9 Conveying

This chapter covers the transportation of particles by fluids. It considers hydraulic, pneumatic and mechanical conveying means. The former uses liquids the second gases and an example of the latter is a conveyer belt. A basic course in fluid mechanics will equip the reader with sufficient knowledge to calculate the pressure drop for a given flow rate of a uniform, or homogeneous, fluid. When considering particles suspended in flow, however, it is possible for the particle to *slip* in the fluid; i.e. the fluid travels faster than the solid particle. It is also possible for two distinct regions to be visible: a dilute, or emulsion, region with few particles and a dense region below it. This is illustrated in Figure 9.1. In the case of homogeneous flow, where there is no slip and the particles merely add to the effective liquid viscosity and density the methods of analyses covered already in Sections 6.6 and 6.7 are appropriate.

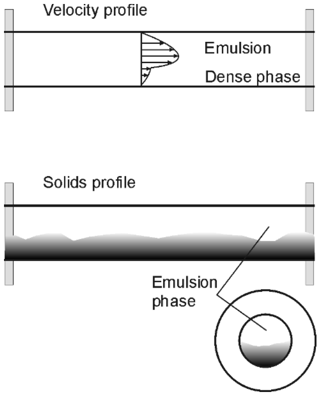

Fig. 9.1 Heterogeneous flow showing only the particles within the dense region

An example of a *positive pressure* pneumatic conveying flowsheet is provided in Figure 9.2. The process is straightforward and requires a blower to provide the motive force, feed silo for solids, a means of controllably passing solids into the conveying line and a destination vessel with particle-gas separation equipment. If the blower was to be positioned after the gas cleaning equipment and the particles sucked through the system it would be *negative pressure* pneumatic conveying. Systems with mixed positive and negative pressures are also possible, such as might occur when there are two conveying lines: one operating under suction on the blower inlet, the other from the blower outlet.

9.1 Heterogeneous flow in liquids

Most of the work in this subject was due to the requirement to move coal, and other minerals, over significant distances as slurries. A resurgence of interest occurred when clean-up of nuclear solids deposited in ponds started. There are two key mathematical analyses required for the flow of solids in a liquid filled pipe: identification of the flow velocity which is insufficient to prevent solids depositing on the bottom of the pipe and the calculation of the pressure drop, or gradient, during the heterogeneous flow. Homogeneous flow is dealt with elsewhere. If the slurry velocity is reduced from a high value which entrains all the solids a point will be reached when solids will be observed to become stationary on the pipe surface. This is the limit deposit-velocity (u_{LDV}) of the heterogeneous suspension. In order to hydraulically convey material efficiently this velocity should be exceeded. An analysis based on boundary layer theory suggests that a correlation of the following form is appropriate

$$u_{\mathrm{LDV}} = \sqrt{K_1 g x_{85}\left(\frac{\rho_{\mathrm{s}}}{\rho}-1\right)^{0.8}\left(\frac{x_{85}}{D}\right)^{K_2}} \tag{9.1}$$

where x_{85} is the particle diameter below which there is 85% by mass of the distribution, K_1 and K_2 are constants. The value of K_1 is 650, when viscous forces predominate, and 0.19 in the turbulent region. The value of the constant K_2 is 0, when viscous forces predominate, and -2 in the turbulent region.

During heterogeneous flow there will be two identifiable regions, as illustrated on Figure 9.1, a homogeneous region flowing above a heterogeneous one. It is assumed that the overall pressure drop, or gradient, for the two phase flow is the sum of the pressure drops in both of these regions. Using the empirical correlation proposed by Durand (Wasp, E.J., Kenny, J.P. and Gandhi, R.L., 1979, Solid-liquid flow slurry pipeline transportation, Gulf Publishing, Houston, Texas.)

$$\Delta P = \Delta P_{\mathrm{w}}\left[1+85C\left(\frac{gD(\rho_{\mathrm{s}}-\rho)}{u^2\rho\sqrt{C_{\mathrm{d}}}}\right)^{1.5}\right] \tag{9.2}$$

where ΔP_{w} is the calculated pressure drop for the homogeneous phase, u is the mean suspension velocity and C_{d} is the particle drag coefficient. The homogeneous phase pressure drop may be calculated using Newtonian flow equations with equation (6.14) for the viscosity. The drag coefficient comes from equation (5.13), with the terminal settling velocity in that equation provided by Stokes' law or The Heywood Tables.

9.2 Dilute phase pneumatic conveying

Particle slip occurs when solids are conveyed by gases but, at low solid concentration, there will be a uniform density of particles throughout the conveying pipe. This is dilute phase pneumatic conveying and is another form of homogeneous flow. At the *saltation* point a significantly greater concentration of solids is found at the base of the pipe. These solids are not stationary, they will still be dragged through the pipe by the gas, but they will have an additional frictional energy loss due to close contact with the pipe wall. Thus, they will have a slower velocity than the particles contained within the emulsion phase above the bottom of the pipe. A phase diagram illustrating flow conditions in dilute, and other, pneumatic conveying regions is illustrated in Figure 9.3.

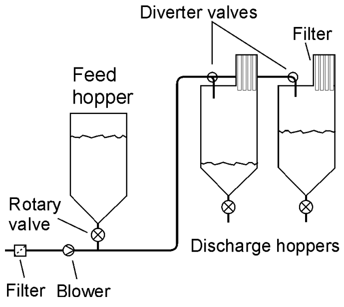

Fig. 9.2 Positive pressure pneumatic conveying system

When designing a dilute phase pneumatic conveying system a key parameter to assess is the gas velocity at which saltation takes place. Operating at gas velocities above this will be in the dilute phase region. An empirical correlation for saltation velocity is due to Rizk

$$u_{\mathrm{salt}} = \left[\frac{4M_{\mathrm{s}}10^{a}g^{b/2}D^{(b/2-2)}}{\rho\pi}\right]^{1/(b+1)} \tag{9.3}$$

where

$$a = 1440\bar{x} + 1.96 \tag{9.4}$$

$$b = 1100\bar{x} + 2.5 \tag{9.5}$$

where M_s is the mass flow rate and SI units must be used throughout.

The saltation velocity is a superficial velocity and the required gas velocity for use in the friction correlations is the interstitial. Also, to ensure that the flow is in the dilute phase region an excess gas velocity of 50% may be employed. Thus, with 50% excess the gas velocity is

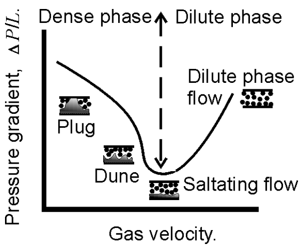

Fig. 9.3 Types of flow found in pneumatic conveying

$$u_g = 1.5\frac{u_{salt}}{\varepsilon} \tag{9.6}$$

where ε is the porosity of the gas phase and is, in general, close to unity. Having established the superficial gas velocity (U_o) the solids velocity (u_s) can be calculated using an equation for slip

$$u_s = U_o(1 - 0.0638x^{0.3}\rho_s^{\ 0.5}) \tag{9.7}$$

where SI units must again be used for dimensional consistency. Clearly, the greater the particle size and solid density the greater the degree of slippage between the gas and particle velocities. The interstitial gas velocity is used to calculate the friction of the gas in the pipe, comes from standard methods for single phase pressure drop calculations. It is assumed that the overall pneumatic conveying pressure drop is the sum of all the *pressure drops* due to the following, which also indicates where the equation originates:

acceleration of the gas (from Bernoulli's equation)

$$\frac{1}{2}\rho\varepsilon u_g \tag{9.8}$$

acceleration of the solids (from Bernoulli)

$$\frac{1}{2}\rho_s(1-\varepsilon)u_s \tag{9.9}$$

friction of the gas on the pipe wall (from friction factor)

$$2f_g\rho u_g^{\ 2}\frac{L}{D}\varepsilon \tag{9.10}$$

friction of the solids on the pipe wall (from friction factor)

$$2f_s\rho_s u_s^{\ 2}\frac{L}{D}(1-\varepsilon)$$

which, using continuity, is the same as

$$2f_sG_su_s\frac{L}{D} \tag{9.11}$$

where G_s is the mass flux of solids,
the static head of the gas is (from Bernoulli)

$$\rho\varepsilon gL\sin\theta \tag{9.12}$$

static head of the solids (from Bernoulli)

$$\rho_s (1-\varepsilon) g L \sin\theta \tag{9.13}$$

where θ is the angle from the horizontal, thus $\sin\theta = 0$ for horizontal conveying and $\sin\theta = 1$ for vertical conveying. It is usually assumed that the pressure drop due to a 90° bend is 7.5 times that of a vertical pipe, i.e. an equivalent length. The solid particle friction factor for use in equation (9.11) depends upon the pipe alignment. For horizontal conveying it has a reminiscent form

$$f_s = \frac{6}{8}\frac{\rho}{\rho_s} C_d \frac{D}{\bar{x}} \left(\frac{u_g - u_s}{u_s} \right)^2 \tag{9.14}$$

but for vertical conveying it must be modified to

$$f_s = \frac{0.057}{2}\frac{D}{u_s}\sqrt{\frac{g}{D}} \tag{9.15}$$

The practical application of these equations is shown in Problem 1, which is a worked solution to be completed for a dilute phase pneumatic conveying system design.

9.3 Dense phase pneumatic conveying

When the gas velocity is lower than that required to produce saltating flow dense phase conveying exists. It is possible to observe dunes, similar to sand dunes, flowing through a conveying pipe. At very high solids loadings, or low velocities, complete plugs of solids may form in the pipe and still be conveyed. However, there is a danger of the pipe completely filling up with solids that become stationary. Hence, the design of high concentration dense phase pneumatic conveying can be critical and it is well known to be an exceedingly difficult subject to model mathematically. All supplying companies require careful test work before specifying such systems.

The advantages of dense phase conveying over dilute phase include: considerably lower product degradation from particle-wall collisions and much lower energy costs because the air velocities are much less than during dilute phase flow. However, the pressure in a dense phase system operating in plug flow is often higher than a dilute phase system. So, compared to a dilute phase system, the blower might need to produce lower gas velocities, but provide higher pressures. The lower velocities found in dense phase systems lead to lower maintenance requirements for such systems.

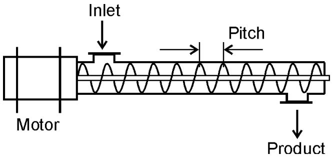

Fig. 9.4 Screw conveyor

9.4 Other conveying equipment

Considering the transportation of mainly dry materials, one of the main advantages of pneumatic conveying is the complete enclosure of the product. Hence, the material is protected from the surrounding environment and vice-versa. Also, pipes can be easily altered to change the flow route, few moving parts mean low maintenance, easy control and the ability to handle a range of products. However, the main disadvantages are: high power, limited distance and limited throughput. When transporting materials in thousands of tonnes per hour a pneumatic conveying system would be prohibitively expensive.

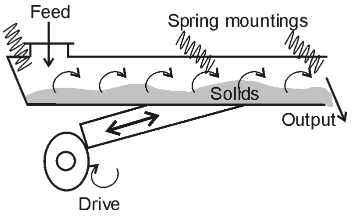

Fig. 9.5 Vibratory conveyor

Alternative popular mechanical conveying methods include: belt conveyors, chain conveyors, screw conveyors, bucket elevators and vibratory conveyors. In most cases the equipment are true plug flow devices and design is straightforward given the mass of material to be conveyed and the manufacturer's data sheets on motor power and capacity. However, screw and vibratory conveyors can have a small amount of axial mixing, but this is not significant for throughput calculations. The reader will undoubtedly be familiar with a conveyor belt. Illustrations of a screw conveyor and vibratory conveyor are provided in Figures 9.4 and 9.5, respectively. Drives for vibratory conveyors can be mechanical, eccentric wheels, electromagnetic and hydraulic. These drives give varying degrees of amplitude and frequency. Conveying speed is generally less than 0.4 m s^{-1} with a vibratory conveyor. The mass flow rate (M_s) for a screw conveyor can be calculated from the following formula

$$M_s = A' u_s \rho_b E_f \tag{9.16}$$

where A' is the cross-sectional area available for flow (i.e. not occupied by the screw and shaft) and E_f is the filling efficiency. This efficiency does *not* relate to the introduction of solids into the conveyor, it is the fill level within the device; i.e. the area occupied by the bed of solids compared to the cross-sectional area. Thus, it takes in to account any space above the bed of solids. The solids velocity inside a screw conveyor (u_s) is the product of the blade pitch and the revolutions per second, assuming no slippage of particles.

Bucket elevators are designed to raise material and the loading and discharging of such elevators is illustrated in Figure 9.6. Chain conveyors, sometimes called en-masse conveyors, provide an arrangements of flights suitably spaced along a chain and the product to be conveyed is dragged by the flights through a trough that is usually completely enclosed. Product is normally introduced into the conveyor through a hole in the top of the trough and discharged through a hole at the bottom. The slip between the particles and the flights determines the efficiency of the device; ideally this should be zero. Chain velocity is usually less than 0.5 m s^{-1} and widths of up to 0.5 m are possible.

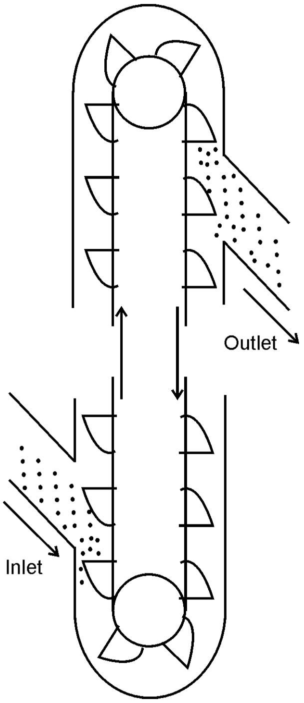

Fig. 9.6 Bucket elevator loading and discharge

Particle properties that are important for all of these conveying methods include: moisture and stickiness of the particles, hazard to the environment (and vice-versa), resistance to particle breakage and product temperature. Process requirements that need to be considered include: required angle of inclination, mass throughput, conveying length, automation, sampling, loading and discharge. Careful consideration of the conveyor type and the above list should result in the identification of the most suitable conveying methods for a given system. For example, particularly sticky material might not discharge from a belt conveyor, but a chain or vibratory conveyor could be appropriate. For high throughputs of low value minerals a belt conveyor is appropriate and, if contamination from the environment is not important, including rainwater, the conveyor need not be covered. A search of the Internet will provide many conveyor suppliers and example throughputs for their machinery.

9.5 Summary

The transportation of particulate solids is an important consideration of most processes involving solids. Often equipment selection is based on process considerations such as the need to avoid contamination from the environment of the valuable solid such as a pharmaceutical product. If required throughput is high, normally associated with low value products such as minerals, then a mechanical device is appropriate such as a belt conveyor. If the material is sticky, due to moisture or temperature softening, then a chain conveyor may be required. For most chemical and food processes pneumatic conveying is preferred because it is enclosed and controllable. Using a rotary valve to meter the solid input into the system the solid mass flow rate can be easily relayed to the control room, and changed by it, if the valve is controlled by an inverter.

9.6 Problems

Design a positive pressure dilute phase pneumatic conveying system to transport 800 kg h^{-1} of sand of density 2500 kg m^{-3} and mean particle diameter 80 μm between two points in a plant separated by 30 and 15 m in the vertical and horizontal directions, respectively. Use ambient air ($\mu = 1.84\text{x}10^{-5}$ Pa s; $\rho = 1.2\,\text{kg m}^{-3}$) and assume that eight 90^{o} bends are required in the circuit. Start your worksheet solution based on a pipe with an internal diameter (*D*) of 40 mm, then try the pressure drop using pipe diameters of 50, 63 and 78 mm. Which one would you recommend? Provide answers to the following calculation stages.

1. The saltation velocity (u_{salt}) as given by the Rizk correlation.

2. The design superficial gas velocity is $U_{\text{o}} = 1.5 u_{\text{salt}}$.

3. The solid velocity (u_{s}) is $u_{\text{s}} = U_{\text{o}}(1 - 0.0638\bar{x}^{0.3}\rho_{\text{s}}{}^{0.5})$ - this equation allows for slip.

4. The solid flux (G_{s}) is $G_{\text{s}} = M_{\text{s}} / A$.

5. The porosity (ε) is $\varepsilon = 1 - \dfrac{G_s}{\rho_s u_s}$.

6. The interstitial gas velocity is $u_g = U_o / \varepsilon$.

7. The slip velocity is $u_g - u_s$.

8. The particle Reynolds number is $\mathrm{Re}' = \dfrac{(u_g - u_s)\rho \bar{x}}{\mu}$.

9. The drag coefficient is $C_d = \dfrac{12}{\mathrm{Re}'}\left(1 + 0.15\,\mathrm{Re}'^{0.687}\right)$, valid for 0.2<Re'<800.

10. The flow Reynolds number is.

11. The gas friction factor is $f_g = 2(0.0396\,\mathrm{Re}^{-0.25})$ ...Blasius equation.

12. The pressure drop due to acceleration of the gas is $= 0.5(\rho \varepsilon u_g^{\,2})$.

13. The pressure drop due to acceleration of the solids is $= 0.5(\rho_s (1 - \varepsilon) u_s^{\,2})$.

Considering the *horizontal* lengths (L_H):

14. The *horizontal* solid friction factor is $f_s = \dfrac{6}{8}\dfrac{\rho}{\rho_s} C_d \dfrac{D}{\bar{x}} \left(\dfrac{u_g - u_s}{u_s}\right)^2$.

15. The pressure drop due to gas friction is $= 2 f_g \rho \varepsilon u_g^{\,2} L_H / D$.

16. The pressure drop due to solid friction is $= 2 f_s \rho_s (1 - \varepsilon) u_s^{\,2} L_H / D$.

17. The total horizontal pressure drop is.

Considering the *vertical* lengths (L_V):

18. The *vertical* solid friction factor is $f_s' = \dfrac{0.057}{2}\dfrac{D}{u_s}\sqrt{\dfrac{g}{D}}$.

19. The vertical pressure drop due to solid friction is
$= 2 f_s' \rho_s (1 - \varepsilon) u_s^2 L_V / D$.

20. The vertical pressure drop due to gas friction is
$= 2 f_g \rho \varepsilon u_g^2 L_V / D$.

21. The pressure drop due to the solid's static head is
$\rho_s (1 - \varepsilon) g L_V \sin\theta$.

22. The pressure drop due to the gas static head is $\rho \varepsilon g L_V \sin\theta$.

23. The total vertical pressure drop is.

24. The pressure drop due to ONE bend is
= 7.5(total vertical pressure over distance).
So, the total pressure drop due to all the bends is.

25. The total pressure drop is.

26. After setting the above solution up on a spreadsheet, try internal pipe diameters of 50, 63 and 78 mm.

27. Which pipe diameter would you recommend?

28. Now calculate the gas flow rate in $m^3 s^{-1}$ for each pipe.

29. Which pipe diameter would you recommend now?