Powder Technology 143–144 (2004) 321–330

POWDER TECHNOLOGY

www.elsevier.com/locate/powtec

Numerical predictions of particle degradation in industrial-scale pneumatic conveyors

P. Chapelle[a], H. Abou-Chakra[b], N. Christakis[a], I. Bridle[c], M.K. Patel[a,*], J. Baxter[b], U. Tuzun[b], M. Cross[a]

[a] Centre for Numerical Modelling and Process Analysis, School of Computing and Mathematical Sciences, University of Greenwich, Old Royal Naval College, Park Row, Greenwich, London SE10 9LS, UK

[b] Chemical and Process Engineering, School of Engineering, University of Surrey, Guildford, Surrey GU2 7XH, UK

[c] The Wolfson Centre for Bulk Solids Handling Technology, University of Greenwich, Wellington Street, Woolwich, London SE18 6PF, UK

Abstract

This paper presents an Eulerian-based numerical model of particle degradation in dilute-phase pneumatic conveying systems including bends of different angles. The model shows reasonable agreement with detailed measurements from a pilot-sized pneumatic conveying system and a much larger scale pneumatic conveyor. The potential of the model to predict degradation in a large-scale conveying system from an industrial plant is demonstrated. The importance of the effect of the bend angle on the damage imparted to the particles is discussed.

Keywords: Numerical prediction; Pneumatic conveyor; Particle degradation

1. Introduction

Pneumatic conveying of granular materials is applied in many industrial situations because of its flexibility, simplicity and environmental compatibility. However, attrition or degradation of the particulate material being conveyed is commonly observed, particularly in the dilute-phase flow mode. This may affect the product quality and cause severe difficulties in subsequent material handling operations. Degradation during dilute-phase pneumatic conveying results mainly from high-velocity impacts of the particles with the pipe walls [1].

Studies of degradation in pneumatic conveying systems in the literature have been 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 conveyor is the only way to assess degradation. Unfortunately, for most of the industrial systems it is impossible to access the inlet and the outlet. The methods used to predict degradation in pneumatic conveyors involve either building a pilot sized conveyor scaled to the actual plant component dimensions (e.g., Ref. [2]) or using a small-scale air blast rig (e.g., Ref. [3]). However, it is often difficult to extend with confidence the results obtained to the real processes.

On the other hand, most computational models for pneumatic conveying systems concentrate only on the detailed description of the flow of the solids and gas phases and disregard the damage imparted to the particle (e.g., Ref. [4]). In the context of dilute-phase systems, most of the calculations have been performed using the Euler/Lagrange approach. A number of models include the effects of particle–wall collisions on the particle trajectory [5,6].

More recently, a group of models for predicting particle degradation in dilute-phase pneumatic conveying has been published. All models incorporate particle fragmentation characteristics obtained from results from particle single impact studies. These models however differ in the method of describing the flow of the gas–solids mixture through the pipeline. Salman et al. [7] and Han et al. [8] used a Lagrangian approach to simulate particle trajectory through a pipe. Their models were validated for the case of small pneumatic conveying systems consisting of up to two pipe bends. It should be noted that the application of the Lagrangian approach for the particulate phase is not deemed to be computationally effective in large-scale pneumatic conveyors due to the large amount of memory and CPU time require-

* Corresponding author. Tel.: +44-20-8831-8702; fax: +44-20-8331-8695.

E-mail address: m.k.patel@gre.ac.uk (M.K. Patel).

0032-5910/$ - see front matter
doi:10.1016/j.powtec.2004.04.024

ments. An Eulerian framework based on macroscopic balance equations was chosen by Chapelle et al. [9] to describe the flow of the gas–solids mixture. This model, coupled with the calculation of particle degradation propensity, was used to predict particle degradation in a large-scale pneumatic conveying system with several pipe bends of 90° angle.

In the present study, the model developed by Chapelle et al. is extended in order to account for degradation in pneumatic conveyors consisting of pipe bend of different angles. The model is then used to investigate degradation of granular materials in industrial large-scale pneumatic conveying systems. The importance of the effect of the particle angle of impact on particle damage is analysed from the simulations. The capability of the model to give good quantitative predictions of particle degradation is discussed.

2. Numerical models

This section outlines the key features of the numerical model for predicting particle degradation during dilute-phase pneumatic conveying. A more detailed presentation of the model can be found in Ref. [9].

2.1. Flow model

2.1.1. Straight pipe

Two types of gas–solids flow pattern can be identified in a straight pipe element: a strand-type flow region immediately downstream of a bend created due to the centrifugal force encountered by the particles while travelling around the bend, followed by a fully suspended flow region after dispersion of the strand.

The approach used for modelling the strand-type flow is based on the work of Bradley et al. [10]. This model is a one-dimensional model, which describes the flow of two layers (namely, the dense strand and the suspended flow above it) with separate velocity and exchanging momentum between them due to shear forces at their interface. It is based on a force balance on elements of the strand and of the suspended flow region above it. The force balance equations for a strand element of length δ_1 and the corresponding suspended flow region are given respectively by:

$$\tau_{str}S_{str} = \rho_b \delta_1 \frac{\pi D^2}{4}(1-\phi)a_{str} \quad (1)$$

$$\tau_{str}S_{str} + \tau_{susp}\ S_{susp} = \Delta P_{susp}\frac{\pi D^2}{4}\phi \quad (2)$$

where S_{str} and S_{susp} are the contact areas respectively between the strand and the suspended flow and between the suspended flow and the pipe wall, ΔP_{susp} is the pressure drop, in the suspended flow region, ρ_b is the material bulk density in the strand, a_{str} is the acceleration of the strand element, D is the pipe diameter, and (1-ϕ) represents the fraction of the pipe cross-sectional area covered by the strand. τ_{str} and τ_{susp} represent the friction forces respectively between the strand and the suspended flow and between the suspended flow and the pipe wall. In writing Eq. (2), the friction force between the strand and the pipe wall was assumed to be negligible. For pipe elements inclined with respect to the horizontal, the gravity force acting on the strand is taken into account in Eq. (2).

The friction force between the strand and the suspended flow τ_{str} is modelled in analogy to single phase flow by using an equivalent Moody friction factor:

$$\tau_{str} = \frac{\rho_{air}f_{str}}{2}(v_{air} - v_{str})^2 \quad (3)$$

where ρ_{air} is the air density and v_{air} and v_{str} are the air and strand velocities, respectively. The value of the friction factor f_{str} obtained from the Moody diagram is increased in order to account for the additional momentum transfer resulting from the interchange of particles between the strand and the suspended flow. The friction force between the suspended flow and the pipe wall τ_{susp} is calculated in a similar way as τ_{str}.

In the fully suspended flow region, the air and particles velocities are assumed to be identical. A conventional first approximation method to calculate the total pressure drop along an elemental length consists of splitting the pressure gradient into two parts [11,12]:

$$\Delta P = \Delta P_{air} + \Delta P_{solids} \quad (4)$$

where ΔP_{air} is the pressure drop expected with air only in the pipe and calculated from Darcy's equation and ΔP_{solids} represents the additional pressure drop caused by the particles present in the gas [12]:

$$\Delta P_{solids} = K\delta_1\rho_{susp}v_{air}^2 \quad (5)$$

with ρ_{susp} the suspension density and K an empirical coefficient.

2.1.2. Bend

Experimental observations show that the pressure drop caused by a bend does not occur in the bend itself, but in the straight section downstream of the bend [13]. Particles on their way through a bend are decelerated as a result of bouncing and sliding contacts with the pipe wall under the effect of the centrifugal force. The change in particle velocity in a bend is found by applying Newton's law, where the particle–wall interactions are characterized by a coefficient of friction μ and a coefficient of restitution e:

$$v = ev_0\exp(-\mu\theta) \quad (6)$$

where v_0 is the particle velocity at the bend inlet and θ is the angular position of the particles inside the bend. Assuming a constant mass flow rate of solids within the pipeline, the fraction of the pipe cross-sectional area occupied by the strand (1-ϕ) at the outlet section of the bend can be worked out from the particle velocity value.

2.1.3. Numerical solution procedure

The solution procedure in a straight section is based on the subdivision of the pipe into elemental lengths. Calculation proceeds forwards along the pipeline, taking into account each element in turn. The boundary condition on pressure is set either at the outlet of the pipeline (for a positive pressure system) or at the inlet of the pipeline (for a vacuum system). Therefore, for a positive pressure system, the calculation procedure works with a guessed value of the pressure at the pipe inlet and is iterated to obtain the known pressure value at the pipe outlet. The solution of each element is achieved iteratively by using a central difference scheme.

2.2. Degradation model

In dilute-phase pneumatic conveying systems, bends are the most serious points of particle damage [1,7], and so degradation is considered to occur only by impact at the bends. Particle degradation in a bend is represented by a single impact, since it has been observed that the first impact of the particles in the bend causes the major damage [7]. Moreover, it is assumed that a given value of the bend angle corresponds to a given value of the angle of impact of the particle. This assumption is supported by experimental results. In an earlier work [9], it has been shown that degradation occurring at a 90° angle bend can be accurately represented by a single impact of 90° angle. As will be demonstrated in the present paper, predictions of particle damage in 45° angle bend based on a similar approximation show also reasonable agreement with experimental observations. Fatigue phenomena, by which a particle breaks when collisions occur a number of times, are ignored as a first approximation. Hence, each impact of a particle is considered independent of the next.

The overall change in the particle size distribution between the inlet and the outlet of a bend is described by the following matrix equation:

$$[\mathbf{B}] \cdot \{\boldsymbol{i}\} = \{\boldsymbol{o}\} \tag{7}$$

where the vectors $\{\boldsymbol{i}\}$ and $\{\boldsymbol{o}\}$ are the particle size distributions, respectively at the inlet and outlet of the bend and $[\mathbf{B}]$ is a matrix (referred in the following as 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. A column of the matrix describes the fate of a given size class in the input size distribution.

The breakage matrices are obtained from the results of single particle impact tests at a specified impact angle and velocity carried out in a laboratory scale degradation tester [14]. An interpolation procedure has been developed to enable the calculation of breakage matrices for a range of impact velocities and particle sizes from a limited number of impact tests across this range [15].

3. Experimental aspects

A rotating disc accelerator-type degradation tester designed to assess the propensity of particle degradation by impact was used in this study [14]. This tester can control both the velocity of the particles and the angle of impact. The degradation tester consists of a 100-mm diameter rotating disc (the rotation velocity of which can be varied continuously and fixed at any given value) composed of eight radial channels of 10 mm internal diameter (see Fig. 1 detail A). During operation, a 5-g particle input sample is fed into the central hole of the rotating disc. The particles are accelerated through the eight radial channels by the centrifugal and Coriolis forces and ejected from the end of the acceleration tubes. At the point of exit, they enter a free trajectory phase until they impact onto the targets, which are equally spaced around a ring fitted around the acceleration disc (see Fig. 1

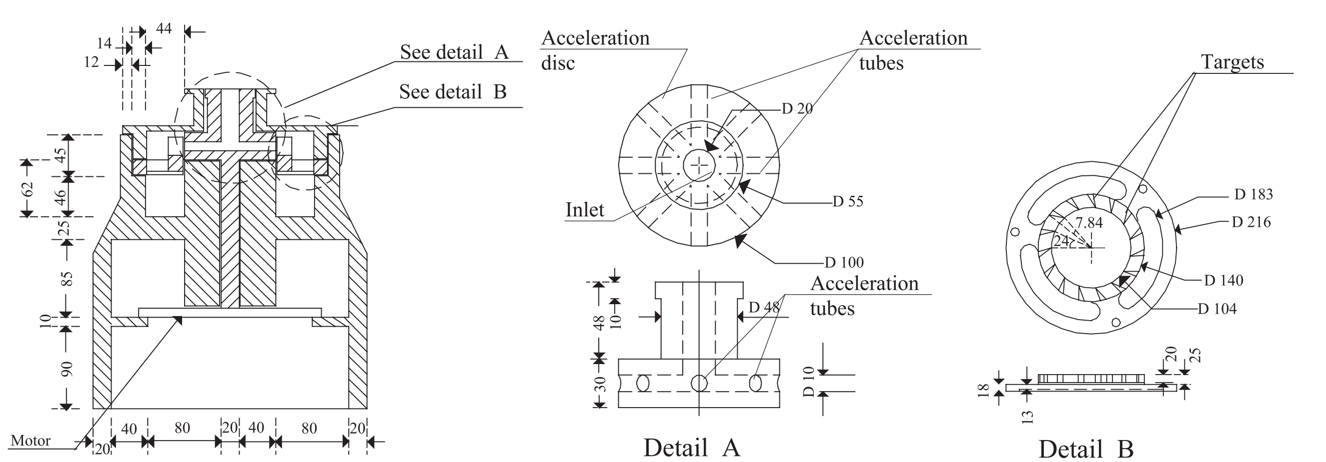
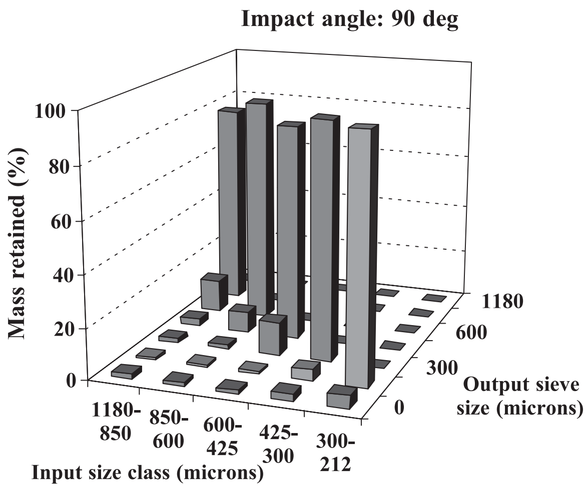
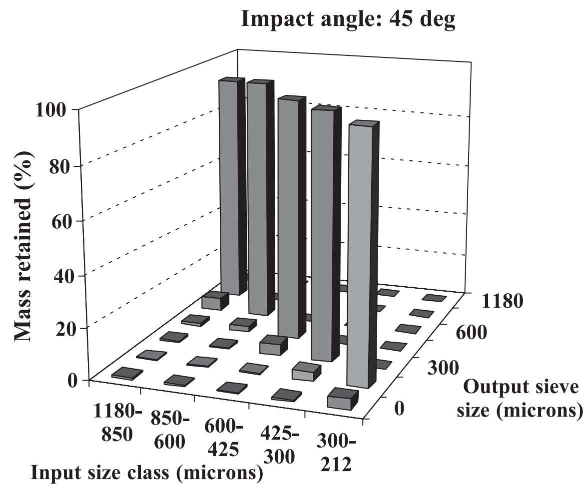


Fig. 1. Schematic of the rotating disc of the degradation tester.

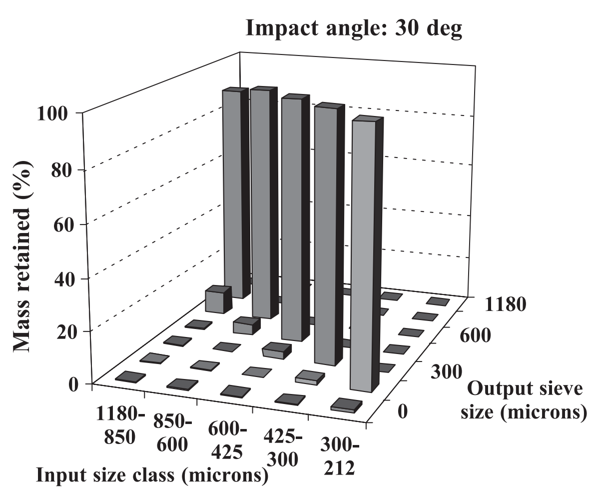
detail B). A degradation test yields the change in the particle size distribution of an input sample of particles being subjected to a single impact at a certain velocity. The input sample can be a polydispersed material or monosized particles as appropriate. The former will provide information on the collective breakage behaviour; 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 can then be analysed in order to assess the



	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



	1180-850	850-600	600-425	425-300	300-212
1180	0	0	0	0	0
850	92.3	0	0	0	0
600	5	96.3	0	0	0
425	1	2.4	94.7	0	0
300	0.6	0.5	4.4	95.9	0
212	0.4	0.3	0.4	3.4	95.9
0	0.7	0.5	0.5	0.7	4.1



	1180-850	850-600	600-425	425-300	300-212
1180	0	0	0	0	0
850	89.5	0	0	0	0
600	9	94.7	0	0	0
425	0.4	4.4	96.5	0	0
300	0.3	0.3	2.9	98.1	0
212	0.3	0.2	0.2	1.6	98.6
0	0.5	0.4	0.4	0.3	1.4

Fig. 2. Particle size distribution resulting from degradation tests of various size classes of granulated sugar samples for an impact velocity of 14 m/s at different impact angles.

amount of degradation caused under the designed test conditions. Benefits of this facility are that the particle velocity is closely controlled, the tester is portable and only a small quantity of material is required for each test. The data obtained from single particle impact studies are then utilized to build appropriate breakage matrices, which correlates the input particle size distribution to the resulting size distribution after impact and breakage [15].

The granular material used for the present study is granulated sugar with a solids density of 1660 kg/m^3 and a bulk density of 700 kg/m^3. The internal friction angle between particles is 37°. As an illustrative example, the breakage matrices built from data of degradation tests at different impact angles for a constant particle velocity of 14 m/s are presented in Fig. 2. The experimental errors resulting from the degradation tests were below 2% for all samples. The impact angle has considerable influence on the propensity of the particle to degrade. As one may expect, decreasing the impact angle causes a reduction in the amount of degradation undergone by the particles. Indeed, the smaller impact angle results in a higher proportion of unbroken particle in each input size class (i.e., first nonzero element in each column of the breakage matrix). This trend can be attributed to the reduction of the normal component of the particle velocity at lower impact angle. The effect of the impact angle in the angle range (from 30° to 45°) is less significant than that in the angle range (from 45° to 90°). It is seen that for the two largest input size classes, the proportion of unbroken particles decreases slightly, yet within the experimental uncertainty, as the impact angle is reduced from 45° to 30°. The effect of the impact angle on degradation observed in Fig. 2 shows the same trend as that reported by Salman et al. [3], who presented a comprehensive study of this effect for aluminium oxide particles.

4. Comparison between the predictions of the numerical model and experimental data

4.1. Pilot-sized pneumatic conveyor

A series of pneumatic conveying tests of granulated sugar was carried out in a pilot-sized pneumatic conveyor test rig. The conveyor was composed of a single bend of 45° angle connecting two horizontal straight pipes of 8 and 7.5 m in length, respectively. The internal diameter of the pipeline was 38.1 mm. Particle degradation under three different conveying velocities (9, 16 and 22 m/s) was investigated. The experimental uncertainty was calculated to be 5%. The numerical model was used to calculate

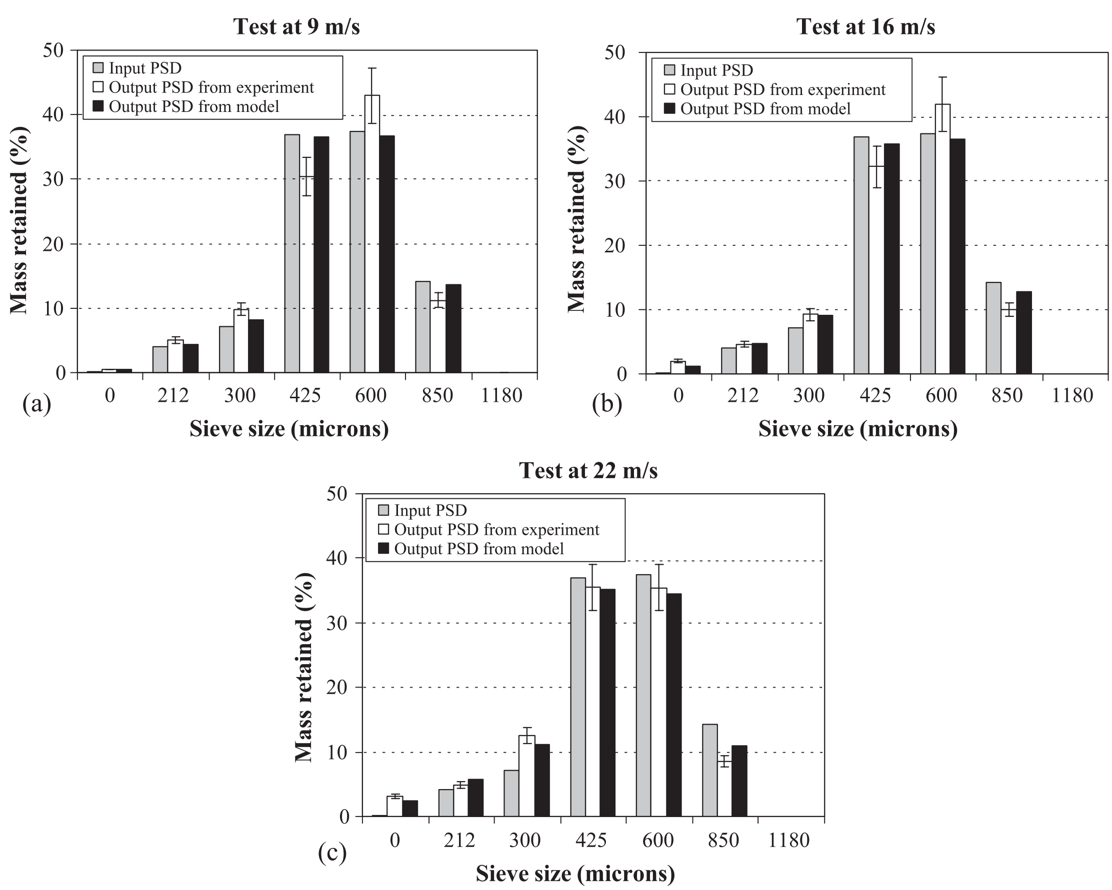


Fig. 3. Comparison between the particle size distributions (PSD) measured in the pilot-sized pneumatic conveyor and predicted by the model for different conveying velocities: (a) 9 m/s, (b) 16 m/s and (c) 22 m/s.

Table 1
Comparison of the mass resting below and above 300 μm measured in the pilot-sized pneumatic conveyor and predicted by the model for different conveying velocities

	9 m/s		16 m/s		22 m/s	
	Experiment	Model	Experiment	Model	Experiment	Model
< 300 μm	5.6%	4.9%	6.7%	5.9%	8.0%	8.2%
≥ 300 μm	94.4%	95.1%	93.4%	94.1%	92.0%	91.8%

degradation in the pilot-sized pneumatic conveyor by using breakage matrices built from experimental data for 45° angle single impact. Similar experiments and simulations for the case of a conveyor test rig consisting of a single 90° bend have been presented in previous work [9].

Fig. 3 compares the particle size distribution at the conveyor outlet predicted by the model to that measured experimentally for each conveying velocity. The comparison is reasonably good with an averaged relative discrepancy of ± 15% (the maximum discrepancy is less than ± 30%). The lowest size ranges (below 425 μm) show much better agreement than the highest size ranges (above 425 μm). It should be noted that the model is especially very effective in predicting the amount of the finest particles. This point is of particular importance for the quantitative assessment of degradation and final product quality in industry, where the percentage of fines resulting from the conveying process is generally of primary interest. The accuracy of the model predictions can be considerably improved by reducing the total number of size classes in the problem. For example, data in Table 1 comparing the measured and predicted amounts of materials below and above 300 μm show that the model predictions lie much closer to the experimental results. From the results presented in Fig. 3, it can be concluded that data on 45° angle impact gives a reasonable approximation of the degradation taking place in pipe bends of 45° angle. Note that a similar conclusion was drawn for the case of bends of 90° angle in Ref. [9].

4.2. Industrial pneumatic conveyor

Experimental data were obtained for particle degradation in a pneumatic conveying system from an industrial plant. The conveying pipeline is used to transport bulk material from a tanker into a storage silo. The 30-m-long pipeline with internal diameter of 0.1 m consists of five straight pipe elements and four bends of 45° angle. The pipeline geometry is shown in Fig. 4. It was impossible experimentally to access the outlet section of the conveyor to obtain sample of materials. Thus, in order to assess the degradation taking place in the conveying line, it was decided to compare the particle size distribution at the inlet of the pipeline to the distribution measured at the silo outlet when discharging the silo. The intake samples were collected after the mechanical feeder device into the conveyor. The output samples were collected during emptying of the receiving hopper. A manual sampling technique was utilized which consisted of a large sampling tray passed across the full stream of material at a constant speed. Negligible degradation of the particles was assumed to take place within the silo during filling and discharging. The following operating conditions for the conveying system were used: an inlet air velocity of 13.1 m/s and a particle suspension density of 26 kg/m^3. The conveyor is operated with a positive pressure system. The material transported in the pipeline is granulated sugar with the same properties as those given in Section 3.

Particle degradation in the conveying system was predicted using the model based on 45° impact angle experimental data. The predictions of the numerical model for the change in the particle size distribution during conveying are compared to the available experimental data in Fig. 5. The amplitudes of the error bars represent the standard deviations associated with the dispersion in the composition of the material sample taken at various times during the silo discharge. Comparison of the predicted and measured output particle size distributions shows reasonable agreement, with an averaged relative discrepancy of ± 15% (the maximum discrepancy is less than ± 30%). It can be seen that there is particularly good agreement for the lowest size ranges (below 300 μm), as observed previously in the case of the pilot-sized single bend conveyor.

Although the experimental results are reproduced with certain error levels due to the simplifying assumptions of the model, these results do demonstrate the capabilities of the

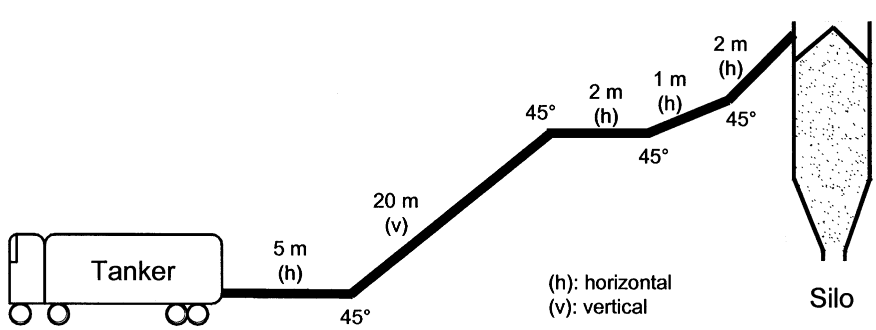


Fig. 4. Layout of the pneumatic conveyor from an industrial plant.

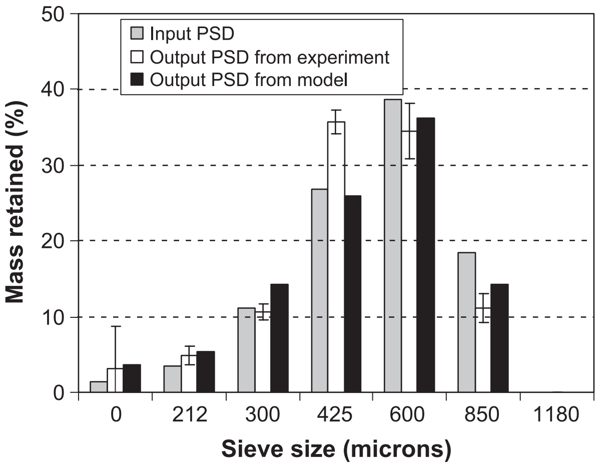


Fig. 5. Comparison between the particle size distributions (PSD) measured in the large-scale pneumatic conveyor and predicted by the model.

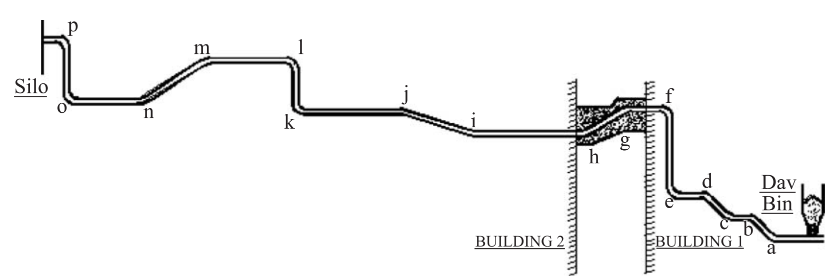
numerical model to simulate particle degradation in an industrial conveyor. The model is capable of giving good quantitative predictions of the fractions of the smallest particles in the system. The fractions of the largest particles are also well predicted. The present model is a significant advance over the current methods available for determining particle degradation in an industrial pneumatic conveyor. Moreover, it is computationally inexpensive.

5. Simulation of a large-scale pneumatic conveying system

Having achieved a measure of validation of the numerical model, it has been applied to investigate particle degradation in an industrial large-scale pneumatic conveying system including bends of different angles. The conveying system is a typical industrial configuration. It is a 65.3-m-long pipeline including 17 straight pipe elements and 16 bends of different angles (30°, 45° and 90°). The layout and the geometrical parameters of the pipeline are shown in Fig. 6. Unfortunately, but like for most of the industrial conveyors, the amount of degradation in the conveying system could not be measured experimentally because of the practical difficulties, which arise for sampling the material either at the conveyor outlet or further downstream at the outlet of the silo.

The simulation was performed for the following operating conditions: an inlet air velocity of 15 m/s and a particle suspension density of 10 kg/m^3. The properties of the granulated sugar used in this study are identical to those given in Section 3. In order to model degradation in 30° bends, an approximation similar to that validated for bends of 45° and 90° angles was used, which consists in representing the degradation taking place in a 30° bend by a single particle impact at 30°.

The calculated profiles of the air and particle velocities along the pipeline are shown in Fig. 7. Due to the expansion of the air in the pipeline, the air velocity increases along the pipe to a value of approximately 23 m/s at the pipeline outlet. As a result of the momentum transfer between the air and the particulate phase, particles are accelerated in straight pipe elements. Through pipe bends, particles are considerably slowed down due to particles impacting with or sliding along the bend walls. On exiting a bend, particles, which are mainly conveyed in the form of a strand, are progressively reaccelerated towards the air velocity. After dispersion of the strand further downstream, the particle flow becomes fully dispersed with equal particle and air velocities. In the present simulation, a fully dispersed flow region occurs only in the straight pipe element between bends l and m.



Bend	Angle	Bend	Angle
a	45°	i	30°
b	45°	j	30°
c	45°	k	90°
d	45°	l	90°
e	90°	m	30°
f	90°	n	30°
g	30°	o	90°
h	30°	p	90°

Pipe	Length	Pipe	Length
In→a	1 m	i→j	1 m
a→b	1 m	j→k	9 m
b→c	1 m	k→l	3 m
c→d	1 m	l→m	18 m
d→e	1 m	m→n	2 m
e→f	5 m	n→o	2 m
f→g	3 m	o→p	3 m
g→h	2.3 m	p→Out	1 m
h→i	10 m		

Fig. 6. Pipeline geometry for the industrial large-scale pneumatic conveying system.

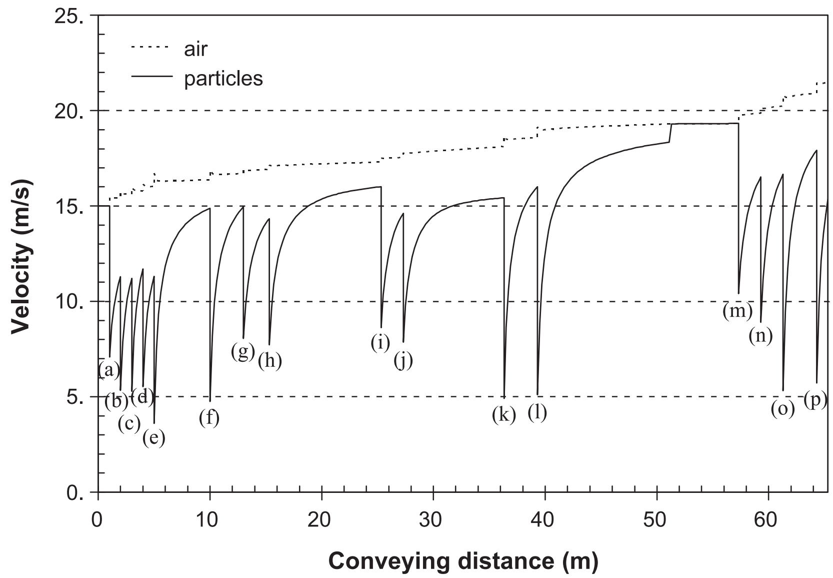


Fig. 7. Calculated profiles of the air and particle velocities along the pipeline. The indexes (a, b...p) refer to the location of the bends along the pipeline.

The variation of the harmonic mean size of the particle distribution in each bend obtained by the numerical simulation is plotted in Fig. 8. The harmonic mean size X_h is expressed as:

$$\frac{1}{X_h} = \sum \frac{w_i}{d_i} \tag{8}$$

where w_i is the fraction of material retained between sieves of mean size d_i. The bulk material experiences considerable degradation during conveying, as the mean particle size at the conveyor outlet is equal to less than 50% of its initial value at the inlet of the pipeline. Fig. 8 shows a nonuniform overall rate of degradation, with a greater gradient for bends of 90° angle (i.e., bends e, f, k, l, o and p). However, it can be seen a mainly constant degradation rate for groups of bends with the same angle. This is due to the similar values of the particle velocity in each bend as illustrated in Fig. 7. Such an identical degradation rate for bends with the same angle is not likely to occur in a real conveying system, due to the possible influence of the number of impacts undergone by a particle on its degradation propensity. This last effect cannot be accounted for by the present model, which treats as a first approximation each bend in the same way no matter of its location along the conveying line.

The change in the full particle size distribution through each bend is presented in Fig. 9. In the histograms of Fig. 9, columns relative to bends with the same angle are displayed using the same colour. As the number of passes through a

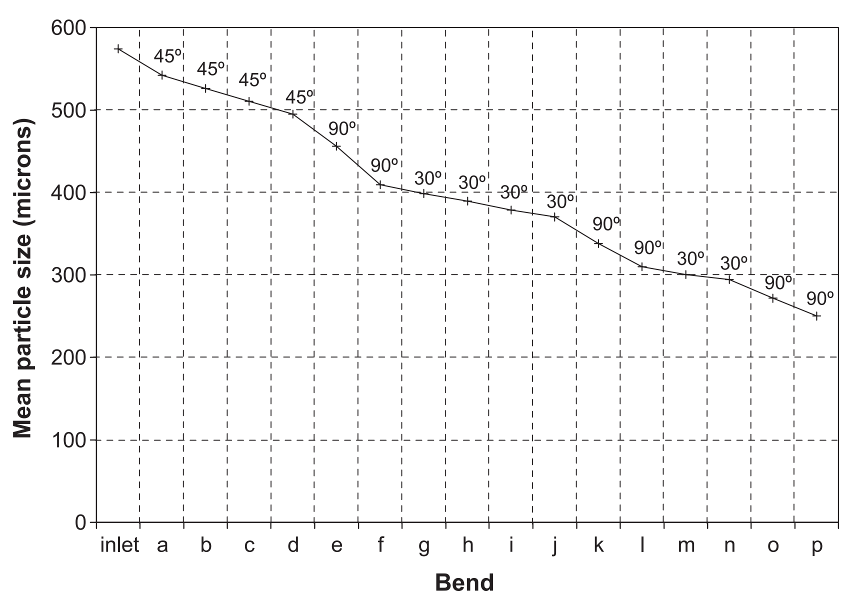


Fig. 8. Variations of the harmonic mean size of the particle distribution after each pipe bend. The points have been labelled with the bend angle value.

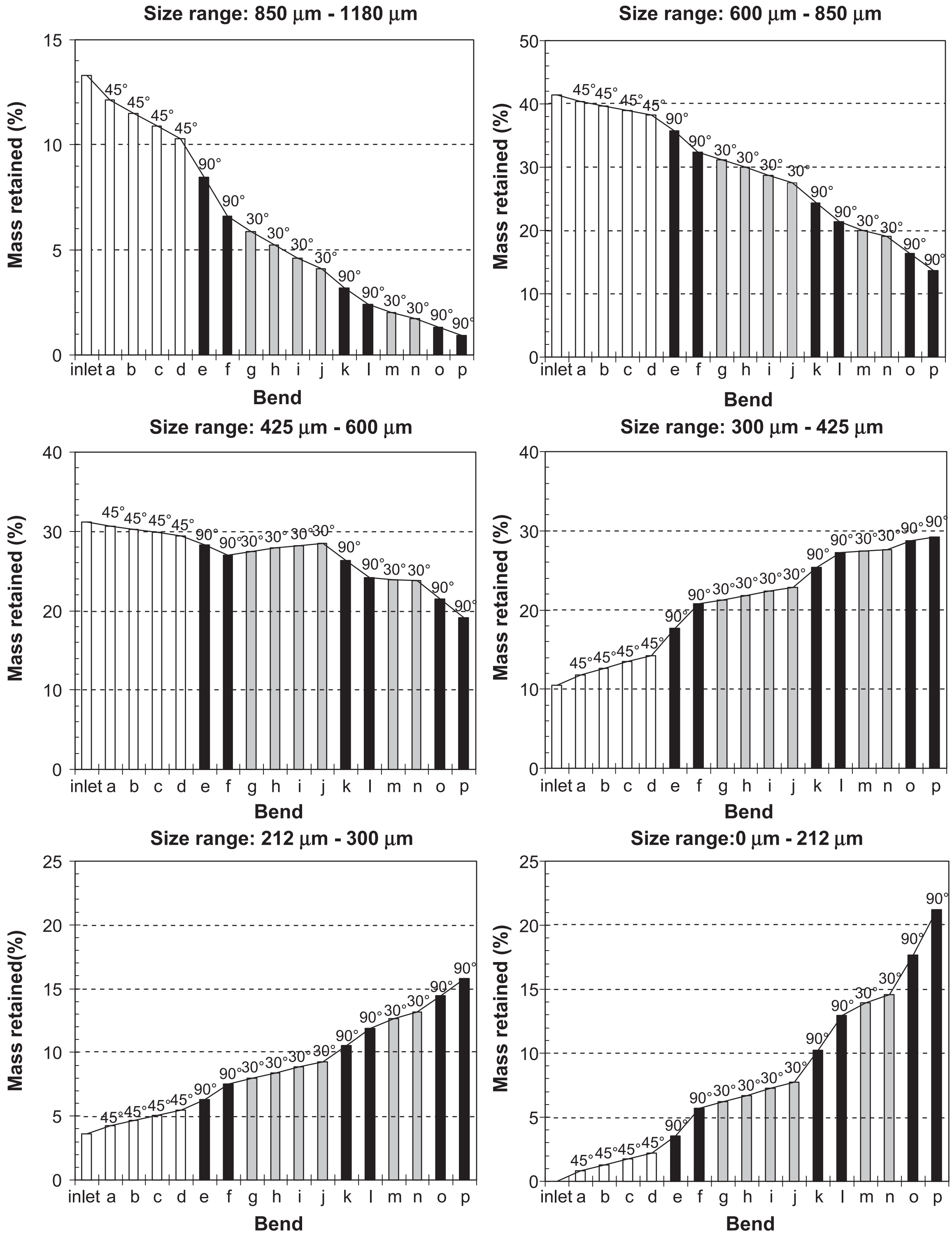


Fig. 9. Variations of the particle size distribution after each pipe bend. The following code of colours has been used to represent the histogram columns: white for bends of 45° angle, black for bends of 90° angle and grey for bends of 30° angle. The labels above each column correspond to the bend angle.

bend increases, the fractions of the larger particles (above 425 μm) gradually decrease, whereas the fractions of the smaller particles (below 425 μm) gradually increase. At the end of the conveying line, more than 22% of the material ends up as fines (particle size below 212 μm) and the fraction of the largest particle has decreased to more than 90% of its initial value. As noted in Fig. 8, the bends of 90° angle are responsible of the steepest rate of degradation. Bends e, k and o (which correspond in particular to a change in pipeline level from horizontal to vertical) are the points of most severe particle damage. The simulation results presented here indicate as anticipated that the bend angle plays a strong role in the degradation of conveyed particles and that the damage imparted to the particles can be substantially reduced by using bends of lower angles. It is also interesting to note that there is little difference in the rate of degradation caused by bends of 30° and 45° angles.

6. Conclusions

The model of particle degradation, during dilute-phase pneumatic conveying, developed by Chapelle et al. has been extended in order to describe the degradation taking place in pipe bends of different angles, validated and applied to an industrial context. Generalizing the approach presented in an earlier work for the single case of 90° bends, impact degradation of the particles in pipe bends has been represented by a single impact at a given angle characteristic of the angle of the bend. The effect of the particle angle of impact on degradation was demonstrated and discussed. For validating the model, the numerical predictions were compared with detailed measurements from a pilot sized pneumatic conveying system and a pneumatic conveyor from an industrial plant. Although the model is based on several simplifying assumptions, the agreement was found to be reasonably good, with an averaged error of about 15%. The model is particularly effective at capturing the fines production. The simulation of an industrial large scale pneumatic conveying system including various bends of different angles has shown, as might be logically expected, that lower bend angle tends to reduce the rate of damage to the particles.

Future work is aimed at improving the degradation model by including the effects of multiple impacts of the particles in a bend and the influence of the number of impacts on the particle degradation propensity. The developed numerical model should form a powerful engineering tool to support the design and optimisation of existing and new dilute-phase pneumatic conveyors, where material quality is a major requirement.

References

[1] H. Kalman, Attrition control by pneumatic conveying, Powder Technology 104 (1999) 214–220.

[2] I. Bridle, M.S.A. Bradley, S.R. Woodhead, R.J. Farnish, Effect of bend geometry on particle attrition in pneumatic conveyors, Powder to Bulk Proceeding of the International Conference on Powder and Bulk Solids Handling, London, 2000.

[3] A.D. Salman, D.A. Gorham, A. Verba, A study of solid particle failure under normal and oblique impact, Wear 186–187 (1995) 92–98.

[4] A. Yilmaz, E.K. Levy, Formation and dispersion of ropes in pneumatic conveying, Powder Technology 114 (2001) 168–185.

[5] M. Sommerfeld, Modelling of particle–wall collisions in confined gas–particle flows, International Journal of Multiphase Flow 18 (6) (1992) 905–926.

[6] N. Huber, M. Sommerfeld, Modelling and numerical calculation of dilute-phase pneumatic conveying in pipe systems, Powder Technology 99 (1998) 90–101.

[7] A.D. Salman, M.J. Hounslow, A. Verba, Particle fragmentation in dilute phase pneumatic conveying, Powder Technology 126 (2002) 109–115.

[8] T. Han, A. Levy, H. Kalman, DEM simulation for attrition of salt during dilute-phase pneumatic conveying, Powder Technology 129 (2003) 92–100.

[9] P. Chapelle, N. Christakis, H. Abou-Chakra, I. Bridle, M.S.A. Bradley, M.K. Patel, M. Cross, Computational model for prediction of particle degradation during dilute phase pneumatic conveying: modelling of dilute phase pneumatic conveying, Advanced Powder Technology 15 (1) (2004) 31–49.

[10] M.S.A. Bradley, R.J. Farnish, L.M. Hyder, A.R. Reed, A novel analytical model for the acceleration of particles following bends in pneumatic conveying systems, in: A. Levy, H. Kalman (Eds.), Handbook of Conveying and Handling of Particulate Solids, Elsevier, 2001, pp. 411–423. ISBN: 0-444-50235-1.

[11] O. Molerus, Overview: pneumatic transport of solids, Powder Technology 88 (1996) 309–321.

[12] L.M. Hyder, The effect of particle size and density on pressure gradients in horizontal pipelines in lean phase pneumatic conveying, PhD thesis, University of Greenwich, London, UK, 1999.

[13] M.S.A. Bradley, D. Mills, Approaches to dealing with the problem of energy loss due to bends, Proc. 13th Powder and Bulk Conference, Rosemont, Illinois, USA, 1988, pp. 705–715.

[14] H. Abou-Chakra, U. Tuzun, I. Bridle, M.C. Leaper, M.S.A. Bradley, A.R. Reed, An investigation of particle degradation by impact within a centrifugal accelerator type degradation tester, Proceedings of the Institution of Mechanical Engineers. Part E, Journal of Process Mechanical Engineering 217 (4) 2003, pp. 257–266.

[15] P. Chapelle, H. Abou-Chakra, N. Christakis, M. Patel, A. Abu-Nahar, U. Tuzun, M. Cross, 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, Advanced Powder Technology 15 (1) (2004) 13–29.