

AIR POLLUTION CONTROL – PARTICULATE MATTER

I. Objectives

The objectives of this course are to provide background information on the topic of air pollution and its control, to develop knowledge about the characteristics of particulate matter (PM), especially those characteristics that influence our choice of control systems, to discuss the various means of collecting and removing particles from the air stream (controlling PM air pollution), and to review in detail the design and operations of two major technologies for control of PM pollution – electrostatic precipitators and fabric filter baghouses.

II. Introduction

Air pollution can be defined as harmful gases or particles in the outdoor atmosphere in high enough concentrations to be injurious to human health or welfare, plants, animals or things, or unreasonably interfere with the enjoyment of life or property. Primary air pollutants (those emitted directly to the air), and secondary pollutants (those formed by reactions in the atmosphere such as ground-level ozone) are both serious problems. Some pollutants are emitted in very large quantities, including particulate matter (PM), and the gaseous pollutants: sulfur dioxide (SO₂), nitrogen oxides (NO_x), volatile organic compounds (VOCs), and carbon monoxide (CO). Table 1 gives some data on the estimated U.S. emission rates of each of these primary pollutants in 1998. All of the above pollutants except VOCs are also called criteria pollutants, because the U.S. EPA has established ambient (outdoor air) standards based on measurable health effects (the criteria for the standards).

Particulate matter (PM) is the term used to describe very small diameter solids or liquids that remain suspended in the atmosphere. PM-10 and PM-2.5 refer to particulate matter less than 10 and 2.5 micro-meters (μm) in diameter, respectively. (The symbol m means one one-millionth, and the term micron often is used in place of micro-meter; thus, one micron is equal to one one-millionth of a meter.) Particles are emitted from a variety of sources, including fossil-fuel combustion, metals and mineral processing, agricultural fields, and many others, but by far the largest category is fugitive dust from roads. Even though the industrial categories emit relatively smaller amounts of PM-10, many millions of dollars are spent each year in controlling these sources.

Air-pollution control is regulatory driven, meaning that sources must comply with regulations and standards set by federal and state agencies. Modern air pollution standards were originally mandated by Congress and established by the U.S. EPA to protect the health and promote the well-being of individuals and of communities. These standards were set by government with input from professional organizations as a result of increased awareness of pollutants and their effects upon living organisms, especially people. Federal legislation and regulations have been developed over a period of three decades with input from many interested groups. Some of these laws were the Air Pollution Control Act of 1955, the Motor Vehicle Air Pollution Control Act of 1965, the far-reaching Clean Air Act Amendments (CAAA) of 1970, the CAAA of 1977, and the comprehensive CAAA of 1990. Compliance with these laws requires not only proper environmental engineering design and operation of pollution-abatement equipment but careful analysis and accurate measurements of specified pollutants and environmental quality parameters.

Table 1. National U.S. Emissions Estimates, 1998 (10⁶ tons/yr)

<u>Source Category</u>	<u>CO</u>	<u>SO₂</u>	<u>NO_x</u>	<u>VOC</u>	<u>PM-10</u>
Sta. Sources – Fuel Comb					
Electric Utilities	0.42	13.22	6.10	0.05	0.30
Industrial Furnaces	1.11	2.90	2.97	0.16	0.25
Residential & Other	3.84	0.61	1.12	0.68	0.54
Sub-total: Fuel Comb.	5.37	16.73	10.19	0.89	1.09
Sta. Sources – Manuf.					
Chemicals & Petroleum	1.50	0.64	0.29	0.89	0.10
Metals Processing	1.50	0.44	0.09	0.08	0.17
Other Processes	0.71	0.37	0.42	7.05	0.44
Sub-total: Manuf.	3.71	1.45	0.80	8.02	0.71
Waste Disposal	1.15	0.04	0.10	0.43	0.31
Sub-total: all sta. sources	10.2	18.2	11.1	9.3	2.1
Mobile Sources					
On-Road Vehicles	50.4	0.33	7.77	5.33	0.26
Non-Road Vehicles*	19.9	1.08	5.28	2.46	0.46
Sub-total: Mobile Sources	70.3	1.41	13.0	7.8	0.72
Miscellaneous	8.9	0.01	0.33	0.79	26.6**
TOTAL ALL SOURCES	89.5	19.6	24.4	17.9	29.4

* Non-road vehicles include airplanes, boats, trains, lawn equipment, farm vehicles, construction equipment, etc.

** Note: Miscellaneous PM-10 distributed approximately as follows:

Natural sources, mostly wind erosion	1.6
Agriculture and forestry	4.4
Wildfires/managed burns	0.7
Fugitive dust: paved and unpaved roads	12.0
Other	7.9

Source: US EPA (EPA-454/R-00-003, March 2000)

There are two types of standards: *ambient air quality standards* (AAQS) that deal with concentrations of pollutants in the outdoor atmosphere, and *source performance standards* (SPS) that apply to emissions of pollutants from specific sources. AAQS are always written in terms of concentration (e.g., micrograms per cubic meter – $\mu\text{g}/\text{m}^3$, or parts per

million – ppm), while SPS are written in terms of mass emissions per unit of time or per unit of production (e.g., tons of pollutant emitted per year, or kg of pollutant per ton of product produced).

National ambient air quality standards (NAAQS) were set by the Environmental Protection Agency for the criteria pollutants at levels to protect public health. The current standards are presented in Table 2. It should be noted that some states have set their own standards, which are stricter than those listed. Note also that some pollutants have more than one standard (depending on the averaging time, or time of exposure).

Table 2. National Ambient Air Quality Standards

<u>Pollutant</u>	<u>Averaging Time</u>	<u>Primary Standard</u>
PM-10	Annual arithmetic mean	50 $\mu\text{g}/\text{m}^3$
	24-hour average	150 $\mu\text{g}/\text{m}^3$
PM-2.5	Annual arithmetic mean	15 $\mu\text{g}/\text{m}^3$
	24-hour average	65 $\mu\text{g}/\text{m}^3$
CO	1-hour average	35 ppm
	8-hour average	9 ppm
SO ₂	Annual arithmetic mean	80 $\mu\text{g}/\text{m}^3$
	24-hour average	365 $\mu\text{g}/\text{m}^3$
NO ₂	Annual arithmetic mean	0.053 ppm
O ₃	3-year average of annual 4 th highest daily 8-hour maximum	0.08 ppm

In the 1970s, EPA established health-based air quality standards for total PM, but changed the standards to PM-10 in the late 1980s, and changed them again in 1997 to PM-2.5 in recognition of the more serious health effects of smaller particles. Breathing air with PM-2.5 has several extremely adverse effects on the respiratory system; in addition PM 2.5 causes reduction in visibility (small particles scatter light very effectively). PM of all sizes contribute to other damages such as the soiling of buildings and other materials.

Table 3. Selected examples of new source performance standards (NSPS).

1. Steam electric power plants
 - a. Particulates: 0.03 lb/million Btu of heat input (13 g/million kJ).
 - b. NO_x: 0.20 lb/million Btu (86 g/million kJ) for gaseous fuel.
0.30 lb/million Btu (130 g/million kJ) for liquid fuel.
0.60 lb/million Btu (260 g/million kJ) for anthracite or bituminous coal.
 - c. SO₂: 0.20 lb/million Btu (86 g/million kJ) for gas or liquid fuel. For coal-fired plants, the SO₂ standard requires a scrubber that is at least 70% efficient and may be more than 90% efficient depending on the percent sulfur in the coal. The maximum permissible emissions rate is 1.2 lb SO₂ per million Btu of heat input.
2. Solid waste incinerators. A maximum 3 hr. average concentration of 0.18 g/dscm* corrected to 7% O₂.
3. Sulfuric acid plants. A maximum 3 hr. average SO₂ emission of 2 kg/metric ton of acid produced.

4. Iron and steel plants. PM may not exceed 50 mg/dscm, and the opacity must be 10% or less except for 2 min in any hour.

* dscm means dry standard cubic meter

Source performance standards (or emissions standards) are very numerous because of the variety of sources, so only a few examples (with emphasis on PM control) are given in Table 3. These or similar source performance standards dictate to companies what emission limits they will have to meet for new plants, and thus help determine what kind of PM control technology they must employ. The next example problem illustrates typical calculations using these standards.

Example Problem 1

Calculate the daily emissions of PM and SO₂ from a 500-MW coal-fired power plant which meets the performance standards listed in Table 3, including an SO₂ standard of 1.2 lb/million BTU heat input. Assume that the plant has an overall efficiency of 39%.

Solution

First calculate the heat input rate for a 39% efficient plant:

$$E_{in} = \frac{500 \text{ MW}}{0.39} \times \frac{1000 \text{ kW}}{\text{MW}} \times \frac{24 \text{ hr}}{\text{day}} \times \frac{3412 \text{ BTU}}{\text{kWh}} = 1.05 \times 10^{11} \text{ BTU/day}$$

$$\text{PM emitted} = \frac{0.03 \text{ lb}}{10^6 \text{ BTU}} \times \frac{1.05 \times 10^{11} \text{ BTU}}{\text{day}} \times \frac{1 \text{ ton}}{2000 \text{ lb}} = 1.6 \text{ tons/day}$$

$$\text{SO}_2 \text{ emitted} = \frac{1.2 \text{ lbSO}_2}{10^6 \text{ BTU}} \times 1.05 \times 10^{11} \frac{\text{BTU}}{\text{day}} \times \frac{1 \text{ ton}}{2000 \text{ lb}} = 63 \text{ tons/day}$$

III. Characteristics of Particulate Matter

Before we attempt to design a PM control device, we must obtain information about the particles and the gas stream that is carrying them. Important characteristics of the particles include size, size distribution, density, stickiness, corrosivity, resistivity, toxicity, and others. Gas stream characteristics of importance are temperature, humidity, chemical composition, volumetric flow rate, and particulate loading (mass concentration of particles in the gas). Finally, we must know the regulatory requirements for control (either a percent removal or an allowable emission rate or loading in the outlet gases). Many of the devices used for collecting particles exploit the vast difference in the physical size (and mass) of particles and gas molecules. Figure 1 illustrates the large range of sizes of various types of particles.

Because most collection devices work better on larger particles than on smaller ones, an important characteristic is the size distribution of particles. As seen in Figure 1, particles that must be collected can be much smaller than the diameter of a human hair (50 to 150 μm), and even smaller than the diameter of a red blood cell from an adult human (about 7.5 μm). Thus, if the PM being emitted consist of mostly particles larger than 20 μm , the collection task is much easier than if the PM distribution is heavily weighted towards particles less than 5 μm . In the two cases, we probably can use two different types of control devices. Also, if the temperatures and humidities of the two gas streams are quite different, then different control devices are probably needed. Finally, a single device generally works better on larger, denser particles and collects them with a higher efficiency than smaller lighter particles. Therefore, the device will exhibit a higher

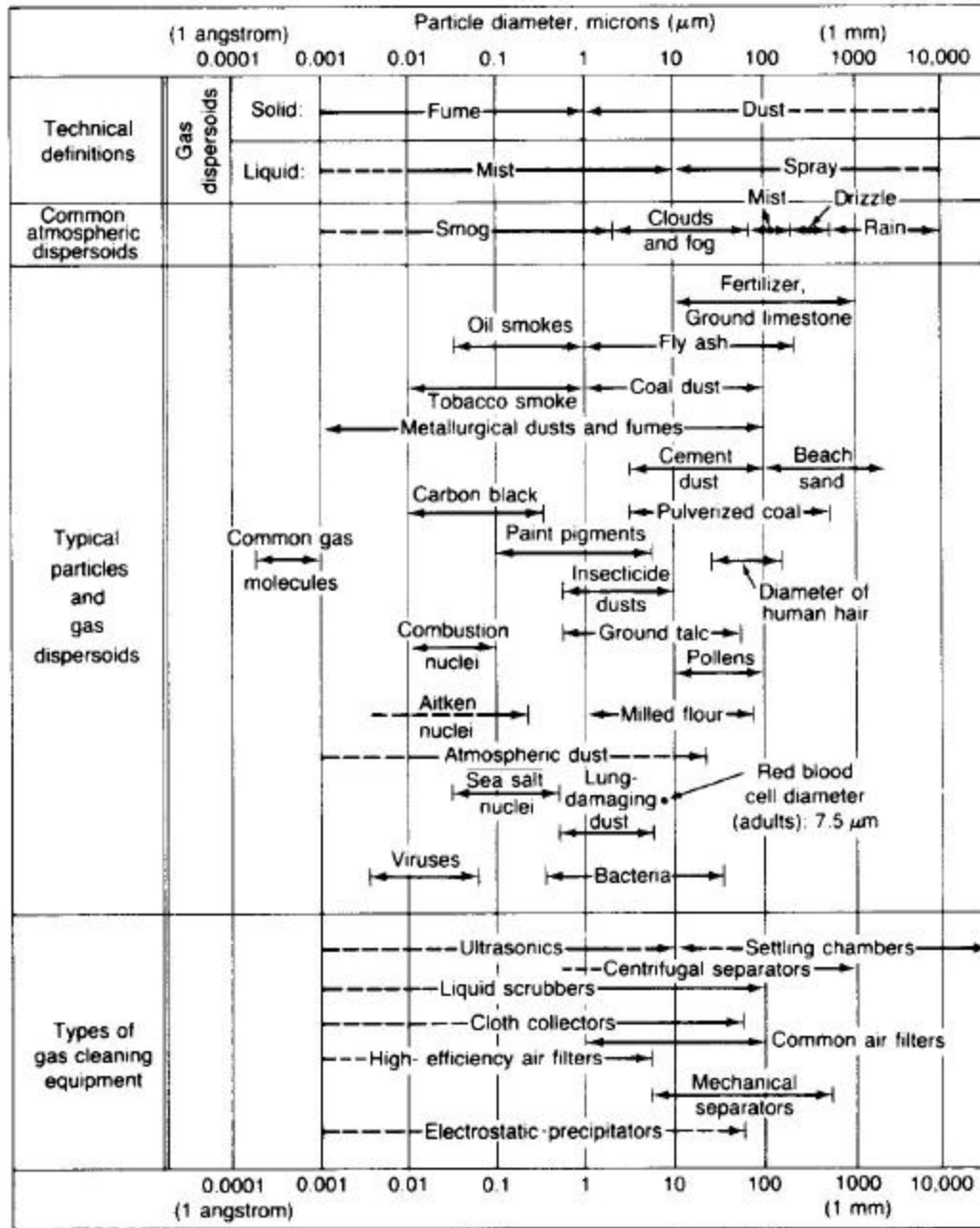


Figure 1. Sizes of Particles and Examples of Particle-in-Gas Dispersoids

Adapted from *Lapple, 1961*.

efficiency on those larger sized particles than on the smaller ones. To determine the overall collection efficiency of the device, it is usually important to know something about the size distribution of particles.

Control Efficiency. In all cases, the efficiency of PM control is based on the mass percent of the incoming PM that is collected or removed from the gas stream. That is, collection efficiency is calculated as:

$$\eta = \frac{\text{Mass rate of particles collected}}{\text{Mass input rate of particles}} \times 100\% \quad (1)$$

where: η = particle collection efficiency, percent

Air pollution control devices operate on a continuously flowing stream of contaminated air or exhaust gas. The dusty gas flows into the device, and most of the particles are separated from the gas stream and collected as solids, while the entire air flow continues through the device (see Figure 2).

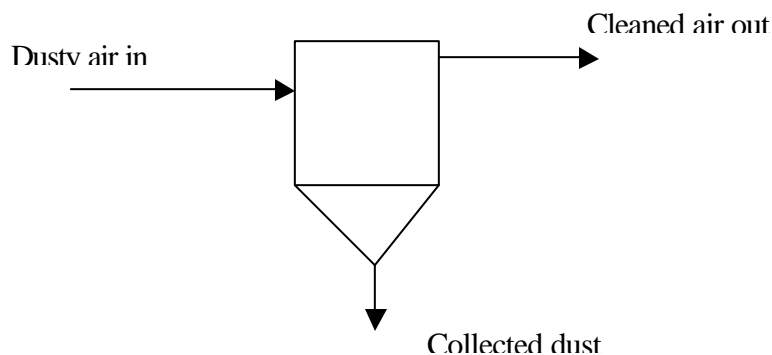


Figure 2. Schematic diagram of particulate matter air pollution control device

The gas volumetric flow rate often is the same at the inlet and the outlet side of the device. Therefore the collection efficiency can be calculated based on mass loadings (or concentrations) of particles in the inlet and outlet gas streams:

$$\eta = \frac{L_i - L_e}{L_i} \times 100\% \quad (2)$$

where: L = mass loading or concentration of PM in the gas, $\mu\text{g}/\text{m}^3$

i or e = subscripts indicating inlet or exiting gas

Example Problem 2

Consider the coal fired power plant of Example Problem 1. Assume that it burns coal at the rate of 3800 tons per day, and that the coal has an ash content of 4.5%. Calculate the overall efficiency required for a PM control system for this plant.

Solution

From Example Problem 1, the allowable PM emission rate is 1.6 tons per day. In order to calculate the efficiency, we must first calculate the mass input rate of ash (PM).

$$\text{ash input} = 3800 \text{ tons/day of coal} \times 0.045 = 171 \text{ tons/day of ash}$$

The PM collected is just the input minus the output, and the required efficiency for a control system is given by:

$$\eta = \frac{171 - 1.6}{171} \times 100\% = 99.1\%$$

Collection by Impaction, Interception, and Diffusion. When a flowing gas approaches a stationary object (such as a fabric filter thread, or a large water droplet, the flow streamlines will

diverge around the object. Because of their inertia, particles in the gas will not follow the streamlines exactly, but will tend to continue their motion in the original direction. If the particles have enough mass and inertia, and are located close enough to the object before the streamlines begin to diverge, the particles will collide with the object and be collected.

Impaction of particles occurs when the center of mass of a particle strikes the object. Interception is the phenomenon that occurs when the particles center of mass would closely miss the object, but because of the particle's size, the edge of the particle strikes the edge of the object, and the particle is collected. Diffusional collection occurs when a small particle is following a streamline that would cause it to miss the object, but because of random motions of the particle (diffusion), the particle veers away from the streamline and strikes the object. These three mechanisms are illustrated in Figure 3, and all three mechanisms can be employed in collecting particles in various control devices. The particles may be forced to move in a direction away from the gas flow streamlines by inertial forces, gravitational forces, electrostatic forces and others.

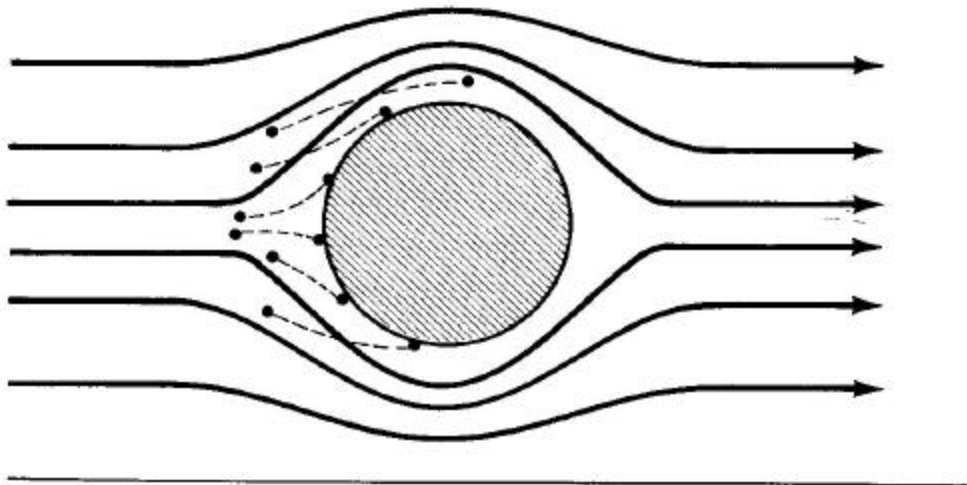


Figure 3. Collection of particles on a stationary object

Adapted from *Cooper and Alley, 2002*.

A simple means of explaining impaction is to use the concept of *stopping distance*. If a particle diverges from the fluid streamlines with an initial velocity v_0 , the frictional drag forces of the fluid on the particle will slow it down and eventually stop it. The distance it takes for the particle to come to rest is called the stopping distance. The particle velocity in its original direction is given by:

$$v = v_0 e^{-t/T} \quad (3)$$

where: v = particle velocity, m/s

v_0 = initial velocity, m/s

t = time from moment of divergence, sec

T = characteristic time of the system (a function of the particle and the gas properties),
sec

Integration of this equation from time zero to infinity gives the stopping distance, which in equation form, is the product of initial velocity times characteristic time:

$$X_{\text{stop}} = v_0 T \quad (4)$$

where: X_{stop} = stopping distance, m

If the particle stops before striking the object, it can be swept around the object by the diverging streamlines of gas flow. If the particle does not stop in time, it will strike the object, and is considered to be collected. The stopping distance is very small for small particles, sometimes in the range of 10's to 100's of microns. A useful parameter in determining if a

particular particle will be collected by a particular object is the impaction number, defined as the ratio of stopping distance to object diameter:

$$N_I = X_{\text{stop}} / D_o \quad (5)$$

where: N_I = impaction parameter, dimensionless

D_o = object diameter, same units as X_{stop}

If the impaction number is large (significantly greater than 1.0), this means that the stopping distance is large compared with the object diameter, and that the particle is very likely to be collected. If the impaction number is small (significantly smaller than 1.0), then the particle is not likely to impact onto the object and will not be collected.

IV. Air Pollution Control Options for PM

The most effective control often is simply a step or steps to prevent pollution from being formed. In recent years, such steps have been taken in many industries. Nevertheless, no process can be made 100% efficient, and so there will always be some air pollution emissions that must be controlled. Engineers have developed several large, interesting, and important pollution control devices for industrial sources of particulate matter.

Overview of PM Control Devices. There are several major types of control devices for removing particulate matter from exhaust gases before the gases are emitted into the atmosphere. These include cyclones, wet scrubbers, electrostatic precipitators, and baghouses. In the following few paragraphs we give a brief description of each device, stating their comparative advantages and disadvantages for removing particulate matter. We will explore ESPs and baghouses in more detail later in this lesson.

A **cyclone** is designed to remove particles by causing the entire gas stream to spin in a vortex at high velocity inside a cylindrical chamber. The centrifugal force acts more strongly on the larger, denser particles and flings them preferentially toward the inside wall of the cyclone where they impact and then fall to the bottom of the cyclone. The gas flows out through the top of the cyclone (still carrying some of the smaller, lighter particles), while the collected dust is removed from the bottom. Advantages of cyclones are that they are simple, rugged, and inexpensive. Also, they collect the PM in a dry form so that it can be re-used or recycled. The major disadvantage is that the collection efficiency tends to be somewhat low. In fact, the efficiency of a cyclone is often too low to be able to use the cyclone as a final control device. Therefore, cyclones are often used as pre-cleaners. Furthermore, moving the gas through a cyclone at high enough velocities to collect a reasonable fraction of the PM, creates a substantial pressure drop (which means an increase in operating costs).

Wet scrubbers operate on the principle of collision between particles and water droplets, collecting particles in the larger, heavier water drops. The water falls through the upward-flowing gases, colliding with and removing particles, and accumulates in the bottom of the scrubber. The “dirty” water is pumped from the scrubber and treated to remove the solids as a wet sludge. Advantages of wet scrubbers include being able to handle flammable or explosive dusts, provide cooling of the gases, and neutralize acid mists and vapors. Disadvantages include a high potential for corrosion, a high use of water, and a waste liquid or wet sludge effluent that must be treated and/or disposed. The capital and operating costs of wet scrubbers vary considerably with type of scrubber, efficiency desired, and location of the country.

An **electrostatic precipitator (ESP)** removes particulate matter from a gas stream by creating a high voltage drop between electrodes. A gas stream carrying particles flows into the ESP and between sets of large plate electrodes; gas molecules are ionized, the resulting ions stick to the particles, and the particles acquire a charge. The charged particles are attracted to and collected on the oppositely charged plates while the cleaned gas flows through the device. While the gas flows between the plates at velocities in the range of 1 to 3 meters per second, the particles move towards the plates at a velocity (called the drift velocity) that is in the range of 1 to 10 meters per minute. During the operation of the device, the plates are rapped periodically to knock off the layer of dust that builds up. The dust is collected dry and can be disposed of or recycled.

ESPs are large and expensive to buy, but have the important advantage that they collect particles with very high efficiencies. Another major advantage is that they present very little resistance to gas flow therefore cause only a slight pressure drop even when operating on flows as large as a million cubic feet per minute. Therefore their operating costs are not as large as one might expect. Many coal-fired power plants use ESPs.

A **baghouse** can be thought of as a giant multiple-bag vacuum cleaner. The polluted gas stream (containing the particles) is forced to flow through cloth filter bags. The dust is filtered from the gas stream, while the cleaned gas passes through the cloth and is exhausted to the atmosphere. The bags are periodically cleaned (two methods are by shaking the bags or by blowing clean air backwards through them) to knock the dry dust down to the bottom hoppers where it can be removed to be either recycled or disposed.

The capital costs of baghouses are high, but their efficiencies are so high that they have become very popular as final control devices. Many power plants, and a variety of dry-process industries use fabric filtration as a control technology. Baghouses have been used at cement plants, at steel mills, and at hospitals to control incinerator emissions. When powdered lime and activated carbon is injected into the gases before flowing into the baghouse, the system will control not only particulate matter, but also HCl gases and mercury fumes. The biggest operating cost comes from forcing large volumetric flows of air or combustion gases through the bags, which creates a substantial pressure drop.

To summarize the immediately preceding discussion, there are several different types of particulate matter control devices, with varying efficiencies and costs. Each has its own advantages and disadvantages, and site-specific engineering is needed to make the best choice. However, two of the most efficient and most widely-used types of PM control devices are ESPs and baghouses. Later in this course we explore these two types of devices in more detail.

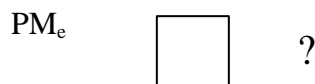
When two control devices operate in series, the overall PM collection efficiency of this system is the sum of the masses of PM collected by each device divided by the PM mass that flowed into the lead device. See the next example problem.

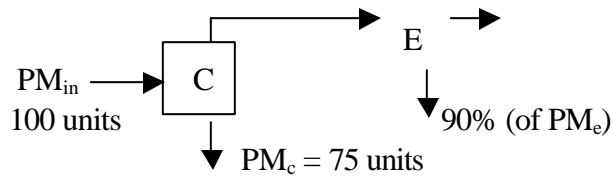
Example Problem 3

Calculate the overall efficiency of a particulate control system composed of a cyclone (75% efficient) followed by an electrostatic precipitator (90% efficient).

Solution

The overall system looks like this;





First, assume that PM input (PM_{in}) = 100 mass units. Then, PM collected in cyclone (PM_c) = $0.75 \times 100 = 75$ units.

Note: PM exiting the cyclone (PM_e) = $100 - 75 = 25$ units. (= PM into ESP).

PM collected by ESP = 0.90×25 units = 22.5 units

Total PM collected by both devices = $75 + 22.5 = 97.5$ units.

Overall efficiency of system is

$$\eta_E = \frac{97.5}{100} = 0.975$$

$$\eta_E = \underline{\underline{97.5\%}}$$

In Example Problem 3, we analyzed each piece of equipment, and then added the collected PM to get the total collection efficiency. Let us define fractional penetration as one minus the fractional efficiency:

$$Pt = 1 - \eta / 100 \quad (6)$$

Then, it should be obvious that penetration is the fraction of particle pass-through and that overall penetration for two devices in series is

$$Pt_{overall} = Pt_1 \times Pt_2 \quad (7)$$

Thus, the overall efficiency of collection for two devices in series is

$$\eta_{\text{overall}} = (1 - Pt_{\text{overall}}) \times 100\% \quad (8)$$

Combining equations (3) and (4) allows us to solve Example Problem 3 directly. That is,

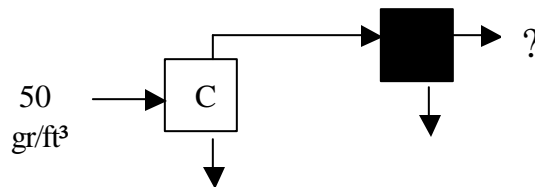
$$\eta = (1 - 0.25 \times 0.1) \times 100\% = 97.5\%$$

Example Problem 4

A stream of gas from a manufacturing plant contains 50 gr/ft³ of PM. Regulations require an overall control efficiency of 98.5%. The proposed control system consists of a cyclone (70% efficient) followed by an ESP. Calculate (a) the allowable outlet concentration of PM, and (b) the efficiency of the ESP.

Solution

The overall system looks like this;



$$(a) C_{\text{out}} = (1 - .985)50 = 0.75 \text{ gr / ft}^3$$

$$(b) Pt_c = 1 - 0.7 = 0.30$$

$$PM_{\text{cyclone out}} = 0.30(50) = 15 \text{ gr/ft}^3$$

$$h_E = \frac{15 - 0.75}{15} = 0.95 \text{ or } 95\%$$

V. Electrostatic Precipitators

Background. Electrostatic precipitation is a mature technology, having been used to control fly ash from coal fired power plants for more than 75 years. *Fly ash* is a term used to describe

the fine particles of non-combustible minerals that remain suspended in the combustion gases after burning pulverized coal. However, ESP technology has continued to improve over the years, and is still very effective, finding use in many coal fired power plants, as well as in numerous other combustion and non-combustion processes that emit PM. In the 1930s and 1940s, fly-ash ESPs were built that achieved efficiencies near 95%. By the 1950's, guarantees were being made for efficiencies of 97%-98%. By the 1970's, electrostatic precipitator (ESP) specifications were often above 99.5% efficiency. Modern ESPs have been designed for efficiencies greater than 99.9%. Keep in mind that the seemingly small improvement in collection efficiency (from 99.5% to 99.9%) actually corresponds to an 80% decrease in PM emissions (from 0.5% to 0.1%).

The process of electrostatic precipitation involves (1) the ionization of contaminated air (and particles) flowing between electrodes, (2) the migration and collection of the particles on oppositely charged plates, and (3) knocking the particles off the plates and into hoppers, and (4) the removal of the material from the hoppers. The air flows freely through the ESP, but the particles are left behind on the plates. The collected material is periodically knocked off or washed off the plates, and is collected in the bottom of the ESP. The ESP is unique among air pollution control devices in that the forces of collection act only on the particles and not on the entire air stream. This phenomenon typically results in a high collection efficiency with a very low air pressure drop.

In addition to dry ESPs (the focus of this section), wet ESPs can be used when there is a potential for explosion, when the particulates are sticky or are liquid droplets, or when the dry dust has an extremely high resistivity (resistivity is a property of particles that is quite important

in the design and operation of the ESP, and will be discussed in more detail later in this section of the course). ESPs have several advantages and disadvantages in comparison with other particulate control devices.

Advantages of ESPs

- Very high efficiencies, even for very small particles
- Can handle very large gas volumes with low pressure drop
- Dry collection of valuable material, or wet collection of fumes and mists
- Can be designed for a wide range of gas temperatures
- Low operating costs, except at very high efficiencies

Disadvantages of ESPs

- High capital costs
- Will not control gaseous emissions
- Not very flexible, once installed, to changes in operating conditions
- Take up a lot of space
- Might not work on particulates with very high electrical resistivity

Design Equations. A cutaway view of an ESP is shown in Figure 4. As can be seen, there are a number of parallel plates with wires hanging down between them. The plates have a height of H (often 10 – 20 feet), and a spacing between them of D (on the order of 1 foot). The wires are typically charged negatively, and the plates are grounded. In many ESPs, the charge differential can be as high as 100,000 volts across an air gap that is only 6 to 12 inches. The dusty air flows into the ESP through a grid of openings (shown in the right side of Figure 4) to help the flow divide equally and uniformly among all the ducts.

The total gas volumetric flow rate divides into N-1 channels, where N = number of plates in parallel across the width of the ESP. The velocity of gas through the ESP is given by:

$$u = Q/A_f \quad (9)$$

where: Q = gas volumetric flow, ft³/min

A_f = cross sectional area for flow, ft²/min

u = linear gas velocity, ft/min

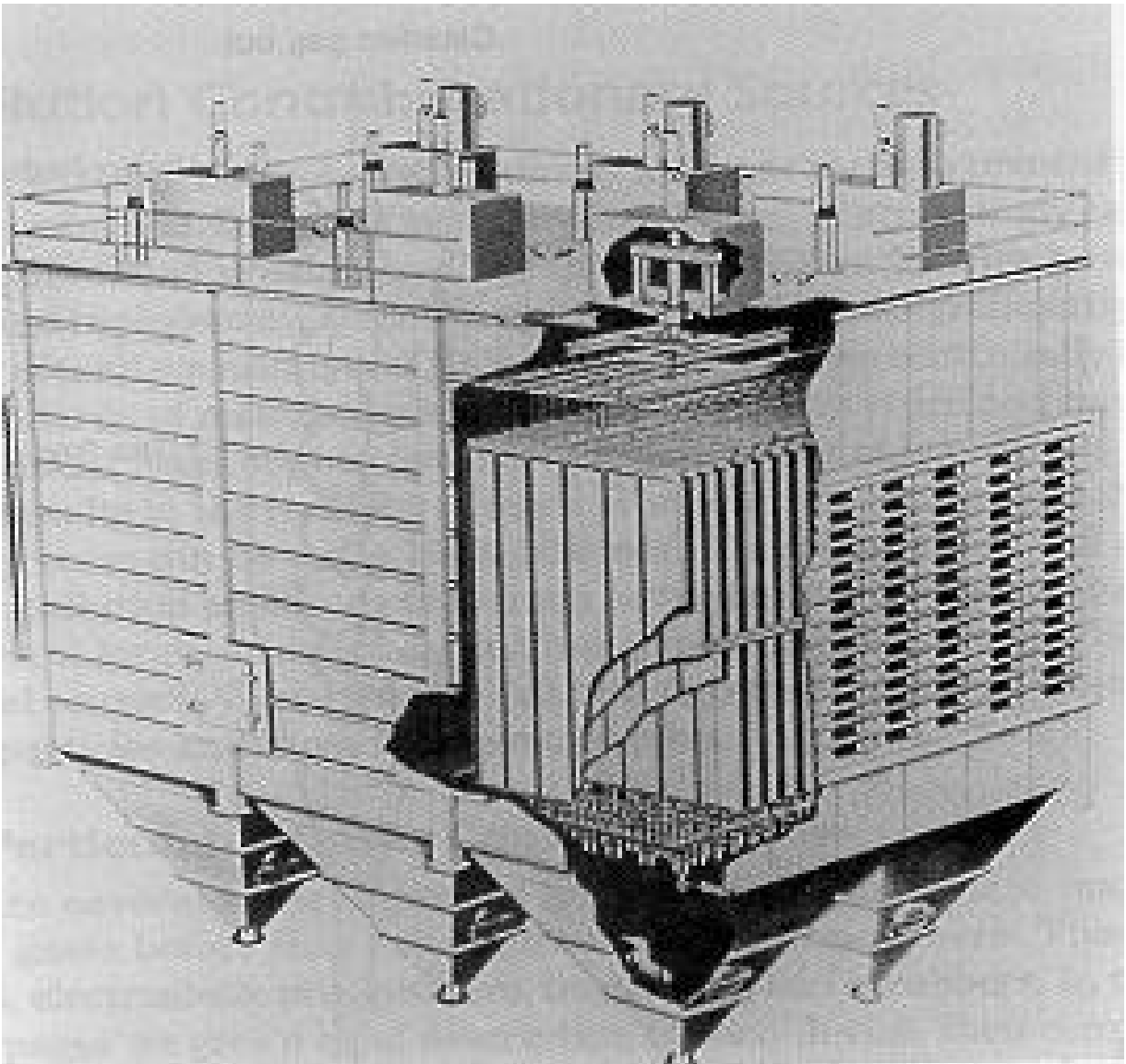


Figure 4. Cutaway view of an Electrostatic Precipitator

Adapted from *Cooper and Alley, 2002*.

Note that the cross sectional area for gas flow is just:

$$A_f = D \times H \times (N-1) \quad (10)$$

where: D =duct width, ft

H = duct height (plate height), ft

N = number of plates in parallel across the width of the ESP

The velocity at which particles approach the plates is much different from the gas velocity through the ESP. The particles migrate across the direction of the gas flow at a speed called the drift velocity, which is given the symbol w . The drift velocity is a key parameter for the design of an ESP. The other key parameter is the total plate collection area, given the symbol A . This area is the total area of all the steel plates available to collect particles. Because plates are usually placed in several sections in the direction of flow (see Figure 2 , which has 3 sections in the direction of flow), the total plate collection area is equal to the area of one plate (double-sided) area times the number of channels in one section of the ESP times the number of sections in the direction of flow. The number of channels or ducts is just one less than the number of plates in parallel.

$$A = A_p \times N_s \times (N-1) \quad (11)$$

where: A = total plate collection area, ft²

A_p = double-sided area of one plate, ft²

N_s = number of sections in the direction of flow

N = number of plates in parallel

Note that the double-sided area of one plate is simply:

$$A_p = H_p \times L_p \quad (12)$$

where: H_p = height of a plate, ft

L_p = length of a plate, ft

Now that we have introduced the meanings of the terms, we can present the key ESP design equation, the **Deutsch equation**. The Deutsch equation relates overall particle collection efficiency to the gas volumetric flow that must be treated and the two key parameters: particle drift velocity and total collection area. The Deutsch equation is:

$$\eta = 1 - e^{-Aw/Q} \quad (13)$$

where: η = fractional collection efficiency

Equation (13) indicates that the efficiency increases with increasing A and w , and decreases with increasing Q . Any consistent set of units can be used for w , A and Q (for example, ft/min, ft², and ft³/min, respectively).

Example Problem 5

(a) Calculate the total plate area required to achieve 98% efficiency in an ESP that is treating 100,000 ft³/min of air. The effective drift velocity is 20 ft/min.

(b) Assuming the plates are 15 ft high and 6 ft long, and that there will be 3 sections in the direction of flow, calculate the number of plates required.

Solution

(a) Rearranging Eq. (13),

$$\ln(1 - \eta) = -A w/Q$$

$$A = - (Q/w) \times \ln(1 - \eta)$$

$$A = - (100,000/20) \times \ln(1 - 0.98)$$

$$A = - 5000 \times \ln(0.02)$$

$$A = 4961 \text{ ft}^2$$

(b) The double-sided plate area = $2 \times 15 \times 6 = 180 \text{ ft}^2$

Solving eq () for N, we get:

$$N = A/(A_p \times N_s) + 1$$

$$N = 4961 / (180 \times 3) + 1$$

$$N = 10.2 \text{ (Round up to 11 plates in parallel.)}$$

The number of plates in parallel is the number of plates in one section. Therefore, the total number of plates in the ESP is $11 \times 3 = 33$ plates.

Design Considerations. The complete design of an ESP includes calculating the needed electrical energization, sizing and determining the configuration of the plates, determining the structural needs, and specifying the rapping, dust removal, and performance-monitoring systems. Although the detailed mechanical design of an ESP is usually left to the vendor, it behooves us to know some of the details about electrical energization and plate configuration.

Corona. An electrical field (or corona) must be established to charge particles. **Corona** is the *ionization of gas molecules by high energy electrons in the region of a strong electric field*. The excess electrons generated by the corona are readily attached onto electronegative gases such as oxygen or SO₂. In turn, the negatively charged gas ions that are

produced are adsorbed onto particles, which then migrate to the relatively positively charged plates. Typically, the discharge electrodes (wires) are energized while the collecting plates are grounded, but the wires can establish either a positive or negative corona. Negative corona (in which the wires have a negative charge) has inherently better voltage/current characteristics, and is used more frequently. However, negative corona produces more ozone than positive corona. For this reason, positive corona, even though less efficient, is used for all indoor air cleaning applications.

Particulate Resistivity. In addition to size and size distribution, a very important property of the particles is *resistivity*. Once particles have migrated to a plate, they are considered to be collected. However, collected particles can be re-entrained into the gas, thus lowering the net ESP efficiency.

*The **resistivity** of a material (e.g., fly ash) is a measure of its resistance to electrical conduction.* Resistivity is extremely important because it can vary widely, and because it strongly influences particle collection efficiency. Once collected, particles begin to lose their charge to the plate. This transfer of charge completes the electrical circuit, produces current flow, and allows maintenance of the voltage drop between the wires and the plates. If the resistivity is too low (that is, the dust is a good conductor), the electrostatic charge is drained off too quickly and the dust is re-entrained into the gas. If the resistivity is too high (that is, the dust is a good insulator), the charge does not drain off at the collecting plates. In this situation, first a “back corona” develops, reducing the ionization and migration of particles in the gas, and second, the particles remain strongly attracted to the plate and are difficult to “rap” off.

The resistivity of a material is determined experimentally by establishing a current flow through a slab of the material with known geometry. It is important to make resistivity measurements of freshly collected dust in the actual flue gas stream produced from burning the particular coal to be used. Thus, such measurements should be made in the field rather than in the laboratory. Resistivities measured in the lab on the “same” dust can be from 100 to 1000 times greater than field resistivities (White 1984).

The resistivity \mathbf{P} of materials ranges from 10^{-3} to 10^{14} ohm-cm, but for coal fly ashes, \mathbf{P} usually ranges from 10^8 to 10^{13} ohm-cm (White 1977) or about 5 orders of magnitude. The resistivity of dry cement dust can exceed 10 ohm-cm (U.S. Environmental Protection Agency, 1985). ESP design and operation are difficult for resistivities above 10^{11} ohm-cm.

The major factors influencing fly-ash resistivity are temperature and chemical composition (of the fly ash and of the combustion gases). The conductivity of the dust layer is derived from two effects: volume conduction through the material itself, and surface conduction via adsorbed gases or liquids. Volume conduction decreases with increased temperature, whereas surface conduction increases with T. Therefore, resistivity (which is the inverse of conductivity) has a distinct maximum value. Unfortunately for power boiler operators, this maximum occurs at about 250-350F.

The temperature of the maximum resistivity is unfortunate because operators often cannot reduce ESP temperatures below 250 F without risking the condensation of sulfuric acid on some of the cold surfaces. On the other hand, temperatures above about 350 °F result in unnecessary loss of heat out the stack, which represents a monetary loss.

Resistivity decreases with increased coal sulfur content because of increased adsorption of conductive gases by the fly ash. In the past, resistivity changes were responsible for increased fly-ash emissions when power plants switched from high-sulfur coal to low-sulfur coal to reduce SO₂ emissions. However, in some cases, increases in resistivity caused by switching to a lower-sulfur coal can be partially offset by adding certain chemicals (such as ammonia or SO₃) to the flue gas. This technique is known as *flue gas conditioning*.

A highly resistive dust increases the occurrence of sparking in the precipitator, and forces a lower operating voltage. A serious back corona can develop, which reduces both particle charging and collection. The effects of resistivity are more significant above 10¹¹ ohm-cm, but can be accounted for in design by the effective drift velocity. The effect of higher resistivity is to lower the effective drift velocity.

Internal Configuration. The design of the internal configuration of an ESP often involves more art than science. The even distribution of gas flow through the ducts is very important to the proper operation of an ESP, as are uniform plate spacing, proper electrode arrangement, “trueness” of plates (plates must be flat and parallel such that all points between two adjacent plates are equidistant), slopes of hoppers, adequate numbers of electrical sections, and many other features.

Although there have been improvements in computer models for ESP design, reliance is still placed on experience and pilot-scale studies. Some practical design parameters are listed in Table 4.

Table 4. Values of Selected Design Parameters for ESPs

<u>Parameter</u>	<u>Range of Values</u>
Drift velocity	3 – 30 ft/min
Channel (duct) spacing	1 – 2 ft
Gas velocity	4 – 8 ft/sec
Aspect ratio (= $N_s \times L_p / H_p$)	0.5 – 1.5 (must be > 1.0 for $\eta > 99\%$)
Power density	1 – 3 watts/ft ²
Number of electrical sections	
In the direction of flow	2 – 8
Total in the ESP	3 – 30 sections per 100,000 ft ³ /min

Adapted from *Cooper and Alley, 2002*.

Using the information given in Table 4 and a basic understanding of the configuration of an ESP, we can estimate the overall size of an ESP. For instance, the overall width of the precipitator is virtually equal to the number of ducts plus a little extra for the two side of the box.

The overall length of the precipitator is given by

$$L_o = N_s L_p + (N_s - 1) L_s + L_{en} + L_{ex} \quad (14)$$

where: L_o = overall length, ft

N_s = number of electrical sections in the direction of flow

L_p = plate length, ft

L_s = spacing between electrical sections, ft

L_{en} = entrance section length, ft

L_{ex} = exit section length, ft

The spacing between sections can be 1 -3 ft, and the entrance and exit length each can be 10 ft or more. Plates for large fly-ash ESPs are often 10-30 feet high and 3-15 feet long (length is measured in the direction of gas flow). The ESP height can be 1.5 to 3 times the plate height due to hoppers, superstructure, controls, and so forth.

The number of electrical sections (in the direction of flow) ranges between 2 and 8, and depends on the aspect ratio and the plate dimensions. However, the number of sections must be sufficient to provide the minimum total collection area required but not a great excess of area. The number of sections is chosen by experience, with each section being energized by one transformer/rectifier (T/R) set. The designer must balance the increased capital cost of providing more T/R sets against the risk of only providing a few sections, each with many plates. With only a few large sections, the failure of one T/R set may cause unacceptably poor performance of the ESP and require that the whole process be shut down.

In reality, ESP performance improves with increasing sectionalization. There are several fundamental reasons for this phenomenon. Electrode alignment and spacing are more accurate for smaller sections. Smaller rectifier sets are more stable and can operate at higher voltages. Larger numbers of electrical sections allow for meeting the overall efficiency targets even if one or more sections become inoperable. However, adding these extra sections increases the capital cost.

Plates and Wires. The type and positioning of the collecting plates and the charging wires can be major factors in the operation and maintenance of an ESP. The plates are usually steel sheets with stiffeners. Baffles are added to reduce turbulence (and thus reduce dust re-entrainment) in the vicinity of the plates. The plates should be true (perfectly flat) and should be

hung straight and parallel so that the spacing between plates at any point is uniform to within 0.5 cm.

The discharge electrodes in older U.S. ESPs are wires (of about 2.5 mm diameter) kept taut by weights and positioned through guides to prevent excess swaying. The wires tend to be high maintenance items. Corrosion can occur near the top of the wires because of air leakage and acid condensation. Also, long weighted wires tend to oscillate. The middle of the wire can approach the plate quite closely, causing increased sparking and wear. In the past, European designs favored rigid, mast-type supports for the wires, and many used barbs on the wires, or serrated strips instead of round wires. Companies on both continents have begun using rigid electrodes because they have advantages over either wires or wire-frame (mast-type electrodes).

Removal of Particle Dust. After collection, the accumulated dust on the plates must be removed periodically so that the ESP can continue to function properly. Dust removal is accomplished by rapping the plates, causing a vibration that knocks off the layers of dust. The dust falls into hoppers and is then discharged through pneumatic tubes or screw conveyors to a loading facility. The wires also collect some dust; they are also rapped or vibrated periodically. The plates remain energized during rapping.

The two basic approaches to rapping are the American approach and the European approach. In most American designs, the plates are rapped by a falling weight. The intensity of the rap is easily adjusted by varying the height from which the weight is dropped, or by adjusting the acceleration-field strength. In a typical European design, rapping is accomplished by a fixed size rotating hammer. Thus, to adjust the rapping intensity, the hammers must physically be

changed. Generally, one rapping unit is provided for every 1200 to 1600 square feet of collection area (U.S. Environmental Protection Agency 1985). Both designs allow for convenient adjustment of the rapping interval, which can vary from 1 to 10 minutes.

ESP hoppers catch the falling dust and provide temporary storage. Most hoppers have a pyramidal shape that converges to either a round or square discharge. Hopper walls must be steeply sloped (usually greater than 60%) to prevent dust caking and bridging. Also, hoppers are often heat traced because warm ash flows much better than cold ash. Usually, about 60-70% of the dust is removed through the first (inlet) set of hoppers. However, in case of failure of the first electrical set, the dust load is transferred to the next downstream hopper. Therefore, liberal sizing of the hoppers is recommended. Proper support structure must be provided so that a hopper will not collapse when filled with dust.

Power Consumption. Operating power consumption in an ESP mainly comes from corona power and pressure drop, with corona power being the main source. Even though the gas pressure drop is low (typically less than 1 inch of water), the gas volume flow is high. There, the cost of fan power needed to pull the air through an ESP is not negligible.

Corona power can be approximated by the equation

$$P_c = I_c V_{avg} \quad (15)$$

where: P_c = corona power, watts

I_c = corona current, amps

V_{avg} = average voltage, volts

Even though voltages in ESPs are very high, the current flow due to gas ion migration is low, so the electrical power consumption is reasonably low. The power density is the ratio of corona

power to collection area, and the effective drift velocity can be related to the corona power density as follows:

$$w_e = k \sqrt{P_c/A} \quad (16)$$

where: w_e = effective drift velocity, ft/min

P_c/A = power density, watts/ft²

k = an empirical constant.

For well-built fly-ash ESPs, k is in the range from 0.5 to 0.7 for units of w_e in ft/sec and P_c/A in watts/ft². Although the power density often increases (sometimes by as much as a factor of ten) from the air inlet of the ESP to the outlet, the overall power density (total corona power/total plate area) is a fairly stable and representative parameter. Typical values of the overall power density are 1-2 watts/ft² (U.S. Environmental Protection Agency, 1985). By substituting Eq. (16) into Eq. (13) (the Deutsch equation), the corona power can be related to the collection efficiency as follows:

$$\eta = 1 - e^{-kP_c/Q} \quad (17)$$

White (1977) has shown Eq (17), with $k = 0.55$ for P_c in units of watts, and Q in units of ft³/s, to be reasonably accurate for efficiencies up to about 98.5%. For efficiencies above 98.5%, the required corona power increases non-linearly with an increase in efficiency

Example Problem 6

An ESP is to be designed to treat 90,000 ft³/min of gas to remove particles at an efficiency of 98%. Estimate the required corona power in kW.

Solution

First, convert 90,000 ft³/min to ft³/s

$$90000 \text{ ft}^3/\text{min} \times 1\text{min}/60 \text{ s} = 1500 \text{ ft}^3/\text{s}$$

Next, rearranging equation (17), we get

$$-k P_c/Q = \ln(1 - ?)$$

$$P_c = -\ln(1 - ?) Q/k$$

$$P_c = -\ln(0.02) 1500/0.55$$

$$P_c = 10670 \text{ watts} \quad \text{or} \quad 10.7 \text{ kW}$$

VI. Baghouses

General. A baghouse is nothing more than a “house full of bags.” The bags are usually made of cotton, wool, synthetic, or glass fibers, and there may be hundreds of bags within one structure. This kind of fabric filtration is a well-known and practiced method for separating dry particles from a stream of gases (usually air or combustion gases). The dusty gas flows into and through the fabric, leaving the dust on the inside of the bag, while the cleaned gas exits through the bag to the other side and then out the baghouse. The fabric does some filtering of the dust, but really is more important in its role as a support medium for the layer of dust that quickly accumulates on it. This dust layer actually does the highly efficient filtering of small particles for which baghouses are known. A cutaway view of one compartment of a shaker baghouse is shown in Figure 5.

There are many different types of fabrics, different sizes of bags, different ways of flowing the gases through the bags, and different ways of cleaning the bags within the baghouse. Extended operation of a baghouse requires that the bags be periodically cleaned, and that the dust be removed from the baghouse. The three common types of baghouses (based on cleaning methods) are shaker, reverse-air, and pulse-jet baghouses. In a shaker baghouse, the dusty air flow is blocked from the compartment to be cleaned, and the bags are shaken to knock off the dust. In a reverse-air baghouse, the dusty air flow is blocked from the compartment to be cleaned, and the clean air is forced to flow gently backwards through the bags, dislodging the particles. In a pulse-jet baghouse, a blast of compressed clean air flows briefly into the bags, while they are still filtering dusty air, knocking off some dust. In all cases the dislodged chunks of

dust fall by gravity and is collected in hoppers, and can be removed without further disturbing the air filtering process.

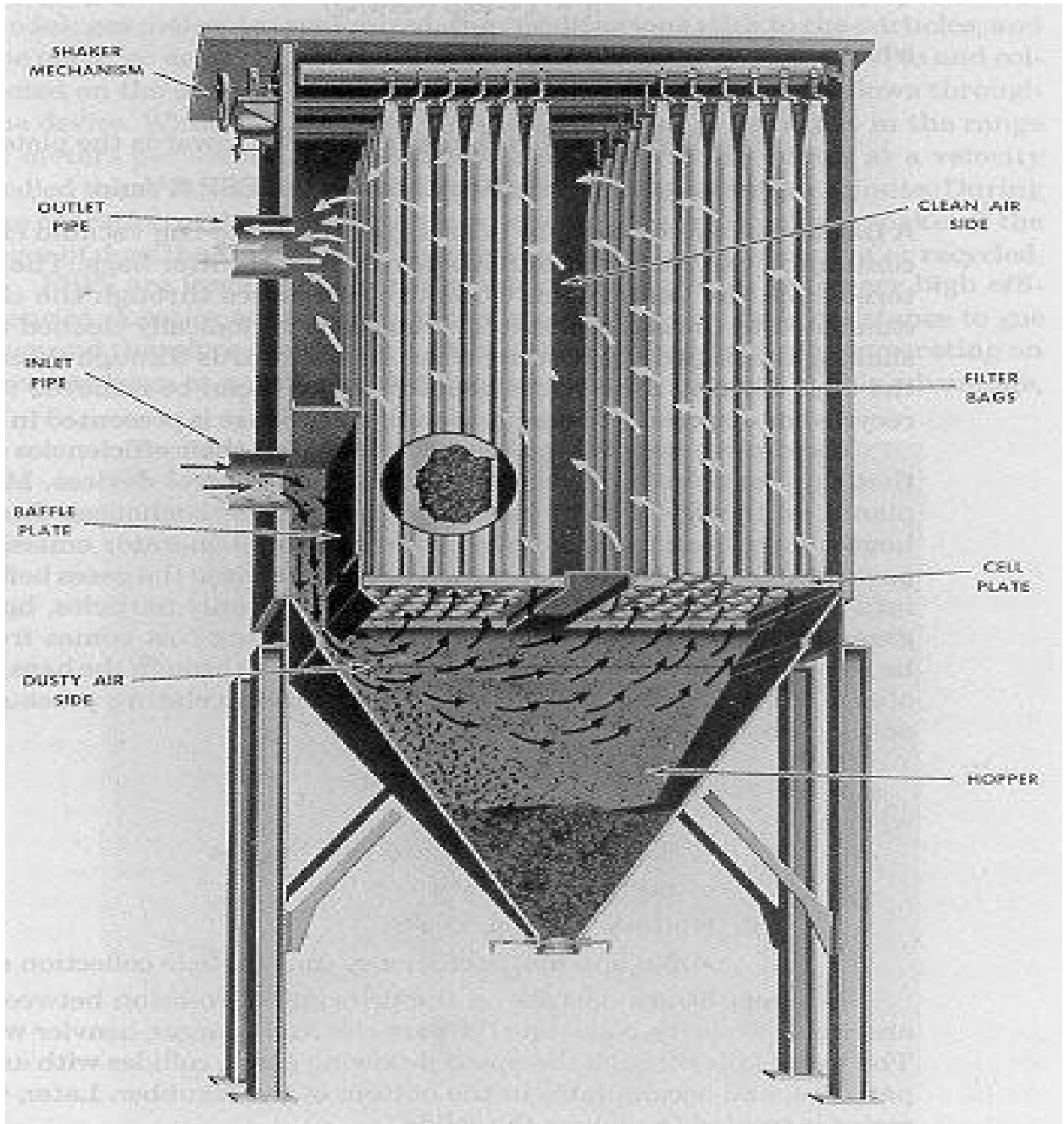


Figure 5. Cutaway view of a shaker-type baghouse

Adapted from *Cooper and Alley, 2002*.

Although the detailed mechanical design of a baghouse is usually left to the vendor, the student should be familiar with the principles of design and operation of baghouses in order to select the right ones for each application. Baghouses have several advantages and disadvantages as shown below:

Advantages of baghouses

- High collection efficiencies even for very small particles
- Can operate on a wide variety of dusts
- Modular in design and construction; modules can be manufactured in the factory and assembled in the field
- Reasonable pressure drops

Disadvantages of baghouses

- They take up a lot of space
- Fabrics can be harmed by high temperatures or corrosive chemicals
- Cannot operate in highly humid conditions
- Potential for fire or explosion

The advantages of baghouses often outweigh the disadvantages, and their use increased remarkably from the early 1970's through the 1990's. The use of baghouses has become widely accepted, and fabric filtration is often preferred over ESPs for PM control in U.S. electric power plants. This industry's use of baghouses grew from almost nothing in 1975 to 57

installations on over 16,000 MW of installed capacity in 1989, and baghouses are now chosen for more than half of new power plant installations (Cooper and Alley, 2002).

Design and Selection of Shaker and Reverse-Air Baghouses. It is interesting to note that fabric filters, when designed and operated properly, are almost 100% efficient at collecting particles. So efficiency is not generally a design concern! With a high collection efficiency as a “given,” the design of a baghouse involves the selection of the right fabric and type of baghouse (cleaning method) to fit the process gas stream, and choosing the best superficial filtering velocity, V .

Before we proceed further, it is important to understand the concept of superficial filtering velocity. The superficial filtering velocity (also known as the *air/cloth ratio*) is the average volumetric flow rate of gas divided by the area of cloth through which it passes. This average velocity is calculated by

$$V = Q/A \quad (18)$$

Where: V = superficial filtering velocity, ft/min (or cfm/ft²)

Q = gas volumetric flow rate, ft³/min (or cfm)

A = fabric area, ft²

The choice of the right fabric and the selection of the correct design value of V are greatly influenced by the temperature of the gas stream, and the type of PM to be collected. Table 5 provides data on the maximum recommended temperatures for various fabrics. Generally speaking, the higher the temperature tolerance, the more expensive the fabric, so from an economic point of view, we would want to select a fabric from a position higher in the table rather than lower, if possible.

Table 5. Recommended Maximum Operating Temperatures for Various Fabrics

<u>Fabric</u>	<u>Temperature, °F</u>
Cotton	180
Wool	200
Nylon	200
Polypropylene	200
Dacron	275
Nomex	400
Teflon	400
Glass	550

Adapted from *Cooper and Alley, 2002*.

For most baghouses, the superficial filtering velocity must be kept very low (just a few feet per minute) in order to provide for good filtration, and to avoid large pressure drops (and the accompanying high operating costs). Therefore, if we have a large gas flow to treat, we must provide an enormous amount of cloth area. See the following example.

Example Problem 7

A dusty gas from a fertilizer plant is flowing at the rate of 24,000 cfm at 220 °F. What type of cloth do you recommend? If the design filtering velocity must be limited to 2.0 fpm, what is the cloth area needed?

Solution

From Table 5, we see that 220 °F is too high for the first four fabric choices, so we recommend Dacron. Any of the other fabrics positioned lower in the table would also work, but would likely be more expensive than necessary.

For the second part of this problem, rearrange equation (18) to get

$$\begin{aligned} A &= Q/V \\ &= \frac{24000 \text{ ft}^3/\text{min}}{2.0 \text{ ft/min}} \\ &= 12,000 \text{ ft}^2 \end{aligned}$$

Actually the previous example was a bit simplified in that we did not consider the number of compartments. Both shaker and reverse-air baghouses are built with a number of identical compartments. The baghouse works with all compartments operating in parallel, filtering dust. Periodically, one compartment is taken off-line for cleaning. When one compartment is taken off-line for cleaning, the same total gas flow must now flow through the remaining compartments. This causes the velocity in each of those to go up for that brief cleaning period (a few minutes at most). It is recommended that the maximum filtering velocity be calculated based on the cloth area contained in N-1 compartments for a baghouse that has N compartments. The cloth area in N-1 compartments is called the Net Cloth Area, and is just the cloth area in one compartment multiplied times N-1.

Because shaker and reverse-air baghouses have been in use for many years, a vast amount of operating experience has been collected, and is used in the design of new baghouses. Table 6 provides data on the recommended maximum filtering velocities for various dusts.

Table 6. Shaker and Reverse-Air Baghouses – Maximum Filtering Velocities

<u>Type of Dust</u>	<u>Max. Filtering Velocity, cfm/ft² or ft/min*</u>
Activated charcoal, detergents, carbon black, metal fumes	1.5
Aluminum oxide, fertilizer, iron ore, lime, fly ash	2.0
Ceramics, chrome ore, flour, flint, glass, plastics, cement, gypsum	2.5
Cork, feeds, grains, marble, salt	3.0
Leather, paper, tobacco, wood	3.5

* Based on net cloth area

Adapted from *Cooper and Alley, 2002*.

Example Problem 8

A dusty gas from a fertilizer plant is flowing at the rate of 24,000 cfm. If it is determined that 5 compartments will be used, what is the cloth area in each compartment? Also what is the total cloth area for the baghouse?

Solution

In the previous problem we used a design filtering velocity of 2.0 fpm. Now, from Table 6, we see that this is the correct value for fertilizer but that it must be based on the net cloth area. Therefore, the 12,000 ft⁻² of fabric we calculated previously is the net cloth area for this baghouse. That is, this much cloth is contained in the 4 compartments that remain filtering while one is off-line for cleaning. Thus the area per compartment is

$$\text{Area in one compartment} = 12,000 \text{ ft}^2 / 4 = 3,000 \text{ ft}^2$$

The total cloth area for the baghouse is 5 compartments x 3,000 ft² = 15,000 ft²

How do we determine how many compartments we should specify? Although one might think that it would be related to the total flow rate, past experience has shown that the best and most reliable indicator is the net cloth area. Thus Table 7 relates net cloth area and number of compartments.

Table 7. Number of compartments vs net cloth area

<u>No. of Compartments</u>	<u>Net Cloth area, ft²</u>
2	1-4000
3	4,001-12,000
4-5	12,001-25,000
6-7	25,001-40,000
8-10	40,001-60,000
11-13	60,001-80,000
14-16	80,001-110,000
17-20	110,001-150,000

Adapted from *Cooper and Alley, 2002*.

Pressure Drop.

Recall that efficiency for a properly designed baghouse will be very high, and thus not a concern. Therefore, after selecting the type and numbers of bags, the proper filtering velocity, and a reasonable number of compartments, the designer's main concern is the pressure drop. As time passes and dust builds up on the fabric, the layer of dust caught on the cloth (through which the gas must pass) gets thicker. This thicker layer of dust offers more resistance to gas flow, thereby increasing the pressure drop.

The weight of dust deposited per unit area of fabric is called the areal dust density and is the product of the concentration of dust in the gas times the superficial filtering velocity times the time since the last cleaning. In equation form it is:

$$W = L V t \tag{19}$$

Where: W = areal dust density, g/m^2

L = concentration of dust in the gas, g/m^3

V = superficial filtering velocity, m/min

t = time since last cleaning, min

The filter drag is defined as the pressure drop divided by the filtering velocity, or

$$S = ? P / V \tag{20}$$

Where: S = filter drag, $Pa-min/m$

$? P$ = pressure drop, Pa

V = filtering velocity, m/min

The filter drag model is a linear equation that relates S and W through two constants that are functions of the cloth and the dust. These constants are usually determined empirically. The filter

drag model helps engineers predict the pressure drop that will be experienced in a baghouse.

The filter drag model is:

$$S = K_e + K_s W \quad (21)$$

where: K_e , and K_s are constants.

Example Problem 9

Calculate the maximum expected pressure drop in a shaker baghouse after 4 hours (240 minutes) of operation with $L = 500,000 \mu\text{g}/\text{m}^3$, and $V = 0.9 \text{ m}/\text{min}$. Also, $K_e = 500 \text{ Pa}\cdot\text{min}/\text{m}$, and $K_s = 3.5 \text{ Pa}\cdot\text{min}\cdot\text{m}/\text{g}$.

Solution

$$W = LVt = 500,000 \mu\text{g}/\text{m}^3 \times 1.0 \text{ g}/10^6 \mu\text{g} \times 0.9 \text{ m}/\text{min} \times 240 \text{ min} = 108 \text{ g}/\text{m}^2$$

$$S = 500 \text{ Pa}\cdot\text{min}/\text{m} + 3.5 \text{ Pa}\cdot\text{min}\cdot\text{m}/\text{g} \times 108 \text{ g}/\text{m}^2 = 878 \text{ Pa}\cdot\text{min}/\text{m}$$

$$? P = V \times S = 0.9 \text{ m}/\text{min} \times 878 \text{ Pa}\cdot\text{min}/\text{m} = 790 \text{ Pa}$$

Design and Selection of Pulse-Jet Baghouses.

Pulse-jet baghouses have been

introduced to the industry relatively recently (within the last 40 years), and have captured a large share of the baghouse market due to their advantages over traditional shaker or reverse-air methods of cleaning. In the pulse-jet baghouse, the bags are supported on wire cages, and the air is filtered from the outside of the bag to the inside, leaving the dust on the outside. A short pulse of high-pressure (about 100 psi) air is blasted through a venturi nozzle into the center of the bag, causing the fabric to ripple and knock off the dust from the outside. This happens every few minutes.

These baghouses are designed as one large compartment, and operate continuously. The bags are cleaned by this pulse of air every few minutes, but are not taken off-line during cleaning. In addition, the fabric used to make bags for a pulse-jet baghouse is much thicker and sturdier than that used in a shaker or reverse-air design, so the filtering velocity can be considerably higher in a pulse jet system than in the other types (see Table 8). This combination of higher filtering velocities and no extra compartments, allows the pulse-jet baghouse to be much smaller (for the same dusty air flow) than a traditional baghouse. This also makes the pulse-jet cheaper to buy.

Table 8. Pulse-jet Baghouses – Maximum Filtering Velocities

<u>Type of Dust</u>	<u>Max. Filtering Velocity, cfm/ft² or fpm*</u>
Graphite, detergents, carbon, metal fumes	5-6
Clay, plastics, starch, sugar, paint pigments	7-8
Aluminum oxide, cement, gypsum, lime, limestone, quartz, talc	9-11
Cocoa, chocolate, flour, grains, sawdust, tobacco	12-14

* fpm = ft/min

Adapted from *Cooper and Alley, 2002*.

A dusty gas from a gypsum processing operation is flowing at the rate of 30,000 cfm. A pulse jet baghouse is being considered. What design filtering velocity should you select, and how much fabric area will be needed?

Solution

From the table, the recommended design filtering velocity is 9-11 ft/min; let us choose 10 fpm. The total fabric area required will be $3,000 \text{ ft}^2$ ($= 30,000 \text{ cfm}/10 \text{ fpm}$).

Pulse jet baghouses have one disadvantage compared with shaker or reverse-air systems. A substantial air compressor is required to compress the air needed for pulse cleaning. This usage of compressed air is a major operating expense of pulse-jet baghouses, and can equal or exceed the cost of the main blower that moves the dusty air through the baghouse.

VII. Summary

Particulate matter (PM) is one of the primary forms of air pollution. PM is emitted from numerous industrial, mobile, residential and even natural sources. PM-10 and PM 2.5 are tiny particles that can be extremely deleterious to human health and can cause a variety of environmental problems, including impaired visibility even in areas far removed from the source. Particles have unique characteristics that influence how we may capture them and remove them from the gas stream. Efficient collection of particles is especially dependent on their size, but the calculation of collection efficiency is based only on the mass percent collected.

A number of devices have been developed to collect particles, among which are cyclones, wet scrubbers, ESPs and baghouses. Each device has advantages and disadvantages, and their costs may vary widely, thus making a site-specific engineering study imperative to find

the optimum solution to any particulate control problem. ESPs and baghouses are among the most efficient PM control devices, and are often used to control this form of air pollution.

ESPs operate by causing the gas to flow between plates with a high voltage drop between them. An electrical charge is placed on the particles and the particles drift over to and are collected on oppositely charged plates. The key design parameters are the gas flow, the drift velocity and the area of the plates. The plates are rapped at frequent intervals to knock the dust off the plates and into hoppers where it can be removed from the ESP and disposed of or recycled. ESPs are highly efficient and produce a very low pressure drop. But once they have been designed and constructed for a particular combination of gas conditions and type of dust, they cannot easily be adapted to other conditions.

Baghouses operate by forcing the gas to flow through fabric bags. The gas passes through the bag but the dust is caught and builds up on the fabric. This layer of dust then does the highly efficient filtering of small particles for which baghouses are known. The key design parameters are the gas volumetric flow rate, the superficial filtering velocity, the type of fabric, the net cloth area, and the number of compartments. The bags are cleaned by various methods that knock the dust off the bags and into hoppers where it is removed from the baghouse and recycled or disposed of. Baghouses are extremely efficient, and have a moderate pressure drop. The fabrics have temperature and humidity limitations, but are generally able to collect any type of dust.

Examination Questions

1. Of the five primary air pollutants discussed in this course, which one is not a gas?
 - a. VOC
 - b. CO
 - c. NO_x
 - d. SO₂
 - e. PM

2. Of the following sources of PM-10, which one has the highest annual emissions rate?
 - a. coal-fired power plants
 - b. petroleum refineries
 - c. waste disposal facilities
 - d. paved and unpaved roads

3. How big is a micron?
 - a. one one-hundredth of a meter
 - b. one one-thousandth of a meter
 - c. one one-millionth of a meter
 - d. one one-billionth of a meter

4. Which control device depends on spinning the particles in a vortex?
 - a. cyclone
 - b. baghouse
 - c. ESP
 - d. wet scrubber

5. The calculation of collection efficiency for a PM control device is based on:
 - a. the numbers of particles collected
 - b. the mass of the particles collected
 - c. the diameters of the particles collected

- d. the volume of particles collected
6. A particulate removal system consists of a cyclone followed by an electrostatic precipitator. The cyclone is 65% efficient and the ESP is 95% efficient. Calculate the overall efficiency of the system.
- a. 150%
 - b. 30.5%
 - c. 98.25%
 - d. 61.75%
7. A particulate removal system must achieve 99.4% overall efficiency. Calculate the required efficiency of a ESP if it is preceded by an 80% efficient cyclone.
- a. 19.4%
 - b. 95%
 - c. 97%
 - d. 99%
8. Assuming compliance with federal NSPS, the allowable daily rate of emissions of PM from a coal-fired power plant producing 800 MW of electrical power at an overall thermal efficiency of 40% is about:
- a. 1200 lb/day
 - b. 2700 lb/day
 - c. 3200 lb/day
 - d. 4900 lb/day
9. Which of the following statements is true about typical ESPs?

- a. ESPs have a high efficiency and high pressure drop
 - b. ESPs have a low efficiency and high pressure drop
 - c. ESPs have a high efficiency and low pressure drop
 - d. ESPs have a low efficiency and low pressure drop
10. In an ESP, the efficiency is directly proportional to:
- a. the volumetric flow rate of gas
 - b. the plate area
 - c. the resistivity of particles
 - d. the concentration of dust in the gas
11. The term “corona” refers to
- a. a measure of the resistivity
 - b. the effect of build-up of dust on the bags
 - c. the pulsing effect of high pressure air
 - d. the ionization of gas molecules by high energy electrons
12. Which of the following statements about coal fly ash is NOT true:
- a. resistivity decreases with increasing coal sulfur content
 - b. resistivity at first increases but later decreases with increasing temperature
 - c. collection efficiency is not influenced by changes in resistivity
 - d. resistivity of coal fly ash can range over 5 orders of magnitude
13. With regard to ESPs, the term “rapping” refers to:
- a. a modern style of singing
 - b. the cleaning of dust off the plates

- c. the knocking sound heard when an ESP malfunctions
- d. the plastic film that covers a new electrode when it is shipped

14. What is responsible for the highly efficient filtering of small particles in a baghouse?
- a. The finely woven cloth
 - b. The layers of fabric placed on top of one another
 - c. The wire mesh cages that support the fabric
 - d. The layer of dust that accumulates on the fabric
15. The air/cloth ratio is also known as:
- a. the superficial filtering velocity
 - b. the pulsing jet of cleaning air
 - c. volumetric flow rate of filtered air
 - d. the length/diameter ratio of filter bags
16. The areal dust density is a measure of
- a. the superficial filtering velocity
 - b. permeability of the dust layer
 - c. the weight of dust collected per square meter of fabric
 - d. the weight of dust collected per unit volume of air flow
17. Given a pressure drop of 6 Pa, and a superficial filtering velocity of 1.5 m/min, the Filter Drag is calculated to be:
- a. 4.0 Pa-min/m
 - b. 4.5 Pa-min/m
 - c. 7.5 Pa-min/m
 - d. 9.0 Pa-min/m

18. “Cleaning the dust off the bags is accomplished by a gentle air flow through the bags in a direction opposite to the normal filtering flow” describes the type of cleaning used by:
- a pulse-jet baghouse
 - a reverse-air baghouse
 - a shaker baghouse
 - a flow-splitter baghouse
19. Which type of baghouse is typically built with just one large compartment, and is cleaned while continuing to operate?
- a pulse-jet baghouse
 - a reverse-air baghouse
 - a shaker baghouse
 - a flow-splitter baghouse
20. Compressed air usage is a major cost of which kind of baghouse?
- a pulse-jet baghouse
 - a reverse-air baghouse
 - a shaker baghouse
 - a flow-splitter baghouse
21. When the center of mass of a particle strikes a stationary object, that mechanism of collection is called:
- impaction
 - interception
 - diffusion

d. streamlining

22. A particle has the best chance of being collected on an object if the value of the impaction number is:

a. 0.25

b. 0.75

c. 1.2

d. 3.5

23. If the fractional collection efficiency of a PM control device is 0.92, then the penetration of that device is:

a. -0.92

b. 0.08

c. 1.08

d. 1.92

24. What is one problem with a wet scrubber that you don't have with a cyclone, baghouse, or ESP?

a. Efficiency of collection is too low

b. Pressure drop is too high

c. Disposal of a wet sludge

d. Takes up too much space

25. Which particles would be collected best in a cyclone?

a. large, dense particles

b. small, light particles

- c. large, light particles,
 - d. small dense particles
26. Electrical power consumption in an ESP is relatively low because of:
- a. the low voltage
 - b. the low current flow
 - c. the low gas flow
 - d. the high efficiency
27. Total operating power consumption in an ESP is due mainly to corona power and:
- a. efficiency
 - b. rapping
 - c. pressure drop
 - d. power density
28. Pressure drop in an operating baghouse increases with:
- a. time on-line
 - b. amount of dust collected on the fabric
 - c. superficial filtering velocity
 - d. all of the above
29. What is the recommended maximum filtering velocity for cement dust in a shaker or reverse air baghouse?
- a. 2.0 ft/min
 - b. 2.5 ft/min
 - c. 3.0 ft/min

- d. 3.5 ft/min
30. What is the recommended maximum filtering velocity for cement dust in a pulse-jet baghouse?
- a. 5-6 ft/min
 - b. 7-8 ft/min
 - c. 9-11 ft/min
 - d. 12-14 ft/min
31. An ESP is to treat a gas stream flowing at $50,000 \text{ ft}^3/\text{min}$ with a 97.5 % efficiency. If the effective drift velocity is 12.0 ft/min, calculate the required plate area in ft^2 .
- a. 7,580 ft^2
 - b. 9,210 ft^2
 - c. 12,850 ft^2
 - d. 15,370 ft^2
32. An ESP is being designed. It is calculated that $20,000 \text{ ft}^2$ of collection plate area is needed, and it has been decided to use 4 sections in the direction of flow. Calculate the total number of plates in this ESP, if each plate is 8 ft long by 15 ft tall.
- a. 66
 - b. 88
 - c. 110
 - d. 132
33. The technique of adding a chemical such as ammonia or SO_3 into a flue gas to reduce particle resistivity and improve collection efficiency in an ESP is called:

- a. flue gas conditioning
 - b. flue gas scrubbing
 - c. flue gas partitioning
 - d. flue gas condensing
34. How many compartments would you specify for a shaker baghouse that requires 50,000 ft² of fabric area?
- a. 3
 - b. 5
 - c. 7
 - d. 9
35. What is the average filtering velocity for a baghouse with 50,000 ft² that is filtering 100,000 ft³/min?
- a. 2.0 fpm
 - b. 2.5 fpm
 - c. 3.0 fpm
 - d. 3.5 fpm
36. Why is it important to keep the superficial filtering velocity low in a baghouse?
- a. to keep the areal dust density low
 - b. to keep the pressure drop low
 - c. to keep the cleaning time low
 - d. to keep the hoppers full
37. What kind of standards deal with concentrations of pollutants in the outdoor atmosphere?

- a. ESP standards
- b. baghouse standards
- c. source performance standards
- d. ambient air quality standards

38. The distance it takes for a particle to come to rest in a fluid after the fluid has diverged from

its original direction is called the:

- a. characteristic time
- b. critical path
- c. stopping distance
- d. characteristic distance

39. What is a typical range of drift velocity in a coal fly ash ESP?

- a. 3 – 30 ft/min
- b. 1 – 2 ft/min
- c. 4 – 8 ft/sec
- d. none of the above

40. The Deutsch equation applies to the design of:

- a. a cyclone
- b. a wet scrubber
- c. an ESP
- d. a baghouse

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