Computational Modelling of Particle Degradation in Dilute Phase Pneumatic Conveyors

P. Chapelle[a], N. Christakis[a], H. Abou-Chakra[b], U. Tuzun[b], I. Bridle[c], M.S.A. Bradley[c], M.K. Patel[a] and M. Cross[a]

[a] Centre for Numerical Modelling and Process Analysis, University of Greenwich, Old Royal Naval College, Park Row, Greenwich, London, SE10 9LS, UK
{p.chapelle, n.christakis, m.k.patel, m.cross}@gre.ac.uk
[b] Chemical and Process Engineering, School of Engineering, University of Surrey, Guildford, Surrey, GU2 7XH, UK
{h.abou-chakra, u.tuzun}@surrey.ac.uk
[c] The Wolfson Centre for Bulk Solids Handling Technology, University of Greenwich, Wellington Street, Woolwich, London, SE18 6PF, UK
{i.bridle, m.s.a.bradley}@gre.ac.uk

Abstract. The aim of this paper is to develop a mathematical model with the ability to predict particle degradation during dilute phase pneumatic conveying. A numerical procedure, based on a matrix representation of degradation processes, is presented to determine the particle impact degradation propensity from a small number of particle single impact tests carried out in a new designed laboratory scale degradation tester. A complete model of particle degradation during dilute phase pneumatic conveying is then described, where the calculation of degradation propensity is coupled with a flow model of the solids and gas phases in the pipeline. Numerical results are presented for degradation of granulated sugar in an industrial scale pneumatic conveyor.

1 Introduction

Degradation of particles is of major concern in dilute phase pneumatic conveying systems. Degradation may affect the product quality and cause severe difficulties in material handling, because of the change in particle properties such as particle size distribution, shape and/or surface area. Degradation during dilute phase pneumatic conveying occurs mainly as a result of impact or shear loads induced by collisions of the particles with or sliding along the pipe walls [1].

So far, studies of degradation in pneumatic conveying systems reported in the literature 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 conveyor is the only way to assess degradation, yet, for most of the systems it is impossible to access the inlet and the outlet. The methods to predict degradation in pneumatic conveyors are either to build a pilot sized conveyor scaled to the actual plant component dimensions (e.g. [2]), or to use a small scale air blast rig (e.g. [3]). However, it is often difficult to extend with confidence the results obtained to the real processes. On the other hand, current computational approaches for simulating

V. Kumar et al. (Eds.): ICCSA 2003, LNCS 2667, pp. 493-502, 2003.

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. [4]). In the context of dilute phase systems, most of the calculations have been performed using the Euler/Lagrange approach. Such models are able to take into account the effects of particle-wall collisions on the particle trajectory [5]. However, there is at present limited experimental information available to support the development of a general model of particle degradation processes.

A powerful mathematical representation of degradation processes is the population balance model, which has been extensively used in the literature in the field of grinding processes (e.g. [6,7]). This approach consists in performing a population balance for a size class, based on the knowledge of two statistical functions: the breakage function which characterizes the fragment size distribution produced during breakage and the selection function which is the rate of degradation. No attempt has been made to apply this model to the study of degradation in pneumatic conveying systems, due among others to the lack of detailed experiments required to determine the breakage parameters.

The present work concerns the development of a model to predict particle degradation in dilute phase pneumatic conveying systems. A numerical procedure to determine particle impact degradation propensity from particle single impact tests carried out in a laboratory scale degradation tester is developed based on a matrix representation of degradation processes. Coupling the calculation of degradation propensity with a model of the flow of the solids and gas phases in the conveying pipeline allows then particle degradation in dilute phase pneumatic conveying systems to be predicted.

2 Calculation of Degradation Propensity from Single Impact Tests

2.1 Degradation Tester

The degradation tester is a bench-scale unit for assessing degradation by impact under well-defined and controlled particle velocity and angle of impact [8].

The degradation tester consists of a balanced disc where the velocity of rotation can be varied continuously and fixed at any given value (Fig. 1). The rotating disc (see Fig. 1 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 disc. These 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, the particles enter a free trajectory phase until they impact onto the targets. The targets are equally spaced around a ring fitted around the acceleration disc (see Fig. 1 detail B). A degradation test will yield the particle size distribution from an input sample being subjected to impacts at a certain velocity. 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.

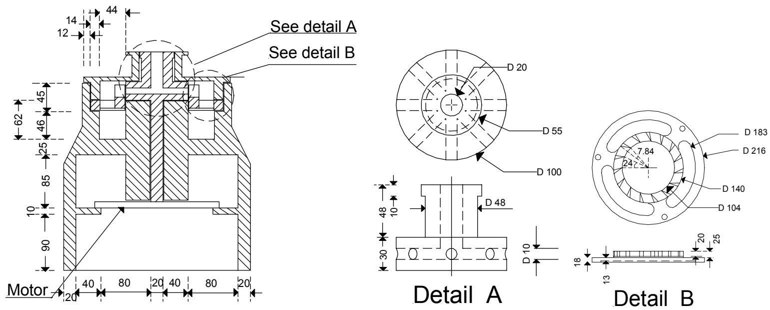

Fig. 1. Schematic of the rotating disc of the degradation tester.

2.2 Numerical Procedure for the Determination of the Extent of Degradation

The size range is divided into several size classes indexed from 1 (coarse) to n (fines). A matrix analysis of degradation processes is based around the following equation:

$$[B]\cdot\{i\} = \{o\} \tag{1}$$

where {i} and {o} are column vectors representing the particle size distributions respectively before and after the degradation event, and [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. A column of the matrix describes the fate of a given size class in the input size distribution. Each column can be determined separately using the results from impact tests on a single size fraction sample in the degradation tester.

The interpolation procedure described below is intended to allow the amount of degradation on a full particle size distribution under a range of impact velocities and particle sizes to be determined, by measuring the breakage matrix for a limited number of cases across this range. The calculation procedure proceeds in three steps:

1. When the defined sieve sizes are different from those used to determine the experimental breakage matrices, a breakage matrix for the desired sieve sizes at a given impact velocity is calculated through bilinear interpolation from the breakage matrix measured at this velocity [9]. Because the variations of the fragment size distribution are generally very sharp, it has been found that the matrix can be more accurately interpolated by treating separately the diagonal elements and the first element below them in the same column. A diagonal element is determined by a 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 normalizability condition (i.e. the sum of elements of each column of the matrix equals to unity) is used to calculate the first element below the diagonal element in the same column.

2. The amount of degradation on the investigated size distribution at each of the impact velocities used in the experimental tests is then evaluated through equation (1) by using the known breakage matrices.
3. Finally, the degradation at an intermediate velocity is estimated by an N-order polynomial interpolation (where N is the number of velocities for which tests have been performed) from the set of values calculated in the second step [9].

As will be demonstrated, this simple interpolation procedure gives satisfactory estimates. It may be advisable to restrict the application of the size interpolation method to cases for which the number of investigated sieve sizes is less than or close to the number of sieve sizes used to determine experimentally the breakage matrices. The main interest in the size interpolation procedure is to "shift" the matrix within a range of values of the sieve sizes.

3 Description of the Numerical Models

3.1 Flow Model

Straight pipeline

Downstream of a bend, as a result of being slowed down inside the bend, particles are mainly transported in a form of a strand, in which a high concentration layer of particles occupies the lower portion of the pipe. In the upper portion of the pipe, particles are suspended in the transport gas. As particles on the top of the layer are picked up from the surface by the gas stream flowing more quickly, the layer is gradually eroded and decreases in depth along the pipeline. A point is reached where the layer of solids vanishes and all the particles are transported as a homogeneous gas-solid suspension flow. This mode of flow is called fully suspended flow.

The approach used for modelling the strand type flow is based on the model 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 δl and the corresponding suspended flow region are given respectively by:

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

$$\tau_{str} S_{str} + \tau_{susp} S_{susp} = \Delta P_{susp} \frac{\pi D^2}{4} \phi \tag{3}$$

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. In writing equation (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 equation (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:

$$\tau_{str} = \frac{\rho_{air} f_{str}}{2} (v_{air} - v_{str})^2 \qquad \mathbf{(4)}$$

where ρ_{air} is the air density and v_{air} and v_{str} are the air and strand velocities. 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. The pressure drop along an elemental length is split into two parts [11]:

$$\Delta P = \Delta P_{air} + \Delta P_{solids} \qquad \mathbf{(5)}$$

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

$$\Delta P_{solids} = K\,\delta l\,\rho_{susp} v_{air}^2 \qquad \mathbf{(6)}$$

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

<u>Bend pipeline</u>

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 contact with the pipe wall under the effect of the centrifugal force. The change in particle velocity in a bend can be calculated from Newton's law, where the particle-wall interactions are characterized by a coefficient of friction μ and a coefficient of restitution e:

$$v = e v_0 \exp(-\mu\theta) \qquad \mathbf{(7)}$$

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.

Numerical solution procedure

The solution procedure in a straight section is based on the subdivision of the pipe up 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.

The model of acceleration of the strand type flow has been previously validated through comparisons against pressure measurements obtained in an industrial scale pneumatic conveying system [10].

3.2 Degradation Model

Since the most extensive damage during dilute phase pneumatic conveying is caused by particle-bend wall collisions [1], particle degradation is considered to occur only by impact at the bends. As will be justified later, degradation of a particle in a bend is represented by a single impact. Fatigue phenomena, by which a particle breaks when collisions occur a number of times, are ignored as a first approximation.

The overall change in the particle size distribution between the inlet and the outlet of a bend is described by an equation equivalent to (1), where the vectors $\{i\}$ and $\{o\}$ are defined as the particle size distributions, respectively at the inlet and outlet of the bend. The bend outlet particle size distribution $\{o\}$ is calculated using the method presented in Sect. 2.2, for the impact velocity involved in the bend, which is considered to be the particle velocity at the bend inlet calculated from the flow model. Experimental breakage matrices must be constructed from results of impact experiments carried out at an impact angle representative of the angle of collision in the bend, which is dependent on the bend angle. However, evaluating the angle, at which the particles impact on the wall, is impossible without calculating the full particle trajectories. Therefore, a simplified model is proposed, in which a given value of the bend angle is assumed to correspond to a given value of the particle impact angle. As will be demonstrated in the following section, this approach enables a satisfactory characterization of degradation processes in 90° angle bends.

4 Numerical Results and Discussions

4.1 Validation of the Degradation Model against Tests in a Pilot Sized Conveyor

Degradation in a single bend was investigated by developing a pilot sized pneumatic conveyor test rig, which allows material to be conveyed around one bend into a receiving hopper (Fig. 2a). A series of tests using granulated sugar at different conveying velocities (9, 16 and 22 m/s) for a 90° angle bend geometry were undertaken. The experimental uncertainty was calculated to be 5 %.

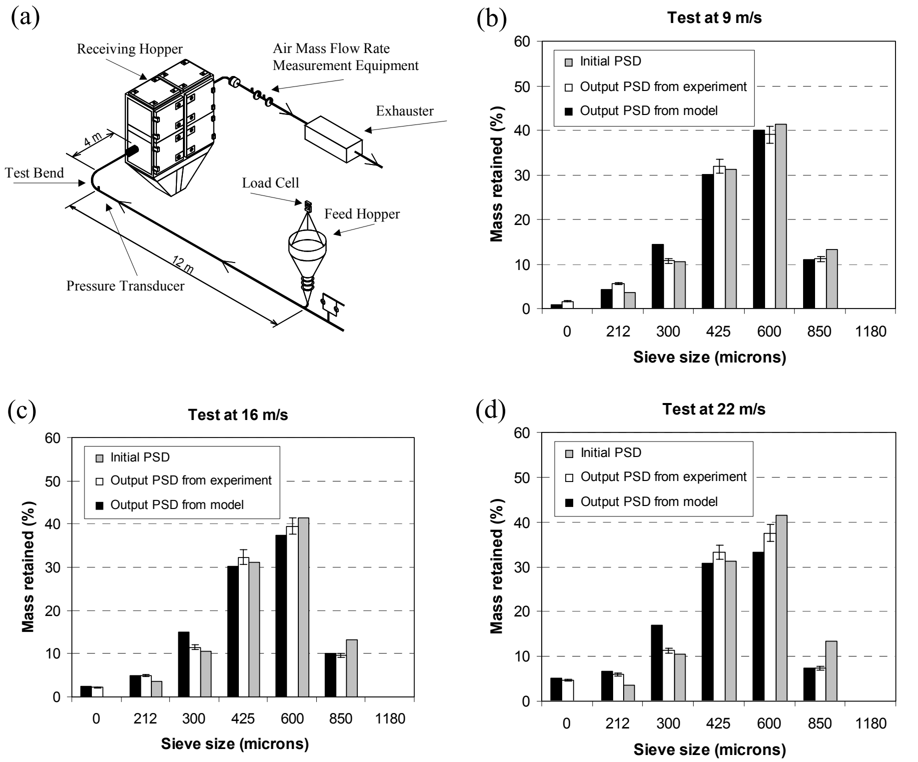

Fig. 2. (a) Schematic of the pilot sized pneumatic conveyor test rig. (b-d) Comparison between the particle size distributions measured (PSD) in the pilot-sized pneumatic conveyor and predicted by the model.

The amount of degradation on the particle size distribution used during the tests in the pilot sized rig has been calculated using the degradation model presented in Sect. 3.2 from experimental breakage matrices measured for three velocities (7, 14 and 21 m/s) in the degradation tester. These results are compared against those obtained in the pilot size pneumatic conveyor in Fig. 2(b-d). Good agreement is found between the outlet particle size distribution measured and that calculated for each impact velocity. These results demonstrate that degradation occurring in a 90° angle bend can be adequately described using 90° angle single impact experimental data.

4.2 Application to a Large Scale Pneumatic Conveying System

As an illustrative application, the model presented above has been used to study degradation in an industrial scale dilute phase pneumatic conveying system. The layout of the pipeline with internal diameter of 5.3 cm is shown in Fig. 3a. The conveyed materials is granulated sugar of solids density of 1600 kg/m^3 The simulations were performed for operational conditions usually employed in industrial practice, namely a conveying velocity of 18 m/s and a suspension density of 15 kg/m^3. At the inlet of the pipeline, particles were assumed to be homogenously dispersed and the gas and particle velocities were assumed to be identical. Table 1 summarizes the values of the parameters in the flow model used for the calculations. An elemental length of 0.2 m was used for solving the governing equations of the strand type flow. It was verified that an additional reduction in the value of the elemental length had no significant influence on the results of the simulation.

Table 1. Values of the parameters in the flow model used for the calculations.

Parameter	**Value**
Friction factor strand / suspended flow	3
Friction factor suspended flow / pipe wall	0.00115
Friction factor air / pipe wall	0.0044
Coefficient characterizing the pressure drop caused by the particles	$1.6.10^{-6}$
Bend wall friction coefficient	0.25
Coefficient of restitution	0.8

The predicted profiles of the air pressure and the air and particle velocities along the conveying line are presented in Fig. 3(b,c). The air expands along the pipe, with a total pressure drop over the whole pipeline of the order of $1.5.10^4$ Pa. It can be seen that the pressure distribution downstream of each bend is characterized by a high pressure gradient in the section immediately adjacent to the bend, followed by a lower pressure gradient far downstream of the bend. This pressure drop profile around a bend is similar to the one observed in the experiments of [13]. Experiments for a wide range of materials and operating conditions show that the length, over which the development of the pressure drop induced by a bend occurs (i.e. the distance which is necessary for the pressure drop to approach a steady gradient), is of the order of 8 m [12], which is in reasonable agreement with the value of 6 m predicted by the present model.

Expansion of the air causes an increase in the air velocity, and thus in the particle velocity as a result of the momentum transfer between the gas and solids phases. In a bend, particles are considerably slowed down due to particle-wall interactions. The reduction of particle velocity around a bend is on average about 45 %. Downstream of a bend, the particles, which are conveyed in the form of a strand, are progressively re-accelerated towards the air velocity. For this example, none of the straight pipe sections is long enough to disperse completely the strand before reaching the next bend. It may be noted that the drop of the particle velocity in the bend, and the subsequent creation of a strand, is accompanied with a marginal increase of the air velocity at the bend exit due to the reduction of the pipe cross-sectional area occupied by the air.

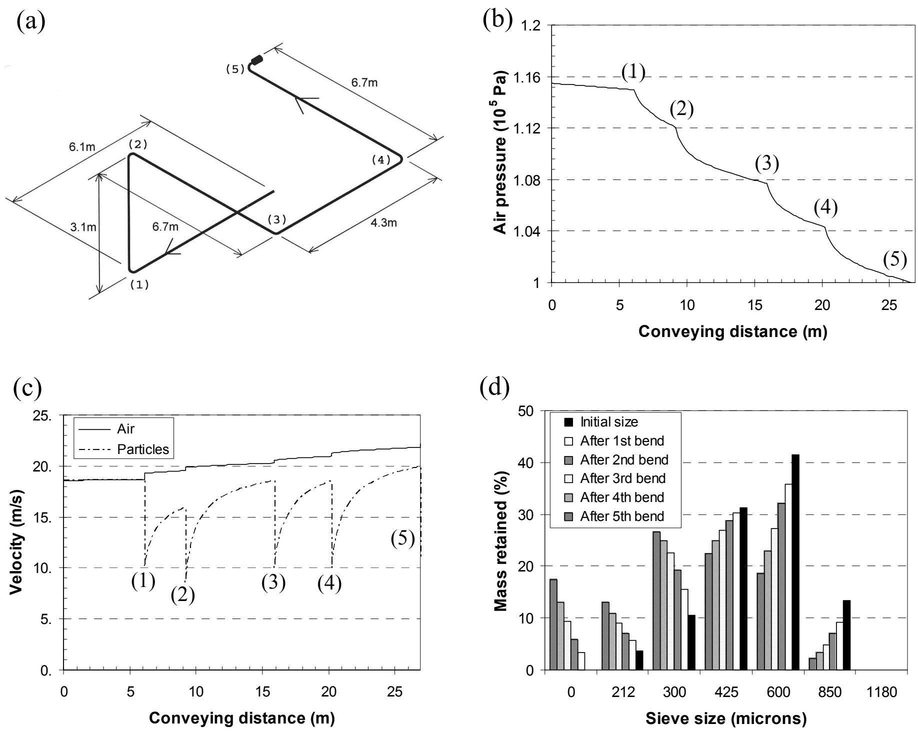

Fig. 3. (a) Layout of the industrial scale pneumatic conveying line. (b) Prediction of the model for the air pressure profile along the pipeline. (c) Prediction of the model for the air and particles velocities profiles along the pipeline. The indexes *(i, i=1,...,5)* refers to the location of the bends along the pipeline. (d) Particle size distributions after each pipe bend.

The full particle size distribution after each bend is presented on Fig. 3d. The materials experiences significant degradation, as the size distribution is considerably altered after conveying through five bends. As the number of passes through a bend increases, the fractions of the largest particles (> 425 μm) decrease, whereas the fractions of the smallest particles (< 425 μm) increase. At the end of the conveying line, almost 18 % of the material turns out to be dust (defined as particles smaller than 200 μm) and the fraction of particles larger than 850 μm decreases to 80 % of its initial value. The high degradation observed in this simulation can be explained by the relatively high conveying velocity used and the large bend angle considered.

5 Conclusions

Calculation of the propensity of particle degradation due to impact, based on the experimental determination of breakage matrices, has been combined with a simple physical flow model of the gas and solids phases to predict degradation during dilute phase pneumatic conveying. By comparing the results of the degradation model to those obtained in a pilot sized pneumatic conveyor test rig, it has been demonstrated that the breakage matrices constructed from data on 90° angle single impact tests give a good representation of the amount of degradation occurring in a 90° angle pipe bend. Numerical simulations for a large scale pneumatic conveying system were presented and discussed.

The performance of the model is promising and further experimental work is planned to obtain data sufficient to validate the model for an industrial scale pneumatic conveyor. Moreover, work is currently underway in order to enable the model to account for different bend angles, multiple impacts in a bend and the effect of the number of impacts on the particle degradation behaviour. This should lead to a powerful engineering tool, which can be employed for process control and optimization of the operating conditions

References

1. Kalman, H.: Attrition control by pneumatic conveying. Powder Tech. 104 (1999) 214-220
2. Bridle, I., Bradley, M.S.A., Woodhead, S.R., Farnish, R.J.: Effect of bend geometry on particle attrition in pneumatic conveyors. In: Powder to Bulk, Proceeding of the International Conference on Powder and Bulk Solids Handling, London (2000)
3. Salman, A.D., Gorham, D.A., Verba, A.: A Study of Solid Particle Failure Under Normal and Oblique Impact. Wear 186-187 (1995) 92-98
4. Yilmaz, A., Levy, E.K.: Formation and dispersion of ropes in pneumatic conveying. Powder Tech. 114 (2001) 168-185
5. Huber, N., Sommerfeld, M.: Modelling and numerical calculation of dilute-phase pneumatic conveying in pipe systems. Powder Tech. 99 (1998) 90-101
6. Austin, L.G.: Introduction to the mathematical description of grinding as a rate process. Powder Tech. 5 (1971/72) 1-17
7. Hogg, R.: Breakage mechanisms and mill performance in ultrafine grinding. Powder Tech. 105 (1999) 135-140
8. QPM research project, QPM Degradation Tester: User Guide. QPM Web Page http://www.qpm.org.uk/QPM-Degradationtester.htm (accessed on 12/11/02) (2002)
9. Press, W.H., Teukolsky, S.A., Vetterling, W.T., Flannery, B.P.: Numerical recipes in Fortran: The art of scientific computing. 2nd edn. Cambridge University Press (1992)
10. Bradley, M.S.A., Farnish, R.J., Hyder, L.M., Reed, A.R.: A novel analytical model for the acceleration of particles following bends in pneumatic conveying systems. In: Levy, A., Kalman, H. (eds.): Handbook of Conveying and Handling of Particulate Solids. Elsevier Science (2001) 411-423
11. Molerus, O.: Overview: Pneumatic transport of solids. Powder Tech. 88 (1996) 309-321
12. Hyder, L.M.: The effect of particle size and density on pressure gradients in horizontal pipelines in lean phase pneumatic conveying. PhD Thesis, Univ. of Greenwich, London (1999)
13. Bradley, M.S.A., Mills, D.: Approaches to dealing with the problem of energy loss due to bends. In: Proc. 13th Powder & Bulk Conference, , Rosemont, Illinois, USA (1988) 705-715