18

Fluidized Motion Conveying Systems

1 INTRODUCTION

Although these conveying systems have been in use for well over one hundred years, they have been rather neglected. This is despite the fact that they are widely used for materials such as cement, fly ash and alumina, and are very economical to operate. The main problem is that they have, until recently, only been able to operate on a downward incline and as a consequence have been referred to as air-assisted gravity conveyors or "air slides". They have now been developed to operate horizontally and have considerable potential for further development.

Fluidized motion conveying can be regarded as an extreme form of dense phase pneumatic conveying. It is essentially an extension of this method, with the bulk particulate material made to flow along a channel. In the air-assisted gravity conveyor the channel is inclined at a shallow downward angle and the predominant factor causing flow is the gravitational force on the material. It this for this reason that air-assisted gravity conveying systems are potentially very economical to operate.

1.1 Conveying Technique

The technique to achieve conveying is essentially to maintain an aerated state in the bulk particulate material, from the moment that it is fed into the upper end of the channel, to the point at which it is discharged.

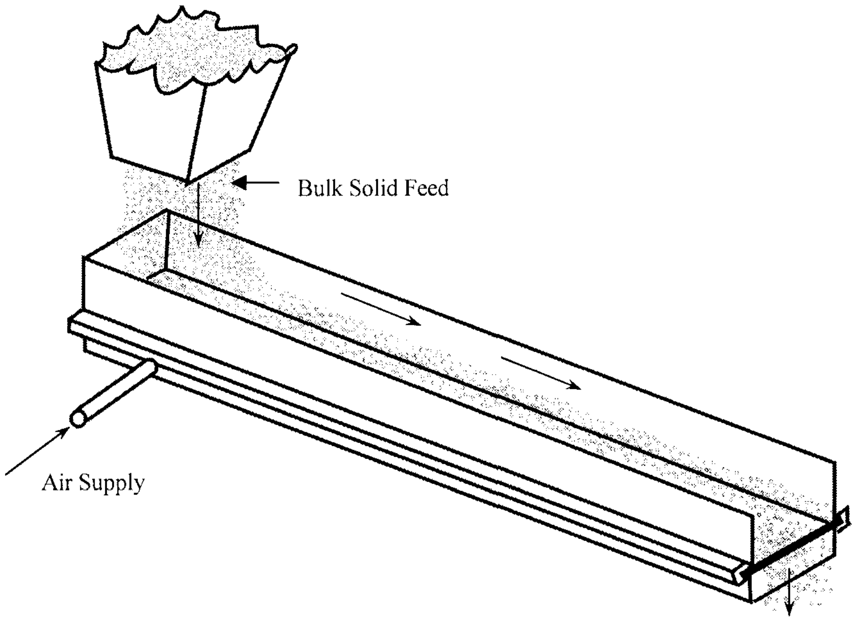

Figure 18.1 The principle of air-assisted gravity conveying.

This is achieved by means of the continuous introduction of air, or other gas, at a relatively low flow rate and pressure, into a plenum chamber, in order to fluidize the material. The principle of operation is illustrated with the sketch in Figure 17.1.

The air passes through a false bottom, or membrane, made of a suitable porous material, which runs the entire length of the channel. With powdered materials, and those containing fine particles, the channel is generally enclosed, as shown in Figure 18.2 [1]. By this means the entire conveying system can be totally enclosed. The fluidizing air, after passing through the bed of material sliding on the membrane, flows over the top of the bed of material and is vented through a suitable filter unit.

Since the bulk solid material is kept live by means of the steady flow of air, the material flows freely down the slope, even when the angle of inclination is relatively small. The quantity of air used is kept to the absolute minimum necessary in order to reduce both the inter-particulate forces, and the frictional forces between the particles and the internal channel surfaces, sufficient to allow the material to flow [1]. The air requirements for fluidized motion conveying systems, therefore, are relatively low and so they do need to be maintained between reasonably close limits in order to optimize conveying conditions.

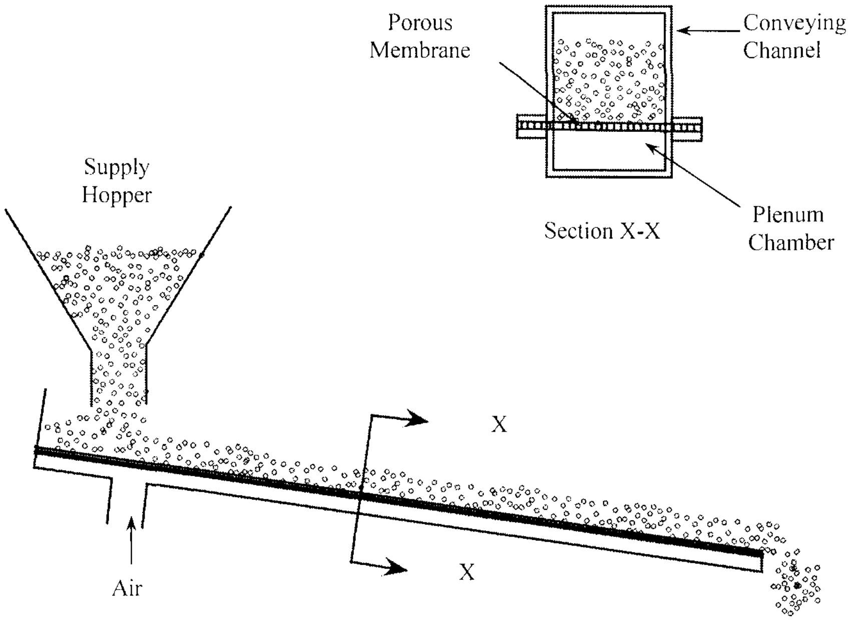

Figure 18.2 Typical air-assisted gravity conveyor.

1.2 System Advantages

Fluidized motion conveying has all the advantages of pneumatic conveying, but with few of the disadvantages. It provides a totally enclosed environment for the material, is very flexible in layout, and has no moving parts. With air-assisted gravity conveyors the only drawback is the fact that material can only be conveyed on a downward gradient, but as mentioned above, the system does have development potential that is making horizontal conveying, at least, a distinct possibility.

A particular advantage over pneumatic conveying is that the conveying velocity is very low. In dilute phase pneumatic conveying, solids loading ratios that can be achieved are very low and conveying velocities are consequently relatively high. As a result, power requirements are much higher than almost any alternative mechanical conveying system. Operating problems associated with abrasive particles, such as the erosive wear of system components, and degradation of friable particles, can be so severe that pneumatic conveying, as a means of transport, is often not considered for such materials.

If, in a pneumatic conveying system, the material can be conveyed in dense phase, power requirements will be lower and operating problems will generally be reduced. In fluidized motion conveyors, however, solids loading ratios are even higher and conveying velocities are much lower than those in dense phase conveying. As a result, power requirements are on a par with belt conveyors, and operating problems associated with abrasive and friable materials are almost non-existent.

1.3 Design Tolerance

The general principle of fluidized motion conveying is very simple and this method of conveying has a particular advantage of being essentially 'workable'. With pneumatic conveying systems it is critical that the conveying line inlet air velocity is correctly specified. Because air is compressible, and very much higher air pressures are used in pneumatic conveying than in fluidized motion conveying, ensuring that the correct inlet velocity is achieved and maintained in a pneumatic conveying system is not a simple matter.

If this inlet air velocity is too high the material flow rate may be reduced, the power requirements will be excessive, and operating problems will be severe. If this velocity is too low, the material may not convey at all, and the pipeline is likely to block. With fluidized motion conveyors a great deal of latitude is available in the design of installations, and provided that a few basic requirements are met, they will generally operate without trouble.

1.4 Historical

It is not known when aeration of a bulk solid material was first used as an aid to conveying, but one of the earliest relevant patents appears to have been that of Dodge, in Germany, in 1895 [2]. He proposed the use of air, entering an open channel through slits in the base, to transport coarse grained materials, such as grain. Real progress in the method of conveying was not made until some thirty years later when it was found that the gravity conveying of aerated powders was ideally suited to the conveying of cement.

The German company Polysius was a pioneer in the development of air-assisted gravity conveying. They were followed by the Huron Portland Cement Company of America. Huron's plant at Alpena, Michigan, was one of the first to make extensive commercial use of this method of conveying. They employed "Airslides", as they came to be called, at various stages of the production process, from grinding mill discharge to finished cement. The third organization that played a prominent part in developing and establishing air-gravity conveyors was the Fuller Company, which manufactured them under license from Huron [1].

Although the air-assisted gravity conveyor first came to prominence for the transport of cement, and is still widely used for this material, many other types of bulk particulate material are now handled with relative ease. Pulverized fuel ash, from the power generation industry, and alumina, from the aluminum industry, are commonly conveyed by this means, as well as diverse substances such as coal dust, sand, and numerous plastic and metal powders.

Typical of the large installations described in some detail in the published literature are a 55,000 ton storage plant and an 88,000 ton ship loading plant, both handling alumina [3], and a Canadian aluminum smelter capable of handling

175,000 ton of alumina per year [4]. Various sizes of conveying channel are used in these installations, one of the largest being a 3 ft wide channel which could transport alumina from a surge hopper to a main silo at a rate of 1650 ton/h.

1.5 Conveying Principles

Considering the advantages that fluidized motion conveyors can offer over other forms of bulk solids transport, particularly in terms of low power consumption, the use of these conveyors is not as widespread as might be expected. To some extent this may be the result of a lack of confidence on the part of the design engineer, since even air-gravity conveying remains something of an art.

In order to enable systems to be optimally designed, rather than over-designed, some understanding of the phenomena involved in air-float, or fluidized motion conveying, is necessary. Observation of a particulate bulk solid being conveyed by this means along a duct will immediately suggest a similarity to a liquid flowing in an inclined channel. It will also be evident that the continuous supply of air that is necessary to maintain the liquid like state of the material has a close affinity to the gas fluidization process.

The basic principles of static fluidization, therefore, are first extended to deal with the flow of fluidized bulk particulate materials. The design, construction and operation of practical air-assisted gravity conveyors is then discussed at some length. Consideration is finally given to a number of interesting variations on the conventional air-float conveyor in which the transported material flows along a horizontal, or even an upward inclined channel.

2 THE FLOW OF FLUIDIZED MATERIALS

When particulate materials become fluidized under the influence of a continuous upward flow of a gas, they tend to display many of the characteristics of liquids. One of these characteristics is the ability to maintain a horizontal free surface, and another is the ability to flow from a higher to a lower level. This means that a fluidized material will flow from a hole in the side of a vessel. If a horizontal pipe was fitted to the hole the material would continue to flow, provided that the pipe was not so long that complete de-fluidization occurred along its length. If it were possible to keep the material in its fluidized condition, as it passed along the pipe, the flow could be maintained almost indefinitely.

2.1 Pipeline Conveying

In pneumatic conveying, materials that have very good air retention properties can generally be conveyed in dense phase over a reasonable distance, quite naturally. A flow of high pressure air is all that is required to keep the material on the move through the pipeline. For materials with poor air retention properties, it is necessary to introduce air into the material by some means, continuously along the length of the pipeline, in order to achieve dense phase flow, as discussed in the previous chapter.

2.1.1 The Gattys System

A patented method which can give a material artificial air retention properties is the Gattys 'Trace Air' system. In this system air at a relatively low pressure is supplied continuously to the material in the pipeline through an internal perforated pipe which runs the whole length of the conveying line. The motive force comes from a pressure drop along the conveying line created by pumping air in at the upstream end, as in conventional pneumatic conveying.

An alternative, although unpractical, method is to have a continuous portion of the pipeline wall itself made of a porous material. From an external source of air the material could be fluidized through the porous section of pipe, and the high pressure air within the pipeline would provide the motive force. This principle forms the basis of the more recent developments that allow the channel to run horizontally. If the pipeline were to be inclined, gravity would provide the motive force and the air supply within the pipeline would not be needed.

2.2 Fluidized Flow

This combination of gravitational force with fluidization provides the basis of a potentially very economical method of transporting bulk solids. Figure 18.3 shows a different approach to the same concept of continuous fluidized flow. This illustrates quite simply the fundamental principle on which the air-assisted gravity conveyor operates.

2.2.1 Angle of Repose

Most free flowing particulate materials display a natural angle of repose of around 35 to 40 degrees, as illustrated in Figure 18.3a. In order to get such a material to flow continuously, under gravity alone, on an inclined surface, it would be necessary for the slope of the surface to be greater than this angle of repose, as shown in Figure 3b. Materials that exhibit some degree of cohesiveness have much larger angles of repose. Such materials will often not flow, even on steeply inclined surfaces, without some form of assistance, such as vibration of the surface. The introduction of air to a bulk particulate material can also provide a means of promoting flow.

This can be achieved by supporting the material on a plate made of a suitable porous substance and allowing air to flow upwards through the membrane into the material. Air introduced into a material by this means can significantly reduce the natural angle of repose. The material will then flow continuously from the plate when it is inclined at a very shallow angle. The angle of the plate need only be greater than the fluidized angle of repose of the material, as shown in Figure 18.3c. For most free flowing materials the fluidized angle of repose is between about 2 and 6 degrees.

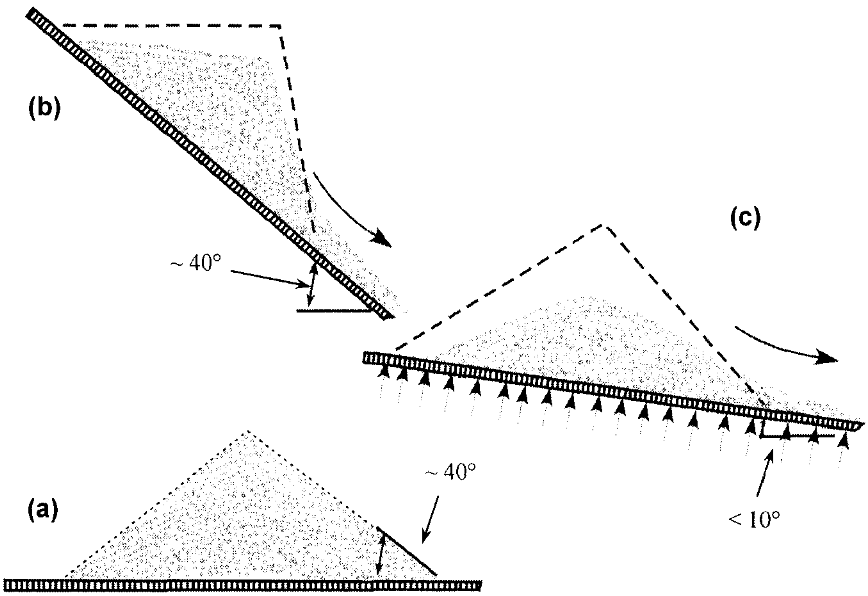

Figure 18.3 Influence of aeration on angle of repose. (a) No aeration on horizontal pile of material, (b) no aeration on steep incline, and (c) with aeration on shallow incline.

2.3 Channel Flow

This phenomenon of fluidized flow can form the basis of a simple and reliable method of bulk solids transport. All that is required is a channel having a porous base through which air can flow. The air must be available over the entire length of the channel and so a plenum chamber needs to be provided beneath, as shown in Figure 18.2.

2.3.1 Starting Flow

It is an essential requirement that sufficient air should pass into and through the material in the channel to cause it to flow. The porous base, therefore, must be of high enough resistance to ensure that when part of it is covered by material, the air does not by-pass this section. Air flow will always have the tendency of taking the path of least resistance. This is a particular problem on start up, as illustrated in Figure 18.4.

If the material on the channel becomes starved of air, it will not flow any further down the channel. On starting the flow, therefore, the air velocity into the stationary material must exceed the minimum value of fluidizing air velocity for the material, U_{mf}, even when a large part of the porous membrane is uncovered.

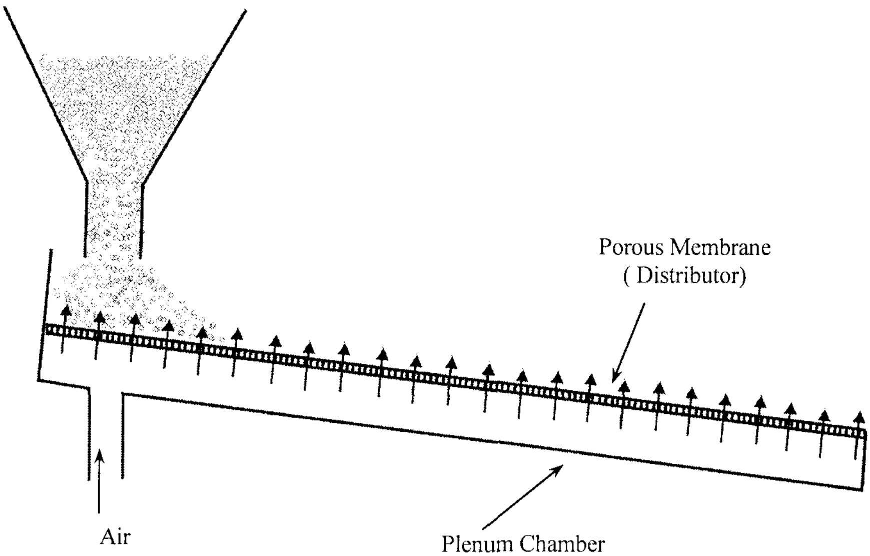

Figure 18.4 Starting flow of material on inclined channel.

2.3.2 Channel Slope

The other essential condition to be met is that the downward slope is sufficient to permit a steady continuous flow of the fluidized material. Provided that these conditions are satisfied, the air-assisted gravity conveyor will normally prove to be a trouble free and very economical method of transporting a wide range of powdered and granular materials.

The appearance of the flowing aerated powder in the channel can depend upon a number of properties that might together be termed the 'flowability' of the material. Thus a very free flowing dry material having a relatively low natural angle of repose would be likely to fluidize very well. Such a material would have good flowability and in this state would flow smoothly along a channel inclined at just one or two degrees to the horizontal, as illustrated earlier in Figure 18.2.

Visual observation of the flowing material would show distinct liquid like characteristics such as a smooth or slightly rippled surface. A partial obstruction to the flow could set up a plume, and a more substantial obstruction could set up a standing wave. In contrast, a material that is cohesive can show a markedly different behavior in an air-assisted gravity conveyor [5, 6].

2.3.3 Cohesive Materials

Very cohesive materials are unsuitable for conveying in channels in this manner. Materials that are only slightly cohesive, however, can usually be conveyed provided that the slope of the channel is greater than about 6 to 10 degrees. Observation of these materials suggests that the particles are not fluidized, but move virtually as a solid mass of material sliding along the channel, as illustrated in Figure 18.5.

Irregular zigzag cracks in the flowing bed of material, and the craggy appearance of its free surface, suggests similarities to the channeling and slugging behavior that can occur in stationary fluidized beds. These cohesive materials could well be expected to exhibit such characteristics.

2.3.4 Flow Mechanisms

It is not clear as to what is the dominant factor that causes the improved flowability that results from the continuous aeration of materials. It could result from the air filtering through the solid particles and reducing the contact forces between them. Alternatively it could come from the formation of air layers between the bed of particles and the channel surfaces, with a consequent sharp reduction of the boundary shear stresses.

3 SYSTEM PARAMETER INFLUENCES

The main difficulty with the study of the flow of fluidized solids, and the reason why it will be difficult to develop an exact mathematical analysis, is the large number of variables involved.

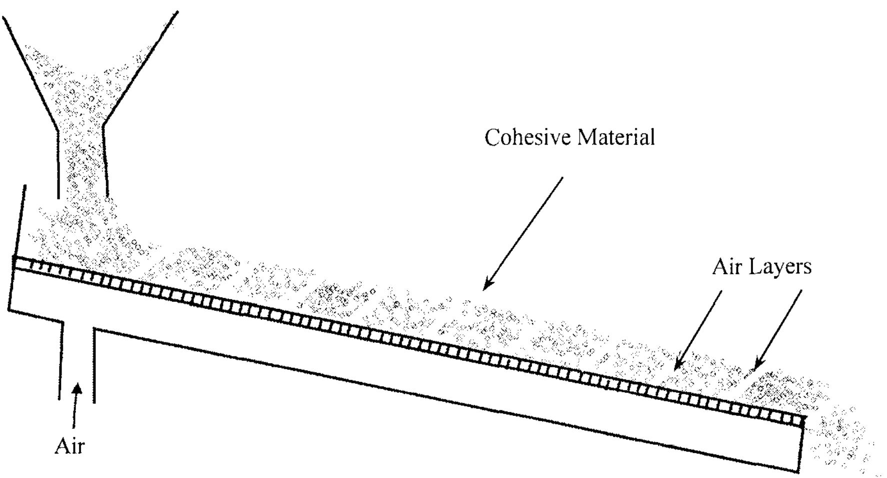

Figure 18.5 Flow of cohesive material on inclined channel.

With parameters such as particle shape, for example, there is a lack of a precise and convenient definition that can be used for modeling. The shortage of experimental data on the influence of these more complex parameters adds to the already considerable problems.

In order to simplify the situation, it is as well initially to set aside all the variables that contribute to what may be termed the 'nature' of the particulate bulk solid. Thus only a very general comparison will be made between the flow behavior of different materials, with no attempt to investigate, in depth, the effects of material characteristics such as particle density, particle size and shape, or their distributions.

3.1 Variables Considered

The study then becomes restricted to the flow of a given aerated material in an inclined channel. The main variables, therefore, are the mass flow rate of the material, the width and slope of the channel, the depth of the flowing bed of material, and the superficial velocity of the air. Note that the superficial air velocity is given by the volumetric flow rate of the air, divided by the surface area of the porous channel base. Most of the experimental work and theoretical analyses carried out by various researchers have concentrated on the relationships among these five parameters [7].

3.1.1 Bed Depth Control

The majority of commercial installations involving air-assisted gravity conveying rely on some form of flooded feed to the upper end of the conveying channel. In these the depth of the flowing bed is of little practical interest, provided that it does not increase to the extent that the channel becomes blocked. In experimental investigations, however, it is likely that the bed depth would be the independent variable, as the other parameters can usually be controlled without undue difficulty. A consideration of the influence of variables such as the channel slope, superficial air velocity, and solids mass flow rate, gives a useful insight into the mechanism of fluidized flow in inclined channels.

3.2 Bed Depth and Channel Slope

In general, for a given solids mass flow rate and superficial air velocity, the depth of the flowing bed would tend to increase as the inclination of the conveying channel is reduced. At relatively steep slopes this effect is not very significant, but as the channel slope approaches the minimum at which flow can occur, the depth of bed increases rapidly. This effect is illustrated in Figure 18.6.

An increase in the solids mass flow rate would result in a shift of the curves upwards. A similar result would be caused by a change in the superficial air velocity. It is evident from the shape of the curves on Figure 18.6 that there is an approximate minimum slope at which a fluidized material will flow.

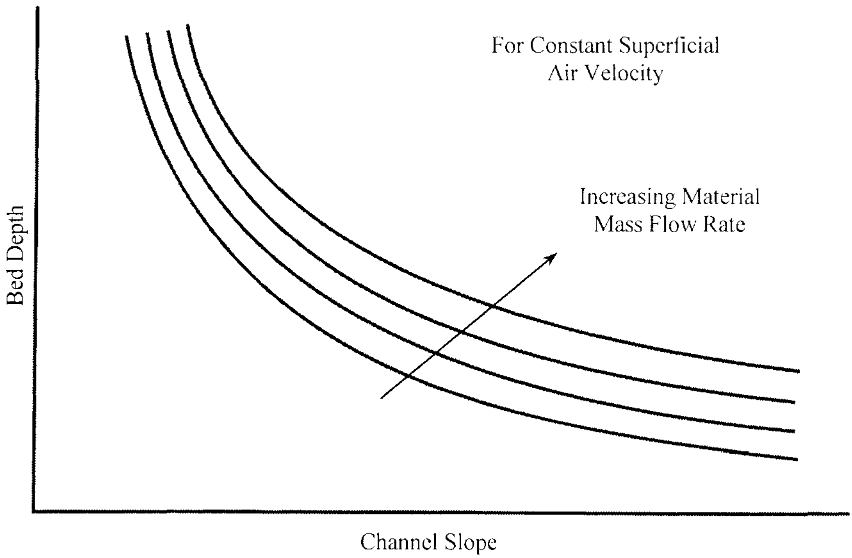

Figure 18.6 Influence of channel slope and material flow rate on bed depth.

The actual value of this minimum channel slope depends mainly upon the nature of the material involved and, to a lesser extent, upon the solids mass flow rate and the superficial air velocity. Attempting to convey at a slope less than this minimum value can result in a rapid thickening of the material bed to the point at which the channel becomes blocked. Conveying at slopes much greater than the minimum necessary does not yield a significant advantage, and does not make the best use of available headroom.

3.2.1 Mathematical Analysis

It is not easy to express mathematically the relationship between the bed depth and the channel slope, since so much depends upon the nature of the conveyed material. One form of expression that has been proposed is:

$$\dot{m}_p = C\, h^x\, b^{4-x}\, Sin\, \alpha \qquad (1)$$

where $\dot{m}_p$ = material flow rate

h = bed depth

b = channel width

C = a coefficient

x = an index

and α = channel slope

The index, x, has a value between 1 and 3, depending upon the aspect ratio of the flow. Aspect ratio is defined as the bed depth divided by channel width and is equal to h/b. Unfortunately the coefficient C is not constant, but depends upon the nature of the conveyed material, and upon the flow conditions.

An alternative expression from Ref 7 is:

$$\dot{m}_p = K_1 \, \rho_b \, h^2 \left(b \, g \, \rho_b \, Sin\alpha - K_2 \right) \quad - - - - \quad (2)$$

where ρ_b = bulk density of material
g = gravitational acceleration
and K_1 and K_2 are constants

K_1 and K_2 are constants for a given bulk particulate material. It has been found that Equation 2 can represent quite closely the form of the relationship between bed depth and channel slope, as indicated on Figure 18.6. At the present time, however, insufficient information is available on the values of constants K_1 and K_2. Whilst it seems probable that for different bulk solids, these constants will depend primarily on particle size and density, much more experimental work needs to be done to validate the suggestion.

3.3 Bed Depth and Superficial Air Velocity

A similar variation of bed depth occurs as a result of varying the superficial air velocity, as shown in Figure 18.7. In this case the set of curves shown is plotted for a constant solids mass flow rate, with each curve representing a different channel slope.

Again there appears to be a tendency towards an optimum air flow which, as previously remarked, is related to the slope of the conveying channel. Reducing the air flow rate to less than the optimum can cause the flowing material to become de-fluidized. This results in a sudden fall in the material flow velocity and a consequent thickening of the bed, often to the point of total cessation of flow. On the other hand, an increase of the air flow rate much above the optimum produces little advantage, and is merely wasteful of energy.

3.3.1 Mathematical Analysis

No reliable mathematical model has yet been found that will allow prediction of the variation of the depth of the flowing suspension with the superficial air velocity. To make the problem even more difficult, there appears to be considerable inconsistency between different kinds of bulk solids with regard to the quantity of air required in relation to minimum fluidizing velocity. This, perhaps, is not surprising since a very similar situation exists with regard to the pneumatic conveying of bulk materials.

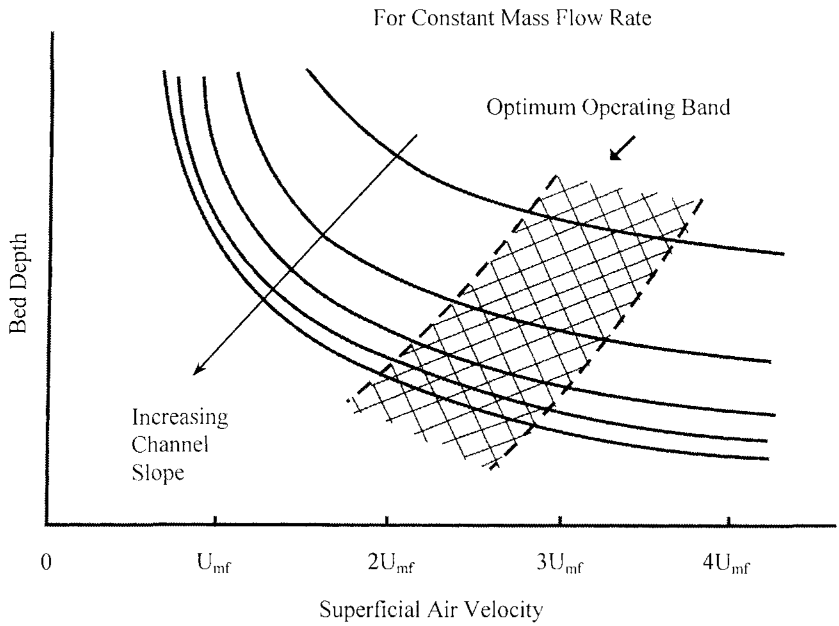

Figure 18.7 Influence of superficial air velocity and channel slope on bed depth.

Thus, whilst most free flowing materials can be conveyed satisfactorily at superficial velocities of around 2 to 3 U_{mf}, some bulk solids require air flows that are much higher multiples of U_{mf}. Again, further experimental work needs to be undertaken to investigate the possibility of predicting the influence of superficial air velocity on flow behavior from easily measured characteristics of a bulk solid. These may have to be in terms of air retention and permeability, rather than particle size and density.

3.4 Bed Depth and Solids Mass Flow Rate

Observation of actual flows of fluidized materials in inclined channels suggest that although the bed depth will increase if the solids mass flow rate is increased, as shown in Figure 18.6, the relationship is not one of direct proportionality. It has, in fact, been found that the bed depth tends to vary as the square root of the solids mass flow rate, as indicated by Equation 2.

This means that in most practical situations the relationship between the bed depth and the material mass flow rate is almost linear, but as the material flow rate is reduced towards zero, the bed depth begins to decrease sharply. This is illustrated in Figure 18.8.

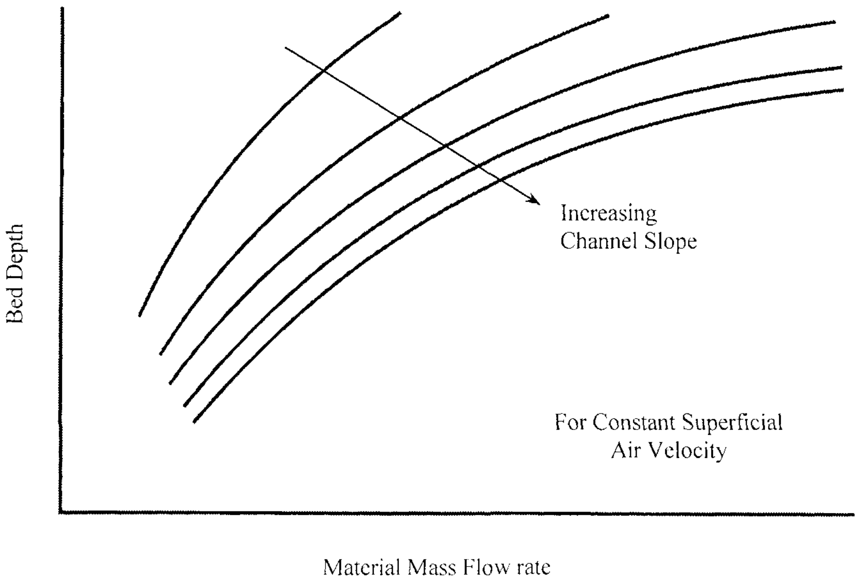

Figure 18.8 Influence of material flow rate and channel slope on bed depth.

3.4.1 Channel Clearing

It is a peculiarity of air-assisted gravity conveyors that when the solids feed is reduced, the flow becomes unstable, and then stops, before the bed depth becomes zero. This means that the base of the channel cannot be completely cleared of the conveyed material simply by shutting off the solids feed.

3.5 Solids Flow Rate and Channel Width

There is no satisfactory experimental information in the literature on the relationships between channel width, bed depth and the mass flow rate of the conveyed material. Some researchers have attempted to compare data collected from channels of two and three different widths, but the range has been severely restricted and the results, therefore, have been inconclusive.

Because of the relatively large quantities of material that can be transported by the wider air-gravity conveyors, prohibitive costs have limited research rigs to channel widths being a maximum of about six inches. Industrial installations are commonly up to about two feet in width, and sometimes wider. Some caution, therefore, should be exercised when projecting data gathered on small experimental rigs to these greater widths.

Naturally, if the channel slope, superficial air velocity and bed depth are kept constant, the material mass flow rate should be approximately proportional to the channel width. It is more realistic, however, to recognize that conveying channels are usually operated at a constant aspect ratio (bed depth/channel width) and therefore the conveying capacity is normally taken to be proportional to the square of the width. This is depicted graphically in Figure 18.9.

3.6 Other Influences

Although, for a given bulk particulate material, the main parameters influencing its flow are those discussed above, there are several other system influences that can cause changes to occur during conveying. The most significant of these are moisture, electrostatic charging and particle segregation.

3.6.1 Moisture

It is well known that changes in the moisture content of powders can seriously affect their handling characteristics, and this is especially true in the case of fluidization and fluidized flow. Whilst a small increase in moisture may be beneficial in reducing the tendency of the material to hold an electrostatic charge, too much moisture can cause normally free-flowing materials to become so cohesive that they cannot be fluidized.

Although air quantities required for fluidizing are relatively small, it would be recommended that the air for fluidizing should be dried, particularly if the conveyed material is hygroscopic. Since the conveying system itself is almost totally enclosed, materials are unlikely to absorb moisture from the atmosphere during conveying.

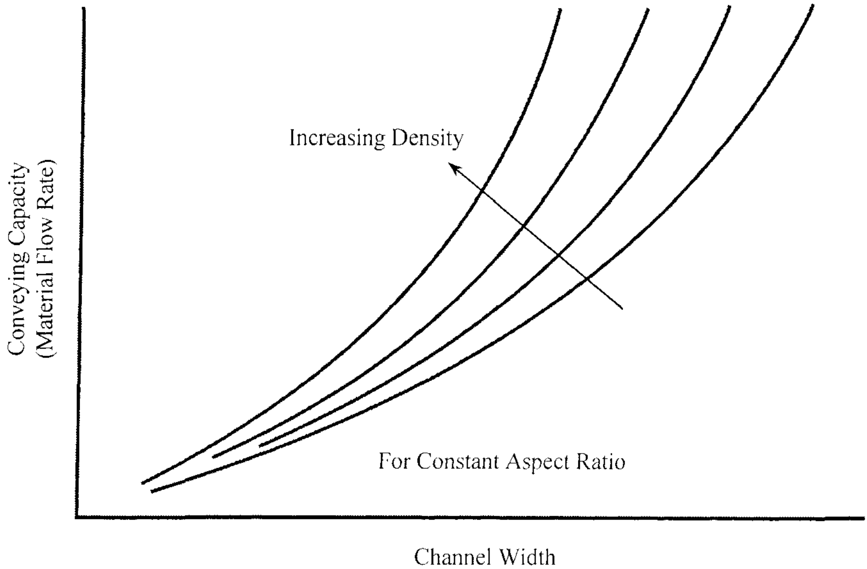

Figure 18.9 Influence of channel width and density on conveying capacity.

3.6.2 Electrostatic Charging

Electrostatic charging can have a similar effect on both flow and fluidizing as moisture. Air drying, however, will not help in this case, as mentioned above with respect to moisture content. If the conveyed material is potentially explosive, electrostatic charging could present a considerable hazard. In this case the material could be fluidized with nitrogen.

3.6.3 Segregation

There is a natural tendency for segregation to occur in fluidized beds. This tendency for the coarser particles to drift down towards the porous membrane can also occur in flowing fluidized materials.

Where the channel is short, and relatively steeply inclined, there would be little opportunity for segregation to occur. In longer channels, however, the problem may become significant. In extreme cases a deposit of coarse particles may continuously build up on the bottom of the channel until the material flow ceases altogether.

4 MATERIAL INFLUENCES

Almost any bulk particulate material having good fluidizing characteristics will, when suitably aerated, flow easily down an inclined surface. Such materials can, therefore, be transported satisfactorily in an air-assisted gravity conveyor. Although it is often stated that being easily fluidizable is an essential requirement for conveying in this manner, many materials that are slightly cohesive can also be conveyed.

Very cohesive materials, however, are generally unsuitable for air-assisted gravity conveying. Materials that are cohesive by virtue of being damp or sticky come into this category, as do powders of extremely fine particle size that have a tendency to smear over the channel surface, and hence blind the porous membrane.

4.1 Geldart's Classification

The work of Geldart in classifying bulk solids according to their fluidization behavior [8] provides a useful guide to the suitability of powders and granular materials for air-assisted gravity conveying. Geldart's classification is in terms of the mean particle size, and the difference in density between the particles and the fluidizing medium. Four different groups of material are identified.

The classification is presented in Figure 18.10. In this representation, particle density rather than density difference is employed. This is because in fluidizing with air, the density of the air can be disregarded as it is negligible compared with almost any particle.

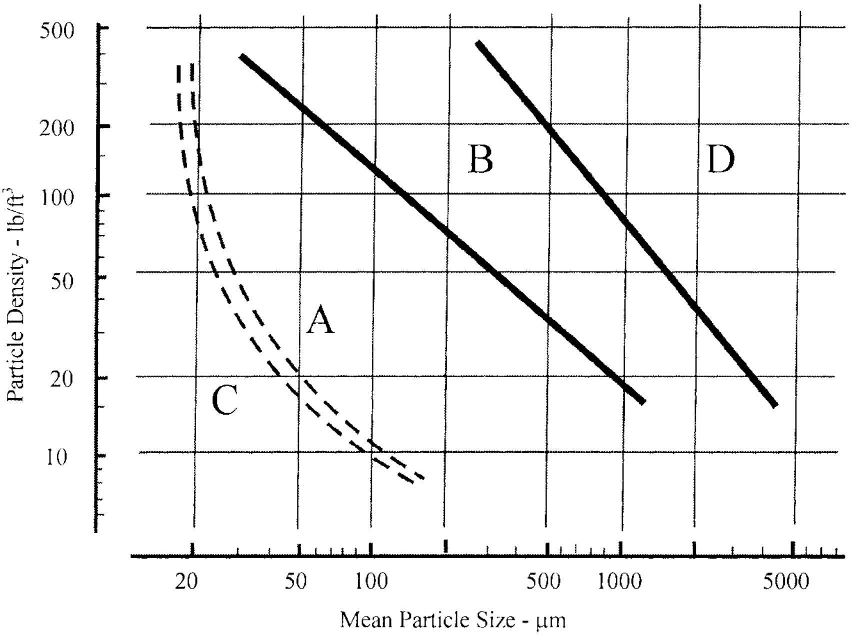

Figure 18.10 Geldart's classification of fluidization behavior for fluidization with ambient air.

4.1.1 Fine Granular Materials

In general, materials in Group B, which includes most fine granular materials, in the mean particle size range from about 50 to 1000 micron, and density range of 75 to 250 lb/ft^3, are the easiest to convey. These will flow very well at very shallow channel slopes. When the supply of fluidizing air is shut off, the bed collapses rapidly and the flow stops. As a result there are unlikely to be any problems with air retention.

4.1.2 Large Granular Materials

Group D covers materials of larger particle size and high density granular materials. These materials can usually be conveyed in the same manner as the group B materials. The quantity of fluidizing air required, however, tends to become rather large. As a result other forms of transport, such as belt conveyors, might prove to be more suitable.

4.1.3 Air Retentive Materials

Group A materials typically includes powders and very fine granular materials of low particle density. These materials should convey well in an air-assisted gravity conveyor, but they may have a tendency to continue flowing for a time after the fluidizing air has been shut off. This property of air retentive materials must be taken into account when designing conveying systems, since the angle of repose for a material, as illustrated in Figure 18.3a, cannot be relied upon to stop material flow.

4.1.4 Cohesive Materials

Group C includes cohesive materials that are difficult to fluidize satisfactorily because of high inter-particulate forces resulting from the very small particle size, electrostatic effects or high moisture content. The dividing line between groups C and A is very indistinct and the only way of properly assessing the suitability of doubtful materials for air-assisted gravity conveying is by practical experiment in a small scale test rig.

As previously mentioned, it may be found that apparently unsuitable materials will, by a combination of flowing and sliding, move continuously along an inclined channel. The slope of the channel, however, will need to be greater than that for group A and B materials.

4.2 Material Suitability

At the present time it is still necessary to rely heavily on experience when making an assessment of whether a given material is suitable for air-assisted gravity conveying. Geldart's chart should help in this respect, however, and laboratory tests should provide confirmation in case of doubt. Many different kinds of powders and granular materials have, and are being, transported successfully by air-assisted gravity conveyor. Practical information obtained, unfortunately, tends to be jealously guarded by the conveying equipment manufacturers. This does have the effect of slowing system development and advancement of the technology.

5 PRACTICAL AIR-ASSISTED GRAVITY CONVEYING

As has been previously explained, conveying on a downward slope has the great advantage of gravity to assist the flow of the aerated bulk solid. This is the traditional, low energy application of air-float conveying, and commercial units are available under a variety of trade names. Figure 18.11 represents a basic air-gravity conveyor in which the conveyed bulk solid flows continuously under gravity from the inlet to the discharge point.

In this form the device is also widely employed as discharge aids, or flow assistors, mounted on the floor inside silos, bunkers, railway wagons, trucks, etc. They enable containing vessels such as these to be made with a virtually flat base, and thus to have a substantially greater capacity [9, 10]. In these applications the channel is generally very much shorter than when used for the transport of materials.

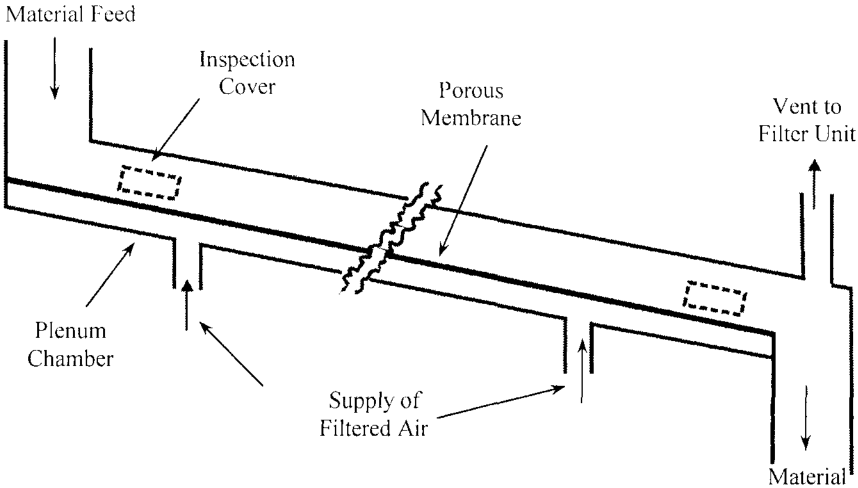

Figure 18.11 Arrangement of a typical air-gravity conveyor.

5.1 Channel Construction

The basic construction of a practical air-gravity conveyor is very simple, and this is one of its main advantages over other methods of bulk solids transport. For transport applications the conveyor consists essentially of two U-section channels, with one inverted, and the porous membrane clamped between them. Figure 18.12 shows a typical clamping arrangement for the duct sections and membrane.

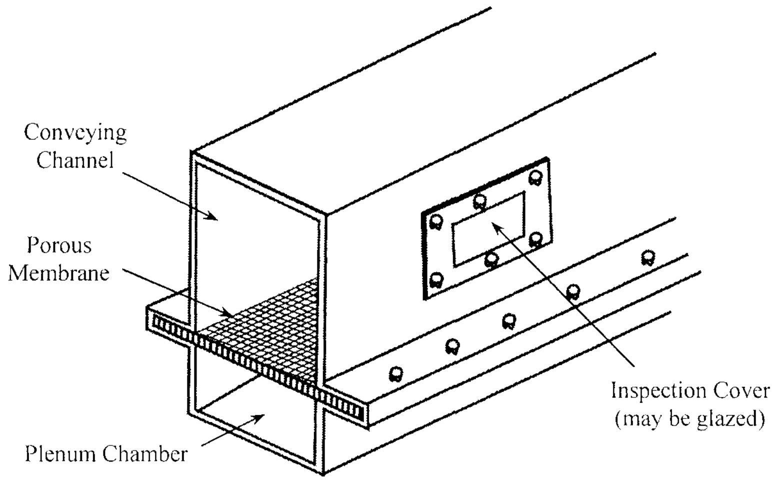

Figure 18.12 Typical conveying duct section.

The lower channel serves as a plenum chamber to which air is supplied at one or more points, depending upon the overall length of the conveying system. The presence of the covered top channel renders the conveyor virtually free from problems of dust leakage. It would, however, also operate quite satisfactorily as an open channel, as it often must when operating as a discharge aid.

The conveyors can be manufactured in a range of standard bolt-together components, which include straight and curved sections of various widths. A range of accessories are also available, such as flow diverters, inlet and discharge ports, inspection windows, gate valves, access ports and scrap traps.

5.2 Material Feeding

Where precise control of the material flow rate is not required, flooded feed from the supply hopper to the conveying duct should be satisfactory. The system is then effectively self-regulating and, with free flowing powders, there should be little risk of the conveyor becoming choked, provided that the slope of the channel and the flow rate of the fluidizing air are sufficient.

Some measure of solids flow control may be achieved with a gate or baffle in the conveying duct, positioned close to the inlet from the hopper. Placing a flow regulating gate near the outlet end of the conveyor is generally not advisable as the whole channel could fill with material backing up from the gate. Problems would then occur with venting of the fluidizing air and with erratic flushing of the material under the gate as it opens.

Solids flow control at the inlet end, although basically more reliable, does present a problem on long channels because of the considerable delay between making an adjustment to the control gate, and seeing the effect of this adjustment at the lower end of the channel. In fact, where it is important to control the material flow rate within relatively close limits, it becomes almost essential to install some form of buffer hopper close to the discharge point.

As an alternative to a regulating gate in the conveying duct, the material flow control could take place at the hopper outlet. A conventional rotary vane feeder or screw feeder would be ideal for the purpose. For a consistent free flowing material it is possible that a pinch valve or an iris valve would be suitable.

5.3 Porous Membrane

A variety of different materials may be employed as the porous membrane. Some typical examples are woven cotton, polyester belting, sintered plastic, ceramic tiles, and laminated stainless steel mesh.

5.4 Venting

When the conveyor is covered, it is necessary for the top channel to be adequately vented through suitable filters. With short conveyors it may be sufficient to rely on the air escaping with the powder from the outlet end of the channel, and then through the vent system of the discharge hopper, if one is in use. If the conveying system is long, or if there is a possibility of the channel outlet becoming choked with material, it is better to vent from two or more points between the inlet and the outlet.

5.5 Access Ports

It is likely to prove useful to have inspection or access ports fitted at convenient positions along the duct, especially in the region of the inlet and outlet, and in other positions where blockage may occur. An inspection point was shown earlier in Figure 18.12. These can be glazed if required.

5.6 Material Discharge

A wide choice of discharge arrangements is possible, ranging from a simple open end, to telescopic loading spouts. Some care should be taken with the venting of air from the conveying duct to avoid excessive blowing through the discharge point, but otherwise there should be no problem with this part of the plant.

Controlling the location at which a material is discharged from an air-assisted gravity conveyor is likely to be more satisfactory than controlling the rate of discharge. Using appropriate bends, diverters and outlet ports it is possible to construct quite complex systems. Figure 18.13 illustrates an ingenious but simple solution to the problem of automatically controlling the feed of material to a stockpile.

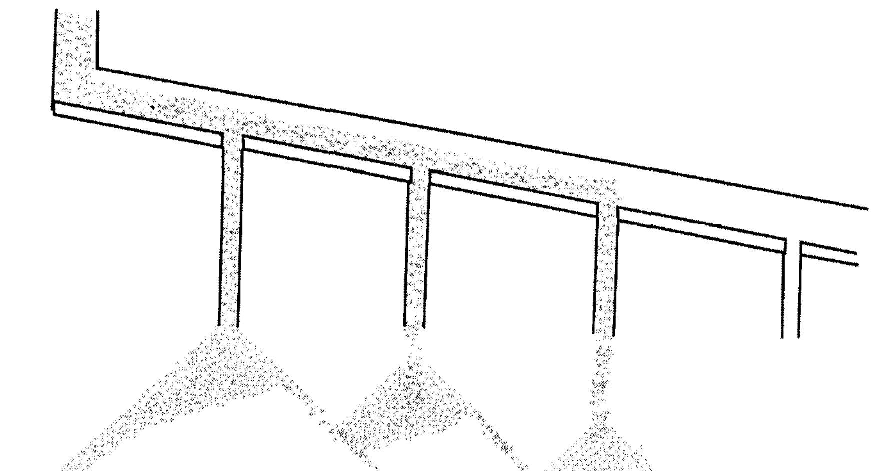

Figure 18.13 Stockpile feeding through multiple discharge outlets.

This shows an overhead air-gravity conveyor discharging the fluidized material down each of a succession of outlet spouts until the rising level of the stockpile causes them to cease discharging. Material will automatically flow over the top of any blocked discharge spouts, along the channel membrane, to flow through the next outlet available. Many functions, such as this, can be carried out automatically, and without the need of any valves or moving parts in the system, particularly with Group B materials.

5.7 Components

One of the advantages of air-gravity conveying systems is their versatility, and most manufacturers of these systems supply them as standard components which bolt together to suit the user's particular requirement. In addition to the basic straight channel units and intake and discharge sections, components normally available include the following:

- Bends: right hand and left hand.
- Y-pieces to divide the flow from one channel into two or three, or to recombine into one.
- Flow diverters, often used in conjunction with side discharge boxes, to allow the operator to direct the flow as required.
- Flow control gates or baffles: for either manual or automatic operation.
- Material traps for the collection and subsequent removal of heavy impurities in the flow.

The construction of these components is basically quite straightforward. As an example, a typical pattern of a flow diverter, or side discharge box, is illustrated in Figure 18.14.

6 DESIGN PARAMETERS

In terms of system design, the main parameter to consider, in order to achieve the desired material flow rate, is the channel width. The correct specification of the air requirements and channel slope, however, is essential in ensuring that the system will operate satisfactorily. These three parameters are considered in detail, along with the influence of conveying distance.

6.1 Channel Width

The main parameter governing the capacity of an air-gravity conveyor is the channel width. In the literature published by manufacturers of these conveyors, and in other sources giving basic design data, quantities described as 'typical capacities' are given. Such capacities are generally given as a function only of the channel width, with little, if any, indication of how such data would be modified for different types of conveyed material, and for different slopes and air flow rates.

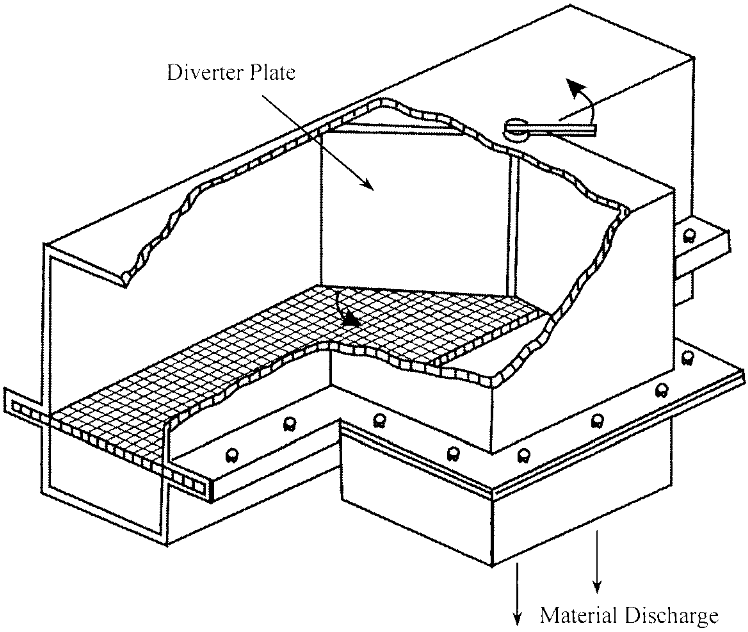

Figure 18.14 Duct diverter facility.

This, however, is not as unreasonable as it first appears in view of the fact that, provided the slope and air flow rate exceed the required minimum or optimum values for the particular material being conveyed, they will have little influence on the material flow rate. These points were illustrated earlier in Figures 18.6 and 18.8.

6.1.1 Modeling

A useful preliminary estimate of the channel width required for a given application may be made by regarding as constant the average velocity and the bulk density of the flowing suspension. The velocity and density are, in fact, both functions of the channel slope and the fluidizing air velocity. By taking them as being constant, the width of a conveyor required to handle a given mass flow rate of a material is given approximately by:

$$b = \left(\frac{r_e \, \dot{m}_p}{r_a \, \rho_b \, U_p} \right)^{0.5} \qquad (3)$$

where b = channel width

r_e = expansion ratio of bed

$\dot{m}_p$ = mass flow rate of material

r_a = conveying aspect ratio

ρ_b = bulk density of material

and U_p = velocity of the conveyed material

By taking suitable average values of the quantities U_p, r_e and r_a, and introducing the particle density ρ_p in place of the bulk density ρ_b a convenient 'rule-of-thumb' equation may be proposed as:

$$b \approx 0 \cdot 65 \left(\frac{\dot{m}_p}{\rho_p} \right)^{0 \cdot 5} \quad \text{ft} \qquad \text{- - - - - - - - -} \qquad (4)$$

6.1.2 Capability Chart

If the mass flow rate of conveyed material, $\dot{m}_p$, is given in ton/h and the particle density, ρ_p, in lb/ft^3, the channel width, b, will be given in feet. This relationship has been used to plot the chart presented in Figure 18.15, which provides a quick reference for determining the approximate channel size for a given application.

It should be noted that normal industrial practice would be unlikely to permit the widest channels to operate with a conveying aspect ratio as high as 0·5, as used for the chart, and so caution should be exercised in this respect when using the above equations or chart.

6.2 Channel Slope

Equation 18.2 has been proposed to show the relationship between the channel slope and the other system parameters. However, it was pointed out that the use of this equation is restricted by a lack of information on the values of the constants K_1 and K_2. At the present time, therefore, it is still necessary to resort to laboratory tests if an accurate indication of the optimum channel slope at which to convey a given material is required.

In most industrial applications air-gravity conveyors are installed with a slope of 2 to 10 degrees. The lower level of inclination depends very much upon the type of material being transported. The degree of initial aeration of the conveyed material, and the nature of the porous membrane, may also influence the minimum slope that can be used.

In general about 1° is sufficient for very free flowing materials. Although such a low angle may suit the plant layout, it will not necessarily be the optimum for maximum flow, and a slope of around 3° may be more appropriate. More cohesive materials may require a minimum slope of 7 to 10 degrees for satisfactory transport, and continuous trouble free operation.

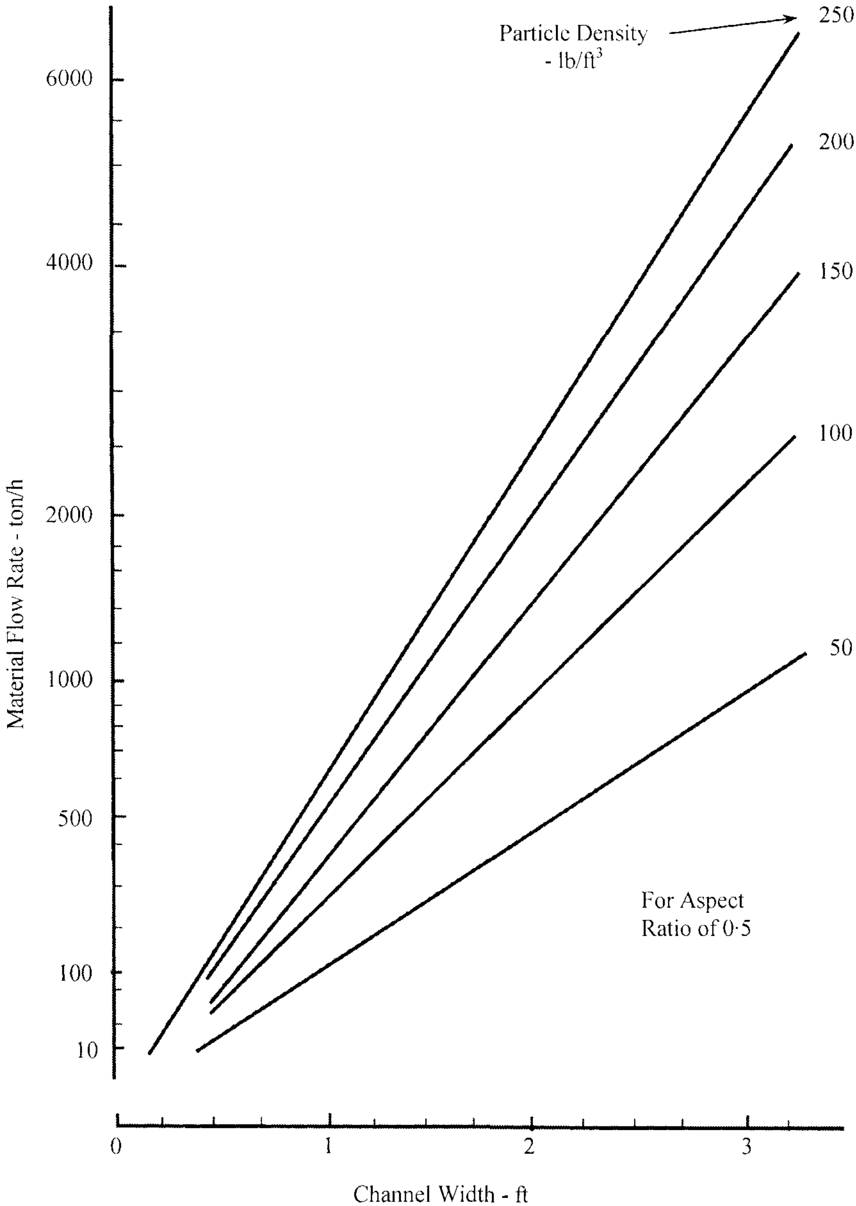

Figure 18.1 Chart giving approximate conveying capabilities.

6.3 Conveying Distance

Provided that the continuous downward slope can be maintained, there is generally no limit to the length of conveying channel that can be used. This is because gravity provides the motive force and not pressure drop, as in pneumatic conveying, and horizontal fluidized motion conveyors. Air-assisted gravity conveyors of 500 ft or more in length are not unknown.

It is necessary, of course, to arrange the air supply so that a uniform pressure exists beneath the distributor, or porous membrane, and in very long conveyors is usual to provide air inlets at several points along the length of the plenum chamber. It may also be advisable to vent the conveying channel at several points to prevent the build-up of an excessive air velocity over the top of the material being conveyed.

6.4 Air Requirements

In order to specify the air requirements of an air-assisted gravity conveyor it is necessary to establish the volumetric flow rate of the air through the porous base of the channel and the pressure within the plenum chamber.

6.4.1 Air Supply Pressure

The pressure of the air in the plenum chamber is clearly a function of the resistance of the porous base of the channel, but it also depends upon the depth of the conveyed material in the channel. For the purpose of analysis it can be assumed that the conveyed material is fully supported by the air. It is then possible to estimate the pressure on the upper surface of the porous membrane by simple fluid mechanics, for any required aspect ratio of the flowing bed.

Knowledge of the permeability of the porous base would then permit the pressure in the plenum chamber to be estimated. For the membrane, permeability is expressed as the volumetric air flow rate per unit area, per unit pressure drop across it. If this information is not available for the membrane material, it can be measured quite easily in a permeameter. The flow resistances of the air from the air mover to the plenum chamber, and of the air through the venting system, must then be added to give the air supply pressure needed for the specification.

In practice, however, it is difficult to predict with any confidence an optimum value for this parameter because of the uncertainty over the actual pressure drop across the flowing bed of material. As mentioned previously, it is essential that the porous membrane is of sufficiently high resistance to ensure a uniform distribution of air into the conveyed material. Typically the pressure of the air in the plenum chamber is found to be approximately 10 to 20 inch water gauge.

6.4.2 Volumetric Flow Rate

The flow rate of air that must be supplied to the air-gravity conveyor depends principally upon the length and width of the channel and the nature of the bulk particulate material to be conveyed. The air flow rate can most conveniently be expressed in terms of the volumetric flow rate per unit area of the porous channel base. This, of course, is the superficial velocity of the air, from the plenum chamber into the conveyed material.

The value of the superficial velocity that is required, and must be maintained, can be predicted approximately from a knowledge of the fluidization characteristics of the bulk particulate material. Both the channel slope and the material flow rate, however, will also have an influence. The optimum value of superficial air velocity at which the conveyor can be operated economically, without undue risk of stoppage of the material flow, is likely to be between two and three times the minimum velocity, U_{mf}, at which the material could be fluidized, as illustrated earlier in Figure 18.7.

For very free flowing materials, on a relatively steep incline, an air velocity only slightly in excess of the minimum fluidizing velocity may be sufficient. For very fine powders, however, air velocities up to ten times U_{mf} may be needed. In addition to being wasteful of energy, operation at too high an air velocity can cause problems as a result of fine particles being entrained in the air stream leaving the top surface of the material being conveyed along the channel.

The designer, therefore, requires some knowledge, not only of the minimum fluidizing velocity of the material to be conveyed, but also of the air velocity at which entrainment can begin. Many methods of predicting U_{mf} for bulk particulate materials are to be found in the published literature. Figure 18.16 is a chart based on one of these correlations for materials fluidized with air at a condition close to normal ambient [1]. Also shown on this chart are approximate values of U_t, the terminal velocity of particles in free fall in still air. The air velocity at which particle entrainment can begin corresponds approximately to this velocity.

For a particulate material of known particle size and density, Figure 18.16 allows a fairly reliable estimate to be made of the minimum fluidizing velocity. With a knowledge of the diameter of the smallest particles in the material, Figure 18.16 also allows prediction of the air velocity at which these fine particles may begin to be carried upwards from the surface of the bed.

Approximate ranges of the types of fluidization behavior, as given by Geldart's classification, are also shown on Figure 18.16. They are superimposed on the lines corresponding to the minimum fluidizing condition, thus helping to provide a useful prediction of the likely behavior of a particulate material in an air-assisted gravity conveyor.

7 OPERATING PROBLEMS

It has been stated that air-assisted gravity conveyors are usually trouble free in operation, and whilst this is true, there are one or two ways in which problems may arise.

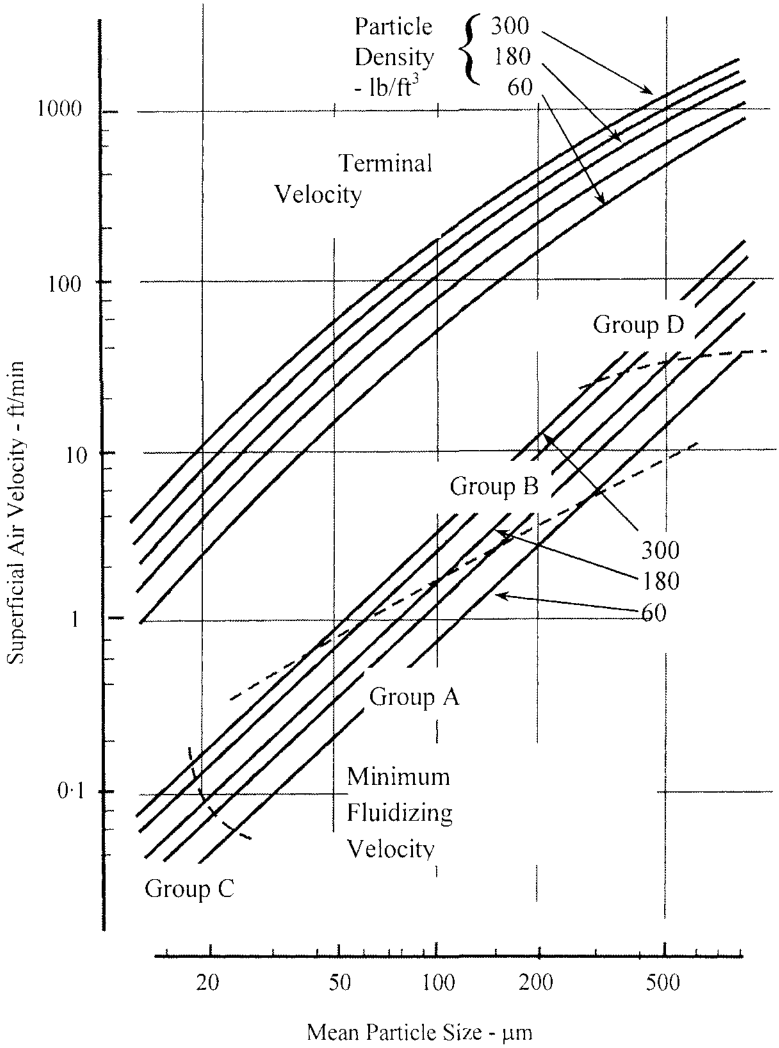

Figure 18.16 Minimum fluidizing velocity and terminal velocity for a bed of particles fluidized with air.

One potential source of trouble is the porous membrane that forms the base of the conveying channel. There are many examples of installations in which the same membrane has been in use continuously for a number of years. In other cases, however, replacement is necessary at quite frequent intervals. There is probably little that can be done about blinding of the pores in the top surface of the membrane, but precautions can be taken against deterioration of the underside by ensuring that the main air supply is adequately filtered.

A further precaution concerns the need for the porous membrane to withstand a certain amount of ill use. It appears to be common practice for operatives to attempt to relieve suspected blockages with the aid of an iron bar, or similar implement, wielded against the outside of the channel. If inspection ports are provided these are often accessed with the not uncommon result that the porous distributor is cracked, in the case of ceramic tiles, or punctured, in the case of woven fabrics.

Blockage of the conveying channel is unlikely to occur unless the porous membrane is damaged, or the nature of the conveyed material changes drastically, such as becoming wet. Both of these cases would tend to cause local, or complete de-fluidization of the flowing material. Erratic flow in the conveying channel is unlikely to be caused by the air-gravity conveying system itself, unless the slope is too shallow or the bed depth is too great. It is more probable that the feed to the channel would be at fault, as a result of material arching in the hopper supplying the conveyor, for example.

8 HORIZONTAL AND UPWARD TRANSPORT

It has already been established, through the example of the air-gravity conveyor, that a fluidized material will flow along a channel, in the manner of a liquid, provided that there is an input of energy to the material sufficient to maintain the flow. In view of the many positive features that air-gravity conveying has to offer, it is not surprising that there have been a number of attempts to devise modifications to the basic system that would permit material to be transported horizontally or on an upward slope.

One such example uses a series of stepped air-gravity channels, joined together by vertical air lifts. Other methods, some of them exhibiting considerable ingenuity, rely on inclined air jets, or on the pressure gradient set up in a partitioned channel, to provide the forward motivation necessary for the material. A number of these systems are examined in detail below.

8.1 The Jet-Stream and Similar Conveyors

The simplest method of generating a flow of a fluidized material along a horizontal channel is to introduce air through the base and/or sides of the channel in a series of forward facing jets. A number of interesting variations on this approach have been proposed.

8.1.1 Distributor Types

The Jet-Stream conveyor, and similar types, have all the air entering the channel through louvers, or angled slits, in the base. Such a base is illustrated in Figure

18.17. Provided that a significant component of the velocity is in the horizontal direction, the material to be conveyed will 'float' along on the resulting cushion of air.

In the Jet-Stream itself [11, 12], air at very low pressure flows from a plenum chamber through a flat plate punched with a series of louvers, which forms the base of the conveying channel. The louvers are laid out in rows, offset and staggered to ensure a uniform distribution of air jets, whilst maintaining adequate rigidity of the plate. The spacing of the perforations, their shape and the percentage of open area may be varied depending upon the material being conveyed. With fine granular materials the depth of the louvers would be very small compared with the width, to minimize back flow of particles into the plenum chamber.

8.1.2 Operating Experience

The amount of published data available on the various methods of horizontal conveying is somewhat limited. The first work on the multi-louvered base-plate appears to have been that of Futer [12] who conveyed shelled corn, 17 Mesh (1100 micron) sand and 35 Mesh (500 micron) aggregate, at rates of up to 165 ton/h, in a channel 12 in wide and 10 ft long. Kovacs and Varadi [13] using similar base-plates conveyed granulated sugar in a channel 6 in wide and 25 ft long.

From the published literature it appears that conveying channels fitted with louvered or slotted base-plates have proved to be very successful for transporting cartons and packets, but rather less so for bulk particulate materials, especially where these are of fine particle size. The main difficulty when conveying such materials seems to be in maintaining a uniform flow of air, since the very low resistance of the distributor plate means that the air flow is seriously affected by the amount of material in the channel.

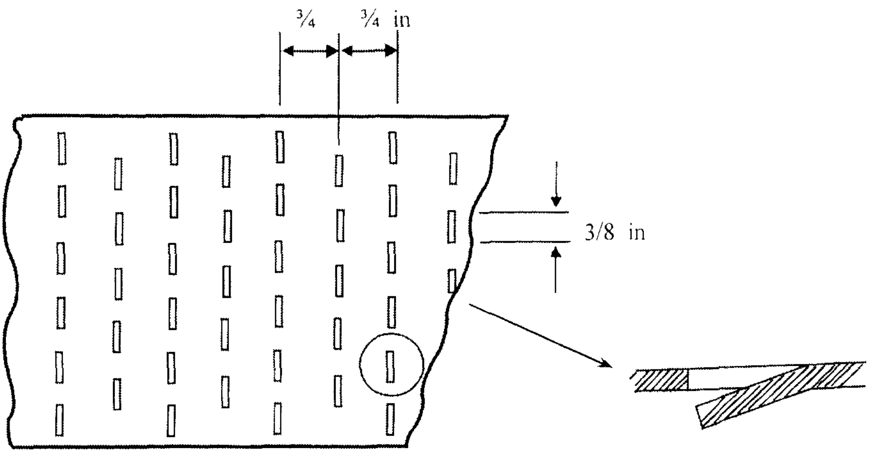

Figure 18.17 Perforated plate distributor.

The relatively high velocity of the air jets from the distributor, which can be up to 6000 ft/min [12], may cause unacceptable degradation of friable materials. It has been shown [13] that backing the slotted plate with a porous fabric can give some improvement in air distribution, but the reduction in air velocity from the slots largely destroyed the capability of the conveyor to operate on the horizontal.

8.1.3 Combination Conveyor

An interesting variant of the conveying channel with a slotted base is illustrated in Figure 18.18 [14]. This example again represents an attempt to overcome the disadvantages of the simple slotted base by separating the fluidizing air from the propulsion air, by the ingenious device of making angled slits in the porous base-plate. The resulting jets of air thus drive the fluidized material up the sloping sections and along the channel.

8.2 The Pneumatic Escalator

Shinohara and Tanaka [15, 16] have described a device that has some affinity to the air jet conveyors and which they called a 'Pneumatic Escalator'. In construction this device is similar to the conventional air-gravity conveyor, except that plastic plates are fitted across the conveying channel to form a series of inclined cells. The system is illustrated in Figure 18.19.

Air passing through the porous membrane lifts the particles up the inclined plates from one cell to the next. In common with other forms of air jet conveyor, however, the quantity of air required tends to be large. Although the device appeared to work well on an upward slope of 3°, with conveying still possible at a slope of 26°, most of the channels tested were only 0·6 inches in width. It would not appear to have been tried on a commercial scale.

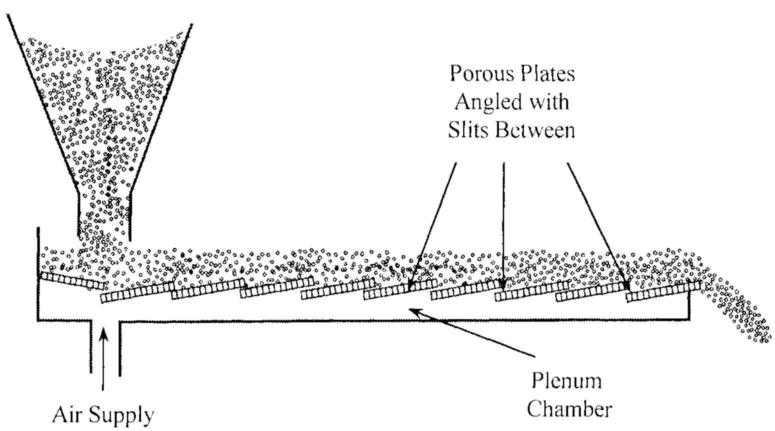

Figure 18.18 A combination of porous distributor and directional air jets.

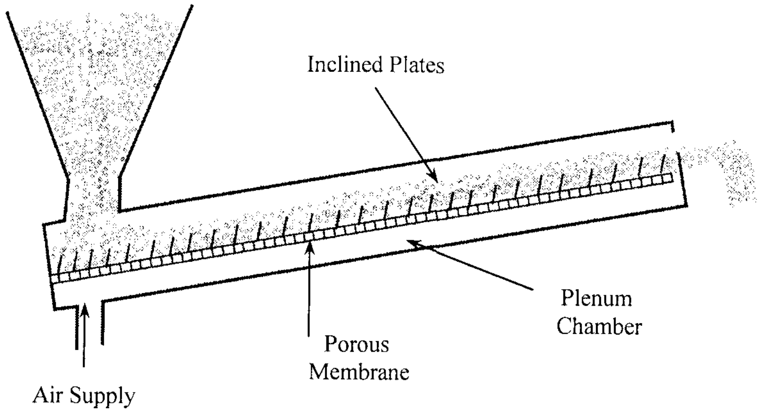

Figure 18.19 The pneumatic escalator.

8.3 The Isler Conveyor

A rather different approach to upward air-float conveying has been used by Isler [17]. He developed a system in which a pressure gradient was set up in the conveyed material. This was achieved by dividing both the plenum chamber and the material flow channel into separate compartments, supplied with air at different flow rates. This system is illustrated in Figure 18.20. The test channel was 20 ft long and 10 in wide.

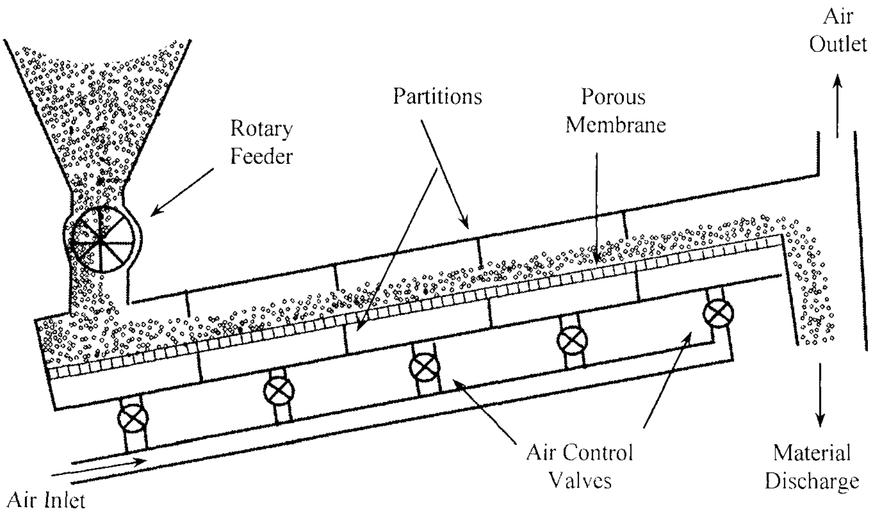

Figure 18.20 The Isler conveyor.

Cement was conveyed at a rate of 20 ton/h, although this was claimed to be well below the capacity of the channel. The maximum upward slope at which the channel was operated was about 12°. Whilst this design of conveyor apparently requires much less air than most of the others operating horizontally, and on upward inclines, this type of pressurized conveying channel is not so versatile, and it loses some of its simplicity in design. In order to operate at pressure, some form of air lock type feeder is needed. Control valves are required on the air supply to the plenum chamber compartments, and these have to be carefully adjusted. They also have to be readjusted if the material flow rate needs to be changed. Because of the compartmental nature of the device, the continual reduction of pressure and consequent expansion of the air means that the distance over which the conveyor could practically operate is limited.

8.4 The Stepped Conveyor

Although the novel forms of air-float conveyor described above are interesting, and may be useful in certain specialized applications, they all fail to take full advantage of the major characteristic of fluidized materials, which is their liquid-like behavior in flowing from a higher to a lower level under gravity. It is this feature that makes the air-gravity conveyor such an attractive proposition for the economic transport of bulk particulate materials at high rates and over long distances, provided that a continuous downward slope can be maintained.

It has been suggested [18] that where there is insufficient headroom for the installation of a single long conveyor of adequate slope, the distance required might be achieved by using short lengths of inclined conveyor, joined by risers supplied with air at a slightly higher pressure. Such an arrangement is illustrated in Figure 18.21.

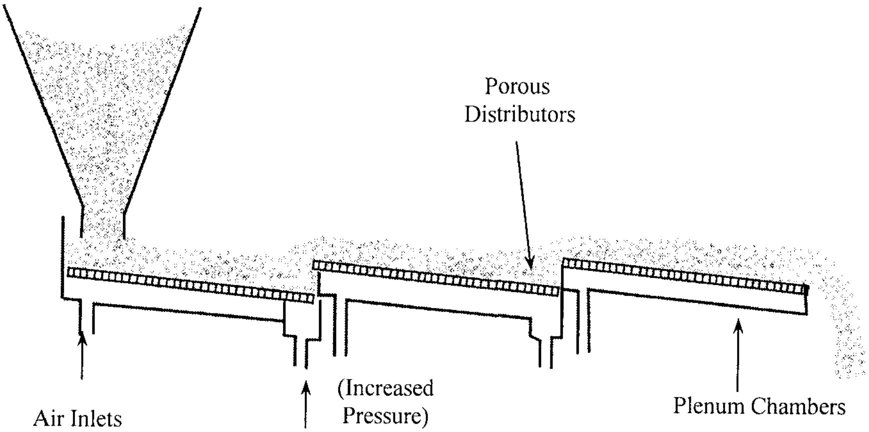

Figure 18.21 Multi-section stepped conveyor.

8.5 Potential Fluidization

Hanrot [19] describes a pressurized horizontal conveying system developed by Aluminum Pechiney to convey alumina. The alumina was to be conveyed from a single supply point to more than one hundred outlets. Electrolysis pots on a modern aluminum smelter were required to be filled and the distance from the silo to the furthest pot hopper was about 600 ft. Air at a pressure of 1·5 psig is used. A sketch of the system is given in Figure 18.22 and this illustrates the principle of operation.

A conventional channel is employed, but the channel runs full of material. Balancing columns are positioned on the conveying duct and are used for de-dusting. This is not a continuously operating system in the application described. It is a batch type system and its object is to meet the demands of the intermittent filling of the pot hoppers. With several hundred such pot hoppers to fill, however, the system must be operating on a semi-continuous basis at least. Of all the systems presented, this pressurized system probably has the greatest potential for future development.

With the channel running full, flow up a slight incline is a logical extension for development, but this will start to require a significant increase in air pressure, and the channel will have to be designed to be more pressure-tight to meet these demands. Simple modeling, based on static fluid mechanics, can be applied here to illustrate the increase in pressure required.

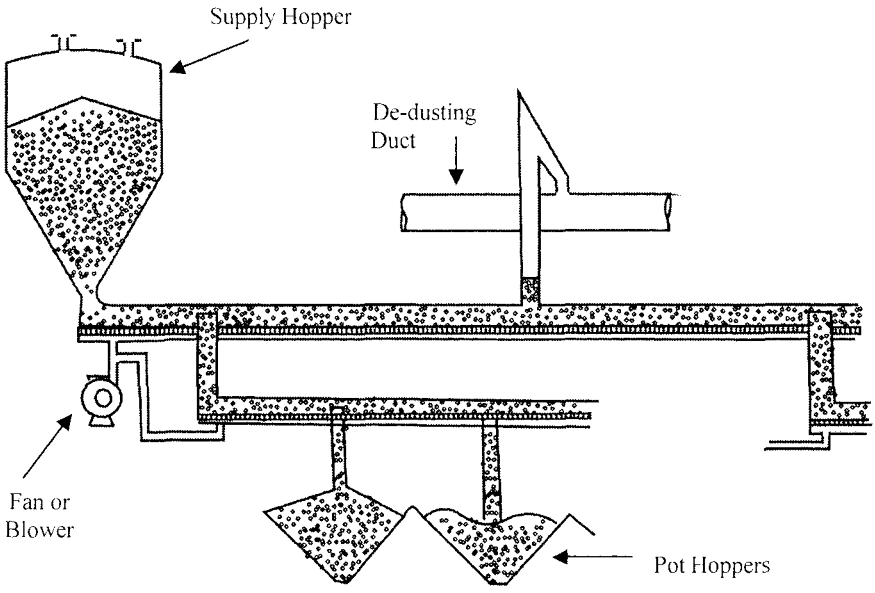

Figure 18.22 Principle of potential fluidization ducts.

The hydrostatic relationship is:

$$\Delta p = \frac{\rho\, g\, H}{144\, g_c} \quad \text{lbf/in}^2 \qquad \text{- - - - - - - - - - - - -} \qquad (5)$$

where Δp = pressure drop required - lbf/in^2
ρ = bulk density of fluidized material - lb/ft^3
g = gravitational acceleration - ft/s^2
H = vertical lift - ft
and g_c = gravitational constant - ft lb/lbf s^2

Thus for a typical material having a bulk density of about 50 lb/ft^3, the pressure drop required to lift the material a vertical distance of say 10 ft, would be about 3½ lbf/in^2.

REFERENCES

1. C.R. Woodcock and J.S. Mason. Bulk Solids Handling - An Introduction to the Practice and Technology. Blackie and Son Ltd. 1987.
2. J. Dodge. Procedure for transportation of materials in conveying channels using pressurized air. DRP88402, 1895. German Patent.
3. R.E. Leitzel and W.M. Morrisey. Air-float conveyors. Bulk Materials Handling, Vol 1, pp 307-325, Ed M.C. Hawk, Univ Pittsburgh, Sch Mech Eng. 1971.
4. E. Bushell and R.C. Maskell. Fluidized handling of alumina powder. Mech Handling, Vol 47, No 3, pp 126-131. March 1960.
5. C.R. Woodcock and J.S. Mason. Fluidized bed conveying - art or science? Proc Pneumotransport 3, BHRA Conf, paper E1. Bath, UK. April 1976.
6. C.R. Woodcock and J.S. Mason. The flow characteristics of a fluidized PVC powder in an inclined channel. Proc 2nd Powder and Bulk Solids Conf, pp 466-475. Chicago. May 1977.
7. C.R. Woodcock and J.S. Mason. The modeling of air-assisted bulk particulate solids Flow in Inclined Channels. Proc Pneumotransport 4, Paper D2. BHRA Conf. Calif. June 1978
8. D. Geldart. Types of gas fluidization. Powder Technol, Vol 7, pp 285-292. 1973.
9. R.E. Leitzel and W.M. Morrisey. Air-float conveyors. Bulk Materials Handling, Vol 1, pp 307-325. Ed M C Hawk, Univ Pittsburgh Sch Mech Eng. 1971.
10. M.N. Kraus. Pneumatic Conveying of Bulk Materials. The Ronald Press Co. New York. 1968.
11. D. Martin. No-transfer-point open conveyor. Process Engineering, p 39. July 1974.
12. R.E. Futer. Conveying solids with co-operating series of air jets. ASME paper 68-MH-31. 1968.
13. L. Kovacs and S. Varadi. Conveying granulated sugar through aerated channels. Proc 2nd Conf on Pneumatic Conveying, paper B10, pp 131-139. Pecs, Hungary. In German. March 1978.

14. W. Stegmaier. Horizontally conveying pneumatic chutes. Forden und Heben, Vol 26, No 6, pp 621-624. In German. 1976.
15. K. Shinohara and T. Tanaka. A new device for pneumatic transport of particles. Jnl Chem Eng of Japan, Vol 5, No 3, pp 279-285. 1972.
16. K. Shinohara, K. Hayashi, and T. Tanaka. Residence time distribution of particles with pneumatic escalator. Jnl Chem Eng of Japan, Vol 6. No 5, pp 447-453. 1973.
17. W. Isler. An air-slide type conveyor for horizontal and upward inclined transport. Zement-Kalk-Gips, Vol 10, pp 482-486. In German. 1960.
18. EEUA Handbook No 15. Pneumatic handling of powdered materials. Constable and Co, London. 1963.
19. J-P. Hanrot. Multipoint feeding of hoppers, mounted on aluminum smelter pots, by means of potential fluidization piping. Proc 115th An Mtg The Met Soc of AIME, pp 103-109. New Orleans. March 1986.