Chapter 9

Control of Primary Particulates

PRIMARY PARTICULATES : CONTROL DEVICES

- ***WALL COLLECTION DEVICES***
  - Settling chambers
  - Cyclones
  - Electrostatic precipitators
- ***DIVIDING COLLECTION DEVICES***
  - Filters (surface and depth)
  - Scrubbers

GRAVITY SETTLING CHAMBERS

- Gas behavior can be characterized by limiting cases:
  - Block or plug flow , and
  - mixed flow

- The names *plug flow* (or *block flow)* model, and *mixed flow model* have been used in Air Pollution Control (*de Nevers*) differently from common usage in reactor notation (*Levenspeil*) as illustrated next.

Gas behavior: *Plug flow (block flow)*

de Nevers

- no mixing in the direction of fluid flow

  (x, horizontal)
- no mixing in the transverse direction of particle motion

  (y, horizontal, or z vertical)

Levenspiel

- no mixing in the direction of fluid flow (x, horizontal)
- well mixed in transverse direction

  (y, horizontal, or z vertical)

Gas behavior: *Mixed flow*

de Nevers

- no mixing in the direction of fluid flow (x, horizontal)
- well mixed in transverse direction

  (y, horizontal, or z vertical)

Levenspiel

- well mixed in all directions (x, y, z)

GRAVITY SETTLING CHAMBERS

- Particle removal efficiency related to:
  - residence time in chamber
  - terminal settling velocity
  - distance to travel before hitting the wall

$$V_{gas} = \frac{Q_{gas}}{W_{idth} H_{eight}}$$

$$t_{residence} = \frac{L_{ength}}{V_{gas}}$$

$$\text{settling distance} = tV_{\text{terminal}}$$

Figure 9.1 de Nevers

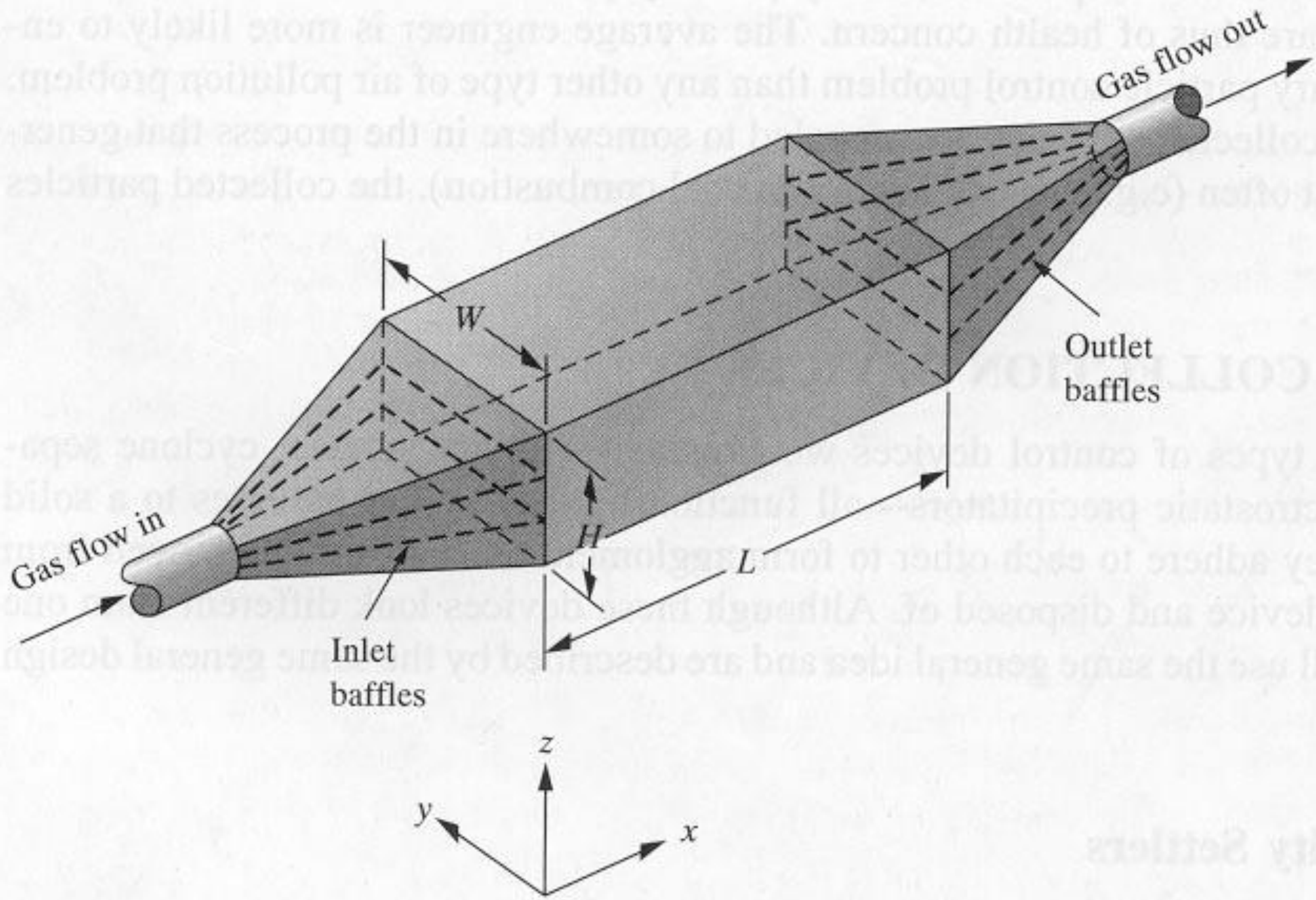
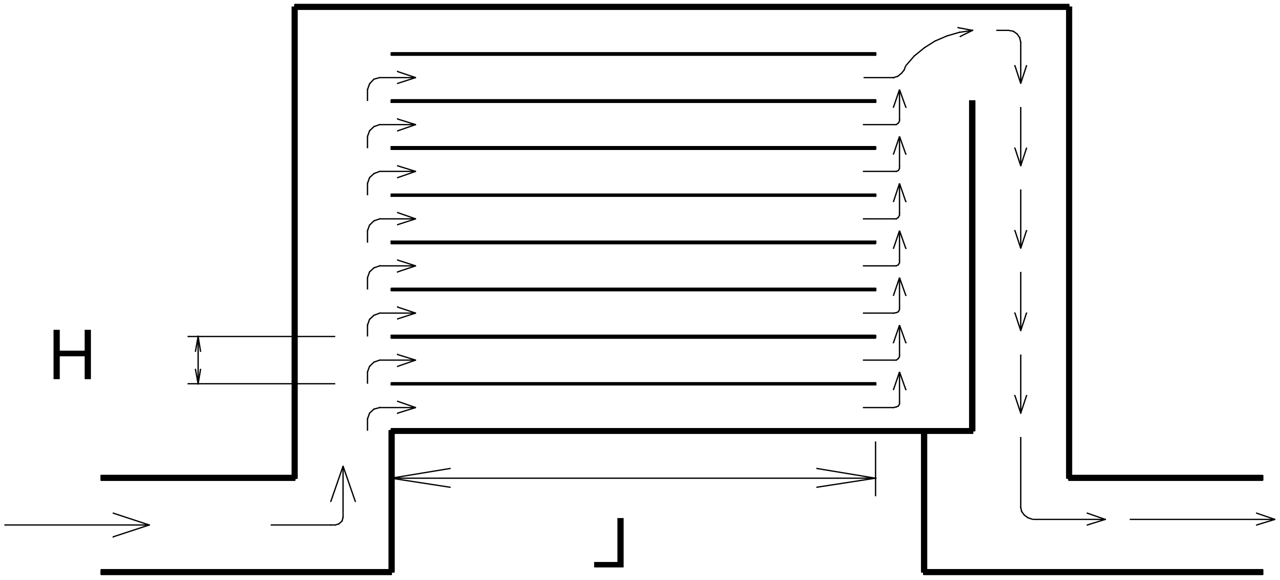


FIGURE 9.1
Schematic of a typical gravity settler.

Gravity settling chamber



Novel designs based on multiple chambers in parallel

SETTLING CHAMBER : CAPTURE EFFICIENCIES

- **Plug flow**

$$\eta_{plug} = \frac{L_{ength} V_{\text{terminal}}}{H_{eight} V_{gas}}$$

- **Mixed Flow**

$$\eta_{mixed} = 1 - \exp - \left(\frac{L_{ength} V_{\text{terminal}}}{H_{eight} V_{gas}} \right)$$

$$\eta_{mixed} = 1 - \exp - \left(\eta_{plug} \right)$$

Example 9.1

Calculates *efficiencies* as a function of particle diameter (hence terminal settling velocity) for the two models using:

Height = 2 m

Length = 10 m

V_{gas} = 1 m/s

Results plotted in Fig 9.2

Figure 9.2 de Nevers

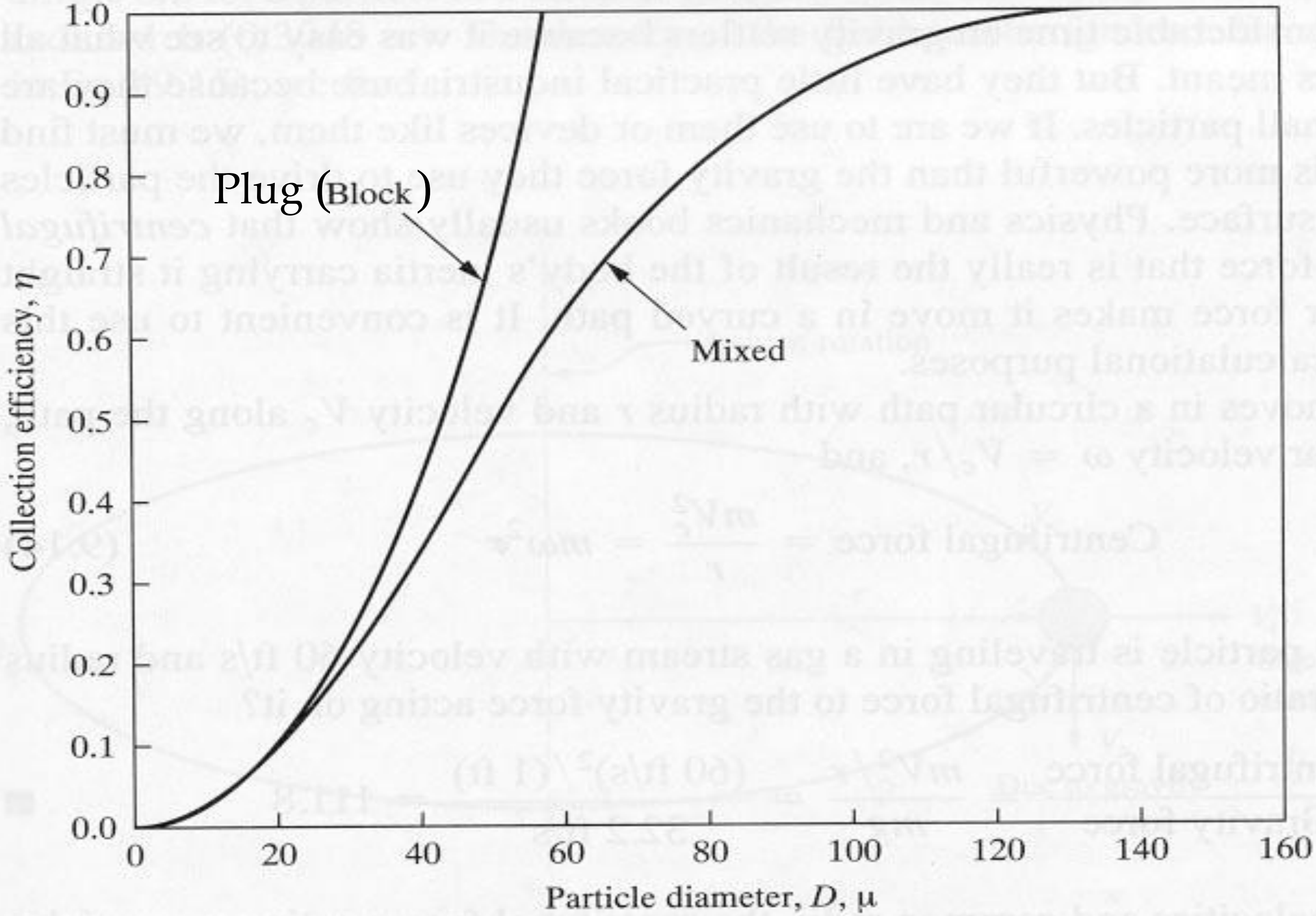


FIGURE 9.2
Comparison of the efficiencies for a gravity settler, calculated by the block and mixed models (see Example 9.1).

WALL COLLECTION DEVICES

- Gravity settling is effective for large particles

  (more than 100 micrometers), in reasonably sized chambers
- For *smaller* particles, the terminal settling velocity is too small
- To collect *smaller* particles: Impose an external force greater than gravity

  - Centrifugal - CYCLONES

  - Electrostatic - ESP

Cyclone

Figure 9.4 de Nevers

For standard Cyclone:

$W = 0.25\ D_o$

$H = 0.5\ D_o$

$H_1 = H_2 = 2\ D_o$

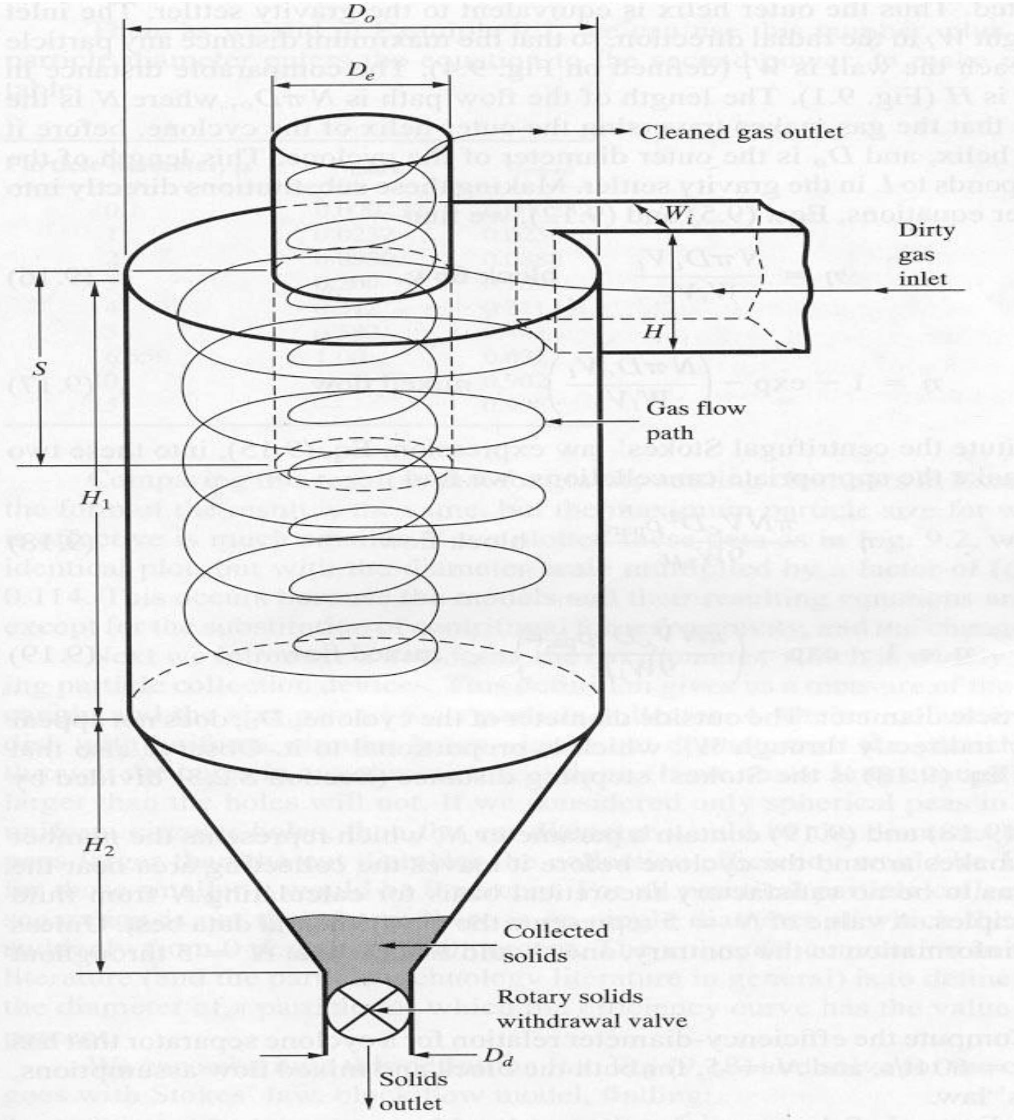


FIGURE 9.4
Schematic of a cyclone separator. Dimensions are typically based on the overall diameter D_o. Taken as ratios to that dimension, $W_i = 0.25$, $H = 0.5$, $H_1 = 2$, $H_2 = 2$, $D_e = 0.5$, $S = 0.625$, $D_d = 0.25$. For example, if $D_o = 1$ ft, then $W_i = 0.25$ ft, etc. Ashbee and Davis [2] show a table with six sets of values for these dimension ratios. The principal differences are that high-efficiency cyclones have smaller values of W_i whereas high-throughput cyclones have larger values of W_i and of D_e. The dimension ratios here are for the "conventional" design.

CYCLONES

- Principles similar to settling chambers
- More complex geometry and flow patterns

$$F_{centrifugd} = \frac{m_{ass} V^2{}_{\text{circular}}}{r_{adius}}$$

- At 60 ft/s circular velocity and 1 ft radius:

$$\frac{F_{centrifugd}}{F_{gravity}} = \{(m.V_{circular}2)/r\}/(mg) = 112$$

CYCLONES

$N \equiv$ number of turns for the gas in the cyclone before exit

$$V_{\text{circular}} = \frac{Q_{gas}}{(W_{idth} H_{eight})_{\text{of inlet duct}}}$$

$$\eta_{plug} = \frac{N \pi D_o V_{\text{terminal}}}{W_{idth} V_{circular}}$$

$$\eta_{mixed} = 1 - \exp - \left(\eta_{plug} \right)$$

substitutions directly into the gravity settler equations, Eqs. (9.5) and (9.12), we find

$$\eta = \frac{N\pi D_o V_t}{W_i V_c} \qquad \text{block flow} \tag{9.16}$$

and

$$\eta = 1 - \exp - \left(\frac{N\pi D_o V_t}{W_i V_c} \right) \qquad \text{mixed flow} \tag{9.17}$$

If we then substitute the centrifugal Stokes' law expression, Eq. (9.15), into these two equations, and make the appropriate cancellations, we find

$$\eta = \frac{\pi N V_c D^2 \rho_{\text{part}}}{9 W_i \mu} \qquad \text{block flow} \tag{9.18}$$

and

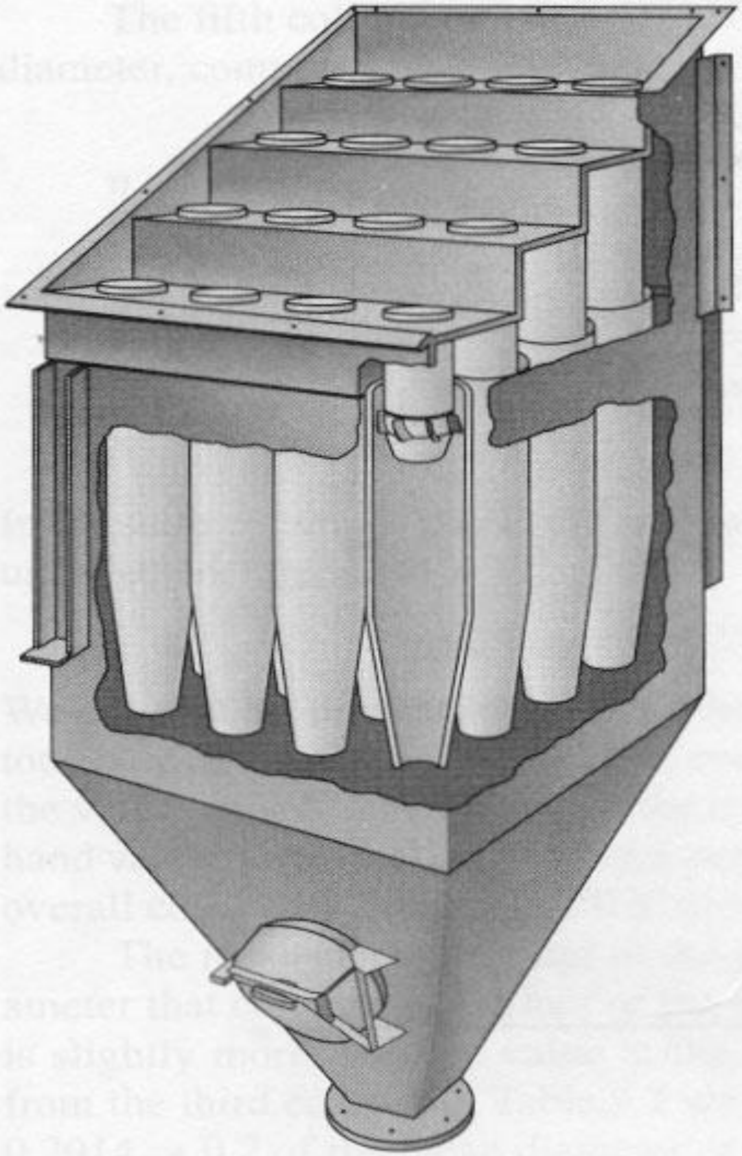
$$\eta = 1 - \exp - \left(\frac{\pi N V_c D^2 \rho_{\text{part}}}{9 W_i \mu} \right) \qquad \text{mixed flow} \tag{9.19}$$

Here D is the particle diameter. The outside diameter of the cyclone, D_o, does not appear directly but only indirectly through W_i, which is proportional to it. Observe also that the right side of Eq. (9.18) is the Stokes' stopping distance (Section 8.2.4) divided by $W_i/2\pi N$.

MULTICLONES

In Series: Vc same for all

Figure 9.5
de Nevers



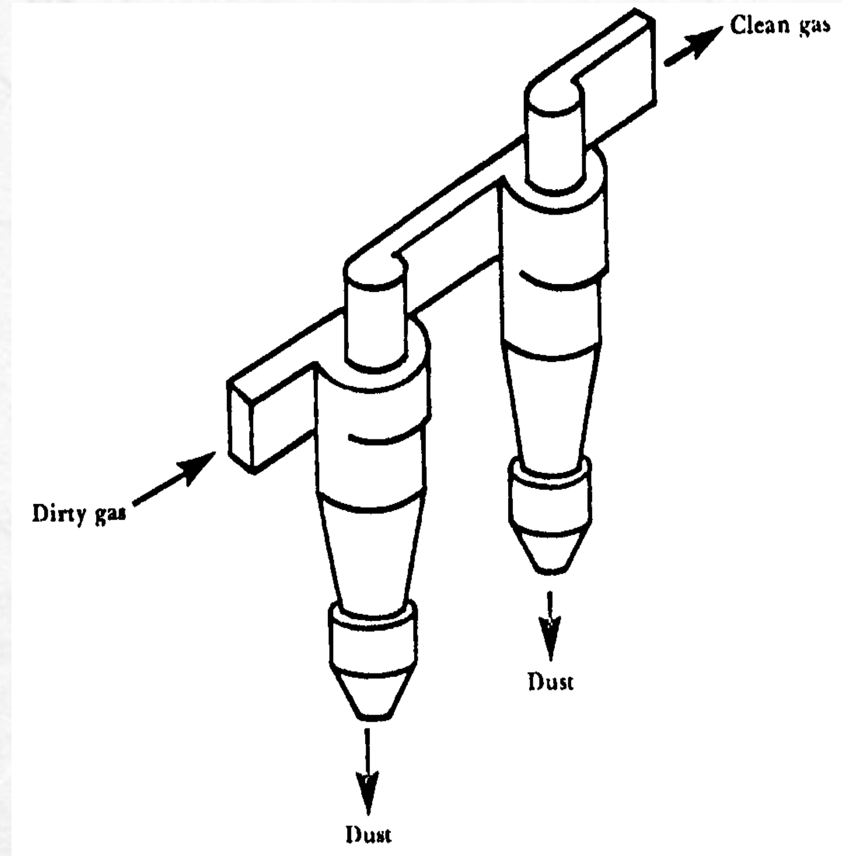


FIGURE 9.5
A multiclone, which places a large number of small cyclones in parallel. (Courtesy of Joy Environmental.)

CYCLONE COLLECTION EFFICIENCY

With Particle Size Distribution

- Collection efficiency varies with particle terminal velocity, which in turn varies with particle diameter D and density

- 'Cut Diameter' D_{cut} is the diameter which has collection efficiency of 50%

CYCLONE COLLECTION EFFICIENCY ESTIMATE OF CUT DIAMETER

- Using Stoke's region expression for $V_{terminal}$ and plug flow model (*neither of which are particularly good representations of the actual situation*) we can obtain:

$$D_{cut} = \sqrt{\frac{9W_{inlet}\mu}{2\pi N V_c \rho_{particle}}}$$

- This turns out to be a reasonable estimate of D_{cut}
- Empirical data on standard cyclones is required for more precision

Collection efficiency vs. particle diameter

The plug flow efficiency obtained earlier can be written:

$$\eta_{plug} = kD^2$$

where k incorporates all the other parameters kept constant

Thus: $0.5 = kD_{cut}^2$ and $\frac{\eta_{plug}}{0.5} = \left(\frac{D}{D_{cut}}\right)^2 = r^2$

$$\eta_{mixed} = 1 - \exp - (\eta_{plug}) = 1 - \exp - (0.5 r^2)$$

Empirical equation for typical cyclone:

$$\eta = \frac{r^2}{1 + r^2}$$

where $r = \frac{D}{D_{cut}}$

(Eq. 9.21)

Figure 9.6 de Nevers (Example 9.6)

- Eqn 9.18 plug flow and Stoke's law
- Eqn 9.19 mixed flow and Stoke's law
- Eqn 9.21 empirical

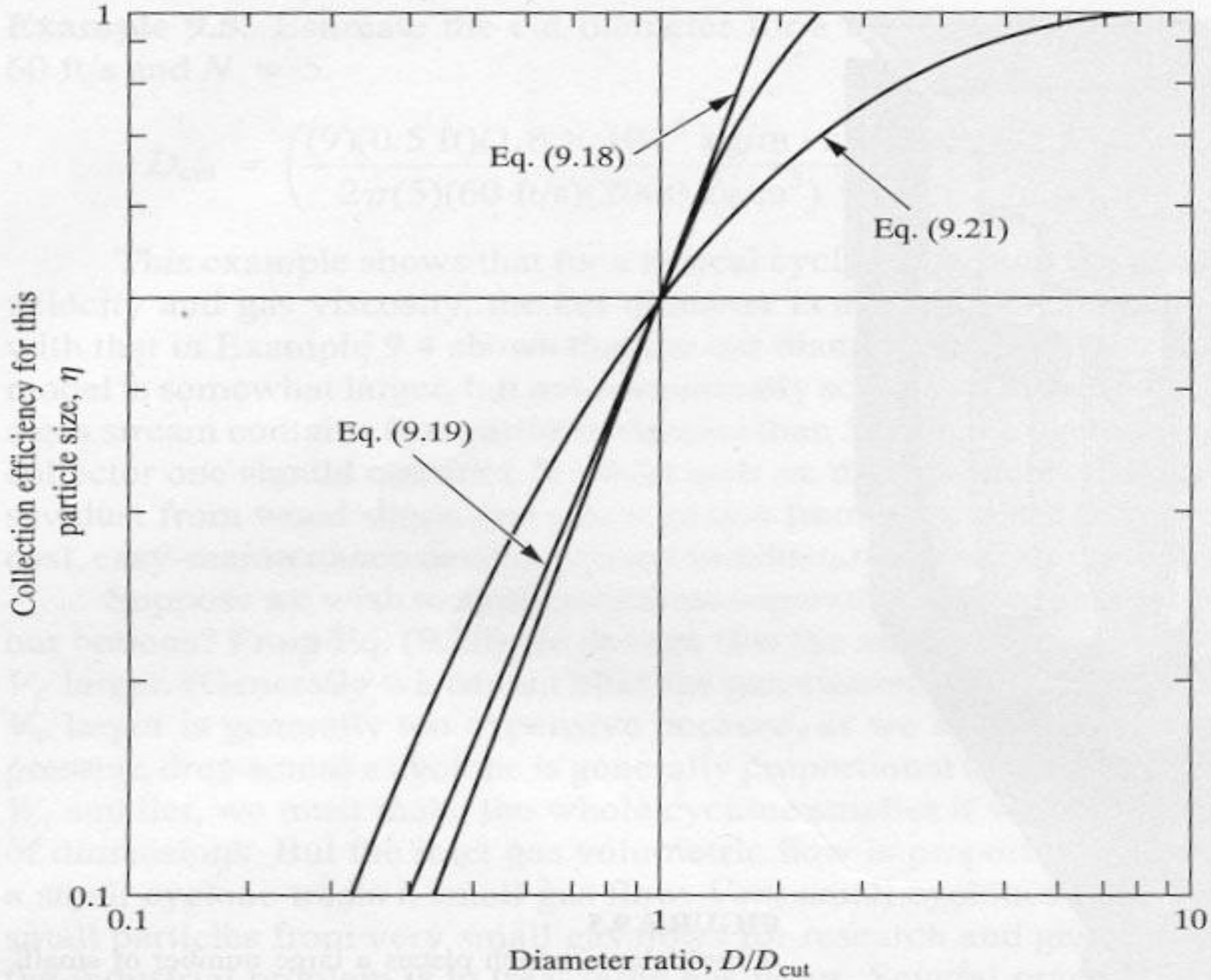


FIGURE 9.6
Collection efficiency vs. particle diameter curves for cyclones. Here, all three curves must pass through 0.5 at $D = D_{cut}$ because of the definition of D_{cut}. Equation (9.21) is very close to the experimental results for typical cyclones.

Cyclone Performance for various Applications

Efficiency vs. particle size	% Of particles below 10 μm in size	Efficiency range
Fly ash (power)		
Spreader stoker-fired boilers	20	90—95
PC-fired boilers	42	75—90
Cyclone-fired boilers	65	55—65
Nonmetallic minerals (when collector is part of process and collector catch is reusable)		
Cement (kilns and process)	40	70—85
Asphalt plant	10	80—95
Lightweight aggregate (kiln)	30—40	80—90
Refractory clays (kiln)	40—50	70—80
Lime (kiln)	40—50	75—80
Fertilizer plant (process equipment)	40	80—85
Steel (ore beneficiation)		
Pelletizing (vertical shaft and rotary kiln)	10—40	80—95
Foundry (general)	10—40	80—95
Chemical process (drying, calcining)	10—40	80—95
Incinerators (municipal)	20—40	65—75
Coal processing (thermal drying)	10	90—97
Petroleum (catalytic cracking process)	0.6	99 +
General industrial application (in plant)	10—60	65—95

ELECTROSTATIC PRECIPITATORS (Cottrell precipitators)

- Principle of ESPs: charge the particles, use electrostatic force to attract them to wall

$$\textit{Field strength, } E = \frac{\partial V}{\partial x} \quad \frac{\textit{applied voltage}}{\text{distance}}$$

$$e.g. \frac{40\,kV}{0.1\,m} = 400\,\frac{kV}{m}$$

$$\textit{Higher at the wire, because of geometry } (5 - 10\,\frac{MV}{m})$$

ESP

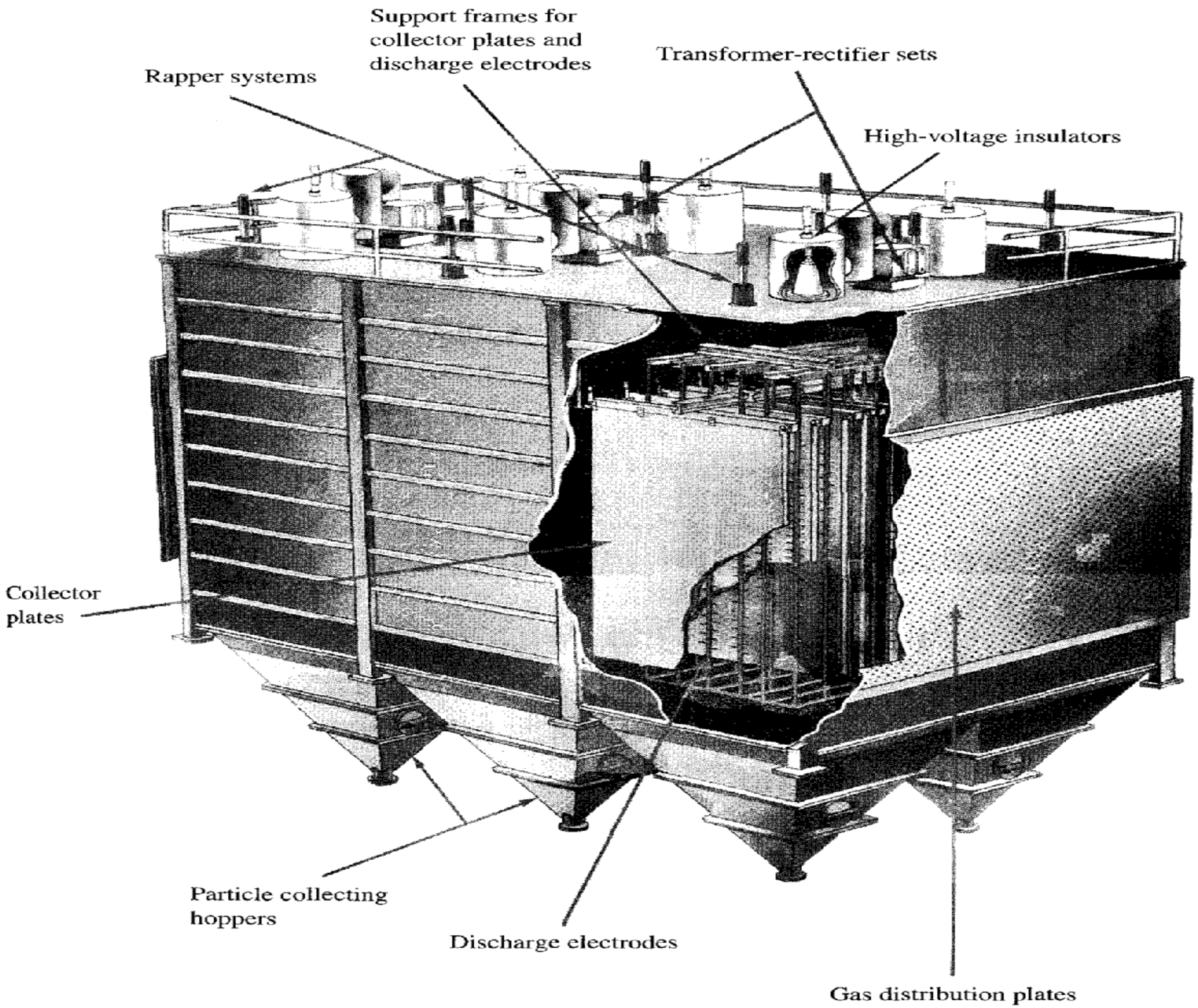


FIGURE 9.8
Cutaway view of a large, modern ESP showing the various parts. In this design the wire discharge electrodes have been replaced by rigid frames with many short, pointed stubs. (Courtesy of The Babcock and Wilcox Company, Barberton, Ohio.)

ESP

Figure 9.7 de Nevers

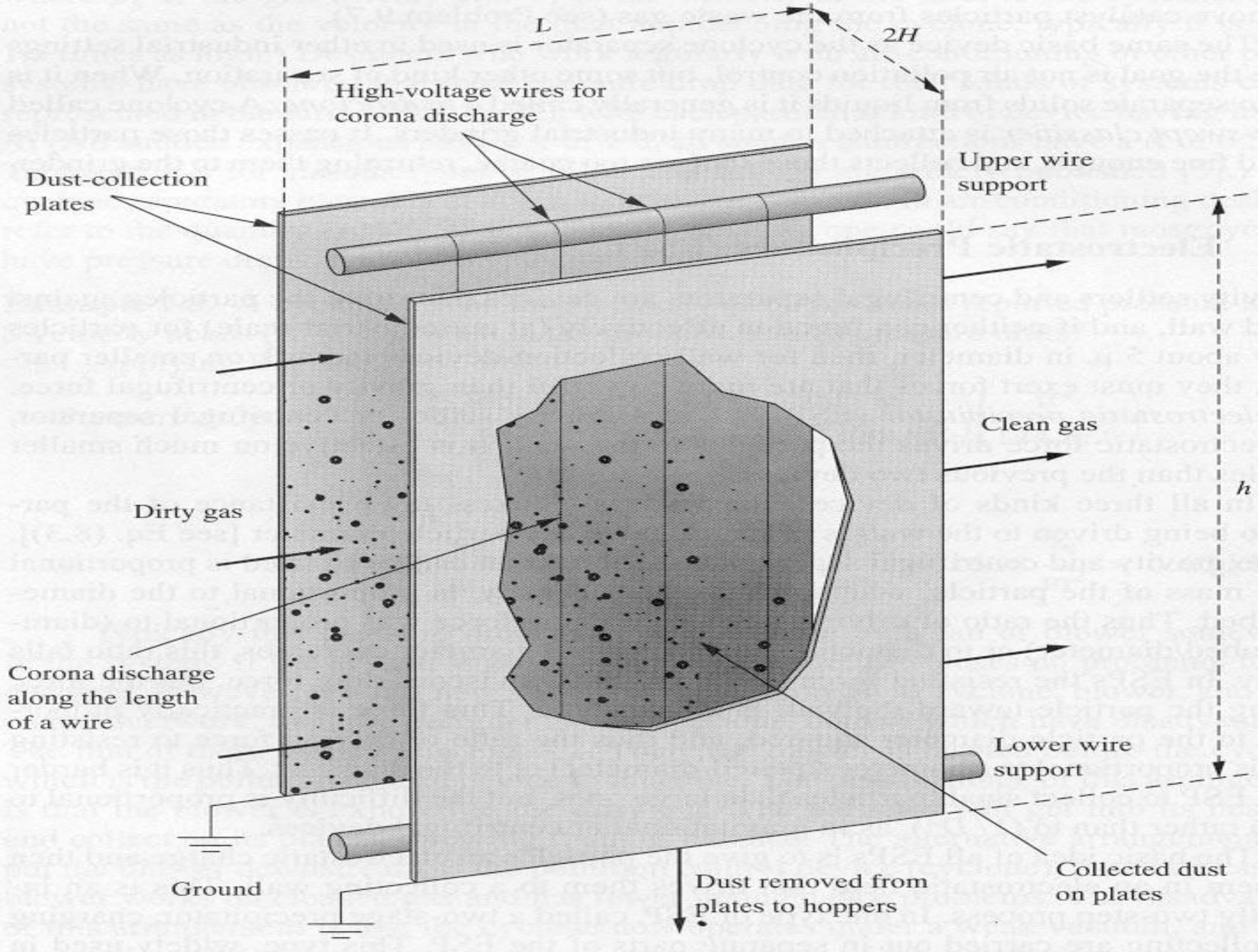


FIGURE 9.7
Diagrammatic sketch of a simplified ESP with two plates, four wires, and one flow channel. Industrial-size ESPs have many such channels in parallel; see Fig. 9.8.

ESPs

- Note similarities of geometry between settling chamber and ESP.
  - *H* : the height through which particles must travel, at right angles to gas flow, before hitting wall
  - *L* : distance travelled by gas in the collection device.
- *H* will be smaller in ESP, the velocity of particles much higher because of the electrostatic force.

How ESPs works to collect particles

A. Corona discharge at the wire:
- electrons collide with gas molecules,
- knock out electrons,
- positively charged gas ions migrate to wire and discharge particles

B. Field charging away from the wire:
- as electrons fly towards wall, they collide with particles in their path and are captured by particles,
- negatively charged particles attracted to wall and discharge there.

C. Diffusion charging:

for particles smaller than ~0.15 μm, the interaction with electrons can be significantly due to their random motion as a result of electron-gas molecule collisions

Particle Charge

- For particles larger than about 0.15 , the dominant charging mechanism is *field charging*.
- 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

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

q: charge, *coulombs*

ε : dielectric constant *relative to free space*

ε_0: $8.85E-12\ \dfrac{C}{V.m}$ *for free space*

ε_{air} :1.0006, $\varepsilon_{particles}$:4 – 6

D: *particle diameter, m*

E_0 : *local field strength, V / m*

Drift velocity

(I.e. terminal settling velocity under electrostatic force)

- *Force on particle:* ***F = q.E*** *(take $E = E_p$, local field)*

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

- *By equating Stoke's -drag force:* $F_d = 3\pi\mu D V_t$ *to electrostatic force (above), terminal settling velocity is equal to drift velocity of particle in electrical field:*

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

Drift velocity

(I.e. terminal settling velocity under electrostatic force)

- 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 Vt.
- Typical modern ESPs have gas velocities of 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.

Particle charge & Drift velocity

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

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

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

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

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

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

Collection efficiency

- ***Plug (Block) flow:***

$$\eta = \frac{w.A}{Q}; by...setting...w = V_t$$

$$\eta_{block} = \frac{V_t.L}{H.V_{avg}}; V_{avg} = \frac{Q}{A}; A = L.h$$

- ***Mixed flow:***

$$\eta_{mixe} = 1 - \exp(-\frac{wA}{Q}) \quad Deutsch - Andersen \;\; equation$$

$$\eta_{mixed} = 1 - \exp\left(-\frac{wA}{Q}\right)^k \text{ modified } D - A, \;\; k \sim 0.5$$

$$considering...ParticleSi\,zeDistribution$$

Collection efficiency

- 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 D2 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.

TABLE 9.2
Typical values of the drift velocity encountered in industrial practice

Application	Drift velocity w, ft/s
Pulverized coal (fly ash)	0.33–0.44
Paper mills	0.25
Open-hearth furnace	0.19
Secondary blast furnace (80% foundry iron)	0.41
Gypsum	0.52–0.64
Hot phosphorus	0.09
Acid mist (H_2SO_4)	0.19–0.25
Acid mist (TiO_2)	0.19–0.25
Flash roaster	0.25
Multiple-hearth roaster	0.26
Portland cement manufacturing (wet process)	0.33–0.37
Portland cement manufacturing (dry process)	0.19–0.23
Catalyst particles	0.25
Gray iron cupola (iron-coke ratio = 10)	0.10–0.12

Source: Ref. 6.

Safety

- The power supply to the wire must sense 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 sub-supplies 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.)

Summary of particle device efficiencies

- Settling Chamber:

$$\eta_{mixed} = 1 - \exp - \left(\eta_{plug}\right)$$

$$\eta_{plug} = \frac{L_{ength} V_{\text{terminal}}}{H_{eight} V_{gas}}$$

- Cyclones:

$$\eta_{mixed} = 1 - \exp - \left(\eta_{plug}\right)$$

$$\eta_{plug} = \frac{N \pi D_o V_{\text{terminal}}}{W_{idth} V_{circular}}$$

- ESPs

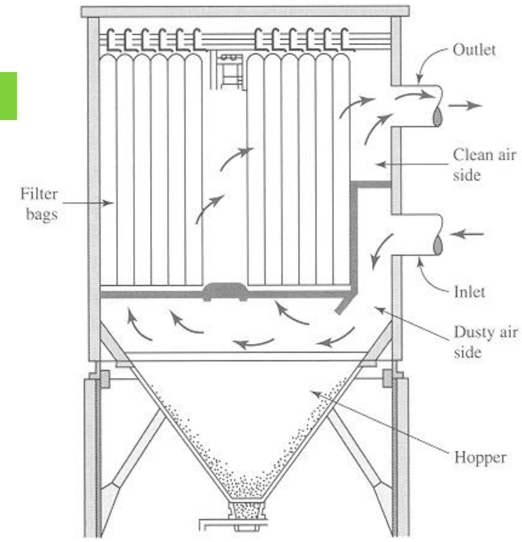
$$\eta_{mixe} = 1 - \exp\left(-\frac{wA}{Q}\right)$$

$$\eta = \frac{w.A}{Q}$$

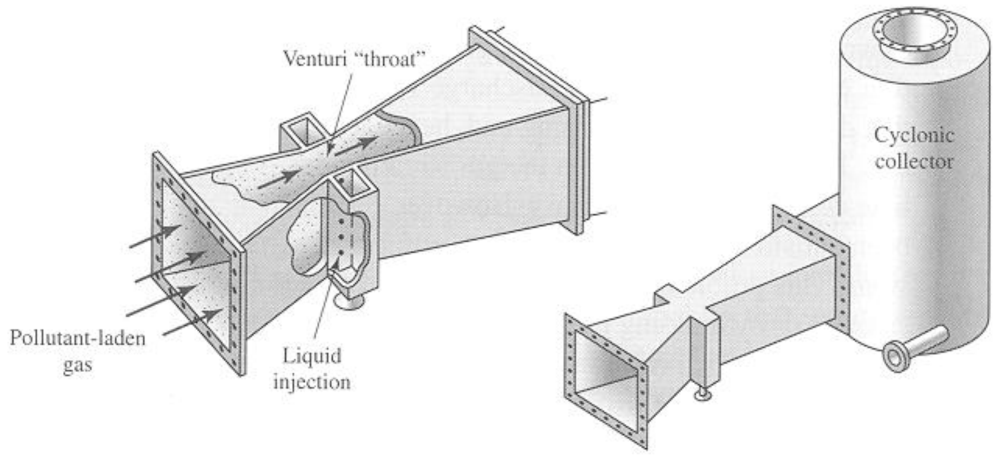
$$w = \frac{D\varepsilon_0 E^2 \left(\frac{\varepsilon}{\varepsilon + 2}\right)}{\mu}$$

Other DIVIDING COLLECTION DEVICES

- Filters
  - Surface filters
  - Depth filters



- Scrubbers



(see Text: Air Pollution Control- de Nevers, Chapter 9)