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Material Characterization and its Importance to Pneumatic Conveying

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SUMMARY

A simple means has been developed to reduce conveying velocities, reduce wear and power, and to increase the reliability of pneumatic conveying systems for powders. This paper describes the work carried out by Macawber Engineering and the advantages to be gained from the systems developed.

less, attempted fluidization of wet coal to the point where dilute-phase conditions have been produced with resulting high degradation of the coal.

There are materials, which due to their particle shape, size and distribution, produce impermeable plugs in the pipeline caused by the smaller particles wedging in the interstices of the larger particles within the plug. The resulting mass of material produces frictional resistances within the pipe which as *Marcus* and *Klintworth* [3] pointed out can produce pressure drops that increase exponentially with plug length. The result is a serious pipeline blockage which may be impossible to clear by normal methods (air injection, high pressure, etc.). Some systems which use short slug conveying or employ defensive systems have been successful in overcoming this problem. The user/designer, however, should practice extreme care when designing or selecting systems to handle these types of materials.

5. The Effect of Material Characteristics on System Performance

As we have seen, certain material characteristics can determine or limit the choice of pneumatic conveying regime. When making this assessment, the effects on system performance should be taken into account. These effects are chiefly pipe erosion, product degradation, and material segregation, and the conveying of explosive powders. All of these effects appear to be related by material velocity and conditions inside the pipeline.

Dilute-phase systems, we have seen, are characterized by high material velocities and fully suspended, homogeneous flow with a high degree of inter–particle and particle–pipewall collisions. If moderately or highly abrasive material is conveyed in this manner, or even with highly fluidized dense-phase systems, substantial and rapid pipewear will occur.

Work carried out by *Mills, Mason* and *Agarawal* [9] demonstrated that a relationship between velocity and the rate of erosion exists, expressed as:

$$E=(V_1/$$

where E = Increase in rate of erosion

$\frac{V_1}{V_2}$ = Increase in velocity

It is suspected that a similar relationship may exist with regard to product degradation although particle turbulence in the pipe also contributes to the overall level of degradation. If very stable conditions in the pipeline can be combined with low material velocities (such as those observed in the solid dense-phase regime), then extremely low rates of product degradation can be achieved with even the most friable of products.

A blended material may comprise several different types of powders, combined together for a specific purpose or process. High velocity will cause the different powders to separate due to differing particle density or size. This, of course, is a highly undesirable situation from the user's point of view, especially if a complex process has been employed to blend the material in the first place. Clearly, each of these applications will benefit from lower velocity conveying, i.e., one of the dense-phase regimes.

Dense-phase conveying is also beneficial when conveying explosive powders since the air/material mixture is usually outside of the range that would support a spontaneous explosion in the pipeline. Also, the lower velocity helps reduce the build-up of static electricity. With explosive powders, the problem is more critical in the feed/receiving bins and the pressure vessels where swirling clouds of dust form a serious risk. These risks can be minimized by employing such measures as conveying/purging with an inert gas, properly grounding all equipment and pipelines, effectively sealing all valves and filters and using low-sparking materials of construction.

6. Material Characterization/Testing

What steps should the designer take to safeguard against "problem" materials and poor system performance? Many organizations are now carrying out material characterization testing and classifications using bench tests with the results correlated to previously observed conveying conditions.

In the 1970s, *Geldhart* [4] and *Dixon* [5, 6] developed classifications which by comparing mean particle size and particle density with observed results of fluidization, produced groups of materials which could be expected to behave in a certain manner. In recent years, work by *Woodcock* and *Mainwaring* [7], *Mills* and *Jones* [8] and *Mainwaring* and *Reed* [10] have compared permeability factors and air retention factors with particle density and unit pressure drops to produce more reliable, predictive classifications.

By carrying out bench tests, information may be gained to assist the designer in the selection of conveying phase, and in some cases, the conveying equipment itself. The best method, however, remains that of carrying out production scale tests. Such tests can yield not only air flow and pressure data, but also actual measured material velocities and observed flow patterns via transparent pipes.

7. Conclusions

Material characterization is of prime importance when designing and selecting pneumatic conveying systems. Bench tests and correlations can be extremely useful in predicting the probable flow patterns of materials. Full scale testing remains the best method of establishing conveying criteria and observing flow patterns.

Finally, there is a pressing need to form internationally agreed material characteristic standards and eliminating, as far as possible, subjective characteristics.

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Material Characterization and Its Importance to Pneumatic Conveying System Design

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1. Introduction

The design of any type of pneumatic conveying system is determined by two important considerations:

a) The system objectives, i.e., what is required of the system in terms of capacity, conveying distance, distribution, etc.

b) The characteristics of the material to be conveyed.

Most engineers and system users will be aware that operating costs, capacity, conveying distance, etc., are important features when selecting the type and size of the system to be used.

System performance and any limitation to performance are, however, dependent upon the characteristics of the material which is to be handled. Material characteristics can, in fact, directly determine the choice of conveying regime and system type. This, in turn, can determine system capital and operating costs.

2. Material Characteristics

The characteristics of a bulk solid material are different for each type and grade of material. Some properties such as explosiveness and hygroscopicity are applicable to just a few cases. Other characteristics such as bulk density and particle size distribution are common to all bulk materials.

One of the problems in describing material characteristics, especially if a design specification is being written, is that there are, as yet, no internationally agreed standards. Therefore, a certain amount of subjectivity exists in material property descriptions and confusion as to the terms used.

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Before considering the effects upon pneumatic conveying systems and selection of suitable conveying regimes, we should review the most important characteristics.

2.1 Bulk Density

Bulk density can be expressed as "packed" (alternatively called "compacted"), or as loose (or poured). Pneumatic conveying system design is based upon the loose bulk density, since in order to feed material into a pneumatic conveying system device such as a rotary valve or pressure vessel, the material is likely to be free flowing or in a fluidized state.

The difference between loose and packed bulk density can be expressed as the "compressibility factor". This can be useful. For instance, a high compressibility may indicate possible flow problems out of hoppers and silos.

Bulk density is used when sizing rotary valves and other volumetric devices and for calculating capacities.

Particle density, which is the mass of the particle divided by the particle's volume, is used in predictive studies, for instance, *Geldhart* and *Dixon* classifications. The particle density in combination with particle size and shape also affects minimum conveying velocity.

2.2 Particle Size, Shape and Distribution

It is now believed that this group of characteristics is the main influence on pneumatic conveying regime and system type. These three characteristics appear to combine in different ways to affect other properties such as air retention, permeability, angle of repose, minimum conveying velocity and so on.

Mean particle size has been used by *Geldhart*, *Dixon*, *Marcus* and others to construct predictive classifications of material types. One should also consider the maximum particle size since the conveying pipeline diameter should be at least three times the dimension of the maximum particle size. In the dilute-phase regime, particle size and shape combine with particle density to determine the minimum conveying velocity (see also 4.1).

Particle size distribution is an analysis of the bulk material particles broken down by percentage into its various size fractions. Collection of this information is important since a wide particle distribution will produce different conveying results than that of a narrow distribution. Indeed, materials with uniform distributions, i.e. particles of the same size, will handle differently to those materials with varying distributions.

Particle shape is, unlike particle size and distribution, a descriptive term rather than a physically measurable one. Table 1 describes an example of a particle shape classification for powders (British Standard 2955). Naturally choice of the particle shape can vary from individual to individual and subjective error can creep in. Research by several groups has shown that round, smooth particles are "easier" to convey than angular particles with rough surfaces.

Table 1: Particle shape classification for powders below 1,000 μm

Term	Definition
Acicular	Needle-shaped
Angular	Sharp-edged or having roughly polyhedral shape
Crystalline	Of geometric shape, freely developed in a fluid medium
Dendritic	Having a branched crystalline shape
Fibrous	Regularly or irregularly thread-like
Granular	Having an approximately equidimensional but irregular shape
Irregular	Lacking any symmetry
Nodular	Having a rounded irregular shape
Spherical	Globule shaped

It can be seen that materials such as plastic pellets which can be described as uniformly sized, round and smooth, will be quite easy to convey, especially in the plug flow, dense-phase regime. And yet, these materials have traditionally been conveyed in the dilute-phase at high velocity, resulting in the production of snakeskins and angel hair.

2.3 Moisture Content

Moisture content, generally water, is the proportion of water to water-plus-solids and is expressed as a percentage by weight. When considering moisture content, two terms are used:

a) Surface (or free) moisture which is the water present on the surfaces of the particles.

b) Inherent (or chemically bound) which is the water of crystallization found within the structure of the particles.

Since the surface moisture can radically affect the way in which a material behaves, this property is considered the more important of the two.

Any water present on particle surfaces can result in surface tension effects which inhibit the movement of the particles relative to each other, causing the bulk solid to become cohesive (see also 2.4), resulting in poor gravity flow characteristics. Moisture can also penetrate the gaps between the particles preventing air from entering the material thus making it difficult to fluidize.

Moisture can react with the bulk solid itself producing effects that may be hazardous. For instance, calcium carbide reacts with water to produce a flammable gas. Other materials may produce toxic fumes when in contact with moisture. Such materials must, therefore, be kept dry to prevent any hazardous conditions from occurring.

2.4 Cohesiveness and Adhesion

The degree of cohesiveness of a material describes its "flowability" under gravity only. A powder exhibiting low cohesiveness, such as sand for instance, will freely flow under gravity conditions from bins and silos. A powder described as highly cohesive, such as Titanium Dioxide, would have such poor flow properties that it would not flow from a bin without a specific form of flow assistance such as vibration or aeration.

Cohesiveness can be caused by several factors such as electrostatic charging, surface tension effects caused by moisture, or simply the particle shape itself which causes the particles to lock together.

Cohesiveness describes the internal flow properties of a material. External flow properties are the extent to which a material is "adhesive". Some materials may stick to the internal surfaces of bins, pressure vessels and pipelines. Successive layering of deposited material in pipelines, for instance, can be serious, causing blockages if precautions are not taken during the design stage.

2.5 Hardness and Abrasiveness

One of the factors that cause a material to be abrasive is its hardness. Abrasiveness and hardness are both somewhat subjective characteristics. Nevertheless, the designer/user of a pneumatic system should strive to make as accurate an assessment as possible since highly abrasive materials cause substantial erosion to pipelines and components, especially in high velocity systems.

Mohs' scale of hardness (Table 2) is an indication as to the hardness of a material, but this has to be combined with the particle shape to assess the material's abrasiveness properly. Materials that are high on *Mohs*' scale and which have angular or sharp-edged particle shapes will produce highly abrasive materials.

Unfortunately the only classification that seems to refer to material abrasiveness describes materials as non, mildly, moderately or highly abrasive. This, of course, may not communicate the correct information to a designer and, clearly some better numerical assessment of abrasiveness is required.

Table 2: *Mohs*' scale of hardness

Mohs' scale	Material	Explanation of test
1	Talc	very soft, can be crumbled between fingers
2	Gypsum	moderately soft, can scratch lead
3	Calcite	can scratch fingernail
4	Fluorite	can scratch a copper coin
5	Apatite	can scratch a knife blade with difficulty
6	Feldspar	can scratch a knife blade
7	Quartz	will scratch glass
8	Topaz	"
9	Corundum	"
10	Diamond	"

2.6 Temperature

High material temperature can cause changes in the characteristics of that material. For instance, 5 mol Borax will undergo chemical changes at temperatures as low as 100 °F, causing it to become cohesive and sticky. Others, such as resins and sugars, can soften to the point where serious coating of internal pipe walls and surfaces of pressure vessels will take place.

Materials at very high temperatures, for example, boiler ash, foundry knock out sand, etc., will require special consideration with respect to the conveying system hardware such as infeed valves. High temperatures also reduce the abrasion resistance of mild steel, making it more susceptible to erosion from abrasive materials. In these cases, higher resistant materials of construction such as Ni-hard cast iron may be used.

2.7 Friability

Friability is a characteristic of a material which describes its fragility. The more friable a material is, the greater its tendency to degrade at an increasing rate as the velocity of conveying increases. If the product degradation is of concern to the user, care must be taken to insure that a conveying regime is chosen that will provide the lowest possible velocity and the most stable pipeline conditions.

2.8 Chemical Properties

There are several chemical properties that must be considered when designing a pneumatic conveying system. The most important of these are hygroscopicity, explosiveness and corrosiveness.

If a material is hygroscopic, it will possess the ability to absorb moisture from its surroundings and from the conveying medium. This moisture can change the other characteristics of the material, such as permeability, cohesiveness, etc., and can react dangerously with the material (refer to 2.1).

An explosive powder is described as one which, when dispersed in air can be ignited by a spark, flame or heated coil. Most carbon-based powders (e.g., sugar, flour, coal dust, etc.) are considered explosive as well as metal powders such as magnesium and aluminum and various other chemicals and plastics.

Certain chemical properties of a material can interact with the materials of construction of a system to cause oxidation or corrosion. A salt, for instance, may be hygroscopic and absorb moisture, which in turn, reacts with the salt and attacks the pipeline and components of the system.

2.9 Permeability and Air Retention

During the past few years, considerable research has been carried out investigating the permeability and air retention properties of bulk solid materials.

The permeability of a material is an indication of its readiness or ability to accept air and become fluidized. A simple test can be carried out to determine a permeability factor which can be used in various material classifications. Air retention is the ability of a material to retain air and remain in a fluidized state. Sand, for instance, has a low air retention capability, whereas cement and flyash exhibit high air retention characteristics. These properties are determined primarily by particle shape, size and distribution.

Permeability is considered to be a significant property with regard to discontinuous dense-phase plug flow. Air retention appears to be an indication of the suitability of a material for conveying in the continuous, dense-phase moving bed flow regime.

3. Conveying Regime Types

Most designers are aware that there are several variations in flow patterns during pneumatic conveying. Simple terms such as dilute-phase and dense-phase are not adequate to describe these variations.

Wens and *Simon* [1] identified a series of ten flow patterns which ranged from full suspension flow to pipeline blockage as the conveying velocity was progressively reduced. This series of flow patterns, however, contains several unstable flow types which are, from a practical design standpoint, undesirable.

Jodlowski [2] listed four stable flow regimes (Fig. 1) as follows:

a) *Dilute Phase*: Conveying occurs above the saltation velocity, and flow is fully suspended and homogeneous.

b) *Continuous Dense Phase*: Material moves by saltation over a steadily moving bed.

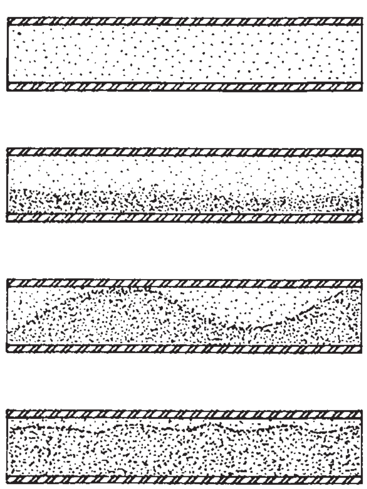

Fig. 1: *Jodlowski*'s stable flow classification:
a) dilute phase – homogeneous flow
b) continuous dense phase – moving bed flow
c) discontinuous dense phase – plug flow
d) solid dense phase – extrusion flow

Table 3: Comparative data for pneumatic conveying regimes

Flow Regime	Average velocity ft/min		Phase density	Air-to-material ratio	Conveying pressure psi
	air	material			
Dilute phase	4,500-7,000	4,000-6,500	below 15	over 100:1	less than 10
Continuous dense phase	1,500-4,500	1,000-3,000	15-50	20 to 100:1	10 to 40
Discontinuous dense phase	500-2,500	200-1,500	20-150	below 30:1	15 to 60
Solid flow dense phase	400-1,000	100-500	over 30	below 20:1	above 20

c) *Discontinuous Dense Phase*: Conveying takes place at well below the saltation velocity during which the material moves in a pulsatile manner, often with plugs of particles filling the whole cross-section of the pipe.

d) *Solid Dense Phase*: The conveyed material is effectively extruded through the pipe as a continuous plug.

Table 3 provides comparative parameters of these regimes. It should be noted that this data should be used for comparison only between the regimes for the same material and conveying distance.

4. Material Characteristics and Pneumatic Conveying Regimes

There are now many choices available to the designer/user of a pneumatic conveying system. The four regimes described above are subject to different types of conveying system offered by many different manufacturers. The designer, however, should be aware that their choice of system may be limited by the nature of the material being conveyed.

Some materials exhibit "natural" tendencies to be conveyed in a certain manner. Polyethylene pellets, for instance, will naturally form plugs when conveyed in the discontinuous dense-phase regime.

Other materials are unable to be conveyed in a certain manner without the use of specialized systems fitted with "defensive" equipment such as air by-pass systems and anti-blocking devices.

4.1 Dilute-Phase System Limitations

Conveying in the dilute-phase regime requires that the minimum conveying velocity exceeds the saltation velocity. That is, the velocity at which material begins to fall out of the air stream or "saltate". For most powders with narrow particle size distributions, this is not a problem. However, as the mean particle size increases, particularly if those materials have high particle densities, the saltation velocity is also likely to increase. Eventually the velocity may become so high that the airflow required to support such velocities becomes inefficient in energy terms. In this case, one of the dense-phase regimes should be considered.

If the particle distribution is wide, there is the possibility of pipeline plugging if the minimum conveying velocity is not high enough to prevent saltation of the larger, heavier particles.

Dilute-phase systems operate at generally high velocities, and this can cause problems, depending on the nature of the material to be conveyed. Some cohesive materials can "plate" onto pipeline internal surfaces (especially on bends) at high velocity. Materials which are abrasive will cause severe erosion and friable materials will degrade rapidly at high velocity (see 5.). Again, if these conditions exist, dense-phase systems should be seriously considered.

4.2 Dense-Phase System Limitations

Within the dense-phase conveying regimes there are many variations in equipment types, mainly due to system manufacturers providing system hardware designed to achieve dense-phase conditions. Many of these systems rely on fluidization of the material to be conveyed, and this can be quite successful providing the material is capable of being fluidized. Some materials, such as sand, do not fluidize easily and have poor air retention/fluidization characteristics. This usually results in higher and higher volumes of air being used in an attempt to achieve proper vessel evacuation and to prevent pipeline blockages. This, in turn, results in higher material velocities, which in the case of sand causes accelerated pipewear.

In other cases, the condition of the material may not permit fluidization. Wet coal, for instance, is difficult to fluidize because the moisture present between the coal particles prevents air from entering the material. Some systems have, neverthe-