ENVIRONMENTAL PROTECTION AGENCY

APTI 413: Control of Particulate Matter Emissions

Student Manual: Chapter 4

APTI: 413 CONTROL OF PARTICULATE MATTER EMISSIONS, 5TH EDITION

Student Manual

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**The National Association of Clean Air Agencies (NACAA) represents air pollution control agencies in 53 states and territories and over 165 major metropolitan areas across the United States.*

State and local air pollution control officials formed NACAA (formerly STAPPA/ALAPCO) over 30 years ago to improve their effectiveness as managers of air quality programs. The associations serve to encourage the exchange of information among air pollution control officials, to enhance communication and cooperation among federal, state, and local regulatory agencies, and to promote good management of our air resources.

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Chapter 4

This chapter will take approximately 2 hours to complete.

OBJECTIVES

Terminal Learning Objective

At the end of this chapter, students will be able to understand the different mechanisms involved in removing particles from a gas stream.

Enabling Learning Objectives

4.1 List mechanisms involved in separating particles form a gas stream.

4.2 List fundamental steps involved in collecting particulate matter in control devices.

4.3 Identify parameters important to the collection of particles by gravity.

4.4 Define terminal settling velocity.

4.5 Define the three flow regions as a function of Reynolds Number.

4.6 Identify parameters important to the collection of particles by centrifugal force.

4.7 Identify parameters important to the collection of particles by inertial impaction.

4.8 Identify parameters important to the collection of particles by Brownian motion.

4.9 Identify parameters important to the two mechanisms of charging particles.

4.10 Differentiate between Thermophoresis and Diffusiophoresis and how each affects particle collection

4.11 Define the mass efficiency of a control devicee.

Checks on Learning

Chapter and Review Problems

Particle Collection Mechanisms

This chapter introduces the student to the ways particles separate from a gas stream, steps in Particulate Matter Control, and the calculations used to determine particle collection efficiency and the calculations permitters will use to determine particle collection efficiency.

4.1 Collection Mechanisms

There are several mechanisms that can act to cause particles to be separated from a gas stream. Which specific mechanism or combination of mechanisms acts and which particular mechanism dominates is strongly dependent on particle size.

- Gravitational settling
- Centrifugal inertial force
- Inertial impaction
- Brownian motion
- Electrostatic attraction
- Thermophoresis
- Diffusiophoresis

Each of these mechanisms applies one or more forces to a particle, such as electrostatic force or inertial force, to cause it to move to a collecting surface. If it were possible to account for all of the forces acting on a particle, then particle motion could be evaluated from:

(4-1)

$$\Sigma F = m_p a_p = m_p \frac{dv_p}{dt}$$

Where

ΣF = sum of all forces acting on the particle ($g \cdot cm/sec^2$)
m_p = mass of the particle (g)
a_p = acceleration of the particle (cm/sec^2)
v_p = velocity of the particle (cm/sec)
t = time (sec)

(4-2)

$$\Sigma F = \frac{m_p a_p}{g_c}$$

Where

ΣF = sum of all forces acting on the particle (lb_f)
m_p = mass of the particle (lb_m)
a_p = acceleration of the particle (ft/sec^2)

$$g_c = 32.2 \; {lb_m ft}/{lb_f sec^2}$$

Where

g_c = gravitational constant

As indicated, this form is used in the English system, where g_c is needed to convert pounds of mass to pounds of force.

4.2 Steps in Particulate Matter Control

Three fundamental steps are involved in the collection of particulate matter in high efficiency particulate control systems, such as fabric filters and electrostatic precipitators.

- Initial capture of particles on surfaces
- Gravity settling of solids into the hopper
- Removal of solids from the hopper

The particle collection mechanisms described in this section control the effectiveness of the first two steps: initial capture of the incoming particles and gravity settling of the collected solids. Particle size distribution is important in each of these steps. As indicated in the following examples, there are significant differences in the particle size ranges involved.

A pulse jet fabric filter uses inertial impaction, Brownian motion and electrostatic attraction to capture particles in the size range of 100 μ.m to less than 0.01 μm onto the dust layers present on the exterior surfaces of the bags. At regular intervals, the bag cleaning cycle is activated. Large chunks of dust cake are dislodged from the bag surface and fall into the hopper. These agglomerated chunks of solids are usually in the

range of 10,000 to 50,000 micrometers (1.0 cm to 5.0 cm). Due to their relatively large size, they fall rapidly into the hopper. However, if the bag compartment is cleaned improperly, the solids can be dislodged in very small agglomerates that might settle too slowly. Proper gravity settling of the solids, Step 2 of particle collection, is crucial to the proper operation of the fabric filter.

In electrostatic precipitators, the dust is deposited on collection plates by electrostatic forces. The initial capture of particles is efficient over the entire size range of 0.1 μm to 100 μm. The particulate matter that accumulates on these collection plates must be discharged to the hoppers below during routine intervals. The cleaning systems in precipitators create disturbances that break off layers or clumps of accumulated solids that fall by gravity into the hopper. As the solids fall downward, they are swept toward the outlet of the precipitator by the horizontally moving gas stream. If the solids clumps are too small, gravity settling is too slow to allow the solids to reach the hopper before the gas stream carries them out of the collector. For this reason, gravity settling is an important second step in particulate matter control in electrostatic precipitators.

The performance of air pollution control equipment is dependent on all three of these steps. Inertial impaction, Brownian motion and electrostatic attraction primarily control the effectiveness of initial capture. Gravity settling is responsible for settling of large clunks of solids during Step 2.

4.3 Gravitational Settling

To determine the extent to which a particle or agglomerated solid clumps can be collected by gravitational settling, it is necessary to calculate the forces exerted on the material. These forces are the *gravitational force*, F_G, *buoyant force*, F_B, and the *drag force*, F_D.

Gravitational Force

The gravitational force F_G, which causes the particles and masses to fall, can be expressed:

(4-3)

$$F_G = m_p g = p_p V_p g$$

Where

F_G = force of gravity (g · cm/sec^2)
m_p = mass of the particle (g)
g = acceleration of particle due to gravity (980 cm/sec^2)
ρ_p = density of the particle (g/cm^3)
V_p = volume of the particle (cm^3)

To simplify calculations, particles are assumed to be spheres. Accordingly, the volume

of the particle is:

(4-4)

$$V_p = \frac{\pi d_p^{\ 3}}{6}$$

Where

d_p = physical diameter of the particle (cm)

Substituting Equation 4-4 into Equation 4-3 gives:

(4-5)

$$F_G = \frac{\pi d_p^{\ 3} p_p g}{6}$$

Buoyant Force

Acting to resist the downward force of gravity is the upward force of buoyancy. This force occurs because of the gas displaced by the particle and is given by:

(4-6)

$$F_B = m_g g = p_p V_p g$$

Where

F_B= force of buoyancy (g · cm/sec^2)
m_g = mass of the displaced gas (g)
g = acceleration of particle due to gravity (980 cm/sec^2)
ρ_g = density of the gas(g/cm^3)
V_p = volume of the particle (cm^3)

The force of buoyancy depends on the gas density

Gravitational force depends on particle density

Substituting Equation 4-4 into Equation 4-6 gives:
(4-7)

$$F_B = \frac{\pi d_g^{\ 3} p_g g}{6}$$

The force of buoyancy depends on the gas density, which is on the order of 10^{-2} lb_m/ft^3, while the gravitational force depends on the particle density, which is on the order of 10^2 lb_m/ft^3. Accordingly, the buoyant force is comparatively small and can be neglected.

Drag Force

As the particle begins to move downward as a result of the force of gravity, it encounters a resistive force that increases as the downward velocity increases (see Figure 4-1). This force is called the drag force:

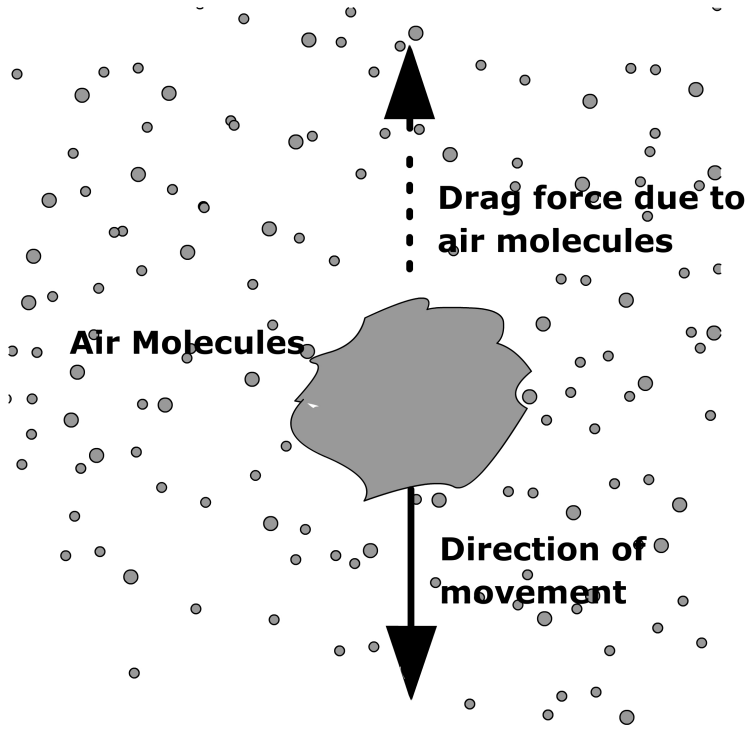

Figure 4-1. Drag force on a particle

(4-8)

$$F_D = \frac{A_p p_p V_p^2 C_D}{2} = \frac{\pi d_p^2 p_g v_p^2 C_D}{8}$$

Where

F_D = force of drag ($g \cdot cm/sec^2$)

A_p = cross-sectional area of the particle (cm^2) = $\frac{\pi d_p^2}{4}$

ρ_g = density of the gas(g/cm^3)
v_p = velocity of the particle (cm/sec)
C_D = drag coefficient (dimensionless)

The three identified flow regions: laminar, transition, and turbulent are all related to the Reynolds number

When a particle moves through a gas, it displaces the gas immediately in front of it, imparting momentum to the gas. The drag force produced is equal to the momentum per unit time imparted to the gas by the particle. A portion of the particle's velocity, v_p, is transferred by momentum to the gas as gas velocity, v_g. The amount of energy imparted from v_p to v_g is related to a friction factor which is called the drag coefficient, C_D.

Drag Coefficient

The value of C_D is related to the velocity of the particle and the flow pattern of the gas around the particle. The particle Reynolds number discussed in Chapter 1 is used as an

indicator of this flow pattern:
(4-9)

$$Re_p = \frac{d_p v_p p_g}{\mu_g}$$

Where

Re_p = particle Reynolds number (dimensionless)
d_p = particle diameter (cm)
v_p = particle velocity relative to the gas (cm/sec)
ρ_g = gas density (g/cm^3)
μ_g = gas viscosity (g/(cm · sec)

Low Reynolds numbers indicate laminar (smooth flow)

High Reynolds numbers indicated turbulent (erratic flow like white caps on the water)

From experimentation, it has been observed that three particle flow regions exist: laminar (sometimes termed *Stokes*), transition, and turbulent (sometimes termed *Newton*). These regions are related to the particle Reynolds number, as shown in Figure 4-2.

For low values of the particle Reynolds number (Re_p<l), the flow is considered laminar. Laminar flow is defined as flow in which the fluid moves in layers smoothly over an adjacent particle surface. For much higher values of the particle Reynolds number (Re_p>1,000), the flow is turbulent. Turbulent flow is characterized by erratic motion of fluid, with a violent interchange of momentum throughout the fluid near the particle surface. For particle Reynolds numbers between 1 and 1,000, the flow is said to be in the transition region, where the flow can be either laminar or turbulent, depending on local conditions. In most air pollution control applications, particles less than 100 μm are in the laminar flow region. Transition and turbulent flow conditions are relevant primarily to the gravity settling of large agglomerates in fabric filters and electrostatic precipitators.

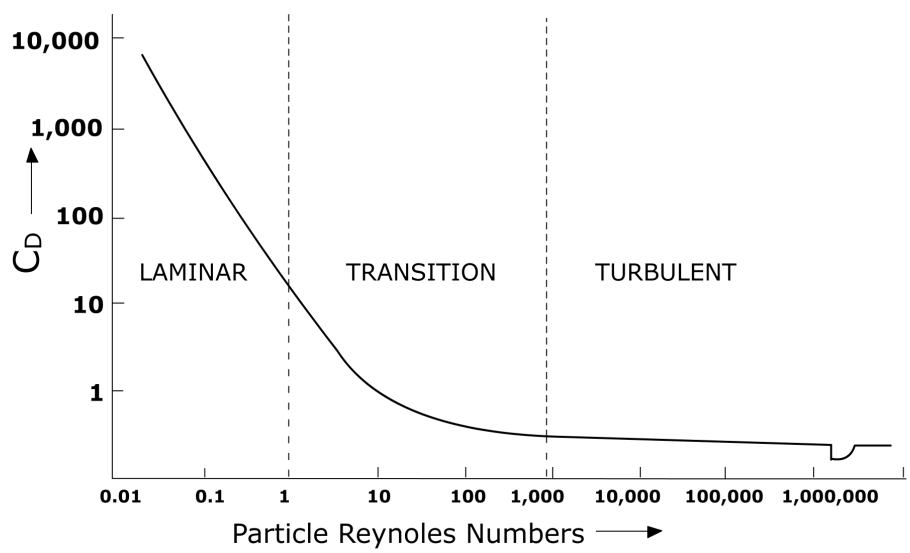

Figure 4-2. Relationship between C_D and Re_p for spheres

Mathematical expressions relating the values of C_D and Re_p can be derived from the data illustrated in Figure 4-2. Equations for determining C_D in each flow region are as follows:

(4-10)

$$\text{Laminar } (Re_p < 1) \qquad C_D = \frac{24}{Re_p}$$

(4-11)

$$\text{Transition } (1 < Re_p < 1{,}000) \qquad C_D = \frac{18.5}{Re_p^{0.6}}$$

(4-12)

$$\text{Turbulent } (Re_p > 1{,}000) \qquad C_D = 0.44$$

Cunningham Slip Correction Factor

If the size of the particle is greater than approximately 3 μm in diameter, the gas appears continuous around the particle, and mathematical relationships developed for continuous media, like those above, are applicable. However, if the particles are smaller than 3 μm in diameter, the gas appears as individual molecules. These small particles are able to slip between the gas molecules and fall faster than relationships developed for continuous media predict. To correct for this, Cunningham deduced that the drag coefficient should be reduced for small particles. Thus, the drag coefficient equation for the laminar region is modified to include a term called the *Cunningham slip correction factor*, C_c.

(4-13)

$$C_D = \frac{24}{Re_p C_C}$$

The Cunningham slip correction factor can be estimated from:

(4-14)

$$C_D = 1 + \frac{6.21 \text{x} 10^{-4} T}{d_p}$$

Where

T = absolute temperature (K)

d_p = particle diameter (μm)

Figure 4-3 illustrates the effect of particle size and gas stream temperature on the Cunningham slip correction factor.

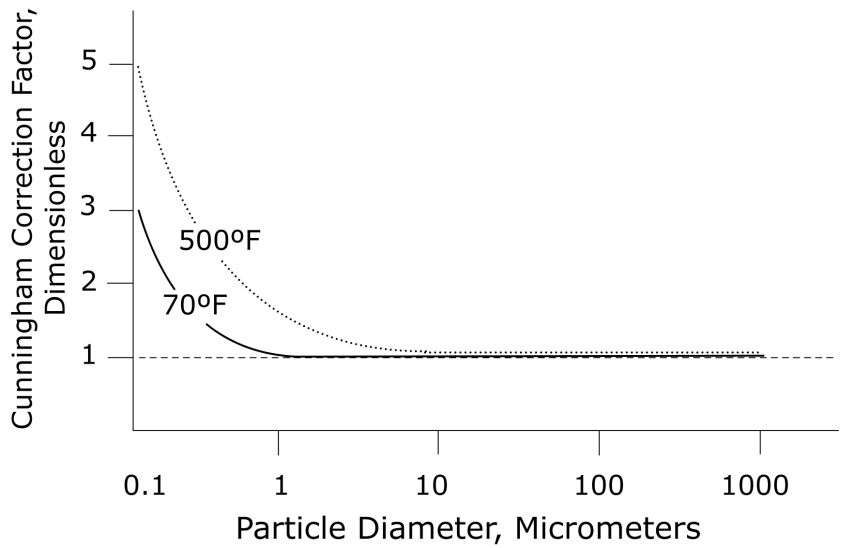

Figure 4-3. Cunningham correction as a function of particle size and gas temperature

Calculation of Drag Force

The drag force for each region can now be calculated by substituting Equation 4-13, 4-11 or 4-12 into Equation 4-8:

(4-15)

$$\text{Laminar} \quad (Re_p < 1) \qquad F_D = \frac{3\pi\mu_g v_p d_p}{C_C}$$

(4-16)

$$\text{Transition} \quad (1 < Re_p < 1{,}000) \qquad F_D = 2.30 \quad (d_p v_p)^{1.4} \mu_g^{0.6} p_g^{0.4}$$

(4-17)

$$\text{Turbulent } (Re_p > 1{,}000) \quad F_D = 0.05\pi(d_p v_p)^2 p_g$$

Where

μ_g = gas viscosity (g/(cm · sec)
d_p = particle diameter (cm)
ρ_g = gas density (g/cm^3)
v_p = particle velocity relative to the gas (cm/sec)
C_c = Cunningham slip correction factor (dimensionless)

4.4 Terminal Settling Velocity

Recall Equation 4-1 and refer to Figure 4-4:

(4-18)

$$\Sigma F = F_G - F_D = m_p a_p = m_p \frac{dv_p}{dt}$$

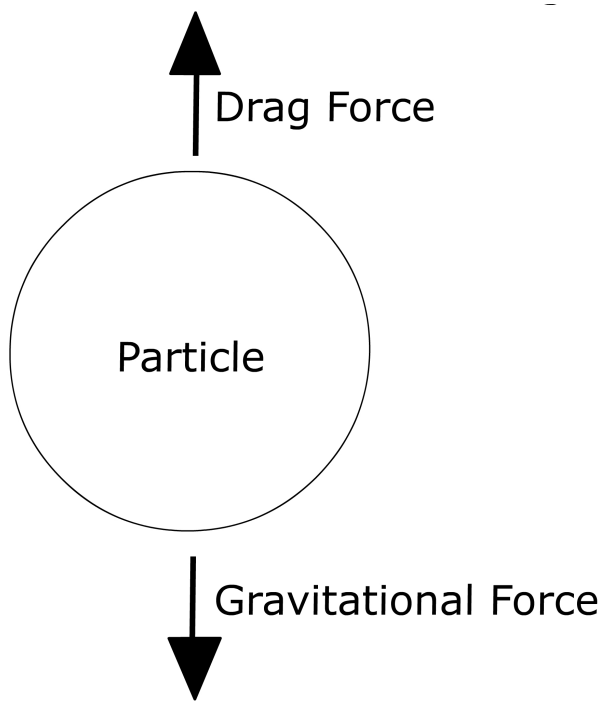

Figure 4-4. Gravitational and drag forces

Note that the buoyant force has been neglected. As the particle accelerates, the velocity will increase. The drag force on the particle also increases with increasing velocity. At some point, a velocity value will be reached where the drag force will be as large as the gravitational force. At this point, the net force will be zero, and the particle will no longer accelerate. This constant velocity, where all the forces balance, is called the *terminal settling velocity*. At the terminal settling velocity:

(4-19)

$$F_G - F_D = 0$$

(4-20)

$$\text{Laminar}\,(Re_p < 1) \quad v_t = \frac{g C_C p_p d_p^{\,2}}{18\mu_g}$$

Terminal settling velocity equations for each region are derived by substituting Equation 4-5 and Equation 4-14, 4-16 or 4-17, as appropriate, into Equation 4-19 and solving for particle velocity:

(4-21)

$$\text{Tansition}\ (1 < Re_p < 1{,}000) \quad v_t = \frac{0.153 g^{0.71} \rho_p^{0.71} d_p^{1.14}}{\mu_g^{0.43} \rho_g^{0.29}}$$

(4-22)

$$\text{Turbulent}\ (Re_p > 1{,}000) \quad v_t = 1.74 \left(\frac{g \rho_p d_p}{\rho_g} \right)^{0.5}$$

Where

v_t = terminal settling velocity (cm/sec)
g = acceleration of particle due to gravity (980 cm/sec^2)
C_c = Cunningham slip correction factor (dimensionless)
ρ_p = particle density (g/cm^3)
μ_g = gas viscosity (g/(cm · sec)
d_p = physical particle diameter (cm)
ρ_g = gas density (g/cm^3)

An ideal measuring instrument would measure size composition and real-time response.

4.5 Determination of Flow Region

In order to determine the settling velocity of a particle, the flow region must be known so that the appropriate terminal settling velocity equation can be selected. However, in order to determine the flow region, the particle Reynolds number must be calculated and this requires knowledge of the particle velocity we are trying to determine. The following equation allows the flow region to be determined without first determining the particle Reynolds number:

(4-23)

$$K = d_p \left(\frac{g \rho_p \rho_g}{\mu_g^2} \right)^{0.33}$$

Where

g = acceleration of particle due to gravity (980 cm/sec^2)
ρ_p = particle density (g/cm^3)
μ_g = gas viscosity (g/(cm · sec))
d_p = physical particle diameter (cm)
ρ_g = gas density (g/cm^3)

Values of K correspond to the different flow regions, as shown in Table 4-1. Once the flow region has been determined, the appropriate equation can be used to calculate the settling velocity of the particle.

Table 4-1. K Values for Flow Region	
Laminar region	K<2.62
Transitional region	2.62<K<69.12
Turbulent region	K>69.12

Example 4-1 Calculate the terminal settling velocity in 20°C air of a 45 μm diameter particle with a density of 1 g/cm^3.

Solution:

Calculate K to determine the flow region:

$$K = d_p\left(\frac{g\rho_p\rho_g}{\mu_g^{\,2}}\right)^{0.33} = 45\text{x}10^{-4}\,\text{cm}\left[\frac{\left(980\,\text{cm}/\text{sec}^2\right)\left(1.0\,\text{g}/\text{cm}^3\right)\left(1.20\text{x}10^{-3}\,\text{g}/\text{cm}^3\right)}{\left(1.80\text{x}10^{-4}\,\text{g}/\text{cm}\cdot\text{sec}\right)^2}\right]^{0.33}$$

$K = 1.41$ or laminar

Assume $C_C = 1.0$

$$v_t = \frac{gC_C\rho_p d_p^{\,2}}{18\mu_g} = \frac{\left(980\,\text{cm}/\text{sec}^2\right)\left(1.0\,\text{g}/\text{cm}^3\right)\left(45\text{x}10^{-4\text{cm}}\right)^2}{\left(1.80\text{x}10^{-4}\,\text{g}/\text{cm}\cdot\text{sec}\right)^2} = 6.13\,\text{cm}/\text{sec}$$

Example 4-2 Calculate the terminal settling velocity in 20°C air of a 2 μm diameter particle with a density of 1 g/cm^3.

Solution:

Calculate K to determine the flow region :

$$K = d_p \left(\frac{g \rho_p \rho_g}{\mu_g^2} \right)^{0.33}$$

$$= 2x10^{-4}\,cm \left[\frac{\left(980\ cm/sec^2\right)\left(1.0\ g/cm^3\right)\left(1.20x10^{-3}\ g/cm^3\right)}{\left(1.80x10^{-4}\ g/cm \cdot sec\right)^2} \right]^{0.33}$$

$K = 0.06$ or laminar

$$C_C = 1 + \frac{6.21\,x10^{-4}\,T}{d_p} = 1 + \frac{6.21\,x10^{-4}\,(293\ K)}{2\,\mu m} = 1.09$$

Calculate the terminal settling velocity :

$$v_t = \frac{gC_C \rho_p d_p^2}{18\,\mu_g} = \frac{\left(980\ cm/sec^2\right)(1.09)\left(1.0\ g/cm^3\right)\left(2x10^{-4cm}\right)^2}{18\left(1.80x10^{-4}\ g/cm \cdot sec\right)^2}$$

$$= 0.013\ cm/sec$$

Summary

Equations 4-20, 4-21 and 4-22 have been used to calculate the terminal settling velocities of particles from 0.1 μm to 100,000 μm. These data (see Table 4-2) demonstrate that the terminal settling velocities are virtually negligible for particles less than 10 μm, moderate for particles in the size range of 10-80 μm, and relatively fast only for particles larger than 80 μm.

It is for this reason that air pollution control devices that employ only gravitational settling to accomplish initial separation are limited to pre-cleaners that are designed to reduce the large-particle fraction before entering fans or the primary control device. In most systems, gravity settling is employed only for the removal of large agglomerated masses or clumps of dust (1,000 to 100,000 micrometers) that have been collected on bags, precipitator plates, or other collection surfaces. These large clumps of material have high terminal settling velocities.

Table 4-2. Terminal Settling Velocities of Unit Density Spheres at 25°C		
Particle Size (µm)	**Terminal Settling Velocity at 25°C (cm/sec)**	**Flow Condition**
0.1	0.000087	Laminar
1.0	0.0035	Laminar
10.0	0.304	Laminar
50.0	7.5	Laminar
80.0	19.3	Laminar
100.0	31.2	Transitional
200.0	68.8	Transitional
1,000.0	430.7	Transitional
10,000.0	1,583	Turbulent
100,000.0	5,004	Turbulent

4.6 Centrifugal Inertial Force

Inertial force can be an effective collection mechanism when a particulate-laden gas stream is made to flow in a circular manner within a cylinder, as shown in Figure 4-5. Inertial force that is applied in a spinning gas stream is often termed *centrifugal force*.

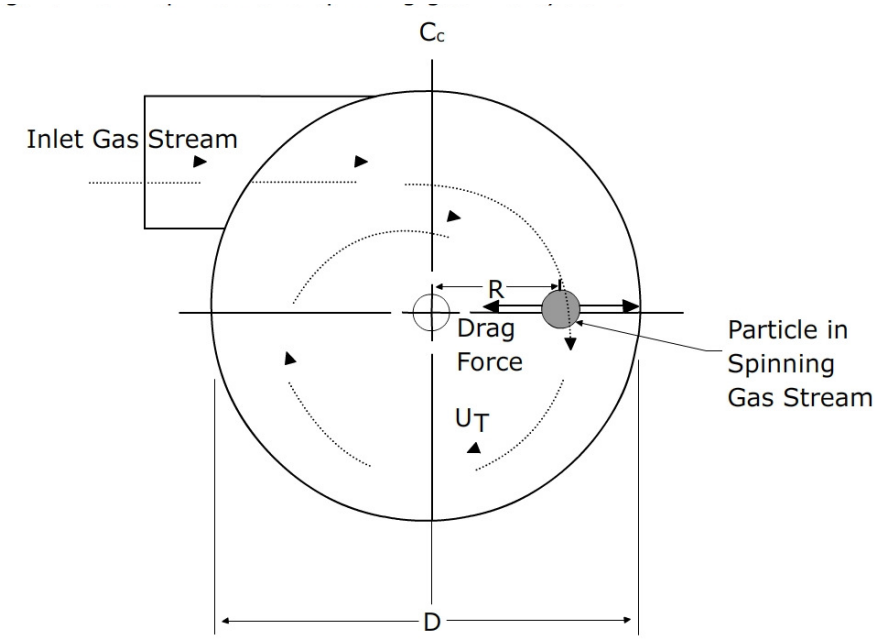

Figure 4-5. Top view of spinning gas in a cyclone

The movement of particles due to inertial force in a spinning gas stream is estimated using the same procedure described for terminal settling velocity due to gravitational force. Accordingly:

(4-24)

$$F_C - F_D = 0$$

The equation for centrifugal force is:

(4-25)

$$F_C = \frac{m_p u_T^2}{R}$$

Where

F_C = centrifugal force (g · cm /sec^2)
m_p = mass of the particle (g)
u_T = tangential velocity of the gas (cm/sec)
R = radial position of the particle (cm)

Note that for centrifugal force, the term "u_T^2/R' is similar to the gravitation force term "g" used in the discussion of gravitational settling.

Expressing the mass of the particle (m_p) in Equation 4-25 in terms of the particle density and the particle volume (see Equations 4-3 and 4-4) yields the following equation:

(4-26)

$$FC = \frac{\Pi d_p^3 \rho_p u_T^2}{6R}$$

Where

d_p = physical particle diameter (cm)
ρ_p = particle density (g/cm^3)

For small particles that have particle Reynolds numbers in the laminar range, the drag force is (see Equation 4-15):

(4-27)

$$F_D = \frac{3\pi\pi_g v_p d_p}{C_C}$$

The velocity of the particle radially across the gas streamlines and toward the wall of the cyclonic chamber is then given by substituting Equations 4-26 and 4-27 into Equation 4-24 and solving for particle velocity:

(4-28)

$$v_p = \frac{C_C d_p^{\,2} \rho_p u_T^{\,2}}{18 \mu_g R}$$

Where

V_p = radial particle velocity (cm/sec) (g · cm /sec^2)
C_c = Cunningham slip correction factor (dimensionless)
ρ_p = particle density (g/cm^3)
μ_g = gas viscosity (g/(cm · sec))
d_p = physical particle diameter (cm)
u_T = tangential velocity of the gas (cm/sec)
R = radial position of particle (cm)

This equation illustrates that the velocity of the particle moving across the gas stream lines in the cyclone and toward the cyclone wall is proportional to the square of the particle size. This means that cyclones will be substantially more effective for large particles than for small particles. At any given particle size, the particle radial velocity will be proportional to the square of the gas stream tangential velocity and inversely proportional to the cyclone radius. These two parameters determine the extent to which the gas stream is spinning within the cyclone. High velocities increase the spinning action and therefore increase particle radial velocity and particle collection. A small cyclone radius makes the gas stream turn more sharply and therefore also increases cyclone efficiency.

4.7 Inertial Impaction

The inertia of a particle in motion in a gas stream can cause it to strike slow-moving or stationary obstacles in its path (see Figure 4-6). As the gas stream deflects to flow around the obstacle, the particle, because of its inertia, is displaced across the gas streamlines and toward the direction of the target. If it has sufficient inertia, the particle contacts the obstacle and is captured.

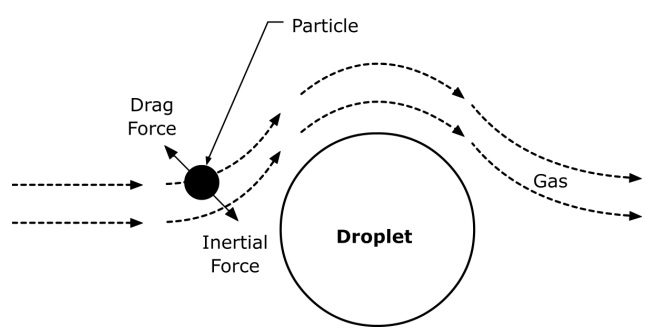

Figure 4-6. Inertial impaction

The efficiency of impaction can be evaluated using the same general procedures used

to evaluate gravitational settling and centrifugal force. For particles having a Reynolds number less than 1 (drag force Equation 4-15), the effectiveness of impaction can be related to the inertial impaction parameter shown in Equation 4-29. As the value of this parameter increases, particles have a greater tendency to move radially toward the collection target. As the value of the parameter approaches zero, the particles have a tendency to remain on the gas streamlines and pass around the target.

(4-29)

$$\Psi_I = \frac{C_C d_p^{\,2} y_p \rho_p}{18 \mu_g D_C}$$

Where

Ψ_I = inertial impaction parameter (dimensionless)

C_c = Cunningham slip correction factor (dimensionless)

d_p = physical particle diameter (cm)

y_p = difference in velocity between the particle and the target (cm/sec)

D_c = diameter of collection target (cm)

ρ_p = particle density (g/cm^3)

μ_g = gas viscosity (g/(cm · sec)

Note that, in some texts, the inertial impaction parameter is termed the Stokes number and sometimes has a value that is twice that shown in Equation 4-29.

The inertial impaction parameter indicates that collection efficiency by impaction will be greatest when the particle size is large, the relative velocity is high and the collection target is small.

4.8 Brownian Motion

Brownian motion (diffusion) is only important for particles less that 0.3 μm

Particle Diffusion is not a major player in air pollution control systems

Very small particles (0.2 μm to 0.002 μm) deflect slightly when they are struck by gas molecules. The deflection is caused by the transfer of kinetic energy from the rapidly moving gas molecule to the small particle. An exaggerated illustration of this motion is shown in Figure 4-7.

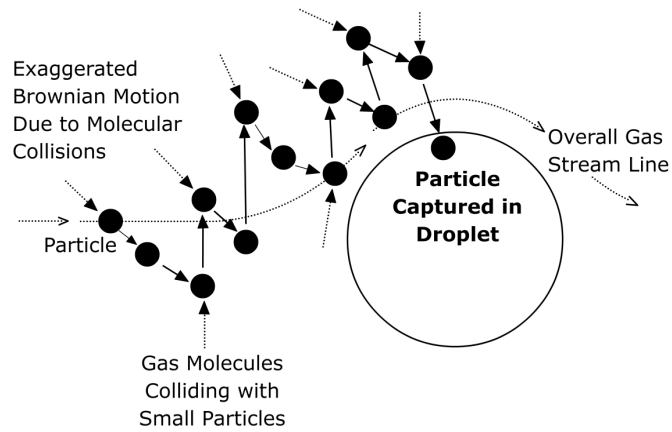

Figure 4-7. Brownian motion

The effectiveness of Brownian motion can be related to the diffusional collection parameter given in Equation 4-30. As the value of this parameter increases, particles have an increasing tendency to be collected by Brownian motion.

(4-30)

$$\Psi_D = \frac{\mathscr{D}_p}{D_c v_p}$$

Where

ψ_D = diffusional collection parameter (dimensionless)
$\mathscr{D}_p$ = particle diffusivity (cm^2/sec)
D_c = diameter of collection target (cm)
v_p = relative velocity between particle and collection target (cm/sec)

Particle diffusivity is given by:

(4-31)

$$\mathscr{D}_p = \frac{C_c kT}{3\pi\pi_g d_p}$$

Where

$\mathscr{D}_p$ = Particle diffusivity
k = Boltzmann constant ($g \cdot cm^2/sec^2 . K$)
T = absolute temperature (K)
C_c = Cunningham slip correction factor (dimensionless)
μ_g = gas viscosity (g/cm .sec)
d_p = physical particle diameter (cm)

Substituting Equation 4-31 into Equation 4-30 gives:

(4-32)

$$\Psi_D = \frac{C_C kT}{3\pi\pi_g d_p D_C v_r}$$

The diffusional collection parameter indicates that collection efficiency by diffusion will be greatest when the particle size is small, the relative velocity is low and the collection target is small.

Field charging becomes less important as particle size decreases.

Diffusion charging becomes more important as particle size decreases.

Brownian motion or diffusion is important only for particles less than about 0.3 μm and is responsible for the slight increase in the observed collection efficiencies of air pollution control devices in this size range. However, diffusion rates are low even for particles in the 0.3 to 0.01 μm size range. Accordingly, particle diffusion is not significant in the majority of air pollution control systems.

4.9 Electrostatic Attraction

The following two particle charging mechanisms are active in air pollution control devices used to collect particulate matter:

- Diffusion charging
- Field charging

Field charging is the dominant charging mechanism for particles larger than 2 μm. It becomes progressively less important as the particle size decreases. Conversely, diffusion charging is more effective on particles smaller than 0.4 μm, and it becomes progressively more important as particle size decreases.

Diffusion or ion charging is the result of the collisions of unipolar ions with particles in a gas stream. These collisions are caused by the random Brownian motion of both the ions and the particles. Diffusion charging continues until electrical charges on the surface of the particle are sufficiently strong to repel approaching ions. The number of electrical charges that accumulate on the surface of a particle due to this mechanism is given by:

(4-33)

$$d_d = \frac{d_p kT}{2e^2} \ln\left(1 + \frac{\pi d_p c_i e^2 N_i t}{2kT}\right)$$

Where

n_d = number of charges deposited by diffusion charging
d_p = particle diameter (cm)
k = Boltzmann constant ($k = 1.4 \times 10^{-16} g \cdot cm^2/sec^2 \cdot K$)
T = absolute temperature (K)
c_i = ion velocity ($c_i = 2.4 \times 10^4$ cm/sec)

e = charge of an electron ($e = 4.8 \times 10^{-10}$statcoulomb)
t = time (sec)
N_i = ion concentration (number/cm^3)

Diffusion charging does not require an electrical field. However, particles that acquire an electrical charge will be influenced by any field that exists. These particles will move along the electrical field lines to an area of lower field strength (e.g., a collection surface).

Field charging occurs when particles placed in a strong electrical field with a high concentration of unipolar ions have sufficient mass to locally disrupt the field lines. The ions move to the particle surface along electric field lines that intersect the particle. The transfer of electrical charge continues until the field strength of the particle is sufficient to repel the electrical field. This point is termed the *saturation charge*. The number of electrical charges that accumulate on the surface of a particle at saturation charge is given by:

(4-34)

$$n_f = \left(\frac{3\varepsilon}{\varepsilon + 2}\right)\left(\frac{Ed_p^{\,2}}{4e}\right)$$

Where

n_f = number of charges deposited by field charging
d_p = particle diameter (cm)
ε = dielectric constant of the particle (dimensionless)
e = charge of electron ($e=4.8 \times 10^{-10}$ statcoulomb)
E = electrical field strength (statvolts/cm)

Equation 4-34 indicates that the number of charges placed on a particle due to field charging is related to the square of the particle diameter. This level of charge is achieved extremely quickly. Once charged, the particles will be influenced by the electrical field, developing a force directed toward the collection surface.

The charge on a particle is usually expressed as the number of charges, n, times the smallest unit of charge, the charge on an electron, e (4.8×10^{-10} statcoulombs). The force on a particle with n units of charge in an electrical field, E, is given by:

(4-35)

$$F_E = neE$$

Where

F_E = electrostatic force (dyne)
n = number of charges
e = charge of electron ($e=4.8 \times 10^{-10}$ statcoulomb)
E = electrical field strength (statvolts/cm)

The forces created in an electric field can be thousands of times greater than gravity. The velocity with which particles in the electric field migrate can be determined in a manner similar to that shown for gravity settling and centrifugal force:

(4-36)

$$F_E - F_D = 0$$

(4-37)

$$neE - \frac{3\pi\mu_g d_p v_p}{C_C} = 0$$

(4-38)

$$vp = \omega = \frac{neEC_C}{3\pi\mu_g d_p v_p}$$

The particle velocity toward the collecting service, is called the *migration velocity* or *drift velocity*. This relationship applies to particles in the laminar region. When Re_p>1.0, a more complicated procedure is required.

Example 4-3 Determine the migration velocity of a 2 μm unit-density particle carrying 800 units of charge in an electric field of 2kV/cm. Assume that the gas temperature is 20°C:

Solution To solve this problem, the following relationships are used:

300 volts = 1 statvolt
1 statvolt = 1 statcoulomb/cm
1 dyne = 1 statcoulomb^2/cm^2 = 1 g·cm/sec^2
C_C = 1.09 (as calculated in Example 4-2)

The electric field in centimeter-gram-second units is:

$$E = 2\frac{kV}{cm} = 2{,}000\ \frac{v}{cm}\left(\frac{statvolt}{300\ volts}\right) = 6.67\ \frac{statvolts}{cm} = 6.67\ \frac{statcoulom\ \ bs}{cm^2}$$

$$\omega = \frac{neEC_C}{3\pi\mu_g d_p} = \frac{(800)(4.8x10^{-10}\ statcoulom\ \ bs)\left(6.67\ \frac{statcoulom\ \ bs}{cm^2}\right)(1.09)}{3\pi\left(1.8x10^{-4}\ g/cm\cdot\sec\right)(2x10^{04}\ cm)} = 8.23\ cm/\sec$$

It is apparent that the *migration* velocity for the 2 μm particle is substantially greater than the *settling* velocity for the same size particle. This is due to the much greater force imposed by the electrostatic field.

4.10 Thermophoresis and Diffusiophoresis

Thermophoresis and diffusiophoresis are two relatively weak forces that can affect collection of submicrometer particles. Thermophoresis is particle movement caused by temperature differences on opposite sides of the particle. The gas molecule kinetic energies on the hot side of the particle are higher than they are on the cold side. Therefore, collisions with the particle on the hot side transfer more energy than molecular collisions on the cold side. Accordingly, the particle is deflected toward the cold area.

Diffusiophoresis is particle movement caused by concentration differences on opposite sides of the particle. When there is a strong difference in the concentration of molecules on opposite sides of the particle, there is a difference in the number of molecular collisions. The particle moves toward the area of lower concentration.

Phoretic forces can be important when the evaporation or condensation of water is involved, since these conditions create substantial temperature and concentration gradients. The normal differences in gas stream temperature and concentration are not sufficient to cause significant particle movement.

4.11 Particle Size-Collection Efficiency Relationships

Due to the combined action of the various collection mechanisms described in the previous sections, the performance of particulate control devices often has the particle size-efficiency relationship form shown in Figure 4-8. Above 100 μm, particles are collected with very high efficiency by inertial impaction, electrostatic attraction, and even gravitational settling. Efficiency remains high throughout the range of 10-100 μm due to high inertial or electrostatic forces (depending on the type of collector), both of which are proportional to the square of the particle diameter. For particles less than 10 μm, the limits of inertial forces and electrostatic forces begin to become apparent, and the efficiency drops. Efficiency of these collection mechanisms reaches low levels between 1 μm and 0.1 μm, depending on such factors as gas velocities (inertial forces) and electrical field strengths (electrostatic attraction). Below 0.3 μm, Brownian motion begins to become effective. Accordingly, the overall efficiency curve begins to rise in the very small size range.

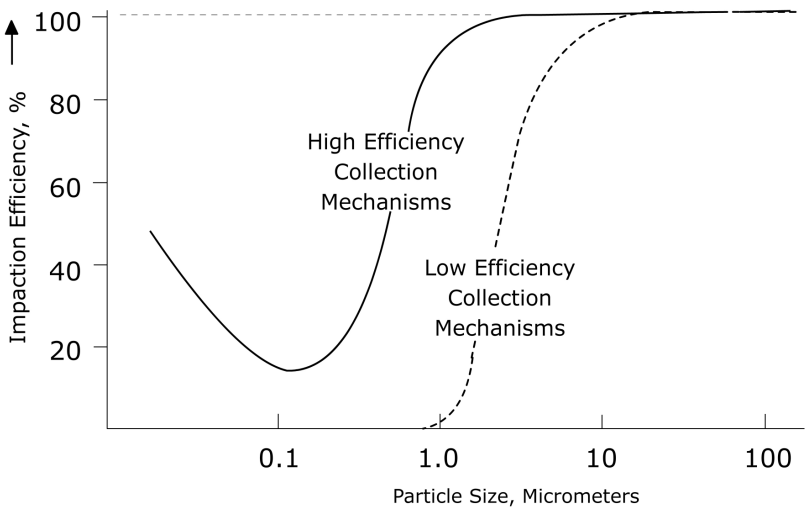

Figure 4-8. General relationship between collection efficiency and particle size

The combined result of these various collection mechanisms is a minimum collection efficiency in the particle size range of 0.1 μm to 0.5 μm. Collection mechanisms in many devices are not highly efficient for particles in this range. These particles can be classified as difficult-to-control due to the inherent limitations of the collection mechanisms. Sources generating high concentrations of particles in the 0.1 μm to 0.3 μm size range may be an especially challenging control problem.

The actual extent of this dip in particulate control capability varies substantially among the types of particulate control systems. The dip is most noticeable in wet scrubbers and electrostatic precipitators. Fabric filters generally have a minimal decrease in overall efficiency in this range due to the multiple-collection mechanisms inherently present. Cyclonic collectors generally are inefficient for particles less than 1 to 3 μm (low efficiency mechanism curve).

Operators of stationary sources that generate large fractions of the total particulate matter in the 0.1 to 0.3 μm range may need to modify the process to alter the particle size distribution or use a pretreatment system to *grow* the particles to a more easily collected size range. These options are discussed in Chapter 8.

Review Questions

1. What is the main role of gravity settling in high efficiency particulate control systems?
   a. Initial capture of particles in the gas stream being treated
   b. Collection of solids dislodged during the cleaning cycle
   c. Minimization of the particulate matter in the gas stream prior to the inlet of the particulate matter control device.
   d. None of the above.

2. How is the collection efficiency of a cyclonic collector related to the particle size?
   a. It increases proportional to the cube of the particle diameter.
   b. It increases proportional to the square of the particle diameter.
   c. It increases proportional to the particle diameter.
   d. It is independent of the particle diameter.

3. How is the collection efficiency of an air pollution control device using inertial impaction (e.g., particulate wet scrubber) related to the particle size?
   a. It increases proportional to the cube of the particle diameter.
   b. It increases proportional to the square of the particle diameter.
   c. It increases proportional to the particle diameter.
   d. It is independent of the particle diameter.

4. How does the effectiveness of Brownian motion relate to the particle size?
   a. It increases proportional to the cube of the particle diameter.
   b. It increases proportional to the square of the particle diameter.
   c. It increases proportional to the inverse of the particle diameter.
   d. It increases proportional to the inverse of the square of the particle diameter.

Review Question Answers

1. What is the main role of gravity settling in high efficiency particulate control systems?
b. Collection of solids dislodged during the cleaning cycle

2. How is the collection efficiency of a cyclonic collector related to the particle size?
b. It increases proportional to the square of the particle diameter.

3. How is the collection efficiency of an air pollution control device using inertial impaction (e.g., particulate wet scrubber) related to the particle size?
b. It increases proportional to the square of the particle diameter.

4. How does the effectiveness of Brownian motion relate to the particle size?
c. It increases proportional to the inverse of the particle diameter.

Review Problems

1. Calculate the terminal settling velocities in 20°C air of spherical particles having the following physical diameters and a density of 1 g/cm^3.

a. 1 μm

b. 10 μm

c. 100 μm

Review Problem Solutions

Solution for part a.

Calculate K to determine the flow region:

$$K = d_p\left(\frac{g\rho_p\rho_g}{\mu^2}\right)^{0.33} = 1x10^{-4}cm\left[\frac{\left(980\,{}^{cm}\!/_{\sec^2}\right)\left(1.0\,{}^{g}\!/_{\sec^3}\right)\left(1.20x10^{-3}\,{}^{g}\!/_{\sec^3}\right)}{\left(1.80x10^{-4}\,{}^{g}\!/_{cm\cdot\sec}\right)^2}\right]^{0.33}$$

$$= 0.03 \;\; \textit{Therefore, the flow region is laminar.}$$

$$\textit{Calculate the Cunningham slip correction factor:}$$

$$C_C = 1 + \frac{6.21x10^{-4}T}{d_p} = 1 + \frac{6.21x10^{-4}(293K)}{1\mu m} = 1.18$$

$$\textit{Calculate the terminal settling velocity:}$$

$$v_t = \frac{\left(980\,{}^{cm}\!/_{\sec^2}\right)(1.18)\left(1.0\,{}^{g}\!/_{\sec^3}\right)\left(1x10^{-4}cm\right)^2}{18\left(1.80x10^{-4}\,{}^{g}\!/_{cm\cdot\sec}\right)^2} = 0.0036\,{}^{cm}\!/_{\sec}$$

Solution for part b.

Calculate K to determine the flow region:

$$K = d_p\left(\frac{g\rho_p\rho_g}{\mu^2}\right)^{0.33} = 10x10^{-4}cm\left[\frac{\left(980\,{}^{cm}\!/_{\sec^2}\right)\left(1.0\,{}^{g}\!/_{\sec^3}\right)\left(1.20x10^{-3}\,{}^{g}\!/_{\sec^3}\right)}{\left(1.80x10^{-4}\,{}^{g}\!/_{cm\cdot\sec}\right)^2}\right]^{0.33}$$

$= 0.31$ *Therefore, the flow region is la*min*ar.*

Calculate the Cunningham slip correction factor:

$$C_C = 1 + \frac{6.21x10^{-4}T}{d_p} = 1 + \frac{6.21x10^{-4}(293K)}{10\mu m} = 1.02$$

*Calculate the ter*min*al settling velocity*:

$$v_t = \frac{\left(980\,{}^{cm}\!/_{\sec^2}\right)(1.02)\left(1.0\,{}^{g}\!/_{\sec^3}\right)\left(1x10^{-4}cm\right)^2}{18\left(1.80x10^{-4}\,{}^{g}\!/_{cm\cdot\sec}\right)^2} = 0.3085\,{}^{cm}\!/_{\sec}$$

Solution for c.

Calculate K to determine the flow region:

$$K = d_p\left(\frac{g\rho_p\rho_g}{\mu^2}\right)^{0.33} = 100x10^{-4}cm\left[\frac{\left(980\,{}^{cm}\!/_{\sec^2}\right)\left(1.0\,{}^{g}\!/_{\sec^3}\right)\left(1.20x10^{-3}\,{}^{g}\!/_{\sec^3}\right)}{\left(1.80x10^{-4}\,{}^{g}\!/_{cm\cdot\sec}\right)^2}\right]^{0.33}$$

$= 3.12$ *Therefore, the flow region is transition.*

Calculate the Cunningham slip correction factor :

$$C_C = 1 + \frac{6.21x10^{-4}T}{d_p} = 1 + \frac{6.21x10^{-4}(293K)}{100\mu m} = 1.00$$

Calculate the terminal settling velocity :

$$v_t = \frac{o.153g^{0.71}\rho_p^{\ 0.71}d_p^{\ 1.14}}{\mu_g^{\ 0.43}\rho_g^{\ 0.29}} = \frac{\left(980\,{}^{cm}\!/_{\sec^2}\right)\left(1.0\,{}^{g}\!/_{\sec^3}\right)\left(100x10^{-4}cm\right)^{1.14}}{\left(1.80x10^{-4}\,{}^{g}\!/_{cm\cdot\sec}\right)^2\left(1.80x10^{-4}\,{}^{g}\!/_{cm^3}\right)^{0.29}}$$

$= 3.085\,{}^{cm}\!/_{\sec}$

References

Beachler, D.S., and J.A. Jahnke, *Control of Particulate Emissions,* APTI Course 413 Student Manual, EPA 450/2-80-066, October 1981.

Noll, K.E., *Fundamentals of Air Quality Systems,* American Academy of Environmental Engineers, 1999.