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Control Devices, Technologies, and Systems

I. INTRODUCTION

One of the methods of controlling air pollution mentioned in the previous chapter is pollution removal. For pollution removal to be accomplished, the polluted carrier gas must pass through a control device or system, which collects or destroys the pollutant and releases the cleaned carrier gas to the atmosphere. The control device or system selected must be specific for the pollutant of concern. If the pollutant is an aerosol, the device used will, in most cases, be different from the one used for a gaseous pollutant. If the aerosol is a dry solid, a different device must be used than for liquid droplets.

Not only the pollutant itself but also the carrier gas, the emitting process, and the operational variables of the process affect the selection of the control system. Table 32.1 illustrates the large number of variables which must be considered in controlling pollution from a source [1–4].

Once the control system is in place, its operation and maintenance become a major concern. Important reasons for an operation and maintenance (O&M) program [2] are (1) the necessity of continuously meeting emission regulations, (2) prolonging control equipment life, (3) maintaining productivity of the process served by the control device, (4) reducing operation costs, (5) promoting

TABLE 32.1

Key Characteristics of Pollution Control Devices and/or Systems

Factor considered	Characteristic of concern
General	Collection efficiency Legal limitations such as best available technology Initial cost Lifetime and salvage value Operation and maintenance costs Power requirement Space requirements and weight Materials of construction Reliability Reputation of manufacturer and guarantees Ultimate disposal/use of pollutants
Carrier gas	Temperature Pressure Humidity Density Viscosity Dewpoint of all condensibles Corrosiveness Inflammability Toxicity
Process	Gas flow rate and velocity Pollutant concentration Variability of gas and pollutant flow rates, temperature, etc. Allowable pressure drop
Pollutant (if gaseous)	Corrosiveness Inflammability Toxicity Reactivity
Pollutant (if particulate)	Size range and distribution Particle shape Agglomeration tendencies Corrosiveness Abrasiveness Hygroscopic tendencies Stickiness Inflammability Toxicity Electrical resistivity Reactivity

better public relations and avoiding community alienation, and (6) promoting better relations with regulatory officials.

The O&M program has the following minimum requirements: (1) an equipment and record system with equipment information, warranties, instruction manuals, etc.; (2) lubrication and cleaning schedules; (3) planning and scheduling of preventive maintenance; (4) a storeroom and inventory system for spare parts and supplies; (5) listing of maintenance personnel; (6) costs and budgets for O&M; and (7) storage of special tools and equipment.

A. The Vacuum Cleaner: Particulate Matter Control Device

Controlling particulate matter (PM) emissions tracks fairly closely the homeowner demands for devices to remove dust, so let us consider the ubiquitous vacuum cleaner. We can learn much about this technology by visiting the local department store. Amelia has asked us to pick out the optimal vacuum cleaner. Please join me on the shopping trip.[1]

First, she has specified a cyclone system, not a bag system. All vacuum cleaners work on the principle of pressure differential. The laws of potentiality state that flow moves from high to low pressure. So, if pressure can decrease significantly below that of the atmosphere, air will move to that pressure trough. If there is a big pressure difference between air outside and inside, the flow will be quite rapid. So, the "vacuum" (it is really a pressure differential) is created inside the vacuum cleaner using an electric pump. When the air rushes to the low pressure region it carries particles with it. Increasing velocity is proportional to increasing mass and numbers of particles that can be carried. This is the same principle as the "competence" of a stream, which is high (i.e. can carry heavier loads) in a flowing river, but the competence declines rapidly at the delta where stream velocity approaches zero. This causes the river to drop its particles in descending mass, i.e. sedimentation of heavier particles first, but colloidal matter remaining suspended for much longer times.

Two of the most common types of particle collection systems in industry are cyclones and bag systems. The vacuum cleaner is a microcosm of both technologies. The vacuum cleaner, the cyclone, and the bag (fabric filter) are all designed to remove particles. In the US, the Clean Air Act established the national ambient air quality standards (NAAQS) for PM in 1971. These standards were first directed at total suspended particulates (TSP) as measured by a high-volume sampler, i.e. a device that collected a large range of sizes of particles (aerodynamic diameters up to 50 μm). Particles aggravate bronchitis, asthma, and other respiratory diseases. Certain subpopulations of people are sensitive to PM effects, including those with asthma, cardiovascular or lung disease, as well as children and elderly people. Particles can also damage structures, harm vegetation, and reduce visibility. In 1987, the Environmental Protection Agency (EPA) changed the indicator for PM from TSP to PM_{10}, i.e. particle matter $\leq 10\,\mu m$ diameter.[2] The NAAQS for PM_{10}

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[1] This is for the most part a true story. In fact, Amelia is my daughter.

[2] The diameter most often used for airborne particle measurements is the "aerodynamic diameter." The aerodynamic diameter (D_{pa}) for all particles greater than 0.5 μm can be approximated as the product of the Stokes particle diameter (D_{ps}) and the square root of the particle density (ρ_p):

$$D_{pa} = D_{ps}\sqrt{\rho_p} \qquad (32.12)$$

(continued)

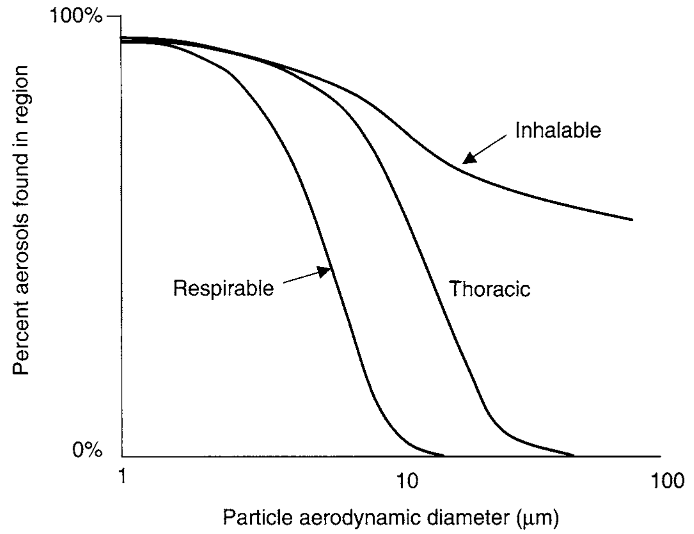

Fig. 32.1. Three regions of the respiratory system where particle matter is deposited. The inhalable fraction remains in the mouth and head area. The thoracic fraction is the mass that penetrates the airways of the respiratory system, while the smallest fraction, i.e. the respirable particulates are those that can infiltrate most deeply into the alveolar region.

was a 24-h average of 150 μg m^{-3} (not to exceed this level more than once per year), and an annual average of 50 μg m^{-3} arithmetic mean. However, even this change did not provide sufficient protection for people breathing PM contaminated air, since most of the particles that penetrate deeply into the air–blood exchange regions of the lung are quite small (see Fig. 32.1). So, in 1997, the US EPA added a new fine particle (diameters ≤ 2.5) known as $PM_{2.5}$.[3]

In a cyclone (Fig. 32.2), air is rapidly circulated causing suspended particles to change directions.

Due to their inertia, the particles continue in their original direction and leave the air stream (see Fig. 32.3). This works well for larger particles because of their relatively large masses (and greater inertia), but very fine particles are more likely to remain in the air stream and stay suspended. The dusty air is

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If the units of the diameters are in μm, the units of density are g cm^{-3}.

The Stokes diameter D_{ps} is the diameter of a sphere with the same density and settling velocity as the particle. The Stokes diameter is derived from the aerodynamic drag force caused by the difference in velocity of the particle and the surrounding fluid. Thus, for smooth, spherical particles, the Stokes diameter is identical to the physical or actual diameter.

Aerosol textbooks provide methods to determine the aerodynamic diameter of particles less than 0.5 μm. For larger particles gravitational settling is more important and the aerodynamic diameter is often used.

[3] For information regarding particle matter (PM) health effects and inhalable, thoracic and respirable PM mass fractions see US Environmental Protection Agency, 1996, Air Quality Criteria for Particulate Matter. Technical Report No. EPA/600/P-95/001aF, Washington, DC.

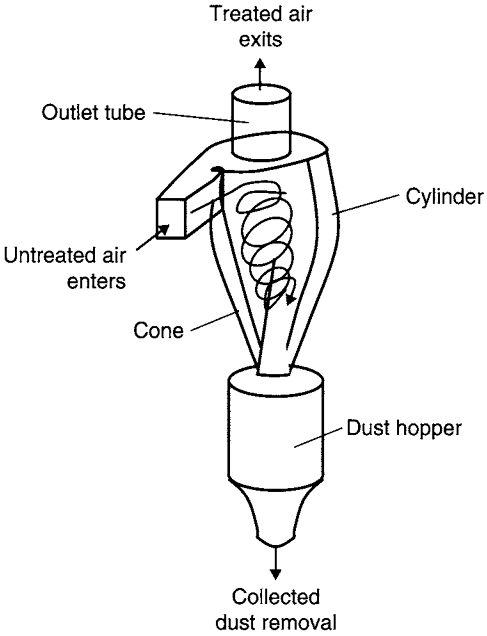

Fig. 32.2. Schematic of a simple cyclone separator. *Source*: US Environmental Protection Agency, 2004, Air Pollution Control Orientation Course, http://www.epa.gov/air/oaqps/eog/course422/ce6.html; accessed September 20, 2004.

introduced in the cyclone from the top through the inlet pipe tangential to the cylindrical portion of the cyclone. The air whirls downward to form a peripheral vortex, which creates centrifugal forces. As a result individual particles are hurled toward the cyclone wall and, after impact, fall downward where they are collected in a hopper. When the air reaches the end of the conical segment, it will change direction and move upward toward the outlet. This forms an inner vortex. The upward airflow against gravitation allows for additional separation of particles. The cyclone vacuum cleaner applies the same inertial principles, with the collected dust hitting the sides of the removable cyclone separator and falling to its bottom.

The other technology of vacuum cleaners is the bag. Actually, the engineering term for a "bag" is a fabric filter. Filtration is an important technology in every aspect of environmental engineering (i.e. air pollution, waste water treatment, drinking water, and even hazardous waste and sediment cleanup). Basically, filtration consists of four mechanical processes: (1) diffusion, (2) interception, (3) inertial impaction, and (4) electrostatics (see Fig. 32.4). Diffusion is important only for very small particles ($\leq 0.1\,\mu m$ diameter) because the Brownian motion allows them to move in a "random walk" away from the air stream. Interception works mainly for particles with diameters between 0.1 and $1\,\mu m$. The particle does not leave the air stream but comes into contact with the filter medium (e.g. a strand of fiberglass or fabric fiber). Inertial impaction, as explained in the

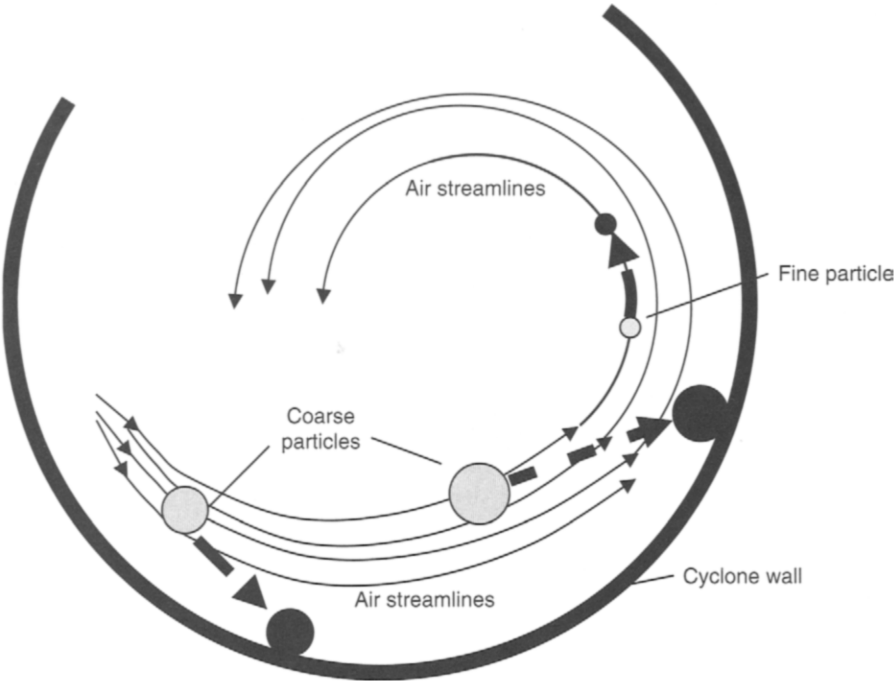

Fig. 32.3. Inertial forces in a cyclone separator. Coarse (heavier) particles' inertial forces are large enough that they leave the air stream of the vortex and collide with the cyclone wall. Fine particles have smaller mass so that their inertial forces cannot overcome the air flow, so they remain suspended in the air stream.

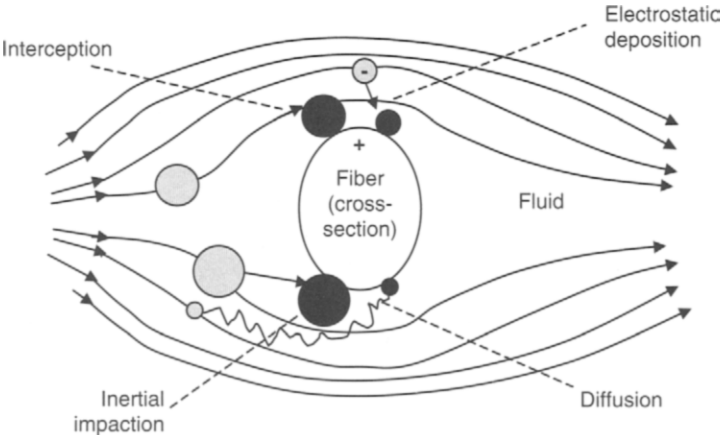

Fig. 32.4. Mechanical processes important to filtration. Adapted from: Rubow, K. L., Filtration: fundamentals and applications, in *Aerosol and Particle Measurement Short Course*. University of Minnesota, Minneapolis, MN, August 16–18, 2004.

cyclone discussion, collects particles sufficiently large to leave the air stream by inertia (diameters $\geqslant 1\,\mu m$). Electrostatics consist of electrical interactions between the atoms in the filter and those in the particle at the point of contact (Van der Waal's force), as well as electrostatic attraction (charge differences between particle and filter medium). These are the processes at work in large scale electrostatic precipitators (ESPs) that are employed in coal-fired power plant stacks around the world for particle removal. Other important factors affecting filtration efficiencies include the thickness and pore diameter or the filter, the uniformity of particle diameters and pore sizes, the solid volume fraction, the rate of particle loading onto the filter (e.g. affecting particle "bounce"), the particle phase (liquid or solid), capillarity and surface tension (if either the particle or the filter media are coated with a liquid), and characteristics of air or other carrier gases, such as velocity, temperature, pressure, and viscosity.

Environmental engineers have been using filtration to treat air and water for several decades. Air pollution controls employing fabric filters (i.e. baghouses), remove particles from the air stream by passing the air through a porous fabric. The fabric filter is efficient at removing fine particles and can exceed efficiencies of 99%. Based solely on an extrapolation of air pollution control equipment, a bag-type vacuum cleaner should be better than a cyclone-type vacuum cleaner. However, this does not take into operational efficiencies and effectiveness, which are very important to the consumer and the engineer. Changing the bag and insuring that it does not exceed its capacity must be monitored closely by the user. Also, the efficiency of the vacuum cleaner is only as good as the materials being used. Does the bag filter allow a great deal of diffusion, interception, and inertial impaction? The cyclone only requires optimization for inertia.

Selecting the correct control device is a matter of optimizing efficiencies. Which brings us to Amelia's second selection criterion, i.e. the vacuum must have a HEPA filter. I am not sure if she knows that the acronym stands for "high-efficiency particle air" filters, but she knows that it is needed to remove more of the "nasty" dust. In this case, HEPA filters are fitted to equipment to enhance "efficiency." Efficiency is often expressed as a percentage. So a 99.99% HEPA filter is efficient enough to remove 99.99% particles from the air stream. This means that if 10 000 particles enter the filter, on average only one particle would pass all the way through the filter. This is exactly the same concept that we use for incinerator efficiency, but it is known as destruction removal efficiency (DRE). For example, in the US, federal standards require that hazardous compounds can only be incinerated if the process is 99.99% efficient, and for the "nastier" compounds (i.e. "extremely hazardous wastes") the so-called "rule of six nines" applies (i.e. DRE $\geqslant$99.9999%). The HEPA and DRE calculations are quite simple:

$$\text{DRE or HEPA efficiency} = \frac{M_{\text{in}} - M_{\text{out}}}{M_{\text{in}}} \times 100 \tag{32.1}$$

Thus, if $10\,\text{mg}\,\text{min}^{-1}$ of a hazardous compound is fed into the incinerator, only $0.001\,\text{mg}\,\text{min}^{-1} = 1\,\mu\text{g}\,\text{min}^{-1}$ is allowed to exit the stack for a hazardous waste. If the waste is an extremely hazardous waste, only 0.00001 mg $\text{min}^{-1} = 0.01\,\mu\text{g min}^{-1} = 10\,\text{ng min}^{-1}$ is allowed to exit the stack. Actually, this same equation is used throughout the environmental engineering discipline to calculate treatment and removal efficiencies. For example, assume that raw wastewater enters a treatment facility with $300\,\text{mg L}^{-1}$ biochemical oxygen demand (BOD_5), $200\,\text{mg L}^{-1}$ suspended solids (SS), and $10\,\text{mg L}^{-1}$ phosphorous (P). The plant must meet effluent standards $\leq 10\,\text{mg L}^{-1}$ BOD_5, $\leq 10\,\text{mg L}^{-1}$ SS, and $\leq 1\,\text{mg L}^{-1}$ P, so using the efficiency equation we know that removal rates of these contaminants must be 97% for BOD_5, 95% for SS, and 90% for P. The pure efficiency values may be misleading because the ease of removal can vary significantly with each contaminant. In this case, gravitational settling in the primary stages of the treatment plant can remove most of the SS, and the secondary treatment stage removes most of the BOD, but more complicated, tertiary treatment is needed for removing most of the nutrient P.

As I shopped for the cyclone-HEPA vacuum cleaner, I came across some additional technical terminology (i.e. "allergen removal"). I am not completely certain what this means, but I believe it is a filtration system that does not quite have the efficiency removal of a HEPA filter. However, this points out the somewhat chaotic nature of environmental engineering. Remember, the smaller particles are the ones that concern most health scientists. However, there has been a resurgence of interest in particles ranging between 2.5 and 10 μm aerodynamic diameter, referred to as coarse particles. These may consist of potentially toxic components, for example, resuspended road dust, brake lining residues, industrial byproducts, tire residues, heavy metals, and aerosols generated by organisms spores (known as "bioaerosols"), such as tree pollen and mold spores. Figure 32.1 shows that a large fraction of these coarse particles may deposit to the upper airways, causing health scientists to link them to asthma. And, since asthma appears to be increasing in children, there may be a need to reconsider the importance of larger particles. In fact, the US EPA is considering ways to develop a federal reference method (FRM)[4] for coarse particles to complement its $PM_{2.5}$ FRM.

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[4] The FRM is certified reference analogous to the National Institute for Standards and Testing (NIST) standard reference material (SRM), which is standard of known quality to be used by scientists and engineers, allowing them:

(a) to help to develop and validate representative and accurate methods of analysis,
(b) to verify that tests meet validated performance criteria,
(c) to calibrate systems of measurements,
(d) to establish acceptable quality assurance (QA) programs,
(e) to provide test materials for inter-laboratory and inter-study comparisons and proficiency test programs.

Rather than materials, however, the FRM applies to environmental measurement equipment against which all other equipment is compared. For example, in ambient monitoring the US federal standard method dictates how to monitor a specific pollutant, such as aerosols or sulfur dioxide (SO_2). The FRM may be specified by technique (such as a particular physical principle, like a gravimetric or an optical technique for estimating mass) for or by design (such as a particular system for collecting and weighing particles).

Thus, equipment selection has been complicated by some fairly technical specifications. Efficiency is an important part of effectiveness, although the two terms are not synonymous. As we discussed, efficiency is simply a metric of what you get out of a system compared to what you put in. However, you can have a bunch of very efficient systems that may *en toto* be ineffective. They are all working well as designed, but they may not be working on the right things, or their overall configuration is not optimal to solve the problem at hand. So, the correct control device is the one that gives not only optimal efficiency, but one that effectively addresses the specific pollution problem at hand.

II. REMOVAL OF DRY PM

Dry aerosols, or particulate matter (PM), differ so much from the carrying gas stream that their removal should present no major difficulties. The aerosol is different physically, chemically, and electrically. It has vastly different inertial properties than the carrying gas stream and can be subjected to an electric charge. It may be soluble in a specific liquid. With such a variety of removal mechanisms that can be applied, it is not surprising that PM, such as mineral dust, can be removed by a filter, wet scrubber, or ESP with equally satisfactory results.

A. Filters

A filter removes PM from the carrying gas stream because the particulate impinges on and then adheres to the filter material. As time passes, the deposit of PM becomes greater and the deposit itself then acts as a filtering medium. When the deposit becomes so heavy that the pressure necessary to force the gas through the filter becomes excessive, or the flow reduction severely impairs the process, the filter must either be replaced or cleaned.

The filter medium can be fibrous, such as cloth; granular, such as sand; a rigid solid, such as a screen; or a mat, such as a felt pad. It can be in the shape of a tube, sheet, bed, fluidized bed, or any other desired form. The material can be natural or man-made fibers, granules, cloth, felt, paper, metal, ceramic, glass, or plastic. It is not surprising that filters are manufactured in an infinite variety of types, sizes, shapes, and materials.

The theory of filtration of aerosols from a gas stream is much more involved than the sieving action which removes particles in a liquid medium. Figure 32.4 shows three of the mechanisms of aerosol removal by a filter, as well as diffusion (which can be important for very small particles). In practice, the particles and filter elements are seldom spheres or cylinders.

Direct interception occurs when the fluid streamline carrying the particle passes within one-half of a particle diameter of the filter element. Regardless of the particle's size, mass, or inertia, it will be collected if the streamline passes sufficiently close. Inertial impaction occurs when the particle would miss the filter element if it followed the streamline, but its inertia resists the change in direction taken by the gas molecules and it continues in a direct enough course to be collected by the filter element. Electrostatic attraction occurs because the particle, the filter, or both possess sufficient electrical charge to overcome the inertial forces; the particle is then collected instead of passing the filter element. Note that size separation ("sieving") plays little or no role in filtration.

1. *Filter Efficiency*

Particles can be measured as either mass or count. Particle count is the number of particles in a given band of mass, such as particles with aerodynamic diameters greater than 10 μm (coarse fraction), those with diameters less than 10 μm, but greater than 2.5 μm (PM_{10} fraction), and those with diameters less than 2.5 μm ($PM_{2.5}$ fraction, also known as the fine fraction). However, the bands can be further subdivided. For example, there has been concern recently about the so-called "nanoparticles." These have diameters less than 100 nm. Filtration is the most common method used to measure particles in the air. So, a sample taken from a filter could show bands within the fine fraction may resemble that shown in Table 32.2.

Since filtration is important in both measuring and controlling particle matter, expressions of filter efficiency are crucial to air pollution technologies. Equation 32.1 provides the overall efficiency of any air pollution removal equipment. The efficiency (E) equation can be restated specifically for particles:

$$E = \frac{N_{\mathrm{m}} + N_{\mathrm{out}}}{N_{\mathrm{m}}} \tag{32.2}$$

$$E_{\mathrm{m}} = \frac{C_{\mathrm{m}} + C_{\mathrm{out}}}{C_{\mathrm{m}}} \tag{32.3}$$

Where N is the number of particles (count) and C is the mass concentration (m: entering; out: exiting). Note the similarity between Eqs (32.2) and (32.3) and DRE [Eq. (32.1)].

TABLE 32.2

Mass of Particles Collected on a Filter (Fictitious Data)

Size range (μm)	Count (number of particles)	Mass (μg)	Flow rate (L min^{-3})	Integration time (min)	Mass concentration (μg m^{-3})	Description
>10	2	100	16	60	96	Reentrained dust
>2.5 < 10	20	10	16	60	9.6	Tailpipe emission
>0.01 < 2.5	200	1	16	60	0.96	Suspended colloids
<0.01	20 000	0.1	16	60	0.096	Nanoparticles; mainly carbon (fullerenes = C-60)

Pollution control equipment often characterizes efficiency in terms of the fraction entering versus that exiting the filter known as particle penetration (P):

$$P = \frac{N_{\text{out}}}{N_{\text{m}}} = 1 - E \tag{32.4}$$

$$P = \frac{C_{\text{out}}}{C_{\text{m}}} = 1 - E_{\text{m}} \tag{32.5}$$

Obviously, penetration and efficiency are inversely related, so if a filter inefficient a large number or mass of particles is penetrating the filter. This is obviously not good, so the air pollution engineer needs to specify the tolerances for filtration in any design of measurement or control technologies. Inherent to penetration calculations is the velocity of air entering the system. The front (entry side) of the filter is known as the face, so face velocity (U_0) is the air's velocity just before the air enters the filter:

$$U_0 = \frac{Q}{A} \tag{32.6}$$

where Q is the volumetric flow and A is the area of the cross section through which the air is passing. However, since the flow is restricted to the void spaces of the filter, the actual velocity in the filter itself is higher than the face velocity (same air mass through less volume). This is true for flow through any porous medium, such as polyurethane traps (see Fig. 16.2) and columns of sorbant granules, like XAD resins. Thus the velocity within the filter (U_{filter}):

$$U_{\text{filter}} = \frac{Q}{A(1-\alpha)} \tag{32.7}$$

where α is the packing density (solidity),[5] which is inverse to the filter (or trap) porosity:

$$\alpha = \frac{\text{filter fiber volume}}{\text{total filter volume}} = 1 - \text{porosity} \tag{32.8}$$

It is tempting to think of filters as sieves; however, they are really quite different. In fact, fibrous filters are more akin to numerous microscopic layers of filters, each with a specific probability of catching a particle, depending on the particle's shape and size. Therefore, the efficiency is enhanced with filter thickness.[6] Recall, that size capture is not one of the most important

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[5] This is analogous to bulk density used by soil scientists.

[6] For more information on monodisperse aerosols and collection probabilities, see Chapter 9, Filtration, in *Aerosol Technology*, 2nd ed. (Hinds, W. C., ed.). Wiley-Interscience, New York).

mechanisms for collection, compared to inertial impaction, interception, and electrostatics (see Fig. 32.4).

Other lesser mechanisms that result in aerosol removal by filters are (1) gravitational settling due to the difference in mass of the aerosol and the carrying gas, (2) thermal precipitation due to the temperature gradient between a hot gas stream and the cooler filter medium which causes the particles to be bombarded more vigorously by the gas molecules on the side away from the filter element, and (3) Brownian deposition as the particles are bombarded with gas molecules that may cause enough movement to permit the aerosol to come in contact with the filter element. Brownian motion may also cause some of the particles to miss the filter element because they are moved away from it as they pass by.

Regardless of the mechanism which causes the aerosol to come in contact with the filter element, it will be removed from the gas stream only if it adheres to the surface. Aerosols arriving later at the filter element may then, in turn, adhere to the collected aerosol instead of the filter element. The result is that actual aerosol removal seldom agrees with theoretical calculations. One should also consider that certain particles do not adhere to the filter element even though they touch it. As time passes, the heavier deposits on the filter surface will be dislodged more easily than the light deposits, resulting in increased reentrainment. Because of plugging of the filter with time, the apparent size of the filter element increases, causing more interception and impaction. The general effect of all of these variables on the particle buildup and reentrainment is shown in Fig. 32.5.

The pressure drop through the filter is a function of two separate effects. The clean filter has some initial pressure drop. This is a function of filter material, depth of the filter, the superficial gas velocity, which is the gas velocity perpendicular to the filter face, and the viscosity of the gas. Added to the clean filter resistance is the resistance that occurs when the adhering particles form a cake on the filter surface. This cake increases in thickness as approximately a linear function of time, and the pressure difference necessary to cause the same gas flow also becomes a linear function with time. Usually, the pressure available at the filter is limited so that as the cake builds up the flow decreases. Filter cleaning can be based, therefore, on (1) increased pressure drop across the filter, (2) decreased volume of gas flow, or (3) time elapsed since the last cleaning.

Industrial filtration systems may be of many types. The most common type is the baghouse shown in Fig. 32.6. The filter bags are fabricated from woven material, with the material and weave selected to fit the specific application. Cotton and synthetic fabrics are used for relatively low temperatures, and glass cloth fabrics can be used for elevated temperatures, up to 290°C.

The filter ratio for baghouses, also called the *gas to cloth ratio*, varies from 0.6 to 1.5 m^3 of gas per minute per square meter of fabric. The pressure drop across the fabric is a function of the filter ratio; it ranges from about 80 mm of water for the lower filter ratios up to about 200 mm of water for the higher ratios. Before selecting any bag filter system, a thorough engineering study

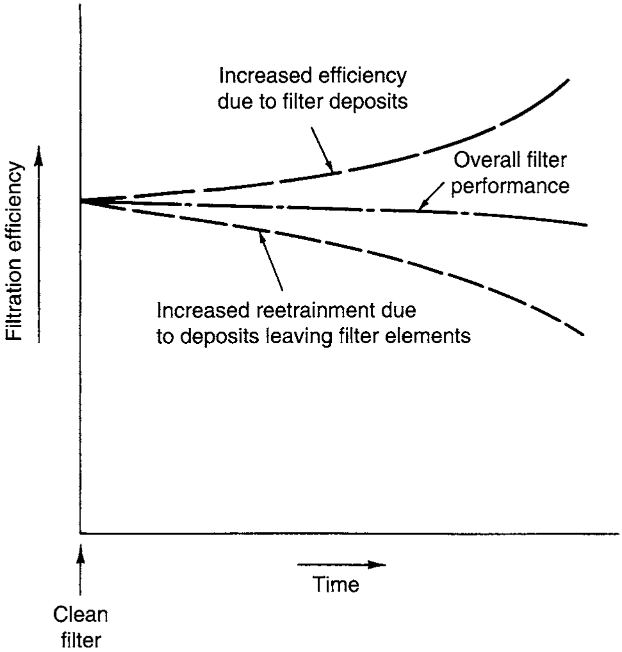

Fig. 32.5. Filtration efficiency change with time.

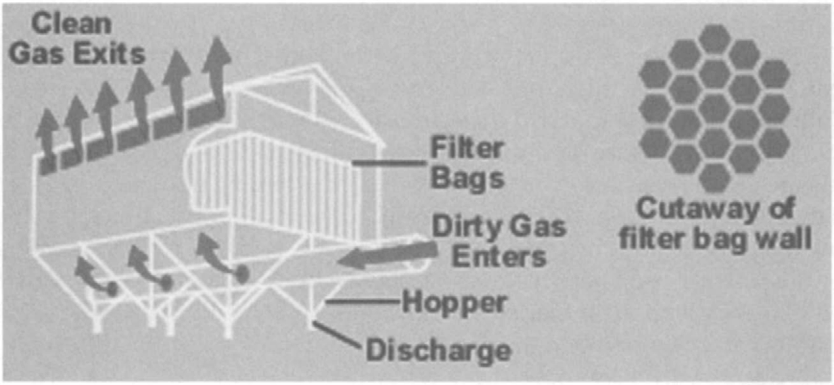

Fig. 32.6. Industrial baghouse. *Source*: U.S. Environmental Protection Agency; Air Pollution Control Orientation Course, "Source Control Technology; Control of Particulate Pollutants from Stationary Sources: Fabric Filters": www.epa.gov/apti/course422/images/baghouse.jpg; accessed on June 30, 2007.

should be made, followed by a consultation with different bag and baghouse manufacturers.

The bags must be periodically cleaned to remove the accumulated PM (Note in Fig. 32.5 the general downward trend in efficiency with time). Bag cleaning methods vary widely with the manufacturer and with baghouse style and use. Methods for cleaning include (1) mechanical shaking by agitation of the top hanger, (2) reverse flow of gas through a few of the bags at a time, (3) continuous cleaning with a reverse jet of air passing through a series of orifices on a ring as it moves up and down the clean side of the bag, and (4) collapse and pulsation cleaning methods.

The cleaning cycles are usually controlled by a timing device which deactivates the section being cleaned. The dusts removed during cleaning are collected in a hopper at the bottom of the baghouse and then removed, through an air lock or star valve, to a bin for ultimate disposal.

Other types of industrial filtration systems include (1) fixed beds or layers of granular material such as coke or sand; some of the original designs for cleaning large quantities of gases from smelters and acid plants involved passing the gases through such beds; (2) plain, treated, or charged mats or pads (common throw-away air filters used for hot air furnaces and for air conditioners are of this type); (3) paper filters of multiple plies and folds to increase filter efficiency and area (the throwaway dry air filters used on automotive engines are of this type); (4) rigid porous beds which can be made of metal, plastic, or porous ceramic (these materials are most efficient for removal of large particles such as the 30-μm particles from a wood sanding operation); and (5) fluidized beds in which the granular material of the bed is made to act as a fluid by the gas passing through it. Most fluidized beds are used for heat or mass transfer. Their use for filtration has not been extensive.

B. Electrostatic Precipitators

High-voltage ESPs have been widely used throughout the world for particulate removal since they were perfected by Fredrick Cottrell early in the twentieth century [5]. Most of the original units were used for recovery of process materials, but today gas cleaning for air pollution control is often the main reason for their installation. The ESP has distinct advantages over other aerosol collection devices: (1) it can easily handle high-temperature gases, which makes it a likely choice for boilers, steel furnaces, etc.; (2) it has an extremely small pressure drop, so that fan costs are minimized; (3) it has an extremely high-collection efficiency if operated properly on selected aerosols (many cases are on record, however, in which relatively low efficiencies were obtained because of unique or unknown dust properties); (4) it can handle a wide range of particulate sizes and dust concentrations (most precipitators work best on particles smaller than 10 μm, so that an inertial precleaner is often used to remove the large particles); and (5) if it is properly designed and constructed, its operating and maintenance costs are lower than those of any other type of particulate collection system. The ESP takes advantage of the electrostatics of particles (see Fig. 32.4). The particles move advectively with the gas stream, which is travelling horizontally through the ESP unit (into the photograph shown in Fig. 32.7). The particles become charged and then are attracted by the charge differential to either side, where they are captured.

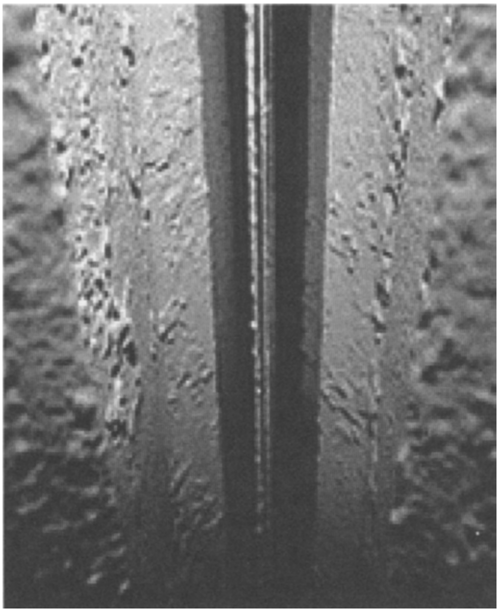

Fig. 32.7. View inward of a single gas passage through an electrostatic precipitator. The opening is about 20 cm.

Three of the disadvantages of ESPs are as follows: (1) the initial cost is the highest of any particulate collection system, (2) a large amount of space is required for the installation, and (3) ESPs are not suitable for combustible particles such as grain or wood dust.

The ESP works by charging dust with ions and then collecting the ionized particles on a surface. The collection surfaces may consist of either tubular or flat plates. For cleaning and disposal, the particles are then removed from the collection surface, usually by rapping the surface.

A high-voltage (30 kV or more) DC field is established between the central wire electrode and the grounded collecting surface. The voltage is high enough that a visible corona can be seen at the surface of the wire. The result is a cascade of negative ions in the gap between the central wire and the grounded outer surface. Any aerosol entering this gap is both bombarded and charged by these ions. The aerosols then migrate to the collecting surface because of the combined effect of this bombardment and the charge attraction. When the particle reaches the collecting surface, it loses its charge and adheres because of the attractive forces existing. It should remain there until the power is shut off and it is physically dislodged by rapping, washing, or sonic means.

In a tube-type ESP, the tubes are 8–25 cm in diameter and 1–4 m long. They are arranged vertically in banks with the central wires, about 2 mm in diameter, suspended in the center with tension weights at the bottom. Many innovations, including square, triangular, and barbed wires, are used by different manufacturers.

A plate-type ESP is similar in principle to the tubular type except that the air flows across the wires horizontally, at right angles to them. The particles are collected on vertical plates, which usually have fins or baffles to strengthen them and prevent dust reentrainment. Figure 32.8 illustrates a large plate-type precipitator. These precipitators are usually used to control and collect dry dusts.

Problems with ESPs develop because the final unit does not operate at ideal conditions. Gas channeling through the unit can result in high dust loadings in one area and light loads in another. The end result is less than optimum efficiency because of much reentrainment. The resistivity of the dust greatly affects its reentrainment in the unit. If a high-resistance dust collects on the plate surface, the effective voltage across the gap is decreased. Some power plants burning high-ash, low-sulfur coal have reported very low efficiency from the precipitator because the ash needed more SO_2 to decrease its resistivity. The suggestion that precipitator efficiency could be greatly improved by *adding* SO_2 or SO_3 to the stack gases has, not surprisingly, met with much skeptism.

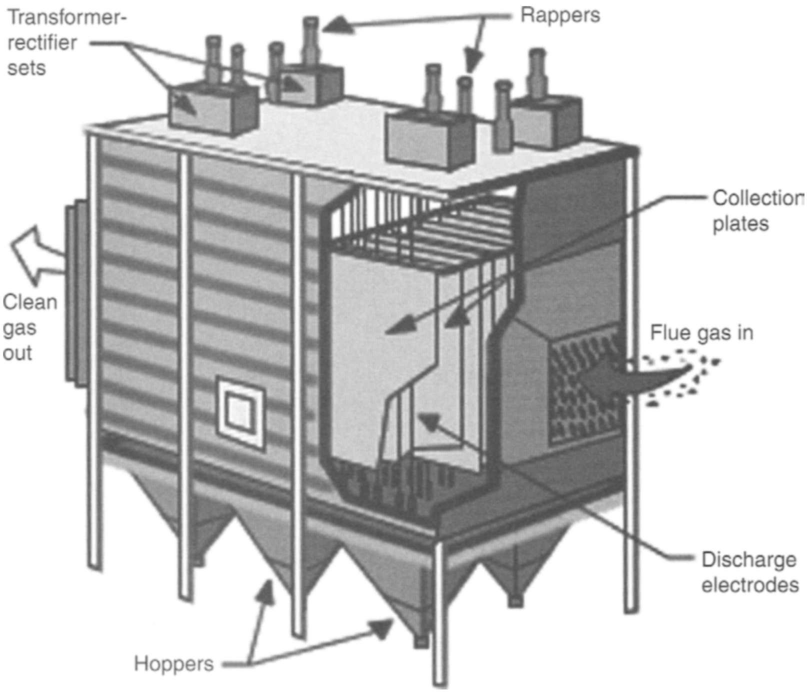

Fig. 32.8. Commercial plate-type ESP. *Source*: U.S. Environmental Protection Agency. "Basic Concepts in Environmental Sciences—Module 6: Air Pollutants and Control Techniques"; http://www.epa.gov/eogapti1/module6/matter/control/control.htm; accessed on June 30, 2007.

C. Inertial Collectors

Inertial collectors, whether cyclones, baffles, louvers, or rotating impellers, operate on the principle that the aerosol material in the carrying gas stream has a greater inertia than the gas. Since the drag forces on the particle are a function of the diameter squared and the inertial forces are a function of the diameter cubed, it follows that as the particle diameter increases, the inertial (removal) force becomes relatively greater. Inertial collectors, therefore, are most efficient for larger particles. The inertia is also a function of the mass of the particle, so that heavier particles are more efficiently removed by inertial collectors. These facts explain why an inertial collector will be highly efficient for removal of 10-μm rock dust and very inefficient for 5-μm wood particles. It would be very efficient, though, for 75-μm wood particles.

The most common inertial collector is the cyclone, which is used in two basic forms: the tangential inlet and the axial inlet. Figure 32.9 shows the two types.

In actual industrial practice, the tangential inlet type is usually a large (1–5 m in diameter) single cyclone, while the axial inlet cyclone is relatively small (about 20 cm in diameter and arranged in parallel units for the desired capacity).

For any cyclone, regardless of type, the radius of motion (curvature), the particle mass, and the particle velocity are the three factors which

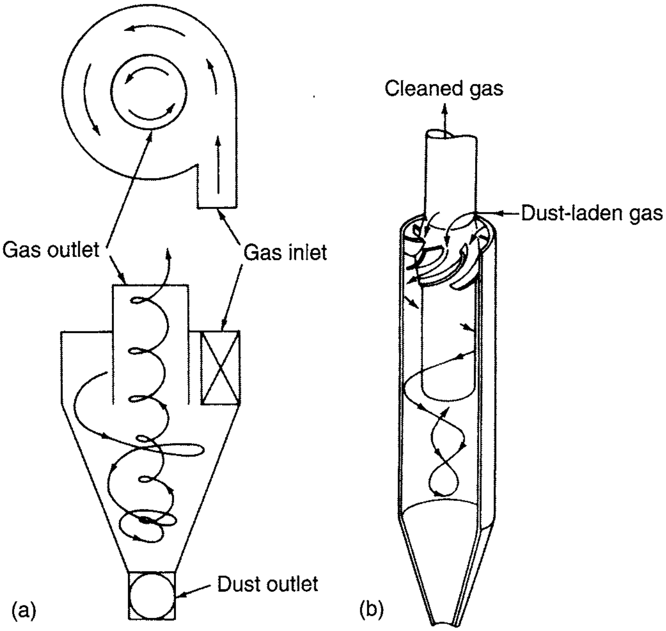

Fig. 32.9. (a) Tangential inlet cyclone. (b) Axial inlet cyclone.

determine the centrifugal force exerted on the particle. This centrifugal force may be expressed as

$$F = MA \tag{32.9}$$

where F: force (centrifugal), M: mass of the particle, and A: acceleration (centrifugal), and

$$A = \frac{V^2}{R} \tag{32.10}$$

where V: velocity of particle and R: radius of curvature. Therefore:

$$F = \frac{MV^2}{R} \tag{32.11}$$

Other types of inertial collectors which might be used for particulate separation from a carrying gas stream depend on the same theoretical principles developed for cyclones. Table 32.3 summarizes the effect of the common variables on inertial collector performance.

Although decreasing the radius of curvature and increasing the gas velocity both result in increased efficiency, the same changes cause increased pressure drop through the collector. Design of inertial collectors for maximum efficiency at minimum cost and minimum pressure drop is a problem which lends itself to computer optimization. Unfortunately, many inertial collectors, including the majority of the large single cyclones, have been designed to fit a standard-sized sheet of metal rather than a specific application and gas velocity. As tighter emission standards are adopted, inertial collectors will probably become precleaners for the more sophisticated gas cleaning devices.

D. Scrubbers

Scrubbers, or wet collectors, have been used as gas cleaning devices for many years. However, the process has two distinct mechanisms which result

TABLE 32.3

Effect of Independent Variables on Inertial Collector Efficiency

Independent variable of concern	Increase or decrease to improve efficiency
Radius of curvature	Decrease
Mass of particle	Increase
Particle diameter	Increase
Particle survace/volume ratio	Decrease
Gas velocity	Increase
Gas viscosity	Decrease

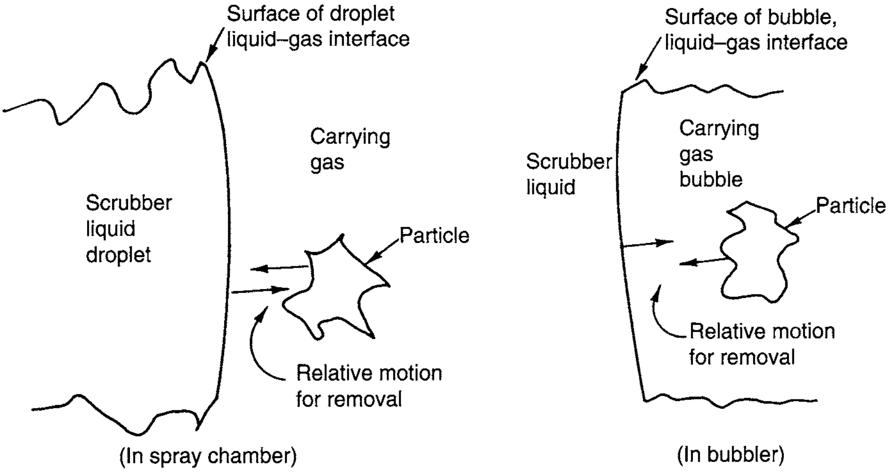

Fig. 32.10. Wetting of aerosols in a spray chamber or bubbler.

in the removal of the aerosol from the gas stream. The first mechanism involves wetting the particle by the scrubbing liquid. As shown in Fig. 32.10, this process is essentially the same whether the system uses a spray to atomize the scrubbing liquid or a diffuser to break the gas into small bubbles. In either case, it is assumed that the particle is trapped when it travels from the supporting gaseous medium across the interface to the liquid scrubbing medium. Some relative motion is necessary for the particle and liquid–gas interface to come in contact. In the spray chamber, this motion is provided by spraying the droplets through the gas so that they impinge on and make contact with the particles. In the bubbler, inertial forces and severe turbulence achieve this contact. In either case, the smaller the droplet or bubble, the greater the collection efficiency. In the scrubber, the smaller the droplet, the greater the surface area for a given weight of liquid and the greater the chance for wetting the particles. In a bubbler, smaller bubbles mean not only that more interface area is available but also that the particles have a shorter distance to travel before reaching an interface where they can be wetted.

The second mechanism important in wet collectors is removal of the wetted particles on a collecting surface, followed by their eventual removal from the device. The collecting surface can be in the form of a bed or simply a wetted surface. One common combination follows the wetting section with an inertial collector which then separates the wetted particles from the carrying gas stream.

Increasing either the gas velocity or the liquid droplet velocity in a scrubber will increase the efficiency because of the greater number of collisions per unit time. The ultimate scrubber in this respect is the venturi scrubber, which operates at extremely high gas and liquid velocities with a very high pressure drop across the venturi throat. Figure 32.11 illustrates a commercial venturi scrubber unit.

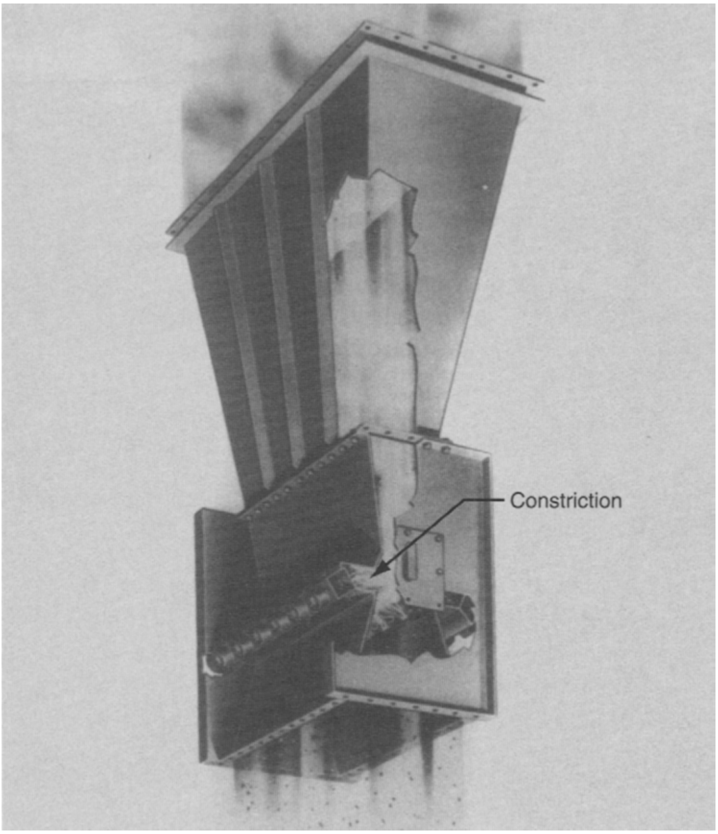

Fig. 32.11. Venturi scrubber; so-called since the velocity of the air is increased as it moves through a constricting channel. *Source*: American Air Fitter Company.

E. Dry Scrubbers

Dry scrubber is a term that has been applied to gravel bed filters that recirculate the gravel filter medium using some type of external cleaning or washing system. Some units also use an electrostatic field across the gravel bed to enhance removal of the particulate material. The dry scrubber may have to be followed by a baghouse to clean the effluent to acceptable standards. The advantage of dry scrubbers is their ability to remove large quantities of particulate pollutants, such as fly ash, from hot gas streams.

F. Comparison of Particulate Removal Systems

When selecting a system to remove particulate from a gas stream, many choices concerning equipment can be made. The selection could be made on the basis of cost, gas pressure drop, efficiency, temperature, resistance, etc. Table 32.4 summarizes these factors for comparative purposes. The tabular

TABLE 32.4

Comparison of Particulate Removal Systems

Type of collector	Particle size range (μm)	Removal efficiency	Space required	Maximum temperature (°C)	Pressure drop (cmH_2O)	Annual cost (US$ per year m^{-3})[a]
Baghouse (cotton bags)	0.1–0.1	Fair	Large	80	10	28.00
	1.0–10.0	Good	Large	80	10	28.00
	10.0–50.0	Excellent	Large	80	10	28.00
Baghouse (Dacron, nylon, Orlon)	0.1–1.0	Fair	Large	120	12	34.00
	1.0–10.0	Good	Large	120	12	34.00
	10.0–50.0	Excellent	Large	120	12	34.00
Baghouse (glass fiber)	0.1–1.0	Fair	Large	290	10	42.00
	1.0–10.0	Good	Large	290	10	42.00
	10.0–50.0	Good	Large	290	10	42.00
Baghouse (Teflon)	0.1–1.0	Fair	Large	260	20	46.00
	1.0–10.0	Good	Large	260	20	46.00
	10.0–50.0	Excellent	Large	260	20	46.00
ESP	0.1–1.0	Excellent	Large	400	1	42.00
	1.0–10.0	Excellent	Large	400	1	42.00
	10.0–50.0	Good	Large	400	1	42.00
Standard cyclone	0.1–1.0	Poor	Large	400	5	14.00
	1.0–10.0	Poor	Large	400	5	14.00
	10.0–50.0	Good	Large	400	5	14.00
High-efficiency cyclone	0.1–1.0	Poor	Moderate	400	12	22.00
	1.0–10.0	Fair	Moderate	400	12	22.00
	10.0–50.0	Good	Moderate	400	12	22.00
Spray tower	0.1–1.0	Fair	Large	540	5	50.00
	1.0–10.0	Good	Large	540	5	50.00
	10.0–50.0	Good	Large	540	5	50.00
Impingement scrubber	0.1–1.0	Fair	Moderate	540	10	46.00
	1.0–10.0	Good	Moderate	540	10	46.00
	10.0–50.0	Good	Moderate	540	10	46.00
Venturi scrubber	0.1–1.0	Good	Small	540	88	112.00
	1.0–10.0	Excellent	Small	540	88	112.00
	10.0–50.0	Excellent	Small	540	88	112.00
Dry scrubber	0.1–1.0	Fair	Large	500	10	42.00
	1.0–10.0	Good	Large	500	10	42.00
	10.0–50.0	Good	Large	500	10	42.00

[a] Includes costs for water and power, operation and maintenance, capital equipment and insurance (in 1994 US$).

values must not be considered absolute because great variations occur between types and manufacturers. No table is a substitute for a qualified consulting engineer or a reputable manufacturer's catalog.

III. REMOVAL OF LIQUID DROPLETS AND MISTS

The term *mist* generally refers to liquid droplets from submicron size to about 10 μm. If the diameter exceeds 10 μm, the aerosol is usually referred to as a *spray* or simply as *droplets*. Mists tend to be spherical because of their surface tension and are usually formed by nucleation and the condensation of vapors [6]. Larger droplets are formed by bursting of bubbles, by entrainment from surfaces, by spray nozzles, or by splash-type liquid distributors. The large droplets tend to be elongated relative to their direction of motion because of the action of drag forces on the drops.

Mist eliminators are widely used in air pollution control systems to prevent free moisture from entering the atmosphere. Usually, such mist eliminators are found downstream from wet scrubbers. The recovered mist is returned to the liquid system, resulting in lowered liquid makeup requirements.

Since mist and droplets differ significantly from the carrying gas stream, just as dry particulates do, the removal mechanisms are similar to those employed for the removal of dry particulates. Control devices developed particularly for condensing mist will be discussed separately. Mist collection is further simplified because the particles are spherical and tend to resist reentrainment, and they agglomerate after coming in contact with the surface of the collecting device.

A. Filters

Filters for mists and droplets have more open area than those used for dry particles. If a filter is made of many fine, closely spaced fibers, it will become wet due to the collected liquid. Such wetting will lead to matting of the fibers, retention of more liquid, and eventual blocking of the filter. Therefore, instead of fine, closely spaced fibers, the usual wet filtration system is composed of either knitted wire or wire mesh packed into a pad. A looser filtration medium results in a filter with a lower pressure drop than that of the filters used for dry particulates. The reported pressure drop across wire mesh mist eliminators is 1–2 cm of water at face velocities of $5\,\mathrm{m\,s^{-1}}$. The essential collection mechanisms employed for filtration of droplets and mists are inertial impaction and, to a lesser extent, direct interception.

B. Electrostatic Precipitators

ESPs for liquid droplets and mists are essentially of the wetted wall type. Figure 32.12 shows a wet-wall precipitator with tubular collection electrodes [1]. The upper ends of the tubes form weirs, and water flows over the tube ends to irrigate the collection surface.

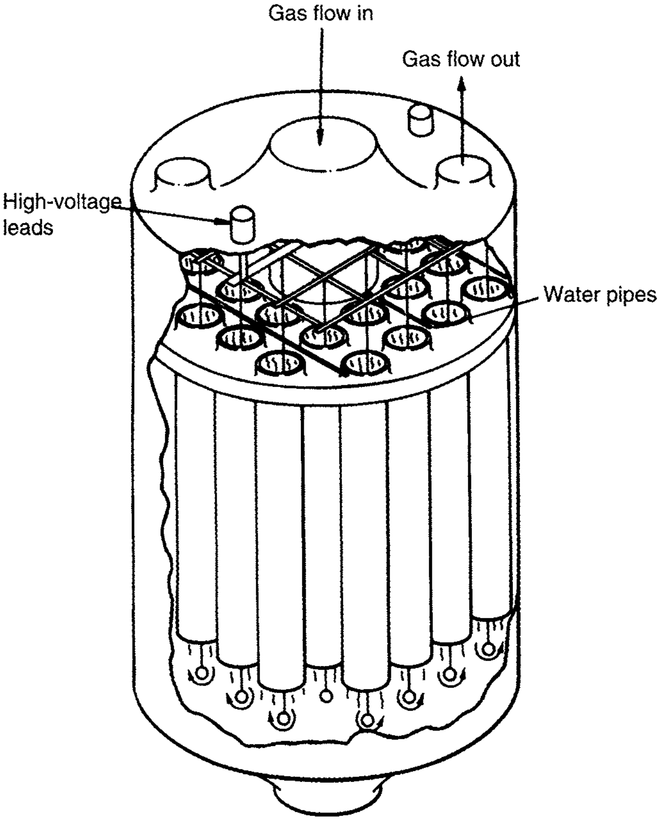

Fig. 32.12. Wet-wall ESP with tubular collection electrodes. *Source*: Oglesby Jr., S., and Nichols, G. B., Electrostatic precipitators, in *Air Pollution*, 3rd ed., Vol. IV (Stern, A. C., ed.), p. 238. Academic Press, New York, 1977.

Figure 32.13 shows an alternative type of wet precipitator with plate-type collection electrodes. In this design, sprays located in the ducts formed by adjacent collecting electrodes serve to irrigate the plates [1]. These are often supplemented by overhead sprays to ensure that the entire plate surface is irrigated. The design of such precipitators is similar to that of conventional systems except for the means of keeping insulators dry, measures to minimize corrosion, and provisions for removing the slurry.

C. Inertial Collectors

Inertial collectors for mists and droplets are widely used. They include cyclone collectors, baffle systems, and skimmers in ductwork. Inertial devices can be used as primary collection systems, precleaners for other devices, or mist eliminators. The systems are relatively inexpensive and reliable and have low pressure drops.

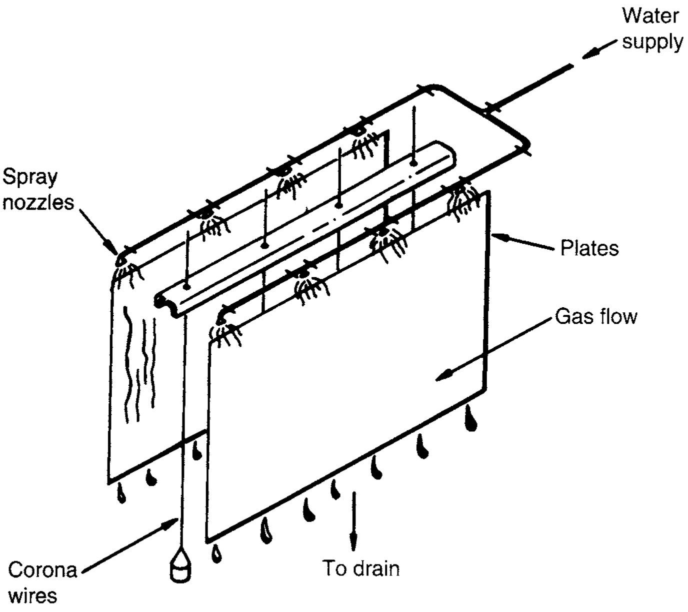

Fig. 32.13. Wet ESP with plate collection electrodes. *Source*: Oglesby Jr., S., and Nichols, G. B., Electrostatic precipitators, in *Air Pollution*, 3rd ed., Vol. IV (Stern, A. C., ed.), p. 239. Academic Press, New York, 1977.

Cyclone mist eliminators and collectors have virtually the same efficiency for both liquid aerosols and solid particles. To avoid reentrainment of the collected liquid from the walls of the cyclone, an upper limit is set to the tangential velocity that can be used. The maximum tangential velocity should be limited to the inlet velocity. Even at this speed, the liquid film may creep to the edge of the exit pipe, from which the liquid is then reentrained.

Baffle separators of the venetian blind, V, W, and wave types are widely used for spray removal. They have small space requirements and low pressure drops. They operate by diverting the gas stream and ejecting the droplets onto the collector baffles. Efficiencies of single stages may be only 40–60%, but by adding multiple stages, efficiencies approaching 100% may be obtained.

D. Scrubbers

A widely used type of scrubber for mists and droplets is the venturi scrubber. It has been used for the collection of sulfuric acid and phosphoric acid mists with very high efficiency. The scrubbing contact is made at the venturi throat, where very small droplets of the scrubbing liquid (usually water) are injected. At the throat, gas velocities as high as 130 m s^{-1} are used to increase collision efficiencies. Water, injected for acid mist control, ranges from 0.8 to

2.0 L m^{-3} of gas. Collection efficiencies approaching 100% are possible, but high efficiencies require a gas pressure drop of 60–90 cm of water across the scrubber. Normal operation, with a submicron mist, is reported to be in the 90–95% efficiency range [1].

One problem in using scrubbers to control mists and droplets is that the scrubber also acts as a condenser for volatile gases. For example, a hot plume containing volatile hydrocarbon gases, such as the exhaust from a gas turbine, may be cooled several hundred degrees by passing through a scrubber. This cooling can cause extensive condensation of the hydrocarbons, resulting in a plume with a high opacity. Teller [7] reports that cooling of exhaust gases from a jet engine in a test cell by the use of water sprays can result in droplet loadings 10–100% greater than those measured at the engine exhaust plane because of the condensation of hydrocarbons which were normally exhausted as gases.

E. Other Systems

Many unique systems have been proposed, and some used, to control the release of mists and droplets, such as:

1. Ceramic candles are thimble-shaped, porous, acid-resistant ceramic tubes. Although efficiencies exceeding 98% have been reported, the candles have high maintenance requirements because they are very fragile.
2. Electric cyclones utilize an electrode in the center of the cyclone to establish an electric field within the cyclone body. This device is more efficient than the standard cyclone. It is probably more applicable to mists and droplets than to dry particulates, due to possible fire or explosion hazards with combustible dusts.
3. Sonic agglomerators have been used experimentally for sulfuric acid mists and as mist eliminators. Commercial development is not projected at this time because the energy requirements are considerably greater than those for venturi scrubbers of similar capacity.

IV. REMOVAL OF GASEOUS POLLUTANTS

Gaseous pollutants may be easier or more difficult to remove from the carrying gas stream than aerosols, depending on the individual situation. The gases may be reactive to other chemicals, and this property can be used to collect them. Of course, any separation system relying on differences in inertial properties must be ruled out. Four general methods of separating gaseous pollutants are currently in use. These are: (1) absorption in a liquid, (2) adsorption on a solid surface, (3) condensation to a liquid, and (4) conversion into a less polluting or nonpolluting gas.

A. Absorption Devices

Absorption of pollutant gases is accomplished by using a selective liquid in a wet scrubber, packed tower, or bubble tower. Pollutant gases commonly controlled by absorption include sulfur dioxide, hydrogen sulfide, hydrogen chloride, chlorine, ammonia, oxides of nitrogen, and low-boiling hydrocarbons.

The scrubbing liquid must be chosen with specific reference to the gas being removed. The gas solubility in the liquid solvent should be high so that reasonable quantities of solvent are required. The solvent should have a low vapor pressure to reduce losses, be noncorrosive, inexpensive, nontoxic, nonflammable, chemically stable, and have a low freezing point. It is no wonder that water is the most popular solvent used in absorption devices. The water may be treated with an acid or a base to enhance removal of a specific gas. If carbon dioxide is present in the gaseous effluent and water is used as the scrubbing liquid, a solution of carbonic acid will gradually replace the water in the system.

In many cases, water is a poor scrubbing solvent. Sulfur dioxide, for example, is only slightly soluble in water, so a scrubber of very large liquid capacity would be required. SO_2 is readily soluble in an alkaline solution, so scrubbing solutions containing ammonia or amines are used in commercial applications.

Chlorine, hydrogen chloride, and hydrogen fluoride are examples of gases that are readily soluble in water, so water scrubbing is very effective for their control. For years hydrogen sulfide has been removed from refinery gases by scrubbing with diethanolamine. More recently, the light hydrocarbon vapors at petroleum refineries and loading facilities have been absorbed, under pressure, in liquid gasoline and returned to storage. All of the gases mentioned have economic importance when recovered and can be valuable raw materials or products when removed from the scrubbing solvent.

B. Adsorption Devices

Adsorption of pollutant gases occurs when certain gases are selectively retained on the surface or in the pores or interstices of prepared solids. The process may be strictly a surface phenomenon with only molecular forces involved, or it may be combined with a chemical reaction occurring at the surface once the gas and adsorber are in intimate contact. The latter type of adsorption is known as *chemisorption.*

The solid materials used as adsorbents are usually very porous, with extremely large surface-to-volume ratios. Activated carbon, alumina, and silica gel are widely used as adsorbents depending on the gases to be removed. Activated carbon, for example, is excellent for removing light hydrocarbon molecules, which may be odorous. Silica gel, being a polar material, does an excellent job of adsorbing polar gases. Its characteristics for removal of water vapor are well known.

Solid adsorbents must also be structurally capable of being packed into a tower, resistant to fracturing, and capable of being regenerated and reused after saturation with gas molecules. Although some small units use throw-away canisters or charges, the majority of industrial adsorbers regenerate the adsorbent to recover not only the adsorbent but also the adsorbate, which usually has some economic value.

The efficiency of most adsorbers is very near 100% at the beginning of operation and remains extremely high until a breakpoint occurs when the adsorbent becomes saturated with adsorbate. At this breakpoint the slope of the percentage of mass of gaseous fluid that is not sorbed increases dramatically with time. It is at the breakpoint that the adsorber should be renewed or regenerated. This is shown graphically in Fig. 32.14.

Industrial adsorption systems are engineered so that they operate in the region before the breakpoint and are continually regenerated by units. Figure 32.15 shows a schematic diagram of such a system, with steam being used to regenerate the saturated adsorbent. Figure 32.16 illustrates the actual system shown schematically in Fig. 32.15.

C. Condensers

In many situations, the most desirable control of vapor-type discharges can be accomplished by condensation. Condensers may also be used ahead of other air pollution control equipment to remove condensable components. The reasons for using condensers include (1) recovery of economically

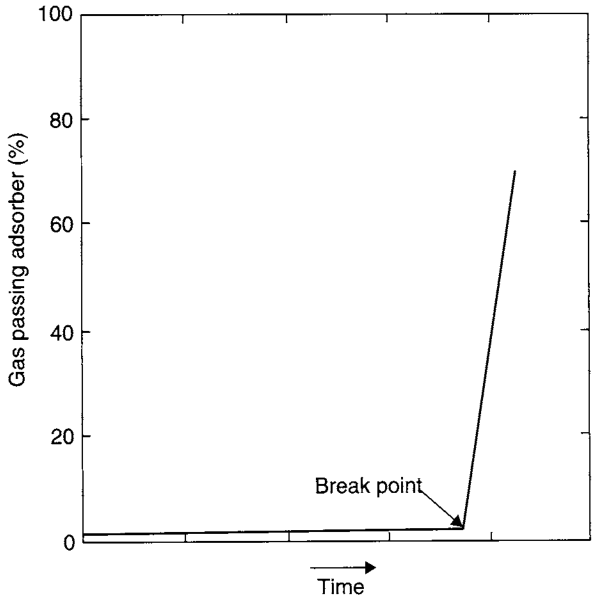

Fig. 32.14. Adsorbent breakpoint at saturation with adsorbate.

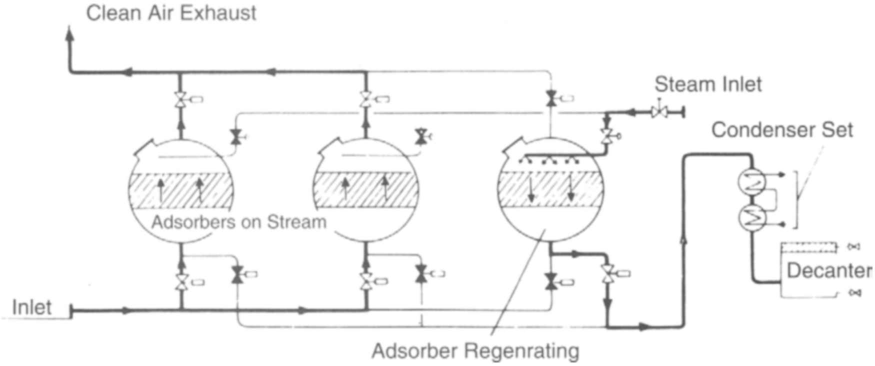

Fig. 32.15. Flow diagram for adsorber. *Source*: The British Ceca Company, Ltd.

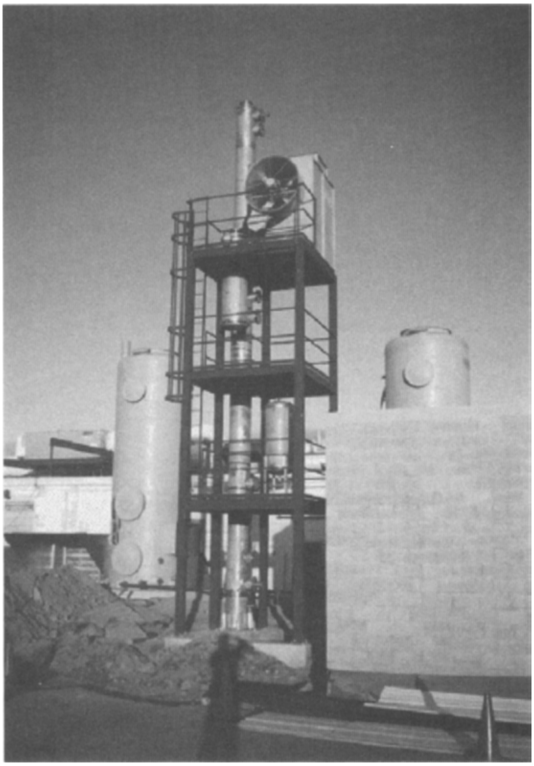

Fig. 32.16. Pollution control facility in Milford foundry, New Hampshire includes an adsorption tower. Gaseous emissions are introduced at the base of the treatment column, where a gas diffuser ensures that they are evenly distributed through the system. The gas then contacts purification liquid in the packing of sorbents (e.g. zeolite) in the absorption zone. A second diffuser ensures that the purification liquid is evenly spread. *Source*: Environ-Access, Inc. (1996). Environmental Fact Sheet, "Treatment of Air and Gas: Treatment of Gaseous Emissions through a Wet Scrubber—MESAR Environair Inc." (F2-03-96), Sherbrooke, Quebec, Canada.

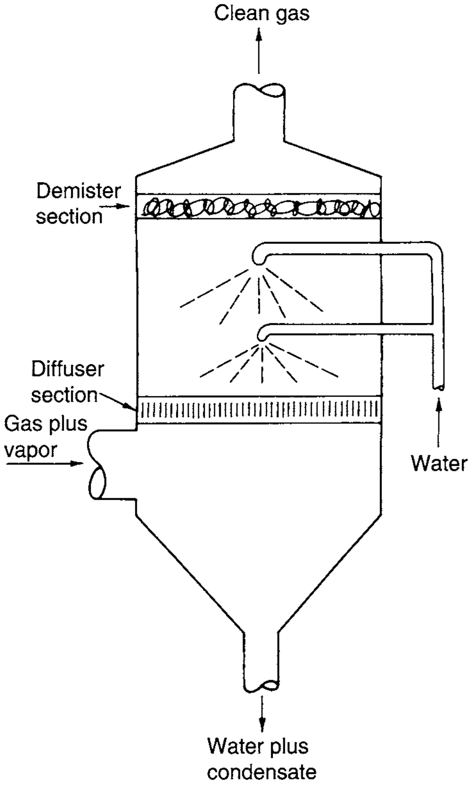

Fig. 32.17. Contact condenser.

valuable products, (2) removal of components that might be corrosive or damaging to other portions of the system, and (3) reduction of the volume of the effluent gases.

Although condensation can be accomplished either by reducing the temperature or by increasing the pressure, in gas-removal practice it is usually done by temperature reduction only.

Condensers may be of one or two general types depending on the specific application. Contact condensers operate with the coolant, vapors, and condensate intimately mixed. In surface condensers, the coolant does not come in contact with either the vapors or the condensate. The usual shell-and-tube condenser is of the surface type. Figure 32.17 illustrates a contact condenser which might be used to clean or preclean a hot corrosive gas.

Table 32.5 lists several applications of condensers currently in use. For most operations listed, air and noncondensable gases should be kept to a minimum, as they tend to reduce condenser capacity.

D. Conversion to Nonpollutant Material

A widely used system for the control of organic gaseous emissions is oxidation of the combustible components to water and carbon dioxide. Other

TABLE 32.5

Representative Applications of Condensers in Air Pollution Control

Petroleum refining	Petrochemical manufacturing	Basic chemical manufacture	Miscellaneous industries
Gasoline accumulator	Polyethylene gas vents	Ammonia	Dry cleaning
Solvents	Styrene	Chlorine solutions	Degreasers
Storage vessels	Copper napthenates		Tar dipping
Lube oil refining	Insecticides		Kraft paper
	Phthalic anhydride		
	Resin reactors		
	Solvent recover		

systems such as the oxidation of H_2S to SO_2 and H_2O are also used even though the SO_2 produced is still considered a pollutant. The trade-off occurs because the SO_2 is much less toxic and undesirable than the H_2S. The odor threshold for H_2S is about three orders of magnitude less than that for SO_2. For oxidation of H_2S to SO_2, the usual device is simply an open flare with a fuel gas pilot or auxiliary burner if the H_2S is below the stoichiometric concentration. If the SO_2 is above emission or other operation limits, it will also have to be treated (e.g. by scrubbing).

Afterburners are widely used as control devices for oxidation of undesirable combustible gases. The two general types are (1) direct-flame afterburners, in which the gases are oxidized in a combustion chamber at or above the temperature of autogenous ignition and (2) catalytic combustion systems, in which the gases are oxidized at temperatures considerably below the autogenous ignition point.

Direct-flame afterburners are the most commonly used air pollution control device in which combustible aerosols, vapors, gases, and odors are to be controlled. The components of the afterburner are shown in Fig. 32.18. They include the combustion chamber, gas burners, burner controls, and exit temperature indicator. Usual exit temperatures for the destruction of most organic materials are in the range of 650–825°C, with retention times at the elevated temperature of 0.3–0.5 s.

Direct-flame afterburners efficient and economical when properly operated. Cost to operate and maintain these systems are similar to those of the auxiliary gas fuel systems. Operating and maintenance costs are essentially those of the auxiliary gas fuel. For larger industrial applications, the overall cost of the afterburner operation may be considerably reduced by using heat recovery equipment as shown in Fig. 32.19. In fact, this is an example of the green engineering approach known as co-generation. In some innovative schemes, heat recovery can provide heat for reactors in neighboring industries. Boilers and kilns also provide efficient pollutant destruction of volatile organic compounds and other vapor phase pollutants in numerous industrial settings. Thermal processes are treated in greater detail in Chapter 33

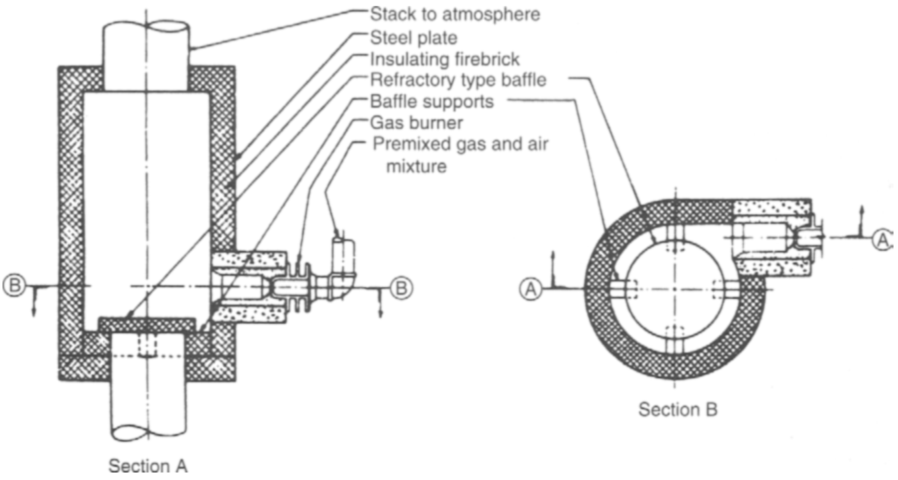

Fig. 32.18. Direct-fired afterburner. *Source*: Los Angeles Air Pollution Control District.

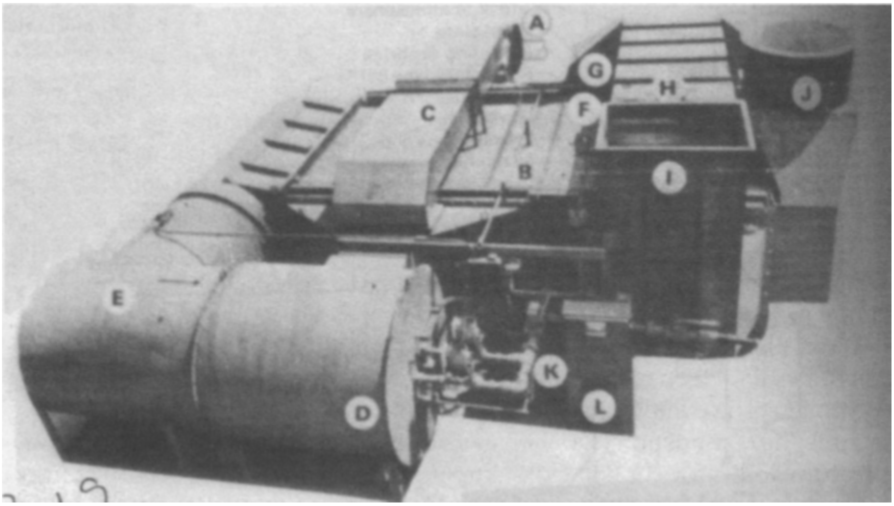

Fig. 32.19. Afterburner with heat recovery. (A) Fume inlet to insulated forced draft fan ($310\,m^3/min$ at 230°C). (B) Regenerative shell-and-tube heat exchanger (55% effective recovery). (C) Automatic bypass around heat exchanger for temperature control (required for excess hydrocarbons in fume steam under certain process conditions). (D) Fume inlet and burner chamber internally insulated (fume steam raised to 425°C by heat exchanger). (E) Combustion chamber, refractory lined for 815°C duty (operating at 760°C for required fume oxidation to meet local regulations). (F) Discharge stream leaving regenerative heat exchanger at 520°C enters ventilating air heat exchanger for further waste heat recovery. (G) Ventilating air fan and filter ($310\,m^3/min$ of outside air). (H) Automatic bypass with dampers for control of ventilating air temperature. (I) Heated air for winter comfort heating requirements leaves at controlled temperature. (J) Discharge stack (470°C). (K) Combustion safeguard system with dual burner manifold and controls for high turndown. (L) Remote control panel with electronic temperature controls. *Source*: Hirt Combustion Engineers.

(in particular, note the afterburner system following the rotary kiln in Fig. 33.2).

Catalytic afterburners are currently used primarily in industry for the control of solvents and organic vapor emissions from industrial ovens. They are used as emission control devices for gasoline-powered automobiles (see Chapter 35).

The main advantage of the catalytic afterburner is that the destruction of the pollutant gases can be accomplished at a temperature range of about 315–485°C, which results in considerable savings in fuel costs. However, the installed costs of the catalytic systems are higher than those of the direct-flame afterburners because of the expense of the catalyst and associated systems, so the overall annual costs tend to balance out.

In most catalytic systems there is a gradual loss of activity due to contamination or attrition of the catalyst, so the catalyst must be replaced at regular intervals. Other variables that affect the proper design and operation of catalytic systems include gas velocities through the system, amount of active catalyst surface, residence time, and preheat temperature necessary for complete oxidation of the emitted gases.

E. Biological Control Systems

Waste streams with low to moderate concentrations of volatile organic compounds (VOCs) may be treated with biological systems. These are similar to biological systems used to treat wastewater, classified as three basic types: 1. biolfilters; 2. biotrickling filters; and 3. bioscrubbers.

Biofilms of microorganisms (bacteria and fungi) are grown on porous media in biofilters and biotrickling systems. The air or other gas containing the VOCs is passed through the biologically active media, where the microbes break down the compounds to simpler compounds, eventually to carbon dioxide (if aerobic), methane (if anaerobic), and water. The major difference between biofiltration and trickling systems is how the liquid interfaces with the microbes. The liquid phase is stationary in a biofilter (see Fig. 32.20), but liquids move through the porous media of a biotrickling system (i.e. the liquid "trickles").

A particularly valuable form of biofiltration uses compost as the porous media. Compost contains numerous species of beneficial microbes already acclimated to organic wastes. Industrial compost biofilters have achieved removal rates at the 99% level. Biofilters are also the most common method for removing VOCs and odorous compounds from air streams. In addition to a wide array of volatile chain and aromatic organic compounds, biological systems have successfully removed vapor phase inorganics, such as ammonia, hydrogen sulfide and other sulfides including carbon disulfide, as well as mercaptans.

The operational key is the biofilm. The gas must interface with the film. In fact, this interface may also occur without a liquid phase (see Fig. 32.21). According to Henry's Law, the compounds partition from the gas phase

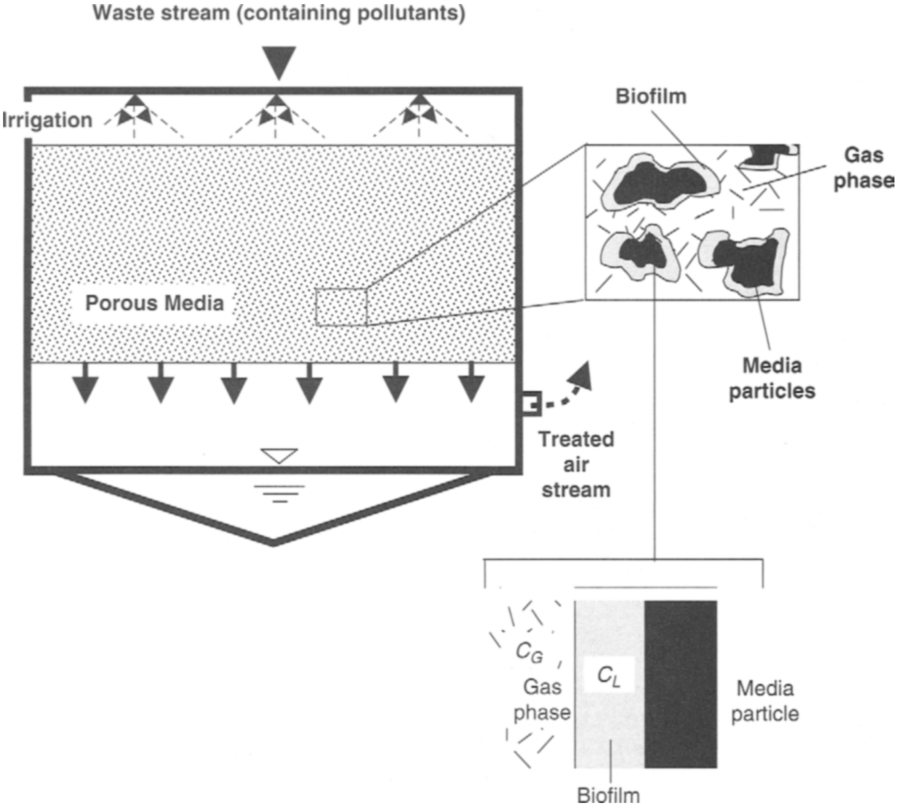

Fig. 32.20. Schematic of packed bed biological control system to treat volatile compounds. Air containing gas phase pollutants (C_G) traverse porous media. The soluble fraction of the volatilized compounds in the air stream partition into the biofilm (C_L) according to Henry's Law: $C_L = \frac{C_G}{H}$; where H is the Henry's Law constant. Adapted from Ergas, S. J. and Kinney, K. A. "Biological Control Systems" in: Air and Waste Management Association, Air Pollution Control Manual, 2nd ed, W. T. Davis (ed.), John Wiley & Sons, Inc., New York, pp. 55–65, 2000.

(in the carrier gas or air stream) to the liquid phase (biofilm). Compost has been a particularly useful medium in providing this partitioning.

The bioscrubber is a two-unit setup. The first unit is an adsorption unit (see previous discussion in this Chapter). This unit may be a spray tower, bubbling scrubber or packed column. After this unit, the air stream enters a bioreactor with a design quite similar to an activated sludge system in a wastewater treatment facility. Bioscrubbers are much less common in the US than biofiltration systems [9].

All three types of biological systems have relatively low operating costs since they are operated near ambient temperature and pressure conditons.

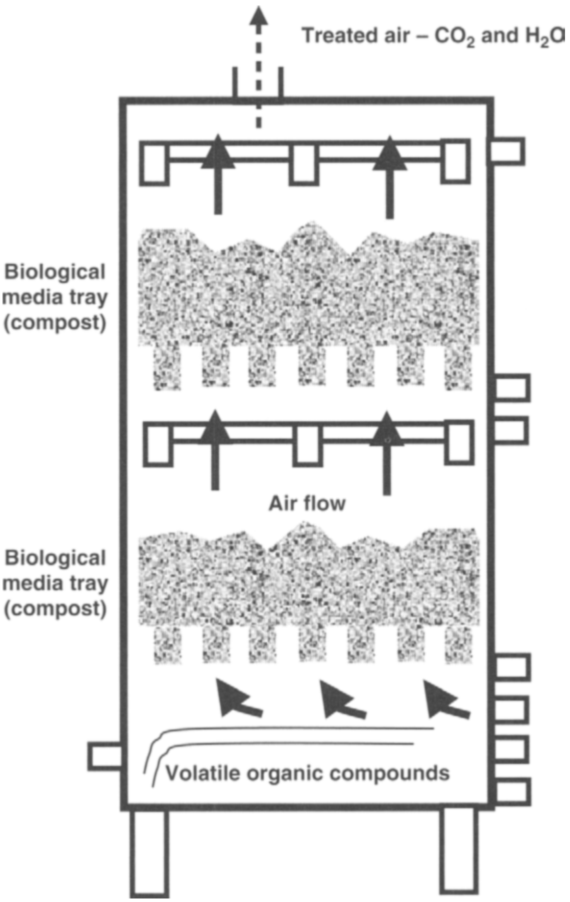

Fig. 32.21. Biofiltration without a liquid phase used to treat vapor phase pollutants. Air carrying the volatilized contaminants upward through porous media (e.g. compost) containing microbes acclimated to break down the particular contaminants. The wastes at the bottom of the system can be heated to increase the partitioning to the gas phase. Microbes in the biofilm surrounding each individual compost particle metabolize the contaminants into simpler compounds, eventually converting them into carbon dioxide and water vapor.

Power needs are generally for air movement and pressure drops are low (<10 cm $H_2O\,m^{-1}$ packed bed). Other costs include amendments (e.g. nutrients) and humidification. Another advantage is the usual small amount of toxic byproducts, as well as low rates of emissions of greenhouse gases (oxides of nitrogen and carbon dioxide), compared to thermal systems. Success is highly dependent on the degradability of the compounds present in the air stream, their fugacity and solubility needed to enter the biofilm (see Fig. 32.19), and pollutant loading rates. Care must be taken in monitoring the porous media for incomplete biodegradation, the presence of substances that may be toxic to the microbes, excessive concentrations of organic acids and alcohols, and pH. The system should also be checked for shock and the presence of dust, grease or other substances that may clog the pore spaces of the media [9].

F. Comparison of Gaseous Removal Systems

As with particulate removal systems, it is apparent that many choices are available for removal of gases from effluent streams. Table 32.6 presents some of the factors that should be considered in selecting equipment.

For the control of SO_2, several systems are currently in development and use. Table 32.7 briefly explains these systems.

TABLE 32.6

Comparison of Gaseous Pollutant Removal Systems

Type of equipment	Pressure drop (cmH_2O)	Installed cost (1990 US$ per m^3)	Annual operating cost (1990 US$ per m^3)
Scrubber	10	9.80	14.00
Absorber	10	10.40	28.00
Condenser	2.5	28.00	7.00
Direct-flame afterburner	1.2	8.20	8.40 + gas
Catalytic afterburner	2.5	11.60	28.00 + gas
Biological control systems	Low (e.g. <1 in compost)	variable (low to moderate)	variable (low to moderate)

TABLE 32.7

Possible Sulfur Dioxide Control Systems

Method	Remarks
Limestone or lime injection (dry)	Calcined limestone or lime reacts with sulfur oxides. They are then removed with a dry particulate control system.
Limestone or lime injection (wet)	Calcined limestone or lime reacts with sulfur oxides, which are then removed by wet scrubbers.
Sodium carbonate	Sodium carbonate reacts with sulfur oxides in a dry scrubber to form sodium sulfite and CO_2. Sodium sulfite is then removed with a baghouse.
Citrate process	Citrate is added to scrubbing water to enhance SO_2 solution into water. Sulfur is then removed from the citrate solution.
Copper oxide adsorption	Oxides of sulfur react with copper oxide to form copper sulfate. Removal with a dry particulate control system follows.
Caustic scrubbing	Caustic neutralizes sulfur oxides. This method is used on small processes.

V. REMOVAL OF ODORS

An odor can be described as a physiological response to activation of the sense of smell [1]. It can be caused by a chemical compound (e.g. H_2S) or a mixture of compounds (e.g. coffee roasting). Generally, if an odor is objectionable, any perceived quantity greater than the odor threshold will be cause for complaint. The control of odors, therefore, becomes a matter of reducing them to less than their odor thresholds, preventing them from entering the atmosphere, or converting them to a substance that is not odorous or has a much higher odor threshold. Odor masking is not recommended for a practical, long-term odor control system.

A. Odor Reduction by Dilution

If the odor is not a toxic substance and has no harmful effects at concentrations below its threshold, dilution may be the least expensive control technique. Dilution can be accomplished either by using tall stacks or by adding dilution air to the effluent. Tall stacks may be more costly if only capital costs are considered, but they do not require the expenditure for energy that is necessary for dilution systems. In addition, if the emission contains other pollutants, taller stacks will increase the distance travelled by the pollutant and, thus, will contribute to the long-range transport and the potential cumulative effects of these pollutants.

The odor threshold for most atmospheric pollutants may be found in the literature [1]. By properly applying the diffusion equations, one can calculate the height of a stack necessary to reduce the odor to less than its threshold at the ground or at a nearby structure. A safety factor of two orders of magnitude is suggested if the odorant is particularly objectionable.

Odor control by the addition of dilution air involves a problem associated with the breakdown of the dilution system. If a dilution fan, motor, or control system fails, the odorous material will be released to the atmosphere. If the odor is objectionable, complaints will be noted immediately. Good operation and maintenance of the dilution system become an absolute requirement, and redundant systems should be considered.

B. Odor Removal

It is sometimes possible to close an odorous system in order to prevent the release of the odor to the atmosphere. For example, a multiple-effect evaporator can be substituted for an open contact condenser on a process emitting odorous, noncondensable gases.

Another possible solution to an odor problem is to substitute a less noxious or more acceptable odor within a process. An example of this type of control is the substitution of a different resin in place of a formaldehyde-based resin in a molding or forming process.

Many gas streams can be deodorized by using solid adsorption systems to remove the odor before the stream is released to the atmosphere. Such procedures are often both effective and economical.

C. Odor Conversion

Many odorous compounds may be converted to compounds with higher odor thresholds or to nonodorous substances. An example of conversion to another compound is the oxidation of H_2S, odor threshold 0.5 ppb, to SO_2, odor threshold 0.5 ppm. The conversion results in another compound with an odor threshold three orders of magnitude greater than that of the original compound.

An example of conversion to a nonodorous substance would be the passage of a gas stream containing butyraldehyde, $CH_3CH_2CH_2CHO$, with an odor threshold of 40 ppb, through a direct-fired afterburner which converts it to CO_2 and H_2O, both nonodorous compounds. It should be noted that using a direct-fired afterburner, particularly one without heat recovery, to destroy 40 ppb is not an economical use of energy, and some other odor control system may be more desirable.

The physical and chemical characteristics of the particles and gases needing treatment determine the appropriate devices to be deployed. Engineers and planners must carefully consider many factors when selecting air pollution control systems. The next chapter provides insights into how this can be done for hazardous pollutants and other emergent contaminants.

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QUESTIONS

1. List the similarities and differences of pollution control systems for solid PM and liquid droplets.
2. You wish to design a baghouse to clean 3000 m^3 at a filter ratio of 3 m^3 m^{-2} of cloth. The filter bags are 15 cm in diameter by 3-m long. If you design a "square" baghouse with the bags on 30-cm centers, what would be the exterior dimensions, neglecting ductwork? An alternative system uses 15-mm-diameter porous plastic tubes 1 m long on 25-mm centers. For the same filter ratio and flow, what would be the exterior dimensions for a "square" enclosure?
3. For a given cyclone collector, plot centrifugal force as a function of particle specific gravity (0.50–3.00), gas velocity (175–1750 m min^{-1}), and radius of curvature (30–250 cm).
4. List the advantages and disadvantages of using a baghouse, wet scrubber, or ESP for particulate collection from an asphalt plant drying kiln. The gases are at 250°C and contain 450 mg m^{-3} of rock dust in the 0.1–10 μm size range. Gas flow is 2000 m^3 min^{-1}. Consider initial and operation cost, space requirement, ultimate disposal, etc.
5. Suppose a gaseous process effluent of 30 m^3 min^{-1} is at 200°C and 50% relative humidity. It is cooled to 65°C by spraying with water that was initially at 20°C. What volume of saturated gas would you have to design for at 65°C? How much water per cubic meter would the system require? How much water per cubic meter would you have to remove from the system?
6. If an ESP is 90% efficient for particulate removal, what overall efficiency would you expect for two of the ESPs in series? Would the cost of the two in series be double the cost of the single ESP? List two specific cases in which you might use two ESPs in series.
7. The gaseous effluent from a process is 30 m^3 min^{-1} at 65°C. How much natural gas at 8900 kg cal m^{-3} would have to be burned per hour to raise the effluent temperature to 820°C? Natural gas requires 10 m^3 of air for every cubic meter of gas at a theoretical air/fuel ratio. Assume the air temperature is 20°C and the radiation and convection losses are 10%.

8. For Question 7, if heat recovery equipment were installed to raise the incoming effluent to 425°C, how much natural gas would have to be burned per hour?
9. Choose a representative area (a city, county, region, etc.) and prepare a table showing the change in air pollution emission if natural gas were used as a fuel instead of oil and coal.
10. Why are "oxides of nitrogen" and "oxides of sulfur" usually reported in emission inventory tables rather than the actual oxidation states?
11. For a given area estimate the yearly pollutants emitted by automobiles using the figures for gallons of gasoline sold supplied by (a) the gasoline dealers association and (b) the local taxation authorities.