Challenges in Pneumatic Conveying

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Abstract
Challenges in pneumatic conveying have been explored in an attempt to provide the researcher and practicing engineer with a realistic view of the topic. While much has been achieved in the field in both modeling and experimental understanding, one can not rely totally on these predictions for complete design reliability. The most difficult topic is the individual properties of the various materials that are attempted to be conveyed. These material properties place limitations on the designer sometime because of their finest and others because of delicate nature in requiring that no change in the product occurs during the conveying operation. Unusual applications of pneumatic conveying are reviewed including such conditions as electrostatic generation, temperature and pressure effects.

Introduction
Pneumatic transport sometimes is the forgotten sister of many solids handling and processing operations. The general philosophy has been to worry about the design of the processing unit and then tack on the transport aspect of the operation. Often times, one finds that the transport section is the limiting aspect of the design. The conditions that are carefully controlled in the process can be completely upset by transfer, for example, in the plugging of coal transport lines to blast furnaces. One of the crucial elements of a transport operation is the properties of the materials. If one has developed studies using spherical Geldart type A materials, false confidences can be built such that a simple change in shape or surface characteristics of the particles cause an inoperative transport operation. Solids that are particularly difficult to transport are fine, cohesive materials such as carbon black and titanium oxide. Polymers can be easy to transport when their surface properties do not interfere with the pipe wall. A sticky, bouncy polymer that interacts intensely with the pipe wall has shown unique challenges for transport.

When it comes to the dense phase, one is faced with other kinds of challenges that do not come to light in a dilute phase transport systems. In dense phase conveying the contact between the wall and the particles is intimate and unique. Because piping can vary with surface roughness a system can change its degree of transportability as time proceeds in running the process.

Examples of the challenging materials in dilute and dense phase conveying can be cited:
• Granulated Sugar – This material is particularly sensitive to temperature effects. One can experience local temperature rises at impact points in the transport line. In addition the attrition of the sugar due to wall impacts often causes the product to be unacceptable for the customer. If one is able to address the temperature and attrition effects, care must be concentrated then on the moisture content of the sugar. High humidities can cause caking of the sugar and with this conveying problems arise. These effects of temperature, attrition and moisture of the sugar can change with time and the transport position in the line. One often finds that food stuffs can present the designer with unit material properties that require novel conveying operations.
• Carbon Black – Very fine materials such as carbon black are always challenging to convey or handle due to their cohesive nature. The use of flexible piping in the conveying process can help eliminate the deposits that tend to build upon the walls of systems that have rigid piping. The natural vibrations of the transport line can keep the pipe wall free from these deposits.
• Fine Coal – Coal Liquids – In the conveying of certain materials such a coal there is a high potential for deposits to build up on the bend due to the local temperature rise that occurs due to the impact of the solids with the wall. These
deposits can grow and in a very short period of time block the total pipeline. Coal liquids which are solids at ambient temperatures can soften and cause deposits to build as they are conveyed also due to the local temperature changes caused by impact of the particles and the wall.

- Titanium Dioxide – This fine material also presents conveying challenges. The biggest problem with titanium dioxide conveying is fluctuations in pressure drop. A system can periodically spike in pressure when dilute phase conveying conditions are present. It can be conjectured that these spikes are due to wall deposits in the transport line.

- Tacky Solids – Many polymer have unusual properties. The most challenging are those that have tacky surfaces. It some respects this material may be well not convey pneumatically because of the “glue” that exists between individual particles and the high potential for plugging.

Even if one recognizes the unique properties of materials sometimes one encounters unanticipated behavior for a conveying operation. One of these occurred in the vertical conveying of particles when reducing the conveying velocity at a constant solids flow rate. As one would expect, the pressure drop per unit length decreased as the velocity decreased but at a certain point the pressure rose reaching a local maximum and then fell before reaching a non conveying condition. This experiment was done both with increasing and decreasing velocities obtaining the same results. Upon close analysis with a simplified model one finds that at the larger velocities if one conjectures that the particles are behaving in a clustering manner with a larger effective particle size upon lowering the velocity instabilities are increased to break apart the cluster having the system behavior as if the particles are individual. Figure 1 shows this behavior and indicates the size of the proposed clusters and their component particles, (Klinzing et al., 1987). This effect has since been observed by others in the conveying of vastly different materials in the same pipeline, for example, in the conveying of diamonds with much heavier rock.

**Property Effects**

The ideal situation would be a series of basic tests that could be carried on the powder materials that will give the designer the ability to design out or around the problems or make decisions on which material would be more likely to succeed in pneumatic conveying.

One test for powders that has received much attention is that of the shear stress under various load conditions, Jenike type testing. These tests have proved invaluable in the design of bins and hoppers but have not been used as extensively in pneumatic conveying design. Such results are particularly applicable for dense phase conveying systems were intimate particle-particle and particle-wall interactions occur. The analysis of Konrad et al. (1980) first pointed to the importance of the shear stresses in powders to dense phase conveying operations. Other who have explored these avenues have been Aziz and Klinzing (1988) and Mi (1994).

Some interesting measurements that have been made by Molerus and Nywlt (1984) show the effective angle of friction of particle systems have on varying degrees of fines present in the material. As the fines content increases to about 40 percent fines, one sees a decrease in the effective angle of friction. Conjectures can be made that this biomodal distribution provides a ball bearing type lubrication to the powder by the presence of fines. This finding should be helpful in the analysis of dense phase plug systems and permit one to try to optimize plug transport with less energy being expended.

The shape of the particle being conveyed can also increase the pressure loss as shown comparing crush glass with rounded particles, Klinzing (1984).

The conveying of sodium bicarbonate in a crytalline form has showed some yet unresolved challenges. In the production of two lots of this material one was found to convey and other would not. Upon close inspection of the material properties including size and shape no differences were discernible. Since the conveying lines were the same, it is conjectured that some surface chemical difference although slight has an effect on the conveying properties, Rizk (1985).

An unusual conveying operation that can present some challenges is that of conveying crush iced. The bond that is produced between a metal surface and
the transported ice can cause considerable friction. While the plugs formed in the lines in these cases ultimately melt, a considerable disruption of the conveying operation can occur. The use of plastic pipe for the conveying of the crushed ice has proved to be superior since a thin film of melted water lubricates the ice as it is transported in the pipeline, Sheer (1991).

One of the most abrasive materials known to conveying is feldspar. In designing such conveying systems the number of geometry changes should be minimized in order to reduce pipe erosion especially in bends, Solt (1984). Another abrasive material is broken glass chars from fluorescence lights. Conveying this material can erode away the pipeline in very short order, Solt (1984).

Smokeless gun powder has been handled using dilute phase transport at a number of powder manufacturing facilities. The difficult property of this material is that it carries its own oxidant and as such conveying in a non oxygen atmosphere will not eliminate explosions. Care is taken in such operations to have dilute phase conveying be sure that no build up of powder in the transport line occurs where a hot spot can develop.

Uranium oxide powder is a very dense material that does not behave as normal powders. The dispersivity of this powder is almost like that of a large rocks with integrity. One important aspect of this powder in conveying and processing is its particle size distribution. Good conveying can be obtained when there is a bi-modal distribution of particles. The fines again are suspected of lubricating these mixtures.

Fibrous materials can change size and shape as they are conveying in a transport line. In the conveying of shredded tobacco a dog leg in the transport line is sometimes used in order to break apart the agglomerated fibrous ball that can grow in the system. Fiber glass can also show unique behavior with transport distances usually breaking down into fine fibers from cotton balls geometries.

**Challenging and Unusual Conveying Conditions**

Particulate materials placed in certain conveying environments respond by causing problems for the designer. Geometry is one of these environments that are crucial for an operative conveying system. The straighter the conveying line with few bends the more reliable the system. A good rule of thumb states that one should never place more than two bends in close repetition. The distances should be greater than about 20 feet between bends if possible. Water and air go through such bend geometries easily although expending more energy but particles have added difficulties due to the excessive particle wall contacts seen in these arrangements. Another phenomenon seen in bends that can cause problems in conveying applications is the splitting of the streams in the vicinity following a bend arrangement. As the particle go around a bend, roping of the flow is seen due to the secondary flows caused in bends. Particles concentrate in a rope like form causing difficulty in the equal splitting of the solids.

Inclined flows can also show some unique behaviors. One observes that the horizontal pressure drop per unit length is less than that of the vertical pressure drop but as the angle of inclination varies between the horizontal to the vertical one notes that at about 75 to 80 degrees of inclination there is a large increase in the pressure drop per unit length over that of the vertical value. One finds that this phenomenon is due to the interaction of the particles with the pipe wall which can sometimes cause a refluxing of the particles, Figure 2. One sees that the bottom half of the pipeline carries the majority of the particles often causing refluxing. Figure 3 shows this pressure drop.

**Fig. 2 Retrograde dunes in inclined flow.**

**Fig. 3 Pressure drop with angle of inclination.**
behavior as the angle of inclination varies, Klinzing et al. (1997).

**Electrostatic Phenomenon**

If one has a relative humidity of 75% or more electrostatic or triboelectric effects will seem strange as a concern in pneumatic conveying. Lower relative humidities trigger triboelectric effect by the contacting of particles of different surface properties. If a system is not well grounded such as plastic and glass piping, one finds very large and dangerous forces produced by the rubbing of materials with the wall of different surface conditions. In the generation of electrostatic forces pneumatic conveying ranks highest among all such operations.

Kleber (1994) made a fascinating review of the history of electrostatic effects at a meeting concentrating on this topic sponsored by the Nisshin Flour Mill Corporation. Figure 4 shows the concept of electrostatic charging applied to the spraying in the 1700's.

One of the earliest observation of the effect of electrostatics on pressure drop was shown by Richardson and McLean (1960). Using a system that would recycle the solid particles one sees as time proceeds the overall pressure drop increases. This pressure drop growth is attributed to the increased energy required to overcome the electrostatic forces generated on the particles being conveyed.

Electrostatics influences the flow patterns that are seen in horizontal conveying. With the non electrostatic condition one sees a rather gradual transitions from the dilute phase flow to the condition where the particles have all deposited on the bottom of the pipeline due to insufficient transport gas. Figure 5 shows this behavior along with the electrostatic influences which changes the flow patterns with a dominance of wall interactions due to charging, Dhodapkar (1990).

For vertical flow the electrostatic effect was found to build to a point were clustering of particles occurs until discharge occurs. At the discharge point the particle are dispersed into a homogeneous flow pattern from whence the whole process begins again. Figure 6 portrays this behavior, Plasynski (1991).

Under the same conditions ones sees rather dramatic changes in the pressure drop and its fluctuations shown in Figure 7, Klinzing (1994). This shows the intense wall interactions that occur when electrostatic forces are present.

The electrostatic effects in pneumatic conveying can produce some very unusual behaviors. In one horizontal conveying system the particles were being
conveyed with air of varying relative humidities. A 6 foot section of glass pipe separated two copper pipes producing a large section of non conductive transport. As the humidity was decreased, one would see the particles migrate to the wall of the glass section in a rather abrupt fashion and then begin to flow again the main air flow along the wall section of the pipe. Increasing the relative humidity caused a reversal of the phenomenon, Myler (1988). Figure 8 depicts this flow reversal phenomenon that was observed.

The relative humidity of the air transporting the solids has an effect to increase the pressure loss in a vertical transfer line as shown in Figure 9. At the same time the pressure fluctuations seen when the relative humidities are low is also significantly increased. It was been found that the solids loading at the minimum pressure drop point in vertical flow can be presented by relationship

\[ R = \frac{Fr^x}{10^6} \]

The relative humidity also affects the values of this expression. Joseph and Klinzing (1983)

<table>
<thead>
<tr>
<th>Relative Humidity</th>
<th>x</th>
<th>( \delta )</th>
</tr>
</thead>
<tbody>
<tr>
<td>55%</td>
<td>2.51</td>
<td>1.97</td>
</tr>
<tr>
<td>16%</td>
<td>4.38</td>
<td>4.96</td>
</tr>
</tbody>
</table>

Joseph and Klinzing also found under the presence of electrostatics increased pressure drop due in the choking region was present.

**Temperature Effects**

Some interesting observations have been seen in conveying material that is affected by temperature at high temperatures. Using a coal slag material it was found that this material softens with temperature cutting down its ordinarily abrasive characteristics at the low temperature. Figure 10 shows this decreased erosion of a ceramic pipe liner seen for the material as the temperature of conveying is increased. One can also see that as a pipe roughens in time as in the case
of a ceramic pipe liner that the pressure drop in the pipe will increase dramatically. This is due to the increased friction between the gas and the solids walls but also by the increased friction experience between the conveying particles and the pipe wall. Rebound angles change dramatically for rough pipes and can be seen in Figure 11, Borzone and Klinzing (1990)

**Pressure Effects**

Some interesting behaviors are seen when the pressure is increased in a pneumatic conveying system. While the pressure is not enough to cause a liquid phase the interaction between the particles and gas up to pressure of 4238 kPa show a more sluggish behavior. For small particles about 100 microns in size slugging rather than choking was observed in vertical transport. Large size particles did choke. There appears to be a non linear relationship at high pressure between the gas friction and solids friction while at lower pressures these effects are linear in nature and can be combined to obtain the overall pressure loss. Using an expression suggested by Weber one can represent the frictional terms for the gas and solid as

$$f_g = 0.1/Re^{0.131} [1/1+\mu^{0.7}]$$

$$f_s = 0.7848\mu^{0.906}Fr^{-1.02}$$

This indicates that there is more solids friction contribution in a high pressure system that in the a lower pressure system.

**Reduced Gravity Flows**

There has been interest by NASA is the possibility of conveying particulate matter namely illemite of the moon’s surface. This material which contains oxygen exists is a dust format on the surface of the moon. Reducing this ore with hydrogen can release oxygen which is needed for life support. In addition titanium metal is recovered which can be used on building of structures. Mechanical devices do no fare well in dusty environments thus the use of pneumatic conveying has been suggested. The differences between conveying on the moon and earth are that the gravitation field is 1/5 of that on earth and there is no atmosphere to draw upon. Conveying of solids under reduced gravity has been explored by two investigators in order to try to understand the conveying operation at reduced gravity which also provides an opportunity to explore the effect purely frictional forces in pneumatic conveying. Nemecek (1986) designed and built a facility to test our reduced gravity conditions proposing to probe the pure frictional effect seen under zero gravity. Sullivan et al. (1992) performed a number of experiments under reduced gravity. The choking velocity for 150 micron glass spheres were determined to be 1/2 to 1/3 the velocity at 1 g when the gravity was 0.16 to 0.38 g. The pressure drops were also seen to be reduced by a similar amount under reduced gravity conditions. Using the Rizk expression for saltation velocity the saltation velocity is seen with vary with the square root of the gravity term. This finding compared favorably with the results obtained under reduced gravity conditions.

**Literature**

5) Kleber, W., NEPTIS 3, Kyoto (1994)
Author's short biography

George E. Klinzing

Professor Klinzing is in the Chemical and Petroleum Engineering Department of the University of Pittsburgh where he does research and teaching in the area of solids processing with an emphasis on pneumatic conveying. He has studied several facets of pneumatic conveying from electrostatic generation to dense phase conveying operations. Most of his research has explored experimental phenomena using this as a basis to develop modeling and design procedures. He has written three books on pneumatic conveying along with a sizeable series of peer-reviewed articles.