CHAPTER 9

CONTROL OF PRIMARY PARTICULATES

As discussed in Chapter 8, most of the fine particles in the atmosphere are secondary particles. Nonetheless, the control of primary particles is a major part of air pollution control engineering. Many of the primary particles, e.g., asbestos and heavy metals, are more toxic than most secondary particles. Although primary particles are generally larger than secondary particles, many primary particles are small enough to be respirable and are thus of health concern. The average engineer is more likely to encounter a primary particle control problem than any other type of air pollution problem. If possible the collected particles are recycled to somewhere in the process that generates them. Most often (e.g., ash and soot from coal combustion), the collected particles go to a landfill.

9.1 WALL COLLECTION DEVICES

The first three types of control devices we consider—gravity settlers, cyclone separators, and electrostatic precipitators—all function by driving the particles to a solid wall, where they adhere to each other to form agglomerates that can be removed from the collection device and disposed of. Although these devices look different from one another, they all use the same general idea and are described by the same general design equations.

9.1.1 Gravity Settlers

A gravity settler is simply a long chamber through which the contaminated gas passes slowly, allowing time for the particles to settle by gravity to the bottom. It is an old, unsophisticated device that must be cleaned manually at regular intervals. But it is simple to construct, requires little maintenance, and has some use in industries treating very dirty gases, e.g., some smelters and metallurgical processes. Furthermore, the mathematical analysis for gravity settlers is very easy; it will reappear in modified form for cyclones and electrostatic precipitators.

Figure 9.1 shows a gravity settler. Its cross-sectional area (WH) is much larger than that of the duct approaching it or leading the gas away from it, so that the gas velocity inside is much lower than in either of those two ducts. Baffles of some kind are used to spread the incoming flow evenly across the settling chamber; without baffles most of the flow will go through the middle and poor particle collection will result.

To calculate the behavior of such a device, chemical engineers generally rely on one of two models. Either we assume that the fluid going through is totally unmixed *(block flow* or *plug flow model)* or we assume total mixing, either in the entire device or in the entire cross section perpendicular to the flow *(backmixed* or *mixed model)*. Each of these sets of assumptions leads to simple calculations. The observed behavior of nature most often falls between these two simple cases, so that with these two models we can set limits on what nature probably does. Both models are widely used in air pollution control device calculations. We will calculate the behavior of a gravity settler both ways.

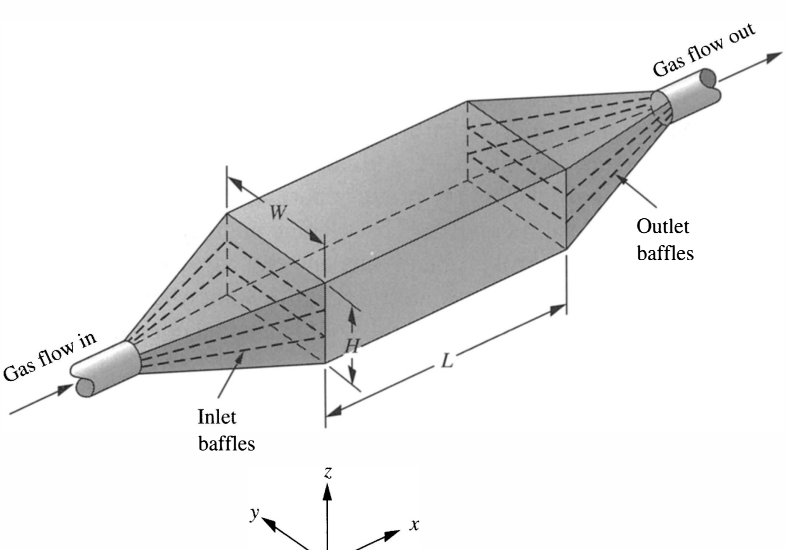

FIGURE 9.1
Schematic of a typical gravity settler.

For either block or mixed flow, the average horizontal gas velocity in the chamber is

$$V_{\text{avg}} = \frac{Q}{WH} \tag{9.1}$$

For the block flow model, we will assume

1. The horizontal velocity of the gas in the chamber is equal to V_{avg} everywhere in the chamber (but see Problem 9.1).
2. The horizontal component of the velocity of the particles in the gas is always equal to V_{avg}.
3. The vertical component of the velocity of the particles is equal to their terminal settling velocity due to gravity, V_t.
4. If a particle settles to the floor, it stays there and is not re-entrained.

With these assumptions we can compute the behavior of a gravity settling chamber according to the block flow model.

Consider a particle that enters the chamber some distance h above the floor of the chamber. The length of time the gas parcel it entered with will take to traverse the chamber in the flow direction is

$$t = \frac{L}{V_{\text{avg}}} \tag{9.2}$$

During that time the particle will settle by gravity a distance,

$$\text{Vertical settling distance} = t\,V_t = V_t \frac{L}{V_{\text{avg}}} \tag{9.3}$$

If this distance is greater than or equal to h (its original distance above the floor), then it will reach the floor of the chamber and be captured. If all the particles are of the same size (and hence have the same value of V_t), then there is some distance above the floor (at the inlet) below which all of the particles will be captured, and above which none of them will be captured. If we now further assume that all of the particles are the same size, that they are distributed uniformly across the inlet of the chamber, and that they do not interact with one another, then we can say that the fraction of particles that will be captured, which is the fractional collection efficiency, is

$$\text{Fraction captured} = \eta = \frac{L\,V_t}{H\,V_{\text{avg}}} \qquad \text{for block flow} \tag{9.4}$$

To compute the efficiency-particle diameter relationship, we replace the terminal settling velocity in Eq. (9.4) with the gravity-settling relations described in Sec. 8.2.2. For most air pollution applications, Stokes' law [Eq. (8.4) with the air density ignored] is appropriate; substituting it in Eq. (9.4), we find

$$\eta = \frac{L g D^2 \rho_{\text{part}}}{H\,V_{\text{avg}}\,18\mu} \qquad \text{for block flow} \tag{9.5}$$

Now to consider the mixed flow model, we assume that the gas flow is totally mixed in the z direction but not in the x direction. (Most real gas flows are turbulent, leading to internal mixing in process equipment.) This makes sense, because mixing in the x direction moves particles both up- and downstream, with little effect on collection efficiency, whereas mixing in the z direction leads to a decrease in collection efficiency. We then consider a section of the settler with length dx. In this section the fraction of the particles that reach the floor will equal the vertical distance an average particle falls due to gravity in passing through the section, divided by the height of the section, which we may write as

$$\text{Fraction collected} = \frac{V_t\,dt}{H} \tag{9.6}$$

The change in concentration passing this section is

$$dc = -c \cdot (\text{fraction collected}) = -\frac{c V_t\,dt}{H} \tag{9.7}$$

The time the average particle takes to pass through this section is

$$dt = \frac{dx}{V_{\text{avg}}} \tag{9.8}$$

Combining these equations and rearranging, we have

$$\frac{dc}{c} = -\frac{V_t}{H V_{\text{avg}}}\,dx \tag{9.9}$$

which we may integrate from the inlet ($x = 0$) to the outlet ($x = L$), finding

$$\ln\frac{c_{\text{out}}}{c_{\text{in}}} = -\frac{V_t L}{H V_{\text{avg}}} \qquad \text{mixed flow} \tag{9.10}$$

or

$$\eta = 1 - \left(\frac{c_{\text{out}}}{c_{\text{in}}}\right) = 1 - \exp - \left(\frac{V_t L}{H V_{\text{avg}}}\right) \tag{9.11}$$

Finally we can substitute for V_t from Stokes' law, finding

$$\eta = 1 - \exp - \left(\frac{L g D^2 \rho_{\text{part}}}{H V_{\text{avg}} 18\mu}\right) \qquad \text{mixed flow} \tag{9.12}$$

Comparing this result with that for the block or plug flow assumption, Eq. (9.5), we see that Eq. (9.12) can be rewritten as

$$\eta_{\text{mixed}} = 1 - \exp(-\eta_{\text{block flow}}) \tag{9.13}$$

Example 9.1. Compute the efficiency-diameter relation for a gravity settler that has $H = 2$ m, $L = 10$ m, and $V_{\text{avg}} = 1$ m/s for both the block and mixed flow models, assuming Stokes' law.

Here we can get the result using only one computation and then using ratios. First we compute the block flow efficiency for a 1-μ particle, viz.,

$$\eta = \frac{LgD^2\rho_{\text{part}}}{18\mu H V_{\text{avg}}} = \frac{(10\text{ m})(9.81\text{ m/s}^2)(10^{-6}\text{ m})^2(2000\text{ kg/m}^3)}{(18)(1.8 \times 10^{-5}\text{ kg/m}\cdot\text{s})(2\text{ m})(1\text{ m/s})} = 3.03 \times 10^{-4}$$

For 1-μ particles the block flow assumption leads to an efficiency of 3.03×10^{-4}. The mixed assumption leads to practically the same result, viz.,

$$\eta_{\text{mixed}} = 1 - \exp(-3.03 \times 10^{-4}) = 3.029 \times 10^{-4}$$

To find the efficiencies for other particle diameters, we observe that the block efficiency is proportional to the particle diameter squared, so we make up a table of block flow efficiencies by simple ratios to the value for 1 μ, and then compute the corresponding mixed flow efficiencies as just shown.

Particle diameter, μ	η_{block}	η_{mixed}
1	0.000303	0.000303
10	0.0303	0.0298
30	0.273	0.239
50	0.76	0.53
57.45	1.00	0.63
80	—	0.86
100	—	0.95
120	—	0.99

These values are shown in Fig. 9.2 on page 254. ■

For small particles, for which the calculated collection efficiencies are small, the mixed and block flow models give practically the same answer. For larger particles the calculated collection efficiencies become larger, and the two models give different answers. The block flow model shows the efficiency reaching 100 percent for a particle diameter of 57.45 μ, whereas the mixed flow model shows the efficiency asymptotically approaching 100 percent for particles larger than about 100 μ. If one substitutes a diameter of 100 μ in the block flow equation one finds an efficiency of 303 percent, which is meaningless.

One may gain some insight into these two models by asking what the dust pile on the floor would look like if we ran a gravity settler with a single-size dust for a long period of time and then shut it down. In the block flow model, we would expect a pile of absolutely uniform height ending abruptly at that length for which $L = HV_{\text{avg}}/V_t$. For the mixed model we would expect a pile that is deepest at the inlet end and whose depth falls exponentially, approaching zero depth asymptotically as L becomes large.

This type of device would be useful for collecting particles with diameters of perhaps 100 μ (fine sand) but not for particles of air pollution interest, whose diameters go down to fractions of a micron. We could increase the efficiency by

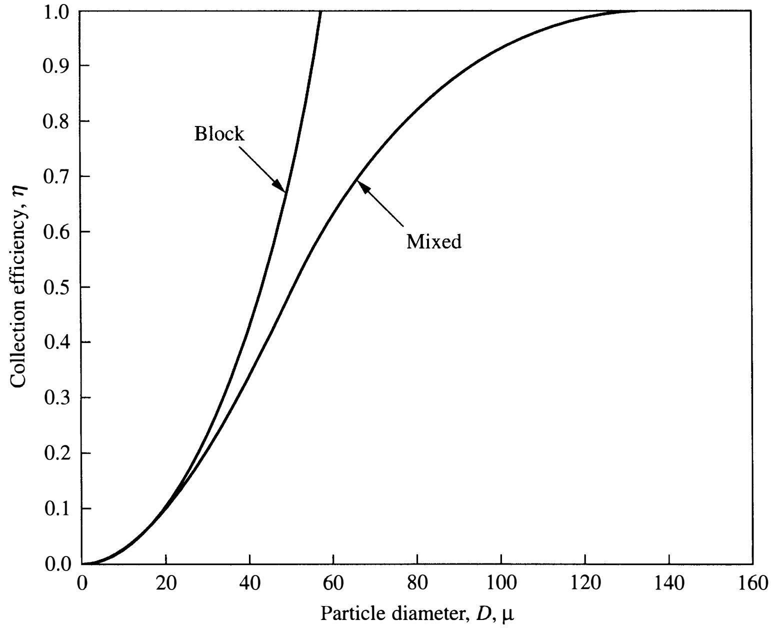

FIGURE 9.2
Comparison of the efficiencies for a gravity settler, calculated by the block and mixed models (see Example 9.1).

making L larger (which makes the device very long and expensive), by making H smaller (which is sometimes done by subdividing the chamber with horizontal plates, which makes the cleanup much more difficult), by lowering V_{avg} (which requires a larger cross-sectional area and hence larger and more costly device), or by increasing g. The latter is the only practical alternative; it requires substituting some other force for the force of gravity in driving the particles from the gas stream to the collecting surface.

Small gravity settlers used for particle sampling are sometimes called *horizontal elutriators.* In them air flow is very slow, and particles are collected by gravity on greased plates for subsequent microscopic examination [1] (see Problem 9.3).

9.1.2 Centrifugal Separators

We have spent considerable time on gravity settlers because it is easy to see what all their mathematics mean. But they have little practical industrial use because they are ineffective for small particles. If we are to use them or devices like them, we must find a substitute that is more powerful than the gravity force they use to drive the particles to the collection surface. Physics and mechanics books usually show that *centrifugal force* is a pseudoforce that is really the result of the body's inertia carrying it straight while some other force makes it move in a curved path. It is convenient to use this pseudoforce for calculational purposes.

If a body moves in a circular path with radius r and velocity V_c along the path, then it has angular velocity $\omega = V_c/r$, and

$$\text{Centrifugal force} = \frac{mV_c^2}{r} = m\omega^2 r \tag{9.14}$$

Example 9.2. A particle is traveling in a gas stream with velocity 60 ft/s (18 m/s) and radius 1 ft. What is the ratio of centrifugal force to the gravity force acting on it?

$$\frac{\text{Centrifugal force}}{\text{Gravity force}} = \frac{mV_c^2/r}{mg} = \frac{(60\text{ ft/s})^2/(1\text{ ft})}{32.2\text{ ft/s}^2} = 111.8 \qquad \blacksquare$$

At even modest velocities and common radii, the centrifugal forces acting on particles can be two orders of magnitude larger than the gravity forces. For this reason centrifugal particle separators are much more useful than gravity settlers.

For further work we will use a centrifugal equivalent of Stokes' law, given in Eq. (8.4). We obtained Stokes' law by equating the (gravitational minus buoyant) force to the Stokes' form of the drag force. Normally we drop the buoyant term for particles in gases because it is small. To obtain the centrifugal equivalent, we need only substitute the centrifugal force for the gravitational force (or the centrifugal acceleration for the gravitational acceleration, since the masses are equal). In Eqs. (8.2) and (8.4) we replace g by V_c^2/r or by $\omega^2 r$. Doing this poses a problem, because now there are two velocities in the equation that are not the same. To save confusion we will call the terminal settling velocity in the radial direction V_t and the velocity along the circular path V_c. The relation of these two is sketched in Fig. 9.3.

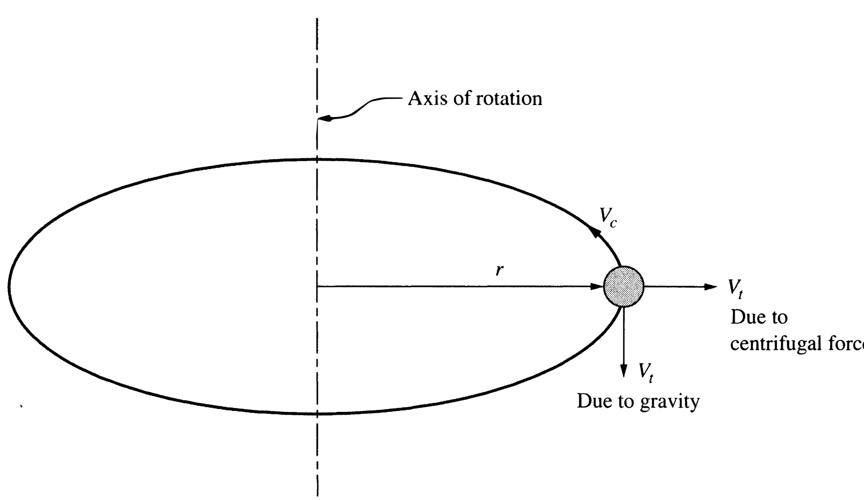

FIGURE 9.3
Relation of defined terms for rotational motion.