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Revision Memo

12/02 Corrections and minor updates.

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SCOPE

This section deals with the subject of dilute and dense phase pneumatic conveying and storage of fine solids. It primarily covers the movement of solids between process vessels and storage vessels. Circulation between process vessels is covered in detail in **Section VI-A**. Additional information on pneumatic conveying system and equipment design can be obtained from the Planning and Design Division of ER&E Projects Department.

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1. Rossetti, S. J., *Design and Troubleshooting of Pneumatic and Other Gas Conveying Systems*, EE.3E.76, February, 1976.
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4. Design Practices Section IX, *Compressors*.
5. Yeich, W. G., *A Guide for Safe Design of Dust Handling Systems*, EE.84E.84, 1984.
6. Davuluri, R., *Dense Phase Conveying Design Procedure, Software Development and Use*, PSRI Research Report 76, 1999.

ADDITIONAL LITERATURE

1. Croote, R. A., Hardcastle, J. M., *Solids Flow in Bins*, EE.5KW.84, February, 1984

CONVEYING OF FINE SOLIDS

A wide variety of materials are transported within Exxon in pneumatic conveying systems including fresh and waste catalyst, coal, coke and many chemicals. These systems are used to convey fine solids from offsite areas to and from onsite storage vessels and process vessels. Since pneumatic systems are enclosed, product contamination, material loss, and dust emissions are reduced or eliminated. By conveying with a dry or inert gas, the properties of some materials may be protected in transit. Pneumatic systems are also easily automated with conveying hardware being integrated with state-of-the-art control systems.

In addition to material transport, a dilute phase pneumatic conveying system can be used to simultaneously cool the solids being conveyed. Cooling may be required for safe shipment and disposal of material outside the refinery. In this case, finned pipe is utilized to transfer heat from the solids to the atmosphere. Applications include the cooling of product coke and waste catalyst fines that were previously collected in an electrostatic precipitator. Inlet temperature to the system have ranged from 400-600°F (200-320°C) and exit temperatures have been 150-200°F (65-95°C). See **Section VI-D** for more details.

PNEUMATIC CONVEYING SYSTEMS

A pneumatic conveying system has four primary components: a source of conveying gas, normally a fan or compressor, a feeder and directly associated storage vessel which feeds the solids into the gas stream, a transport line, and a solids-gas disengaging device. The major function of the conveying system is to move material reliably from one point to another. This usually requires:

- No plugging or buildup of material within the system.
- Minimal wear due to impact or abrasion.
- Minimum attrition of the bulk solid being conveyed.
- Minimal spillage and dust generation/evolution.
- Reasonable power requirements.
- Flow rate control of the solids being conveyed.

Except for power requirements, the ability of the system to meet the above requirements is strongly influenced by the interface between the pneumatic conveyor line and the upstream and downstream equipment (e.g., a feeder, hopper or bin).

[Table 1](#) provides a summary of the capabilities of the various compressor types typically used in pneumatic conveying systems. Also see **Reference (4)**. When sizing the compressor, the total system pressure drop must be considered. This includes pressure drop associated with the transport line, solids feeder, conveying gas flow rate control, and the solids-gas disengaging device.

There are several types of feeders which can be used to meter the solids and/or transport the solids across the differential pressure and into the pneumatic conveying line. The rotary feeder (also known as rotary valve, rotary air lock, star feeder) is the most common feeder used in pneumatic conveying. It is capable of both metering the solids and transporting the solids across the differential pressure and into the conveying line.

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PNEUMATIC CONVEYING SYSTEMS (Cont)

[Table 2](#) summarizes the various types of feeders that are available. Pressure differential between the upstream and downstream sides of the feeder is the key feeder application parameter.

Transport line design is the focus of this section and is covered in detail in following pages. Design procedures are described that determine conveying gas rate, system pressure drop, and system horsepower for various line sizes. Conveying gas velocities must meet saltation, plugging, and erosion criteria. Final design is an economic and operational optimization of line size, gas rate, and horsepower.

The recovery of the solids from the conveying gas stream is required from both functional and environmental control standpoints. This is usually accomplished in cyclones and/or bag filters. Pneumatic conveying systems may be either "open" or "closed loop." An open system normally uses air as the conveying gas and the air is released to atmosphere after the solids are separated from the gas. Closed loop systems, which recycle the conveying gas, are used when an inert or dry gas is needed as the conveying medium.

TYPES OF SYSTEMS

Pneumatic conveying can be conducted in the dilute phase or dense phase mode. Dilute phase systems are used more extensively within Exxon and have a long history of commercial application in various industries. Dense phase systems are receiving greater attention recently particularly in applications where it is necessary to minimize particle attrition and conveying equipment wear. Minimum dust generation and simpler gas/solids environmental control equipment are other considerations in the use of dense phase conveying.

Dilute phase transport is characterized by a low solids to gas ratio [usually less than 0.5 lb solids/ft³ of gas (8 kg solids/m³ gas)], high gas velocities [usually 30 to 90 ft/sec (9 to 27 m/s)], low total pressure drops, and the ability to function over fairly long distances. In a dilute phase system, the solids particles are distributed uniformly throughout the conveying line cross section and along the length as they are transferred. Vacuum, low pressure, and most pull-push systems convey material in a dilute phase. Dense phase systems operate at gas velocities less than those required to suspend the solids in the gas stream. In dense phase conveying, the transport line may be filled with solids at one or more cross sections.

Saltation, or solids buildup in the pipe, is an important factor since how these buildups are controlled to maintain conveying without plugging the transport line is a key design feature. Dense phase systems are characterized by high solids to gas ratios [over 1 lb solids/ft³ of gas (16 kg/m³ gas)], low velocities, and high-pressure drops. Dense phase systems tend to be more complex due to the fact that the higher pressure operations requires a lock hopper/blow tank for injecting solids into the conveying line.

TYPES OF DILUTE PHASE SYSTEMS

[Figures 1, 2](#) and [3](#) illustrate the three types of systems in use - vacuum, positive pressure, and pull-push.

A negative pressure system is characterized by the gas pressure at the solids feed point being close to atmospheric pressure and the gas at the solids-gas disengaging point being under a vacuum. The vacuum pump (fan or blower) is located downstream of the solids-gas disengaging point.

A negative pressure system has a limited practical conveying range because of the limited achievable vacuum and hence the limited system differential pressure which can be developed. In addition, the higher the vacuum, the less dense the gas becomes, and the more gas per weight of solid conveyed is required. In general, negative pressure systems work best where the total conveying distance does not exceed 250 ft (75 m) and the total differential pressure of the system less than 7 lb/in.² (50 kPa).

Negative pressure systems are particularly suited for transporting solids from several pickup points to a single discharge point. This is because of the relative simplicity of the pickup manifold in the vacuum systems.

The two primary advantages of a negative pressure system are: (1) ease of feeding material into the conveying gas, and (2) cleanliness. In most applications of negative pressure systems, the solids to be conveyed are stored in an atmospheric pressure bin and the conveying gas at the feed point is at a slight negative pressure. This allows a simple screw or rotary feeder acting only as a metering device to be used to feed the solids into the conveying gas. In the case of very free-flowing solids, such as plastic beads or pellets, a slide valve to meter the solids flow may suffice. In addition, a negative pressure system allows the use of a manually manipulated suction nozzle to unload drums or other containers in place of inverting or dumping the contents from the container. As mentioned, the other principle advantage is cleanliness. Negative pressure systems minimize problems with fugitive dust, as all leaks are inward. This is particularly useful when handling toxic or corrosive material.

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PNEUMATIC CONVEYING SYSTEMS (Cont)

The primary disadvantage of the negative pressure system is that the source of vacuum is located downstream of the solid-gas disengaging device and is subject to damage should there be a carryover of solids from this device. This is particularly important if a rotary lobe type vacuum blower with close clearances is used.

A positive pressure system is characterized by the gas pressure at the solids feed point being at a positive pressure and the gas pressure at the solids-gas disengaging point being close to atmospheric pressure.

The principle advantages of the positive system are: (1) the capability for relatively long distance conveying, and (2) the location of the blower or fan in a dust-free services. Positive pressure systems can be used to convey solids over distances greater than 500 ft (150 m).

The disadvantage of the positive pressure system is the difficulty in keeping the feeder, which feeds the solids from a lower pressure into the higher pressure conveying gas functioning satisfactorily. Also, because the conveying gas is generally at a higher pressure than the solids, there will be gas leakage through the upstream process. On the other hand, positive pressure systems are preferred for closed-loop, inert gas systems because they prevent the ingress of oxygen into the system.

Negative pressure and positive pressure systems can be combined in order to capture the advantages of both types of systems into a single system. These systems are well suited for conveying solids from several pickup points to various discharge points. They combine the advantage of easy feeding of material from the storage container associated with the vacuum system with the longer conveying distances of the pressure system. Although it is possible to use a single blower, system layout and configuration usually dictates that separate blowers be used for each side.

DILUTE PHASE DESIGN PROCEDURE

The following dilute phase pneumatic conveying design procedure was developed based on extensive laboratory and literature data (4). It was verified in a number of commercial applications in line sizes up to 12 in. (0.3 m) in vertical transport, and up to 60 in. (1.5 m) in horizontal transport. Use in larger lines has not been tested, but there are no indications that the procedure is not satisfactory for use in larger lines. Pressure drop was satisfactorily predicted in the conveying of plastic pellets ($\pm 10\%$) and in coke handling. Saltation velocities were also satisfactorily predicted in these services.

General Considerations

Minimum length horizontal and vertical sections should be used in laying out a dilute phase pneumatic transport system. Inclined piping, either upflow or downflow, is not generally recommended because operating problems are frequently encountered at each end. The number of elbows should also be minimized since elbows are sources of flow disturbances, additional pressure drop and particle attrition. Elbows are also prone to erosion. (Plugged Tees are frequently used in place of elbows to minimize erosion.)

The system should be designed to operate in the dilute phase. Therefore, horizontal sections should be designed to operate at gas velocities high enough to keep all solids in suspension. Vertical sections should also be designed to operate at gas velocities high enough to insure uniform upward flow of solids and gas.

A trial and error design procedure is used to design a pneumatic conveying system. After the conveying system is laid out, a tentative pipe diameter is chosen, the gas rate needed to transport the solids is calculated, and the total system pressure drop is determined. Trade offs between pipe diameter, pressure drop and conveying gas rate are then made to select the proper system. Detailed calculation procedures are described later. The underlying equations for the calculations are described in the next sections.

Vertical Transport

Three flow regimes can occur in vertical gas/solids flow, a dilute phase, a transition phase and a dense phase regime. At high velocities both gas and solids flow upward in a uniform dilute phase flow regime. As the gas velocity decreases, the solids near the wall slow down due to friction and gravity effects and a transition phase begins to develop. Solids velocity effects are described by the "slip" velocity which is the difference between gas and solids velocities due to gravity, wall friction and acceleration effects. At some point, solids near the wall approach zero vertical velocity and solids concentration near the wall begins to increase. As gas velocity decreases further, the solids near the wall begin to move downward with gas and other solids moving upward in the center of the pipe. The flow in this annular transition phase regime is quite unstable and small variations in gas flow cause large changes in the pressure drop. Large particles cannot be transported properly at these velocities and can cause line choking. Because of instability and possible choking problems, vertical transport systems should not be designed to operate in the annular flow regime. As gas velocity is decreased further, the dense (bubbling or slug) flow phase develops. Risers described in [Section VI-A](#) are examples of vertical systems, which can operate in the dense phase.

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PNEUMATIC CONVEYING SYSTEMS (Cont)

- Solids Velocity** - Slip velocity in vertical gas/solids flow is a function of gas velocity, gas and solids physical properties, pipe size and material. Solids velocity, U_s can be determined from a momentum balance to be:

$$U_s = \frac{U_g - U_{et} \left[1 - \frac{\Delta P_g (144)}{2 \rho_p H} \right]}{1 + \frac{C U_{et}}{4 g D}} \quad (\text{ft/s}) \quad \text{Eq. (1c)}$$

$$U_s = \frac{U_g - U_{et} \left[1 - \frac{10^3 \Delta P_g}{2g \rho_p H} \right]}{1 + \frac{C U_{et}}{4 g D}} \quad (\text{m/s}) \quad \text{Eq. (1m)}$$

- where:**
- U_g = The gas velocity (ft/s), (m/s)
 - U_{et} = The equivalent terminal settling velocity of the solids based on the cluster diameter (ft/s), (m/s)
 - ΔP_g = The gas pressure drop (psi), (kPa)
 - ρ_p = The particle density (lb/ft³), (kg/m³)
 - H = The conveying section height (ft), (m)
 - C = A constant dependent on pipe material (ft/s), (m/s)
 - D = The pipe internal diameter (ft), (m)
 - g = The acceleration due to gravity (32.2 ft/s²), (9.81 m/s²)

The equivalent terminal settling velocity is obtained from [Figures 1 and 2 of Section VI-E](#). The value of C was determined experimentally and values are given in the table below. Fine particles referred to in the table are those with single particle terminal settling velocities, U_{to} , less than 3.5 ft/s (1.1 m/s), coarse particles have values of U_{to} greater than 3.5 ft/s (1.1 m/s).

TABLE A
VALUES OF PIPE MATERIAL CONSTANT C

	METALLIC PIPE	NON-METALLIC PIPE
Fine Particles	0.66 ft/s (0.20 m/s)	0.34 ft/s (0.10 m/s)
Coarse Particles	0.66 ft/s (0.20 m/s)	0.66 ft/s (0.20 m/s)

- Pressure Drop** - The pressure drop in vertical transport in fully developed flow is the sum of pressure drop due to the static head, to solids friction and to gas friction. The static head loss is given as:

$$\frac{\Delta P_{sh}}{H} = \frac{\rho_m}{144} = \frac{G_s}{144 U_s} \frac{g}{g_c} \quad (\text{psi / ft}) \quad \text{Eq. (2c)}$$

$$\frac{\Delta P_{sh}}{H} = 10^{-3} g \rho_m = 10^{-3} g \frac{G_s}{U_s} \quad (\text{kPa / m}) \quad \text{Eq. (2m)}$$

- where:**
- ΔP_{sh} = The pressure drop due to the static head (psi), (kPa)
 - H = The height of the vertical transport section (ft), (m)
 - ρ_m = The density of the gas/solids mixture flowing in the line (lb/ft³), (kg/m³)
 - G_s = The solids mass flux (lb/ft²s), (kg/m²s)
 - U_s = The solids velocity from [Eq. \(1\)](#) (ft/s), (m/s)
 - g = The acceleration due to gravity (32.2 ft/s²), (9.81 m/s²)
 - g_c = The gravitational conversion factor, (32.2 ft lb mass/s² lb force)

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The pressure drop due to solids friction at the wall can be expressed as:

$$\left(\frac{\Delta P_f}{H}\right)_s = f_s \left[\frac{\rho_m U_s^2}{2 (144) g_c D} \right] \quad (\text{psi / ft}) \quad \text{Eq. (3c)}$$

$$\left(\frac{\Delta P_f}{H}\right)_s = f_s \left[\frac{10^{-3} \rho_m U_s^2}{2D} \right] \quad (\text{kPa / m}) \quad \text{Eq. (3m)}$$

where: $\left(\frac{\Delta P_f}{H}\right)_s$ = The pressure drop per length due to solids friction (psi/ft), (kPa/m)
 f_s = The friction factor which varies with the flow regime
 D = The pipe internal diameter (ft), (m)

For uniform flow, the solids friction factor is inversely proportional to the solids velocity and is a function of C , the pipe material constant. For this case, the ratio of solids friction pressure drop to total solids pressure drop (friction plus static head) can be correlated with the dimensionless number CU_s / gD as shown in [Figure 4](#). [Figure 4](#) is applicable down to the value of CU_s / gD of 1. At values less than 1, annular flow develops and the correlation is no longer applicable.

Pressure drop due to solids friction is determined from the ratio $(\Delta P_f / \Delta P_T)_s$ obtained from [Figure 4](#) as follows:

$$\left(\frac{\Delta P_f}{H}\right)_s = \frac{(\Delta P_f / \Delta P_T)_s}{1 - (\Delta P_f / \Delta P_T)_s} \frac{\rho_m}{144} \frac{g}{g_c} \quad (\text{psi / ft}) \quad \text{Eq. (4c)}$$

$$\left(\frac{\Delta P_f}{H}\right)_s = \frac{10^{-3} g \rho_m (\Delta P_f / \Delta P_T)_s}{1 - (\Delta P_f / \Delta P_T)_s} \quad (\text{kPa / m}) \quad \text{Eq. (4)}$$

This correlation was tested against 200 pressure drop measurements and was found to predict results with a mean deviation of less than 10%.

The gas pressure drop is given by:

$$\frac{\Delta P_g}{H} = f_g \left[\frac{\rho_g U_g^2}{2 (144) g_c D} \right] \quad (\text{psi / ft}) \quad \text{Eq. (5c)}$$

$$\frac{\Delta P_g}{H} = f_g \left[\frac{10^{-3} \rho_g U_g^2}{2D} \right] \quad (\text{kPa / m}) \quad \text{Eq. (5m)}$$

where: f_g = The Fanning friction factor (**Ref. 2**)
 ρ_g = The gas phase density (lb/ft³), (kg/m³)
 U_g = The superficial gas velocity (ft/s), (m/s)

Horizontal Transport

Horizontal flow of gas and solids also exhibits three flow regimes, dilute, transition and dense phase. At high gas velocities, the solids are fully suspended and move in the same direction as the gas, similar to the uniform flow regime in vertical flow. As the gas velocity is decreased, the carrying capacity of the gas is exceeded and solids begin to deposit or "salt out" at the bottom of the pipe. This is the transition phase and is characterized by two-phase flow at the top of the pipe, moving dunes of solids at the bottom of the pipe, high and erratic pressure drops, and unsteady solids flow rates. The gas velocity at which solids begin to drop out is referred to as the saltation velocity. When the gas rate is decreased further, the dense phase develops. Unless the system is designed to operate in the dense phase, the whole cross section of the pipe may be filled with solids and become plugged.

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PNEUMATIC CONVEYING SYSTEMS (Cont)

- **Saltation Velocity** - The optimum gas velocity for horizontal dilute phase conveying systems is 10 to 15% above the saltation velocity. This minimizes gas compressor requirements, erosion and attrition while avoiding saltation. The saltation velocity, V_s , is calculated from:

$$V_s = V_{so} \left[1 + \frac{G_s}{k \rho_p} \right] \quad (\text{ft / s}), (\text{m / s}) \quad \text{Eq. (6)}$$

where: V_{so} = The saltation velocity for a single particle (ft/s), (m/s)
 k = A factor which accounts for the effect of particle size distribution (ft/s), (m/s)

The grouping $G_s / k \rho_p$ accounts for the effect of solids concentration on the saltation velocity.

V_{so} is given by:

$$V_{so} = \frac{Re_o \mu}{\rho_g D} \quad (\text{ft / s}), (\text{m / s}) \quad \text{Eq. (7)}$$

where: Re_o = A Reynolds number obtained from [Figure 5](#)
 D = The pipe diameter (ft), (m)
 μ = The gas viscosity (lb/ft s), (kg/ms)

To obtain Re_o from [Figure 5](#), it is necessary first to calculate the dimensionless quantity Ψ .

$$\Psi = \frac{\pi (n d_p)^3 [(\rho_p / \rho_g) - 1] g \rho_g^2}{48.5 \mu^2} \quad \text{Eq. (8)}$$

where: n = The cluster index obtained from [Figure 2, Section VI-E](#)
 d_p = The weight median particle size (ft), (m)

The quantity Ψ is then used in [Figure 6](#) or [7](#) to obtain Re^* , another Reynolds number. Re^* is then used in [Figure 5](#) to determine Re_o .

The particle size distribution factor k , is obtained from [Figure 8](#). The particle size distribution standard deviation s used in [Figure 8](#) is obtained from a log-probability plot of the particle size distribution. It is given as:

$$s = \frac{d_p @ 50\%}{d_p @ 16\%} \quad \text{Eq. (9)}$$

- **Pressure Drop** - The pressure drop for horizontal flow at gas velocities above saltation is the sum of frictional losses for the gas and solids:

$$\frac{\Delta P_T}{L} = f_g \left[\frac{\rho_g U_g^2}{2 (144) g_c D} \right] + \left[\frac{K G_s}{2 (144) g_c D} \right] \quad (\text{psi / ft}) \quad \text{Eq. (10c)}$$

$$\frac{\Delta P_T}{L} = f_g \left[\frac{10^{-3} \rho_g U_g^2}{2 D} \right] + \left[\frac{10^{-3} K G_s}{2 D} \right] \quad (\text{kPa / m}) \quad \text{Eq. (10m)}$$

where: L = The length of the horizontal section (ft), (m)
 K = The pipe material constant and is 0.66 ft/s (0.20 m/s) for metallic and 0.34 ft/s (0.10 m/s) for non-metallic pipes

This correlation predicted pressure drops with a mean deviation of less than 10% for 100 measurements of pressure drop.

Equations have also been developed for pressure drop at velocities below saltation (1).

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PNEUMATIC CONVEYING SYSTEMS (Cont)

Inclined Transport Lines

Inclined transport lines should be avoided if possible, since solids can accumulate, especially at the bottom, and cause operating problems. If inclined lines cannot be avoided, it is recommended that the gas velocity be increased to at least 25% above saltation velocity. This recommendation is based on limited experience. Pressure drop due to the static head [Equation (2)] should be based on the vertical component of the inclined line. Frictional pressure drop is calculated using Equation (10) based on the total length of the inclined line, not the horizontal component.

Flow Through Elbows

Solids flowing through an elbow are subjected to deceleration entering the elbow, friction in the elbow, and re-acceleration leaving the elbow. Pressure drop through the elbow is caused by a combination of these kinetic and frictional effects. Pressure drop through elbows is high compared to straight runs and the number should be minimized to reduce pressure loss. The pressure drop per elbow ΔP_{el} , is given as a function of the gas velocity head:

$$\Delta P_{el} = (k_g + k_{el} \eta) \frac{\rho_g U_g^2}{2 (144) g_c} \quad (\text{psi}) \quad \text{Eq. (11c)}$$

$$\Delta P_{el} = (k_g + k_{el} \eta) \frac{10^{-3}}{2} \rho_g U_g^2 \quad (\text{kPa}) \quad \text{Eq. (11m)}$$

where: k_g = A constant which accounts for the gas ΔP and equals 0.35
 k_{el} = A factor which accounts for solids ΔP in the elbow and downstream of it. It is a function of the single particle terminal settling velocity and is obtained from Figure 9.
 η = The solids loading ratio and is given by:

$$\eta = \frac{W_s}{U_g \rho_g \frac{\pi}{4} D^2} \quad \text{Eq. (12)}$$

where: W_s = The solids flow rate (lb/s), (kg/s)

This correlation was developed using data measured with elbows having a radius of curvature to pipe diameter ratio of 1 to 4.2. It can be used with ratios of 1.0 and greater.

Elbow pressure drop can also be approximated by one velocity head based on the density of the mixture flowing in the elbow:

$$\Delta P_{el} \cong \frac{\rho_m U_g^2}{2 (144) g_c} \quad (\text{psi}) \quad \text{Eq. (13c)}$$

$$\Delta P_{el} \cong \frac{10^{-3}}{2} \rho_m U_g^2 \quad (\text{kPa}) \quad \text{Eq. (13m)}$$

Elbows should be spaced at least 20 pipe diameters apart to avoid solids accumulation and possible blockage between the elbows. This is caused by failure to re-accelerate the flow leaving the upstream elbow completely due to interference from the downstream elbow. This results in velocities between the elbows low enough to cause solids accumulation. An increase in ΔP over that calculated by the above equation may also occur if the elbows are closely spaced. If close spacing cannot be avoided, consult Process Engineering Department for velocity and pressure drop requirements.

Solids filled Tees, used in place of elbows to reduce erosion, should be treated as elbows for calculation of pressure drop.

Other Sources of Pressure Loss

Pressure drop in pneumatic conveying systems can also result due to acceleration of the flow and to entrance and exit losses at sections where the diameter changes suddenly. Accepted practice is to assume one velocity head pressure loss for each of the above. [See Equation (13) above for elbow pressure drop.] This includes effects of friction and kinetic energy changes on pressure loss. Deceleration of the flow will cause a pressure increase due to the loss of kinetic energy. This effect is also assumed to be equal to the gain of one velocity head based on the density of the flowing mixture.

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PNEUMATIC CONVEYING SYSTEMS (Cont)

Feeders

- **Pickup Velocity** - Solids dropped into a horizontal pneumatic conveying line from a feeder may deposit on the bottom of the line if the localized solids loading near the feeder exceeds the carrying capacity of the conveying gas. The solids must then be picked up by the gas. Since the pickup velocity is numerically similar to the saltation velocity, high local solids concentration may also prevent pickup of the deposited solids. Therefore, the introduction of solids into the pneumatic conveying line must be designed to minimize localized high solids to gas ratios or to increase local gas velocities to prevent excessive solids deposition in the conveying line, high-pressure drop, and possible line plugging. Consult Process Engineering Department for design of the solids feeding section.
- **Pressure Drop** - Solids fed into a pneumatic transport line must be accelerated by the conveying gas until the solids attain their ultimate velocity. Pressure drop caused by solids acceleration is given by:

$$\Delta P_{acc} = \frac{G_s U_g}{144 g_c} \quad (\text{psi}) \quad \text{Eq. (14c)}$$

$$\Delta P_{acc} = 10^{-3} G_s U_g \quad (\text{kPa}) \quad \text{Eq. (14m)}$$

where: G_s = The solids mass flux (lb/ft²s), (kg/m²s)

This is equivalent to one velocity head based on the density of the flowing mixture.

Calculation Procedure

The general calculation procedure used to design a dilute phase pneumatic conveying system consists first in laying out the piping system, estimating a pipe diameter, and then calculating velocities and pressure drops in all parts of the system. If the total pressure drop is not in the desired range, a new pipe diameter is assumed and the calculations repeated until a suitable pressure drop results. Details of the design procedure are as follows. The procedure is also incorporated in the DILTRAN computer program.

1. Prepare piping layout consisting of horizontal and vertical sections and elbows. Avoid inclined piping. Subdivide sections according to pipe size and piping material.
2. Estimate an initial pipe diameter using:

$$D = 0.23 (W_s)^{1/2} \quad (\text{ft}) \quad \text{Eq. (15c)}$$

$$D = 0.1 (W_s)^{1/2} \quad (\text{m}) \quad \text{Eq. (15m)}$$

3. Calculate U_{to} , n , U_{et} , V_{so} and k
 - a. Evaluate gas properties at the average pressure. If $\Delta P_T / P > 0.15$ from the first trial calculation, recalculate gas properties for smaller sections of the system.
 - b. Calculate U_{to} using [Figure 1, Section VI-E](#) ($n = 1$).
 - c. Determine n from [Figure 2, Section VI-E](#).
 - d. Calculate U_{et} using [Figure 1, Section VI-E](#).
 - e. Calculate Ψ using [Equation \(8\)](#).
 - f. Determine Re^* from [Figure 6 or 7](#).
 - g. Determine Re_o from [Figure 5](#).
 - h. Calculate V_{so} from [Equation \(7\)](#).
 - i. Calculate the standard deviation of the particle size distribution, s , from [Equation \(9\)](#).
 - j. Obtain k from [Figure 8](#).
4. Obtain V_s from [Equation \(6\)](#). Calculate the horizontal conveying velocity as $1.15 V_s$.

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5. Calculate the solids velocity in vertical sections, U_s .
 - a. Calculate the pressure drop due to gas, $\Delta P_g / H$ from [Equation \(5\)](#).
 - b. Select the proper value of C , the pipe material constant from [Table A](#).
 - c. Calculate U_s from [Equation \(1\)](#).
6. Check to assure that flow in vertical sections is uniform, CU_s / gD must be greater than 1.0 if U_{et} is less than 3.5 ft/s (1.1 m/s) or greater than 1.5 if U_{et} is greater than 3.5 ft/s (1.1 m/s).
7. If CU_s / gD does not meet the above criteria, increase conveying velocity and repeat Steps 5 and 6.
8. Calculate pressure drop for all vertical sections.
 - a. Calculate the static head pressure drop per length from [Equation \(2\)](#).
 - b. Calculate the solids frictional pressure loss per length from [Equation \(4\)](#) using the value of CU_s / gD from Step 7 and [Figure 4](#) to obtain $(\Delta P_f / \Delta P_T)s$.
 - c. Calculate the gas frictional loss per length from [Equation \(5\)](#).
 - d. Obtain the total pressure drop per length by summing a, b, c above.
 - e. Repeat the above for each vertical section of different diameter and piping material.
 - f. Calculate the total pressure drop by multiplying the pressure drop per length for each section by the height of the section and summing.
9. Calculate pressure drop for all horizontal sections.
 - a. Calculate pressure drop per length for each horizontal section from [Equation \(10\)](#).
 - b. Calculate the total pressure drop by multiplying the pressure drop per length for each section by the length of the section and summing.
10. Calculate pressure drop for elbows.
 - a. Determine elbow coefficient k_{el} from [Figure 9](#) and U_{to} calculated in Step 3.
 - b. Calculate the solids loading ratio η from [Equation \(12\)](#).
 - c. Calculate the pressure drop for each elbow from [Equation \(11\)](#).
 - d. Calculate the total pressure drop for all elbows by summing individual pressure drops.
11. Calculate pressure drop due to solids acceleration at the feeder from [Equation \(14\)](#).
12. Calculate total system pressure drop by summing all above pressure drops. If total ΔP is too high, repeat calculations from Step 2 with larger pipe size.
13. Optimize design by comparing effects of line size on system ΔP , piping and compression costs.

DENSE PHASE DESIGN PROCEDURE

Dense phase pneumatic conveying systems operate at gas velocities below the saltation velocity and choking velocity. Therefore, both horizontal and vertical sections are operated in the dense phase. Three general types of dense phase conveying systems are available from a number of vendors. These are the pulse phase, bypass and simple systems. They are defined below. The proper system for a particular conveying application depends on the nature of the solids to be transported. The systems tend to be mechanically more complex than dilute phase systems and require working with vendors experienced in specification and design of the systems.

ExxonMobil has not developed a design basis for dense phase systems. However, a design approach is available through ExxonMobil's participation in the Particulate Solids Research Institute (PSRI). The PSRI design approach is described below.

For PSRI recommended design procedure, refer also to PSRI Research Report 76.

Types of Dense Phase Conveying Systems

Three general types of dense phase conveying systems are available from equipment vendors. They are the pulse phase, bypass and simple systems.

- **Pulse Phase System** - The pulse phase system consists of a solids feeding system which introduces the solids into the transport line in discrete solid slugs separated by gas. The slugs are formed either by feeding the solids and gas in sequence into the transport line or by use of an air cutter, which slices the solids fed into the transport line into the proper slug lengths. The slugs must be less than a critical length to prevent plugging. The critical length is determined, at least in part, by the angle of internal friction.
- **Bypass System** - In the bypass system, gas and solids are introduced at the feed point, but additional bypass gas is added to the transport line at various points along the length of the line. This adds gas as needed to break up plugs and improve

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conveyability. The gas bypass line can be mounted on the outside or the inside of the transport line. The system usually operates by pressure balance and transport gas is introduced where needed when the pressure drop in the line begins to increase. The function of the added gas is probably to reduce the size of the solid plugs to less than the critical slug length.

- **Simple System** - The simple system consists in introducing gas and solids at the feed point. Special means to form or maintain slugs are not used. The solids are usually fed from a pressurized hopper. One example of this type system is called a "blow pot" and is used to transport solids from storage vessels into process vessels.

The solids flow either as a single plug (extrusion flow), in slugs, which are self-formed to a length less than the critical length, or in stratified dilute and dense phase regions. The stratified flow condition in a horizontal pipe section consists of a dilute phase region in the upper section of the pipe and a moving dense phase, called dunes, in the lower section. The dunes are moved forward by the flow of gas and solids in the dilute phase at the top of the pipe. In vertical sections, a comparable situation exists with segregated dilute and dense phase regions flowing concurrently up the pipe.

Solids Conveyability

The choice between dilute and dense phase conveying systems and the selection of the type of dense phase system is determined largely by the properties of the solids. A conveyability classification based on particle size and the density difference between the solid and gas is shown in Figure 10. Group A solids shown in Figure 10 do not form slugs without external means such as the pulse phase system described above. These solids are fine (ca 30 to 200 μm), easily aerated and retain the aeration gas. They are readily transported with pulse phase or bypass transport systems. Group B solids form weak slugs which partly collapse to form dunes in horizontal flow. Group B solids can best be transported using the bypass system. These solids are intermediate in size (ca 100 to 200 μm) and are more difficult to transport in dense phase systems. Group C solids are very fine (less than 30 to 50 μm) and are not considered good candidates for dense phase transport. Group D solids readily form self-limiting slugs, are coarse (ca 500 μm and greater), are permeable to gas flow and do not retain gas. Group D solids with a narrow size distribution can be transported with a simple system. The recommendations are summarized in Table 3.

Group A solids are most easily transported in dense phase systems. Group B and D solids can also be transported using the proper system but with somewhat more difficulty and, therefore, require more attention to proper design and operational factors. Group B and D solids also require higher gas rates than Group A solids resulting in higher-pressure drop. Group C is not recommended for dense phase transport.

Design Approach

The design approach is used for both horizontal and vertical sections. It can be used to estimate transport line diameter, solids/gas ratio and transport line ΔP . Since this approach has not been verified through Exxon experience, it is recommended that it be used only for preliminary estimates. Final designs should be prepared in cooperation with equipment vendors. Consult Projects Department for vendor recommendations.

The design approach consists of the following steps:

1. Determine the solids classification group from Figure 10.
2. The maximum solids to gas weight ratio (μ_{max}) is that resulting from so called extrusion flow of the solids, i.e., no slugs, no dilute phase regions. The actual solids to gas weight ratio (μ) is less than μ_{max} due to the presence of gas pockets in the line. Select the ratio μ / μ_{max} for the proper system from the following table:

Solids Classification	Transport System	μ / μ_{max}
Group A	Pulse phase	0.3
Group A, B	Bypass	0.1
Group D	Simple	0.4

3. Calculate the pipe diameter from either of the equations given below. For Group A solids:

$$D = 0.8 \left[\frac{M}{\rho_B \sqrt{h}} \right]^{1/2} \quad (\text{ft}) \quad \text{Eq. (16c)}$$

$$D = 1.1 \left[\frac{M}{\rho_B \sqrt{h}} \right]^{1/2} \quad (\text{m}) \quad \text{Eq. (16m)}$$