PNEUMATIC CONVEYING DESIGN GUIDE

David Mills

Butterworths

Pneumatic Conveying Design Guide

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Pneumatic Conveying Design Guide

David Mills PhD
Centre for Industrial Bulk Solids Handling,
Glasgow College,
Glasgow,
UK

Butterworths
London Boston Singapore Sydney Toronto Wellington

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Preface

During the late 1970's, Warren Spring Laboratory (WSL) was funding research into pneumatic conveying by means of an extra mural research award to Thames Polytechnic. By the beginning of the 1980's, government funding for such awards was curtailed and, with much work still to be done, WSL initiated a multi-client project to fund the continuation of the work. UK-based users and manufacturers joined the project, paying a membership fee, and the Department of Industry provided the remaining funds, up to fifty per cent of the project costs.

In 1982, a detailed programme for a two-year project was drawn up and agreed by members. The information and results were presented in a series of confidential reports to members. As part of the programme, a comprehensive test facility was built at Thames Polytechnic, funded by the project. The project was extended to three years with most of the member companies continuing to support it for the third year.

Each report included background explanations and derivations of formulae, etc and the complexity of some of the information led to a decision to produce an Abbreviated Guide which provided the project engineer with all the information required to design, or check the design, for a system but including only essential mathematics.

The project administration was carried out by WSL under the guidance of the then Head of Materials Handling Division, Dr Peter Bransby. The majority of the test work and report writing was carried out by Professor David Mills, then of Thames Polytechnic, under the supervision of the Head of Department, Dr Stanley Mason.

Because each report had to be complete in itself, the total of fifteen reports and appendices included some repetition in both text and diagrams as well as extensive cross-referencing. The difficult job of editing all the information to produce this book was carried out by Dr Pauline Hornsby, a freelance technical writer, with the technical guidance of Mr Chris Duffell of WSL.

The project was supported by the following companies:

Babcock Hydro-Pneumatics
Blue Circle Industries
British Gypsum
British Steel
Central Electricity Generating Board
Claudius Peters
Colmans of Norwich
Conoco
Doulton Industrial Products
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Simon-Carves
Simon-Solitec
Stb Engineering
Sturtevant Engineering
Tate & Lyle
Unilever
Vac-U-Max

It is through the efforts of the individuals and companies mentioned above and others who were involved in the project that this book can be produced now the project confidentiality period has expired. Having only had the responsibility of ensuring its publication, I am particularly indebted to Pauline Hornsby and Chris Duffell for producing a book which will undoubtedly enhance the understanding and application of pneumatic conveying.

Maurice Webb
Head, Marine Pollution and Bulk Materials
Warren Spring Laboratory, 1989

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Part A

Introduction

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Chapter 1

Introduction to the Guide

Summary

An introduction to this *Pneumatic Conveying Design Guide* and an outline of the work and its objectives are given. The state of the art on pneumatic conveying is detailed and the need for the Guide is explained. Definitions of the terms used in pneumatic conveying are given and the nomenclature used throughout the Guide is listed.

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1.1. Introduction

This *Pneumatic Conveying Design Guide* is intended to be of use to both designers and users of pneumatic conveying systems. It has been written on the basis that the reader knows nothing about pneumatic conveying, hence each aspect of the subject is discussed from basic principles and many of the chapters are of an introductory nature.

The Guide also includes detailed data and information on the conveying characteristics (Chapter 7, Determination and Use of the Conveying Characteristics in the Pipeline, Figures 145, 187 to 224) of a number of materials embracing a wide range of properties. The data can be used to design pneumatic conveying systems for the particular materials using logic diagrams for design procedures (Chapter 5, Pneumatic Conveying Design Procedures) and scaling parameters for the conveying line configuration (Chapter 9, Design of the Conveying Line Layout). Where pneumatic conveyors already exist, improving their performance based on optimising the system and uprating and extending systems (Chapter 11, Optimising and Uprating Existing Systems) or adapting them for a change of material (Chapter 5, Pneumatic Conveying Design Procedures) is also discussed.

Operational problems and some solutions are featured (Chapter 12), with an analysis of problems such as erosion, particle degradation and explosions. Trouble shooting is considered (Chapter 13) to enable the cause of plant operating problems, such as pipeline blockage, to be determined and corrected.

References to trade names of equipment are for identification purposes only and do not imply endorsement by Warren Spring Laboratory.

1.2. Availability of Design Data

Pneumatic conveying system design may be based upon previous experience or upon test results. Commercial interests dictate that manufacturers of pneumatic conveyors rarely publish information that could be of value in system design; a single value of material flow rate, conveying distance and, possibly, pipeline bore and air supply pressure is the extent of the information normally given. Even user companies, many of whom have had to 'tune' their own systems, are reluctant to divulge detailed information on conveyor performance.

Different materials are likely to have totally different conveying properties. If a system has to be designed for a material for which no previous experience is available, it will generally be necessary to carry out pneumatic conveying trials. These will generate the data upon which the design can be based.

In this Guide conveying characteristics (Chapter 7, Determination and Use of Conveying Characteristics in the Pipeline, Figures 145, 187 to 224) for some materials are presented which detail the relationship between the main conveying parameters for a material, over a wide range of conveying conditions, and the limits of conveying are clearly identified. With data presented in this form system design is relatively straightforward.

This type of data also allows analysis of existing systems to be carried out. Checks can be made to determine whether a system is operating under optimum conditions and, if not, how this can best be achieved. Similar checks will enable an assessment to be made of the potential for uprating a system. (See Chapter 11, Optimising and Uprating Existing Systems.)

1.3. Scope of the Work

This Guide is intended to be used by both designers and users of pneumatic conveying systems. For those not familiar with pneumatic conveying it provides information on the types of system available and the capabilities of pneumatic conveying systems in terms of material flow rates, conveying distances and power requirements. This should enable a project engineer both to assess alternative tenders received for a pneumatic conveying system and to make comparisons with mechanical systems.

For the designer data on a number of materials is presented (Chapter 8, Effect of Material properties on Conveying Performance; Chapter 9, Design of the Conveying Line Layout; Chapter 15, Bench Scale Test Methods for the Determination of Material Properties Relevant to Pneumatic Conveying; Figures 145, 187 to 224) which could be used for the design of systems to handle these materials. Where system design is based on results obtained from a test rig the actual plant pipeline may have a totally different configuration. To overcome this problem, scaling parameters are presented for conveying distance, pipeline bore, vertical sections and pipeline bends to enable test data to be used reliably (Chapter 9, Design of the Conveying Line Layout). For any given conveying duty a range of air supply pressures and pipeline bores will be capable of meeting the required duty (Chapter 5, Pneumatic Conveying Design Procedures). The design procedures outlined will allow selection of the combination which will give the lowest power requirement.

1.4. Review of Chapters

1.4.1. Chapter 1 Introduction to the Guide

An introduction to this *Pneumatic Conveying Design Guide* and an outline of the work and its objectives are given. The state of the art on pneumatic conveying is detailed and the need for the Guide is explained. Definitions of the terms used in pneumatic conveying are given and the nomenclature used throughout the Guide is listed.

1.4.2. Chapter 2 Types of Pneumatic Conveying System

An introduction to the various types of pneumatic conveying systems and the parameters which influence their capabilities in terms of material flow rate and conveying distance are given. The influence of the material on the conveying system is a major consideration. The well-established conventional pneumatic conveyors are discussed and brief mention made of methods of feeding the conveying line and of disengaging solids from the air at the discharge point. The problems of conveying certain types of bulk material are highlighted and recent developments in pneumatic conveying techniques aimed to overcome such problems are discussed, including single-plug blow tank, plug control and pulse phase systems. Mention is made also of air-assisted gravity conveyors. Capital and operating costs for each type of system are briefly compared.

1.4.3. Chapter 3 Feeding and Discharging the Conveying Line

Feeding material into a pneumatic conveying line and separating the solids from the conveying air at discharge are important aspects of the pneumatic conveying system. Both operations offer a wide choice of alternatives. Positive pressure systems may be fed using rotary valves, venturis, screw feeders or blow tanks, air supply pressure influencing the choice. Blow tanks provide only a batch-wise feed, restricting utilisation of the conveying line. Disengagement of coarse particles can be achieved by using a gravity setting chamber or a cyclone separator whereas finer particles can be removed by a combination of a cyclone separator and a fabric filter. The methods and associated equipment for feeding and discharging pneumatic conveyors are reviewed and their applications, limitations and control discussed.

1.4.4. Chapter 4 Selection of a Pneumatic Conveying System for a Particular Application

The selection of a pneumatic conveying system for a particular application involves consideration of numerous parameters associated with the conveyed material, the conveying conditions and the conveying system. The primary aim is usually for a material to be conveyed at a specified flow rate over a given distance. Extremes of material type are considered: a material having good air retention properties, material type A, and a material having poor air retention properties, material type B. The conveying requirements can usually be met by a wide combination of pipeline bores and conveying line pressure drops. Power consumption, and hence system operating costs, are factors that can be used in the decision-making process but problems of material and system compatibility also have to be taken into account. The inter-relating effects of all these parameters are considered.

1.4.5. Chapter 5 Pneumatic Conveying System Design Procedures

Logic diagrams are presented for pneumatic system design based on both mathematical models and test data. Some of the available equations and bench scale test correlations are evaluated and the more useful relationships are included to show how they can be used in conjunction with the logic diagrams. The design of systems which are required to convey more than one material and in which the conveying distance is variable is considered.

1.4.6. Chapter 6 Theory and Use of Compressed Air in Pneumatic Conveying

One of the most important design decisions to be taken when installing a pneumatic conveying system is the rating of the air mover. This is specified in terms of a delivery pressure and a volumetric flow rate. The flow rate is usually quoted in terms of free air conditions and not at the supply pressure. Since air is compressible, the actual volumetric flow rate increases along the length of a conveying line and, in a high pressure system, the change can be considerable. Conveying air velocity is an important parameter in the design of a pneumatic conveying system. The velocity at the material feed point is particularly critical. The conveying line inlet air velocity, therefore, must be related to a volumetric flow at free air conditions. The influence of pipe bore, pressure and temperature is considered for positive, negative and high pressure systems, and consideration is given to stepped pipelines and the problems of air humidity. A brief review of air movers suitable for pneumatic conveying applications is also included.

1.4.7. Chapter 7 Determination and Use of Conveying Characteristics in the Pipeline

Methods to determine conveying characteristics by mathematical models for single-phase flow and by conveying tests for two-phase flow (material conveying) are given. Conveying characteristics of a material provide a valuable aid to system design. They provide the design data in terms of air flow rate for a given material flow rate and qualify the effect of conveying line pipe bore and conveying distance. In addition, the conveying characteristics identify the minimum conveying conditions and provide the means to determine power requirements, thus enabling comparisons to be made for different conveying systems.

1.4.8. Chapter 8 Effect of Material Properties on Conveying Performance

A goal in pneumatic conveying is to make it possible to design a pneumatic conveying system without the need for carrying out full scale conveying tests with a material. The results of a study into correlations between material properties obtained from bench scale tests and material conveying characteristics obtained from full scale pneumatic conveying trials are given. Correlations were sought as to whether a material will convey in dense phase and what type of pressure drop/material flow rate characteristic is to be expected.

Tests to determine correlations between permeability factor, specific surface and vibrated de-aeration constant and the conveying mode indicate whether a material is likely to convey in dense phase. A material with very good air retention and very poor permeability will convey in dense phase. Further indications can be found by carrying out a particle size analysis. Materials with a very large size distribution are unlikely to convey in dense phase.

1.4.9. Chapter 9 Design of the Conveying Line Layout

It is rarely possible to carry out conveying tests with a material in a pipeline of the same length, bore and geometry as the proposed system. It is necessary either to scale data obtained from previous experience, or to scale data obtained from test work carried out specifically for the purpose. The availability and potential accuracy of scaling parameters are considered. Scaling parameters for conveying distance, pipeline bore, vertical pipelines, pipeline bends and rubber hose are presented. The models necessary for calculating the pressure drop in the empty pipeline are included.

1.4.10. Chapter 10 Design of the Total Conveying System

Designing a complete conveying system requires decisions to be made on the type of material feeding device, air mover and gas–solid separation equipment to be used. The design of the pipeline is particularly important as this will dictate the air requirements for specification of the air mover and filtration unit. Six decision stages are identified and discussed. Material properties and system requirements must be considered at all stages and the interaction between the various components and the system in terms of air leakage, pressure drop and performance must all be taken into account. System requirements and material properties are identified and discussed. Analysis of blow tank cycles is given to provide guidance on the selection of this type of feeding device and its incorporation into the total system. Consideration is given to capital and running costs.

1.4.11. Chapter 11 Optimising and Uprating Existing Systems

The need often arises to increase the throughput of a pneumatic conveying system to keep pace with expanding plant requirements. It may be possible to achieve an increase in conveying rate simply by optimising the existing system. This is an important aspect of uprating pneumatic conveyors. Changes to the air supply present problems because it is not usually obvious what the change should be to achieve a particular result. If components of the conveying system are changed the remainder of the system is likely to be affected, perhaps adversely. The optimising and uprating of existing pneumatic conveying systems are considered in detail.

1.4.12. Chapter 12 Operational Problems and Some Solutions

Potential users are often reluctant to install a pneumatic conveying system because they anticipate operating problems. Pneumatic conveyors can have problems but the situation has been improved by the introduction of new types of conveyor or by modification of existing systems, based on a better understanding of the mechanisms of conveying. This often results in a choice of solutions to a particular problem. The most common problems affecting pneumatic conveyors are examined, including particle degradation and particle melting, system erosion, static electricity, explosion risks, and material deposition in pipelines. Some practical solutions to these problems are presented.

1.4.13. Chapter 13 Trouble Shooting

All types of operating problems arising in pneumatic conveying systems, both during commissioning of a new system and as an established system deteriorates in performance due to component wear, are considered. As the component which fails or gives problems is not necessarily the cause of that failure or problem, five broad areas are identified which enable a clear understanding of the failure or problem in relation to the whole system, the system components and the conveyed material.

1.4.14. Chapter 14 Case Study

Evaluating tenders for a pneumatic conveying system is often difficult because different suppliers may offer totally different systems to meet the requirements of a particular specification. This case study aims to provide guidance on the assessment of systems. First the problem is outlined, then alternative designs are discussed. Finally, some of the possible designs are evaluated in terms of capital and operating costs.

Cement has been chosen as the material for consideration in this case study and a conveying duty specified. The influence of pipeline bore and air supply pressure is investigated over a wide range of conditions. The required data is derived by applying appropriate scaling parameters to test results for the material. Using this basic data a range of conveying systems is considered: continuously operating systems based on twin blow tanks, screw and rotary valve feeders, and batch systems based on single and twin blow tanks.

1.4.15. Chapter 15 Bench Scale Test Methods for the Determination of Material Properties Relevant to Pneumatic Conveying

Details of the bench scale tests carried out on the materials chosen for the programme of pneumatic conveying trials, together with a discussion of the background of each test, are given. The tests were chosen to characterise and define the materials and to provide data on which to base correlations between material properties and pneumatic conveying characteristics. The measured properties of each material are tabulated.

1.5. Use of the Guide

1.5.1. System Selection

For someone who has to select a system for a given duty, Chapter 2, Types of Pneumatic Conveying System, is a good starting point. Chapter 4, Selection of a Pneumatic Conveying System for a Particular Application, should also be consulted. In assessing tenders for a system, Chapter 14, Case Study, provides an insight into the choice between alternative systems, a comparison of components and economic considerations.

It may be necessary to refer to some of the introductory chapters for background information. In Chapter 3, Feeding and Discharging the Conveying Line, for example, a review of material feeding and gas–solid separation devices is given. Air requirements are considered in Chapter 6, Theory and Use of Compressed Air in Pneumatic Conveying, both in terms of mathematical relationships for specifying air movers and a review of air movers suitable for pneumatic conveying applications. Chapter 7, Determination and Use of Conveying Characteristics in the Pipeline, gives the basic approach to conveying line performance and capability in this Design Guide.

1.5.2. System Design

For system design Chapter 5, Pneumatic Conveying System Design Procedures, is the starting point for those familiar with pneumatic conveying systems. Logic diagrams are presented for system design based on the use of mathematical models and experimental data. This relates particularly to the design of the pipeline. Design of the total conveying system is then considered in Chapter 10.

Experimental pipeline conveying data for a range of materials and material/pipeline combinations is presented in Figures 145, 187 to 224. If this, or similar data is to be used for system design, then Chapter 9, Design of the Conveying Line Layout, needs to be consulted also. This provides the necessary parameters to enable the data to be scaled from the test line to the plant pipeline. For the specification of the air mover see Chapter 6, Theory and Use of Compressed Air in Pneumatic Conveying.

1.5.3. System Operation

It is always worth checking that an existing system is working under optimum conditions. If it is not then it is possible that significant savings in power could be made or an increase in throughput could be achieved. This is included in Chapter 11, Optimising and Uprating Existing Systems along with a consideration of how existing systems can be uprated.

Discussion on systems required to handle more than one material and to convey materials over a range of distances is included in Chapter 5, Pneumatic Conveying Design Procedures. Control of pneumatic conveying systems, and in particular those incorporating blow tanks, is included in Chapter 3, Feeding and

Discharging the Conveying Line, and Chapter 11, Optimising and Uprating Existing Systems.

1.5.4. Operating Problems

Chapter 13 is devoted to trouble shooting. This includes advice on problems which may occur during commissioning of a plant as well as under normal operation. A more detailed analysis of specific operating problems, such as bend erosion, particle degradation and explosion risks is given in Chapter 12, Operational Problems and Some Solutions.

1.6. Definitions

1.6.1. Introduction

To provide a uniform approach to the work, basic definitions of conveying phases, air velocities, operating pressures and conveying conditions are given here. The most important point is that dilute and dense are the only conveying phases to which reference is made. This is primarily a function of material properties. The vast majority of materials are capable of being conveyed in dilute phase, or suspension flow, but only certain materials are capable of being conveyed in dense phase, or non-suspension flow, in a conventional pneumatic conveying system.

It is recognised that materials capable of being conveyed in dense phase can be conveyed in a number of different stable flow regimes. There is, however, a smooth transition from one mode of flow to another and this can change along the length of a pipeline.

The mode of flow possible is also dictated by conveying distance and conveying line pressure drop, hence, in terms of system design, much confusion is avoided by referring only to dilute and dense phase.

1.6.1.1. Phase Density

Phase density, ϕ, is the ratio of the mass flow rate of the solids conveyed, $\dot{m}_p$, to the mass flow rate of the air used for conveying, $\dot{m}_a$

$$\text{i.e. } \phi = \frac{\dot{m}_p}{\dot{m}_a} \tag{1}$$

Note: Phase density is used by pneumatic conveying engineers to describe the nature of the gas–solid flow in a pipeline. Other terms used include solids loading ratio, mass ratio and mass flow ratio. It is a useful dimensionless quantity since its value does not vary with the conveying gas pressure and so it remains constant throughout the pipeline.

1.6.1.2. Dilute Phase Conveying

Dilute phase conveying occurs when a material is conveyed in suspension in the flowing gas.

Note: The dilute phase mode of conveying is sometimes referred to as lean phase or suspension flow. In terms of phase density the appropriate range, for most materials, is generally below ten. To keep the material in suspension in the pipeline, it is necessary to maintain a minimum value of conveying line inlet air velocity which, for most materials, is of the order of 13 to 15 $m s^{-1}$ (43 to 50 $ft s^{-1}$). This air velocity produces sufficient drag force on the solid particles to ensure suspension flow. The vast majority of materials can be conveyed in this mode.

1.6.1.3. Dense Phase Conveying

Dense phase conveying occurs when materials are conveyed with air at velocities lower than those required for dilute phase (suspension flow) (see Section 1.6.1.2.), over all or part of the pipeline.

Note: The nature of dense phase flow is very varied, for it depends upon the properties of the bulk solid, the phase density of the conveyed material and the conveying air velocity. Typically it includes flow over a deposited layer, which may itself be moving slowly, and flow in discrete or separate plugs of material. In terms of phase density the approximate range, for most materials, is normally above ten. The range of materials which can be conveyed in this mode, by conventional means, is limited.

1.6.1.4. Low Pressure and Negative Pressure (Vacuum) Conveying

Low pressure and negative pressure conveying systems are those which operate with air supply pressures below one bar gauge (201.3 $kN m^{-2}$).

Note: These systems cover the normal operating range of Roots-type blowers (see Section 6.6.4. and Figure 72) and rotary valve systems (see Sections 2.3.2. and 3.2.3. and Figure 12). Low pressure is not synonymous with dilute phase conveying (see Section 1.6.1.2.). If a material is capable of being conveyed in dense phase, a low pressure system could be used to convey the material in dense phase mode over a short distance.

1.6.1.5. Medium Pressure Conveying

Medium pressure covers the air supply pressure range from one to three bar gauge (201.3 to 401.3 $kN m^{-2}$).

Note: In terms of systems it encompasses blow tanks (see Sections 2.3.7. and 3.2.7.) and screw feeders (see Sections 2.3.2. and 3.2.4.) and some modified systems such as twin rotary valves.

1.6.1.6. High Pressure Conveying

High pressure systems are generally those which operate with air supply pressures greater than three bar gauge (401.3 $kN m^{-2}$).

Note: High pressure conveyors are almost entirely restricted to blow tank systems (see Sections 2.3.7. and 3.2.7. and Figure 12). Blow tanks are not only associated with high pressure systems; they can also be used for feeding low pressure systems. High pressure is not synonymous with dense phase (see Section 1.6.1.3.). Conveying distance has an over-riding effect, as does the material properties.

1.6.1.7. Free Air Conditions

Free air conditions are specified as those at which p = 101.3 $kN m^{-2}$ (standard atmospheric pressure) and t = 15°C (standard atmospheric temperature).

Note: Free air conditions are generally used as the reference conditions for the specification of air movers.

1.6.1.8. Superficial Air Velocity
This is the velocity of the air disregarding the pressure of solid particles or porous media.

Note: In a pipeline it is the air velocity based upon the cross-sectional area and neglecting the space occupied by the conveyed material. For flow through a membrane or across a filter, it is the open duct velocity normal to the surface. Air velocity is dependent upon both pressure and temperature. When conveying air velocities are evaluated at any point in a system, the local values of pressure and temperature at that point must be used.

1.6.1.9. Free Air Velocity
This is the superficial velocity (see Section 1.6.1.8.) of the air at free air conditions (see Section 1.6.1.7.).

1.6.1.10. Minimum Conveying Air Velocity
The minimum conveying air velocity is the lowest superficial air velocity (see Section 1.6.1.8.) which can be used to convey a material.

Note: In dilute phase flow (see Section 1.6.1.2.) it is the lowest air velocity which can be achieved without saltation (see Section 1.6.1.13.) or choking (see Section 1.6.1.14.) occurring. The value of the minimum conveying air velocity in dense phase flow (see Section 1.6.1.3.) is significantly influenced by the phase density (see Section 1.6.1.1.) of the conveyed material.

1.6.1.11. Conveying Line Inlet Air Velocity
This is the superficial air velocity (see Section 1.6.1.8.) at the point where the material is fed into the pipeline.

Note: In a single-bore pipeline this will be the lowest air velocity in the conveying line and so it must be greater than the minimum conveying air velocity (see Section 1.6.1.10.) required to ensure successful conveying of a material. This is variously referred to as the pick-up or entrainment velocity. In a negative pressure system it is approximately equal to the free air velocity (see Section 1.6.1.9.).

1.6.1.12. Conveying Line Exit Air Velocity
This is the superficial air velocity (see Section 1.6.1.8.) at the end of a conveying line where the material is discharged into the receiving vessel.

Note: In a single-bore pipeline this will be the highest air velocity in the conveying line. In a positive pressure system it is approximately equal to the free air velocity (see Section 1.6.1.9.).

1.6.1.13. Saltation
Saltation is the process of deposition of solid particles along a horizontal pipeline.

Note: This phenomenon occurs in dilute phase flow (see Section 1.6.1.2.) when the air velocity falls below the minimum conveying value. The saltation velocity is the minimum velocity at which a dilute phase system will operate and is equivalent to the minimum conveying air velocity (see Section 1.6.1.10.).

1.6.1.14. Choking
Choking occurs in vertically upward flow and is the process which commences

when solid particles near the pipe wall begin to flow downwards. As the process continues the pipeline eventually becomes blocked or chokes.

Note: Choking in vertical transport is somewhat analogous to saltation in horizontal transport (see Section 1.6.1.13.), for both phenomena represent saturation conditions in dilute phase flow (see Section 1.6.1.2.).

1.6.1.15. Null Point

The null point in a system is the position where the pressure is equal to the ambient pressure.

Note: This is generally used in relation to closed loop systems and identifies a natural point of access to the system for monitoring or conditioning.

1.6.1.16. Specific Humidity

Specific humidity, w, is the ratio of the mass of water vapour, m_v, to the mass of air, m_a, in a given volume of the mixture

$$\text{i.e. } w = \frac{m_v}{m_a} \tag{2}$$

1.6.1.17. Relative Humidity

Relative humidity, χ, is the ratio of the partial pressure of the air, at a given temperature, to the partial pressure of the air when saturated, at the same temperature.

Note: Whereas specific humidity (see Section 1.6.1.16.) gives an indication of the amount of water vapour that is actually contained in the air, relative humidity gives an indication of how much more water vapour the air is capable of supporting before it becomes fully saturated. Its value is usually expressed as a percentage.

1.6.1.18. Stoichiometric Value

The dust cloud concentration at which the quantity of air available exactly matches that necessary for combustion of a material.

1.6.1.19. Duning

Duning and duning flow occur during dense phase conveying (see 1.6.1.3.). Material becomes deposited in the pipeline in mounds, or 'dunes'. The deposited layer may itself be moving slowly. Material from the crest of the dunes is entrained by the conveying air, followed by deposition and re-entrainment until the material is discharged at the conveying line exit.

1.6.1.20. Pulsating Flow (Pulsation)

Pulsating flow is continuous alternating high and low rates of flow.

Pulsating solids flow in the pipeline can be caused by pulsating material flow from the feeding device, such as rotary valves, or by pulsating conveying air flow from the air mover, such as Roots-type blowers. Pulsating air flow is a result of continuous alternating high and low air compression by the air mover due to the manner in which the machine operates. Pulsating air flow in the conveying line can be reduced by the use of an air receiver.

1.6.1.21. Hardness
Hardness can be defined as the resistance of a material to an applied pressure or force.

1.6.1.21.1. Mohs' Scale. The Mohs' scale of hardness is based on the ability of each material to scratch ones that come before it on the scale. Each material is allocated a number, 1 for the least hard material through to 10 for the hardest material.

Talc 1, gypsum 2, calcite 3, fluorite 4, apatite 5, feldspar 6, quartz 7, topaz 8, corundum 9, diamond 10.

1.6.1.21.2. Brinell Hardness. The Brinell hardness number is a number proportional to the load (f), or test force (F), of a hard steel ball to the calculated curved area of the indentation formed. The ball diameter is 1, 2.5, 5 or 10 mm. Standard values of the ratio of the load to the square of the ball diameter, (f/D^2), are 30, 10, 5 and 1. The ratio of the diameter of the indentation formed (d) to the diameter of the ball, (d/D), should be between 0.25 and 0.6.

1.6.1.21.3. Vickers Hardness. Vickers hardness is a ratio of the load (F), expressed as kilograms force, of a square-base diamond pyramid shaped indenter, opposite faces containing an angle of 136 degrees, to the sloping area of the indentation formed, expressed in square millimetres. Tests should be made on a flat surface. Correction factors are required when tests are made on cylindrical or spherical surfaces. Standard loads are 1, 2.5, 5, 10, 20, 30, 50 and 100 kg force.

1.6.1.22. Transient
Temporary continuous changing rate of flow caused by non-steady state pneumatic conveying, such as during start-up or shut-down of blow tanks. The changing rate of flow, or transient, decreases as steady state conveying is reached.

1.7. Nomenclature

1.7.1. Symbols

A	pipe cross-sectional area	m^2
b	equivalent length of bends	m
C	conveying air or gas velocity	$m\,s^{-1}$
C	permeability factor	$m^3\,s\,kg^{-1}$, $m^2\,N^{-1}\,s^{-1}$
C_i	conveying line inlet air velocity	$m\,s^{-1}$
C_{min}	minimum conveying air velocity	$m\,s^{-1}$
C_p	specific heat at constant pressure 1000 for air	$kJ\,kg^{-1}\,K^{-1}$
C_v	specific heat at constant volume 714.3 for air	$kJ\,kg^{-1}\,K^{-1}$
D	pipeline bend diameter	m
d	pipeline diameter, bore, size	m
d_p	particle diameter	m
f	friction coefficient	dimensionless
h	total length of horizontal pipeline	m

H	hardness (Vickers)	$kg\,mm^{-2}$
k	constant in 'head' loss term	dimensionless
k'	de-aeration constant	$m\,s^{-1}$
k'_v	vibrated de-aerated constant	$m\,s^{-1}$
L	pipeline length, distance	m
L	bed height	m
L	length of plug	m
L_e	equivalent length of pipeline	m
M	molecular weight	dimensionless
m	mass	kg
$\dot{m}$	mass flow rate	$kg\,s^{-1}$
$\dot{m}_a$	air mass flow rate	$kg\,s^{-1}$
$\dot{m}_p$	material mass flow rate	$t\,h^{-1}$
$\bar{\dot{m}}_p$	time averaged mean value of material flow rate	$t\,h^{-1}$
$\bar{\dot{m}}_p$	mean material flow rate	$t\,h^{-1}$
$\dot{m}_p$	steady state value of material flow rate	$t\,h^{-1}$
$\hat{\dot{m}}_p$	material flow rate to be achieved to reach time averaged duty of batch conveying	$t\,h^{-1}$
$\hat{\dot{m}}_p$	maximum material flow rate	$t\,h^{-1}$
m_v	mass of water vapour	kg
mol	gram molecular weight number of mols = m(mass)/M(molecular weight)	g, (kg)
n	total number of bends	dimensionless
p	conveying air pressure	bar, $kN\,m^{-2}$
p	absolute pressure of air/gas	bar, $kN\,m^{-2}$
p_a	partial pressure of air	bar, $kN\,m^{-2}$
p_i	conveying line inlet air pressure	bar, $kN\,m^{-2}$
p_v	partial pressure of water vapour	bar, $kN\,m^{-2}$
$p_{v_{sat}}$	partial pressure of water vapour when saturated	bar, $kN\,m^{-2}$
Δp	conveying line pressure drop	bar, $kN\,m^{-2}$
Δp	pressure drop	bar, $kN\,m^{-2}$
Δp_a	conveying line pressure drop due to air only (empty line pressure drop, single-phase flow)	bar, $kN\,m^{-2}$
q	air flow rate	$m^3\,s^{-1}$
q	rate of flow of an incompressible fluid through a bed of powder	$m^3\,s^{-1}$
R	characteristic gas constant (R_0/M) 0.287 for air, 0.297 for nitrogen	$J\,kg^{-1}\,K^{-1}$
R_0	universal gas constant, 8.31434	$J\,mol^{-1}\,K^{-1}$
S	particle surface area	m^2
S_v	specific surface	$m^2\,m^{-3}$
S_w	specific surface	$m^2\,kg^{-1}$
t	temperature	°C
T	absolute temperature (= t + 273)	K
U	superficial air velocity	$m\,s^{-1}$
U_{mf}	minimum fluidising velocity	$m\,s^{-1}$
V	volume	m^3
V	particle volume	m^3
$\dot{V}$	volumetric air flow rate	$m^3\,s^{-1}$