Pneumatic Conveying Characteristics of Fine and Granular Bulk Solids†

R. Pan, B. Mi and P. W. Wypych
Department of Mechanical Engineering
University of Wollongong*

Abstract

Fine and granular products possess significantly different pneumatic conveying characteristics. Fine products usually have smooth conveying characteristic curves from dilute- to dense-phase. Between dilute- and dense-phase there is a pressure minimum curve. However, when granular products are conveyed between dilute- and dense-phase, significant fluctuations in pressure and vibration can occur along the pipeline. To obtain reliable operating conditions for the designed pneumatic conveying system, three semi-empirical correlations are developed in this paper for the calculation of the pressure minimum curve for fine powders and the boundaries between dilute-phase, unstable-zone and dense-phase flow for granular products in terms of particle properties and conveying conditions. Finally, a new procedure is presented for the prediction of total pipeline air pressure drop and the economic design of pneumatic conveying systems with the aim of reducing power consumption and particle damage.

1. Introduction

Over the past two decades, pneumatic conveying systems have been employed successfully to transport both fine and granular bulk solids. However, these two types of material display dramatically different pneumatic conveying characteristics.

Fine powders that fluidise readily and also have good air retentive properties (e.g. flyash, pulverised coal) usually can be transported smoothly and reliably from dilute- to dense-phase†. Between dilute- and dense-phase there is a pressure minimum curve. However, when granular products (e.g. plastic pellets, wheat) are conveyed between dilute- and dense-phase, significant fluctuations in pressure and vibration can occur along the pipeline‡. This region is referred to as the unstable zone. These differences in conveying performance can affect significantly the operation of the pneumatic conveying system and should be given adequate consideration during the design stage.

Therefore, to ensure dilute- or dense-phase (depending on the application), it is very important to determine:

• the pressure minimum curve (PMC) for fine powders,
• the boundaries between dilute-phase, unstable zone and dense-phase for granular products.

In this paper, three semi-empirical correlations are presented to calculate the pressure minimum curve for fine powders and the boundaries between dilute-phase, unstable-zone and dense-phase flow for granular products in terms of particle properties and conveying conditions. Also, a new procedure is presented for the prediction of total pipeline air pressure drop and the economic design of pneumatic conveying systems with the aim of reducing power consumption and particle damage. Numerous experiments on a range of fine and granular bulk solids and in different configurations of pipeline have been conducted by the authors. Good accuracy and reliability have been achieved for all the test materials and configurations of pipeline considered in this paper.

2. Flow Pattern

A typical set of pneumatic conveying characteristics for fine products is shown in Fig. 1. When the air mass flow rate is decreased from high to low and along a line at constant product mass flow rate, the pressure drop also decreases and reaches a minimum value. This region usually is referred to as dilute-phase conveying. As the air mass flow rate is decreased further, the pressure drop increases usually at a higher rate than in dilute-phase. This region generally is called dense-phase. Therefore, from

* Wollongong NSW, 2522 Australia
† Received May 30th, 1994
‡ Good accuracy and reliability have been achieved for all the test materials and configurations of pipeline considered in this paper.
Fig. 1, between dilute- and dense-phase there is a pressure minimum curve which is one of the main parameters that should be determined during the design stage.

Fig. 1 General form of pneumatic conveying characteristics for fine products

Fig. 2 shows a typical set of pneumatic conveying characteristics for free-flowing granular bulk solids (e.g., wheat, plastic pellets, rice).

Fig. 2 General form of pneumatic conveying characteristics for granular products

In dilute-phase, the particles are distributed evenly over the entire cross section of the pipe (see point 1 in Fig. 2). When conveying takes place along a line at constant product mass flow rate in the direction of decreasing air mass flow rate, this line reaches a point of minimum pressure. At this stage, a “layer” of particles is being conveyed along the bottom of the pipe (see point 2 in Fig. 2). With such information, it is possible to operate at minimum air flows for dilute-phase by selecting operating conditions say, slightly to the right of pressure minimum.

As the air mass flow rate is decreased further, the particles accumulate on the bottom of the pipeline and form long plugs. These long plugs are “forced” through the pipeline and produce high fluctuations in pressure and vibration. This region is referred to as the unstable zone (see point 3 in Fig. 2).

If the air mass flow rate is reduced even further, it is found that the particles are conveyed gently and in the form of slugs (see point 4 in Fig. 2). Along the horizontal pipeline, the slugs pick up the particles from the stationary layer in front of it and deposit the same quantity of particles behind it. Note that there is no inter-particle motion within the slug itself.

Therefore, from Fig. 2 there are two boundaries separating the dilute-phase, unstable-zone and dense-phase regimes.

3. Test Program

The products and pipelines employed in the test program are listed in Tables 1 and 2.

Coal 1, Coal 2, Coal 3, Coal 4 and Flyash all were fine powders and the others were granular materials.

The compressed air was supplied at a maximum pressure head of ≈ 800 kPag from any combination of three screw compressors. The air mass flow rates were measured by annubar for Pipelines II, VI and VII and by an orifice plate for the other pipelines. The product mass flow rates were obtained from the load cells on which the receiving hoppers were mounted.

The steady-state conveying characteristics for several pipelines and products are shown in Figs. 3 to 10 which clearly demonstrate that fine and granular products display significantly different pneumatic conveying characteristics. Also the experimental data points are superimposed on the figures.

| Product   | \(\phi_s\) (kg m\(^{-3}\)) | \(\phi_p\) (kg m\(^{-3}\)) | \(d_p\) (μm) | \(\phi\) (°) | \(\phi_p\) (°) | Test Pipeline(s) |
|-----------|-----------------|-----------------|------------|-------|-----------|----------------|
| Coal 1    | 1390            | 563             | 30         | -     | -         | I, II          |
| Coal 2    | 1390            | 541             | 18         | -     | -         | I, II          |
| Coal 3    | 1360            | 568             | 29         | -     | -         | I, II          |
| Coal 4    | 1600            | 538             | 41         | -     | -         | III, IV, V     |
| Flyash    | 2197            | 634             | 16         | -     | -         | VI, VII, VIII, IX, X |
| BPP\(^a\) | 834             | 458             | 3760       | 43.8  | 12.1      | VI, X, XI      |
| WPP\(^b\) | 865             | 494             | 3120       | 44.7  | 15.2      | XI             |
| Duralina  | 1494            | 688             | 350        | 34.5  | 17.0      | XI             |
| Wheat     | 1416            | 778             | 3500       | 43.7  | 16.0      | XI             |

\(^a\)BPP = Black Plastic Pellets.  
\(^b\)WPP = White Plastic Pellets.
Table 2  Test pipelines

| Pipeline | D (mm) | L (m) | N_p | N_m | N_v | R (mm) | Feeder |
|----------|-------|------|-----|-----|-----|--------|--------|
| I        | 25.4  | 63   | 9   | 8   | 2   | 254    | BT^6   |
| II       | 52.5  | 48   | 4   | 4   | 1   | 254    | BT     |
| III      | 105   | 110  | 5   | 5   | 1   | 1000   | BT     |
| IV       | 52.5  | 104  | 12  | 11  | 2   | 1000 & 254 | SFB^4 |
| V        | 52.5  | 117  | 12  | 11  | 2   | 1000   | SFB    |
| VI       | 52.5  | 102  | 9   | 9   | 1   | 254    | BT     |
| VII      | 105   | 110  | 5   | 5   | 1   | 1000   | BT     |
| VIII     | 69    | 172  | 5   | 5   | 1   | 1000   | BT     |
| IX       | 69    | 553  | 17  | 17  | 1   | 1000   | BT     |
| X        | 80.5  | 137  | 9   | 9   | 1   | 254    | SFB    |
| XI       | 105   | 96   | 10  | 10  | 1   | 1000   | RV^f   |

^6 BT = Blow Tank.
^4 SFB = Screw-Feeding Blow Tank.
^f RV = Rotary Valve.

---

![Fig. 3](image1)
Fig. 3 Steady-state conveying characteristics of Coal 1 and Pipeline I

![Fig. 4](image2)
Fig. 4 Steady-state conveying characteristics of Coal 2 and Pipeline I

![Fig. 5](image3)
Fig. 5 Steady-state conveying characteristics of Coal 4 and Pipeline III

![Fig. 6](image4)
Fig. 6 Steady-state conveying characteristics of Flyash and Pipeline VI

![Fig. 7](image5)
Fig. 7 Steady-state conveying characteristics of Black Plastic Pellets and Pipeline XI

![Fig. 8](image6)
Fig. 8 Steady-state conveying characteristics of White Plastic Pellets and Pipeline XI

![Fig. 9](image7)
Fig. 9 Steady-state conveying characteristics of Duralina and Pipeline XI

KONA No.12 (1994) 79
4. Prediction of PMC and Boundaries

4.1 Dimensional Analyses

To describe the pressure minimum curve (PMC) for fine powders and the boundaries between dilute-phase, the unstable-zone and dense-phase flow for granular products, the Froude number at the pick-up point is employed in this paper and defined as:

\[ Fr = \frac{V_{li}}{\sqrt{g \cdot D}} \]

For a given pipeline material and conveying air, the Froude number, \( Fr \), can be considered as a function of particle properties and conveying conditions, such as bulk density \( \rho_b \), median particle diameter \( d_p \), pipe diameter \( D \), product mass flow rate \( m_s \), air mass flow rate \( m_t \), and air density at the pick-up point \( \rho_i \). By using dimensional analysis, an expression of the form given in Equation (1) is considered initially.

\[ Fr = k m_s^a m_t^b \rho_i^c \rho_b^d d_p^e D^f \]  \hspace{1cm} (1)

Equation (1) normally would involve the evaluation of seven unknowns, but these may be reduced with the aid of dimensional analysis.

The dimensional equation corresponding to Equation (1) is:

\[ [L^0 M^0 T^0] = [M^{a+b+c+d}] [L^d] [M^c] [L] [T]^{a+b} \]

\hspace{1cm} (2)

Equation (2) may be resolved into three component auxiliary equations:

\[ L: 0 = -3c - 3d + e + f \]  \hspace{1cm} (3)
\[ M: 0 = a + b + c + d \]  \hspace{1cm} (4)
\[ T: 0 = -a - b \]  \hspace{1cm} (5)

There are now six unknowns and three equations; hence three of the unknowns may be expressed in terms of the remaining three unknowns. Numerous combinations are possible. One possible combination is to express \( b, d, \) and \( f \) in terms of \( a, c \) and \( e \). From Equations (3), (4) and (5),

\[ b = -a \]
\[ d = -c \]
\[ f = -e \]

Substituting these values into Equation (1) results in:

\[ Fr = k m_s^a m_t^b \rho_i^c \rho_b^d d_p^e D^f \]

\hspace{1cm} (6)

From Tables 1 and 2, the particle diameter of the fine powders can be neglected compared with the pipe diameter. Also, based on the authors’ experiences, for a given pipeline the particle diameter of fine powders which have similar properties has little influence on the system performance in dilute-phase conveying. However, the pipe diameter still has a great effect on system performance (i.e. \( Fr_i \)). Therefore, Equation (6) is simplified for fine powders as:

\[ Fr_i = k m_s^a \left( \frac{\rho_i}{\rho_b} \right)^c d_p^e D^f \]  \hspace{1cm} (7)

Exponents \( k, a, c \) and \( e \) in Equations (6) and (7) are determined empirically.

4.2 Determination of Exponents

To predict accurately the pressure minimum curve for fine powders and the boundaries between dilute-phase, the unstable zone and dense-phase flow for granular products, the exponents \( k, a, c \) and \( e \) are determined initially by using the experimental data of pressure minima and the boundaries for different pipe diameters and products (e.g. Pipeline I and Coal 1, Pipeline VIII and Flyash for fine powders and Pipeline III and Black Plastic Pellets, Pipeline I and Duralina for granular products). The determined values of the exponent are listed in Table 3.
Table 3 Values of exponent

| Exponent | PMC (see Fig. 1) | Boundary 1 (see Fig. 2) | Boundary 2 (see Fig. 2) |
|----------|-----------------|------------------------|------------------------|
| k        | 3.504           | 3.151                  | 2.959                  |
| a        | -0.230          | -0.018                 | 0.097                  |
| c        | -0.152          | -0.254                 | -0.219                 |
| e        | -0.302          | 0.213                  | 0.069                  |

Hence, Equations (6) and (7) are rewritten as:

\[
Fr_I = 3.504 \, m^{0.230} \, \left( \frac{\dot{q}_h}{\dot{q}_b} \right)^{0.152} \, \frac{D^{0.302}}{} \quad \text{for PMC (8)}
\]

\[
Fr_I = 3.151 \, m^{0.018} \, \left( \frac{\dot{q}_h}{\dot{q}_b} \right)^{0.254} \, \frac{D^{0.213}}{} \quad \text{for Boundary 1 (9)}
\]

\[
Fr_I = 2.959 \, m^{0.097} \, \left( \frac{\dot{q}_h}{\dot{q}_b} \right)^{0.219} \, \frac{D^{0.069}}{} \quad \text{for Boundary 2 (10)}
\]

The pressure minimum curves and boundaries for each pipeline and product then are predicted by using Equations (8), (9) and (10), respectively. Some of the predictions are shown in Figs. 3 to 10, which clearly demonstrate that Equations (8), (9) and (10) have good accuracy and reliability for all the test materials and pipeline configurations considered in this paper.

5. Prediction of Pressure Drop and Economic Operating Point (EOP)

To determine accurately the pressure minimum curve by Equation (8) for fine powders and the boundaries between dilute-phase, the unstable-zone and dense-phase by Equations (9) and (10) for granular products, it is required to predict accurately the total pipeline air pressure drop. Since the properties of the conveyed material have great influences on system performance, to date no general correlations have been developed that can predict accurately the total pipeline air pressure drop for conveying fine products from dilute-to dense-phase and granular products in dilute-phase\(^1\). Fortunately, an accurate test-design procedure has been developed recently\(^4\) where the experimental data from a test rig can be scaled up accurately to actual installations for a given product. Therefore, the following section presents the results from recent investigations into predicting theoretically the pressure loss in the horizontal dense-phase transport of granular products.

5.1 Pressure Drop in Dense-Phase

The following correlation has been developed to predict the pressure gradient for a horizontal particle slug\(^5,6\):

\[
\Delta P = \frac{4 \, \mu_w \lambda}{D} \, \sigma_f + 2 \, \dot{q}_b \, \eta \, \mu_w
\]

\(\lambda\) is the stress transmission coefficient (i.e. ratio of radial stress to axial stress). Note that the radial stress caused by gravity in a horizontal pipe is excluded. Based on the measured results of wall pressure and a theoretical analysis, the following equations have been developed\(^7\) to determine the value of the stress transmission coefficient in a slug.

\[
\lambda = \frac{\sigma_{rw}}{\sigma_x} = \frac{1 - \sin \phi_w \cos (\omega - \phi_w)}{1 + \sin \phi_w \cos (\omega - \phi_w)}
\]

\[
\sin \omega = \frac{\sin \phi_w}{\sin \phi_s}
\]

\[
\phi_s = \frac{4}{3} \phi_w \gamma_b \, 0.33
\]

\(\sigma_f\) is the stress on the front face of the slug and can be estimated by the following equation.

\[
\sigma_f = \alpha \dot{q}_b \, V_s^2
\]

\(\alpha\) is ratio of cross sectional area of stationary layer to pipe and calculated by:

\[
\alpha = \frac{A_{st}}{A} = \frac{1}{1 + V_s/(0.542 \, \sqrt{D})}
\]

\(V_s\) is the slug velocity and the relationship between the slug velocity and the superficial air velocity has been presented\(^8\), that is:

\[
V_s = 105 \, \epsilon \, \frac{d_p}{D} \, \left( \tan \phi_w \right)^{0.33} \, (V_f - V_{f\text{min}})
\]

where \(V_{f\text{min}}\) is the minimum superficial air velocity for horizontal flow,

\[
V_{f\text{min}} = \frac{\dot{q}_s \, g \, \tan \phi_w \, \epsilon^3 d_p^2}{180 \, (1 - \epsilon) \, \eta}
\]

Therefore, the pressure gradient in a single slug can be calculated easily from Equation (11) and the
other relevant expressions. Also, the pressure drop over the entire slug can be obtained if the length of the slug is known.

A dense-phase slug-flow pneumatic conveying system usually contains several slugs along the pipeline. It has been found that the sum of the pressure drop caused by each slug is equal to that caused by a single slug having a total length equal to all the small slugs. This is contrary to the exponential relationship described by Doig. The reason is that the slugs in a low-velocity conveying system are in an aerated state and do not behave like a "mechanical pushing" system. The pressure gradient along this "single" slug still can be calculated by using Equation (11), as long as the mean conditions (based on average air density) are used.

Since the air mass flow rate and the slug velocity in dense-phase are very low, the pressure drop caused by conveying air and the effect of bends on the pressure drop can be neglected (i.e. the pipeline can be approximated as a straight section of pipe with the same actual length).

The total length of slugs in the pipeline can be calculated by the following correlation:

$$L_s = \frac{m_s L}{A (1 - \alpha) \rho_b V_s}$$

The total pressure drop is:

$$\Delta p_{th} = (1 + 1.084 \lambda F_{r_s}^{0.5} + 0.542 F_{r_s}^{-0.5}) \frac{2 g \mu_{r_w} m_s L}{A V_s}$$

(12)

where $F_{r_s} = \frac{V_s^2}{g D}$

Using Equation (12) and the other relevant expressions, curves of constant $m_s$ (i.e. steady-state conveying characteristics) are predicted for black plastic pellets, white plastic pellets and wheat in Pipeline XI.

Figs. 11 to 13 present the pneumatic conveying characteristics for the experiments conducted on pipeline XI. Note that the pressure drops on these figures represent the values of total pressure drop for a 78 m horizontal section of pipeline. Experimental results are superimposed onto each figure for comparison. Figs. 11 to 13 clearly show that the new model presented in this paper has good accuracy and reliability.

5.2 Economical Operating Point for Slug-Flow

The dense-phase slug-flow pneumatic conveying characteristic curves shown in Figs. 11 to 13 demonstrate that, for a given $m_s$, $\Delta p_{th}$ decreases with increasing $m_f$. Also, it can be seen that the pressure gradient increases quite sharply at low values of $m_f$. Theoretically, it is possible to operate at any point along the $m_s$ curve. However, from an energy point of view, this may not be feasible.
That is, it is desirable to operate the slug-flow system at minimal energy. The following equation can be used to estimate the nominal power of the conveying system.

\[ P_n = \Delta p_{th} A V_t \]

Replacing \( \Delta p_{th} \) with Equation (12), then

\[ P_n = (1 + 1.084 \lambda F_{rs}^{0.5} + 0.542 F_{rs}^{-0.5}) \frac{2 g \mu_w m_s L}{V_s} V_t \]

(13)

To minimise power consumption, Equation (13) is differentiated with respect to \( V_t \) and let equal to zero. That is,

\[ k_o^2 V_t^3 - 3 k_o^2 V_{min}^2 V_t^2 + (3 k_o^2 V_{min}^2 V_t - (k_o^2 V_{min}^3) \]

(14)

Three roots of solution can be obtained from Equation (14). Actual calculations have found that two of them are complex and obviously unrepresentative of a real system. The real root is the mean superficial air velocity which minimises energy consumption. From Equation (14), it can be seen that this “economical” superficial air velocity is representative of a given conveyed material and pipe diameter. However, the corresponding “economical” value of \( m_t \) still is dependent on the mass flow rate of solids and pipe length (i.e., due to the air flow being compressible).

As an example, the superficial air velocities at the economical operating point are calculated as 2.76, 3.07 and 4.74 m s\(^{-1}\) for white plastic pellets, black plastic pellets and wheat according to Equation (14).

After the correlations for the prediction of total pressure drop are obtained, it is easy to obtain the economic operating points in terms of minimum energy consumption and low particle degradation.

### List of Symbols & Abbreviations

- \( a, \ldots, f \): Exponents in Equation (1)
- \( A \): Pipe cross sectional area, m\(^2\)
- \( A_{st} \): Cross sectional area of stationary layer, m\(^2\)
- \( D \): Pipe diameter, m
- \( d_p \): Median particle diameter, m
- \( F_{ri} \): Froude number at pick-up point
- \( F_{rs} \): Froude number of slug
- \( g \): Acceleration due to gravity, m s\(^{-2}\)
- \( k \): Coefficient in Equation (1)
- \( k_o \): Coefficient in Equation (14)
- \( L \): Total effective pipeline length, m
- \( L_s \): Total length of slugs, m
- \( l_s \): Single slug length, m
- \( m_f \): Air mass flow rate, kg s\(^{-1}\)
- \( m_s \): Product mass flow rate, kg s\(^{-1}\)
- \( m^* \): Product to air mass flow rate ratio, \( m^* = \frac{m_s}{m_f} \)
- \( N_b \): Number of 90° bends
- \( N_h \): Number of horizontal straight sections
- \( N_v \): Number of vertical lift sections
- \( P_n \): Nominal power, W
- \( R \): Centreline radius of 90° bends, m
- \( V_{li} \): Superficial air velocity at pick-up point, m s\(^{-1}\)
- \( V_{min} \): Minimum superficial air velocity for initiating motion of slug, m s\(^{-1}\)
- \( V_s \): Slug velocity, m s\(^{-1}\)
- \( \alpha \): Ratio of cross sectional area of stationary layer to pipe

6. Conclusions

Fine and granular products have significantly different pneumatic conveying characteristics. Fine products usually can be transported smoothly and reliably from dilute- to dense-phase. However, when granular products are conveyed between dilute- and dense-phase, significant fluctuations in pressure and vibration can occur along the pipeline.

When designing a pneumatic conveying system, it is very important to consider the differences in conveying performance of fine and granular products.

The correlations presented for the determination of the pressure minimum curve for fine powders and the boundaries between dilute-phase, the unstable zone and dense-phase for granular products and for the prediction of total pressure drop along horizontal sections of pipe have been demonstrated to provide good accuracy and reliability for the test materials and configurations of pipeline considered in this paper.
Pressure drop across a single slug, Pa
\[ \Delta P_t \]
Total pipeline air pressure drop, Pa
\[ \Delta P_{th} \]
Total pressure drop for horizontal pipeline, Pa
\[ \phi \]
Internal friction angle, °
\[ \phi_w \]
Wall frictional angle on bright mild steel, °
\[ \phi_s \]
Static internal friction angle, °
\[ \gamma_b \]
Bulk solid specific density
\[ \eta \]
Dynamic viscosity of air, N sm\(^{-2}\)
\[ \lambda \]
Stress transmission coefficient
\[ \mu_w \]
Wall friction coefficient, \( \mu_w = \tan \phi_w \)
\[ \epsilon \]
Bulk voidage, \( \epsilon = 1 - \frac{\rho_b}{\rho_s} \)
\[ \rho_b \]
Loose-poured bulk density, kg m\(^{-3}\)
\[ \rho_{li} \]
Air density at pick-up point, kg m\(^{-3}\)
\[ \rho_s \]
Particle density, kg m\(^{-3}\)
\[ \sigma_l \]
Stress on front face of slug, Pa
\[ \sigma_{rw} \]
Radial stress of slug at wall, Pa
\[ \sigma_s \]
Axial stress of slug, Pa

7. References

1) Pan, R., “Improving Scale-Up Procedures for the Design of Pneumatic Conveying Systems”, PhD Thesis, University of Wollongong, Australia, 1992.
2) Pan, R., Mi, B. and Wypych, P.W., “Design of Pneumatic Conveying Systems for Granular Bulk Solids”, Int. Conf. on Advanced Technology and Equipment of Materials Handling, Shanghai, P.R.China, October, 1994.
3) Murphy, G., “Similitude in Engineering”, The Ronald Press Company, New York, 1950.
4) Pan, R. and Wypych, P.W., “Scale-up Procedures for Pneumatic Conveying Design”, Powder Handling and Processing, Vol. 4, No. 2, 1992, pp 167-172.

5) Konrad, K. and Harrison, D., “Prediction of the Pressure Drop for Horizontal Dense Phase Pneumatic Conveying of Particles”, Pneumotransport 5, Int. Conf. on the Pneumatic Transport of Solids in Pipes, London, UK, April, 1980.
6) Legel, D., and Schwedes, J., “Investigation of Pneumatic Conveying of Plugs of Cohesionless Bulk Solids in Horizontal Pipes”, Bulk Solids Handling, Vol. 4, No. 2, 1984, pp 399-405.
7) Mi, B. and Wypych, P.W., “Investigations into Wall Pressure in Horizontal Slug-Flow Pneumatic Conveying”, Internal Research Report 93-05-BM-1, May, 1993, Department of Mechanical Engineering, University of Wollongong.
8) Mi, B. and Wypych, P.W., “Particle Slug Velocities in Horizontal Slug-Flow Pneumatic Conveying”, Powder Handling & Processing, Vol. 5, No. 3, 1993, pp 227-233.
9) Pan, R. and Wypych, P.W., “Pressure Drop due to Solid-Air Flow in Horizontal and Vertical Pipes”, 4th Int. Conf. on Bulk Materials Storage, Handling and Transportation, Wollongong, Australia, July, 1992.
10) Doig, I.D., “Dense-Phase Pneumatic Conveying”, Chapter 6 in Pneumatic Conveying of Solids, Leung, L.S. (Editor), Department of Chemical Engineering, University of Queensland, Australia, June, 1977.
11) Wypych, P.W., “Introduction to Pneumatic Conveying”, Chapter 1 in Design and Operation of Pneumatic Conveying Systems, Short Course Notes, ITC Bulk Materials Handling, University of Wollongong, Australia, July, 1989.
Author's short biography

Dr. Renhu PAN, BE, ME, PhD

Dr. Pan is a Fellow with the Department of Mechanical Engineering at the University of Wollongong, Australia. Dr. Pan has been involved with the pneumatic conveying of bulk solids since 1988 and his main interest is in the field of researching and developing new technologies for pneumatic conveying system design.

Mr. Bo MI, BE, ME

Mr. Mi received his BE and ME degrees in Mechanical Engineering from the University of Science and Technology Beijing, P.R. China. At present Mr. Mi is working for his PhD degree at the Department of Mechanical Engineering at the University of Wollongong. His main interest is in the areas of researching and developing new technologies for low-velocity pneumatic conveying of bulk solids.

Dr. Peter Wypych, BE, PhD, CPEng, MIEAust

Dr. Wypych is a Senior Lecturer with the Department of Mechanical Engineering at the University of Wollongong and has been involved with pneumatic transportation of bulk solids since 1981. Dr. Wypych also is a consultant of ITC Bulk Materials Handling and has been responsible for over 150 consulting projects assisting industry in the areas of design, trouble-shooting, system upgrading, feasibility studies, and new technology. As a result of this effort, Dr. Wypych has been responsible for setting up one of the largest and most advanced Bulk Solids Handling Laboratories in the World.