$. It was found by us that for isogeometric, flat particle with different fall velocities the $\Phi$-function is identical, if $\bar{v_f}$ is normalized to $\bar{v_f}_{50}$, i.e. the value of $\bar{v_f}$ for which $\Phi = 50$ percent. This $\bar{v_f}_{50}$ value is characteristic for a particle and might be defined as "fall velocity" in that specific classifier configuration. In this way $\Phi (\bar{v_f} / \bar{v_f}_{50})$ described the intrinsic separation capability at any value of $\bar{v_f}$. For a fixed value of $\bar{v_f}$ the $\Phi$-value of various isogeometric, flat particles can be read in dependence of their individual $\bar{v_f}_{50}$-value. In combination with the information on the $n_i (\bar{v_f}_{50})$'s for the components any component efficiency factor may be calculated. The use of $\Phi (\bar{v_f} / \bar{v_f}_{50})$ therefore makes it possible to calculate the efficiency factor defined by Worrel at any superficial air velocity as long as the $\bar{v_f}_{50}$ values of the components are known. This has also been pointed out in our comment to the discussion by Vesilind.

REFERENCES

Senden, M. M. G. and Tels, M.,Chem. Ing. Techn. 51 (1979), No. 2, pp. 132-133.