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Original paper

Computational model for prediction of particle degradation during dilute-phase pneumatic conveying: the use of a laboratory-scale degradation tester for the determination of degradation propensity

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Abstract—The overall objective of this work is to develop a computational model of particle degradation during dilute-phase pneumatic conveying. A key feature of such a model is the prediction of particle breakage due to particle–wall collisions in pipeline bends. This paper presents a method for calculating particle impact degradation propensity under a range of particle velocities and particle sizes. It is based on interpolation on impact data obtained in a new laboratory-scale degradation tester. The method is tested and validated against experimental results for degradation at 90° impact angle of a full-size distribution sample of granulated sugar. In a subsequent work, the calculation of degradation propensity is coupled with a flow model of the solids and gas phases in the pipeline.

Keywords: Dilute phase pneumatic conveying; impact; degradation tester; breakage matrix.

1. INTRODUCTION

The degradation of particles of granulated materials during pneumatic transport is an issue of considerable industrial concern. Degradation is usually an undesired process, and leads to difficulties associated with dust creation, change in the material characteristics and product quality, etc. For example, the resulting change

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in particle shape and particle size distribution might lead to the production of off-specification products, causing severe problems of quality with regard to the end use of the material. The fines generated by attrition can cause a decrease in the material flowability and considerably enhance its propensity for caking. The above difficulties have to be overcome through the use of additional handling and recycling systems. These can significantly increase production costs in processing and handling of particulate materials.

The degradation in pneumatic systems occurs mainly as a result of impact or shear loads [1]. Particles on their way through a pipe bend undergo, for example, extensive impact loads on the bend walls. The most important parameters affecting particle degradation are the air and particle velocities, the solids : air mass ratio, the bend structure and the particle properties, such as the strength, size and shape of the particles [2]. More specifically, in the case of degradation due to impact, the collision velocity, the angle of collision and the elasticity of the collision have been shown to influence significantly particle damage. It is well established that a reduction of the transport velocity can considerably reduce the attrition of particles [1]. Hence, dense-phase pneumatic conveying systems, which operate at low gas velocities, can achieve lower rates of particle attrition. However, not all materials are suitable for dense-phase conveying [3]. Moreover, dilute-phase conveying is still the most widely used technology, as it is the most cost effective and versatile design to use [4].

Studies reported so far in the literature on the degradation in pneumatic conveying systems are largely based on an empirical approach. For an existing system, comparing the particle size distribution of a material at the inlet and the outlet of the system is the only way to assess degradation; however, for most of the systems it is impossible to access the inlet and the outlet. Different methods to predict degradation in pneumatic conveyors have then been developed. These are either to build a pilot-sized conveyor scaled to the actual plant component dimensions [5–8] or use a small-scale air blast rig [9–11]. However, it is often difficult to extend with confidence the results obtained to the real processes, as well as to diagnose and understand how and where the degradation occurs. Another disadvantage of using the above methods is the cost of building the test rigs. On the other hand, computational models of conveying systems, which describe the motion of fluid and particles in the pipe system, based either on the Euler/Lagrange approach [12–14] or on the two-fluid theory [15], do not generally incorporate models for particle degradation or employ any particle degradation data. In the context of dilute-phase systems, most of the calculations have been performed using the Euler/Lagrange approach. To determine particle trajectory, such models are able to take into account particle wall impacts using the momentum equations for the particle wall interactions and including the effect of wall roughness [16, 17]. However, there is at present limited experimental information available on the details of the degradation mechanisms to support the development of a generally applicable model for particle damage. Moreover, the application of the Lagrangian approach for the particulate phase in large-scale pneumatic conveyors is not deemed to be computationally effective due to the large amount of memory and CPU time requirements.

A powerful mathematical representation of degradation processes is the population balance model, founded in the work of Epstein [18] and widely used by many subsequent authors to describe grinding operations of solids materials (see, e.g. [19, 20] for reviews of the population balance model and [21] for a recent example of application). This approach is based on the definition of two statistical functions, the breakage function and the selection function, which allow a population balance to be performed for a given size class. The breakage function is defined as the size distribution of the products of a breakage event and the selection function represents the rate at which degradation occurs. The standard methods for determining these functions include measuring the change in a given monosize class sample or a marked particle size class [22], or extracting the functions from degradation tests by numerical optimization [23]. However, no attempt has been made to apply the population balance approach to the study of pneumatic conveying systems, due in particular to the lack of detailed experiments, which are needed for the determination of the particle breakage parameters.

A matrix representation of degradation processes, based on the concepts of the population balance model, is applied in this paper with the aim of describing particle degradation by impact during dilute-phase pneumatic conveying. A procedure is then presented to determine the extent of impact degradation under a range of particle velocities and particle sizes from single-impact tests carried out in a laboratory-scale degradation tester. The procedure is validated against experimental data from degradation tests on granulated sugar.

2. METHODOLOGY OVERVIEW

As a preliminary, an outline of the methodology developed for predicting the extent of degradation imparted to particles during their transport in dilute-phase pneumatic conveying systems is presented in Fig. 1. The primary mechanism of particle degradation under consideration in the present study is due to particle–bend wall collisions [1].

In the present work, particle single-impact testing at a specified velocity is carried out in a laboratory-scale degradation tester to quantify particle degradation propensity based on particle size analysis and a matrix representation of degradation processes (using the concept of population balance models). Interpolated breakage matrices for a range of both impact velocities and particle sizes are derived from a limited number of experimentally determined breakage matrices.

A computational model of particle degradation occurring during dilute-phase pneumatic conveying is then developed in a subsequent work [24], which combines calculation of the degradation propensity by the use of the above breakage matrices

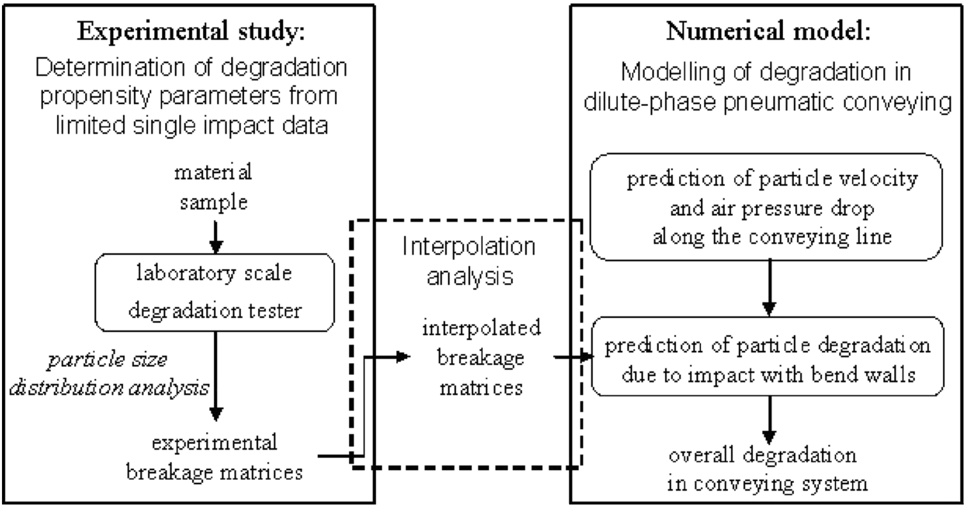


Figure 1. Methodology used for predicting the overall particle degradation in dilute-phase conveying systems from single impact data.

with a flow model of the gas and solids phases in the pipeline. This model provides estimates of the overall degradation in dilute-phase pneumatic conveying systems.

3. EXPERIMENTAL TESTS

3.1. The purpose of the tester

The degradation tester was designed to simulate conditions in transport systems and enable an assessment of the extent of degradation for granular materials in such systems to be made [25]. This tester is a bench-scale unit for assessing degradation by impact. This test facility can control both the velocity of the particles and the angle of impact. Benefits associated with this facility are that the particle velocity is very closely controlled, the tester is portable and only a small quantity of test material is required for each test. A degradation test will yield the particle size distribution from an input sample being subjected to impacts at a certain velocity. The input sample can be a mixture of size fractions or a single-size fraction as appropriate. The former will inform of the collective breakage behavior; the latter will give specific information on the breakage characteristics of a single-size class. The scale of the tester enables the entire degraded batch to be collected and subjected to particle size analysis. The material will be then analyzed in order to assess the amount of degradation caused under the designed test conditions.

3.2. Description of the tester

The degradation tester consists of a balanced disk where the velocity of rotation can be varied continuously and fixed at any given value (see Fig. 2). The rotating

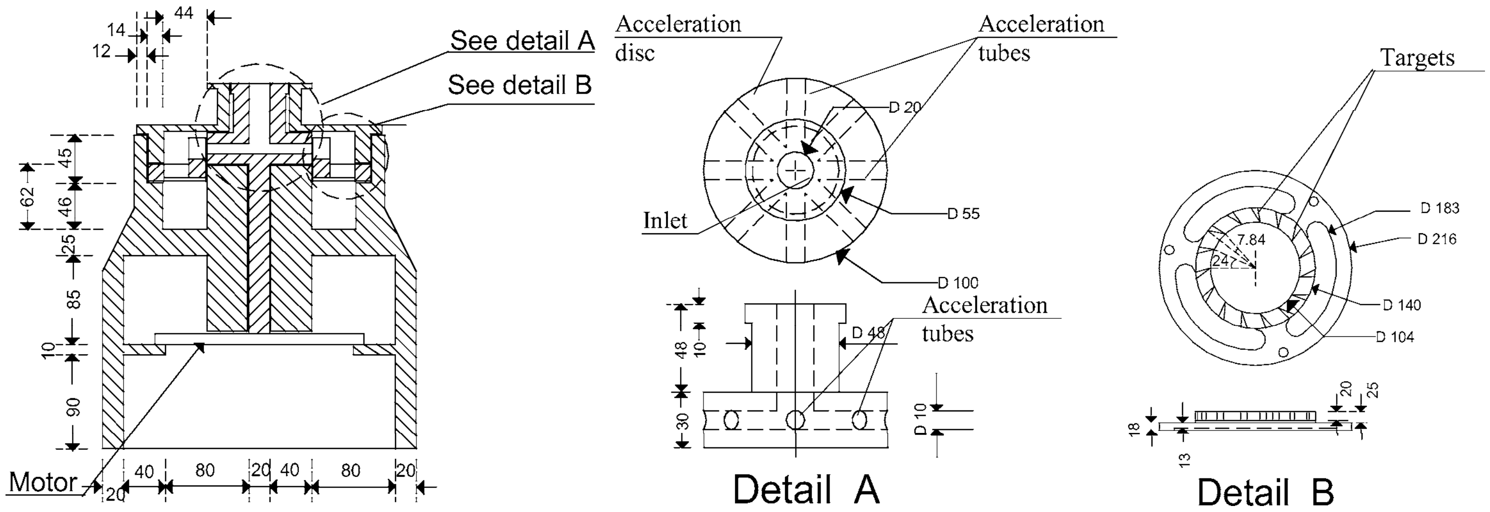


Figure 2. Schematic of the rotating disk of the degradation tester.

disk (Fig. 2, Detail A) is 100 mm in diameter and contains eight radial channels of 10 mm internal diameter. A mechanical arrangement ensures even splitting of the powder into the eight acceleration channels. During operation, the particles are fed into the central hole of the rotating disk. These particles are accelerated through the eight radial channels by the centrifugal and Coriolis forces, and ejected from the end of the acceleration tubes. It was important to assess the magnitude and direction of the particle velocity at exit from the acceleration tubes. The calculation of the particle velocity (V_p) is based upon an analysis of the velocity components of an individual particle exiting the acceleration tube:

$$V_\mathrm{p} = \frac{2\pi R}{\cos(\alpha)} n, \tag{1}$$

where R is the radius of the accelerator disk, n is the rotation (r.p.m.) and α is the exit angle. Burnett [26] referred an approximate value of $\alpha = 40^\circ$. At the point of exit, the particles enter a free trajectory phase until they impact onto the targets. The targets are angled to 90° of the trajectory of the particles exiting the acceleration tubes and are equally spaced around a ring fitted around the acceleration disk (Fig. 2, Detail B).

3.3. Test methodology

Tests were carried out on a single-size fraction sample, to obtain specific information on the breakage characteristics of a single-size class. In order to test individual size fractions, a particulate mixture sample was separated into size fractions, as appropriate, by passing it through a sieve stack. Each size fraction was stored separately. In a series of experiments allowing for systematic step changes in size classes, the input sample of a size fraction was subjected to impacts at a certain velocity. The methodology of carrying out the tests on the degradation tester is presented out sequentially below:

(i) A collection basket was inserted into the tester, the necessary set of targets was fitted in place, the lid was placed and secured to avoid any escape of dust generated during degradation, and the feed hopper was inserted.

(ii) The motor was switched on and the rotating disk was set to the required velocity.

(iii) A 5 g sample was poured in the feed hopper.

(iv) The motor was stopped a moment after the feed hopper empties (the sample will exit the acceleration tube and impact on the target very rapidly).

(v) The lid was removed and brushed down over a tray to collect any dust. The material inside the tester was emptied completely into the tray, ensuring that no particles were left inside.

(vi) The particle size distribution of the degraded sample was recorded.

(vii) To test the reproducibility of the method, a second run was made, with fresh particles of the same size.

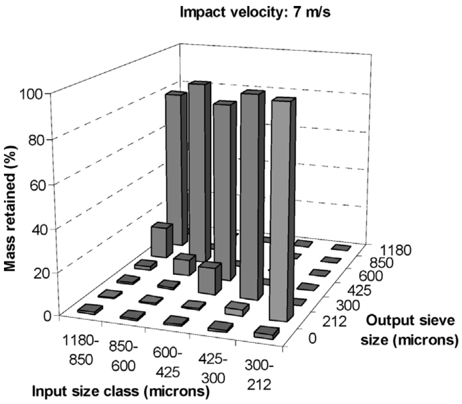
3.4. Experimental results

Once the entire sample of degraded material had been collected from the tester, the degradation analysis was undertaken. The scale of the tester enabled the entire degraded batch to be collected and subjected to the particle size analysis, undertaken according to British Standard [26] procedure for conducting a manual sieve test. The material was then analyzed in order to assess the amount of degradation caused under the designed test conditions.

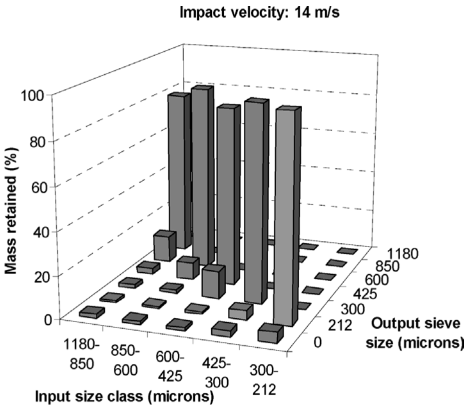
Ninety-degree impact tests were carried out on granulated sugar samples at different particle velocities to assess the amount of degradation caused by the particle velocity. The resulting data of the degradation tests are presented in Fig. 3. The results presented are the average of two runs of fresh particles of the same size and weight. The reproducibility of the resulting data was in general within 1%. An accuracy of 0.001 g on an analytical balance was used during the weighing of the samples; however, in order to assess the experimental error resulting from the degradation tests, and for refined analysis, the error in weight was considered to be equal to 0.01 g for each measurement. The experimental errors resulting from the degradation tests were below 2% for all samples.

It is clear that as the particle velocity increased the amount of degradation generated for a given size class also increased. More severe damage at higher impact velocities appears to be consistent with all size classes. This was expected; as the particle velocity increased, the strength of the particle was not great enough to withstand the resultant impact, hence the particles fractured into smaller particles of comparable sizes. Figure 3 shows clearly that the largest particles break more easily than the smallest. This is believed to be due to the fact that particles of a given material generally have a range of strengths related to their sizes [28], hence the stress required to break large particles is much less than that required for small particles.

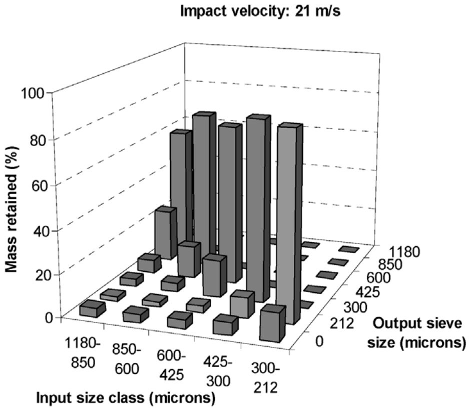
It is seen from Fig. 3 that the effect of the impact velocity on degradation increases with decreasing particle size. For example, increasing the velocity from 7 to 21 m/s increases the proportion of broken particles by a factor of 2 for the size range between 850 and 1180 μm (20.1 and 40.3% at 7 and 21 m/s, respectively), whereas the same variation of the velocity causes an increase in the proportion of broken particles by a factor of about 10 for the size range between 212 and 300 μm (1.2 and 13% at 7 and 21 m/s, respectively). In terms of particle size effect, this observation shows that the effect of the particle size on degradation is smaller with an increase in velocity. This result reflects the fact that, as the impact velocity is increased, the stress induced by the impact becomes gradually sufficient to overcome the strength of every particle.


Impact velocity: 7 m/s

	1180-850	850-600	600-425	425-300	300-212
1180	0	0	0	0	0
850	79.9	0	0	0	0
600	15.4	90.2	0	0	0
425	2.2	7.6	85.7	0	0
300	0.9	0.9	12.9	96.1	0
212	0.5	0.5	0.7	2.7	98.2
0	1.1	0.8	0.8	1.2	1.8


Impact velocity: 14 m/s

	1180-850	850-600	600-425	425-300	300-212
1180	0	0	0	0	0
850	79.7	0	0	0	0
600	12.7	88.3	0	0	0
425	3	7.9	84.6	0	0
300	1.6	1.5	13	92.7	0
212	1	0.8	1	4.4	94.9
0	2	1.5	1.4	2.9	5.1


Impact velocity: 21 m/s

	1180-850	850-600	600-425	425-300	300-212
1180	0	0	0	0	0
850	59.7	0	0	0	0
600	24.5	74.7	0	0	0
425	6.2	15.1	75.2	0	0
300	3.4	4.1	17.4	84.8	0
212	2.1	2.3	3.1	9.6	87
0	4.1	3.8	4.3	5.7	13

Figure 3. Particle size distribution resulting from degradation tests of various size classes of granulated sugar samples at different impact velocities.

4. THEORETICAL

4.1. Matrix analysis of degradation processes

The size range is divided into a number of size classes indexed from 1 (coarse) to n (fines). The breakage matrix approach is based around the following matrix equation:

$$\mathbf{B} \cdot \mathbf{i} = \mathbf{o}, \tag{2}$$

where $\mathbf{i}$ and $\mathbf{o}$ are column vectors, whose entries are the particle mass fraction in each size class, respectively before and after the degradation event, and $\mathbf{B}$ is the breakage matrix, whose elements b_{ij} define the mass fraction of particles of size class j which ends up in size class i as a result of degradation.

The breakage matrix takes the following form (e.g. for four particle size classes):

$$\mathbf{B} = \begin{bmatrix} b_{11} & 0 & 0 & 0 \\ b_{21} & b_{22} & 0 & 0 \\ b_{31} & b_{32} & b_{33} & 0 \\ b_{41} & b_{42} & b_{43} & b_{44} \end{bmatrix}. \tag{3}$$

Each column of the matrix describes the fate of a given size class in the input size distribution. For example, for particles initially in size class 2, b_{42} denotes the proportion degrading to size class 4, b_{32} is the proportion degrading to size class 3 and b_{22} represents the proportion of undegraded material. The sum of the elements of each column must be unity. Each row of the matrix informs of the source of particles ending up in a given class in the output size distribution.

All elements above the diagonal of the breakage matrix are zero, as by definition it is impossible for particles to move to larger size classes.

The breakage matrix constitutes a robust and quantitative means of following the degradation processes for all particles size classes.

4.2. Numerical procedure for the determination of the extent of degradation

Experiments described in Section 3 consist essentially of measuring individual columns of the breakage matrix for a given impact velocity and a given set of sieve sizes. The interpolation procedure described below is intended to allow for an estimation of the amount of degradation on a full particle size distribution, for any set of sieve sizes of the particle distribution and any impact velocity, both within a certain envelope of values, by measuring the breakage matrix for a limited number of cases across this envelope.

The procedure requires as input the breakage matrix for a small number of velocities (typically three to five velocities) obtained from experimental data on single impacts. The calculation methodology, which combines an interpolation with respect to the sieve size and the particle velocity, proceeds in three steps.

(i) The first step is to build the breakage matrices for the set of size classes of the investigated particle size distribution, when these are different from the set of size classes used to determine the experimental breakage matrices. The breakage matrix for the desired set of size classes for a certain impact velocity is calculated through bilinear interpolation from the breakage matrix measured at this velocity [29]. Because of the rapidly varying size distribution of the breakage fragments of a given size class (see columns of the breakage matrices in Section 3), it has been found in practice that the matrix can be more accurately interpolated by treating separately the diagonal elements and the first element below them in the same column. The determination of a diagonal element is performed by a simple linear interpolation from the diagonal coefficients of the experimental matrix. This is due to the observed property that the propensity of particle degradation along the diagonal decreases (i.e. smaller particles tend to degrade less than bigger ones). The first element below the diagonal element in the same column is calculated using the normalizability condition (i.e. the sum of elements of each column of the breakage matrix must be equal to unity).

(ii) The amount of degradation on the investigated size distribution at each of the velocities used in the experimental tests is then evaluated through (2) by using the known breakage matrices.

(iii) Finally, an estimate of the degradation at intermediate velocities is determined by means of an N-order polynomial interpolation [where N is the total number of velocities (v_i) for which tests have been performed] from the set of values ($\mathbf{o}_i$) calculated in the second step. The interpolating polynomial of degree $N-1$ can be written as [29]:

$$P(v) = \sum_{i=1}^{N} R_i(v)\mathbf{o}_i, \tag{4}$$

where:

$$R_i(v) = \prod_{\substack{j=1\\ j\neq i}}^{N} \frac{(v - v_j)}{(v_i - v_j)}. \tag{5}$$

As will be demonstrated, this simple interpolation procedure is found to give satisfactory estimates. Moreover, it guarantees that the values thus calculated will reproduce the experimental points. It may be advisable to restrict the application of the method proposed for interpolating the breakage matrix with respect to the sieve size to cases for which the number of investigated sieve sizes is less than or close to the number of sieve sizes used to measure the breakage matrices. Limited reduction of the experimental work required to build the initial breakage matrices by using the size interpolation method should therefore be expected. The main interest of the size interpolation procedure lies in the capability of 'shifting' the breakage matrix within a range of values of the sieve sizes.

The choice of a generally applicable size interpolation method was found to be difficult because of the likely sharp variations of the fragment size distribution of a given size class, such as in the case of the degradation of granulated sugar presented in Section 3.4. A limitation of the proposed size interpolation method is that it tends to concentrate the interpolation error in the approximation of the first element below the diagonal element in the same column. This may affect the accuracy of the prediction of the fraction of particles ending up in the intermediate-size classes of the distribution. However, the information from the interpolated breakage matrices can be used with confidence to determine the fraction of particles ending up in the smaller-size classes (commonly referred to as fines), which are generally in industrial practice the size classes of interest regarding the assessment of the extent of degradation during pneumatic conveying. This will be clearly demonstrated in the following section, where an interpolated-in-size breakage matrix was calculated and used to estimate the extent of degradation for a full particle size distribution for which experimental data from the degradation tester were available.

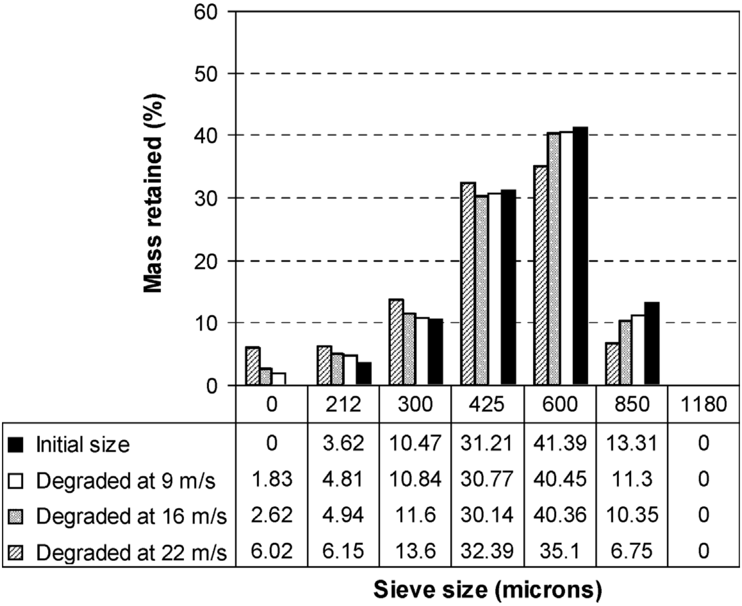
5. VALIDATION OF THE DEGRADATION MODEL AGAINST DEGRADATION TESTS IN THE LABORATORY

5.1. Experimental results

To validate the outcome of the model, degradation tests were carried out using granulated sugar samples consisting of a mixture of size fractions, to obtain specific information on the collective breakage behavior. In order to test the full size distribution, it is important that the particle size distribution is reproduced precisely for each test. The particulate mixture was separated into six size fractions, as appropriate, by passing through a sieve stack. Each size fraction was stored separately. Samples (5 g) were assembled according to the initial particle size distribution of the particulate mixture, using material from the stored size classes.

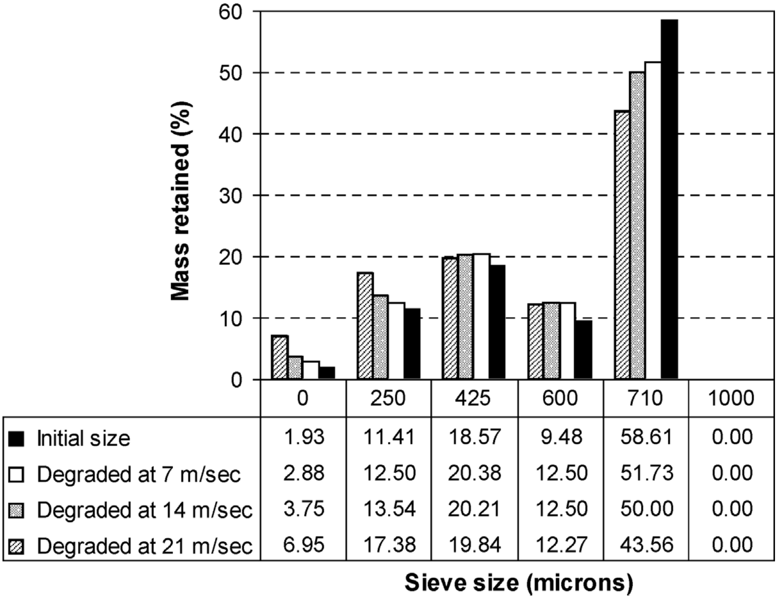
In a series of tests allowing for systematic step changes in particle velocity, the input sample of a full particle size distribution was subjected to 90° impacts at a certain velocity. The methodology of carrying out the tests in the degradation tester is similar to that described in Section 3.3. The experimental uncertainty has been calculated to be as before of the order of 2%. Two series of experiments (referenced as experiments A and B, respectively) were performed with two different initial particle size distributions associated with different sets of sieve sizes.

To illustrate the effect of particle velocity on the amount of degradation obtained during the tests, the entire degraded sample collected from the tester was subjected to particle size analysis. The resulting data are presented in Figs 4 and 5 for experiments A and B, respectively. It is clear that as the particle velocity increased, the net amount of degradation increased.



	0	212	300	425	600	850	1180
■ Initial size	0	3.62	10.47	31.21	41.39	13.31	0
□ Degraded at 9 m/s	1.83	4.81	10.84	30.77	40.45	11.3	0
▩ Degraded at 16 m/s	2.62	4.94	11.6	30.14	40.36	10.35	0
▨ Degraded at 22 m/s	6.02	6.15	13.6	32.39	35.1	6.75	0

Figure 4. Particle size distribution resulting from degradation tests at different particle velocities in experiment A.



	0	250	425	600	710	1000
■ Initial size	1.93	11.41	18.57	9.48	58.61	0.00
□ Degraded at 7 m/sec	2.88	12.50	20.38	12.50	51.73	0.00
▩ Degraded at 14 m/sec	3.75	13.54	20.21	12.50	50.00	0.00
▨ Degraded at 21 m/sec	6.95	17.38	19.84	12.27	43.56	0.00

Figure 5. Particle size distribution resulting from degradation tests at different particle velocities in experiment B.

5.2. Prediction of the extent of degradation

The interpolation procedure described in Section 4.2 has been applied to predict the extent of degradation for the two different size fraction mixtures defined in Section 5.1, by using the experimental breakage matrices for the three velocities 7, 14 and 21 m/s that were presented in Section 3. Direct use of the experimental breakage matrices was possible for the conditions of experiment A. However, since the sieve sizes of the particle size distribution in experiment B are different from those that have been used to measure the breakage matrices in Section 3, breakage matrices for the appropriate sieve sizes employed in experiment B have been generated prior of the simulation from the experimental matrices using the size interpolation procedure. The simulation results for both series of experiments (given in Tables 1 and 2) are compared to the change in the particle size distribution measured in the degradation tester in Figs 6 and 7.

In view of the experimental conditions in experiments A and B, the results in Figs 6 and 7 illustrate the efficacy of the interpolation methods with respect to the impact velocity and to the particle size, respectively. Very good agreement was

Table 1.
Particle size distribution calculated at different particle velocities using the breakage matrices for the conditions of experiment A

Sieve size (μm)	Initial particle size distribution	Degraded at 9 m/s	Degraded at 16 m/s	Degraded at 22 m/s
1180	0.00	0.00	0.00	0.00
850	13.31	10.90	10.13	7.32
600	41.39	39.95	37.40	33.32
425	31.21	30.09	30.15	30.67
300	10.47	14.40	14.93	16.89
212	3.62	4.29	5.01	6.72
0	0.00	0.99	2.39	5.09
Total	100	100	100	100

Table 2.
Particle size distribution calculated at different particle velocities using the breakage matrices for the conditions of experiment B

Sieve size (μm)	Initial particle size distribution	Degraded at 7 m/s	Degraded at 14 m/s	Degraded at 21 m/s
1000	0	0	0	0
710	58.61	50.16	49.48	39.87
600	9.48	12.84	12.27	15.16
425	18.57	19.58	19.75	21.82
250	11.41	14.33	14.43	16.2
0	1.93	3.09	4.07	6.94
Total	100	100	100	100

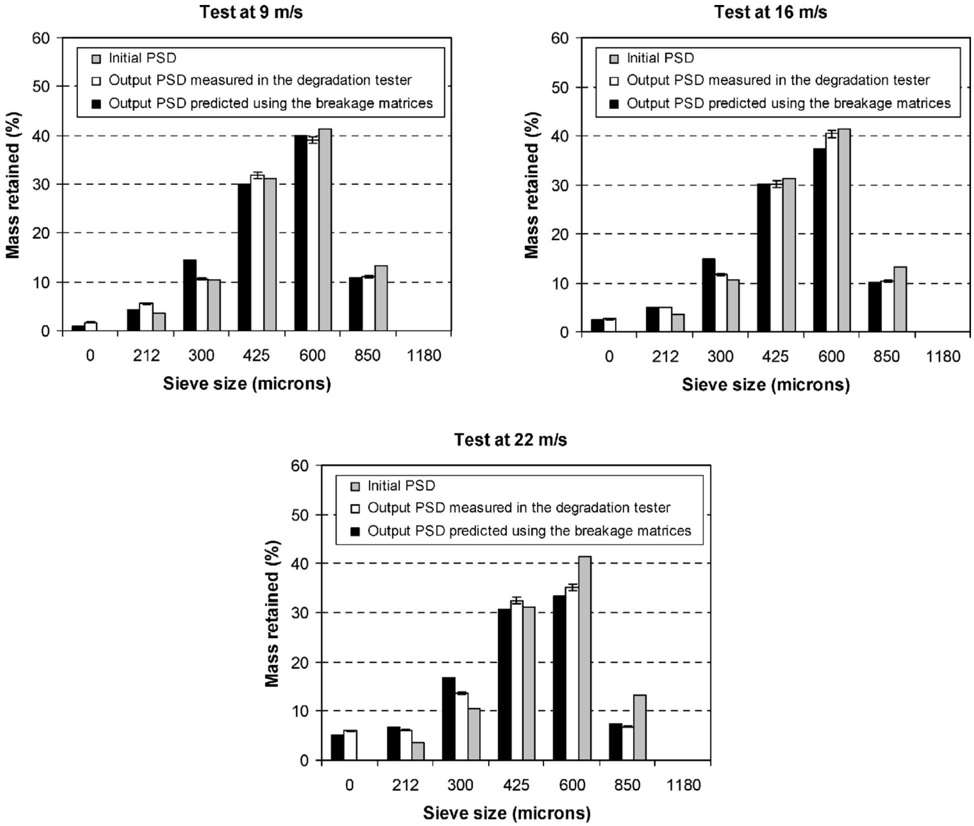


Figure 6. Comparison between the particle size distributions measured in the degradation tester and predicted using the breakage matrices for the conditions of experiment A.

found between the particle size distributions predicted using the breakage matrices and those measured in the degradation tester at each velocity for the two series of experiments. It can be seen in particular that the procedure gave an accurate representation of the fractions of fine particles generated (see lower size classes below 300 and 250 μm for experiments A and B, respectively). This latter point is of particular importance for quantitative assessment of degradation and final product quality (i.e. percentage of fines resulting from the conveying process) in industrial practice.

6. CONCLUSIONS

A methodology has been developed to predict degradation propensity over a range of particle impact velocities and particle sizes. It is based upon interpolation on experimental data for particle single impacts, obtained in a specifically designed degradation tester. The advantages of the degradation tester developed are in particular the fact that the tester is portable and that only a small amount of material

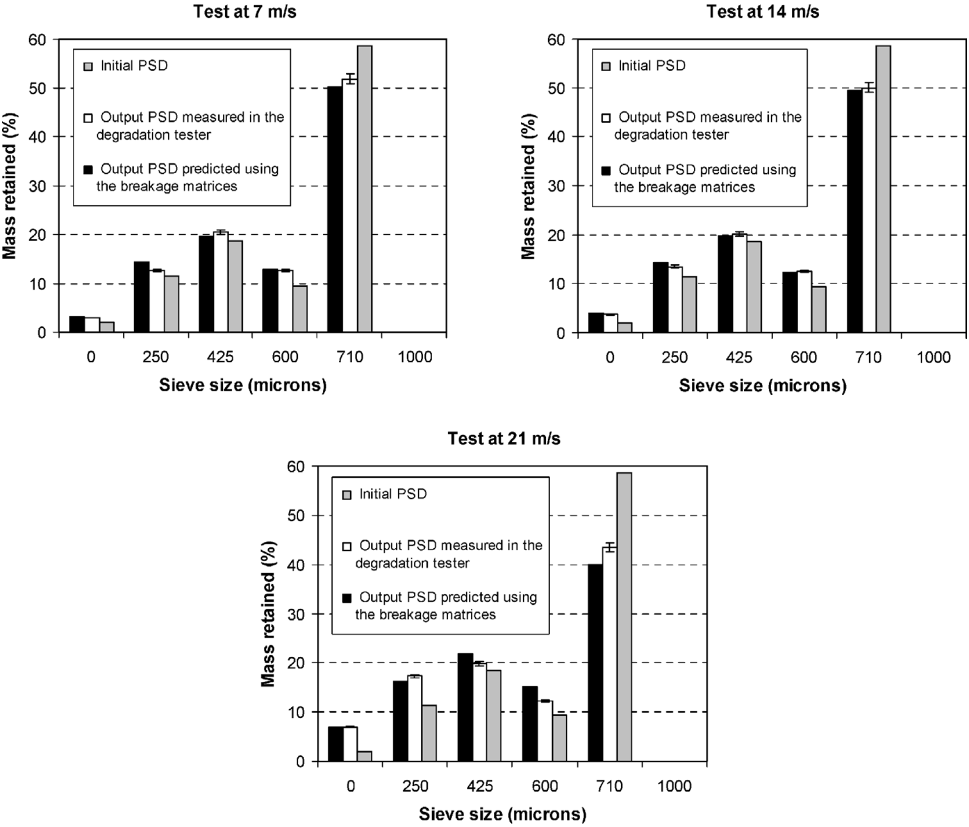


Figure 7. Comparison between the particle size distributions measured in the degradation tester and predicted using the breakage matrices for the conditions of experiment B.

is required for each test. A simple interpolation procedure, based on a matrix representation of degradation processes, has been found to give faithful estimates using a relatively small number of experimental input data. Comparison of the results obtained by this method for a full size distribution sample of granulated sugar at 90° impact angle with those obtained by direct use of the degradation tester shows very good agreement. The method described in this paper is employed in a subsequent work for the prediction of degradation in dilute-phase pneumatic conveying, through its coupling with a flow model of the solids and gas phases in the pipeline.

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