design to refer to the quantity $(\rho_g V^2/2)$ as a *velocity head*, so one could say that most cyclones have pressure drops of about 8 velocity heads.

Example 9.8. A cyclone has an inlet velocity of 60 ft/s and a reported pressure loss of 8 velocity heads ($K = 8$). What is the pressure loss in pressure units?

Applying Eq. (9.22), we find

$$\text{Pressure drop} = 8\left(0.075\ \frac{\text{lbm}}{\text{ft}^3}\right)\left(60\ \frac{\text{ft}}{\text{s}}\right)^2\left(\frac{1}{2}\right)\left(\frac{\text{lbf}\cdot\text{s}^2}{32.2\ \text{lbm}\cdot\text{ft}}\right)\left(\frac{\text{ft}^2}{144\ \text{in.}^2}\right)$$

$$= 0.23\ \frac{\text{lbf}}{\text{in.}^2}$$

$$= 8\left(1.20\ \frac{\text{kg}}{\text{m}^3}\right)\left(18.29\ \frac{\text{m}}{\text{s}}\right)^2\left(\frac{1}{2}\right)\left(\frac{\text{N}\cdot\text{s}^2}{\text{kg}\cdot\text{m}}\right)$$

$$= 1606\ \frac{\text{N}}{\text{m}^2} = 1.61\ \text{kPa} = 0.23\ \text{psi} = 6.4\ \text{in. H}_2\text{O}$$ ■

Typically this pressure drop must be overcome by a fan or blower somewhere in the system. If the system is already under pressure, this poses no problems for the designer. However, if it is a new system that must consist of cyclone, blower, and associated ductwork, then the designer has two options, both of which have disadvantages. The first of these is shown in Fig. 7.2. There the blower is located before the cyclone, which is the pollution control device in this case. The disadvantage of this arrangement is that the blower is exposed to the dirty gas. The particles will get into its bearings and collect on its blades, throwing it out of balance. The alternative arrangement is to put the blower downstream of the pollution control device (cyclone), in which case the blower works on cleaned gas and has fewer maintenance problems. The disadvantage of this arrangement is that the cyclone now operates under a weak vacuum, and if the seal at the solids removal valve is not very good, air will be sucked in and re-entrain the collected particles, degrading the overall collection efficiency. Both systems can be made to work with adequate attention to engineering detail.

There are many other variants on the centrifugal collector idea, but none approaches the cyclone in breadth of application. These devices are simple and almost maintenance-free. Because any medium-sized welding shop can make one, the big suppliers of pollution control equipment, who have test data on the effects of small changes in the internal geometry, have been unwilling to make these data public. However, there do not appear to be designs that are substantially better than the simple one shown in Fig. 9.4. The alternative dimension ratios shown in Ref. 2 allow a smaller cut diameter at the price of a higher pressure drop, or a higher throughput at the price of a larger cut diameter, but not an improvement of one performance measure without a cost in terms of some other performance parameter. There is no reason why one cannot obtain better collection efficiency by placing one cyclone downstream of another; the standard design of catalytic cracker regenerators has two cyclones in series to remove catalyst particles from the waste gas (see Problem 9.8).

The same basic device as the cyclone separator is used in other industrial settings where the goal is not air pollution control, but some other kind of separation. When it is used to separate solids from liquids it is generally called a *hydroclone.* A cyclone called an *air-swept classifier* is attached to many industrial grinders. It passes those particles ground fine enough, and collects those that are too coarse, returning them to the grinder.

9.1.3 Electrostatic Precipitators (ESP)

If gravity settlers and centrifugal separators are devices that drive particles against a solid wall, and if neither can function effectively (at an industrial scale) for particles below about 5 μ in diameter, then for wall collection devices to work on smaller particles, they must exert forces that are more powerful than gravity or centrifugal force. The *electrostatic precipitator* (ESP) is like a gravity settler or centrifugal separator, but electrostatic force drives the particles to the wall. It is effective on much smaller particles than the previous two devices.

In all three kinds of devices, the viscous (Stokes' law) resistance of the particle to being driven to the wall is proportional to the particle diameter [see Eq. (8.3)]. For gravity and centrifugal separators, the force that can be exerted is proportional to the mass of the particle, which, for constant density, is proportional to the diameter cubed. Thus the ratio of driving force to resisting force is proportional to (diameter cubed/diameter) or to diameter squared. As the diameter decreases, this ratio falls rapidly. In ESPs the resisting force is still the Stokes viscous drag force, but the force moving the particle toward the wall is electrostatic. This force is practically proportional to the particle diameter squared, and thus the ratio of driving force to resisting force is proportional to (diameter squared/diameter) or to the diameter. Thus it is harder for an ESP to collect small particles than large ones, but the difficulty is proportional to $(1/D)$ rather than to $(1/D^2)$, as in gravitational or centrifugal devices.

The basic idea of all ESPs is to give the particles an electrostatic charge and then put them in an electrostatic field that drives them to a collecting wall. This is an inherently two-step process. In one type of ESP, called a two-stage precipitator, charging and collecting are carried out in separate parts of the ESP. This type, widely used in building air conditioners, is sometimes called an electronic air filter. However, for most industrial applications the two separate steps are carried out simultaneously in the same part of the ESP. The charging function is done much more quickly than the collecting function, and the size of the ESP is largely determined by the collecting function.

Figure 9.7 shows in simplified form a wire-and-plate ESP with two plates. The gas passes between the plates, which are electrically grounded (i.e., voltage = 0). Between the plates are rows of wires, held at a voltage of typically −40 000 volts. The power is obtained by transforming ordinary alternating current to a high voltage and then rectifying it through some kind of solid-state rectifier. This combination of charged wires and grounded plates produces both the free electrons to charge the

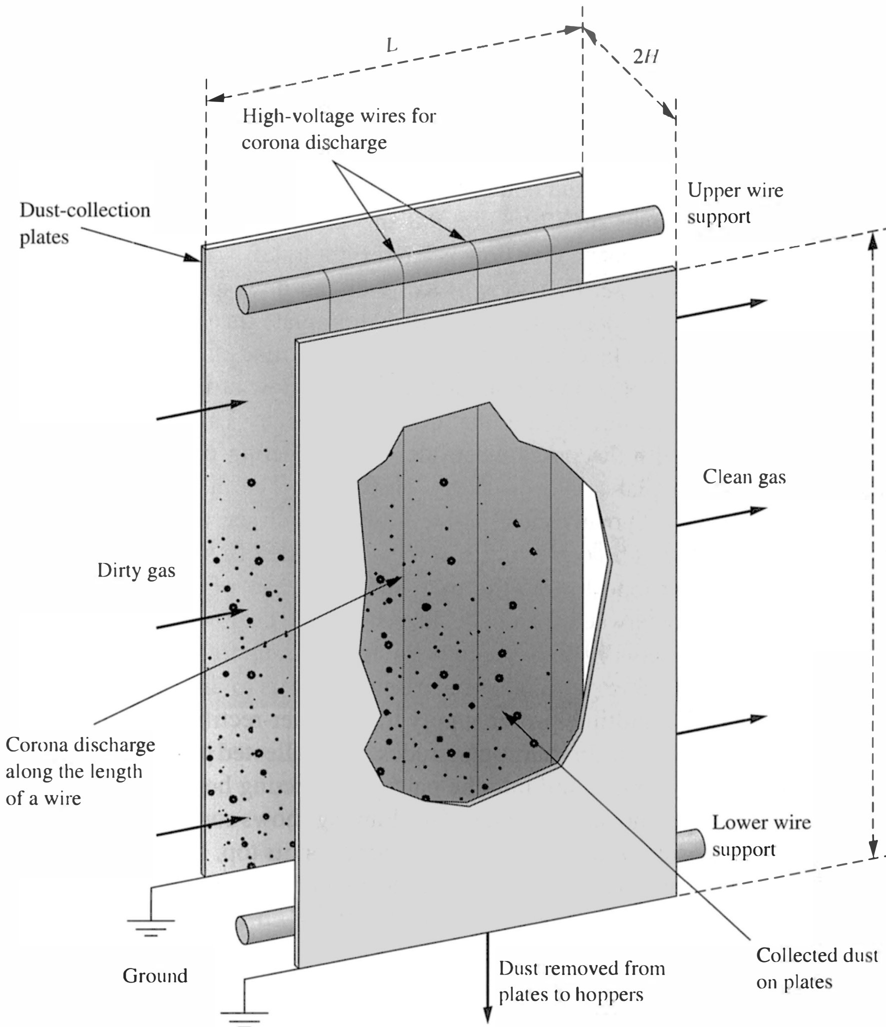

FIGURE 9.7
Diagrammatic sketch of a simplified ESP with two plates, four wires, and one flow channel. Industrial-size ESPs have many such channels in parallel; see Fig. 9.8.

particles and the field to drive them against the plates. On the plates the particles lose their charge and adhere to each other and the plate, forming a "cake." The cleaned gas then passes out the far side of the precipitator as shown in Fig. 9.7.

Solid cakes are removed by rapping the plates at regular time intervals with a mechanical or electromagnetic rapper that strikes a vertical or horizontal blow on the edge of the plate. Through science, art, and experience designers have learned to make rappers that cause most of the collected cake to fall into hoppers below the plates (not shown on Fig. 9.7). Some of the cake is always re-entrained, thereby lowering the efficiency of the system. If the collected particles are liquid, e.g., sulfuric acid mist, they run down the plate and drip off. For liquid droplets the plate is often replaced by a circular pipe with the wire down its center. Some ESPs (mostly the circular pipe variety) have a film of water flowing down the collecting surface, to carry the collected particles to the bottom without rapping.

There are many types of ESPs; Fig. 9.8 shows one of the most common in current use in the United States. Gas flow is from right to left. The gas enters at the right through an inlet diffuser (not shown) in which the flow spreads out from the much narrower duct to the perforated gas distribution plate that distributes the gas evenly across the entrance face of the precipitator. A similar plate and converging nozzle on the left side (not shown) maintain a uniform flow at the outlet and then reduce the cross-sectional flow area to that of the outlet duct. The whole interior of the structure is filled with discharge electrodes and collecting plates; the cutaway shows only one set of plates and discharge electrodes. The discharge electrodes consist of rigid frames with many short, pointed stubs, which serve the same function as the wires in Fig. 9.7. The collecting surfaces are made of sheet metal sections with vertical joints that tend to trap the particles. Each pair of plates, along with the discharge electrode between them, acts like the single channel in the simplified version of an ESP shown in Fig. 9.7. The rappers strike the supports for the discharge electrodes and the collecting plates at regular time intervals to dislodge the cake of collected particles. The multiple power supply transformer-rectifier sets supply DC voltage at ≈ –40 000 V to the discharge electrodes. The collected particles, dislodged from the plates by the rappers, fall into the particle collecting hoppers, from which they are automatically removed to storage. The drawing shows some of the structural steel frame and enclosure of the ESP and the handrail on its top, but not the internal seals that hinder the gas from flowing around the area of the collecting plates.

Each point in space has some electrical potential V. If the electrical potential changes from place to place, then there is an electrical field, $E = \partial V/\partial x$, in that space. If we connect two such points with a conductor, then a current will flow. This V is the voltage we are all familiar with, and E is its gradient in any direction; the units of E are V/m.

In a typical wire-and-plate precipitator, as sketched in Fig. 9.7, the distance from the wire to the plate is about 4 to 6 in., or 0.1 to 0.15 m. With a voltage difference of 40 kV and 4-in. spacing, one would assume a field strength of $40\ \text{kV}/0.1\ \text{m} = 400\ \text{kV/m}$. This is indeed the field strength near the plate. However, all of the electrical flow that reaches the plate comes from the wires, and the surface area of the wires is much lower than that of the plate; thus, by conservation of charge, the driving potential near the wires must be much larger. Typically it is 5 to 10 MV/m. (The first person to utilize this fact was presumably Benjamin Franklin, who invented the sharp, pointed lightning rod.)

When a stray electron from any of a variety of sources encounters this strong a field, it is accelerated rapidly and attains a high velocity. If it then collides with a gas molecule, it has enough energy to knock one or more electrons loose, thus

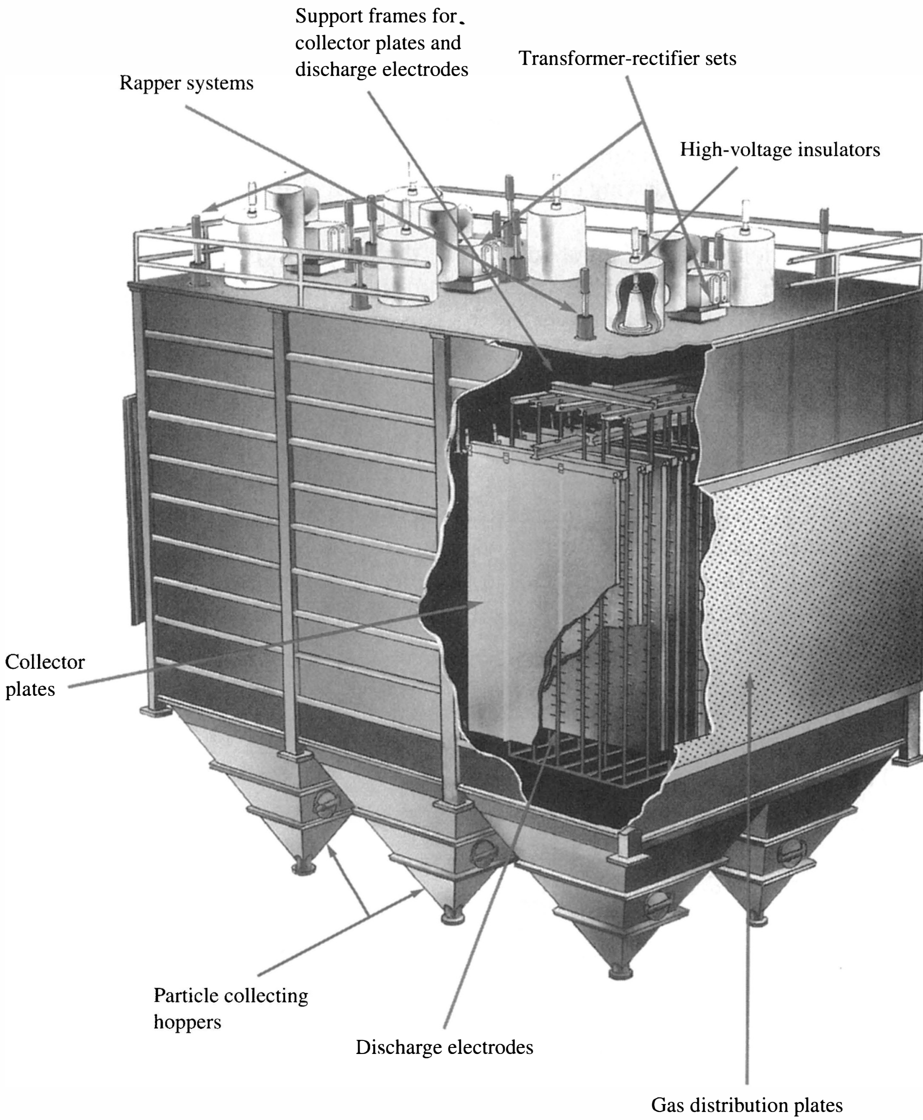

FIGURE 9.8
Cutaway view of a large, modern ESP showing the various parts. In this design the wire discharge electrodes have been replaced by rigid frames with many short, pointed stubs. (Courtesy of The Babcock and Wilcox Company, Barberton, Ohio.)

ionizing the gas molecule. These electrons are likewise accelerated by the field and knock more electrons loose, until there are enough free electrons to form a steady **corona discharge**. In a dark room this discharge appears as a dim glow that forms a circular sheath about the wire. The positive ions formed in the corona migrate to the wire and are discharged. The electrons migrate away from the wire, toward the plate. Once they get far enough away from the wire for the field strength to be too low to accelerate them fast enough to ionize gas molecules, the visible corona ceases and they simply flow as free electrons.

As the electrons flow toward the plate, they encounter particles and can be captured by them, thus charging the particles. Then the same electric field that created the electrons and that is driving them toward the plate also drives the charged particles toward the plate.

For particles larger than about 0.15 μ, the dominant charging mechanism is *field charging*. This is practically equivalent to the capture of any electron by any particle lying in its path. However, as the particles become more highly charged, they bend the paths of the electrons away from them. Thus the charge grows with time, reaching a steady state value of

$$q = 3\pi \left(\frac{\varepsilon}{\varepsilon + 2}\right) \varepsilon_0 D^2 E_0 \tag{9.23}$$

Here q is the charge on the particle, and ε is the dielectric constant of the particle—a dimensionless number that is 1.0 for a vacuum, 1.0006 for air, and 4 to 8 for typical solid particles. The permittivity of free space ε_0 is a dimensional constant whose value in the SI system of units is $8.85 \times 10^{-12}\ \text{C}/(\text{V} \cdot \text{m})$. D is the particle diameter, and E_0 is the local field strength.

Example 9.9. A 1-μ diameter particle of a material with a dielectric constant of 6 has reached its equilibrium charge in an ESP at a place where the field strength is 300 kV/m. How many electronic charges has it?

From Eq. (9.23) we can write

$$q = 3\pi \left(\frac{6}{8}\right) \left(8.85 \times 10^{-12}\ \frac{\text{C}}{\text{V} \cdot \text{m}}\right) (10^{-6}\ \text{m})^2 \left(300\ \frac{\text{kV}}{\text{m}}\right)$$

$$= 1.88 \times 10^{-17}\ \text{C} \times \left(\frac{1.602 \times 10^{19}\ \text{electrons}}{\text{C}}\right) = 300\ \text{electrons} \qquad \blacksquare$$

The value computed in Example 9.9 is typical for this large a particle. The charge is proportional to diameter squared, so that a $\frac{1}{3}$-μ diameter particle would be expected to have about 33 electronic charges.

This charge is the steady-state value, reached after the particles have been in the precipitator a long time. Theoretical calculations show that for most particles in most precipitators this "long time" is much less than the average time a particle spends in the precipitator, so we can use this steady-state value as if the particle had it from the moment of its entry without serious error. If the particle is smaller than about 0.15 μ, then we would make a serious error computing its charge by Eq. (9.23); we must consider the additional charge that is acquired by *diffusion charging*. This latter results from particle-electron collisions caused not by the net motion of the electrons due to the electric field, but by the random motion superimposed on that motion by electron-gas molecule collisions, which make the electron behave like a gas molecule with a Boltzmann velocity distribution. Readers interested in field charging, the time necessary to charge a particle, the mathematics leading to Eq. (9.23), or a thorough treatment of all aspects of ESPs should consult Ref. 6.

The electrostatic force on a particle is

$$F = qE_p \tag{9.24}$$

Here E_p is the local electric field strength causing the force. Why do we use E_p in this equation and E_0 in the previous one? A particle may acquire its charge in a region of high E (near the wire) and then move into a region of lower E (near the plate). If we substitute for q from Eq. (9.23), we find

$$F = 3\pi \left(\frac{\varepsilon}{\varepsilon + 2}\right) \varepsilon_0 D^2 E_0 E_p \tag{9.25}$$

The two subscripts on the Es remind us that one represents the field strength at the time of charging, the other the instantaneous (local) field strength. For all practical purposes we use an average E; and in the rest of this chapter we will use $E_0 = E_p = E$ and write subsequent equations with an E. If the particle's resistance to being driven to the wall by electrostatic forces is given by the Stokes drag force, Eq. (8.3), we can set the resistance force equal to the electrostatic force in Eq. (9.25) and solve for the resulting velocity, finding

$$V_t = \frac{D\varepsilon_0 E^2 \left(\dfrac{\varepsilon}{\varepsilon + 2}\right)}{\mu} = w \tag{9.26}$$

This velocity is called the *drift velocity* in the ESP literature, and is given the symbol w. We will use that symbol here although it is clearly the same as the V_t we found for gravity or centrifugal terminal settling velocities.

Example 9.10. Calculate the drift velocity for the particle in Example 9.9.

$$w = \frac{(10^{-6}\ \text{m})(8.85 \times 10^{-12}\ \text{C/V} \cdot \text{m})(3 \times 10^5\ \text{V/m})^2(6/8) \times (\text{N} \cdot \text{m/C} \cdot \text{V})}{(1.8 \times 10^{-5}\ \text{kg/m} \cdot \text{s})(\text{N} \cdot \text{s}^2/\text{kg} \cdot \text{m})}$$

$$= 0.033\ \frac{\text{m}}{\text{s}} = 0.109\ \frac{\text{ft}}{\text{s}}$$ ■

Since the calculated drift velocity is proportional to the particle diameter, one would compute larger values for the larger particles present in the gas stream.

Equation (9.26) shows that the drift velocity is proportional to the square of E, which is approximately equal to the wire voltage divided by the wire-to-plate distance. If we could raise the voltage or lower the wire-to-plate distance, we should be able to achieve unlimited drift velocities. The limitation here is sparking. The conditions between the wire and the plate are the same ones that exist between a thundercloud and the ground during a thunderstorm. Occasionally an ionized conduction path will be formed between the wire and the plate; this ionized path is then a good conductor and forms a continuous standing spark, which is in every way equivalent to a lightning stroke. The power supply to the wire must sense this sudden increase in current and stop the flow into it to prevent a burnout of the transformer. Normally the current is shut off for a fraction of a second, the lightning stroke ends, and then the field is reestablished. As one raises the values of E, the frequency of sparks increases. These sparks are energetic events that disrupt the cake on the plate (just as lightning strokes cause damage where they touch the earth), thus reducing the collection efficiency, so a large number of sparks are bad. Experimentally it has also been found that setting the voltage low enough to have zero sparks results in too low an E for optimum efficiency. Most ESP control systems are set for about 50 to 100 sparks per minute, which seems to be the optimum balance between the desire to increase E and the desire not to have too many sparks. Furthermore, it is common practice to subdivide the power supply of a large precipitator into many subsupplies so that each part of the precipitator can operate at the optimum voltage for its local conditions, and so that during the fraction of a second in which the system is shut down to neutralize a spark, only a small part of the whole ESP is shut down. (The multiple transformer-rectifiers are shown on the roof of the ESP in Fig. 9.8.)

When we compare the drift velocity here with the terminal settling velocity computed for the same particle in a cyclone separator in Example 9.3, we see that this is only about five times as fast. Why then is an ESP so much more effective than a cyclone for fine particle collection? As mentioned before, the drift velocity is proportional to D for an ESP and to D^2 for a cyclone. But to obtain a high drift velocity in a cyclone, one must use a high gas velocity. Thus, as shown in Example 9.7, the length of time the particle is exposed to centrifugal force in a cyclone is very short. On the other hand, the gas velocity does not enter Eq. (9.26), and the velocity with which the particle approaches the wall is independent of gas velocity. We can make the precipitator large enough that the particle spends a long time in it and has a high probability of capture. Typical modern ESPs have gas velocities of 3 to 5 ft/s (1 to 2 m/s), and the gas spends from 3 to 10 seconds in them. This is in marked contrast to the high gas velocities (and low residence times) necessary to make centrifugal separators work.

Since a precipitator is really a gravity settler in which we have replaced the gravitational force with an electrostatic force as the mechanism for driving the particles to the wall, it seems reasonable to assume that we can predict the behavior of ESPs by using Eqs. (9.5) and (9.11) and substituting the drift velocity w for V_t. Figure 9.7 is, in effect, two gravity settlers back to back, with one being the space between the wires and the far plate, and the other being the space between the wires and the near plate. The particles are driven from the wires toward both of the plates, in opposite horizontal directions. The maximum distance perpendicular to the flow that a particle must travel is the distance from the wire to the plate, which is the equivalent of H in Fig. 9.1.

If we now consider the section between the row of wires and one plate on Fig. 9.7, we see its collecting area is

$$A = Lh \tag{9.27}$$