the devices described in this section. Other devices (e.g., the "biofilters" described in Chapter 10) are not truly filters. Engineers must live with the difference between the technical meaning and that used by nonprofessionals.

9.2.1 Surface Filters

Most of us have personal experience with surface filters, as exemplified by those in a coffee percolator or a kitchen sieve. The principle of operation is simple enough; the filter is a membrane (sheet steel, cloth, wire mesh, or filter paper) with holes smaller than the dimensions of the particles to be retained.

Although this kind of filter is sometimes used for air pollution control purposes, it is not common because constructing a filter with holes as small as many of the particles we wish to collect is very difficult. One only needs to ponder the mechanical problem of drilling holes of 0.1-μ diameter or of weaving a fabric with threads separated by 0.1 μ to see that such filters are not easy to produce. It can be done on a laboratory scale by irradiating plastic sheets with neutrons and then dissolving away the neutron-damaged area. The resulting filters have analytical uses but are not used for industrial air pollution control (although they are used industrially to filter some beers and other products, removing trace amounts of bacteria). Figure 9.11 shows asbestos crystals captured on such a filter. Although these filters are very useful in determining the chemical identity and size distribution of air pollution particles, they are much too expensive and fragile for use as high-volume industrial air cleaners.

Although industrial air filters rarely have holes smaller than the smallest particles captured, they often act as if they did. The reason is that, as fine particles are caught on the sides of the holes of a filter, they tend to bridge over the holes and make them smaller. Thus as the amount of collected particles increases, the cake of collected material becomes the filter, and the filter medium (usually a cloth) that originally served as a filter to collect the cake now serves only to support the cake,

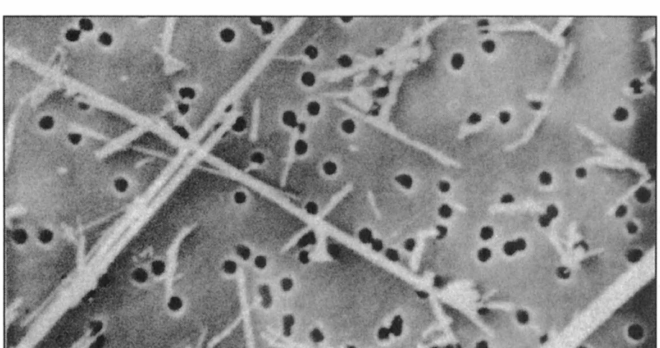

FIGURE 9.11
Scanning electron micrograph of chrysotile asbestos crystals collected on a Nucleopore® polycarbonate analytical filter with holes approximately 0.4 μ in diameter. (Courtesy of the Costar Corporation.)

and no longer as a filter. This cake of collected particles will have average pore sizes smaller than the diameter of the particles in the oncoming gas stream, and thus will act as a sieve for them. The particles collect on the front surface of the growing cake. For that reason this is called a *surface filter.*

One may visualize this situation with a screen having holes 0.75 in. (1.91 cm) in diameter. We could collect a layer of Ping-Pong balls easily on this screen. Once we had such a layer, we could then collect cherries, which, by themselves, could pass through the holes in the screen but cannot pass through the spaces between the Ping-Pong balls. Once we have a layer of cherries, we could put on a layer of peas, then of rice, then of sand. In that way we could collect sand on a screen with holes 0.75 inch in diameter. In typical industrial filters the particles are of a wide variety of sizes, so they do not go onto the screen in layers, but all at once. The effect is the same; very small particles are collected by the previously collected cake on a support whose holes are much larger than the smallest particles collected.

The theory of cake accumulation and pressure drop for this type of device is well-known from industrial filtration. The flow through a simple filter is shown schematically in Fig. 9.12. A fluid containing suspended solids (in this case a dirty gas stream) flows through a *filter medium,* which is most often a cloth, but sometimes a paper, porous metal, or bed of sand. The solid particles in the stream deposit on the face of the filter medium forming the *filter cake.* The cleaned gas, free from solids, flows through both cake and filter medium. If we follow the gas stream from point 1 to point 3 we see that the flow is horizontal and has a small change in velocity because the pressure drops, causing the gas to expand, and because the gas is leaving behind its contained particles. For most filters of air pollution interest, the combined effect of these changes is negligible. Therefore, the only fluid mechanical effect of interest is the decrease in pressure due to the frictional resistance to flow through the filter cake and the filter medium. In most industrial filters, both for gases and liquids, the flow velocity in the individual pores is so low that the flow is laminar. Therefore, we may use the well-known relations for laminar flow of a fluid in a porous medium

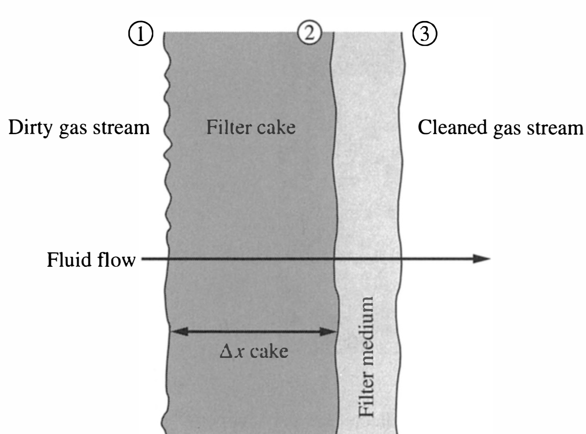

FIGURE 9.12
Flow through a surface filter.

[13], which indicate

$$V_s = \frac{Q}{A} = \left(\frac{-\Delta P}{\mu}\right)\left(\frac{k}{\Delta x}\right) \tag{9.32}$$

Here, k is the *permeability,* a property of the bed (or of the filter medium). For very simple beds, like stacked spheres, k can be calculated with fair accuracy from fluid mechanical principles [13]. For all beds of industrial interest k is determined experimentally, although the values calculated for spheres of comparable size may be used for rough estimates. For a steady fluid flow through a filter cake supported by a filter medium, there are two resistances to flow in series, but the flow rate is the same through each of them. Writing Eq. (9.32) for this flow rate (see Fig. 9.12), we find

$$V_s = \left(\frac{P_1 - P_2}{\mu}\right)\left(\frac{k}{\Delta x}\right)_{\text{cake}} = \left(\frac{P_2 - P_3}{\mu}\right)\left(\frac{k}{\Delta x}\right)_{\text{f.m.}} \tag{9.33}$$

where the subscript "f.m." indicates "filter medium." Solving for P_2, we get

$$P_2 = P_1 - \mu V_s \left(\frac{\Delta x}{k}\right)_{\text{cake}} = P_3 + \mu V_s \left(\frac{\Delta x}{k}\right)_{\text{f.m.}} \tag{9.34}$$

and then solving for V_s, we get

$$V_s = \frac{(P_1 - P_3)}{\mu[(\Delta x/k)_{\text{cake}} + (\Delta x/k)_{\text{f.m.}}]} = \frac{Q}{A_{\text{filter}}} \tag{9.35}$$

This equation describes the instantaneous flow rate through a filter; it is analogous to Ohm's law for two resistors in series. The $\Delta x/k$ terms are called the *cake resistance* and the *cloth resistance.*

The resistance of the filter medium is usually assumed to be a constant that is independent of time, so $(\Delta x/k)_{\text{f.m.}}$ is replaced with a constant α. If the filter cake is uniform, then its resistance is proportional to its thickness. However, this thickness is related to the volume of gas that has passed through the cake by the following material balance:

$$\begin{aligned} \Delta x_{\text{cake}} &= \left(\frac{\text{Mass of cake}}{\text{Area}}\right)\left(\frac{1}{\rho_{\text{cake}}}\right) \\ &= \left(\frac{1}{\rho_{\text{cake}}}\right)\left(\frac{\text{volume of gas}}{\text{area}}\right)\left(\frac{\text{mass of solids removed}}{\text{volume of gas}}\right) \end{aligned} \tag{9.36}$$

Customarily we define

$$W\eta = \left(\frac{\text{Mass of solids removed}}{\text{Volume of gas}}\right)\left(\frac{1}{\rho_{\text{cake}}}\right) = \frac{\text{volume of cake}}{\text{volume of gas processed}} \tag{9.37}$$

Here W is the volume of cake per volume of gas processed, which corresponds to a collection efficiency, η, of 1.00. For most surface filters $\eta \approx 1.00$, so the η is normally dropped when we use Eq. (9.37). Thus

$$\Delta x_{\text{cake}} = \left(\frac{V}{A}\right) W \quad \text{and} \quad \frac{d(\Delta x_{\text{cake}})}{dt} = V_s W \tag{9.38}$$

Here V is the volume of gas cleaned ($V = \int Q\,dt$). Substituting Eq. (9.38) for the cake thickness in Eq. (9.35), we find

$$V_s = \frac{Q}{A} = \frac{1}{A}\left(\frac{dV}{dt}\right) = \frac{(P_1 - P_3)}{\mu[(VW/kA) + \alpha]} \tag{9.39}$$

For most industrial gas filtrations the filter is supplied by a centrifugal blower at practically constant pressure, so $(P_1 - P_3)$ is a constant, and Eq. (9.39) may be rearranged and integrated to

$$\left(\frac{V}{A}\right)^2 \left(\frac{\mu W}{2k}\right) + \left(\frac{V}{A}\right)\mu\alpha = (P_1 - P_3)t \qquad \text{[constant pressure]} \tag{9.40}$$

For many filtrations the resistance α of the filter medium is negligible compared with the cake resistance, so the second term of Eq. (9.40) may be dropped; in such cases the volume of gas processed is proportional to the square root of the time of filtration [14]. See Problems 9.42 and 9.43.

For some industrial gas filtrations a positive displacement blower, which is practically a constant-flow-rate device, feeds the filter at a pressure that steadily increases during the filtration. From Eq. (9.40) we see that for constant k and negligible α the pressure increases linearly with time, because the cake thickness increases linearly with time.

The theory presented here is equally applicable to the filtration of solids from gases or from liquids. In typical gas cleaning applications, k is practically a constant and is independent of pressure. In many filtrations from liquids, particularly filtration of soft or flocculant materials like water-treatment chemicals, k decreases as pressure increases, so the previous integrations that considered k as a constant must be redone with k taken as a function of P.

The two most widely used designs of industrial surface filters are shown in Figs. 9.13 and 9.14 on pages 285 and 286. Because the enclosing sheet metal structure in both figures is normally the size and roughly the shape of a house, this type of gas filter is generally called a *baghouse*. The design in Fig. 9.13, most often called a *shake-deflate* filter, consists of a large number of cylindrical cloth bags that are closed at the top like a giant stocking, toe upward. These are hung from a support. Their lower ends slip over and are clamped onto cylindrical sleeves that project upward from a plate at the bottom. The dirty gas flows into the space below this plate and up inside the bags. The gas flows outward through the bags, leaving its solids behind. The clean gas then flows into the space outside the bags and is ducted to the exhaust stack or to some further processing.

For the baghouse in Fig. 9.13 there must be some way of removing the cake of particles that accumulates on the filters. Normally this is not done during gas-cleaning operations. Instead the baghouse is taken out of the gas stream for cleaning. When the gas flow has been switched off, the bags are shaken by the support to loosen the collected cake. A weak flow of gas in the reverse direction may also be added to help dislodge the cake, thus deflating the bags. The cake falls into the hopper at the bottom of the baghouse and is collected or disposed of in some way. Often metal

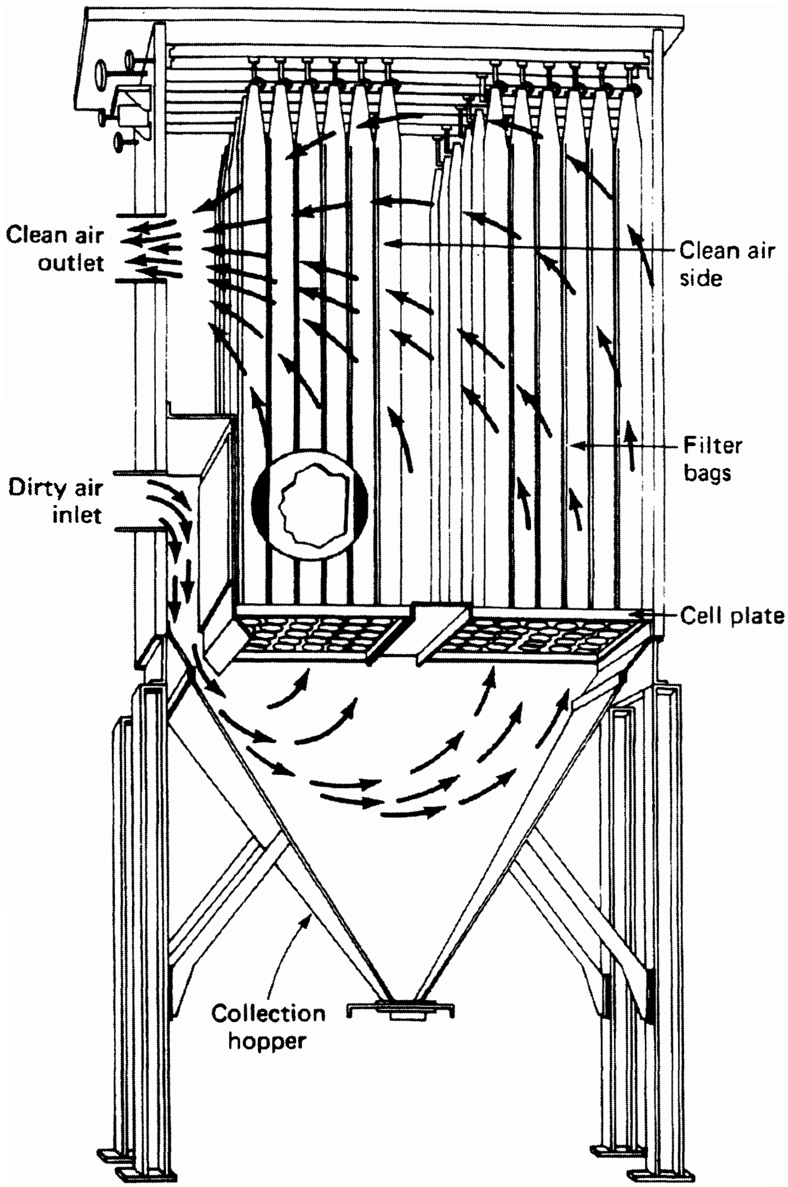

FIGURE 9.13
Typical industrial baghouse of the shake-deflate design. (Courtesy of Wheelabrator Air Pollution Control, Inc.)

rings are sewn into filter bags at regular intervals so that the bag will only partly collapse when the flow is reversed, and a path will remain open for the dust to fall to the hopper.

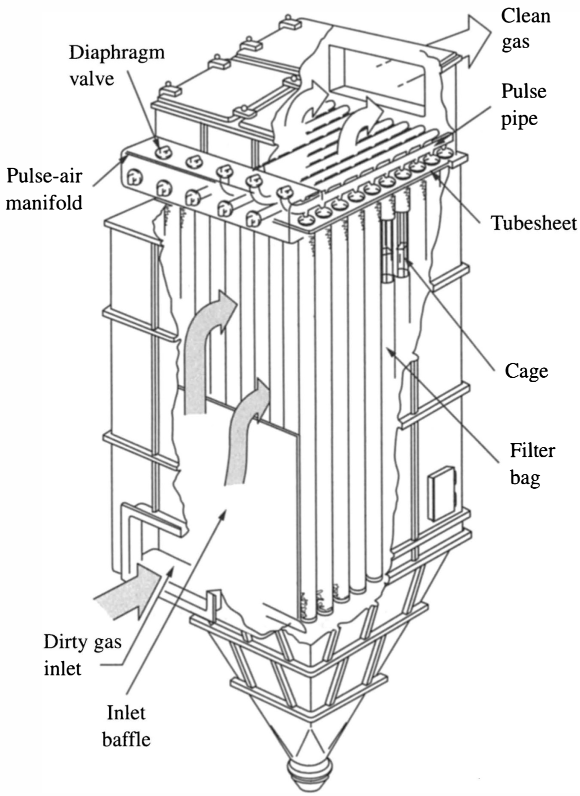

FIGURE 9.14
Typical industrial baghouse of the pulse-jet design. (Courtesy of ABB Fläkt Industriella Processer AB, Sweden.)

Because it cannot filter gas while it is being cleaned, a shake-deflate baghouse cannot serve as the sole pollution control device for a source that produces a continuous flow of dirty gas. For this reason, one either uses a large enough baghouse so that it can be cleaned during periodic shutdowns of the source of contaminated gas or installs several baghouses in parallel. Typically, for a major continuous source like a power plant, about five baghouses will be used in parallel, with four operating as gas cleaners during the time that the other one is being shaken and cleaned. Each baghouse might operate for two hours and then be cleaned for 10 minutes; at all times one baghouse would be out of service for cleaning or waiting to be put back into service. Thus the baghouse must be sized so that four of them operating together provide adequate capacity for the expected gas flow rate.

The other widely used baghouse design, called a *pulse-jet* filter, is shown in Fig. 9.14. In it the flow during filtration is inward through the bags, which are similar to the bags in Fig. 9.13 except their ends open at the top. The bags are supported by internal wire cages to prevent their collapse. The bags are cleaned by intermittent jets of compressed air that flow into the inside of the bag to blow the cake off. Often these baghouses are cleaned while they are in service; the internal pulse causes much of the collected solids to fall to the hopper, but some are drawn back to the filter cloth. Just after the cleaning the control efficiency will be less than just before the next cleaning, but the average efficiency meets the legal control requirements.

Example 9.16. The shake-deflate baghouse on the Nucla Power Station has six compartments, each with 112 bags that are 8 in. in diameter and 22 ft long, for an active area of 46 ft^2 per bag [15]. The gas being cleaned has a flow rate of 86,240 ft^3/min. (This very small power plant had one of the first baghouses on a coal-fired power plant and was the subject of extensive testing.) The pressure drop through a freshly cleaned baghouse is estimated to be 0.5 in. H_2O. The bags are operated until the pressure drop is 3 in. H_2O, at which time they are taken out of service and cleaned. The cleaning frequency is once per hour. The incoming gas has a particle loading of 13 grains/ft^3. The collection efficiency is 99 percent, and the filter cake is estimated to be 50 percent solids, with the balance being voids. Estimate how thick the cake is when the bags are taken out of service for cleaning. What is the permeability, k, of the cake?

First we compute the average velocity coming to the filter surface, V_s.

$$V_s = \frac{Q}{A} = \frac{86\,240 \text{ ft}^3/\text{min}}{(5)(112)(46 \text{ ft}^2)} = 3.35 \frac{\text{ft}}{\text{min}} = 1.02 \frac{\text{m}}{\text{min}}$$

The 5 is used here because one of the six compartments is always out of service for cleaning. In the baghouse literature, V_s is commonly referred to as the *air-to-cloth ratio* or *face velocity.* The dimension of (ft/min) is commonly dropped, so this filter would be referred to as having an air-to-cloth-ratio of 3.35 in countries using English units. In fluid mechanics this would be called a *superficial velocity* to indicate that it is total volumetric flow divided by total cross-sectional area of the filter. It is the same just before the filter cake as inside the filter cake. The velocity inside the pores of the filter is called the *interstitial velocity,* to distinguish it from this superficial velocity. It is larger, because Q is the same for both, but the A is less inside the cake. In most cases the superficial velocity is well-known, because the projected area of the cake is known; but the interstitial velocity is not known, because the interstitial projected area is not known. If the filter remains in service for 1 hour before cleaning and V_s is constant, then 1 square foot of bag will collect the following mass of particles:

$$\frac{m}{A} = cV_s\eta t = \left(13 \frac{\text{gr}}{\text{ft}^3}\right)\left(3.35 \frac{\text{ft}}{\text{min}}\right)(0.99)\left(\frac{60 \text{ min}}{\text{h}}\right)\left(\frac{\text{lbm}}{7000 \text{ gr}}\right)$$

$$= 0.369 \frac{\text{lbm}}{\text{ft}^2} = 1.80 \frac{\text{kg}}{\text{m}^2}$$

The thickness of the cake collected in 1 hour is

$$\text{Thickness} = \frac{m/A}{\rho}$$

$$= \frac{0.369 \text{ lbm/ft}^2}{(2 \text{ g/cm}^3)(0.5)(62.4 \text{ lbm}\cdot\text{cm}^3/\text{ft}^3\cdot\text{g})}$$

$$= 5.9 \times 10^{-3} \text{ ft} = 0.071 \text{ in.} = 1.8 \text{ mm}$$

Taking $\alpha = 0$, we can solve Eq. (9.35) for k, and find

$$k = \frac{V_s \, \Delta x \, \mu}{(-\Delta P)}$$

$$= \frac{(3.35 \text{ ft/min})(0.071 \text{ ft}/12 \text{ in.})(0.018 \text{ cp})(2.09 \times 10^{-5} \text{ lbf} \cdot \text{s/ft}^2 \cdot \text{cp})(\text{min}/60 \text{ s})}{(3 \text{ in. H}_2\text{O})(5.202 \text{ lbf/ft}^2 \cdot \text{in. H}_2\text{O})}$$

$$= 7.96 \times 10^{-12} \text{ ft}^2 = 7.40 \times 10^{-13} \text{ m}^2$$

Those familiar with the flow of fluids in porous media can compare this with values found in groundwater and underground oil flows by converting this to the conventional unit of permeability,

$$k = (7.96 \times 10^{-12} \text{ ft}^2)\left(\frac{\text{darcy}}{1.06 \times 10^{-11} \text{ ft}^2}\right) = 0.75 \text{ darcies}$$

The calculated permeability of this material is roughly the same as that of a highly permeable sandstone. ■

The flow velocities through such filters are very low, typically a few feet per minute. In contrast, in devices like cyclones the flow is about 60 feet per second. A wind velocity equal to the typical flow through such a filter is so low that someone standing in it could not tell in which direction it was blowing and would report that there was no wind at all.

This calculation shows that the collected cake is about 0.07 in. thick, the average increase during one cycle. If the cleaning were perfect, this would be the cake thickness. However, it is hard or impossible to clean the bags completely, and in power plant operation it is common for the average cake thickness on the bags to be up to 10 times this amount. During each cleaning cycle some part of the cake falls completely away, leaving bare patches on the bag; and most of the cake does not come off at all. If one could examine a bag after a cleaning, one would probably see nine-tenths of the surface covered with a cake perhaps 0.7 in. thick, and one-tenth of the bag with a bare surface. The operators would like to clean the bags more thoroughly, but more vigorous cleaning procedures (harder shaking, faster reverse gas flow) tend to wear out the bags faster and lead to more frequent maintenance shutdowns. Most operators have used mild cleaning cycles, leading to long bag lives and low maintenance costs but higher pressure drops than would be needed if all the cake came off the bag at each cleaning cycle [16]. One of the advantages of the pulse-jet design is that it cleans the bags more thoroughly, allowing a higher V_s, at the cost of a somewhat shortened bag life.

Figure 9.15 is a set of typical results from tests of collection efficiency for this kind of filter. The individual lines represent different values of the superficial velocity (face velocity, air-to-cloth ratio). Consider first the curve for 0.39 m/min. We see that at zero fabric loading (new or freshly cleaned cloth) the outlet concentration is high and practically equal to the inlet concentration of about 0.8 g/m^3. As the cake builds up, the outlet concentration declines, finally stabilizing at a value about 0.001 times