

# Freight Pipelines – 2005 Review

H. Kalman<sup>1</sup> and G.E. Klinzing<sup>2</sup>

1. Ben-Gurion University of the Negev, Israel

2. University of Pittsburgh, United States

## 1. Pneumatic Conveying

A basic description of pneumatic conveying systems is provided by Mills [1, 2]. The description includes an introduction, modes of conveying, system types and system selection. In another paper, Mills [3] presented a discussion on the difference between dilute and dense phase flows including examples for cement and alumina. He emphasized two steps to achieving clarity on the subject. Step one is understanding the characteristics that differentiate a dilute phase system from a dense one. These include material compatibility, conveying air velocity, particle velocity and solids loading ratio. Step two is descending into particular process specifications that tip the design choice toward one mode or the other. These include nuances in material properties, pipeline bore, conveying distance, pressure available and conveying air velocity.

Mills [4] published a paper reviewing the research work of the late Professor Predrag Marjanovic. Although Predrag's involvement in research covered a diverse range of topics, including hydraulic transport, fluid mechanics, bulk material characterization and hopper design, the review highlights the work undertaken by Professor Marjanovic for his Ph.D. research and pneumatic conveying, a topic that he continued to investigate during all his active period.

### 1.1 Dilute Phase Flow

In order to carry out simulations of the movement of a relatively large particle in an air stream in a pipe, the aerodynamic forces and the collisions with the pipe wall should be considered. For the aerodynamic conditions, drag force, retarding torque, the lift force due to particle rotation and the lift force due to air velocity gradient are often considered. Salman et al. [5] carried out a 2-D numerical simulation of a particle in a horizontal pipe, and described the variation of the above mentioned aerodynamic forces. Eskin [6] employed the kinetic theory of granular flows to simulate dilute turbulent steady-state gas-particle flows in flat horizontal channels with different wall surface roughness. Salman et al. [5] have shown that the major forces, that control particle motion, are drag in the axial direction, and lift due to air velocity gradient and the spin in the transverse direction. These researchers also stated that the high spin speeds generated by the end of the run caused the Magnus force to become the principle component of lift. In his study Eskin [6] ignored the Magnus force since he considered only non-rotating particles. Salman et al. [5] incorporated an elastic contact model based on rigid body sliding assumed the normal collision to be fully elastic, but they took into account also sliding friction during contact. Eskin [6] used the tangential restitution coefficient to fit the simulation to experimental results. Both models agree well with experimental results.

In order to investigate the role of interclass collisions measurements and analysis of a bidispersed two-phase flow system at low mass loading ratio 0.11 and a moderate ratio of in a fully developed pipe flow were presented by Boree and Caraman [7]. The signature of interparticle collisions was observed by comparing measurements at

high- and low-mass loadings. An analysis of the collision frequency in different regions of the flow showed that, even at loading ratio of 1.1, the mean time scale between collisions is of the order or larger than the particles aerodynamic time constant. Collisions, therefore, cannot significantly decrease the mean free path of the particle fluctuating motion, and transport effects of both longitudinal and radial fluctuating kinetic stresses toward the core region are still high. For a larger increase in mass loading, leading to dominant effects of collisions, one would expect these transport terms to be of minor importance.

## **1.2 Dense Phase Flow**

Dense phase pneumatic conveying has become more and more common in many industrial sectors ranging across chemical, pharmaceutical and food industries, due to its advantages over conventional high-velocity suspension flow in preventing product degradation plant wear and in delivering high throughput and efficient power utilization. Sanchez et al. [8] reviewed the models and correlations for dense phase conveying in an effort to explore existing and new data on the subject and to provide guidance to the designer on the best pressure drop model. Using various data sets the Mi (Konrad)-based model was found to be best for predicting the pressure drop across dense phase plugs. A series of industrial scale tests also shows agreement with the Mi (Konrad)-based model. Experimental findings have been presented by Datta and Ratnayaka [9] to show that the pressure drop coefficient (K) for vertical and horizontal pneumatic conveying for a given bulk material follows a certain pattern. The pressure drop coefficient for vertical pneumatic conveying for a given material has been found to be independent of any variation in particle size distribution, within experimental limits. The pressure drop prediction technique proposed by the authors previously has been validated with the test results. The unique feature of this technique is that it can be applied to both dense-phase and dilute-phase pneumatic conveying situations, as the results ranged from dense-phase to dilute-phase flow conditions (air velocity ranging from 8 to 20 m/s).

Solids deposition in the horizontal pipeline of a pneumatic conveying system was studied by Li et al. [10] both mathematically and experimentally. Mathematically modeled results using the coupled discrete element method (DEM) and computational fluid dynamics (CFD) approach have demonstrated an intensive exchange of particles between the stationary layer (deposited particles) and the moving slug and a variation of solids concentration and pressure and velocity distributions across the slug. A slug wave actually compresses the particle layer just ahead of it, pushing some of the particles up from the layer into the wave. On the other hand, particles at the tail of the slug fall into the bottom part of the pipeline and form a stationary particle layer behind the slug. Experimentally generated data have quantitatively shown a tendency of more solids deposition with lower gas mass flow rate in slug flows except that, below a certain amount of solids mass flow rate, the deposition becomes independent of gas flow rate. An experimental study combined with numerical modeling was carried out by McGlinchey et al. [11] to describe the structure of plugs through the analysis of the measurements of pressure difference in both axial and radial directions. A theoretical explanation of these pressure differences was proposed and agrees with the recorded signals of pressure difference from differential transducers.

## **1.3 Transition Phase**

Experimental results on pickup velocity (critical velocity) measurements for a variety of particulate solids and empirical analysis were presented by Kalman et al.

[12]. The present experiments together with previously published experiments of a number of researchers encompass about 100 measurements of 24 materials for a wide range of particle sizes, shapes and densities. Based on the experimental results, three zones are defined by establishing simple relationships between the Reynolds and Archimedes numbers. The empirical relationships were further modified by taking into account the pipe diameter and particle shape (sphericity). The three-zone model was shown to reasonably correlate to Geldart's classification groups. The saltation velocity after a 90° vertical-to-horizontal elbow was studied by Akilli et al. [13]. Experiments show that saltation velocity is affected by the gas to solids mass flow rate ratio and elbow radius to pipe diameter ratio. The maximum deposit thickness typically occurred near the leading edge of the deposit. The average deposited thickness decreased with increasing gas to solids mass flow rate ratio.

Balasubramanian et al. [14] attempted to study the hydrodynamics and flow regime transitions in a circulating fluidized bed (CFB). The flow regimes in a CFB include the high-velocity fluidized bed and pneumatic conveying. The transport velocity was estimated by the emptying time of the bed and extrapolation techniques. Empirical correlations have been proposed for the transport velocity and the choking velocity.

#### **1.4 Bends**

Bends and elbows play vital roles in giving pneumatic conveying systems considerable flexibility by allowing routing and distribution. Bends, however, could cause some difficulties in pneumatic conveyance. One such problem is that bend erosion is likely to cause a plant stoppage breakdown of the plant; another is particle fragmentation, which may limit the use of the pneumatic conveying system. An important aspect, therefore, in pneumatic conveying is particle trajectory in the bend, which affects the particle velocity, impact angle and the number of impacts of the particle on the bend wall.

The 2-D model of Salman et al. [24], where numerical simulations of particle motion in a dilute horizontal pipe were carried out and variation of aerodynamic forces described, was extended by Salman et al. [15] to bend flow (horizontal to down vertical). The bend flow was found to cause an increase in mean particle velocity compared with a horizontal pipe. Results show that the number of impacts in the bend decreases as the velocity of the particle increases. The results from the simulation agree closely with the experimental time-of-flight measurements.

The characteristics of gas–solid flow after a 90° vertical-to-horizontal elbow were investigated both numerically and experimentally for low conveying gas velocities by Akilli et al. [13]. The time-averaged local particle concentration and velocity were measured using a fiber optic probe at various locations along the length of the horizontal pipe after the elbow. The effects of gas flow velocity, gas to solids mass flow rate ratio and the elbow radius to pipe diameter ratio on particle concentration and velocity profiles, and deposit characteristics were investigated. The numerical simulations indicate that the coarse particles move into the rope-like manner created in the elbow and secondary flows carry the small particles around the pipe circumference through the particle-free regions. Simulations of dilute-phase gas-solid flow in pipe bends of different radii of curvature were conducted using computational fluid dynamics (CFD) by Quek et al. [16]. The renormalization group  $k$ - $\epsilon$  turbulence model was used for the flow calculations of the continuous phase while the Lagrangian approach was used for calculating the discrete-phase trajectory. The model predictions were first validated with particle concentration and velocity

measurements adopted from the literature. Simulation indicates that the rope formation in vertical bend is stronger for the longer bend radius than that in the shorter radius. The inlet turbulence intensity (<10%) does not produce significant effects on particle concentration through the bend whereas particle size is found to have the largest impact on the extent of flow dispersions observed in the bend with different radii of curvature.

Using vertical U-bends in the pneumatic conveying dryer system significantly influence drying behavior since they create enhanced slip velocities between suspended material and the drying medium. On one hand, this slip will increase external heat and mass transfer rates, thereby enhancing drying conditions. On the other hand, increasing the number of bends will cause an increase in pressure drop and could be detrimental to the overall performance of the system. Two-phase CFD calculations, using an Eulerian–Eulerian model and the commercial program Fluent 6.0, were employed by Hidayat and Rasmuson [17] to calculate the gas and particle flows in a vertical U-bend. They have found that the slip velocity is particularly affected by particle diameter, gas velocity and bend radius ratio; whereas the total pressure drop is strongly affected by gas velocity and bend radius ratio. Thus, optimizing gas velocity and bend radius ratio is important in reducing energy consumption.

## **1.5 Attrition and Wear**

Dilute phase pneumatic conveying systems are widely applied in industries to transport bulk solids. Attrition and breakage of solid particles, however, is an unavoidable phenomenon affecting both the conveying characteristics and the quality of particulate materials. The mechanical strength of porous alumina catalyst carrier beads, used in the reforming units with continuous catalytic regeneration, was measured by impact testing by Subero-Couroyer et al. [18]. With this testing method particle strength can be measured of a larger number of particles quickly at higher strain rates than the traditional crushing test, hence providing a better simulation of pneumatic conveying. Frye and Peukert [19] employed numerical simulations that indicate that sliding friction apparently is of importance in dilute phase conveying. Their analysis of particle wall impact conditions in a pipe bend showed that they take place under low wall impact angles of  $5\text{--}35^\circ$  which results in low normal (5–25 m/s) and high tangential (33–44 m/s) impact velocity components. With dynamic mechanical analysis (DMA) they showed that various materials are attrited by different mechanisms (PP and PE by friction and PMMA and PS by impact) and that the glass transition temperature of the polymers is a key factor in the determination of the prevailing attrition mechanism.

Solid particle erosion is a process by which material is removed from a metal surface due to impingement of small solid particles on the metal surface. Prediction of erosion in flow systems requires an understanding of the complex interactions between the fluid and the solids. The complexity of the problem increases significantly in multiphase flow due to the existence of different flow patterns. A new mechanistic model for predicting erosion in elbows in multiphase flow is presented by Mazumder et al. [20]. Particle concentration is known as a main factor that affects erosion rate of pipe bends in pneumatic conveyors. With consideration of different bend radii, the effect of particle concentration on weight loss of mild steel bends has been comprehensively investigated by Deng et al. [21]. Experimental results show that there was a significant reduction of the specific erosion rate, weight loss and the thickness loss of the bends for high particle concentrations. This reduction was

considered to be as a result of the shielding effect during the particle impacts. Deng et al. [22] made a comparison between weight loss from bends on an industrial-scale pneumatic conveyor and erosion rates obtained in a small centrifugal erosion tester. The investigation discussed some of the important parameters, such as: particle velocity, impact angle, bend geometry, particle concentration and particle fracture. The comparison between the prediction and the experimental results shows that the model makes it possible to predict bend material weight loss by utilizing a small-scale erosion tester.

## **1.6 Separation Systems**

Cyclones have long been used for the separation of particulates from contaminated gas streams and for aerosol sampling. There are many advantages that favor the use of cyclones such as simple design, low capital and operational cost, ease of maintenance, and versatility. Xiang and Lee [23] presented a numerical simulation (FLUENT V5.5) of the flow patterns within three cyclones of different cone dimensions. The comparison of the flow field within the three cyclones explains well why the reduction in the cone bottom dimension results in a higher separation efficiency, as observed in the experiment. Obermair et al. [24] investigated the downcomer tube of a cyclone by PDA measurements. These tests provided the first in-situ experimental proof of agglomerated particles in a cyclone. The formation of agglomerates in the cyclone explains how particles of less than 20–50  $\mu\text{m}$  are able to settle in the dust bin in the presence of high velocities. Due to the additional particle separation in the downcomer tube a cyclone with a downcomer tube obtains the best separation efficiency. Zhao [25] analyzed and compared the gas flow patterns in two different cyclone separators with conventional and symmetrical (two inlets) inlet geometries.

Some alternative separators were developed and presented recently. Du et al. [26] reported and investigated a gas–solid separator with a guide baffle and separation baffles developed by the Institute of Process Engineering (IPE) in China for cocurrent down-flow reactors. This separator, however, may be utilized also for dense phase pneumatic conveying. The separator consists of three internal components: a rectangular nozzle which introduces the gas–solid flow into the separator, a guide baffle which is composed of two circular arcs in bilateral symmetry, and a separation baffle which is also composed of two circular arcs, top and bottom, but in up-down symmetry. Asbach et al. [27] developed and presented a gas particle partitioner (GPP) that allows highly efficient separation of gas and particles with no effect on the thermodynamic conditions and substantially no change of the composition of the gas. The GPP is a coaxial arrangement with inner and outer electrode. The GPP utilizes a corona discharge to electrically charge the particles and a strong electric field in a separate unit to take them out of the sample flow. The investigations showed that the separation efficiency was very near 100% for all particles with diameters larger than 25 nm, whereas it decreased for smaller diameters.

## **1.7 Experiments, Measurement Methods, Techniques, Instrumentation**

Zhang and Coulthard [28] presented a theoretical analysis of the spatial sensitivity of the electrostatic meter with ring-shaped electrodes in the time and frequency domains. One goal of the study was to improve its performance and to achieve uniform sensitivity. The experimental data presented in this paper support the overall mathematic modeling, based on electrostatic field theory, using the finite-element method (FEM). Carter et al. [29] assessed the capabilities of a novel combination of

sensor types (electrostatic and digital imaging sensors), for which the basic principles were presented by Carter and Yan [30], attempted to measure the absolute mass flow rate and size distribution of particulate materials in pneumatic conveyance in an on-line and non-intrusive manner. Concentrations of up to 2% by volume have been tested at velocities of up to 20 m/s. In general good results were produced with a level of accuracy ( $\pm 6\%$  for mass flow and  $\pm 2.5\%$  for particle sizing) that would be acceptable in an industrial setting. Another on-line and non-intrusive instrument – optical tomography sensor was used by Rahim et al. [31] for monitoring real-time flow imaging when various baffles are created to block certain areas of a pipe so that flowing particles can be controlled using difference patterns with the same flow rate.

Solids flow dynamics in gas-solid risers is inherently complex. Model refinement through experimental validation requires the acquisition of detailed nonintrusive measurements. Noninvasive computer-automated radioactive particle tracking was employed by Bhusarapu et al. [32] to visualize and quantify in a three-dimensional domain the solids dynamics and mixing in gas solid risers. This technique has the added advantage that, along with the derived Eulerian solids flow field it also provides directly the Lagrangian description of the solids motion. The solids velocity field data are obtained in two different risers at low and high solids fluxes at varying superficial gas velocity. Liu et al. [33] developed, based on particle velocity and size information measured by phase Doppler particle analyzer (PDPA), an algorithm to calculate particle cluster properties for dilute gas–solid flow. Experimental analysis showed that particle cluster properties are closely related to local time-averaged voidage and turbulent fluctuation of particles.

The effect of Reynolds number, mass loading, and particle shape and size on pressure drop in a vertical gas-solids pneumatic conveying line was explored by Henthorn et al. [34]. A commonly used pressure drop correlation, by Konno and Saito, and a state-of-the-art multiphase computational fluid dynamics (CFD) models are then assessed by comparing their predictions to experimental data. The investigation reveals that variations in particle shape greatly affect the pressure drop measured in a vertical conveying line, particularly for highly non-spherical particles. Comparisons between the experimental data and the CFD model and the experimental correlation, however, indicate that both the model and the correlation are currently not able to capture particle shape effects. The turbulence intensity was investigated by Hadinoto et al. [35]. A downward flow of glass bead particles in a vertical pipe is investigated using a two-component LDV/PDPA for a range of Re ( $6400 < \text{Re} < 24,000$ ) and a constant particle loading ( $\mu = 0.7$ ). Two particle sizes of 70 and 200  $\mu\text{m}$  are considered. Compared with the single-phase flow at the same Re, they have found that for 70  $\mu\text{m}$  particles the presence of the particles dampens the gas-phase turbulence intensity at the lowest value of Re and the gas turbulence is enhanced for the largest values of Re. For the 200  $\mu\text{m}$  particles, the intensity is enhanced for all values of Re investigated, except at the lowest value in which the gas turbulence is equal to that of single-phase flow at the same Re. Benson et al. [36] investigated the effect of wall roughness by performing experimental measurements using a laser Doppler anemometer (LDA) system on 150  $\mu\text{m}$  dense glass particles in a fully developed downward channel flow in air with a dilute loading of particles of 15% by mass fraction. They have found that the turbulence intensity of the gas phase is enhanced across the entire channel in the presence of fully rough walls. The rough walls have an even greater impact on the particulate phase. Stream wise particle velocities are reduced up to 40%, and become quite uniform across the channel. Particle fluctuating velocities are nearly doubled near the channel center plane.

## 1.8 Modeling and Simulation

In most pneumatic conveying, both solids flux and gas phase Reynolds number are high and the flow is usually turbulent. The effects of particle–particle collisions and particle phase turbulence must be considered in any mathematical model for simulating gas–particle flows. Rundqvist et al. [37] simulated particle transport in a horizontal two-dimensional (2-D) channel using an Eulerian two-fluid model including a modified  $k - \varepsilon$  model. Comparisons with measurements of air particle flow in a horizontal pipe show qualitative agreement between measurements and calculations. Benyahia et al. [38] implemented a previously developed turbulent gas/solids model that includes the effects of turbulence in the gas phase as well as inter-particle collisions. The numerical calculations were conducted by imposing periodic boundary conditions as well as in a long pipe with different length-to-diameter ratios to achieve a fully developed condition. By comparing to experiments Benyahia et al. concluded that the model is able to predict reasonably well dilute gas/solids flows with appropriate boundary conditions. Heinel and Bohnet [39] introduced a numerical model to consider the particle–wall adhesion in the numerical simulation of horizontal pneumatic conveying of fine powder. By using FLUENT the model is based on the Lagrangian approach for the dispersed phase ( $k-\varepsilon$  model). Additional models for the wall roughness and the particle–particle collision describe their effect on particle–wall adhesion. Wall roughness, as well as particle–particle collisions, leads to an increase of particle adhesion. Furthermore, several parameters are varied (e.g., electrostatic charge of particles, air velocity).

A comprehensive model is developed for vertical pipes by Chan et al. [40] in which a two-equation ( $k-\varepsilon$ ) turbulence model is used for calculating the gas phase. In addition, a transport equation of particle phase turbulent kinetic energy is proposed and used for modeling the particle phase turbulence ( $k_p$  model). Similar to that of the single gas phase, effective viscosity of the particle phase is the sum of the laminar viscosity caused by particle–particle collisions described by kinetic theory and the turbulent viscosity caused by collections of particles described by the  $k_p$  model. Ouyang and Yu [41] presented a two-dimensional study of the gas-solid flow in a vertical pneumatic conveying pipe by means of a hard-sphere model (CFD-DEM). The results show that the main features of plug flow can be reasonably captured by the proposed simulation technique. One finds that increasing superficial gas velocity will increase the velocity of plugs and the frequency of plugs, and the pressure drop through a rising plug increases linearly with the plug length. Increasing the restitution coefficient can promote the momentum transfer between particles and hence the raining down of particles from the back of a plug in vertical pneumatic conveying.

A three-dimensional turbulent gas–solid two-phase flow model for a gas–solid injector is developed by Xiong et al. [42]. The solid phase is simulated by using a Lagrangian approach. In this model, the drag and lift forces on particles, the multi-body collisions among particles and the mutual interaction between gas and particles were taken into account. Interparticle interactions and particle–wall collisions are simulated by using the three-dimensional distinct element method (DEM). Healy and Young [43] discussed two Full Lagrangian methods for calculating the particle concentration and velocity fields in dilute gas-particle flows although not for pneumatic conveying. The correct specification of the initial conditions is non-trivial and of vital importance. The paper describes a method for reducing errors due to differentiation of a ‘noisy’ field.

Much can be learned for simulating pneumatic conveying systems, mainly in dense phase flow, from a variety of papers considering simulation of fluidized beds. Li and Kuipers [44] investigated numerically the formation and evolution of flow structures in dense gas-fluidized beds with ideal collision of particles (elastic and frictionless) by employing the discrete particle method, with special focus on the effect of gas-particle interaction. Koksall and Hamdullahpur [45] carried out a comprehensive investigation on hydrodynamics aspects of secondary air injection in circulating fluidized beds using two-fluid (Eulerian-Eulerian) approach, where a granular kinetic theory model is used to describe the solids phase stresses. Cui et al. [46] undertaken a numerical study (FLUENT) to explore the influence of geometry and flow parameters on the entrainment of solid in a nozzle system immersed in a fluidized riser. Gomez and Milioli [47] described a numerical study on the collisional solid pressure influence upon the hydrodynamics of the gas-solid flow in a 2D riser using a traditional two-fluid formulation.

## **1.9 Design Processes**

Difficulties are encountered sometimes with new chemical products during manufacturing, handling, or marketing due to lack of knowledge in the particle technology area. The major problem discussed by Kalman and Tardos [48] is that, in most cases, this is due to the neglect of the mutual interactions between different unit operations during manufacturing and conveying in the design phase of these new products. Unlike the case with most other materials, it is not sufficient to know the present thermodynamic state of bulk powdery materials in order to determine their attributes since their ‘history’ also affects the material’s properties and behavior, often dramatically. As for pneumatic conveying, they emphasized particle size reduction during pneumatic conveying that may be used as an advantage if one is interested in reducing the particle size of the product anyway. In any case, the size reduction should be taken into account while designing the downstream unit. Furthermore, some processes, such as drying, could be achieved simultaneously during pneumatic conveying. As part of a major research program on quality in particulate manufacturing, computational models have been developed by Chapelle et al. [49] for segregation in silos, degradation in pneumatic conveyors, and the development of caking during storage. They presented a set of simulations of a complete large-scale granular materials handling operation, including the material transport through a dilute-phase pneumatic conveyor. The pneumatic conveying simulations were concentrated on the pressure drop and particle degradation.

Pneumatic conveying test rigs were used by Cowell et al. [50] in conjunction with a mathematical model to generate conveying characteristics for coal at high back pressures. Due to safety considerations, coal and surrogate (cement) were tested at atmospheric back pressure to compare the two materials performance, under similar conveying conditions; and then the surrogate material was tested at elevated back pressure. The similarity of behaviours of the two materials allowed the model to be applied to the data measured for coal and so generate conveying characteristics at conditions typical of entrained flow. The mathematical model used to scale the results to high back pressures (up to 25 bars). Efremenkov et al. [51] considered an upgraded system for controlling pneumatic transportation of glass batch materials. They mainly provided an analysis of various schemes of control over the process of filling the pneumatic-cell pump with material is provided.

## 1.10 Miscellaneous

Many of the studies regarding circulating fluidized beds can be applied to vertical upflow pneumatic conveying. The results of the investigation by Richtberg et al. [52] show a more uniform axial and radial solids distribution with increasing pressure or decreasing density ratios, indicating flow conditions which are different to a well known core-annulus flow structure. This flow structure is defined by a dilute upflow in the core region and a dense downflow in the annulus region which is situated immediately near the wall. Significant solids downflow occur, pointing out massive solids backmixing even at low solid/gas density ratios.

Effects of the particle-particle heat transfer in a gas-solid turbulent flow in a riser were evaluated by Mansoori et al. [53]. An Eulerian/Lagrangian four-way interaction formulation including the particle collisions were used in the numerical simulation. The results showed that the effect of particle-particle heat transfer was more significant for smaller sizes, lower flow Reynolds numbers, and for higher loading ratios. Solid thermal properties, however, did not have a noticeable effect on the inter-particle heat transfer. This was also confirmed by Chagras et al. [54] for loading ratios up to 10, whom conducted a similar numerical work. The particle-particle collisions, however, have been found to increase the overall heat transfer by as much as 8% in vertical pipe flow. Skuratovsky et al. [55] used the two-fluid model for modeling the flow of particulate materials through pneumatic dryer. The model was solved for a two-dimensional steady-state condition and considering axial and radial profiles for the flow variables. In a two-stage drying process the first drying stage the heat transfer controls evaporation from the saturated outer surface of the particle to the surrounding gas. At the second stage, the particles were assumed to have a wet core and a dry outer crust; the evaporation process of the liquid from a particle assumed to be governed by diffusion through the particle crust and by convection into the gas medium. As evaporation proceeds, the wet core shrinks while the particle dries.

Another interesting application is the pneumatic conveying of snow. In Japan, the number of snow storage plants has been increasing for the purpose of storing agricultural products and for the air-conditioning of buildings in summer. A pneumatic snow conveying system, therefore, was developed by in order to transport snow to the snow storage plant, Kobayashi [56]. The system consists of a blower, snow feeder, cyclone separator, and pipeline, and has a capacity to convey wet snow at 10 t/h a distance of 40 m.

## Capsule

Tashiro and Tomita [57] studied the horizontal pneumatic capsule transport of large particles with particle to pipe diameter ratio of 0.6 and particle densities of 928 kg=m<sup>3</sup> and 2193 kg=m<sup>3</sup> was examined experimentally and numerically. The pipe diameter and length were 10mm and 8.8 m, respectively. The mean air velocity was between 14.2m=s and 23.0m=s and the number feed rate of particle was almost constant at seven per second. In this study, the method of characteristics was used for the simulation of gas flow, which considered not only the particle-particle collisions but also the particle-wall collisions. It is found that particle transport is possible even when the mean air velocity is smaller than the terminal settling velocity of particle and that the arrival time intervals at the downstream section are not always uniform although the particles are fed uniformly. Furthermore, the velocity difference between different density particles becomes small as the mean air velocity decreases, because the particle velocities become uniform due to particle-particle collisions, and the ratio

of particle velocity to the mean air velocity is almost independent of air velocity. In addition, it is shown that the particle-wall collision at the pipe joint due to pipeline misalignment can be one of the sources of bouncing motion of particles as shown by simulation results.

## **References**

1. Mills, D. 2005. Pneumatic conveying: Know your options. *Chemical Engineering* 112 (5): 58-63.
2. Mills, D. 2005. Pneumatic conveying: More options, plus guidelines. *Chemical Engineering* 112 (6): 46-51.
3. Mills, D. 2005. Pneumatic conveying: Dilute vs. dense phase. *Chemical Engineering* 112 (1): 51-57.
4. Mills, D. 2005. A review of the research work of Professor Predrag Marjanovic. *Chemical Engineering and Processing* 44 (2): 141-151.
5. Salman, A. D., D. A. Gorham, M. Szabo & M. J. Hounslow. 2005. Spherical particle movement in dilute pneumatic conveying. *Powder Technology* 153 (1): 43-50.
6. Eskin, D. 2005. Modeling dilute gas-particle flows in horizontal channels with different wall roughness. *Chemical Engineering Science* 60 (3): 655-663.
7. Boree, J. & N. Caraman. 2005. Dilute bidispersed tube flow: Role of interclass collisions at increased loadings. *Physics of Fluids* 17 (5): Art. No. 055108.
8. Sanchez, L., N. A. Vasquez, G. E. Klinzing & S. Dhodapkar. 2005. Evaluation of models and correlations for pressure drop estimation in dense phase pneumatic conveying and an experimental analysis. *Powder Technology* 153 (3): 142-147.
9. Datta, B. K. & C. Ratnayaka. 2005. A possible scaling-up technique for dense phase pneumatic conveying. *Particulate Science and Technology* 23 (2): 201-204.
10. Li, J., C. Webb, S. S. Pandiella, G. M. Campbell, T. Dyakowski, A. Cowell & D. McGlinchey. 2005. Solids deposition in low-velocity slug flow pneumatic conveying. *Chemical Engineering and Processing* 44 (2): 167-173.
11. McGlinchey, D., A. Cowell, J. R. Pugh, E. A. Knight, J. Xiang & J. Li. 2005. Axial and radial pressure drops of dense phase plugs. *Particulate Science and Technology* 23 (3): 215-227.
12. Kalman, H., A. Satran, D. Meir & E. Rabinovich. 2005. Pickup (critical) velocity of particles. *Powder Technology* 160 (2): 103-113.
13. Akilli, H., E. K. Levy & B. Sahin. 2005. Investigation of gas-solid flow structure after a 90 degrees vertical-to-horizontal elbow for low conveying gas velocities. *Advanced Powder Technology* 16 (3): 261-274.
14. Balasubramanian, N., C. Srinivasakannan & C. A. Basha. 2005. Transition velocities in the riser of a circulating fluidized bed. *Advanced Powder Technology* 16 (3): 247-260.
15. Wadke, P. M., M. J. Pitt, A. Kharaz, M. J. Hounslow & A. D. Salman. 2005. Particle trajectory in a pipe bend. *Advanced Powder Technology* 16 (6): 659-675.
16. Quek, T. Y., C. H. Wang & M. B. Ray. 2005. Dilute gas-solid flows in horizontal and vertical bends. *Industrial & Engineering Chemistry Research* 44 (7): 2301-2315.
17. Hidayat, M. & A. Rasmuson. 2005. Some aspects on gas-solid flow in a U-bend: Numerical investigation. *Powder Technology* 153 (1): 1-12.
18. Subero-Couroyer, C., M. Ghadiri, N. Brunard & F. Kolenda. 2005. Analysis of catalyst particle strength by impact testing: The effect of manufacturing process parameters on the particle strength. *Powder Technology* 160 (2): 67-80.

19. Frye, L. & W. Peukert. 2005. Identification of material specific attrition mechanisms for polymers in dilute phase pneumatic conveying. *Chemical Engineering and Processing* 44 (2): 175-185.
20. Mazumder, Q. H., S. A. Shirazi, B. S. McLaury, J. R. Shadley & E. F. Rybicki. 2005. Development and validation of a mechanistic model to predict solid particle erosion in multiphase flow. *Wear* 259 (1-6): 203-207.
21. Deng, T., A. R. Chaudhry, M. Patel, I. Hutchings & M. S. A. Bradley. 2005. Effect of particle concentration on erosion rate of mild steel bends in a pneumatic conveyor. *Wear* 258 (1-4): 480-487.
22. Deng, T., J. Li, A. R. Chaudhry, M. Patel, I. Hutchings & M. S. A. Bradley. 2005. Comparison between weight loss of bends in a pneumatic conveyor and erosion rate obtained in a centrifugal erosion tester for the same materials. *Wear* 258 (1-4): 402-411.
23. Xiang, R. B. & K. W. Lee. 2005. Numerical simulation of flow patterns in cyclones of different cone dimensions. *Particle & Particle Systems Characterization* 22 (3): 212-218.
24. Obermair, S., C. Gutsch, J. Woisetschlager, & G. Staudinger. 2005. Flow pattern and agglomeration in the dust outlet of a gas cyclone investigated by Phase Doppler Anemometry. *Powder Technology* 156 (1): 34-42.
25. Zhao, B. T. 2005. Experimental investigation of flow patterns in cyclones with conventional and symmetrical inlet geometries. *Chemical Engineering & Technology* 28 (9): 969-972.
26. Du, L., J. Z. Yao & W. G. Lin. 2005. Experimental study of particle flow in a gas-solid separator with baffles using PDPA. *Chemical Engineering Journal* 108 (1-2): 59-67.
27. Asbach, C., T. A. J. Kuhlbusch & H. Fissan. 2005. Investigation on the gas particle separation efficiency of the gas particle partitioner. *Atmospheric Environment* 39 (40): 7825-7835.
28. Zhang, J. Y. & J. Coulthard. 2005. Theoretical and experimental studies of the spatial sensitivity of an electrostatic pulverised fuel meter. *Journal of Electrostatics* 63 (12): 1133-1149.
29. Carter, R. M., Y. Yan & S. D. Cameron. 2005. On-line measurement of particle size distribution and mass flow rate of particles in a pneumatic suspension using combined imaging and electrostatic sensors. *Flow Measurement and Instrumentation* 16 (5): 309-314.
30. Carter, R. M. & Y. Yan. 2005. An instrumentation system using combined sensing strategies for online mass flow rate measurement and particle sizing. *IEEE Transactions on Instrumentation and Measurement* 54 (4): 1433-1437.
31. Rahim, R. A., P. J. Fea, C. K. San & L. L. Chean. 2005. Real-time image reconstruction for various flow regimes using an optical tomography sensor in a gravity flow conveyor. *Advanced Powder Technology* 16 (4): 399-411.
32. Bhusarapu, S., M. H. Al-Dahhan, M. P. Dudukovic, S. Trujillo & T. J. O'Hern. 2005. Experimental study of the solids velocity field in gas-solid risers. *Industrial & Engineering Chemistry Research* 44 (25): 9739-9749.
33. Liu, X. H., S. Q. Gao & J. H. Li. 2005. Characterizing particle clustering behavior by PDPA measurement for dilute gas-solid flow. *Chemical Engineering Journal* 108 (3): 193-202.
34. Henthorn, K. H., K. Park & J. S. Curtis. 2005. Measurement and prediction of pressure drop in pneumatic conveying: Effect of particle characteristics, mass

- loading, and Reynolds number. *Industrial & Engineering Chemistry Research* 44 (14): 5090-5098.
35. Hadinoto, K., E. N. Jones, C. Yurteri & J. S. Curtis. 2005. Reynolds number dependence of gas-phase turbulence in gas-particle flows. *International Journal of Multiphase Flow* 31 (4): 416-434.
  36. Benson, M., T. Tanaka & J. K. Eaton. 2005. Effects of wall roughness on particle velocities in a turbulent channel flow. *Journal of Fluids Engineering-Transactions of the ASME* 127 (2): 250-256.
  37. Rundqvist, R., C. Ljus & B. van Wachem. 2005. Experimental and numerical investigation of particle transport in a horizontal pipe. *AIChE Journal* 51 (12): 3101-3108.
  38. Benyahia, S., M. Syamlal & T. J. O'Brien. 2005. Evaluation of boundary conditions used to model dilute, turbulent gas/solids flows in a pipe. *Powder Technology* 156 (2-3): 62-72.
  39. Heintz, E. & M. Bohnet M. 2005. Calculation of particle-wall adhesion in horizontal gas-solids flow using CFD. *Powder Technology* 159 (2): 95-104.
  40. Chan, C. K., Y. C. Guo & K. S. Lau. 2005. Numerical modeling of gas-particle flow using a comprehensive kinetic theory with turbulence modulation. *Powder Technology* 150 (1): 42-55.
  41. Ouyang, J. & A. B. Yu. 2005. Simulation of gas-solid flow in vertical pipe by hard-sphere model. *Particulate Science and Technology* 23 (1): 47-61.
  42. Xiong, Y. Q., M. Y. Zhang & Z. L. Yuan. 2005. Three-dimensional numerical simulation method for gas-solid injector. *Powder Technology* 160 (3): 180-189.
  43. Healy, D. P. & J. B. Young. 2005. Full Lagrangian methods for calculating particle concentration fields in dilute gas-particle flows. *Proceedings of the Royal Society A-Mathematical Physical and Engineering Sciences* 461 (2059): 2197-2225.
  44. Li, J. & J. A. M. Kuipers. 2005. On the origin of heterogeneous structure in dense gas-solid flows. *Chemical Engineering Science* 60(5): 1251-1265.
  45. Koksaj, M. & F. Hamdullahpur. 2005. CFD simulation of the gas-solid flow in the riser and a circulating fluidized bed with secondary air injection. *Chemical Engineering Communications* 192(7-9): 1151-1179.
  46. Cui, M., A. Straatman & C. Zhang. 2005. A computational study of gas-solid flow in an enhanced solid entrainment (ESE) nozzle system. *International Journal of Chemical Reactor Engineering* 3: Article A7.
  47. Gomez, L. C. & F. E. Milioli. 2005. Collisional solid's pressure impact on numerical results from a traditional two-fluid model. *Powder Technology* 149(2-3): 78-83.
  48. Kalman, H. & G. I. Tardos. 2005. Elements of particle technology in the chemical industry. *Particulate Science and Technology* 23 (1): 1-19.
  49. Chapelle, P., N. Christakis, J. Wang J, N. Strusevich, M. K. Patel, M. Cross, H. Abou-Chakra, J. Baxter & U. Tuzun. 2005. Application of simulation technologies in the analysis of granular material behaviour during transport and storage. *Proceedings of the Institution of Mechanical Engineers Part E-Journal of Process Mechanical Engineering* 219 (E1): 43-52.
  50. Cowell, A., D. McGlinchey & R. Ansell. 2005. Determination of pneumatic transport capabilities of dry pulverised coal suitable for entrained flow processes. *Fuel* 84 (17): 2256-2266.

51. Efremenkov, V. V., K. Y. Subbotin & A. I. Nosov. 2005. Upgrade of systems controlling pneumatic transport of glass batch materials. *Glass and Ceramics* 62 (9-10): 263-264.
52. Richtberg, M., R. Richter & K. E. Wirth. 2005. Characterization of the flow patterns in a pressurized circulating fluidized bed. *Powder Technology* 155 (2): 145-152.
53. Mansoori, Z., M. Saffar-Avval, H. B. Tabrizi, B. Dabir & G. Ahmadi. 2005. Inter-particle heat transfer in a riser of gas-solid turbulent flows. *Powder Technology* 159 (1): 35-45.
54. Chagras, V., B. Oesterle & P. Boulet. 2005. On heat transfer in gas-solid pipe flows: Effects of collision induced alterations of the flow dynamics. *International Journal of Heat and Mass Transfer* 48 (9): 1649-1661.
55. Skuratovsky, I. A. Levy & I. Borde. 2005. Two-dimensional numerical simulations of the pneumatic drying in vertical pipes. *Chemical Engineering and Processing* 44(2): 187-192.
56. Kobayashi, T. 2005. Pneumatic conveying for snow storage plants. *Particulate Science And Technology* 23 (1): 93-97.
57. Tashiro, H. & Y. Tomita. 2005. Motion of large particles in a horizontal pneumatic pipe, *Particulate Science and Technology* 23 (1): 33-45.