Introduction to the Theoretical and Practical Principles of Pneumatic Conveying

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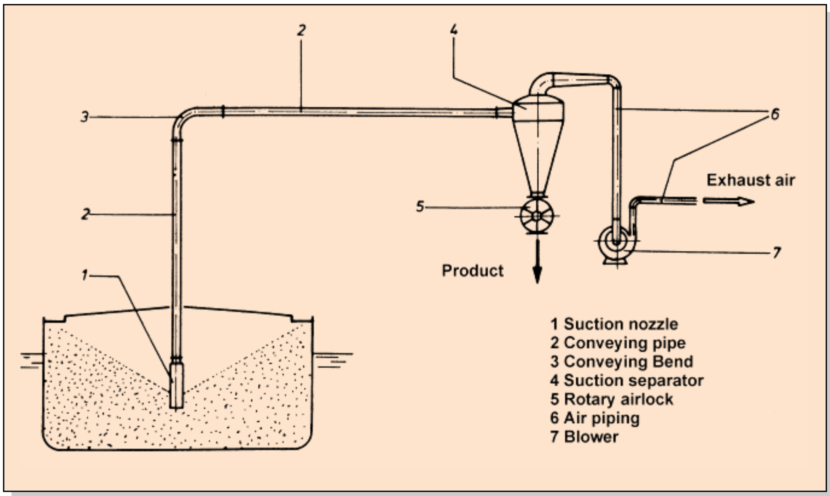
Abstract

The article initially explains the different types of pneumatic systems and the conveying principles, and then analyses the flow in both vertical and horizontal pipes. It also examines the effect of varying air speed, and quantifies the loss of conveying pressure when the pipe bends, showing how this can be translated into equivalent increase in pipe length.



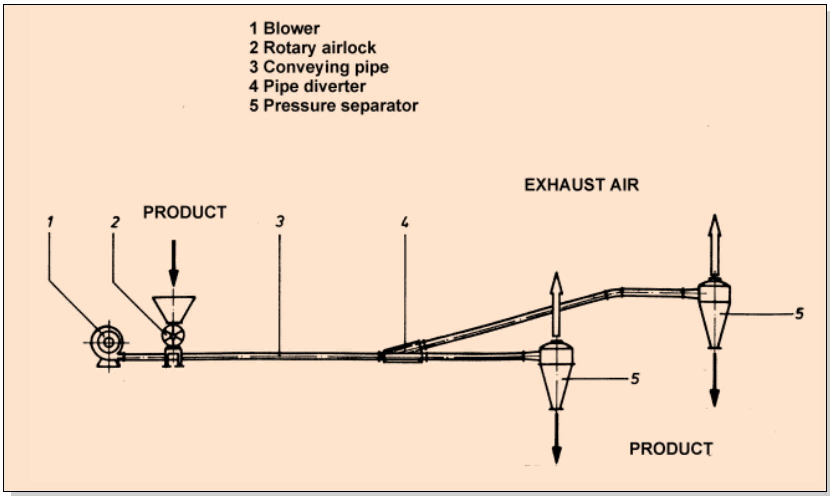


Figure 1 (top)
Pneumatic conveying - suction mode

Figure 2 (above)
Pneumatic conveying - pressure mode

PHYSICAL FUNDAMENTAL PRINCIPLES

Conveying principle and design of a pneumatic conveying system

Pneumatic conveying is based on the physical principle that air, under certain conditions, is able to convey heavy materials. In nature, air can carry many substances, such as sand, snow, leaves, and seeds. Pneumatic conveying causes air to flow by creating a pressure difference between the beginning and end of a pipe.

From basic physics, it is known that the suction of liquid is theoretically limited to 10m height, but for granular material in suction mode, the conveying height is close to unlimited – on condition that an air stream at the necessary speed is available to carry the material. The first pneumatic conveying equipment was used to unload grain from ships before the 19th Century. Later, this new continuous conveying method spread to small and middle size systems, as well as to other bulk products.

Pneumatic conveying systems may be differentiated as low, medium or high pressure. Blowers for industrial applications develop a conveying pressure of approx. 0.5 to 1 bar positive pressure, which corresponds to a vacuum of 0.3 to 0.5 bar. The three systems used are: suction only, pressure only, and combined.

Figure 1 shows the suction only mode. A blower (7) at the end of the pipe creates a vacuum in order to generate the necessary air stream in the pipe. Like in a vacuum cleaner, the product is picked up at the suction nozzle (1) and transported through the pipes (2,3) to the separation cyclone (4). Here the air and product are again separated. The product is taken out from the system through a rotary airlock (5). The air is exhausted from the blower (7) to the atmosphere, or to a filter for cleaning the air. This type of suction layout allows the product to be introduced at a number of points, and be delivered to a central location.

Typical examples of suction only mode are stationary, mobile, self travelling, or floating pneumatic ship unloaders, used for grain and oil seeds carried in ocean going and inland vessels, barges, rail wagons and trucks.

Figure 2 illustrates a pressure only mode system. Here air is taken directly from atmosphere and pressurised by the blower (1). The product to be conveyed is introduced into the system using a rotary airlock (2) which allows the material to enter the air stream in the pipe (3). At the end of the pipe, air and product is separated in a pressure cyclone (5). The product falls downward, and the air is exhausted out of the top.

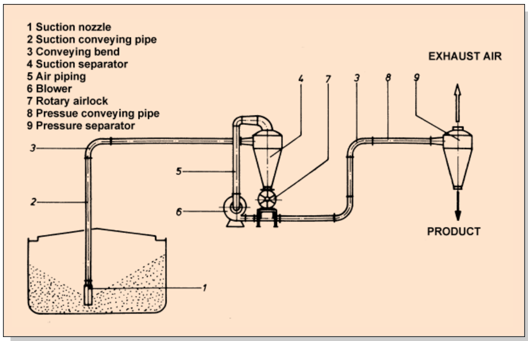


Figure 3 (top)
Pneumatic conveying - suction - pressure mode

Pressure only systems are recommended when the product is introduced at one point, and optionally, using diverter valves (4) transported to different delivery points. Due to the higher pressure differential and specific weight of the air, they have a greater capacity than the suction type.

In practical applications, both modes can be combined to get the benefits of each (Figure 3). The first section of the conveying line uses the suction mode to get the material into the pipe, and the second part uses the pressure mode to achieve higher capacity at longer distances.

The diameters of pneumatic conveying pipes vary between 10 mm (for use in the processing industry) to 800 mm (for large amounts of material, such as grain from ships). The conveying capacity is accordingly different, and ranges from a few kg/h to 1000 t/h. Lines are between 10 and 1000 m in length, and the air speed varies with the material, but is generally between 10 to 30 m/s.

Flow analysis in the conveying pipe

To allow solid matter to be transported, the driving flow forces of the air must be larger than the forces – weight, friction and inertia – acting on the particle. There are three influential factors: the first is the suspension speed of the solid matter w_S; the second is the air speed w; and the third is the mixture relation π, representing the ratio of solid matter to the conveying medium.

Figure 4(a) shows schematically the two most important forces acting on a particle in a vertical air stream. In airflow w, the flow resistance S of the particle acts vertically up, and its weight G acts down. When both forces, S and G, are equal, the particle stays suspended.

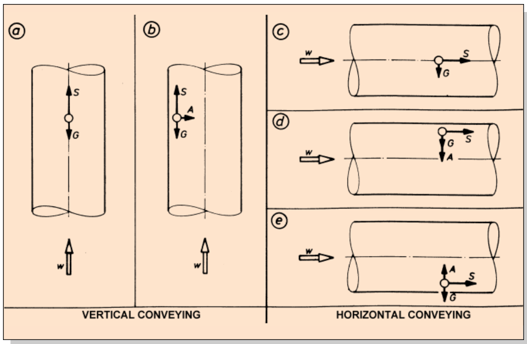


Figure 4 (middle)
Pneumatic conveying - forces acting on a particle in a pipe

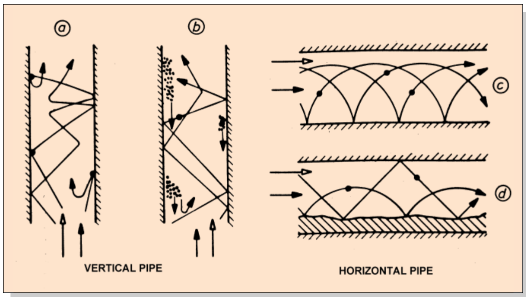


Figure 5 (bottom)
Dilute pneumatic conveying

The necessary air speed w is called the suspension speed w_S. The minimal condition for conveying is that the air speed in a vertical pipe is higher than the suspension speed, and the difference is the real speed of each particle relative to the pipe. Thus:

$$S = c_w * A * \frac{\rho}{2} * w^2$$

where S is the stream force, c_W is the resistance coefficient of the shape, A is the flow face area of the particle (vertical to the flow direction), ρ is the atmospheric density, and w the air speed. The expression $\frac{\rho}{2} w^2$ is also known as dynamic or impact pressure. The suspension speed is influenced by many factors. Primarily, atmospheric density affects the flow force – hence the conveying capacity will slightly increase in high pressure weather conditions, or on very cold days. Furthermore, the suspension speed is determined by c_W, which depends on the shape and surface roughness of the particle. Non-spherical shaped bodies tend to have an advantage, as an elongated shape will fall with the tip down to reduce resistance, which explains the differences in capacity for different grain types under the same conditions.

If the chosen particle is not in the centre of the pipe, but close to the wall as in Figure 4(b), a force A, vertical to the flow direction, arises. This lifting force comes from the non-symmetrical speed profile of the air close to the pipe wall, caused by the boundary layer, and it tries to force the particle to the centre of the pipe.

This effect is clearer in Figures 4(c), (d) and (e), showing horizontal conveying. The particle in the flow at the centre of the pipe in 4(c) is acted on by the flow resistance (towing force) S to the right, and the weight force G down. If the particle is close to the pipe wall, as in 4(d) and 4(e), the lifting force A starts to act. Below the middle of the pipe, the lifting force opposes the weight of the particle.

Theoretically, more forces should be presented in this figure – for example, inertia, friction between particles, friction between particle and wall, and momentum – all of which must be overcome by the air flow. This pneumatic system is known as dilute phase conveying. The particles move by flying, or jumping forward, and are carried (blown), more or less in the same concentration, through the conveying pipe The degree of concentration is expressed through a non-dimensional parameter, the mixture ratio μ. This is the ratio of solid matter transported to the conveyed air mass, in the same unit of time.

Figure 5 shows dilute phase conveying of solid particles in pipes, vertical and horizontal. Due to the variable directions of the speed component, forces acting crosswise make the particles hit the wall of the pipe. There they are retarded, jump back, and need to be accelerated again, which leads to pressure loss in the pipe.

A more or less free flow of the particle is possible with sufficient air speed for vertical conveying, and with a mixture ratio of approximately 10 to 20, as shown in 5(a). A separation of air and product can happen if the air flow nears the suspension speed of the particle, and the mixture ratio is close to 30, as in 5(b). Although some of the solid particles sink, it is possible to obtain overall upstream conveying.

Horizontally, as in 5(c), there is separation caused by the gravity force as soon the air speed is reduced. If the air speed is close to the particle suspension speed, as in 5(d), a deposit, especially fines, is formed along the pipe bottom. Most of the particles move, forming a slug of strong separation in the pipe bends. Blockage may occur if the pressure reserve of the blower is insufficient.

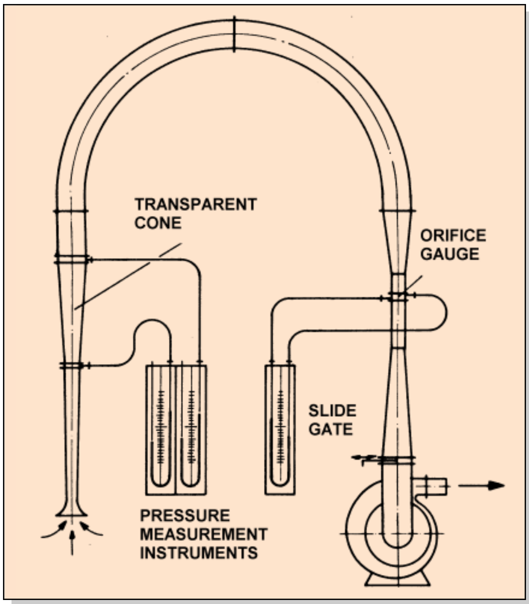


Figure 6
Lab for determination of suspension speed

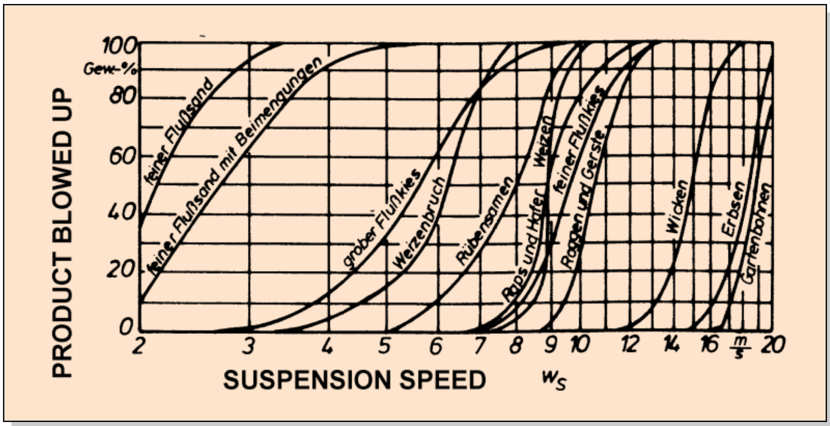


Figure 7
Suspension speed for different products

At any point of the conveying pipe, a minimum air speed – the critical speed – is needed in order to transport the product. It varies according to the characteristics of the product to be conveyed and can be between 10 and 30 m/s. If the air speed falls short, then material deposits on the pipe bottom until finally a blockage occurs. It is not possible to determine the blockage limit beforehand, as it depends on each system's layout and piping configuration.

Higher air speed may transport the material, but will have the following disadvantages:

- The wear caused by the product on the pipe is considerably higher;
- It can cause significant damage to the product granules (product degradation); and
- Higher horsepower is required at the blower to create the conveying pressure.

From fluid dynamics, the electrical power N of a blower needed to move only air can be found from the volume flow of air V, the total required pressure Δp, and the efficiency η, thus:

$$N = \frac{V\Delta p}{\eta}$$

The air flow is also a product of the cross section A and air speed w, therefore:

$$V = A\,w = \frac{\pi d^2}{4}\,w$$

But, from the Bernoulli energy equation, the pressure loss in the pipe at turbulent flow is proportional to the square of the air speed, so that:

$$\Delta p \propto w^2.$$

and thus $N \propto w^3$

which means a higher air speed requires a considerable increase in power.

EMPIRICAL FOUNDATIONS

Air speed

Suspension speed plays a big role in pneumatic conveying, but only a single particle (grain) has been considered up to now. In reality, particles will mainly appear in clouds, and tests have shown that these will sink faster than a single particle. One explanation is to consider the effect of the side sheltered from the wind, as in a bicycle race, where the last rider profits from the lower wind force. Consequently, this means that higher particle concentration in the pipe requires higher air speed to assure perfect transport.

The determination of the suspension speed of a product is possible using simple test facilities, as shown in Figure 6. A transparent conical section is inserted in a vertical suction conveying pipe (on the left). A blower provides the necessary vacuum. In each diameter (section) of this cone there will be a different air speed. At a specific diameter in the conical section, the air speed drops so much that conveying is no longer possible, and the test product particles stay at a certain point of the cone. With suitable measurement tools, and an adjustable air flow, the suspension speed of the product can be found.

Figure 7 shows the resulting diagram of such measurements for a number of different products. The suspension speed w_s is shown on the X-axis logarithmically. For each product, the percentage of the total sample that is blown over can be read on the Y-axis. Fine river sand is on the left, and those grain types, with a smooth surface and spherical shape (such as peas and beans), needing higher suspension speeds are on the right. Because each particle in a sample does not have exactly the same shape and size, there is no precise suspension speed for a product. An average value can be determined when 50% of the product remains. Wheat, for example, has an average suspension speed of 9 m/s.

To design the pipe it is necessary to determine the conveying air speed. It should be high enough above the suspension speed in order to avoid a blockage of the system. For example, the air speed for grain is proven from practical experience to lie between 20 and 25 m/s. The product (particle) speed is the difference of the air speed w and the suspension speed w_s, and it has been found that the ratio of particle speed to air speed is about 0.6. Wheat has a suspension speed of 9 m/s and a required air speed of 23 m/s.

Pressure loss in conveying pipe

Figure 8 plots the principal components of the total pressure loss in the conveying pipe relative to air speed. These factors are:

- The air (without material) generates friction in the pipe that must be overcome. This part of the conveying pressure is shown in the curve Δp_{L}. As pressure drop increases at a square ratio, approximately to the air speed, the latter should be kept as low as possible.

- The conveyed product is constantly retarded at the pipe wall and needs to be accelerated again. This friction gives the pressure drop portion Δ_{PR}. The pressure drop increases approximately linearly with the air speed.

- Blocking forces due to the particles are expressed with Δ_{PF}. If material flow is constant, with falling air speed the amount of material in the pipe increases, the mixture ratio changes and, consequently, the pressure loss increases. This curve is hyperbolic in shape.

Figure 8 (below)
Pressure - air speed curve

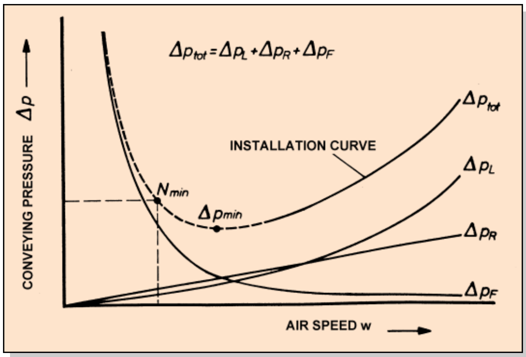


Figure 9 (bottom)
Equivalent length for particle acceleration

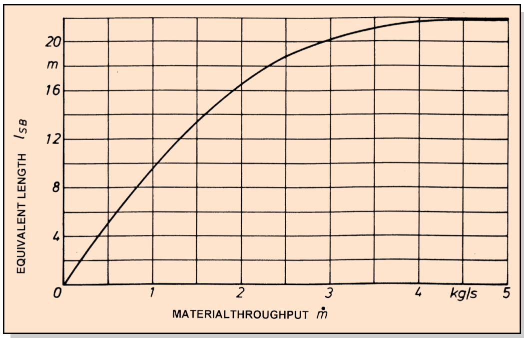


Figure 10 (top)
Material and air flow in a bend

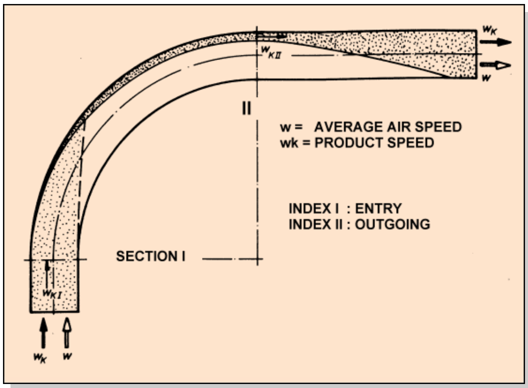
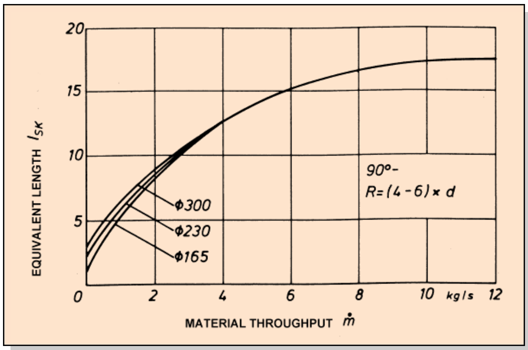


Figure 11 (above)
Equivalent length LSK for conveying bend



Adding all losses creates the total pressure loss curve, or system characteristic curve, Δ_{PTOT}. Its shape depends on the product, the mixture ratio, and the piping configuration, but the parabolic shape is valid for all pneumatic conveying systems.

The power of the blower depends on the conveying pressure Δp and the air speed w. A working point, with a minimal power consumption of N_{min} is shown which does not coincide with the lowest conveying pressure. The working range of dilute phase conveying is located at higher air speed and power consumption in order to avoid blockage in the conveying pipe. The left dashed branch of the curve only relates to dense phase conveying.

Up to now, the conveying pressure needed is only valid for the complete system. The following looks at how each component builds over the conveying line.

Pressure loss caused by material acceleration

The solid particles must be accelerated as quickly as possible to the minimum conveying speed. The acceleration loss takes a large portion of the conveying pressure, which must be generated by the blower. This loss occurs only at the material inlet point in a suction only, or a pressure only, system. In a combined suction/pressure system, it occurs twice: once at the material inlet at the suction nozzle, and again after the suction cyclone at the material re-entry into the pressure piping.

An equivalent length of piping can be used to express the magnitude of the acceleration resistance, and its portion of the total pressure loss in the conveying pipe. It is expressed as the length of horizontal conveying pipe that gives the same pressure loss at constant conveying speed. Figure 9 shows the experimental curve from Segler to get the equivalent length for the acceleration of wheat at an average air speed of 22 m/s independent of the conveying quantity. The asymptotic curve gets closer to a limiting value at a material throughput of over 5 kg/s – a conveying capacity of over 20 t/h. At this point the equivalent length can be considered constant at about 22 m, and is independent of the conveying capacity.

In suction only systems, there is another pressure loss caused by the type of suction nozzle. A value may be added, between 0 and the nozzle acceleration loss (resistance).

Pressure loss in the pipe bend

During the design and construction of suction or pressure conveying systems, it is important to keep the number of changes of direction to a minimum. At the pipe bend, there is a gradual braking of the product in the air stream. An additional product acceleration is required which increases the blower requirement. Higher wear occurs at the bend, requiring special attention such as thicker pipe walls. It may also cause product degradation.

Figure10 shows the product and air stream in a bend. There are four situations:

- Before entry into the bend, up to cross section #I, the product and air are uniformly blended;
- At cross section #I, segregation starts;
- Between cross sections #I and #II, the material is directed to the outer wall because of the centrifugal force. It is retarded by the friction at the wall, and so the material speed Δ_{KI} at entry is higher than the outgoing speed Δ_{KII}; and
- After cross section #II, the air and the product mix again.

Experiments have shown that the pressure drop inside the pipe bend while conveying material is little higher than with only air. The real pressure loss comes only after the direction change caused by the material acceleration. The *equivalent length of a pipe bend* is the length of a horizontal pipe of the same diameter, the same surface roughness, and the same pressure loss as the pipe bend.

Figure 11, from *Segler*, shows the equivalent horizontal length of a 90° pipe bend with a normal radius of curvature of four to six times the pipe diameter. Only for small conveying quantities, of less than 4 kg/s, is there a small dependence on pipe diameter. Over a capacity of 10 kg/s the curve gets close to a limiting value, and for more than 30 t/h a constant equivalent length of approximately 18 m can be used. This means that by saving one bend of 90°, the horizontal conveying line could be extended almost 20m for the same capacity.

Pipe bends of less than 90°, for example 45°, obtain a smaller equivalent length lSK. Test results have shown that there is very little difference between a bend in the horizontal plane and one between the horizontal and the vertical, so the same equivalent length is used.

Pressure loss in vertical conveying

In a vertical, rather than horizontal, pipe there is additional lifting work to be done which generates an extra pressure drop, and there is a rule of thumb that the pressure drop per metre length in the vertical pipe is approximately double the horizontal. Thus, in determining an equivalent length, the vertical length is doubled when finding the total system pressure drop.

NOTE

A more detailed paper on this subject can be downloaded from the company's homepage http://www.neuero.com.

ABOUT THE AUTHOR

Scott Neidigh, President of Neuero Corporation, has been involved, since 1966, in the design and engineering of pneumatic conveying systems for the bulk material handling industry. He is a graduate of Southern Illinois University and the Midwest College of Engineering, where he received Degrees in Machine Design Technology, and Mechanical Engineering. He is also a member of the Society of Automotive Engineers, as well as the American Society of Agricultural Engineers.

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