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Design Considerations of Long-Distance Pneumatic Transport and Pipe Branching

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1.0 INTRODUCTION

The pneumatic transportation of bulk solids through pipelines has been in existence for over one hundred years. Some of the earlier applications included the vacuum unloading of grain from ships and the extraction of sawdust from timber mills.

This method of conveying now is being selected for an increasing number of industrial applications and products and hence, is playing a more vital and integral role in numerous bulk handling operations and processes. Some of the major reasons are listed below.

• Enclosed, safe and environmentally attractive method of transport suitable to a wide variety of products, including those with bacteria-prone, toxic or explosive properties.
• Simple systems requiring a prime mover, a feeding device, a conveying pipeline and a cleaning or disengaging device (Marcus et al., 1990).
• Flexibility in pipeline layout.
• Ability to distribute product to a number of different areas within a plant and/or pick up material from several different locations.
• Low maintenance and manpower costs.
• Multiple use—a single pipeline can be used for a variety of products.
• Ease of automation and control.

Unfortunately, many new and old systems have not been designed properly and are being operated inefficiently. Some of the major consequences include high energy consumption, excessive system erosion, inadequate conveying capacity, unexpected pipeline blockages, excessive product damage and hence, poor quality control and/or increased maintenance. These problems have resulted mainly from

• A lack of appreciation of product properties and/or characteristics
• Inadequate and/or inaccurate design procedures
• Selecting unsuitable hardware and/or mode of transport (Wypych, 1995a)
• Improper commissioning and/or operation of the plant

A significant number of developments have occurred over the past decade to address these important issues of pneumatic conveying (Wypych, 1995a). This chapter summarizes some of the major design considerations that have resulted from this work in relation to long-distance and pipe branching applications.

2.0 LONG-DISTANCE PNEUMATIC CONVEYING

With the advent of high-pressure feeders after World War II (e.g., blow tanks, screw pumps), many designers and users began to apply pneumatic conveying to much greater distances and/or capacities (e.g.,
L \geq 1 \text{ km and/or } m_i \geq 100 \text{ th}^{-1}). \text{ However, in many cases, this resulted in various problems, such as}

- higher than expected pressures and energy consumption,
- excessive transport velocities, system erosion (e.g., pipes, bends) and product damage,
- low system reliability (mainly due to premature failure of valves and instrumentation),
- inadequate conveying capacity, and/or
- unexpected material buildup and/or blockages along the pipeline.

These problems in turn were hampering the successful design and/or operation of long-distance pneumatic conveying systems and hence, the future potential of this method of transport to a wide variety of industries.

To overcome these problems, a number of interesting developments in research and technology have occurred over recent years and these have resulted in the following important design considerations.

- Characterization and classification of the material(s) to be conveyed.
- Improved blow tank design to ensure an efficient and controlled discharge rate of material.
- New test-design procedures for the accurate prediction of pipeline pressure drop, including the effects due to horizontal/vertical flow and bends.
- Stepped-diameter pipelines to minimize pressure drop, velocity, wear and power consumption.
- Reliable valves for blow tank filling, venting and discharge.
- Manual or automatic back-pressure unblocking of conveying pipelines.

2.1 Product Characterization and Classification

The characterization and classification of bulk solids is becoming an increasingly important design requirement to assess the suitability of
pneumatically conveying a material over long distances. The current trends and experiences indicate that the major influential parameters include

- Particle size and distribution
- Particle density, bulk density and particle shape
- Cohesive, wet, sticky and/or electrostatic properties (if applicable)
- Temperature of product and carrier gas
- Permeability (or fluidization) and deaeration characteristics of the material (Mainwaring and Reed, 1987; Jones and Mills, 1989), which depend strongly on the above parameters

Possibly, the most difficult aspect of determining particle size is selecting initially the correct or relevant definition and then calculating a mean or average diameter to represent the complete bulk solid. To some extent, this will depend on the following.

- The measuring apparatus and its principle of operation
- The final application or requirements (e.g., determination of free-settling velocity \(v_\infty\), minimum fluidization velocity \(V_{mf}\), minimum transport velocity \(V_{fmin}\), and/or pipeline air pressure drop \(\Delta p_t\))
- The basis of definition used in a theoretical or empirical relationship (e.g., sieve or volume measurement)

In some cases, especially for very fine powders, researchers have looked at other properties to explain or classify product behavior. For example, Geldart et al. (1984) have found that the ratio of “tapped” to “aerated” bulk density provides a good indication of the likely fluidization characteristics of fine and cohesive powders.

However, this section pursues particle size measurement and evaluates its importance (as well as density) for the purpose of classifying the suitability of powders for long-distance pneumatic conveying applications. Initially, an appreciation of the fundamentals and the existing powder classification techniques is required.

**Physical Properties.** To determine or calculate particle size, it is important to be aware of the following different definitions and related properties (Geldart and Abrahamsen, 1981; Allen, 1975).
\[ d_p = \text{Arithmetic mean of adjacent sieve sizes.} \]
\[ d_{pm} = \text{Mean particle size from a standard sieve analysis,} \]
\[ \frac{\sum (\Delta M)}{d_p} \]

where \( \Delta M \) is the mass percent of product between adjacent sieves.

\[ d_{pwm} = \text{Weighted mean diameter (Allen, 1975) based on sieve analysis,} \]
\[ \frac{\sum (\Delta M d_p)}{\sum (\Delta M)} \]

\[ d_{sv} = \text{Diameter of a sphere with the same surface area to volume ratio as the particle.} \]
\[ d_{svm} = \text{Mean surface volume diameter,} \]
\[ \frac{\sum (\Delta M)}{\Delta M d_v} \]

\[ d_v = \text{Diameter of a sphere with the same volume as the particle.} \]
\[ d_{vm} = \text{Mean (equivalent) volume diameter,} \]
\[ \frac{\sum (\Delta M)}{d_v} \]

\[ d_{vwm} = \text{Volume weighted mean diameter (Allen, 1975),} \]
\[ \frac{\sum (\Delta M d_v)}{\sum (\Delta M)} \]
\[ d_{50} = \text{Median particle diameter (Allen, 1975).} \]

\[ d_{50} = d_{v50} \text{ for a volume diameter distribution.} \]

\[ d_{50} = d_{p50} \text{ for a sieve size distribution.} \]

\[ \Psi = \text{Particle sphericity (Geldart and Abrahamsen, 1981).} \]

\[ \Psi = \text{Eq. (6)} \frac{d_{sv}}{d_v} \]

Assuming the following results of Geldart and Abrahamsen (1981) and knowing (or assuming) appropriate values of sphericity, the various diameters \(d_{sv}, d_{v50}, d_{p50}, \) and \(d_{vm}\) may be determined for any given material. This information is particularly useful when it becomes necessary to compare the classification of different bulk solids, whose size distributions were determined on different machines or using different techniques (e.g., sieve analysis, volume-based measurement).

\[ 1.1 < \frac{d_v}{d_p} < 1.2, \quad \text{Average } \frac{d_v}{d_p} = 1.127 \]

Some typical values of sphericity are listed below.

- Pulverized coal \( \psi \approx 0.56 \) (angular)
- Cement \( \psi \approx 0.59 \) (angular)
- PVC powder \( \psi \approx 0.81 \) (irregular spheroids)
- Calcined alumina \( \psi \approx 0.84 \) (coarse spheroids)
- Hydrated alumina \( \psi \approx 0.86 \) (rough spheroids)
- Fly ash \( \psi \approx 0.90 \) (approximate spheres)

After determining the relevant physical properties (i.e., particle size, solids particle density and bulk density), the next step is to evaluate some of the existing techniques of powder classification.
**Powder Classification Techniques.** The Geldart (1973) fluidization, and Dixon (1981) slugging classifications have been found useful in explaining:

- some of the feeding problems that can occur in blow tank feeders (Wypych and Arnold, 1986a),

- the differences that can occur in flow performance and minimum transport behavior (Wypych and Arnold, 1984).

Modifications to the Geldart (1973) fluidization diagram have been proposed by Molerus (1982) and Zenz (1984), but are not considered here as they require some knowledge or measurement of particle adhesion forces and bulk surface tension, respectively. That is, detailed investigations into evaluating and/or developing such fluidization diagrams are beyond the present scope of work.

Another useful classification technique that makes use of two different bench-type experiments (i.e., permeability and deaeration) has been presented by Mainwaring and Reed (1987). The above three classifications are described in the following sections.

**Geldart (1973) Fluidization Classification.** An “ideal” fluidization curve is presented in Fig. 1, which also shows schematically a typical fluidization test chamber (with the relevant variables $\Delta h$, $\Delta p$ and $V_f$). Also, the method of determining $V_{mf}$ (i.e., using the “Air-Decrease Test”) is demonstrated in Fig. 1. However, due to varying material properties (e.g., cohesion, wide size distribution), the “actual” variation of pressure in a fluidized bed may be quite different to that shown in Fig. 1 (Anon., 1983). Such information can be useful in providing further insight into a material’s behavior with air, which is important for pneumatic conveying, especially when long distances are involved.

Using fluidization data obtained from several researchers, Geldart (1973) characterized powders into four groups (i.e., A, B, C and D), according to their fluidization behavior and developed a classification diagram, as shown in Fig. 2. Note that $\rho_f$ is the “operating” air density. The interested reader is directed to the Geldart (1973) paper for detailed descriptions of the various groups (including a numerical technique to distinguish between each one), and the Geldart et al. (1984) paper for more recent investigations into the fluidization of cohesive powders.
Figure 1. “Ideal” fluidization curve, showing typical test chamber and relevant parameters $\Delta h$, $\Delta p$, $V_f$ and $V_{mf}$.

Figure 2. Fluidization Classification Diagram. (Geldart, 1973.)
The classification diagram of Geldart (1973) was never intended to predict pneumatic conveying behavior. However, it has been accepted by many researchers that the aeration and fluidization characteristics of bulk solids are important parameters in determining dense-phase suitability, such as fluidized dense-phase and low-velocity slug-flow (Wypych, 1995a). Based on experience and as explained later, this information is useful also in evaluating qualitatively a material’s performance over long distances. Hence, it is important to appreciate the differences between the following four categories, as proposed by Geldart (1973).

**Group A** powders show a limited tendency to form bubbles and generally exhibit considerable bed expansion between the minimum fluidization velocity \( V_{mf} \) and the minimum bubbling velocity \( V_{mb} \). These powders also retain aeration and the fluidized bed collapses very slowly when the gas is turned off.

**Group B** materials fluidize readily and tend to form bubbles, which grow rapidly by coalescence. However, bed expansion is small. That is, the minimum bubbling velocity, \( V_{mb} \), usually is approximately equal to (or only slightly greater than) the minimum fluidizing velocity \( V_{mf} \). The fluidized bed does not retain its aeration and collapses quickly when the gas supply is removed.

**Group C** powders are of small particle size, cohesive by nature and hence, difficult to fluidize. Either the fluidized bed lifts as a solid plug of material or forms stable channels of air flow, which allows the fluidizing gas to escape. The latter phenomenon is referred to simply as “channelling”. It may be possible to fluidize such powders by mechanical agitation (e.g., stirring, vibration).

**Group D** products generally are of large particle size and/or very high solids particle density. In some respects, fluidization behavior is similar to Group B, although higher gas velocities are required for fluidization.

Note the “mean diameter” used by Geldart (1973) is actually a *surface volume mean diameter* \( d_{svm} \), based on Eq. (3). However, comparing the fluidization curves of several materials with the Geldart (1973) diagram (e.g., fly ash, pulverized coal, coarse ash, PVC powder and screened coke), Wypych (1989b) found the following:
• The reciprocal form of particle size definition, i.e., Eqs. (1), (3) and (4), tends to “overemphasize” the influence of the finer particles (i.e., in terms of the Geldart [1973] classification descriptions),

• The weighted or product type of definition, i.e., Eqs. (2) and (5), tends to “under-emphasize” the influence of the finer particles (or overemphasize the coarse end of the size distribution),

• The relatively wide particle size distributions of the pulverized coal and fly ash (e.g., 1 µm to 200 µm) seem to be the major contributing factor to the effects described above (i.e., the materials tested by Geldart [1973] had fairly narrow size distributions),

• The discrepancies described above are not so apparent for PVC powder, which had a relatively narrow size distribution (i.e., with respect to fly ash and pulverized coal),

• The median particle diameter, \( d_{50} \), seems to provide a better indication of fluidization performance, as described by Geldart (1973).

Therefore, based on the results of Wypych (1989b), the Geldart (1973) classification diagram does seem to provide a reasonable technique for predicting fluidization behavior (i.e., using \( d_{50} \) instead of \( d_{50} \) for products having a wide particle size distribution). However, it should be noted that when Geldart proposed his classification diagram, he suggested a shaded boundary region between Groups A and C. This indicates that some degree of overlap may exist between the two categories (i.e., some typical Group C powders could display Group A performance, or vice-versa). However, for the following reasons, it is believed that ultimately the actual product(s) should be tested in a large-scale fluidization test rig (e.g., similar to the one shown in Fig. 1), so that actual characteristics and behavior may be established and confirmed.

• Perhaps the greatest difficulty in predicting fluidization performance via the Geldart (1973) classification is deciding on a single diameter to represent the complete material, especially if the product possesses a wide particle size distribution. This is supported to some extent by the more recent bulk density approach proposed by Geldart et al. (1984).
There is some doubt over the location of the boundary separating Groups A and C. The particle size versus density relationship proposed by Geldart (1973) may not be sufficient to define these regions. For example, refer to Geldart et al. (1984).

Products lying close to a particular boundary may exhibit fluidization behavior from either one of the adjoining categories (e.g., a product which is in close proximity of the A-B boundary may exhibit characteristics from either Group A or B). It is difficult to estimate the “error” or “tolerance” associated with each boundary (e.g., between Groups A and B, or B and D).

Appreciating the possible limitations of the Geldart (1973) classification diagram, this technique still provides a good initial indication of what to expect when a given product is fluidized or mixed with air. Even though fluidization may be confirmed by experiment and used subsequently in the design of feeders (e.g., to establish possible rat-holing problems inside a blow tank, Wypych and Arnold, 1986a), the application of such information to predicting pneumatic conveying performance is a different matter and in fact, has been found to be inadequate (Wypych and Arnold, 1986b; Lohrmann and Marcus, 1984).

**Dixon (1981) Slugging Classification.** In an attempt to describe the natural behavior of different solids in dense-phase, Dixon (1979) developed theoretical slugging diagrams for different pipe diameter systems on the basis of the Geldart (1973) fluidization classification diagram (i.e., Groups A, B, C and D). Although Dixon’s diagrams were based on slugging criteria (Yang, 1976) for vertical transport, he indicated that they also generally support the observed behavior of materials in horizontal pipes. However, Dixon (1981) stated that there is some doubt over the location of the boundary between Groups A and C, and he subsequently reproduced this Geldart boundary directly onto the slugging diagrams. Refer to Figs. 3 and 4 for examples of slugging diagrams for 50 and 100 µm NB pipe diameter systems. For detailed descriptions of the various slugging classifications and the mathematical formulae to distinguish between each category, the reader is referred to the papers (Dixon, 1979; Dixon, 1981).
Figure 3. Slugging diagram for 50 mm pipe diameter system. (Dixon, 1981.)

Figure 4. Slugging diagram for 100 mm pipe diameter system. (Dixon, 1981.)
A brief description of each of the four “slugging” categories, as suggested by Dixon (1979) is listed below.

**Group A** powders are the best candidates for dense-phase conveying and can achieve high solids/gas loadings. Note the “dense-phase” referred to here actually is “fluidized dense-phase” (Wypych, 1995a).

**Group B** powders can be troublesome (e.g., severe pipe vibrations) if high solids/gas loadings are contemplated.

**Group C** products arguably are the worst candidates for (fluidized) dense-phase conveying. This can be attributed to their poor fluidization characteristics. If these can be overcome, and it is possible that not all Geldart (1973) Group C powders possess poor fluidizing characteristics, then they should show the good performances attributable to Group A powders.

**Group D** materials are also good candidates for dense-phase conveying. Although they have relatively low solids/gas ratios (i.e., compared with Group A powders), they probably can be conveyed at higher loadings than Group B materials. Note the “dense-phase” referred to here actually is “low-velocity slug-flow” (Wypych, 1995a).

The following comments are based on the findings of Wypych (1989b) who compared the actual conveying characteristics of several materials with the slugging classifications of Dixon (1979) and Dixon (1981).

- For a product that is well contained “inside” a particular group (i.e., A, B, C or D), the Dixon (1981) slugging diagram and classifications generally provide a good initial indication of what to expect when the product is conveyed in the dense-phase mode.

- It is believed that the one main factor that will “upset” the suggestions of Dixon (1979, 1981) is particle size distribution. Note that a similar problem was described earlier for the Geldart (1973) diagram. Also, it is quite possible that differences in “particle shape” could contribute to this effect. For example, Dixon (1979, 1981) based most of his suggestions and observations on plastic powders and granules (i.e., relatively smooth particles with narrow size ranges).
• Materials that lie close to or are on a classification boundary may exhibit slugging behavior from either one of the adjoining categories. This could be explained further by the “particle size distribution” problem or limitation described above.

• The “particle to pipe diameter” ratio may be an influential parameter in predicting dense-phase performance. For example, this diameter effect was noticed recently when the good dense-phase (low-velocity slug-flow) performance of a granulated sugar in a 105 mm diameter pipeline could not be repeated in a 155 mm diameter pipeline. The shift to the “right” of the Group B-D boundary (i.e., as seen in Figs 3 and 4) with increasing pipe diameter would explain this difference in performance.

• The change in slugging characteristics of a given material due to increasing or decreasing operating pressure is difficult to confirm.

To emphasize some of the above comments and suggestions (as well as some of those presented earlier in relation to the Geldart [1973] diagram), the PVC powder results (Wypych, 1989b) are summarized below.

• PVC powder: \(d_{v50} = 152 \mu m, \rho_s = 1400 \text{ kg m}^{-3}, \rho_{bl} = 575 \text{ kg m}^{-3}\)

• According to the fluidization diagram presented in Fig. 2, PVC powder was found to be classified as Geldart (1973) Group A (although close to the A-B boundary). Testing the product in a fluidization rig (Wypych, 1989b) confirmed the good fluidization characteristics suggested by Geldart (1973). This result was supported by the material’s excellent air-gravity conveying performance (Wypych and Arnold, 1985a). Based on these results, it would be reasonable to assume that this material would be suited to fluidized dense-phase.

• However, the PVC powder was tested in a 52 mm internal diameter pipeline, 71 m in length, and found to exhibit unstable plugging in the vicinity of saltation or minimum pressure (i.e., prior to the fluidized dense-phase region). That is, dilute-phase transport was only possible on this test rig. Also, solids/gas loadings were quite low (e.g., max \(m^* = 20\)). Note that the unstable plugging was accompanied by sudden increases in pressure and severe pipe vibrations.
These unexpected results were confirmed by the Group B classification of Dixon (1979, 1981), (i.e., could be troublesome in dense-phase and produce severe pipe vibrations).

The above results demonstrate the danger of predicting the suitability of dense-phase based on only fluidization characteristics. Similar limitations have been observed by Lohrmann and Marcus (1984) with three Geldart (1973) Group A materials. In contrast, the Group B suggestions of Dixon (1979, 1981) not only confirm the observed minimum transport behavior (e.g., pipe vibrations, require high velocities), but also seem to explain the observed (Wypych, 1989b) flow behavior (i.e., dunes growing to fill the pipe causing the high velocity slugs of air to force their way through the material).

The apparent anomaly between poor dense-phase performance and good fluidization characteristics (as suggested by the PVC powder results) seems to be explained by the property of deaeration. That is, although this material displayed good fluidization characteristics and is classified as Geldart (1973) Group A, it was found to deaerate quickly. For example, on several occasions the expanded bubbling bed was seen (Wypych, 1989b) to lose its height in less than one second (i.e., after the fluidizing air was removed). On the other hand, “good” dense-phase materials, such as pulverized coal and fly ash, usually display excellent fluidization characteristics but also retain their aeration for considerable lengths of time (e.g., 10 to 30 minutes).

**Mainwaring & Reed (1987) Classification Diagrams.** The empirical classification technique proposed by Mainwaring and Reed, 1987, emphasizes the importance of permeability (obtained from a fluidization test) and deaeration. Jones and Mills, 1989 came to a similar conclusion and suggested further that the ratio of tapped to poured bulk density provides a good indication of the air retentive properties of a given material. Also, Geldart et al., 1984 proposed a similar ratio to distinguish between Group A and Group C powders.

The classification technique (Mainwaring and Reed, 1987) basically consists of two empirically-based diagrams, as shown in Figs. 5 and 6. To use these graphs, the following factors need to be determined.

- Pressure drop per unit length of bed, $\Delta p/\Delta h$, see Fig. 1.
- Value of $\Delta p/\Delta h$ at minimum fluidization, $(\Delta p/\Delta h)_m$, see Fig. 1.
- Permeability factor, $\kappa_p = A/B = V_f/(\Delta p/\Delta h)$, Fig. 1.
• \( V_{mf} = \kappa_p (\Delta p/\Delta h)_{mf} \).
• Deaeration factor, \( \kappa_d = t(\Delta p/\Delta h) \), where \( t \) = time taken for a deaerating bed to reach a pressure drop per unit length of \( \Delta p/\Delta h \).
• Factor, \( X = (\kappa_d/\rho_p)/(\Delta p/\Delta h) \).

Figure 5. Pressure drop per unit length versus permeability factor. (Mainwaring and Reed, 1987.)
Figure 5 is a plot of permeability factor $k_p$ versus $(\Delta p/\Delta h)_{mf}$ and contains the boundary $V_{mf} = 50$ mm s$^{-1}$. Figure 6 is a plot of $k_d/\rho_s$ versus $(\Delta p/\Delta h)_{mf}$ and contains the boundary $X = 0.001$ m$^3$ s kg$^{-1}$. By using both Figs. 5 and 6, it is possible to propose the following three criteria relating to the potential modes of pneumatic conveying in conventional pipelines.
• If for a given material, $V_{mf} > 50 \text{ mm s}^{-1}$ (i.e., above the boundary shown in Fig. 5) and $X < 0.001 \text{ m}^3 \text{s kg}^{-1}$ (i.e., below the boundary shown in Fig. 6), then dense-phase low-velocity slug-flow (Wypych, 1995a) is possible (e.g., mustard seed, polyethylene powder, 1000 µm sand, polyethylene pellets and granulated sugar). Note that dilute-phase also is possible.

• If $V_{mf} < 50 \text{ mm s}^{-1}$ and $X > 0.001 \text{ m}^3 \text{s kg}^{-1}$, then fluidized dense-phase (Wypych, 1995a) is possible (e.g., cement, pulverized coal, flour, fly ash). Note that dilute-phase also is possible.

• If $V_{mf} < 50 \text{ mm s}^{-1}$ and $X < 0.001 \text{ m}^3 \text{s kg}^{-1}$, then “fluidized” dense-phase or low-velocity slugging flow is not possible in a conventional pipeline (e.g., slate dust, zircon sand, fly ash grits). That is, single-slug conveying (Wypych, 1995a), bypass conveying (Wypych, 1995a) or dilute-phase may have to be considered for these materials.

**Application to Long-Distance Pneumatic Conveying.** From the above three classifications, there is sufficient evidence to suggest that powder classification (i.e., to select ultimately the most suitable mode of conveying for a given product and its behavioral properties) depends on the following properties:

• Particle size distribution and density.
• Particle shape or sphericity (as indicated by the definitions of diameter).
• Deaeration and permeability.
• The ratio of tapped to poured (or perhaps fluidized) bulk density.
• Diameter of conveying pipeline or particle to pipe diameter ratio.

Also, it seems that most of these properties are interdependent. For example, deaeration and permeability (Mainwaring and Reed, 1987) and perhaps the bulk density ratio (Jones and Mills, 1989) seem to provide an adequate mechanism to detect changes in material performance due to different particle size distribution, density and/or shape. However, possibly the greatest disadvantage or limitation of these empirical techniques is the need to standardize the experimental apparatus and techniques. For exam-
ple, the measured values of deaeration rate depend on the size of the plenum chamber and to some extent the type of gas distributor. Also, different devices and techniques are available to determine vibrated or tapped bulk density. Standardization is necessary so that the results will be applicable on an international level and can be used/compared by other researchers.

Based on the previous classifications and discussions, as well as the author’s own experiences, it is suggested that the following design procedure and considerations be adopted to provide an initial indication of dense-phase suitability, which as described below also has been found useful in assessing conveying performance over long distances.

- For a given bulk solid, determine particle size distribution, median particle diameter $d_{50}$ (e.g., using a Coulter Counter or a Malvern Laser Diffraction Analyser) and $\rho_s$.

- Classify the bulk solid according to the Geldart (1973) fluidization diagram. This information is useful in estimating say, potential rat-holing problems inside blow tanks. If the material is relatively close to a classification boundary, then expect fluidization behavior from either one of the adjoining groups.

- Test the bulk solid in a fluidization chamber to confirm both the Geldart (1973) classification and the material’s air retention properties (i.e., by undertaking deaeration experiments).

- Classify the bulk solid according to the Dixon (1979, 1981) slugging diagram that matches the existing or proposed diameter of pipeline. Based on the research and consulting experience of the author, the following possibilities are proposed in relation to the Dixon (1979) classifications.
  - Typical Group A materials (e.g., cement, baghouse fly ash, pulverized coal, carbon fines) are the best candidates for “fluidized” dense-phase (Wypych, 1995a) and long-distance pneumatic conveying. It is possible to achieve high values of solids/gas loading (e.g., $m^* = 150$ over 200 m; $m^* = 25$ over 1 km). These materials retain their aeration for considerable lengths of time.
— Typical Group B materials (e.g., alumina, PVC powder, fine sand, castor sugar) may cause serious problems in fluidized dense-phase (e.g., unstable plugging, severe pipe vibrations, high pressures) and hence, may need to be transported in dilute-phase over long distances (i.e., using conventional pipelines). It still may be possible to convey these materials in “dense-phase” using low-velocity slug-flow or bypass pipelines (Wypych, 1995a). Also, for the coarser Group B materials (e.g., fine sand, castor sugar), it may be possible to consider the alternative of single-slug dense-phase conveying (Wypych, 1995a). Of these three options, bypass conveying is preferred when long distances are involved, especially when $L > 500$ m.

— Typical Group C materials (e.g., precipitator fly ash, lead fume, zinc dust) may behave like Group A powders (i.e., good fluidized dense-phase or long-distance performance). However, these materials can be quite cohesive and it is important to ensure buildup problems do not occur inside the blow tank feeder or along the pipeline. For example, precipitator fly ash with $d_{50} \approx 10$ µm has been conveyed successfully and efficiently over long distances, whereas lead fume with $d_{50} = 5$ µm has been found to cause buildup and eventual blockage problems inside the pipeline. Flexible hoses or “collapsible” pipelines may be used to prevent this buildup of material. Another option is to consider low-velocity plugging using either an air-knife at the beginning of the pipeline or a bypass conveying pipeline. In some cases, the plugs tend to be “self-cleaning”. However, these options do not become practical over long distances and must be considered carefully in terms of capital and maintenance costs.

— Many typical Group D products (e.g., wheat, rice, sugar, plastic pellets, cereals, barley, malt, agglomerated milk powder) have relatively narrow
size distributions, high permeability and display natural slugging ability (Wypych and Hauser, 1990) and good low-velocity slug-flow (Wypych, 1995a). However, this mode of flow usually is limited to conveying distances of $L < 500$ m. The Group D materials that possess wide size distributions (especially a considerable amount of fines) and/or unusual particle shape (e.g., crushed coal, petroleum coke, crushed bath, rice hulls) usually are not suited to low-velocity conveying. In these cases, the options are dilute-phase or single-slug dense-phase (i.e., these materials usually are too coarse for bypass conveying). However, when long distances are involved, dilute-phase may be the only practical option.

— If any material is in the vicinity of a classification boundary (i.e., Group A-B or Group B-D boundary), then due to particle size distribution it is possible that the material may exhibit flow behavior or performance from either one of the adjoining categories.

**Case Study.** The above approach was applied recently to investigations into blockage problems occurring on a long-distance pneumatic conveying system handling baghouse fly ash at a coal-fired power station. It was reported by the operator that the blockages

- occurred mainly at the beginning of the pipeline,
- were accompanied by severe pipe vibrations,
- eventually cleared themselves after a period of time.

During a site inspection it was found that in between baghouse cleaning cycles, each blow tank was allowed to be filled with the coarser particles falling through the dust collection hopper. A sample of material was collected directly from a blockage inside the pipeline and also from the receiving silo which contained the conveyed product. The physical properties of the “successful” (fine) material were found to be $d_{50} \approx 15$ μm, $\rho_s \approx 2200$ kg m$^{-3}$ and $\rho_{bl} \approx 900$ kg m$^{-3}$, and for the “troublesome” (coarse) material $d_{50} = 100$ μm, $\rho_s \approx 1900$ kg m$^{-3}$ and $\rho_{bl} = 800$ kg m$^{-3}$. Note a considerable amount of unburnt particles was observed in the latter sample.
and this explained the somewhat lower value of $\rho_s$. As a result of applying the powder classification techniques (Geldart, 1973; Dixon, 1981) and the other suggestions made in this chapter, it was found that

- the fine ash was classified as a Group C powder—this material was conveyed successfully in fluidized dense-phase over long distances,
- the coarse ash was classified as a Geldart (1973) Group A material—subsequent fluidization tests confirmed good fluidization characteristics but poor air retention properties (i.e., the material deaerated quickly as soon as the fluidizing air was removed),
- the coarse ash according to Dixon (1981) was classified as Group B in a 50 mm NB pipe system and was located on the Group A-B boundary in a 100 mm NB pipe system (i.e., refer to Figs. 3 and 4).

Based on these findings as well as the nature of the blockages, the coarse ash was considered as a typical Dixon (1981) Group B material (i.e., troublesome in fluidized dense-phase causing severe pipe vibrations). It was recommended to the power station that the baghouse operating sequence be changed in such a way to ensure the blow tanks were filled only during the cleaning cycle. This change was made easily via the control system and the plant has been operating successfully since this time.

### 2.2 Blow Tank Design

Some typical "conventional" blow tank designs are illustrated in Fig. 7. This type of feeder has been used successfully in industry to handle a wide range of products over relatively short distances (e.g., $L = 100$ to 200 m). However, the application of this type of blow tank to greater distances and/or capacities (usually in conjunction with a second blow tank unit in series or parallel to ensure an essentially continuous mode of flow) resulted in a number of problems.

- Incomplete and/or inefficient discharge of material from each blow tank mainly due to rat-holing or funnel-flow effects promoted by
  - low pressure drop across the bed of material (under steady-state conditions),
Figure 7. “Conventional” blow tank feeders: (a) bottom-discharge arrangement; (b) top-discharge arrangement.
— cohesive properties of the bulk solid, and/or
— inappropriate method of blow tank air injection (e.g., single-point injection, excessive top-air promoting material compaction),

- Flow instabilities or even pipeline blockage during start-up procedures due to surge effects caused by the initial high pressure drop across the blow tank (and hence high instantaneous flow rate of material),

- Pipeline blockage during shutdown procedures due to surge effects caused by the sudden venting of high pressure air down the pipeline (and hence, acceleration of product towards the end of the pipeline).

To avoid these problems, a number of significant developments have occurred in the area of blow tank design, such as:

- Cone-dosing valve (Cürtén, 1982) to control and meter the product into the pipeline. This is achieved by the movement of a double cone in the vicinity of the blow tank outlet. The cone moves continuously up and down inside the vessel but the stroke is adjusted by a proportional-integral (PI) controller based on a conveying line back-pressure measuring signal and set-point. The higher the conveying or operating pressure, the lower the cone set point inside the vessel thus restricting the flow of solids into the conveying pipeline (until a satisfactory conveying pressure is restored). Furthermore, the cone dosing system provides an additional and useful feature of mechanical agitation (and hence, flow assistance) of materials possessing cohesive and/or poor flow properties, such as manganese oxide (Wypych, 1989a).

These developments have resulted in a much more reliable and efficient blow tank feeding system, especially for long-distance applications, as shown in Fig. 8. Such systems now have been used successfully in many installations throughout Australia to meet the increasingly demanding requirements of conveying capacity and distance.
Figure 8. Preferred tandem blow tank feeding system for long-distance pneumatic conveying.

Note, other options to control the discharge of material from the blow tank feeder include a rotary valve and an oscillating or modulating valve (Marcus, et al., 1980), as shown in Figs. 9 and 10, respectively. However, the former option requires special start-up and shutdown procedures (e.g., minimizing pressure drop across the valve) and is limited to low-temperature and low-abrasive applications. Also, the valve needs to be designed to handle high static pressures and will add to the capital and maintenance cost of the system. The latter option of using a modulating valve will increase maintenance costs, especially if the same valve is used for blow tank isolation.

It should be realized also that either option shown in Fig. 9 or 10 will produce a non-symmetrical flow pattern inside the blow tank (i.e., due to preferential feeding at the blow tank outlet) and hence, promote the possibility of arching, rat holing and/or formation of dead regions. For these reasons, the combined fluidizing-discharge-cone and cone-dosing valve system shown in Fig. 8 is preferred.
Case Study. As a part of the initial design of two 350 MW units for a coal-fired power station, it was required to:

- collect all the ash from the electrostatic precipitators and economizers,
• transfer this material at \( m_s = 100 \text{ t h}^{-1} \) over a total distance of \( L = 1.5 \text{ km} \) to a final storage silo, and

• provide a fly ash resale facility outside the boundaries of the power station (i.e., to enable easy access for the contractors to pick up and deliver the ash to various cement plants).

Tandem 7 m³ bottom-discharge cone-dosing blow tanks, similar to those shown in Fig. 8, were employed for this purpose and also to regulate the feed of material into the pipeline and alleviate the occurrence of imminent blockages (Wypych, 1995b).

2.3 Conveying Characteristics

When it is necessary to design or evaluate a proposed pneumatic conveying system, it is recommended strongly that the designer obtain as much information as possible on the actual material(s). Armed with the knowledge of steady-state conveying characteristics, it is quite a simple task to determine the minimum conveying velocity, optimal operating conditions for the product, and the pipeline diameter and compressor/blower rating to suit a given \( m_s \) and \( L \).

Alternatively, conveying characteristics may be used to investigate operational problems that an existing plant may be experiencing (e.g., frequent blockages, reduced conveying rates). Problems of excessive product degradation and/or system wear also may be minimized by using such information to establish a safe minimum value of \( m_s \) for a given \( m_t \). That is, conveying characteristics will determine whether an existing plant is operating at an optimal condition. If not, they will reveal what modifications would be necessary to achieve the desired result.

Conveying characteristics also will provide useful information when an existing plant needs to be upgraded to achieve say, a higher conveying rate of solids. For example, it will be possible to determine whether the system and the material will be able to cope with the increased pressure and/or air flow requirements (i.e., whether the combination of pipe size and blower/compressor rating will be sufficient).

The determination of steady-state conveying characteristics for a given product and test rig has been the subject of a number of earlier investigations such as Mason et al. (1980) and Mills et al. (1982). A standardized test procedure also has been developed and presented by
Wypych and Arnold (1985b) and hence, only a brief description is presented here. The test procedure basically consists of three different types of experiments which are applied to the material until sufficient data have been collected for the determination of conveying characteristics. The steady-state parameters generated specifically for this purpose are

- $m_f = \text{Supplied mass flow rate of air (kg s}^{-1}\text{)},$
- $\Delta p_t = \text{Total pipeline air pressure drop (kPa)},$
- $m_s = \text{Mass flow rate of solids or conveying rate (kg s}^{-1}\text{ or t h}^{-1}\text{)}$.

Some typical examples of pneumatic conveying characteristics for three different fly ash samples conveyed on the same long-distance test rig are presented in Figs 11, 12 and 13. Some important information regarding these materials and results is summarized below.

- **Fly Ash A1 (Fig. 11):** $d_{50} = 5 \mu\text{m}, \rho_s = 2540 \text{ kg m}^{-3}, \rho_{bt} = 670 \text{ kg m}^{-3}$, Geldart (1973) and Dixon (1981) Group C material.
- **Fly Ash A2 (Fig. 12):** $d_{50} = 75 \mu\text{m}, \rho_s = 2500 \text{ kg m}^{-3}$ and $\rho_{bt} = 1175 \text{ kg m}^{-3}$, Geldart (1973) Group A material but Dixon (1981) Group B material. The latter was confirmed by the nature of the blockages obtained on the test rig (e.g., severe pipe vibrations), as well as the rapid observed deaeration rate of the material.
- **Fly Ash B (Fig. 13):** $d_{50} = 12 \mu\text{m}, \rho_s = 2215 \text{ kg m}^{-3}$ and $\rho_{bt} = 955 \text{ kg m}^{-3}$, Geldart (1973) and Dixon (1981) Group C material. It is interesting to see how much lower the pressures are for this material compared with Fly Ash A1.

A company was intending to transport Fly Ash A2 through a long-distance conveying system that was designed to handle $45 \text{ t h}^{-1}$ of Fly Ash A1. From Figs 11 and 12, it can be seen quickly that A2 would have required almost twice as much air than A1 and hence, a significant increase in running costs and possibly wear.

The above three conveying characteristics demonstrate the wide range of performances that can occur for fly ash and hence, the importance of employing such information in the design and optimization of long-distance systems.
Figure 11. Test rig conveying characteristics of fly ash A1, \( L = 945 \) m, \( D = 69/81 \) mm and \( r = 1 \) m.

Figure 12. Test rig conveying characteristics of fly ash A2, \( L = 945 \) m, \( D = 69/81 \) mm and \( r = 1 \) m.
2.4 Pressure Drop Prediction

For long-distance and/or large-throughput applications, it is essential to predict accurately the total pipeline air pressure drop, $\Delta p_t$. For example, even with a “good” existing model predicting say, $\Delta p_t = 500 \text{ kPa} \pm 30\%$, the resulting uncertainty still would be too great (i.e., 350 to 650 kPa) and could lead to serious operating problems (e.g., inadequate capacity, pipeline blockage). Also, various major deficiencies exist with current models, such as the following:

- Existing correlations usually are based on low values of air density, whereas $\rho_f$ can have a significant effect on $\Delta p_t$.
- Products that are suited to long-distance transportation usually have a wide range of particle size (e.g., fly ash, $d = 1 \text{ to } 300 \mu\text{m}$), and it is difficult to represent adequately such materials by the single diameter required by most models.
- Most existing models are suited only to “pure” dilute-phase or dense-phase (high $m^*$) applications, whereas the possible modes of flow over long distances occur between these two extremes (e.g., dune-flow, sliding beds, irregular slugging, etc.—usually at moderate $m^*$).

Figure 13. Test rig conveying characteristics of fly ash B, $L = 945 \text{ m}, D = 69/81 \text{ mm}$ and $r = 1 \text{ m}$. 

![Diagram](image-url)
For these reasons and other complex influences (e.g., large-diameter pipelines, particle-wall friction, particle shape, bends, etc.), it has been accepted that if high accuracy is needed, then some form of empiricism must be adopted. The preferred test-design procedure is listed below.

• Firstly, as described previously, characterize the bulk solid to be conveyed by undertaking particle size, particle density, loose-poured bulk density, fluidization and deaeration tests. Then classify the material using both the Geldart (1973) and Dixon (1981) diagrams to establish possible feeding problems and dense-phase suitability, which provides an indication of long-distance performance. For example, based on experience, Dixon (1981) Group A (and some Group C) powders display good fluidized dense-phase (Wypych, 1995a), as well as long-distance performance (e.g., high \(m^*\)).

• Using a standardized test procedure (Wypych and Arnold, 1985b), determine test rig conveying characteristics, similar to those shown previously in Figs. 11–13.

• Where the required conveying lengths and/or diameters cannot be tested, appropriate scale-up procedures (Pan and Wypych, 1992a) are employed. By monitoring the pressures along the straight sections of a test rig pipeline and also monitoring bend effects, determine exponents \(x_1, \ldots, x_4\) and \(y_1, \ldots, y_4\) in the following pressure drop equations.

\[
\Delta p_s = \Delta p_{sf} + \Delta p_{ss}
\]

where \(\Delta p_{sf}\) can be determined from Wypych and Pan (1991) and

\[
\Delta p_{ss} = \lambda_{ss} m^* \frac{\rho_f m \nu_f^3}{2 D} \Delta L_s
\]

\[
\lambda_{ss} = x_1 \ m^{x_2} \ Fr_m \ x_3 \ \rho_f \ x_4
\]

\[
\Delta p_b = \Delta p_{bf} + \Delta p_{bs}
\]

where \(\Delta p_{bf}\) can be determined from Wypych and Pan (1991) and
Eq. (11) \[ \Delta p_{bs} = \lambda_{bs} m^* \frac{\rho_f \omega^2}{2} \]

Eq. (12) \[ \lambda_{bs} = y_1 m^{x_2} F_0^{x_3} \rho_f^{y_4} \]

Note that the exponents \(x_1, \ldots, x_4\) and \(y_1, \ldots, y_4\) are valid only for the test material and bend geometry, respectively.

To demonstrate the scale-up accuracy of the above design equations, thirty-eight experiments were carried out (Pan and Wypych, 1992a) with a particular fly ash over a very wide range of conveying conditions (i.e., from dilute- to fluidized dense-phase) on the test rig Pipeline I shown in Fig. 14.

In each experiment, it was believed that all the transducers along the pipeline (Tb-Te) were installed beyond any bend effects. Based on the data obtained from these experiments, the exponents in Eqs. (9) and (12) were determined by minimizing the sum of the squared errors of pressure at points Te2, Tc1, Tc2, Tc3 and Tc4, starting from point Te1. The determined values of exponent are listed in Table 1.

Additional experiments then were carried out on Pipelines II and III, which are shown in Figs 15 and 16 respectively and detailed in Table 2.

---

**Figure 14.** Schematic layout of Pipeline I, \(L = 172\, m, D = 69\, mm, r = 1\, m\).
Table 1. Values of Exponent Based on Data Obtained from Pipeline I, $L = 172$ m, $D = 69$ mm and $r = 1$ m

<table>
<thead>
<tr>
<th>Exponent</th>
<th>Value of Exponent</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x_1$</td>
<td>5.306</td>
</tr>
<tr>
<td>$x_2$</td>
<td>-0.436</td>
</tr>
<tr>
<td>$x_3$</td>
<td>-1.934</td>
</tr>
<tr>
<td>$x_4$</td>
<td>-0.117</td>
</tr>
<tr>
<td>$y_1$</td>
<td>0.052</td>
</tr>
<tr>
<td>$y_2$</td>
<td>0.658</td>
</tr>
<tr>
<td>$y_3$</td>
<td>0.673</td>
</tr>
<tr>
<td>$y_4$</td>
<td>-1.495</td>
</tr>
</tbody>
</table>

Figure 15. Schematic layout of Pipeline II, $L = 554$ m, $D = 69$ mm and $r = 1$ m.
Using the above exponents and pressure drop equations, the total pipeline air pressure drop and selected pressures were predicted for each Pipeline I, II and III, starting from the end of pipeline or points along the pipeline. Some of the predictions are presented in Fig. 17, from which it can be seen that the agreement between predicted and experimental values is quite good.
Figure 17. Predicted pressure vs experimental value, based on data from pipeline I. (Note: Te1 → Te4 means the predicted pressure at Te4, starting from Te1).
The above test-design and scale-up procedures have been applied to numerous long-distance systems (e.g., fly ash, pulverized coal) and have been found to provide good accuracy and reliability. Some examples of these results have been presented by Pan and Wypych (1992a) and Pan and Wypych (1994). The interested reader is referred to these papers for further details. The above procedures also have been used successfully to

- Predict conveying characteristics for a wide range of pipeline configurations (Pan and Wypych, 1994)
- Investigate the effect of bend number and radius on conveying performance (Wypych and Pan, 1993)
- Compare the pressure drop caused by horizontal and vertical sections of pipe (Wypych and Pan, 1993)
- Predict the pressure drop of large-throughput cement pneumatic conveying systems (Wypych, 1992)

### 2.5 Stepped-Diameter Pipelines

It is recognized commonly that

\[
\text{Erosion} \propto \text{Velocity}^n
\]

where the power index, \(n\), ranges from 2 for ductile materials to 6 for brittle materials (Marcus et al., 1990). Hence, one direct way of reducing pipeline wear (e.g., pipe, bends) is to limit the “natural” increase in velocity in the direction of flow (i.e., due to the expansion of the carrier gas). This can be achieved by increasing the bore of the conveying pipeline in the direction of flow. Other advantages of stepped-diameter pipelines include the minimization of pressure loss, air flow and hence, power consumption, which are particularly important when considering long-distance and/or large-throughput applications. By selecting accurate stepping pipe criteria and models to predict pressure drop (Wypych and Reed, 1990), it is possible to optimize the design of these pipelines and obtain more efficient transportation over longer conveying distances (e.g., up to \(L = 3\) or 4 km).

Some examples of long-distance stepped-diameter pipeline systems include 100 t h\(^{-1}\) of fly ash over 1.5 km (Wypych, 1995b) and 24 t h\(^{-1}\) of pulverized coal over 1.8 km (Wypych et al., 1990). Some of the different pipeline configurations considered for the latter are repeated in Table 3 below. Note:
The relationship “$Fr_{min} = 6 = constant$” was found to represent adequately the reliable transport limit of this material and hence, was employed as the pipe stepping criterion (i.e., to optimize $L_n$ and minimize $m_f$).

An accurate $\lambda_s$ correlation based on experimental data was employed to predict the values of $\Delta p_t$.

From Table 3 it can be seen that by optimizing the configuration of pipeline, it is possible to reduce pressure loss, air flow, transport velocity, and hence, pipe/bend wear. Depending on hardware requirements and reliability, which would to some extent govern the maximum operating pressure of the system (e.g., say, 400 or 500 kPag), Pipeline Nos. 5 or 6 could be selected for this long-distance application. However, if diverter valves are required at the end of the pipeline, it may be more convenient to select Pipeline No 5 (i.e., $D_1 = 154$ mm instead of 203 mm).

### Table 3. Pipeline Configurations and Predicted Operating Conditions for 24 t h\(^{-1}\) of Pulverised Coal over 1.8 km (Wypych, et al., 1990)

<table>
<thead>
<tr>
<th>Pipe No</th>
<th>$D_1$ (mm)</th>
<th>$L_n$ (m)</th>
<th>$m_f$ (kg/s)</th>
<th>$m^*$ (-)</th>
<th>$\Delta p_t$ (kPa)</th>
<th>Fri (-)</th>
<th>$V_p$ (m/s)</th>
<th>$V_{fe}$ (m/s)</th>
<th>$P$ (kWh/t/km)</th>
<th>% Diff wrt No 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>203</td>
<td>1800</td>
<td>1.22</td>
<td>5.5</td>
<td>272</td>
<td>6</td>
<td>8.5</td>
<td>31.3</td>
<td>6.1</td>
<td>97%</td>
</tr>
<tr>
<td>2</td>
<td>154</td>
<td>1800</td>
<td>0.87</td>
<td>7.7</td>
<td>430</td>
<td>6</td>
<td>7.4</td>
<td>38.8</td>
<td>5.5</td>
<td>77%</td>
</tr>
<tr>
<td>3</td>
<td>127</td>
<td>1800</td>
<td>0.7</td>
<td>9.6</td>
<td>595</td>
<td>6</td>
<td>6.7</td>
<td>46.1</td>
<td>5.2</td>
<td>68%</td>
</tr>
<tr>
<td>4</td>
<td>203</td>
<td>853</td>
<td>0.7</td>
<td>9.6</td>
<td>327</td>
<td>6</td>
<td>8.5</td>
<td>18</td>
<td>3.9</td>
<td>26%</td>
</tr>
<tr>
<td></td>
<td>154</td>
<td>947</td>
<td></td>
<td></td>
<td></td>
<td>6</td>
<td>7.4</td>
<td>14.7</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>154</td>
<td>1117</td>
<td>0.56</td>
<td>12</td>
<td>453</td>
<td>6</td>
<td>7.4</td>
<td>25</td>
<td>3.6</td>
<td>16%</td>
</tr>
<tr>
<td></td>
<td>127</td>
<td>683</td>
<td></td>
<td></td>
<td></td>
<td>6</td>
<td>6.7</td>
<td>10.8</td>
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</tr>
<tr>
<td>6</td>
<td>203</td>
<td>436</td>
<td>0.51</td>
<td>13.2</td>
<td>401</td>
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<td>8.5</td>
<td>13</td>
<td>3.1</td>
<td>0%</td>
</tr>
<tr>
<td></td>
<td>154</td>
<td>733</td>
<td></td>
<td></td>
<td></td>
<td>6</td>
<td>7.4</td>
<td>14.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>127</td>
<td>631</td>
<td></td>
<td></td>
<td></td>
<td>6</td>
<td>6.7</td>
<td>10.8</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### 2.6 Valves

Blow tank technology was introduced extensively after World War II to not only improve plant efficiency but also to extend the future potential of pneumatic conveying (e.g., long-distance and/or large-throughput
applications). However, the resulting higher operating pressures, together
with other factors such as product abrasion and/or high temperatures,
resulted in the premature failure of crucial valves (e.g., blow tank inlet,
blast tank discharge). A wide range of different “off-the-shelf” valves
for gas, hydraulic and/or slurry service then were tested (e.g., ball,
butterfly, plug and air-on-sleeve pinch valves). Unfortunately, most of
these were found unsuitable, achieving service lives from only a few hours
to a few days.

Consequently, more elaborate designs had to be tested and/or devel-
oped for this application of pneumatic conveying. The following two valves
have been found useful in particular areas. Note that in each case it is
imperative to ensure fast actuation time (e.g., 1 second for a 100 mm
nominal bore NB valve and a few seconds for a 300 mm NB valve, if
possible). Large-bore solenoid valves and quick-exhaust valves usually are
required for this purpose. Also, note that each one of the following valves
provides a full cross-sectional area of flow in the open position and a 100%
seal in the closed position. One of the major problems of air-on-sleeve
pinch valves is that they do not provide these important features for
pneumatic conveying applications (e.g., a small hole in a closed sleeve
quickly erodes due to the subsequent high velocities of air and solids).

The high-pressure pinch valve shown in Fig. 18 has been applied
successfully to several abrasive pneumatic conveying applications, mainly
for blow tank discharge. For example, this pinch valve has been quite
successful in handling abrasive and coarse materials, such as crushed
bauxite, zircon and sub 20 mm crushed brick (Wypych, 1995b), as well as
high throughputs, such as 100 t h⁻¹ of cement (Wypych, 1995b). Also, by
replacing existing chrome-plated butterfly valves with high-pressure pinch
valves in cement plants, it has been possible to extend the service life of
blow tank discharge valves from ≈2 weeks to over 8 months (Timms,
1992). However, it is important to select a valve which has the actuating
rods “tagged” or connected to the sleeve. This will ensure a full-bore flow
area when the valve is opened. Note that this type of valve is not suitable
for high-temperature applications (e.g., ≥200 °C), where the sleeve will
work-harden and fail prematurely.

The rotating-disc valve shown in Fig. 19 is gaining popularity for blow
tank inlet and discharge applications. As the disc is spring-loaded and “self-
lapping,” the valve automatically adjusts for wear. Also, as no packing,
seals or o-rings are used (i.e., the disc and seating surfaces are metallic),
Figure 18. High-pressure pinch valve (Larox Pty Ltd).

Figure 19. Rotating-disc valve (Everlasting Valve Co.).
high temperatures and pressures are possible (e.g., up to 900°C and 69000 kPag). The rotating-disc valve has been used successfully (Wypych, 1995b) as a discharge valve for 7 m³ blow tanks transporting hot and abrasive ash from a power station precipitator at a rate of 100 t h⁻¹ over a total distance of 1.5 km. These discharge valves have operated continuously on a 24-hour basis and achieved a service life of at least 12 months (i.e., without any form of maintenance). However, to ensure that the valve body does not fill up with ash, purge-air has been used during actuation of the valve.

2.7 Pipeline Unblocking Techniques

Following numerous blockages on the test facilities at the University of Wollongong (attempting to determine the minimum conveying velocity of various materials over long distances), a pipeline unblocking system was developed and installed at the end of the pipeline. Refer to Fig. 20 for a typical arrangement.

The system incorporates only one component in the pipeline, allowing the pipeline to be back-pressurized from the silo to the blockage with air at a slightly higher pressure than the conveying pressure. The back-pressure then is released in a controlled manner such that the blockage is drawn through the conveying line. These systems have been incorporated successfully in the control circuits of plants handling difficult-to-convey materials and also have been used on conveying pipelines up to 1.5 km in length (Wypych, 1995b).

![Figure 20. Schematic layout of pipeline unblocking system.](image)
2.8 General Considerations

The following comments and recommendations are based on the research findings presented and cited in this paper, as well as the consulting experiences of the author.

For the general purpose of minimizing air flow, transport velocity, wear and power, the fluidized dense-phase mode of flow is preferred for long-distance applications. Efficient blow tank feeders, rotary-screw compressors, refrigerated dryers and stepped-diameter pipelines also are recommended. For products that are not suited to fluidized dense-phase, the possible modes of flow include dilute-phase (suspension flow) or bypass conveying (Wypych, 1995a).

It is believed that the air velocities in a large-diameter dilute-phase system can be 50 to 100% higher than an equivalent well-designed dense-phase system. Hence, much greater wear problems are expected in the dilute-phase system, although significant advances have been made in the technology of wear-resistant materials and bends (Wypych and Arnold, 1993). Other features involved with dilute-phase transport systems include:

- Limited operating pressures (e.g., 80 to 100 kPag for Roots-type blowers)
- Large-diameter pipelines
- Greater conveying velocities and system erosion (i.e., due to the larger pipe diameters)
- Larger dust collectors to cope with the greater volumes of conveying air

Note, the velocities required in large-diameter dilute-phase systems must be high to ensure suspension flow, avoid product deposition, and facilitate good clean-out. This comment is based on personal experiences involved with large-diameter pipeline systems used to unload ships (e.g., 350 mm NB pipelines 25% full of deposited cement) and provide fuel to boilers (e.g., deposition of pulverized coal even at high velocities such as 30 m s\(^{-1}\)). Note, blow tank feeders (i.e., instead of rotary valve feeders) can be used effectively to assist in the cleaning/purging of pipelines (e.g., clean-blow cycle). However, with a Roots-type prime mover and a large-diameter (large-volume) pipeline, the effectiveness of the purge or clean-blow cycle will be reduced significantly (i.e., due to the pressure limit of 100 kPag).
In contrast, a well-designed dense-phase system will operate at significantly less velocities and wear, as well as provide more efficient cleaning/purging operations (i.e., due to having smaller pipe diameters and greater pressures, if needed). One other interesting issue is that a blow tank dense-phase system is inherently more “self-cleaning” than a dilute-phase system (i.e., due to the natural variations in pressure and increased material concentration/turbulence). Quite often dense-phase systems have been installed in Australia to overcome buildup problems displayed by dilute-phase systems, where the air can flow easily over deposited material.

When evaluating a material for the purpose of establishing dense-phase and long-distance suitability, it is important to undertake all the necessary tests (e.g., particle sizing, particle and bulk densities, fluidization and deaeration). Also, if possible, it is useful to compare such results with those obtained on previously conveyed similar materials (e.g., fly ash). However, it should be noted that such an evaluation only is a qualitative one and it is not possible to predict say, minimum air flows or pipeline pressure drop based on such data (i.e., pilot-scale tests normally are required to confirm minimum velocities, friction factors, etc., especially over long distances and for large-diameter pipes).

Many designers and researchers in the past have placed a great deal of emphasis on the importance of solids loading or the solids-to-air mass flow rate ratio, $m^*$. However, it should be realized that this parameter is dependent on particle and loose-poured bulk densities; conveying distance and pressure available; frictional properties and minimum transport conditions of material (which will affect the maximum values of $m^*$). Hence, it is difficult and misleading to apply “general” values of $m^*$ to different systems and materials. The objective always should be to achieve a well-designed long-distance transport system operating at optimal conditions—$m^*$ only should be considered as a consequence of achieving this result.

### 3.0 PIPE BRANCHING

The branching of pipes/ducts in pneumatic conveying has the following two main applications in industry.

- Extraction of dust via a network of branched ducts, where the particulates are transported under vacuum conditions. Some common examples include the control of dust in materials
handling operations, including conveyor transfers, screening, filling bins, ship loading, etc.

- The simultaneous splitting and distribution of solids-gas mixtures for applications requiring multipoint injection, where the mixtures are transported usually under positive-pressure conditions. Some common examples include tuyere injection for blast furnaces, large burner nozzles for pulverized coal-fired boilers, small coal-fired plasma torches providing start-up and support energy for boilers, injection of pulverized fuel into calciners, etc.

Some of the important issues that should be considered when designing, improving or operating any such pipe branching applications are described in the following sections.

### 3.1 Dust Extraction

Most practical dust extraction systems involve multiple hoods linked to a duct network serving a central gas cleaning unit and prime mover. This is very similar to an air conditioning system where the air is supplied from an air handling unit through the duct network to diffusers serving the occupied spaces. In fact, most duct sizing methods are based on air conditioning principles and/or techniques, such as the Total Pressure Method (ASHRAE, 1985), the Velocity Pressure Method (ACGIH, 1992) and the Constant Pressure Gradient Sizing Method (DASCG and AIRAH, 1987). Also, some “air-conditioning” computer programs, such as DONKEY (DASCG and AIRAH, 1988), may be employed to assist in the design of the ductwork (i.e., based on one or two of these sizing methods).

The objective of the design/analysis process is to ensure (as far as possible) that the correct quantity of air flows through each hood. As different air quantities, hood types/sizes and/or duct lengths usually are involved, this is not always a simple task. The correct air flows may be achieved by performing:

- A “rough” duct design and then making adjustments during commissioning using blast gates or dampers to control air flow
- A more involved design where the system is inherently balanced.

The latter method is preferred for the following reasons:
Dampers may increase maintenance costs
Dampers may be tampered with during the life of the plant
Damper control may be prohibited when handling dangerous or explosive materials
The “rough” duct design method may result in premature dust deposition or excessive system erosion (due to incorrect duct sizes and velocities)

Hence, even if the “rough” duct design technique is selected, some form of balancing still should be performed so that the final duct sizes are close to optimal (in terms of pressure and velocity).

The correct application of either sizing technique will result in a duct network that works well on air. It is equally important to ensure that each air flow is adequate to transfer all the particulates from the hood/enclosure to the collection and/or cleaning device. Unfortunately, many dust control systems have been designed and/or are being operated with little or no regard for what actually has to go through the hood-duct network. This can result in:

- Particulate deposition and buildup inside the duct(s)
- Eventual choking of duct branch(es)
- Inefficient performance of the overall dust control system.

Case Study. Such a situation was found to occur in the duct network shown in Fig. 21 and installed to extract iron oxide dust at various points along a cold strip processing line. The stated problems were insufficient suction at the hoods, buildup of contaminant in the hoods and along the processing line (causing cleanup problems due to eventual mixing with hydraulic fluid, lubricant, water, etc.). Analysis of the system found the following:

- Branch II-V contained more bends and was over three times longer than branch I-V
- Branches I-V and II-V were sized to provide an approximate 35%–65% split-up in air flow, respectively (i.e., using pressure-balancing techniques)
- The system would have worked initially on air, however, the lower section of branch II-V was completely blocked with contaminant
• Velocities in excess of 60 m s\(^{-1}\) were occurring in branch I-V causing excessive pressure loss and wear. Note the potential seriousness of wear in ductwork (especially bends/elbows) has been emphasized previously by Eq. (13). For example, assuming \( n = 3 \), which without other data is used to represent most industrial situations, a velocity increase of only 20\% will result in a 73\% increase in wear. Hence, it is important to ensure that the transport velocities are not only adequate to avoid deposition problems but also minimized for wear reasons.

The solution to the above problem is to re-size the entire network, in particular branches I-V and II-V, with the aim of ensuring a suitable minimum transport velocity along each section of duct.

**Minimum Duct Velocity.** Once the types and locations of hoods, enclosures and booths have been established and the exhaust rates determined, it is necessary to design the ductwork to transfer the contaminated gas to the collection or cleaning device. An essential parameter required for this purpose is the minimum duct or conveying velocity, \( V_{f_{\text{min}}} \), which is required to:

![Figure 21. Duct network for extraction of iron oxide dust.](image)
Avoid the gradual buildup of a particular contaminant with time.

Know whether any toxic or bacteria-prone particles are being left inside the ductwork (e.g., for servicing or maintenance purposes).

Establish whether any appreciable buildup will affect dust extraction efficiency.

Unfortunately, the current selection of $V_{min}$ is based on a general list, such as that given in Table 4, where:

- The list of contaminants is very general and open to interpretation.
- The suggested velocities can vary considerably between say, 15 and 20 m s$^{-1}$ (even for the same application area).
- No consideration is given to the influence of particle properties and/or duct diameter.

**Table 4 Minimum Conveying Velocities (ACGIH, 1992)**

<table>
<thead>
<tr>
<th>Nature of Contaminant</th>
<th>Industrial Examples</th>
<th>$V_{min}$ (ft min$^{-1}$)</th>
<th>$V_{min}$ (m s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vapours, gases, smoke</td>
<td>All vapours, gases and smoke</td>
<td>1000-2000</td>
<td>5-10</td>
</tr>
<tr>
<td>Fumes</td>
<td>Welding</td>
<td>2000-2500</td>
<td>10-12</td>
</tr>
<tr>
<td>Very light fine dust</td>
<td>Cotton lint, wood flour</td>
<td>2500-3000</td>
<td>12-15</td>
</tr>
<tr>
<td>Dry dusts and powders</td>
<td>Fine rubber dust, bakelite moulding powder dust, cotton dust, light shavings, soap dust, leather shavings</td>
<td>3000-4000</td>
<td>15-20</td>
</tr>
<tr>
<td>Average industrial dust</td>
<td>Grinding dust, dry buffing lint, coffee beans, granite dust, silica flour, general materials handling, brick cutting, clay dust, foundry, limestone dust, asbestos dust</td>
<td>3500-4000</td>
<td>18-20</td>
</tr>
<tr>
<td>Heavy dusts</td>
<td>Heavy/wet sawdust, metal turnings, foundry tumbling barrels and shake-out, sand blast dust, wood blocks, brass turnings, cast iron boring dust, lead dust</td>
<td>4000-4500</td>
<td>20-23</td>
</tr>
<tr>
<td>Heavy or moist</td>
<td>Lead dust with small chips, moist cement dust, asbestos chunks from machines, sticky buffing lint</td>
<td>&gt; 4500</td>
<td>&gt; 23</td>
</tr>
</tbody>
</table>
For example, for the iron oxide dust considered in the previous case study, Table 2 suggested $V_{f_{min}} = 18$ to 20 m s$^{-1}$ (i.e., assuming an “average industrial dust”). On analysis of the sample, it was found $d_{50} \approx 80$ µm, which appeared to support this classification. However, upon further examination of the actual distribution of size, a significant proportion of the material was found $> 1000$ µm (e.g., large flakes). A minimum conveying velocity of at least $V_{f_{min}} \approx 25$ m s$^{-1}$ was estimated for this “dust.” This explains why the iron oxide material built up and eventually blocked branch II-IV, which was sized/balanced mainly for air distribution purposes and produced transport velocities $< V_{f_{min}}$.

As a result of some recent investigations into the deposition (saltation) of small particles in large diameter ducts (Cable, 1994; Miletich, 1994) and analogous work in pneumatic conveying (Wypych and Reed, 1990; Zenz, 1964; Cabrejos and Klinzing, 1994), some other interesting characteristics of $V_{f_{min}}$ are listed below.

- $V_{f_{min}}$ appears to increase with duct diameter, $D$. This trend has been recognized in many “traditional” pneumatic conveyors (Wypych and Reed, 1990; Zenz, 1964; Cabrejos and Klinzing, 1994), but also appears to be relevant for dust extraction (Cable, 1994; Miletich, 1994), which can be considered as a form of low-concentration pneumatic conveying (e.g., $V_f = 10$ m s$^{-1}$ may be suitable for a particular contaminant in a duct size of $D = 100$ mm but may cause deposition in $D = 300$ mm). Further evidence of this can be seen in the work of Zenz, 1964, who found that single-particle saltation, which is analogous to the deposition of low-concentration particulate suspensions in dust extraction, increases with duct diameter according to the following relationship.

$$V_{fso} \propto D^k$$

where $k = 0.4$ to 0.6. However, based on experience, Eq. (14) appears to provide conservative values of $V_{fso}$, especially in large-diameter ducts. This has been confirmed by Cable (1994) and Miletich (1994) who both employed 200, 300 and 480 mm diameter steel ducts, and Cabrejos and Klinzing (1994) who used a 50 mm diameter copper tube.
• $V_{f_{min}}$ appears initially to decrease with decreasing particle size and then increase for very fine particles (due to cohesive and interparticle forces). This trend is predicted (Wypych, 1993) by three different saltation velocity models and also can be found in many industrial applications. For example, in an article describing the installation of a dust extraction system for very fine clay dust in a brick manufacturing plant (Anon, 1995), it was stated that a high velocity of 24 m s^{-1} was needed to maintain dust suspension—this velocity is approximately equal to the 25 m s^{-1} estimated for the (coarser and heavier) iron oxide dust described above. Note, this example also provides further support to the inadequacy of Table 4, which nominates a velocity of 18–20 m s^{-1} for “clay dust.” It should be noted that these unusually high velocities may be indicative of what would be needed to ensure “clean” ductwork (i.e., without any form of deposition), whereas in practice a small amount of deposited material is considered normal. Nevertheless, it is essential to ensure that such a buildup does not increase gradually with time. Also, in some applications, especially those handling dangerous and/or bacteria prone contaminants, it may be necessary to maintain “clean” ductwork (i.e., for safety, hygienic and/or maintenance reasons).

• The velocity needed to re-entrain deposited particulates ($V_{f_{up}}$) may need to be determined for particular applications. The velocity $V_{f_{up}}$ is being found (Zenz, 1964; Cabrejos and Klinzing, 1994) to be much greater than $V_{f_{min}}$ (i.e., the saltation or deposition velocity) and again increase with duct diameter (Cabrejos and Klinzing, 1994). Also, similar to $V_{f_{min}}$, $V_{f_{up}}$ appears to increase with deceasing particle size, where very fine contaminants are more difficult to re-entrain (i.e., due to interparticle forces).

The further development of accurate models to predict the above parameters (including the effects of particle properties and duct diameter) is being pursued currently, and considerable effort still is required before such models can be applied solely in design practice (i.e., without the need for experience or comparative data).
At this stage, operators of dust control systems should at least be aware of these various issues and their relative importance, which will vary from problem to problem. Hence, it is essential that the engineer or consultant responsible adopts a systematic approach to the solution of the problem in which all the relevant issues are considered and dealt with in the appropriate order.

If accurate design/analysis data are necessary (e.g., $V_{\text{min}}$, $V_{\text{up}}$), it is possible to obtain the information needed by undertaking the appropriate bench-type tests and large-scale test-design procedures, similar to the approaches employed for pneumatic conveying (Pan and Wypych, 1992a; Arnold et al., 1994).

### 3.2 Flow Splitting

The layout of a typical flow-splitting system is depicted in Fig. 22. For an even split-up and distribution of material, it is essential that each pipe branch offers the same resistance to flow. This can be achieved easily by ensuring that each pipe branch has the same length, type and location of bends, as depicted in Fig. 23. This preferred approach is more feasible when small diameters of pipeline are involved. However, the installation of identical pipe branches is not always possible. In such situations, the traditional approach has been to install additional pipes/bends in the lower resistance branches, such as branch Nos. 1 and 4 shown in Fig. 22. The problem with this approach is that bend pressure drop depends not only on conventional parameters, such as $m_p$, $m_s$, material properties, wall material, temperature, bend geometry, etc., but also on bend location (Wypych and Pan, 1993; Pan and Wypych, 1992b). Hence, simply ensuring each pipe branch comprises the same length of pipe and number of bends still can cause inaccuracies in flow splitting efficiency.

By employing accurate test-design procedures (Pan and Wypych, 1992a), it is possible to model and design each pipe branch separately so that the system ultimately is well balanced. However, such a system may not be reliable over time due to uneven wear in the pipes/bends, changes in material property and/or on-site conditions.

**Splitters.** The following common splitters have been introduced to improve the efficiency of flow splitting.
Figure 22. Traditional method of pipe branch layout for injection systems.

Figure 23. Preferred method of pipe branch layout for injection systems.
• Conventional riffle box, as shown in Fig. 24, used normally for 2-way splitting in coal-fired furnace and boiler applications. The ripples plates will be subjected to wear and over time could affect flow splitting efficiency.

• Cone splitter, as shown in Fig. 25, used in general injection applications for up to 8-way splitting and claimed (Hilbert, 1982) to achieve ±10% accuracy in splitting. It should be noted that such figures depend more on the design of the pipe branches downstream of the splitter, rather than the splitter itself.

• Rotary splitter (Selves and Barnes, 1993), which can be used to provide up to 36-way splitting. Due to its intermittent operation, the pulsing flow in the branches downstream of the splitter would not be suitable for applications requiring a smooth and regular injection of material.

The above devices are flow intrusive, subjected to wear and the splitter itself cannot control changing downstream conditions. A potentially more direct and efficient approach is to monitor the change in flow conditions downstream of a splitter (Barnes and Murmame, 1995) and employ active splitters (Selves et al., 1995) to control the split ratio of air and hence, material. Some of the active splitters being investigated and developed by Selves et al., 1995 include:

• Modified riffle box, as shown in Fig. 26, which uses air injection to control the split ratio.

• Induced swirl, as shown in Fig. 27, which imparts to the solids-gas flow a swirling action and also controls the rate and direction of rotation of swirl via tangential nozzles. However, the residual swirl that would occur in the downstream pipe branches may cause problems if several swirl inducers follow one another (Selves et al., 1995). This problem could be eliminated by introducing the dropout box splitter shown in Fig. 28.
Figure 24. Conventional riffle box. (Selves et al., 1995.)

Figure 25. Cone splitter. (Hilbert, 1982.)
Figure 26. Modified riffle box (Selves et al., 1995).

Figure 27. Control of split ratio using induced swirl and a Y splitter. (Selves et al., 1995.)
General Considerations. Some other important considerations that should be made when designing a flow splitting system are listed below.

- The splitter should provide a symmetrical split in all planes and preferably should be installed in the vertical plane (if possible).
- The solids-gas flow upstream of the splitter should be uniform and regular.
- Sufficient upstream pipe should be used to eliminate any flow separation effects caused by in-line components, such as bends and diverters (e.g., “roping” in dilute-phase).
- Special care should be taken when selecting the mode of solids-gas flow. For example, flow separation and roping could occur even in very dilute-phase conveying systems (e.g., $m^* \leq 1$ for coal-fired boilers). Fluidized dense-phase also is possible for some systems and can offer many
advantages (e.g., reduced air flow, velocity, wear, power). However, this mode of flow can be more irregular than dilute-phase (e.g., increased pressure fluctuations) and hence, produce flow splitting problems, even with active splitters. The objective here should be to achieve the minimum air flow that is needed to ensure smooth and consistent flow under all operating conditions.

3.3 Pressure Loss

For dust extraction systems, the concentration of solids usually is quite low. For this reason, the methods employed to calculate pressure loss are based on air-only conditions. Comprehensive information is available (ASHRAE, 1985; ACGIH, 1992) to assist the designer in estimating the pressure loss caused by pipe branches, ducts, elbows, etc.

In contrast, the amount of material being conveyed inside each pipe branch of a flow splitting application is very high and hence, design cannot be based on air-only analyses alone. For example, Low et al., 1987 have proposed the following empirical relationship to determine the head loss of a pipe branch.

\[
K = K_f (1 + C m^a)
\]

where \( K \) is the branch head loss for solids-gas flow, \( K_f \) is the branch head loss for air-only conditions and can be calculated theoretically from (Low et al., 1987), \( C = 0.22 \) and \( a = 1.27 \) appear to represent satisfactorily both 90°- and 45°-branches with different branch diameters and products (Low et al., 1987). Further examples of empirically based pressure loss equations for Y-splitters of various angles and subjected to plastic pellets under different solids loadings have been presented and cited by Marcus et al., 1990.

Good flow splitting design is dependent on the accurate prediction of the pressure drop caused by the various bends, branches and straight sections of pipe. This can be achieved by employing the above branch model(s), proven for the particular material and application, coupled with the accurate “pipeline” test-design procedure described in Sec. 2.4 of this chapter.
NOTATIONS

\( a \) \hspace{1cm} \text{Power index}

\( C \) \hspace{1cm} \text{Constant}

\( d \) \hspace{1cm} \text{Particle diameter, m}

\( d_{s0} \) \hspace{1cm} \text{Median particle diameter, m}

\( d_{p} \) \hspace{1cm} \text{Arithmetic mean of adjacent sieve sizes, m}

\( d_{p50} \) \hspace{1cm} \text{Value of } d_{s0} \text{ based on a sieve size distribution, m}

\( d_{pm} \) \hspace{1cm} \text{Mean particle size from a standard sieve analysis, Eq (1), m}

\( d_{pwm} \) \hspace{1cm} \text{Weighted mean diameter based on a sieve analysis, Eq (2), m}

\( d_{sv} \) \hspace{1cm} \text{Diameter of a sphere with the same surface area to volume ratio as the particle, m}

\( d_{sym} \) \hspace{1cm} \text{Mean surface volume diameter, Eq (3), m}

\( d_{sv50} \) \hspace{1cm} \text{Diameter of a sphere with the same volume as the particle, m}

\( d_{sv50} \) \hspace{1cm} \text{Value of } d_{s50} \text{ based on a volume diameter distribution, m}

\( d_{sym} \) \hspace{1cm} \text{Mean equivalent volume diameter, Eq (4), m}

\( d_{vwm} \) \hspace{1cm} \text{Volume weighted mean diameter, Eq (5), m}

\( D \) \hspace{1cm} \text{Internal diameter of pipe, m}

\( Fr \) \hspace{1cm} \text{Froude No, } Fr = \frac{V_f}{(gD)^{0.5}}

\( g \) \hspace{1cm} \text{Acceleration due to gravity, m s}^{-2}

\( k \) \hspace{1cm} \text{Power index}

\( K \) \hspace{1cm} \text{Pipe branch head loss for solids-gas flow}

\( K_f \) \hspace{1cm} \text{Pipe branch head loss for air-only conditions}

\( L \) \hspace{1cm} \text{Total effective length of pipe or section of pipeline, m}

\( L_h \) \hspace{1cm} \text{Total effective length of horizontal pipe, m}

\( L_v \) \hspace{1cm} \text{Total effective length of vertical pipe, m}

\( m_f \) \hspace{1cm} \text{Air mass flow rate, kg s}^{-1}

\( m_s \) \hspace{1cm} \text{Solids mass flow rate, kg s}^{-1}

\( m^* \) \hspace{1cm} \text{Solids to air mass flow rate ratio, } m^* = m_s m_f^{-1}

\( n \) \hspace{1cm} \text{Power index}

\( NB \) \hspace{1cm} \text{Nominal bore}

\( P \) \hspace{1cm} \text{Specific power, } W \cdot h^{-1} \cdot m^{-1}

\( r \) \hspace{1cm} \text{Centreline bend radius, m}

\( t \) \hspace{1cm} \text{Time, s}

\( V_f \) \hspace{1cm} \text{Superficial air velocity, m s}^{-1}

\( V_{fs0} \) \hspace{1cm} \text{Single-particle saltation velocity, m s}^{-1}

\( V_{jup} \) \hspace{1cm} \text{Re-entrainment velocity, m s}^{-1}

\( V_{mb} \) \hspace{1cm} \text{Minimum bubbling velocity, m s}^{-1}
Minimum fluidization velocity, m s\(^{-1}\)

**Exponents**

- \(x_1, \ldots, x_4\)
- \(y_1, \ldots, y_4\)

**Factors** (Mainwaring and Reed, 1987)

- \(X\)
- \(\Delta h\) Difference in height, m
- \(\Delta L_s\) Length of straight section of pipe, m
- \(\Delta M\) Mass percent of material contained in a given size range, %
- \(\Delta M_i\) Value of \(\Delta M\) for size range \(i\), %
- \(\Delta p\) Pressure drop, Pa
- \(\Delta p_b\) Pressure drop caused by bend, Pa
- \(\Delta p_s\) Pressure drop caused by straight section of pipe, Pa
- \(\Delta p_t\) Total pipeline air pressure drop, Pa
- \(\kappa_d\) Deaeration factor (Mainwaring and Reed, 1987)
- \(\kappa_p\) Permeability factor (Mainwaring and Reed, 1987)
- \(\lambda_b\) Particle-wall friction factor in bend
- \(\lambda_s\) Particle-wall friction factor in straight pipe
- \(\rho_{nl}\) Loose-poured bulk density, kg m\(^{-3}\)
- \(\rho_f\) Air density, kg m\(^{-3}\)
- \(\rho_s\) Particle density, kg m\(^{-3}\)
- \(\psi\) Particle sphericity

**Subscripts**

- \(i\) Initial value (at beginning of pipe)
- \(e\) Final or exit value (at end of pipe)
- \(f\) Fluid (gas)
- \(m\) Mean value (based on average air density)
- \(\text{min}\) Minimum value
- \(n\) Value relating to pipe section \(n\) (starting from end of pipeline)
- \(o\) Value relating to bend outlet
- \(s\) Solids
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