AIR POLLUTION CONTROL METHODS

1. Introduction

Air pollution is defined as the presence in the outdoor atmosphere (ambient air) of one or more contaminants in such quantities and for such duration as to be harmful or injurious to human health or welfare, animal or plant life, or property, or may unreasonably interfere with the enjoyment of life or property (1–3). It is useful to study the causes and sources of the various air pollutants, as well as their physical and chemical characteristics, before air pollution control is discussed. There are many different air pollutants, all with differing physical and chemical characteristics, as well as a vast number and variety of air pollution sources. Therefore, a good understanding of the pollutants and their sources is necessary before a particular control technology can be selected for best application to any particular situation.

Some of the most common pollutants have been well known for decades, and continue to be emitted at rates exceeding millions of tons per year (in the United States alone). These “traditional” air pollutants include particulate matter (PM), sulfur oxides (SO_x), nitrogen oxides (NO_x), volatile organic compounds (VOCs), and carbon monoxide (CO). Another major pollutant is ground-level ozone (O_3). Ozone is not emitted directly; rather it is formed by photochemical reactions in the atmosphere between NO_x and VOCs. Other important pollutants include lead (as leaded gasoline was phased out in the 1980s, the U.S. emissions of lead into the atmosphere dropped by 95% or more), hazardous air pollutants (HAPs), including lead, mercury, formaldehyde, benzene, and many others, several ozone-depleting compounds (such as chlorofluorocarbons), and greenhouse gases, such as carbon dioxide (CO_2) and methane (CH_4). A brief review of the pollutants is presented here; a more thorough discussion of the pollutants and their causes, sources and effects, along with details of the design and operation of air pollution control equipment is presented in textbooks (4,5).

2. Characteristics of Pollutants and Control Approaches

Particulate matter (PM) is the term used to describe very small diameter solids or liquids which remain suspended in the air after being emitted from sources. Also, very small PM can be formed in the atmosphere by reactions between gaseous pollutants. PM-10 and PM-2.5 refer to particulate matter less than 10 and 2.5 μm in diameter, respectively. Particles are emitted from a variety of sources, including fossil-fuel combustion, metals and mineral processing, fugitive dusts from roads, agricultural fields, and many others (6). 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 the 1990s to PM-2.5 in recognition of the more serious health effects of smaller particles. Small particles have especially serious effects on the human respiratory system, and cause reductions in visibility, and soiling and corrosion of materials. Control of PM focuses on physically separating and removing the particles from the exhaust gases in which they are carried, and particle size very much influences the choice of technologies.

Sulfur oxides (SO_x) are produced whenever any substance that contains sulfur is burned. Most of the sulfur oxides are emitted from fossil-fuel combustion sources (such as coal-fired power plants), although nonferrous metal smelters also emit large amounts. More than 90% of the SO_x is emitted in the form of SO_2; however, some SO_3 is formed during combustion and is emitted. Most of the emitted SO_2 is converted slowly to SO_3 or particulate sulfates by oxidization in the atmosphere. The sulfur oxides form acids when they combine with water in the atmosphere, and the resulting acid deposition can have detrimental effects on aquatic and terrestrial ecosystems, and on statues, buildings, etc. Control of SO_x focuses on either desulfurizing the fuel prior to combustion, or removing the SO_x from the exhaust gases (eg, absorption in an aqueous caustic solution or limestone slurry, or other technique).

Nitrogen oxides (NO_x) are formed whenever any fuel is burned in air at a high enough temperature. At very high temperatures, the nitrogen and oxygen in the air react to form NO and NO_2. Nitrogen atoms present in some fuels can also be oxidized to NO_x during combustion. Large-scale emissions of NO_x are contributed about equally from stationary sources and mobile sources (vehicles). Nitrogen oxides contribute significantly to acid deposition, but perhaps the most important adverse effect is that NO_x reacts with VOCs in the presence of sunlight to form ground-level ozone. Control of NO_x is difficult. While some NO_x control can be accomplished by better design and operation of the combustion process, more advanced control (both for large power plants and for automobiles) is often done by catalytically enhanced chemical reactions that convert NO_x into N_2.

Volatile organic compounds (VOCs) is a class of pollutants that includes any organic compounds that can exist in air as vapors. Automobiles and other mobile sources are a major source of VOCs, as are a number of industries (6). Petrochemicals production, and petroleum refining, transport, storage, and marketing account for substantial VOC emissions, as does evaporation of solvents (such as those in oil-based paints, or printing inks). Some VOCs are odorous and some are carcinogenic, but the major problem with VOCs is that they participate with NO_x in photochemical reactions in the atmosphere to form ozone. VOCs can be controlled in many ways, depending on the physical and chemical properties of the individual VOCs.

Carbon monoxide (CO) is a colorless, odorless, tasteless gas that results from the incomplete combustion of any carbonaceous fuel. CO reacts with the hemoglobin in blood to block oxygen transfer. Depending on the concentration of CO and length of exposure, effects of polluted air on humans may range from slight impairment of some functions to dizziness and nausea. The major sources of CO are on-road and nonroad mobile sources. Automobiles, trucks, buses, airplanes, railroads, boats, snowmobiles, construction equipment, lawn and garden equipment, farm vehicles, and other on-road and nonroad sources exhausted over 75 million tons of CO in 1999 (6). Control of CO from on-road mobile sources is typically accomplished via catalytic oxidation, and such controls have been very effective in the United States. In spite of steady increases in the numbers of vehicles and the miles traveled, CO from on-road sources dropped from 78 million metric tons/year in 1980 to 50 million metric tons/year in 1999, primarily due to better engine controls and catalytic converters.

Ozone (O_3) and other oxidants are not emitted from a source *per se*, but are formed by complex photochemical reactions in the atmosphere involving mainly VOCs, NO_x, and sunlight. (See OZONE). The classical term "smog" is defined as a mixture of smoke and fog, and stems from the early part of the 20th century when the major air pollution problems were PM and SO_x. The term smog as used today describes the complex mix of air pollutants found in many cities, including high levels of ozone, but also PM, NO_x, VOCs, SO_x, and many other compounds; it often appears (from a distance) as a visible layer of material hanging over the city. Ozone and other oxidants attack plants and materials, and cause serious health effects including eye, nose, and throat irritation, and premature "aging" of the lungs. Control of ozone problems focuses on controlling emissions of VOCs or of NO_x depending on which compound is present in the air in the "critical" concentration. Detailed emission inventories and modeling are required to determine the best ozone control strategy for each urban area.

Hazardous air pollutants (HAPs) are certain compounds (such as benzene, formaldehyde, vinyl chloride, lead, mercury, and many others) that were specifically identified by the U.S. EPA in the 1990 Clean Air Amendments. HAPs are emitted from a wide variety of sources, both combustion and non-combustion. Most HAPs are not emitted in very large quantities, but are considered serious because of their potential to severely damage human health. Many organic HAPs are controlled by incineration (or better combustion in the source furnace). HAPs from mobile sources are also called mobile source air toxics (MSATs).

Greenhouse Gases include carbon dioxide, methane, and several others. Carbon dioxide (CO_2) has long been ignored as a pollutant, but now is beginning to be recognized as such because its concentration in the atmosphere has reached levels that are causing significant global climate changes, and thus causing harm to human well-being. Predictions of very serious global damages are not uncommon; listed effects include more frequent and more powerful hurricanes, rising sea level and flooding, altered rainfall patterns resulting in major changes in agriculture, more insect infestations, loss of glaciers, and many more. The control of carbon dioxide poses a particularly difficult problem because CO_2 is the natural end product of combustion of any carbonaceous fuel, and the world's major economies all depend very heavily on fossil fuels (coal, oil and natural gas), and will likely continue to depend on them for decades into the future. Furthermore, even if CO_2 can be captured and removed economically from exhaust gases, then another problem appears – appropriate disposal sites must be found for huge quantities of CO_2.

Other categories of air pollution that must be mentioned – *odors* and *indoor air pollution*. Both categories contain many of the same pollutants that have been previously identified, but have some unique properties as well. Odors are not listed in federal laws as a criteria pollutant, but are identified in many state statutes as nuisance pollutants. Odors can be emitted as solid, liquid or gaseous compounds, and their control often involves a combination of processes. Indoor air pollutants can include any of the above discussed pollutants (and more), but because they are indoors, federal ambient standards do not apply. Also, the sources of indoor air pollution may be quite different from the large industrial or mobile sources on which control efforts have been traditionally focused. (See AIR POLLUTION INDOOR).

3. National Air Pollution Standards

There are two types of standards for air pollution – ambient (outdoors) air standards, and source performance standards (emission limits). Both are important to maintaining healthy air quality in any country.

3.1. Ambient Standards. National Ambient Air Quality Standards (NAAQSs) have been promulgated by the U.S. Environmental Protection Agency (and also have been adopted by many states). NAAQSs establish limits on the maximum allowable concentrations of several common pollutants in the outdoor atmosphere. These standards are also tied to the duration of exposure or averaging times, as shown in Table 1.

3.2. Source Performance Standards. There are many, many different types of sources, and thus there are many different source performance standards. These standards are usually stated as emission limits (although some are set as concentrations in the exhaust gas), and can be listed as mass of pollutant emitted per unit of time, or per unit amount of a certain input into the process, or per unit amount of a product or output from the process. Table 2 presents several of the standards.

The two types of standards (ambient and source) work together in establishing the level of control that must be provided for any given source. Source emission standards set a baseline of control, but even if a source is designed to meet that level, if ambient standards are shown to be threatened, the source can be required to provide additional safeguards.

Table 1. **National Ambient Air Quality Standards**[a,b]

Pollutant	Averaging time	Primary standard
PM-10	annual arithmetic mean	50 μg/m^3
	24-h average	150 μg/m^3
PM-2.5	annual arithmetic mean	15 μg/m^3
	24-h average	65 μg/m^3
lead	quarterly average	1.5 μg/m^3
CO	1-h average	35 ppm
	8-h average	9 ppm
SO_2	annual arithmetic mean	80 μg/m^3
	24-h average	365 μg/m^3
NO_2	annual arithmetic mean	0.053 ppm
O_3	8-h average[c]	0.08 ppm

[a] Refs. 4–7.

[b] All standards, except annual averages, are maximums, and are not to be exceeded more than once per year.

[c] This standard is computed as a 3-yr average of the annual 4th highest of the maximum daily 8-h concentrations.

Table 2. **Selected Examples of New Source Performance Standards (NSPS)**[a]

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. SO_2; 0.20 lb/million Btu (86 g/million kJ) for gas or liquid fuel. For coal-fired plants, the SO_2 standard requires a scrubber that is at least 70% efficient. The maximum permissible emissions rate is 1.2 lb of SO_2 per million BTU of heat input; the permissible emissions rate may be less depending on the coal sulfur content and the scrubber efficiency required.
2. Nitric acid plants
   Standard is a maximum 3 h average NOx emission of 1.5 kg NOx (expressed as nitrogen dioxide)/metric ton of acid produced.
3. Sulfuric acid plants
   Applies to plants employing the contact process. Standard is a maximum 3 h average SO_2 emission of 2 kg/metric ton of acid produced. An acid mist standard is a maximum 3-h emission of 0.075 kg/metric ton of acid produced.
4. Iron and steel plants
   Particulate discharges may not exceed 50 mg/dscm, and the opacity must be 10% or less except for 2 min in any hour.
5. *1995 passenger cars*:
   a. CO: 3.4 g/mile
   b. NO_x: 0.4 g/mile
   c. VOC: 0.41 g/mile
   d. PM-10: 0.08 g/mile

[a] Refs. 4,8.

Standards and regulations for HAPs and for greenhouse gases are still evolving. Individual HAPs coming from specific sources have very stringent limits. For example, for municipal waste incinerators, a sampling of the regulations are shown in Table 3. Any emission limits for greenhouse gases require international treaties and cooperation, and so far, the U.S. has not agreed to any specific federal limits. However, a number of international companies with headquarters in the U.S. are making strides in limiting their emissions of CO_2.

In addition to the federal regulations of ambient air, and the setting of federal emission standards for major sources and for motor vehicles, local and state programs and efforts are crucial for the successful control of air pollution. Individual states are often authorized by EPA to administer and enforce air

Table 3. **Selected Emission Standards for New Municipal Waste Combustors**[a]

CO	50 to 150 ppm (depending on type of unit)
dioxins/furans	13 ng/dscm (nanograms per dry standard cubic meter)
PM	24 mg/dscm
cadmium	0.020 mg/dscm
lead	0.20 mg/dscm
mercury	0.080 mg/dscm
SO_2	30 ppm or 80% reduction in raw emissions
HCl	25 ppm or 95% reduction in raw emissions

[a] Ref. 9.

regulations. States administer permitting programs, review programs, and inspection/enforcement programs for new and existing sources to ensure that industries comply with the regulations. They review the annual stack testing that companies must conduct to prove that their emissions are within the limits set by their permits. States and local programs monitor ambient air quality, and track whether counties are in attainment of the air quality standards or not. They conduct emission inventories, and coordinate emissions reductions for one or more specific pollutants that are being emitted from vastly different sources (eg, NO_x from motor vehicles and power plants) to comply with nonattainment rules. The need for air pollution control is often driven by compliance with regulations. Whether a region is meeting air quality regulations is determined by actual measurement or monitoring. This great reliance on monitoring (both ambient and source) makes it important to discuss the measurement techniques used for air pollution determination.

4. Measurement of Air Pollution

Measurement of air pollution falls broadly into two categories: ambient air montioring and source measurement. Ambient air sampling often requires continuous measurements for weeks, months or years. The instruments must be able to detect and quantify pollutant concentrations in the ppm to ppb range for gases. The reader should note that, for air pollution work, the concentrations of gases typically are expressed as parts per million by volume (ppmv, or simply, ppm). One way to think of ppm for gases is volume fraction (which is equal to mole fraction) times one million. For particulate matter (PM), concentrations are expressed as mass of PM per volume of air (depending on the pollutant, the units may be mg/m^3, $\mu g/m^3$, or for certain HAPs, they may be as low as ng/m^3).

Source sampling typically deals with gaseous pollutant concentrations in the ranges of tenths of a volume percent down to tens to hundreds of ppm. However, for dioxins and furans (and for certain other HAPs), very low concentrations must be measured in order to show compliance with stringent emissions limits. In these cases, exhaust gas samples from the source are routed through specially design concentrators for two to three hours, which then are taken back to the laboratory for analysis with very precise instruments.

Note that gaseous concentrations can also be expressed as $\mu g/m^3$ and conversion from ppm to $\mu g/m^3$ is made via the following equation:

$$C_{\mathrm{m}} = 1000\, C_{\mathrm{v}}\, M\mathrm{W}_{\mathrm{p}}/24.45 \qquad (1)$$

where:

C_{m} = concentration based on mass, $\mu g/m^3$
C_{v} = concentration based on volume, ppm
$M\mathrm{W}_{\mathrm{p}}$ = molecular weight of the pollutant gas
24.45 = conversion factor for an ideal gas at 25°C and 1 atm, L/mol

Federal regulations (10) require ambient air monitoring at strategic locations in every designated air quality control region. The number of required locations and complexity of monitoring increases with the population in the region, and with the level of pollution. Continuous monitoring is preferable, but for PM, one 24-hour sample every sixth day is often acceptable. In some extensive metropolitan sampling networks, hourly average results from all the continuous monitors are sent electronically to a computer, where they can be processed and placed onto the web. Special problems have been investigated using portable, vehicle-carried, or airborne ambient sampling equipment. The utilization of remote-guided miniature aircraft has been reported as a practical, cost-effective ambient sampling method (11).

Ambient sampling may fulfill one or more of the following objectives:

- establishing and operating a pollution alert network,
- monitoring the effect of an emission source,
- establishing a baseline prior to a proposed installation of a large source,
- establishing seasonal or yearly trends,
- pinpointing the source of an undesirable pollutant,
- checking for hotspots in the city's transportation network,
- obtaining permanent sampling records for legal action or for modifying regulations, and
- correlating pollutant dispersion with meteorological, climatological, or topographic data, and with changes in societal activities.

The problems of source sampling are distinct from those of ambient sampling. Depending on the objectives or regulations, source sampling may be occasional, or continuous. Typical objectives are:

- demonstrating legal compliance with regulations,
- obtaining emission data,
- measuring product loss or optimizing process operating variables,
- obtaining data for engineering design,
- determining collector efficiency for acceptance of purchased equipment, and
- determining need for maintenance of process or control equipment.

In source sampling, it is crucial to obtain a *representative* sample, and this requires sampling from acceptable positions from within the exhaust stream and at correct sampling velocities. Such stack sampling must adhere to federal regulations, which are more commonly known as the federal Methods. For PM, the well-known Method 5 procedure (12) is used, but there are many other methods (13) for many other pollutants. In addition, practical considerations may force the use of special equipment. Many stacks are quite large, and sampling ports may be located several hundred feet above ground level. Source exhaust gases may be at a high temperature or may contain high concentrations of water vapor or entrained mist, dust, or other interfering substances. Contaminants may be deposited onto or absorbed into the structure of the gas-extractive sampling probes or the adsorbents used to concentrate certain pollutants.

4.1. Sampling of Gaseous Pollutants.

Reference methods have been established by the U.S. EPA for measuring criteria and hazardous pollutants, and instruments have been developed commercially for the following pollutants: carbon monoxide (by nondispersive infrared analysis); ozone and nitrogen dioxide (both by chemiluminescence); hydrocarbons (by gas chromatography coupled with flame-ionization detection); and sulfur dioxide (by West-Gaeke [wet chemistry] method). Gas chromatography coupled with a suitable detector can also be used to measure ambient concentrations of numerous other compounds, such as vinyl chloride monomer, halogenated hydrocarbons and aromatics. In recent years, digital instruments and devices have been commercialized to measure almost any pollutant. These automated analyzers may be used for continuous monitoring of ambient and (in many cases) in-stack pollutants, and EPA has developed continuous instrument procedures as alternatives to the reference methods. The U.S. EPA has also published methodologies for siting and operating ambient monitoring stations, and for conducting source sampling for a variety of pollutants.

For source sampling, EPA has specified extractive sampling trains and analytical methods for pollutants such as PM, SO_2, and SO_3, sulfuric acid mists, NO_x, mercury, beryllium, vinyl chloride, dioxins and furans, and a number of VOCs. Some EPA New Source Performance Standards (NSPS) require continuous monitors on certain sources and for certain pollutants; these may measure CO, opacity, SO_2, and others.

4.2. Sampling of Particulate Matter Pollutants.

The concentration of PM in the ambient air traditionally is measured via gravimetric means over a 24-hour period using a volumetric air sampler (a “Hi-Vol”). With this device, a constant volumetric flow rate of ambient air is drawn through a pre-weighed glass fiber filter. PM is trapped on the filter as the air passes through. The total air volume over the 24-hour period is measured, and the mass of particles caught on the filter is later determined by weighing the filter with PM on it and subtracting the clean filter weight. The mass of PM is then divided by the air volume to determine the average mass concentration of PM in the air during that 24-hour period.

In 1987, the EPA changed from regulating total suspended PM to PM-10, with a new reference method (14). In the PM-10 method, a particle size classification head is attached to a Hi-Vol sampler so that only particulates finer than an aerodynamic diameter of 10 μm are collected on the filter. In the 1990s, the EPA changed from the PM-10 reference method to the PM-2.5 reference method. The PM-2.5 filters, methods, and quality assurance procedures are much more demanding than those used for the old total suspended particulate test, but the fundamental principle (gravimetric methods to determine a time-averaged concentration) remains the same.

Isokinetic source sampling for particulates uses a hollow probe inserted into the exhaust gas stream to remove a composite sample of the particles-in-gas from the stack or vent. The PM is caught on a filter as the gases pass through the rest of the sampling train and on to other instruments. The purpose of stack sampling is to determine representative stack gas concentrations and emission rates, and to prove compliance with emission limits. Isokinetic sampling means that one measures the stack gas velocity at the point of sampling, and then matches the probe sampling velocity to the stack gas velocity. Samples must be collected using a calibrated probe and sampling train as prescribed by EPA Method 5 (or a modified method for specific types of PM). An illustration of the Method 5 stack sampling apparatus is presented on the ActiveSet web site (12). See http://www.activeset.org/methods/5.htm.

Continuous in-stack monitors for PM measure opacity utilizing attenuation of some type of electromagnetic radiation across a path through the exhaust gas. Opacity measurements are affected by the particle size, shape, size distribution, and refractive index, other contaminants, and by the wavelength of the radiation (15,16), and therefore must be calibrated for each source.

Particle size measurements for particulates extracted from a source stack by filtration, electrostatic or thermal precipitation, or impaction may be performed using microscopy, sieve analysis, gas or liquid sedimentation, centrifugal classification, or electrical or optical counters. For aerosol particulate size determination, however, questions arise such as whether the collected particles agglomerate after capture, or whether they are redispersed to the same degree in the measuring media as they were originally. These problems can be avoided mainly by performing aerodynamic particle size measurements on the original aerosol by using devices such as cascade impactors (17).

5. Prevention and Control of Air Pollution

5.1. Preventing and Minimizing Air Pollution. The U.S. EPA has endorsed a hierarchical approach to solving pollution problems. At the base is pollution prevention/waste minimization, which is the most preferred approach. Next comes recycling and reuse of waste materials. Third comes treatment, and fourth is disposal. This hierarchy is shown in Figure 1.

As can be seen, the preferred approach is to first try to prevent and/or minimize pollution. The addition of a control device (treatment) is often not the environmentally best or least costly approach. Process examination may reveal changes or alternatives that can eliminate or reduce pollutants, decrease the

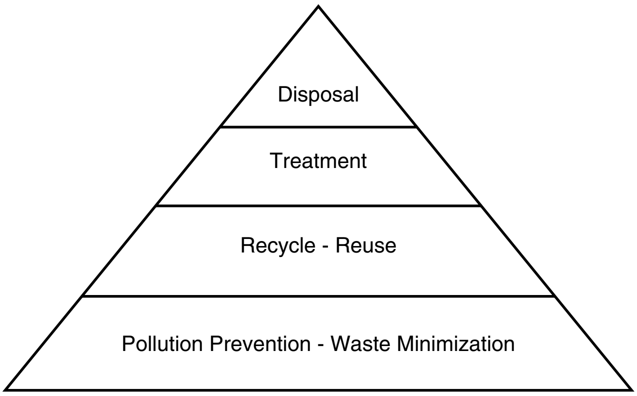


Fig. 1. Hierarchy of solving pollution problems. Reproduced with permission from Ref. 18.

gas quantity to be treated, or render pollutants more amenable to collection. Listed below are some considerations for controlling pollutants without the addition of specific treatment devices (19):

Eliminate leaks or vents of the pollutant.

Seal the system to prevent interchanges between system and atmosphere.
Use pressure vessels.
Interconnect vents on receiving and discharging containers.
Provide seals on rotating shafts and other necessary openings.
Recycle the exhaust stream rather than using fresh air or venting.

Change raw materials, fuels, or processing step to reduce or eliminate the pollutant.

Switch to a non-hydrocarbon based cleaner.
Switch to a lower sulfur fuel.
Change the manner of process operation to prevent or reduce the formation of (or the air entrainment of) a pollutant.
Change the process itself to eliminate the step that produces the pollutant.

Reduce the quantity of pollutant released or the quantity of carrier gas to be treated.

Minimize entrainment of pollutants into a gas stream.
Reduce number of points in system in which materials can become airborne.
Recycle a portion of process gas.
Design hoods to exhaust the minimum quantity of air necessary to ensure pollutant capture.

Use equipment for dual purposes.

Use a fuel combustion furnace to serve as a pollutant incinerator (eg, design a larger volume furnace, or reduce gas flow to increase residence time).

Specific steps to illustrate the above principles include: the substitution of a low sulfur coal at a power plant to reduce SO_2, using a water-based cleaner to rinse printed circuit boards to eliminate VOCs, changing raw materials (eg, eliminating a mercury containing metal ore), reducing operating temperatures to reduce NO_x formation, and installing well-designed hoods at emission points to effectively reduce the air quantity needed for pollutant capture.

5.2. General Principles of Selection of Control Equipment.

Air pollution control (APC) equipment often is designed and manufactured by vendors and selected by consultants or industrial clients in concert with the vendors. The design or selection of the right equipment means devising a system that will solve the pollution problem safely, efficiently, and cost effectively, be relatively easy to operate and maintain, and be able to be expanded or modified to accommodate future plant expansions or future changes in regulations. Engineering considerations include:

Properties of the exhaust gas (eg, gas temperature, pressure, humidity, and flow rate, and time variability of each of these).

Properties of the pollutants (eg, types, sizes, shapes and concentrations of PM, types and concentrations of gaseous pollutants, chemical and physical properties).

Knowledge of the regulations governing emissions (control efficiency required).

The plant space or land available for construction of a new APC system.

The geography, climate and other characteristics of the plant location.

The physical state of matter of a pollutant and its chemical characteristics are very important to the selection of an appropriate APC system – one would not choose an ESP (a well-known collector of particles that uses very high voltage electrostatic charging) to try to control gaseous emissions, nor would it be used to collect gunpowder dust! The total gas flow rate is required to size the APC system. Environmental regulations are crucial because they set (*1*) the allowable outlet concentrations, (*2*) the total mass emissions rate allowed, (*3*) the type of equipment required, or (*4*) the control efficiency required. The plant space available may limit the kind of device that can be installed. Characteristics of the location may seem out of place in the above list, but for example, specifying a wet scrubber collector in a desert area where water is scarce, may not be a wise choice.

In general, for control of PM, one can utilize one or more of the principles of inertial impaction, filtration, electrostatic precipitation, or wet scrubbing to separate and remove particles from a gas stream. For gases, such processes as thermal oxidation, adsorption, absorption (with or without chemical reaction), condensation, or biofiltration can be applied. With these generalities in mind, and with the engineering considerations and criteria in the two bulleted lists above, a tabulated list of possibilities may be developed. This checklist (see Table 4) may be useful as a quick starting point for determining the applicability of certain devices for certain pollution control problems.

Starting with the checklist in Table 4, devices can be eliminated that are too inefficient or that simply are not physically capable of doing the job. When several alternatives might be applicable, then other factors (eg, safety, cost, reliability) must be evaluated. Detailed studies and preliminary engineering designs may well be required to gather sufficient data to make the final decision as to which APC system is to be selected. Typically, more than one type of APC device or system can serve to accomplish the control task, and often several alternatives must be compared. The criteria for such comparison include: (*1*) Control efficiency that can be achieved; (*2*) equipment reliability and operating experience with a particular device; (*3*) total installed cost (initial capital investment); (*4*) operating costs (especially fuel use); (*5*) the wet or dry recovery and reuse of material collected; and (*6*) disposal options and cost of disposal of waste residuals from the APC process.

In comparing alternatives, cost is very important, but the engineer must always recognize that safety is paramount, and that operability and maintainability are key factors as well. Furthermore, sometimes a system with a higher total installed cost may be preferable to one that has a lower initial cost, but that is more costly to operate year after year. Disposal of residuals is a key consideration

Table 4. **Checklist of Applicable Air Pollution Control Devices**

	Pollutant characteristics or control efficiency provided						
	Gaseous		Particulate		Control efficiency		
APC equipment	Odors	Others	Liquid	Solid	Low	Medium	High
Gases							
absorption	●	●	●			●	●
adsorption							
one-use cannisters	●	●					●
regenerative beds	●	●					●
biofiltration	●	●					●
condensation	●	●			●		
chemical reaction		●	●			●	●
Particulates							
cyclones			●	●	●	●	
electrostatic precipitation			●	●		●	●
filtration							
baghouses				●			●
granular beds				●			●
gravitational settling				●	●		
impingement			●	●	●		
wet scrubbers			●	●		●	●
Both							
oxidation							
catalytic oxidizers	●	●					●
incinerators	●	●	●	●			●
RTOs	●	●					●
thermal oxidizers	●	●	●				●
tall stacks[a](dispersion)	●	●	●	●			

[a] Tall stacks are not a control device, but are useful to reduce ground-level concentrations near the source. For certain pollutants, they may be used alone or in conjunction with other control devices.

that sometimes gets overlooked. Some other factors involved in making the final choice (and not included in the above list) are the relative “ruggedness” of the equipment, flexibility to handle a variety of operating conditions, ability to handle combinations of pollutants (sometimes two different devices are needed, but sometimes one device is able to control two different pollutants).

6. Control of Gaseous Emissions

The behavior of gases and vapors, is significantly different from particulates, and greatly influences the selection of control equipment. As the terms are used herein, there is a slight but important difference between a gas and a vapor. Both are in the gaseous state of matter; a gas will remain so over reasonable changes in temperature and pressure. A vapor, on the other hand, is not far removed from becoming a liquid. A small increase in pressure or a small decrease in temperature could result in the vapor condensing into a liquid. Certain kinds of control technologies can work for both gases and vapors, but many are better suited for one or the other, and take advantage of the particular properties of the compounds in question.

Six unit operations or methods are widely used for controlling gaseous emissions: absorption, adsorption, biofiltration, condensation, chemical reaction, and incineration. Atmospheric dispersion from a tall stack, considered as an alternative in the past, is not really a control method, but is still used to help reduce final ambient concentrations to acceptable levels. All control methods can be considered as primarily separation techniques or primarily conversion techniques (though many control technologies employ both separation and conversion). Processes for separation of gases and vapors from air (or other "inert" exhaust gases) include absorption, adsorption, and condensation, whereas conversion techniques include biofiltration, chemical reaction and incineration. It is noted that absorption and biofiltration require that the pollutant be absorbed in an aqueous phase, and such absorption is usually followed by a chemical or biological reaction of the contaminant once it is in the liquid phase.

Although certain unit operations can be applied to different kinds of gases and vapors, often particular methods are found that more applicable to specific pollutants. Adsorption is applicable for many organic pollutants within a certain molecular weight range, and can achieve contaminant removal down to extremely low levels (less than 1 ppm). It is often used for controlling organic vapors in relatively cool streams of air. Biofiltration is preferred for handling large gas volumes that have high humidity and quite dilute contaminant levels (as long as the contaminants are somewhat water soluble and biodegradable). Condensation is best for substances with rather low vapor pressures, but that are present in relatively high concentrations in the air stream. Where refrigeration is needed for the final condensing step, elimination of noncondensible diluents is beneficial. Incineration, suitable only for combustibles, is used to destroy toxic, odorous, and other organic pollutants, and small concentrations of H_2S or CO. Specific gases such as sulfur oxides or nitrogen oxides often require specialized methods, and are discussed later.

6.1. Volatile Organic Compounds (VOCs).

Volatile organic compounds (VOCs) are any organic compound with significant vapor pressure so that it can exist as a vapor in air. Emissions of VOCs come from many sources, including petroleum processing, painting, solvent cleaning, incomplete combustion of fuel, and others. Good attention to VOC control has resulted in significant decreases in U.S. emissions since the Clean Air Act Amendments of 1970: from 14.3 million tons in 1970 to 8.0 million in 1999 (6). There are many techniques that can be applied to VOC control.

Condensation. Control of VOCs by condensation is most effective for streams of air with high concentrations of compounds that have relatively low vapor pressures at room temperature (eg, compounds that are close to being liquids at room temperature) (20,21). The more volatile (higher vapor pressure) substances often require two-stage condensation, usually water cooling followed by refrigeration. Condensation by itself can not produce extremely low outlet concentrations of most VOCs, and so does not suffice as a final pollution control technique. Normally, it is used simply to pre-treat the polluted gas stream and to partially recover the VOCs in question. Condensation can be especially useful as a preliminary treatment ahead of another method such as adsorption or incineration. Both shell-and-tube condensers (often with finned coils), and direct-contact condensers are used. Direct-contact condensers usually atomize a cooled, recirculated, low vapor pressure liquid such as water into the gas. The recycled liquid is often cooled in an external exchanger.

If condensation requires gas stream cooling of more than 40–50°C, the rate of heat transfer may appreciably exceed the rate of mass transfer and a condensate fog may form. Fog seldom occurs in direct-contact condensers because of the close proximity of the bulk of the gas to the cold-liquid droplets. When fog formation is unavoidable, it may be removed with a high efficiency mist collector designed for 0.5 to 5-μm droplets. If atmospheric condensation and a visible plume are to be avoided, the condenser must cool the gas sufficiently to preclude further condensation in the atmosphere, or a re-heater may be needed.

Adsorption. In the adsorption process, the contaminated air stream is passed through a bed of granular activated charcoal or other adsorbent. The VOC molecules are adsorbed onto the surface of the highly porous carbon pellets, while the cleaned air flows through. The physical process of adsorption is similar to condensation. However, major differences are that adsorption can still occur at very low concentrations of vapors, and very high removal efficiencies are possible. Adsorption is a surface phenomenon, and when all the surfaces of the adsorbent have been covered, no more VOCs will be removed from the air stream, and the VOCs will “break through” the bed. Before that occurs, the air stream must be switched to an identical bed. While the polluted air is being treated on the new bed, the old bed is regenerated by passing steam through it countercurrently. The hot steam desorbs the organics and carries them out of the bed, thus renewing the carbon for another cycle of adsorption. The steam and organic vapors are then separated by condensation followed by decantation of the two immiscible liquids. Figure 2 presents a schematic diagram of a carbon adsorption system.

Carbon is the most common adsorbent, but it must be activated to increase its surface area and adsorption capacity. The carbon is activated by partial oxidation under low oxygen conditions. After activation, the carbon pellets become highly porous, and the surface area available for adsorption can be as high as 800–1200 m^2/gram (4). Activated carbon is the best adsorbent for medium-molecular weight organic compounds; very light compounds do not adsorb appreciably, and very heavy organic compounds are hard to remove from the carbon during regeneration. Carbon is one of the few adsorbents that can work with some humidity in the air. The carbon source is often coal, but can be coconut shells, bone char or other organic materials. Other adsorbents include activated alumina, silica gel, or molecular sieves, or carbon that is impregnated with certain compounds to adsorb specific pollutants (eg, carbon with bromine to react with olefins, or with iodine to react with mercury vapor).

Adsorption finds wide application for controlling organic solvents given off during painting, printing, or cleaning, odors from food processing or waste rendering, and organic emissions from many other commercial processes. Because adsorption is exothermic, adsorption is usually selected only when the air stream temperatures are reasonably low, and precooling the air stream often is necessary to ensure a good adsorption equilibrium curve (called an isotherm). The gas stream must not only be cool but also must be dust-free, as particulates can quickly plug a bed packed with carbon granules. Generally, the capacity of

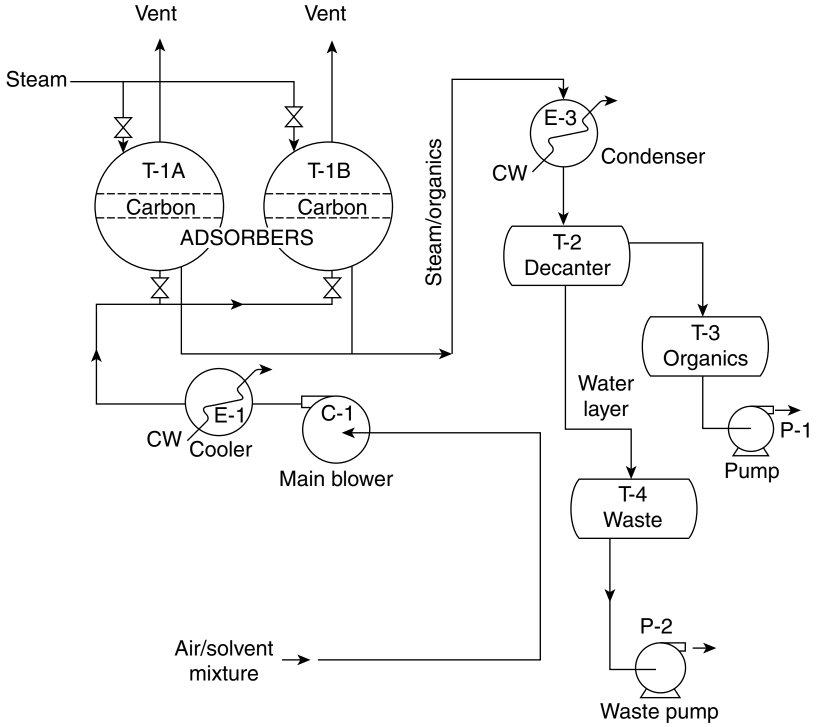


Fig. 2. Carbon adsorption system. Reproduced with permission from Ref. 4.

a solid adsorbent to adsorb a particular vapor (adsorbate) is directly proportional to the solid's surface area, to the molecular weight of the adsorbate, and inversely proportional to its vapor pressure. This capacity is a strong function of the temperature of the gas and the concentration of the adsorbate; this relationship (normalized per unit weight of adsorbent) is portrayed for any particular adsorbent-adsorbate pair as an isotherm. A typical isotherm is shown in Figure 3.

The adsorption process is inherently unsteady-state, with VOCs being removed from the air and accumulated on the carbon as the air stream flows through the bed. This process is called an adsorption wave, and is depicted in Figure 4. A mathematical analysis of an adsorption wave has been presented (5). As mentioned earlier, after the carbon surface becomes saturated with organics, the carbon must then be regenerated. So the air stream is switched to another bed, and then the first bed is regenerated. It is noted that for very small or intermittent applications, the saturated carbon may be simply disposed of (either by simple landfilling for nonhazardous compounds, or by incineration for toxic materials).

The carbon can be regenerated by heating with an inert gas, vacuum stripping, air stripping, or displacement by other materials, but is most often accomplished in large industries by passing hot steam through the bed. The steam heats the bed, desorbs the VOCs and carries them out of the bed to a condenser. Steam usage is often between 1–4 pounds of steam per pound of recovered VOC, or 0.2–0.4 pounds of steam per pound of carbon (4). The liquid organics can then

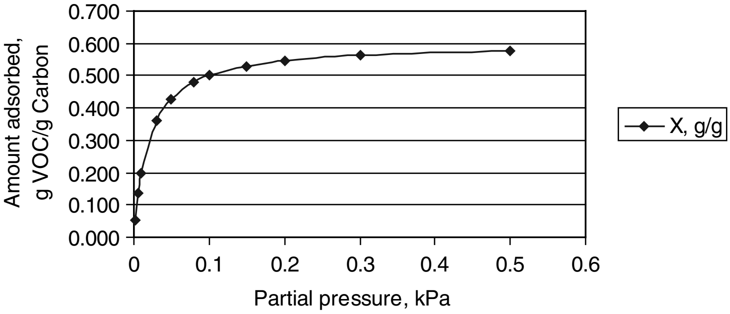


Fig. 3. Typical adsorption isotherm.

be recovered for re-use, recovered for fuel values, or simply disposed of (via biological or physical treatment methods or by incineration). The regeneration process is never perfect, and so the operating capacity of the carbon bed is never as high as the theoretical isotherm would indicate. The true operating capacity is often only 30–40% of the isotherm capacity due to the VOCs remaining on the carbon after regeneration. One example of a small-scale regenerative scheme is the small carbon canisters in automobiles that catch gasoline vapors during

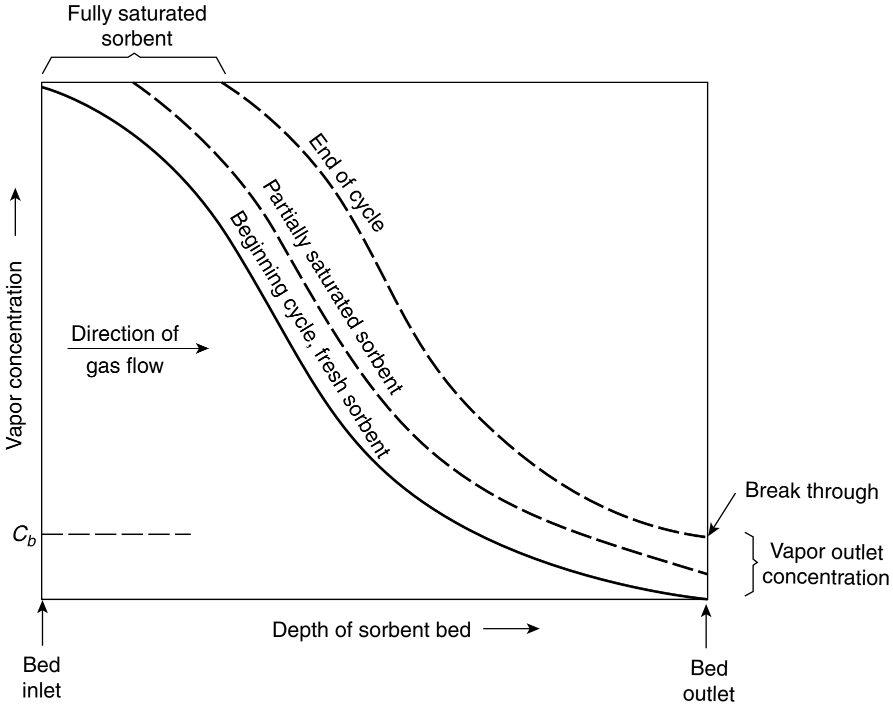


Fig. 4. Adsorption wave passing through a fixed carbon bed. The progressing S-shaped curves indicate the nonadsorbed vapor concentration by position in the bed at different time periods. C_b represents the maximum permissible outlet concentration for release to the atmosphere.

engine start-ups and shut downs. These are regenerated (while the car is in operation after the engine is warm) by passing some of the combustion air in a reverse flow path to desorb the VOCs into the cylinders for combustion.

In industrial designs, the adsorption cycle time is determined by the size of the gas flow, the concentration of the VOCs, and the size of the bed. The cycle time often is in the range of 1 to 8 hours. For larger gas streams, or high pollutant concentrations, a static bed would be exhausted too rapidly and fluidized-bed and traveling-bed systems are used. In a fluidized-bed adsorbent granules are well-mixed and an adsorption wave does not exist. The bed's capacity may be quite low unless staging is practiced. Fluidization's advantage in single-stage beds is that the adsorbent can be removed continuously from the bed through solids flow into a second regeneration vessel and then continuously returned to the adsorption chamber. In traveling-bed systems, spent adsorbent is continuously removed from the bottom, regenerated in another vessel, and continuously recharged at the top of the adsorption bed. Countercurrent flow is used; solids flow downwards and gas flows upwards.

Incineration. One method of air pollution control that can be applied broadly to all types of VOCs is incineration (often called thermal oxidation or afterburning). This method destroys the VOCs by oxidizing the compounds to CO_2 and H_2O; it can also be applied to control combustible particles, including soot, smokes, and organic liquids. It is an excellent process for use in destroying odorous or toxic materials such as pesticides or military nerve agents because it permanently destroys organic compounds. It is not a good method for treating metal-containing compounds. The VOC vapors might be in a concentrated stream, such as emergency releases of hydrocarbons from an oil refinery (which are combusted safely in an elevated flare), or they may be dilute, such as paint solvents from a paint baking oven. Several manifestations of incinerators exist, including direct thermal oxidizers, catalytic oxidizers (found on all modern cars as well as in many industries), and regenerative thermal oxidizers.

For a pure hydrocarbon, the oxidation reaction, as it occurs in air, can be represented as follows:

$$\begin{aligned}\mathrm{C}_n\mathrm{H}_m + (1+\mathrm{X}/100)\,\mathrm{B}\,\mathrm{O}_2 + (1+\mathrm{X}/100)\,3.76\,\mathrm{B}\,\mathrm{N}_2 \rightarrow n\,\mathrm{CO}_2 + m/2\,\mathrm{H}_2\mathrm{O}\\ + \mathrm{X}/100\,\mathrm{O}_2 + (1+\mathrm{X}/100)\,3.76\,\mathrm{B}\,\mathrm{N}_2\end{aligned} \tag{2}$$

where:

n, m = integers
X = % excess air
B = coefficient to balance the stoichiometric oxidation reaction ($B = n + m/4$)
3.76 = molar ratio of nitrogen-to-oxygen in the air

If there are other atoms in the VOC molecule (eg, chlorine, sulfur) then other products of combustion will appear in the balanced equation (eg, HCl, SO_2), and B must be adjusted accordingly. The oxidation reactions typically are not 100% stoichiometric, and will produce very small quantities of pollutants, such as CO, formaldehyde, nitrogen oxides, dioxins and furans, and others. In

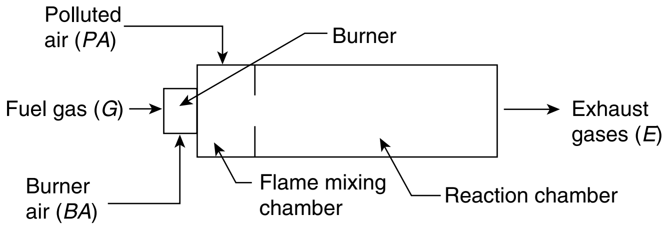


Fig. 5. Schematic diagram of thermal oxidizer. Reproduced with permission from Ref. 4.

reality, however, those other pollutants can be held to very low levels by well-designed and operated systems.

There are several manifestations of vapor and liquid VOC incinerators. The thermal oxidizer is simply an open cylinder with a burner at one end to create a flame. The contaminated air stream flows into the front end, mixes with the flame gases, and flows through the device (see Fig. 5). The device is sized and the fuel requirements are determined by simple engineering calculations based on mass and energy balances. Typically, the fuel requirement is calculated to achieve an oxidation temperature in the range of 1200–2000°F (as required by regulations), the diameter is set to produce an average gas velocity through the hot zone in the range of 10–20 ft/s, and the length is specified to achieve a residence time of 1–2 seconds. Due to high energy costs, it is desirable to keep the inlet concentration of VOCs high (to prevent heating up too much excess air). However, insurance regulations require that the concentration of VOCs in air going to an open-flame device be kept to no more than 25% of the lower explosive limit (LEL) for that particular VOC. Therefore, thermal oxidizers use a lot of fuel, and have a high operating cost.

Catalytic oxidizers can reduce the temperature required for destruction of the VOC by several hundred degrees, and thus can save considerable fuel and operating expense compared with thermal oxidizers. The catalyst is usually stacked honeycomb structures or loosely packed pellets, either of which is made of some sort of ceramic material with a precious metal adsorbed on the surface. Disadvantages of catalytic oxidizers compared with thermal oxidizers are that they have higher capital costs, they can get plugged or poisoned easily, and the catalyst needs replacement every few years.

In this age of high energy costs, heat recovery from thermal oxidizers is very important. There are several ways to recover heat from the hot exhaust gases, including preheating the incoming polluted air or heating a process stream via a shell-and-tube heat exchanger, making steam in a waste-heat boiler, or simply using the hot exhaust in another process (4). A more recent development in thermal oxidizers is a regenerative thermal oxidizer (RTO) depicted in Figure 6. This device operates somewhat like a carbon adsorber; the polluted gases flow through a hot ceramic bed, then into the combustion chamber, and then exit through a cool ceramic bed. Flowing through the hot ceramic bed, the gases get pre-heated while cooling the ceramic, and while going through the cool bed, the gases lose their heat to the ceramic. After a time, the flow path is reversed. A well-designed and operated RTO can recover 90 to 95% of the heat energy of the hot gases, and thus cut fuel costs by that same percentage.

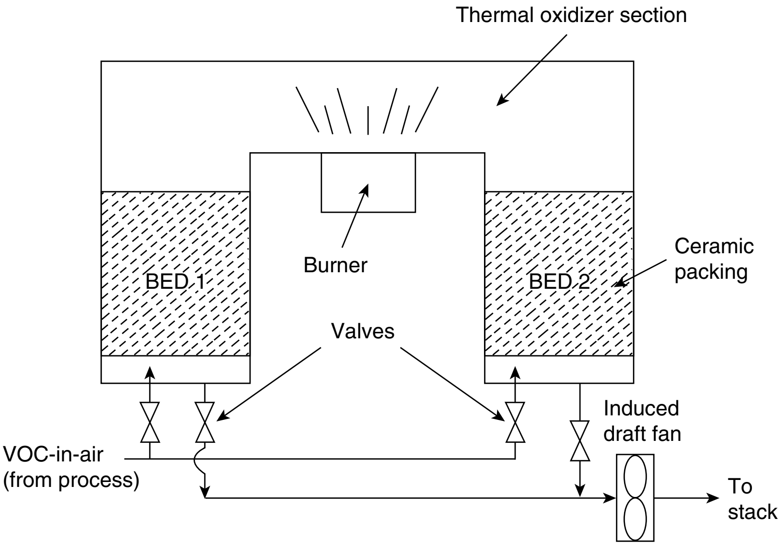


Fig. 6. Schematic diagram of regenerative. Reproduced with permission from Ref. 4.

Keep in mind that energy recovery, whether by a traditional heat exchanger or by an RTO, is achieved by forcing the gas through close contact with a solid surface, and this always results in pressure drop. In general, the higher the degree of energy recovery, the higher is the pressure drop. A rule of thumb is that energy recoveries in heat exchangers of 30, 50 and 70% will have pressure drops of 4, 8, and 15 in. H_2O, respectively (22).

Biofiltration. A relatively recent development in VOC control is biological air pollution control. This can occur in a fixed bed, trickling bed, or a fluidized bio-scrubber device (23,24). The fundamental principle is that gaseous pollutants are absorbed into a liquid phase, taken in by microbes and utilized as a food or energy source, and are destroyed as they are converted into innocuous metabolic end products (CO_2 and H_2O). The process requires careful attention to its design and operation to ensure good contact of the contaminated air with the liquid phase and the biofilm containing the microbes, and to ensure that the microbial population is sustained and maintained in a healthy state. However, for the right applications, and with good attention to detail, these biological control systems can function well for years with high removal efficiency and low operating costs.

The basic process involves contacting the contaminated air stream with a circulating liquid or a wetted bed that contains a healthy population of biomass. The most common application appears to be biofiltration in which the water and biomass are maintained on a stationary media or bed, and the air flows through the bed. Whether the water phase is flowing (as in a scrubber) or is stationary (as in a biofilter), the microbial population lives in the water phase. A schematic diagram showing the cross-section of a biofilter is presented in Figure 7.

The most successful uses of biofilters are for low molecular weight and highly soluble organic compounds, such as alcohols, aldehydes, ketones, and for a variety of odorous gases, including H_2S and NH_3. However, other types of compounds (eg, styrene, and gasoline components, such as benzene and toluene)

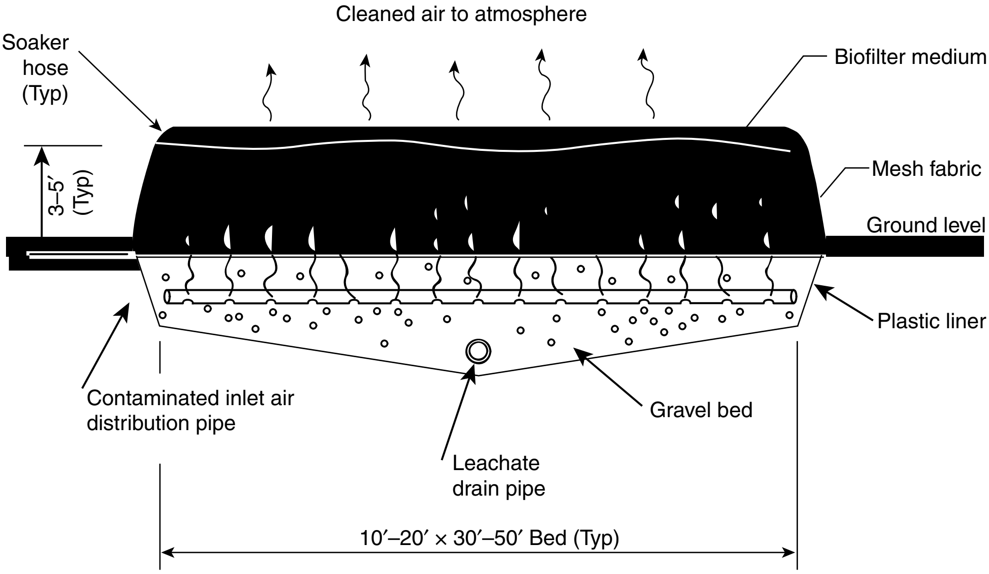


Fig. 7. Schematic diagram of a biofilter. Reproduced with permission from Ref. 4.

have been successfully treated. The maximum removal performance in a biofilter tends to follow the sequence alcohols > esters > ketones > aromatics > alkanes (25). This sequence also tends to be in order of decreasing solubility in water (increasing Henry's coefficients).

Key concerns in the design and operation of biofilters include: identifying the concentration and type of contaminants in the air stream, finding the correct microbial population, selecting a compatible media, maintaining adequate moisture in the bed, sizing the bed to provide adequate residence time for the given air flow rate, and controlling pH, nutrient levels, and temperature in the bed. This technology is best suited for high volumetric flow rate air streams with low concentrations of pollutants. The capital costs are very reasonable, and the operating costs tend to be quite low.

Because each pollutant/media/bacteria/climate/geography combination is different, biofilter designs are based largely on pilot studies and scale-up of those results. In all cases, the designs must ensure that the polluted air is humidified, as even slightly undersaturated air streams can quickly dry out the biofilm and kill the bacteria. Spray towers are used to humidify and cool incoming gases, and soaker hoses are placed inside the bed to replenish any water lost by evaporation within the bed.

As one example, three biofilters were constructed to treat the H_2S-laden gas at a 20 million gallon per day wastewater treatment plant in Orange County, Florida (4). The main source of H_2S was identified as fugitive odorous air emissions from the grit chamber/flow splitter (GCFS) building. H_2S was being released from the wastewater as it flowed through the grit chamber and flow splitter building, and these emissions were not being captured effectively. Furthermore, the air that was being captured was not being scrubbed efficiently by existing chlorine-caustic scrubbers. It was decided to improve the air collection system and to route the odorous air to three upflow biofilters in parallel.

The biofilters were constructed on-site, and included air distribution pipes in an underlying gravel bed, which was underlain by a high-density polyethylene liner. Soaker hoses were installed at two different levels within the media, and a leachate drain pipe in each gravel bed. The biofilter media was a custom blend of local wood chips, screened bark mulch, leaf compost, and a small percentage of oyster shells (for pH control). Construction of the biofilters was completed in July 1998. In August 1998, the three units were balanced and tested to evaluate performance.

To evaluate performance, the units were sampled for inlet and outlet H_2S concentrations weekly from August 1998 through January of 2000. The concentration of H_2S to and from each filter was sampled at one location in the inlet duct, and at three locations at the top surface (air exit) of each bed. The H_2S concentration was measured using a hand-held H_2S meter, and sampling time was approximately 40 seconds per location. The gas exiting through the (open) top surface of the bed was sampled by placing an inverted funnel on the top surface of the bed (to isolate the biofilter exit gas from ambient air), and then sampling the gas exiting from the top spout using a hand-held H_2S meter. Numerous test results showed that these biofilters provided better than 99 percent removal of H_2S (4).

6.2. Control of Acids and Other Gases.

Absorption. Absorption is particularly attractive for water-soluble pollutants in appreciable concentration; it is also applicable to dilute concentrations of gases having high solubility. These include HCl, Cl_2, HF, SO_2, H_2S, NH_3, and others. In many cases, absorption is enhanced by adding chemicals that control pH or that react with the pollutants once they are absorbed. In some instances, a nonaqueous scrubbing liquid may be used, but in most cases the absorbent liquid is water.

There are many types of absorption devices that can be used for removing gaseous contaminants from air, but the equipment most frequently used include packed columns, open spray chambers and towers, cyclonic spray towers, and combinations of sprayed and packed chambers. For particulate-free gas, the counter-current packed tower is the usual choice owing to its good mass transfer characteristics. If the gas stream also carries PM, then open spray chambers are preferred. Plastic packings with extended surface area and high void space are used with wetted temperatures below 85°C. These packings are lightweight, and provide high mass transfer and constant liquid film renewal, while producing only a small pressure drop. Insoluble particulates and heavy loads of soluble ones plug packing rapidly; concurrent flow tends to reduce plugging. Six months of plug-free operation of a parallel-flow bed absorbing SiF_4 in water has been reported (26).

The cross-flow packed scrubber (Figure 8) is even more resistant to plugging and has been used extensively as a pollutant absorber in the phosphate industry to absorb HF and SiF_4 (27). Typical liquid-to-gas ratios range from 1:1 to 3:1 (on a dimensionless mass-to-mass basis). When particulates are present, sprays directed at the bed-retaining grillwork are added upstream. Most of the solids are impacted on the first 150 mm of packing in the gas-flow

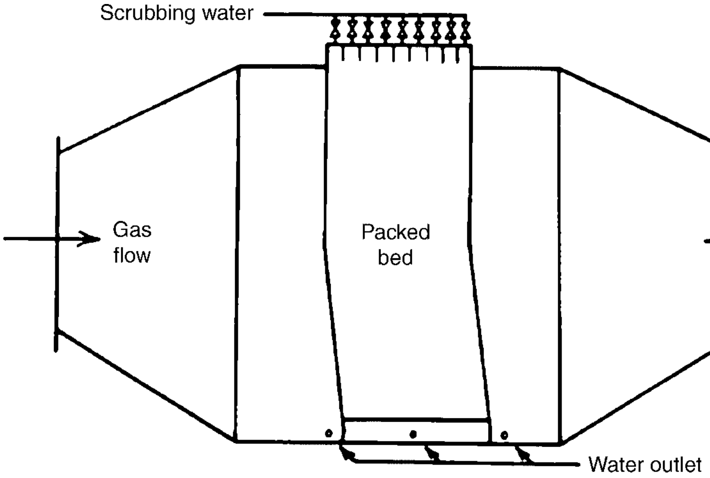


Fig. 8. Horizontal cross-flow scrubber.

direction. To remove deposited solids, the liquid rate over the first 300 mm of packing can be increased significantly to provide a washing action.

Open horizontal spray chambers (26) and vertical spray towers are often used when solids are present, and can be effective at both scrubbing particulates and absorbing soluble gases. Cyclonic spray towers provide slightly better scrubbing when the optimum spray droplet size is used. However, most of these devices are relatively low efficiency absorbers of gaseous pollutants, and are often used more for PM removal. Figure 9 illustrates various spray chambers.

When a high degree of gas absorption (eg, a large number of transfer units) is required, a single open-tower absorption contacting method may be unsatisfactory. Loss of counter-currency resulting from spray entrainment limits the number of transfer units achievable in a single tower. Using vertical spray towers, 5.8 transfer units have been attained (28). Seven transfer units in a commercial cyclonic spray tower have been reported (29) and 3.5 transfer units have been reported in horizontal spray towers. The high-pressure drop venturi scrubber is very well-suited for particulate collection, especially submicrometer particles, and can achieve reasonable gas absorption, but it has been indicated that these scrubbers are limited to 3 transfer units (28).

Water is the most common absorption liquid. It is used for removing highly soluble gases such as HCl and ammonia, and other gases, such as H_2S, HF, and SiF_4, especially if caustic is added to the water. NH_3 can also be absorbed in water if the final contact is acidic. Problems can arise in the initial absorption stages when contacting high concentration gases and volatile neutralizing agents. Vapor phase reactions can produce a submicrometer smoke which is often difficult to wet and collect. These problems can be avoided if initial contact is made at points in the tower where reactant vapor pressures are low. Gases such as SO_2, Cl_2, and H_2S can also be absorbed more readily in alkaline solutions. The most common absorption processes use lime or limestone slurry, though sodium-based caustics are also used (4). Often the scrubbing is enhanced by chemical reactions in the liquid (eg, formation of $CaSO_3$ in an SO_2 scrubber, or

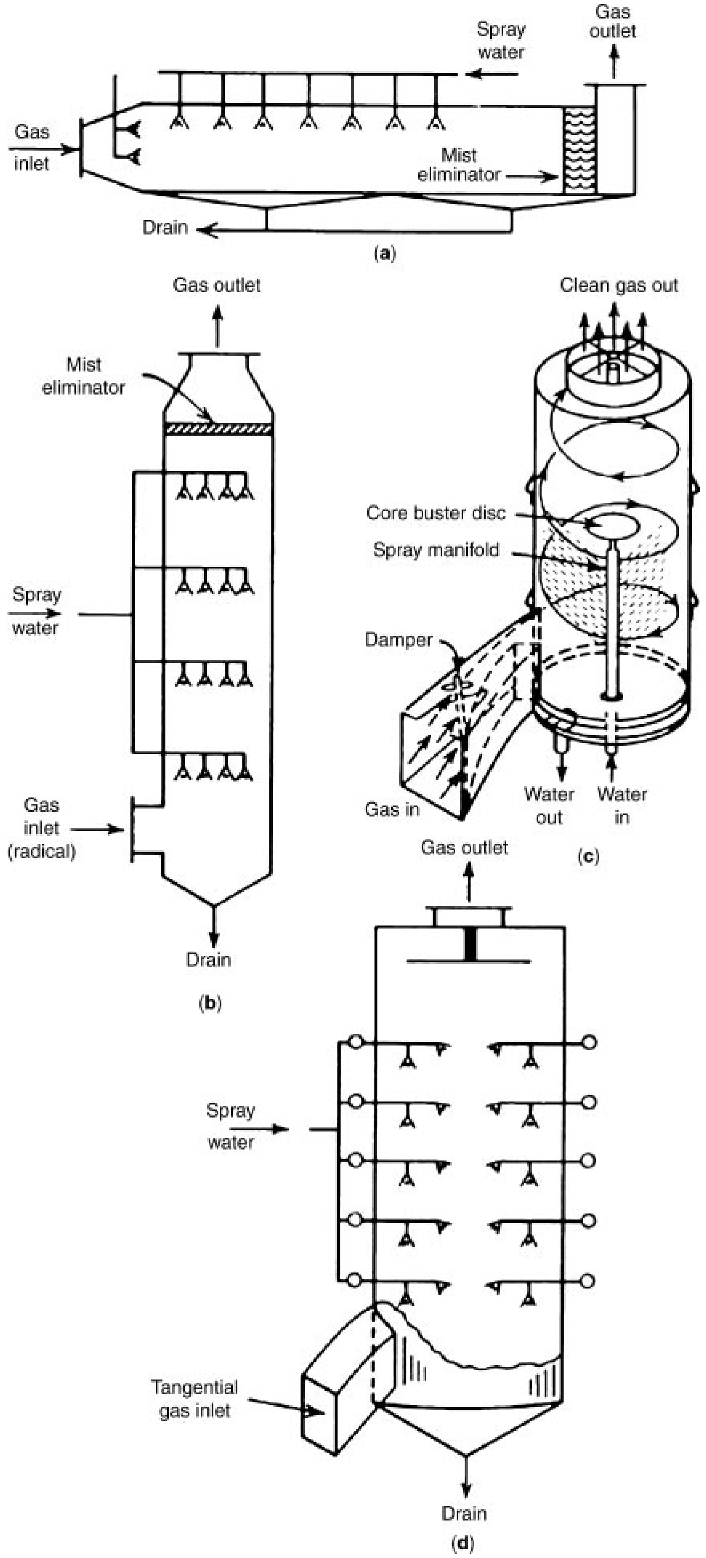


Fig. 9. Types of spray towers: (**a**) horizontal spray chamber; (**b**) simple vertical spray tower; (**c**) cyclonic spray tower, Pease-Anthony type; (**d**) cyclonic spray tower, external sprays.

oxidation of H_2S by chlorine in a chlorine-caustic scrubber). Many absorption processes have been commercialized for removing SO_2 from coal-fired power plant flue gas. Organic liquids such as dialkylaniline, the various ethanolamines, and methyldiethanolamine can also be used for absorption of particulate-free acidic gases, such as H_2S. Low volatility oils and solvents such as kerosene can be used to absorb organic vapors as long as the scrubbing liquid volatility is low enough to prevent vapor loss and atmospheric contamination.

Disposal of recovered gaseous pollutants can be a problem. Precipitation of certain acid gases (especially SO_2) as insoluble sludges may be possible through the addition of lime, limestone, or other reagents. The sludge may be thickened by settling, and dewatered by centrifugation or filtration; however, sludges containing 70% water are not uncommon. Disposal to streams is not feasible and impounding in landfills or tailing ponds is becoming less acceptable. However, large $CaSO_3$/$CaSO_4$ sludge ponds can still be found at many coal-fired power plants. Conversion of the pollutant to a usable form is preferable, but usually involves added expense, even when selling the recovered material. Recovered sulfate and sulfite compounds, if ammoniated, may be incorporated into fertilizer or may be used by nearby sulfate–sulfite pulp and paper mills. Recovery as gypsum for wallboard or other uses is also possible, but occasionally, the sulfur values can be recovered as elemental sulfur or as sulfuric acid in a regenerative process (4). Although HCl can sometimes be recovered as a dilute acid, halogens in general can be especially difficult to recover.

SO_2 Scrubbing. Sulfur dioxide is formed whenever any material containing sulfur is burned. Hence, SO_2 is prevalent in numerous industrial exhausts, including power plants, petroleum refineries, pulp and paper plants, phosphate fertilizer plants, nonferrous metal smelters, and others. For small sources (and some large ones) the best solution is to remove the sulfur prior to combustion, or simply buy a low-sulfur fuel. During the 1990s many coal-fired power plants in the U.S. switched to low-sulfur coal, and many others installed limestone scrubbing systems in response to mandates from the Clean Air Act Amendments of 1990. As a result, SO_2 emissions from U.S. coal-fired power plants has been reduced significantly, from 15.4 million tons in 1989 to 11.8 million in 1999 (6). Worldwide, as of 1998, there was about 250,000 MW of power-generating capacity equipped with flue gas desulfurization systems (30). For the last 30 years, oil refineries have been processing increasingly higher sulfur crude oil, but recovering more of the sulfur and selling it as a by-product. Emissions of SO_2 from oil refineries have dropped from 770,000 tons/yr in 1970 to 244,000 tons/yr in 1999 (6), despite a large increase in the sulfur content and volume of the oil processed.

There are two basic approaches to sulfur dioxide scrubbing: regenerative and throwaway. Within those two broad categories, there are numerous processes. Table 5 summarizes a number of those processes. For exhaust gases that have high concentrations of SO_2 (such as from copper or nickel smelters), it is possible to scrub with water and produce a sulfuric acid stream that can be sold. In the United States and Canada alone, non-ferrous metal smelters produce about 6 million tons of sulfuric acid per year. There are regenerative processes that can be applied at coal-fired power plants, and in Japan and Germany, much sulfur is being recovered this way. However, in the U.S., coal-fired power

Table 5. **Examples of SO_2 Control Processes**

Category	Example of process	References
	Throwaway	
wet scrubbing	lime	30,31
	limestone	31–35
	forced oxidation	31
	inhibited oxidation	36
	dual alkali	32,37
dry scrubbing	lime spray drying	32
	powdered lime injection	38–40
	Trona	38,39,41
	Nahcolite	40,41
	Regenerative	
wet processes	water absorption (with sulfuric acid sales-smelters)	42
	Wellman-Lord	32,43
	magnesium oxide	35
	citrate	37
	carbonate	35,44
	sulfite	35,44
	forced oxidation (with gypsum sales-power plants)	31
dry processes	activated carbon	39,40,41
	copper oxide	38,44,46

plants (this country's largest source of SO_2), mostly use a limestone-based throwaway process (31).

In limestone scrubbing (31), a slurry of water and finely ground limestone is contacted with the exhaust gases. The SO_2 is absorbed, neutralized, and partially converted to calcium sulfite and calcium sulfate. The reactions occur in two steps, and the stoichiometry is as follows:

$$CaCO_3 + H_2O + 2\,SO_2 \rightarrow Ca^{+2} + 2\,HSO_3^{-1} + CO_2$$

$$CaCO_3 + 2\,HSO_3^{-1} + Ca^{+2} \rightarrow 2\,CaSO_3 + CO_2 + H_2O$$

As can be seen by adding the two reactions, the net result is the removal of SO_2 from the gas (and its replacement with CO_2) and the production of a calcium sulfite sludge. There are many, many enhancements that have been made over the last 30 years, and modern processes can be very efficient (greater than 97% SO_2 removal), but the basic problem still is the disposal of the waste sludge. Until the disposal costs become higher than those of recovering the sulfur values, the practice of disposal will continue to be favored. Limestone scrubbing systems are large, complex unit operations, and power plant owners/operators do not want to add even more complexity to their basic business by installing complicated regenerative systems.

NO_x Control. Nitric oxide (NO) and nitrogen dioxide (NO_2) are commonly called NO_x. These compounds are formed whenever there is high temperature combustion of anything using air as the oxygen source. At high temperatures (3000 to 3600°F), the nitrogen and oxygen molecules each split into highly reactive atomic forms, and the atoms recombine as NO_x. The major sources in

the U.S. are power plants, large industrial furnaces, and motor vehicles. NO_x has been one of the most difficult pollutants to control, and emissions in the U.S. have actually risen over the last 30 years – from 20.9 million tons/yr in 1970 to 25.4 million tons/yr in 1999 (6). More than half of all NO_x emissions in the United States comes from mobile sources.

Industrially, there are several methods for controlling NO_x; they can be classified as either combustion modifications or flue gas treatments. Because NO_x formation depends critically on the temperature and oxygen content in the flame zone, and on the time of exposure to these conditions, *combustion controls* attempt to reduce NO_x formation by one or more of the following strategies (4):

(1) Reduce peak temperatures
    Use a fuel-rich primary flame zone
    Increase the rate of flame cooling
    Decrease the adiabatic flame temperature by dilution
(2) Reduce gas residence time
    Change the size and shape of the flame zone
    Increase the gas velocity by dilution
(3) Reduce the oxygen content in the primary flame zone
    Decrease overall excess air rates
    Control the mixing rate of fuel and air
    Stage the combustion to be fuel-rich followed by fuel-lean

Some of the tactics to implement the above strategies are as follows: Low NO_x burners; low excess air firing; flue gas recirculation; off-stoichiometric combustion; gas reburning; reduced air pre-heat; and water injection.

Flue gas treatment technologies focus mostly on chemically reducing the NO_x to N_2 and H_2O. The most widely used technology is selective catalytic reduction (SCR). This capital intensive process has been applied mostly at large power plants, and has had reasonable success. In this process, ammonia (or other reducing agent) is injected into the hot flue gases, and then the mixture is passed over a catalyst. The reactions are

$$4\,NO + 4\,NH_3 + O_2 \rightarrow 4\,N_2 + 6\,H_2O$$
$$2\,NO_2 + 4\,NH_3 + O_2 \rightarrow 3\,N_2 + 6\,H_2O$$

The optimum temperature range for these catalytic reactions is 300–400°C (600–800°F), and the units can achieve about 80% NO_x reduction (4). The catalysts are structured (honeycombed) alumina impregnated with vanadium or tungsten oxides, and are subject to poisoning or plugging by contaminants in the power plant flue gas. Selective noncatalytic reduction (SNCR) accomplishes the same reactions as above, but without the use of catalyst. However, the temperatures required are significantly higher (900–1000°C), and the conversion efficiencies are lower (40–60%).

Carbon Dioxide (CO_2). In this modern day of heightened awareness and concern about global climate change (GCC), it is necessary to touch on the subject of carbon dioxide (CO_2) control. CO_2 is the thermodynamically stable end product of the combustion of any carbonaceous fuel, and is the compound most responsible for GCC (other gases that contribute to GCC are methane, CFCs, and N_2O). The burning of fossil fuels worldwide adds billions of tons of carbon dioxide into the air every year. Excessive emission of CO_2 into the air is resulting in a steady increase in CO_2 concentrations in the atmosphere, and the acceleration of the greenhouse effect. CO_2 levels have risen to unprecedented levels, and temperatures are rapidly rising above historical norms. For more information, visit the web sites: http://cdiac.ornl.gov/trends/co2/graphics/mlo145e_thrudc04.pdf and http://www.giss.nasa.gov/data/update/gistemp/graphs

In this author's view, there is no doubt that GCC is underway, and the above web sites are just two examples that provide hard data evidence of GCC. Other evidence of global warming is more anecdotal, partly because "the weather" is subject to large fluctuations from season to season and from year to year, and partly because the earth is so huge that it takes a long time for "real changes" to show up. "Real changes" are defined to mean those changes that are large enough to say "without a doubt" that they are not part of the "noise" (normal random fluctuations about the mean), and that they are caused by global warming. However, there are several examples of anecdotes that seem particularly compelling. The U.S. weather service keeps temperature records that show that 8 of the 10 hottest years in the 20th century occurred in the ten years from 1990 through 1999 (4). A massive heat wave in Europe in 2003 resulted in the deaths of more than 20,000 people in France and Germany alone; heat waves in the United States in the summer of 2006 (when this is being written) have caused hundreds of deaths so far. There have been widespread incidents of droughts and fires throughout the United States during the last decade. The Inuit Indians in northwestern Canada have stated in research interviews that there are fewer seals and polar bears to hunt due to thinning sea-ice, and warmer weather has brought more mosquitoes that stay longer. Biologists have noted that the range where certain butterflies live has crept northward by more than 100 miles during the past 25 years. Glaciers in Alaska are retreating rapidly. It was noticed in the year 2000 (for the first time since such observations have been recorded) that there was no solid ice – only open water – at the north pole (4).

Although the vast majority of scientists and engineers agree that GCC is happening and is a grave danger, not everyone agrees that GCC is real. Some still argue that it is too soon to take expensive steps to mitigate the rise in CO_2. Everyone agrees that steps to mitigate GCC are very expensive, and may require substantial sacrifices by many people. It has been argued that to undertake such steps prematurely would be foolish. However, in this author's view, to wait much longer is even more foolish.

Because the burning of fossil fuels is so entrenched in the world's economy, there are only two ways to approach the CO_2 emissions problem. The first is to replace the use of fossil fuels with other energy sources – such as solar, wind power, hydroelectric, nuclear, tidal power, geothermal, biomass, and many others. For transportation, the fuels must be mobile, and both ethanol and biodiesel have made tremendous gains in the past few years. These fuels, although still carbon-based, are derived from crops that were grown recently (the plants utilize CO_2

from our current atmosphere), and simply replace that carbon back into the atmosphere when burned. Thus, these biofuels are called carbon-neutral, whereas fossil fuels add "new" carbon to the atmosphere (carbon that had been stored underground for millions of years). Bio-fuels are rapidly gaining acceptance throughout the world. Ethanol is the now the main motor vehicle fuel in Brazil.

The other approach is to continue to burn fossil fuels and to capture the CO_2 before it is emitted. Scrubbing has been proposed as a way to reduce the CO_2 emissions from power plants. Because CO_2 is even less soluble than SO_2, such scrubbing would be very expensive. In addition, the problem of what to do with all that CO_2 would remain. However, numerous suggestions have been made for disposal including sequestering it in deep coal mines, old oil fields, or in the deep oceans (47).

7. Control of Particulate Matter Emissions

Particulate matter (PM) is a term used to describe the many different types, sizes, and shapes of particles that are emitted from the myriad of industrial and other sources. The concentration of PM in a gas is expressed as a total mass concentration ($\mu g/m^3$), which accounts for particles of all types, sizes, and shapes. Because even the smallest particles are significantly larger and heavier than gas molecules, the control of PM often depends simply on separating and removing particles from the exhaust gas stream. Such separation usually makes use of the size and mass differences of PM compared with gases, but the selection of the best separation device often depends on a number of physical and chemical properties of the particles (eg, size, shape, density, electrical properties) as well as characteristics of the gas (eg, temperature, acidity, moisture content).

Particle sizes greatly influence the choice of control equipment. For example, large, heavy particles can be captured either by gravity settling or by centrifugal separation. Smaller particles may be caught efficiently by wet scrubbers, electrostatic precipitators, or fabric filters. Particle size is such an important factor that some further discussion is in order. The aerodynamic diameter of a specific particle is defined as the diameter of a unit density sphere that will settle in still air at the same velocity as the particle in question. Mathematically, the aerodynamic diameter is calculated by:

$$d_\mathrm{a} = (18\,\mu\,V_t / C\,\rho_\mathrm{w} g)^{1/2} \tag{3}$$

where:

d_a = aerodynamic diameter, m
μ = gas viscosity, kg/m·s
V_t = settling velocity, m/s
ρ_w = density of water, kg/m^3
g = gravitational acceleration, m/s^2
C = Cunningham slip correction factor, dimensionless

Settling velocities of various particles in air are given in Figure 10.

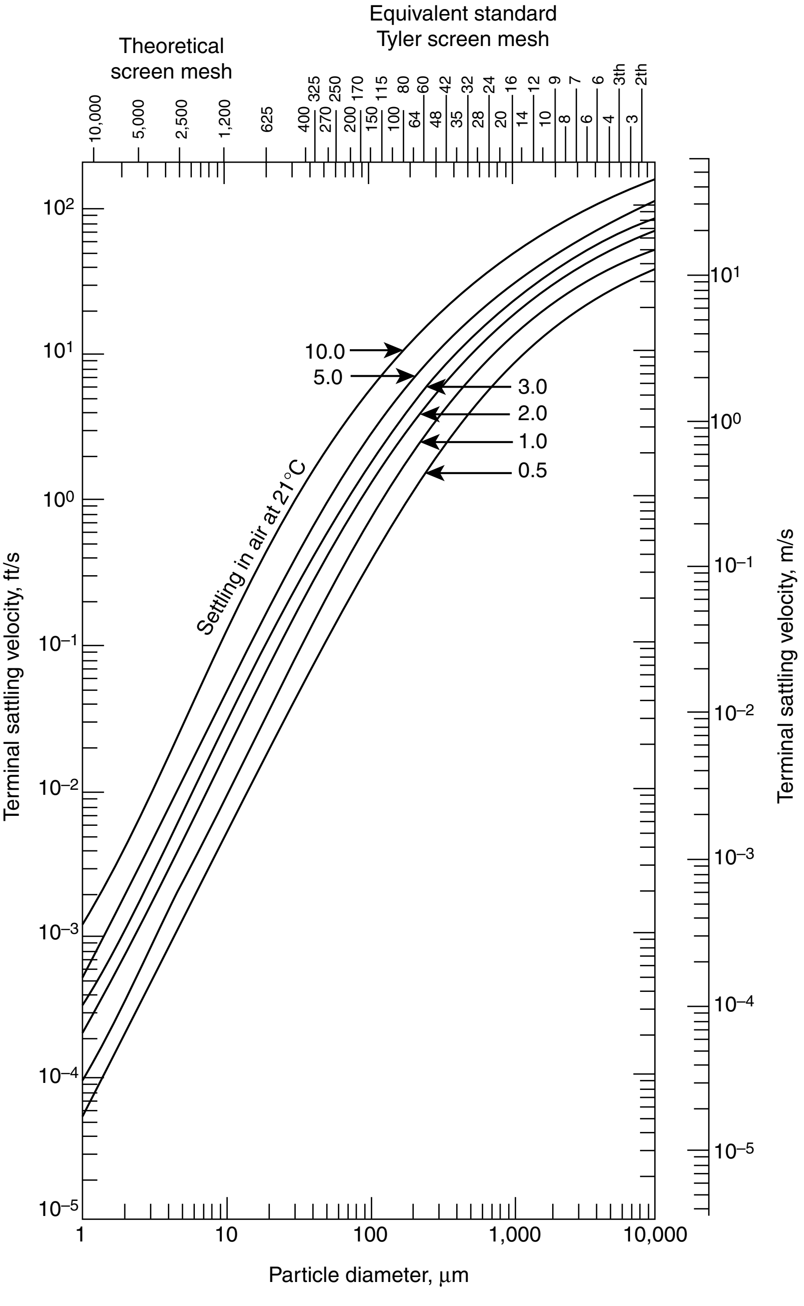


Fig. 10. Terminal velocities in air of spherical particles of different densities settling at 21°C under the action of gravity. Numbers on curves represent true (not bulk or apparent) specific gravity of particles relative to water at 4°C. Stokes-Cunningham correction factor is included for settling of fine particles. The air viscosity is 0.0181 mPa(=P) and density is 1.2 g/L.

The overall collection efficiency (η_o) for any control device is typically calculated on a total mass basis, as shown in the following equation for fractional efficiency.

$$\eta_o = (\text{Mass}_{\text{in}} - \text{Mass}_{\text{out}})/\text{Mass}_{\text{in}} \tag{4}$$

Sometimes a large number of small particles may escape collection, but the overall efficiency is still high because of the overwhelming mass in the larger sizes. The term *penetration* is often used to indicate the fraction of particles that escape collection and penetrate through the device. The penetration (Pt_o) is simply:

$$Pt_o = 1 - \eta_o \tag{5}$$

Particle size distributions can be determined from a device called a cascade impactor. This device has various stages, each with an opening (to admit the air sample) that is immediately followed by an impaction plate. A sample of the air stream carrying the particles is directed through the cascade impactor, and as the air passes through the stages with openings of smaller and smaller sizes, the velocity increases. Large particles that have significant inertia and cannot change direction to avoid the plate are caught in the early stages of the device, and smaller particles are caught in the latter stages. Each stage captures particles of a characteristic diameter.

7.1. Cyclones.

A cyclone is a stationary tube or set of tubes in which the gas flows in a vortex, creating a centrifugal force that moves the particles to the walls of the tube(s). The vortex can be created by the gas entering tangentially or by spin vanes positioned in the cyclone inlet. The particles impact the walls, and slide down to eventually exit by gravity out the bottom of the cyclone. The cleaned (but not perfectly clean) gas exits out the top. A typical tangential entry cyclone is shown in Figure 11.

The advantages of cyclones are that they are low capital cost, have no moving parts, and can operate at high temperatures and under corrosive and erosive conditions. The disadvantages are that they tend to have low efficiencies (especially for small particles), and have high pressure drops. Depending on the design, cyclones trade off efficiency for throughput. Typical collection efficiency curves are shown in Figure 12.

Cyclone Design and Operation. Cyclone efficiency depends on the particles, the gas, and the diameter of the device. Designs for cyclones have changed little over the years, and some of Shepherd and Lapple's original concepts are still used today (48,49). Most cyclones have standardized dimensions that are fixed ratios to the body diameter, and these ratios influence both efficiency and pressure drop (see Table 6).

The cut diameter (the diameter of particles that are collected with a 50% efficiency) can be defined as follows:

$$D_{pc} = \sqrt{\frac{9\,\mu_G\,W_i}{2\,\pi N_e\,V_i\,(\rho_p - \rho_g)}} \tag{6}$$

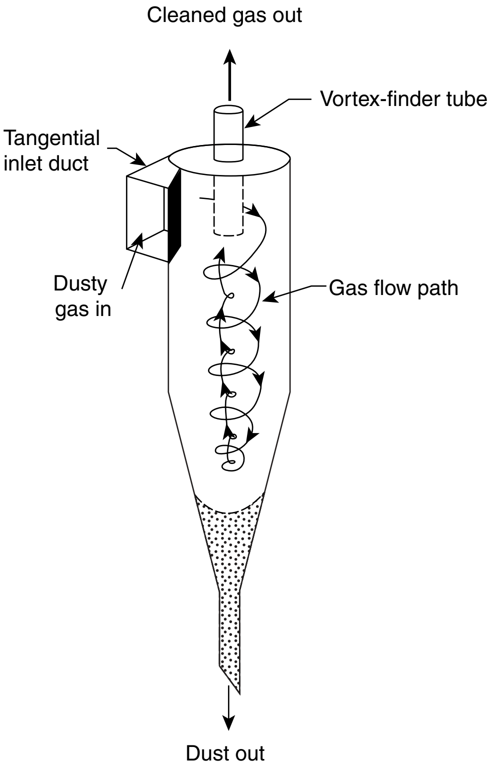


Fig. 11. Schematic diagram of a cyclone. Reproduced with permission from Ref. 4.

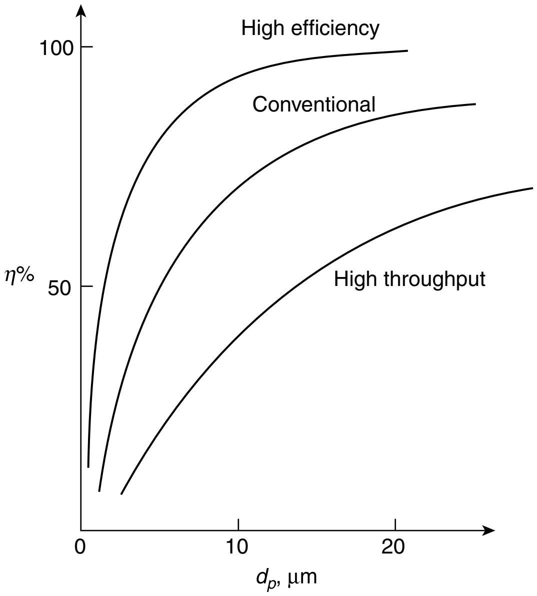


Fig. 12. Cyclone efficiency curves. Efficiency versus size curves represent broad generalizations, not exact relationships. Reproduced with permission from Ref. 4.

Table 6. **Standard Cyclone Dimensions**[a]

	Cyclone type		
	High efficiency[b]	Conventional[c]	High throughput[d]
body diameter	1.0	1.0	1.0
height of inlet	0.44	0.50	0.75
width of inlet	0.21	0.25	0.375
diameter of gas exit tube	0.40	0.50	0.75
length of vortex finder	0.50	0.625	0.875
length of body	1.40	2.0	1.5
length of cone	2.50	2.0	2.5
diameter of dust outlet	0.40	0.25	0.375

[a] As ratios to the body diameter. From Ref. 4.
[b] Ref. 50.
[c] Ref. 51.
[d] Ref. 52.

where:

D_{pc} = cut diameter, diameter of particles collected with 50% efficiency, m
μ_G = gas viscosity, kg/m·s
ρ_g = density of gas, kg/m^3
ρ_p = density of particles, kg/m^3
V_i = inlet gas velocity, m/s
W_i = width of inlet, m
N_e = number of effective turns, dimensionless

Next, the collection efficiency for any size particle is calculated by:

$$\eta_j = [1 + (D_{pc}/D_{pj})^2]^{-1} \tag{7}$$

where:

η_j = collection efficiency for particles in the j^{th} size range
D_{pj} = average diameter of particles in the j^{th} size range

The overall collection efficiency for the cyclone is the weighted average of the collection efficiencies for the various size ranges, as follows:

$$\eta_o = \Sigma \eta_j m_j \tag{8}$$

where:

η_o = overall collection efficiency
m_j = mass fraction of particles in size range j

One of the key operating parameters for any cyclone is the pressure drop. With cyclones, to gain higher efficiency one must decrease the cyclone diameter, and this increases gas inlet velocity and thus pressure drop (eq. 9).

$$\Delta P = 1/2\, \rho_g V_i^2 \,(KHW/D_e^2) \tag{9}$$

where:

ΔP = pressure drop, Pa
ρ_g = density of gas, kg/m^3
V_i = inlet gas velocity, m/s
K = constant that depends on cyclone configuration (often $12 < K < 18$)
H = cyclone inlet height, m
W = cyclone inlet width, m
D_e = cyclone gas exit pipe diameter, m

To design a cyclone, the first step is to assume a body diameter, and then use knowledge of the particulate size distribution and equations to calculate the efficiency. Then check the pressure drop using equation 9. The design objective is to achieve the desired collection efficiency while maintaining a reasonable pressure drop. If the answers achieved with the assumed diameter are not satisfactory, then assume a new diameter and repeat the calculations. This process is best accomplished using a spreadsheet.

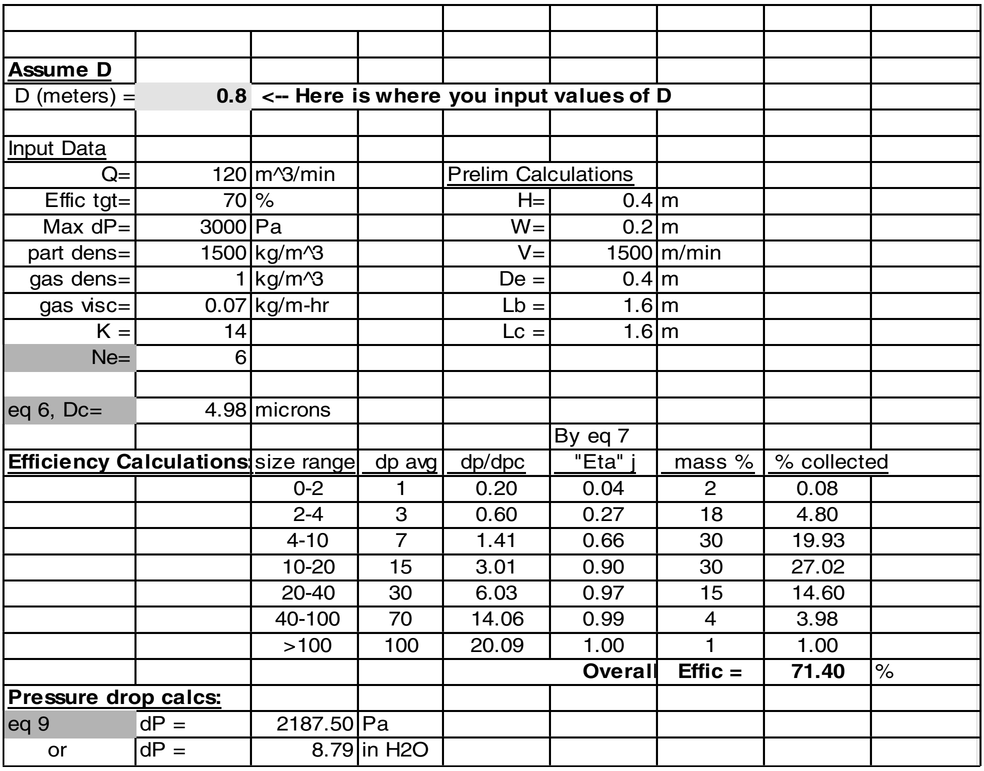
Example Problem. Suppose a conventional cyclone is desired to treat a gas stream of 120 cubic meters/min, carrying particulates with a specific gravity of 1.5, and with a size distribution as shown in Table 7. An efficiency of 70% is needed, but the pressure drop cannot exceed 3000 Pa (12 in. H_2O).

Solution. The method of trial and error is used. A diameter is assumed and then other dimensions of the cyclone are calculated. Equations 6–8 are used to get the efficiency, and equation 9 is used for the pressure drop. All these calculations are amenable to a spreadsheet, where it is quick and easy to assume a new diameter and repeat the calculations, until the objectives are met. The spreadsheet solution is shown in Figure 13.

7.2. Electrostatic Precipitators. The process by which an **electrostatic precipitator (ESP)** removes particulate matter from a gas stream involves the following steps:

Table 7. **Size Distribution of Particles in Cyclone Example Problem**

Size range, μm	D_p, avg, μm	Mass, %
0–2	1	2
2–4	3	18
4–10	7	30
10–20	15	30
20–40	30	15
40–100	70	4
100+	100	1



Assume D								
D (meters) =	**0.8**	**<-- Here is where you input values of D**						
Input Data								
Q=	120	m^3/min		Prelim Calculations				
Effic tgt=	70	%		H=	0.4	m		
Max dP=	3000	Pa		W=	0.2	m		
part dens=	1500	kg/m^3		V=	1500	m/min		
gas dens=	1	kg/m^3		De =	0.4	m		
gas visc=	0.07	kg/m-hr		Lb =	1.6	m		
K =	14			Lc =	1.6	m		
Ne=	6							
eq 6, Dc=	4.98	microns						
					By eq 7			
Efficiency Calculations:		size range	dp avg	dp/dpc	"Eta" j	mass %	% collected	
		0-2	1	0.20	0.04	2	0.08	
		2-4	3	0.60	0.27	18	4.80	
		4-10	7	1.41	0.66	30	19.93	
		10-20	15	3.01	0.90	30	27.02	
		20-40	30	6.03	0.97	15	14.60	
		40-100	70	14.06	0.99	4	3.98	
		>100	100	20.09	1.00	1	1.00	
					Overall	**Effic =**	**71.40**	%
Pressure drop calcs:								
eq 9	dP =	2187.50	Pa					
or	dP =	8.79	in H2O					

Fig. 13. Spreadsheet solution for cyclone example problem.

1. the creation of a high voltage drop between electrodes,
2. distributing the flow of gas between all plates uniformly,
3. the charging, migration, and collection of particles on oppositely charged plates, and
4. the removal of the bulk dust from the plates.

Two major advantages of ESPs are that they collect particles with very high efficiencies and that they present very little resistance to gas flow (therefore causing only a slight pressure drop even when treating very large gas flows). Also, despite the very high voltage drop in an ESP, there is very little current flow. So, with a low pressure drop and only slight electricity usage, the operating cost of an ESP is not as great as one might expect. Other advantages include dry collection of dry materials or wet collection of wet mists. Disadvantages include high capital costs, relative inflexibility to operating changes, and limited application if the particles lack “good” electrical properties.

Method of Operation. A gas stream carrying particles flows into an ESP and passes 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 a few meters per second, the particles move towards the plates at a velocity (called the drift velocity) which is in the range of a few centimeters per second. During the operation of the device, the plates are rapped (weights are dropped onto the top edges of the plates) periodically to remove the layer of dust that builds up. The dust falls into hoppers at the bottom of the ESP, and is removed pneumatically or by screw conveyor to be disposed of or recycled (eg, into concrete).

Dust particles entering the electric field become charged. Both negatively and positively charged ions exist in the small core of ionized gas surrounding the discharge electrode. In a negative polarity precipitator (the wires are negatively charged and the plates are grounded), the positively charged ions are quickly attracted to the discharge electrode (wires) and neutralized. Hence only electrons and negatively charged ions and gases exist outside the corona area and travel through the gas space towards the grounded collecting plates. Two mechanisms of particle charging exist: charging by ion bombardment (often called field charging) and charging by ion diffusion. In field charging, electrons collide with dust particles and charge transfer may occur. Eventually, the particle will develop a charge sufficient to repel other electrons, a phenomenon termed charge saturation. Field charging is rapid and most effective on larger particles. The larger the particle, the higher the charge density, and thus the easier is precipitation. Coarse particles (5–30 μm) can be collected almost completely in a precipitator. The lower size range for effective field charging is on the order of 0.5–1.5 μm, depending on dielectric constant of the particles.

In diffusion charging, particles are too small and mobile for rapid charging by ion bombardment. They become charged by collisions caused by Brownian motion. Diffusion charging becomes efficient on particles smaller than 0.2 μm and has been demonstrated to be effective on particles down to 0.05 μm. These fine particles are charged rapidly and have higher charge density at saturation. Unlike field charging, the rate of charging by diffusion is independent of electric field strength. For particles between 0.2 μm and 1.5–2.0 μm both charging mechanisms are in effect, but neither is highly efficient. Particles in this size range are the most difficult to collect efficiently in an ESP.

Applications. ESPs are used in a large number of coal-fired power plants, but also can be found in numerous other industrial applications. Typically, large industrial ESPs are of the plate-and-wire type, composed of many steel plates in parallel with wires hung between the plates. The gases flow through the spaces between the plates, and the particles are charged by the electric fields between the wires and the plates, and then drift over to the plates to be collected. However, there are a number of other configurations, including tubular ESPs (more useful for collecting mists), and two-stage ESPs (often used for ventilation and indoor air cleaning). Most of this discussion focuses on large industrial ESPs, and in particular, on coal-fired power plant applications.

A complete electrostatic precipitator consists of the following component sub-systems: Discharge electrodes, collecting surfaces (plates or tubes), a suspension and tensioning system for discharge electrodes, a rapping system to remove dust from tubes, dust hoppers and dust-removal system, a gas-distribution system and precipitator housing, and a power supply and control system.

Typical arrangements of the collectors are shown in Figure 14. A plate precipitator may have parallel, flat plates that are tall (10–15 m), not overly long

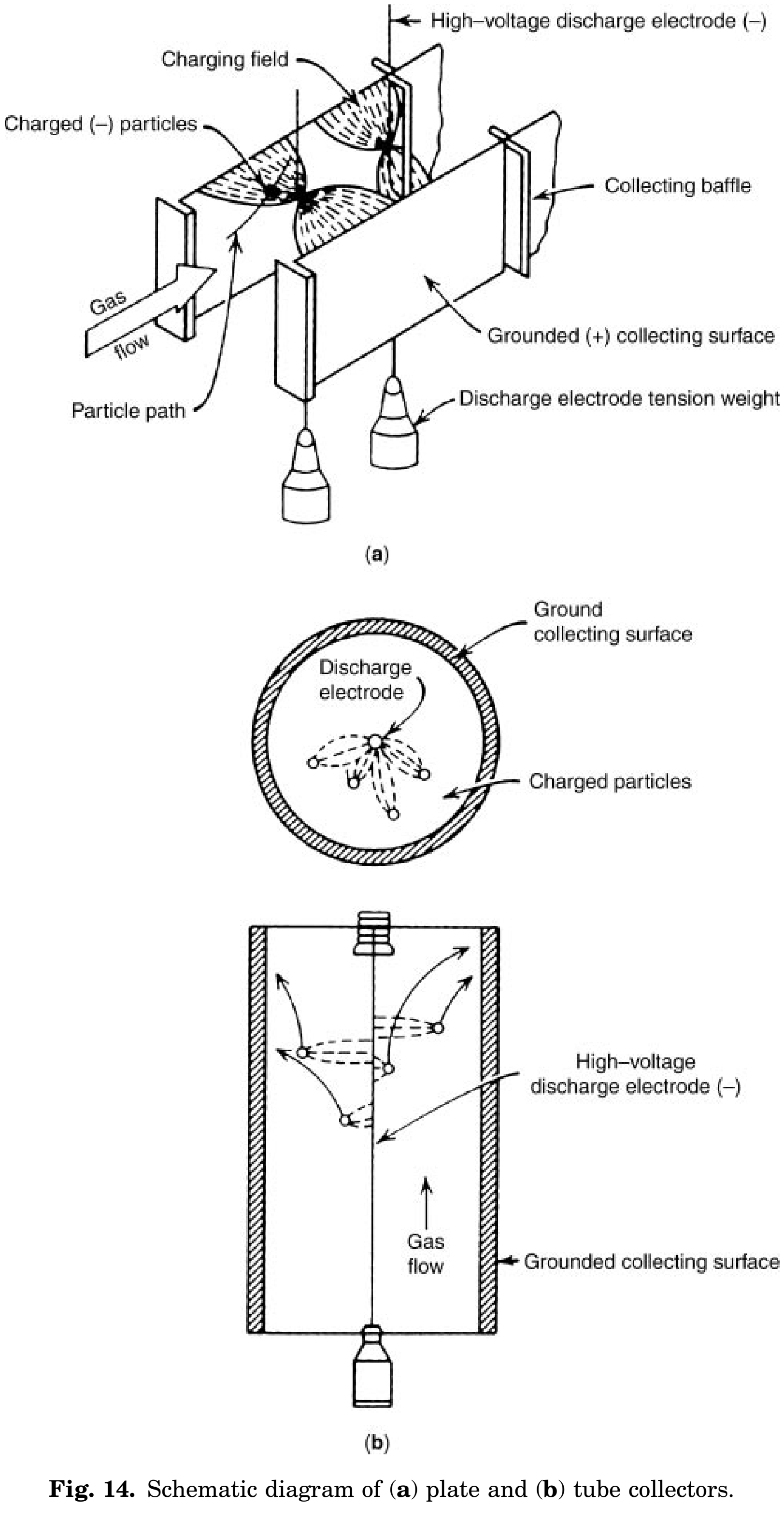


Fig. 14. Schematic diagram of (**a**) plate and (**b**) tube collectors.

(3–5 m), and with 20–40 cm horizontal spacing. The discharge electrodes (wires) are suspended midway between the plates. Plate precipitators are utilized for collecting flyash, for high gas-flow applications, and for particulates which are comparatively coarser than those caught in the tube-type equipment. Plate-type precipitators are lower in cost because both sides of the plate serve as precipitating surfaces.

Tube precipitators are frequently used for liquid mists and sometimes for submicrometer metallurgical fumes. Tubes vary in diameter from 15 to 30 cm OD by 4.5–5.0 m long. One discharge wire is centered in each tube. Dirty gas generally enters at the bottom and travels upward through the tubes. A tube sheet is provided top and bottom; tubes may be rolled or welded into a flat top tube sheet for a mist precipitator. For solids, however, each tube must have a round to square transition at the top end. The tubes are then welded together to form an "egg-crate" sheet. Dust, if deposited on a flat tube sheet, can buildup with a nearly 90° angle of repose and short out the high tension support frame for discharge electrodes.

Figure 15 shows a variety of plate and discharge electrode designs. The most common collecting plate design is flat with vertical, perpendicular baffles at frequent intervals. The plate may be continuous or sectional. The Opzel design is a modification of perpendicular baffles devised to reduce gas-flow resistance. Discharge electrodes may be round wires or small (2.57–4 mm) diameter rods. The smaller the diameter, the higher the intensity of the surrounding electric field. The wires must, however, be sufficiently rugged to withstand both tensioning and thermal stresses. Also, the wires vibrate and sway, and will spark if they get too close to the plate. Thus they must be able to withstand repeated sparkings at the mid-point. In the event of heavy suspended loads or long spans, wire size may become appreciable. In these cases, a 6 to 9 mm square may be a better design choice because the corners produce a higher intensity field locally. Square bars are often twisted to give one 90° turn in 25–35 mm of length, producing a high intensity field which rotates with the length of the discharge electrode. A 5-pointed-star-shaped discharge electrode yields an even higher field intensity. Discharge electrodes with barbs and punched ribbons may also be used to produce higher intensity electric fields.

Design Considerations. The design of ESPs is complicated, but the collection efficiency is reasonably well-modeled by the Deutsch equation:

$$\eta = 1 - e^{(-Aw/Q)} \tag{10}$$

where:

A = area of the collection plates, m^2
w = effective drift velocity of particles towards the plates, m/min
Q = gas volumetric flow through the ESP, m^3/min

The drift velocity in eq. 10 is a key parameter for the design of ESPs. It is a strong function of the type of ash, and the temperature and composition of the flue gas. There are theoretical ways to predict drift velocity from first principles, but the way the equation is used, drift velocity incorporates many of the

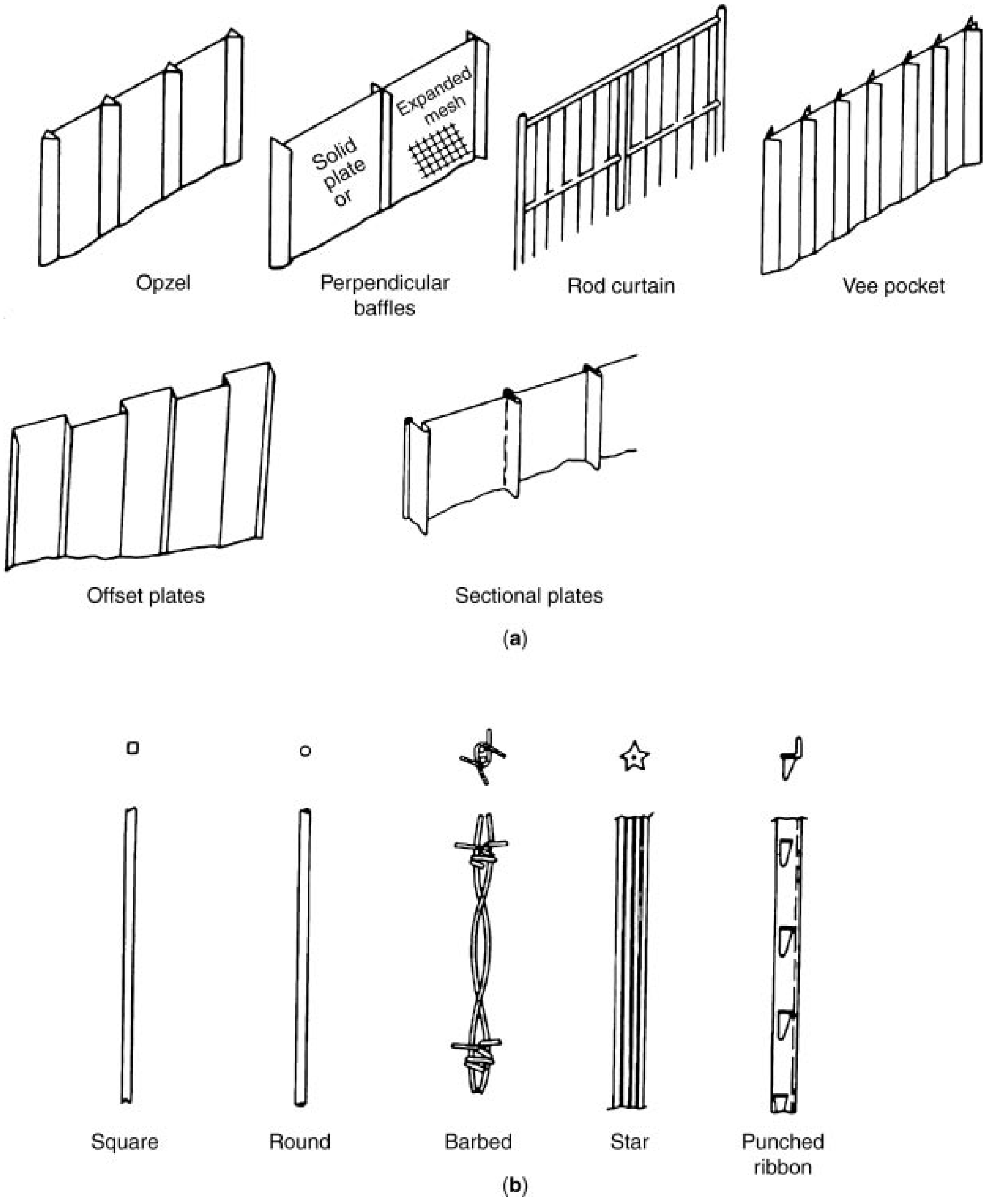


Fig. 15. Types of (**a**) collecting plate and (**b**) discharge electrode designs.

imperfections of the device, and so becomes almost empirical in nature. Companies gather data from their other installations and treat the data as proprietary information. Table 8 provides some typical ranges of drift velocity for various ESP applications.

The usual particle properties of size and size distribution are important, but even more important for ESPs is the electrical property called resistivity, which is a measure of a material's resistance to electrical flow. Once collected, particles

Table 8. **Typical Drift Velocities in Various ESP Applications**

Application	Range of drift velocities, cm/s
pulverized coal fly ash, power plants	3.9–20.4
pulp and paper mills	6.4–9.4
sulfuric acid mist	6.1–8.5
cement kiln dust (wet process)	9.1–12.2
nonferrous metal smelter	1.8
steel open hearth furnace	4.9
iron blast furnace	6.1–14.0

begin to lose their charge to the plates. This transfer of charge completes the circuit and allows the maintenance of a high voltage drop. If particles are too resistive, the charge does not drain off easily and a back-corona can develop, reducing the charging field. Also, the dust tends to stick more tightly to the plates. If the resistivity is too low, the charge drains off too quickly, causing more current flow and allowing the particles to be easily re-entrained in the gas flow.

For coal fly ash, resistivities range from 10^8 to 10^{13} ohm-cm (53), and for dry cement dust, resistivity can be even higher (54). Properties of the coal and the flue gas can greatly affect resistivity. Higher sulfur levels in the coal can lower resisitivity, and the temperature and moisture content of the flue gas can have significant effects. For example, switching from a 2.5% sulfur coal to a 0.5% sulfur coal in the power plant can increase the resistivity of the fly ash by two orders of magnitude (53). The temperature effect is nonlinear, with the resistivity of coal fly ash peaking in the range of 300°F, and dropping by two orders of magnitude as temperature either rises or falls by 100 degrees. By adding 20% water vapor to dry air with cement dust, the resistivity of the cement dust can drop by almost three orders of magnitude (54).

The effect of resistivity changes is often modeled as a change in the effective drift velocity, so that the Deutsch equation remains a valid approach. As resistivity increases by two orders of magnitude, the drift velocity will decrease from 7–8 m/min down to 2–3 m/min (55).

The design of an ESP involves a trial-and-error approach in which a number of variables are adjusted to find an optimal design. Given a drift velocity and gas flow, the design objective is to find the total plate collection area needed to achieve the desired collection efficiency. That is easily done using the Deutsch equation, as illustrated in the example below. However, once the plate area is found, the configuration of the ESP must be determined. Plate heights and lengths, plate spacing, the layout of the plates into sections and in the ESP as a whole (numbers in parallel and in series), the number of sections (both in parallel and in the direction of flow), the corona power, rapping technique and frequency, and numerous other variables must be set. Additionally, the entire unit must be structurally sound, and be able to fit in the available space.

There are thousands of large ESPs at power plants and numerous other industries, and ESPs do experience some operating problems. The problems usually are traceable to poor gas flow distribution, improper voltage control, incorrect rapping procedures, or too frequent or infrequent rapping. For example, dust reentrainment can arise from a localized high gas velocity, rapping problems, or dust resistivity. There is an optimum time interval, force intensity, and direction for rapping to minimize reentrainment. A rapping force normal to the plate is most effective. The intensity of a single rap should be just enough to snap the dust cake loose from the plate and allow it to slide en masse down into the dust hopper. Too intense a blow may shatter the cake and project it out into the bulk gas stream as a cloud of small particles; an inadequate blow will require repeated raps to break the cake loose. Electrostatic forces hold the collected dust to the collection surface and the longer the dust layer is in place, the more tightly it is held. When the cake stays in place too long, greater forces are required to dislodge it and chances of reentrainment are greater. One blow of optimum intensity every 1–2 min, continuous intermittent rapping, is better than a burst of high frequency vibration as discussed in rapping parameter experiments (56,57).

Baffles on the collecting plate tend to keep the bulk gas velocity away from the dust layer, providing a quiescent zone through which dust can slide downward during rapping. Reentrainment can occur at either too high or too low a dust resistivity. With too low a dust resistivity (that is, the dust is too conductive), the dust loses its charge to the collecting plate, randomly tumbles off, and is reentrained. Unburned carbon in flyash is an example. A precipitator is completely unsatisfactory as a collector for very conductive and fine dusts such as carbon black. Nevertheless, even though the technology is nearly one hundred years old, ESPs remain reliable air pollution control devices for large and small industries throughout the world.

Example Problem. Use the Deutsch equation to calculate the total collection area to meet a 98% efficiency target. The gas flow is 8000 m^3/min, and the drift velocity is 5.0 m/min.

Solution. Rearranging equation 10, and taking the natural logarithm of each side,

$$\ln(1-\eta) = -Aw/Q$$

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

$$A = -8000/5[\ln 0.02] = 6259\,\mathrm{m}^2$$

7.3. Fabric Filtration. Fabric filtration is an ancient and well-accepted process for separating dry particulate matter from a gas stream. On an industrial scale, a number of fabric bags are installed in parallel inside a housing (hence the common term “baghouse”) and the dusty gas flows slowly through the bags leaving the dust behind on the fabric. The fabric is cleaned periodically, so the baghouse can continue to operate for long periods of time. There are many different types of fabrics, different ways of weaving them into bags, different ways of placing the bags in the house, different ways of passing the air into the compartments, and different methods for cleaning the dust off the filters. Baghouses are commonly classified by the cleaning method, namely reverse-air, shaker, or pulse-jet.

Baghouses have several advantages: they are the most efficient of all the PM control technologies, they can operate on a wide variety of dusts, they are modular in design and manufacture, they operate with reasonable pressure drops, and they can collect the particles in a dry and re-usable form. Disadvantages include: they require large floor areas, fabrics can be damaged by high temperatures or corrosive gases, they cannot operate in moist environments, and they have the potential for fire or explosion.

Bags and Baghouse Operation and Cleaning. A baghouse is a structure, often with several compartments in parallel, each of which contains and supports many fabric bags in parallel. The filter bags may be woven or felted, an envelope ("pillow case") supported with an internal wire cage, or a long cylinder or stocking hung freely or containing an internal wire cage, and subject to either shaking or reverse flow for dust removal for the older compartmented designs. Pulse-jet baghouses employ a bag cleaning method that involves short blasts of high-pressure air to ripple the fabric and knock off the particulate layer. The availability of fibers is somewhat more limited with felts and one cannot choose a type of weave as with woven fabrics. Bahouses are often classified by the cleaning method; two types of shaker-type baghouses are pictured in Figure 16 (**a**) and (**b**), and a pulse-jet baghouse is shown in Figure 16 (**c**).

In most baghouses, there is a baffle plate or other means of slowing the entering gas and deflecting it downward so that coarse dust particles drop out into the hopper. As the gas flows through the filter media, the majority of the dust is collected by a dust layer built up on the bag surface and the cleaned air then flows to the gas outlet. Deposited dust is removed at intervals to prevent excessive pressure drop. Shaker or reverse air baghouses are always designed with multiple compartments. In these baghouses, dampers (controlled by timers or pressure drop measurements) shut off the air flow through the baghouse compartment when the bags are to be cleaned. In filters designed for continuous use, a number of parallel compartments are provided to handle flow when one compartment is shut off for cleaning.

In the pulse-jet filter, air flow is usually not shut off during bag cleaning. Rather, one row or group of bags are cleaned while the rest of the filter remains in service. Dirty gas flows up around the outside of the bag and then through the cloth leaving the dust on the outside of the bag. An internal wire cage keeps the bag expanded and bag and cages are hung from the top tube sheet. Each tube sleeve contains a venturi casting which extends inside the bag and the cleaned air exits through this casting.

For bag cleaning in a pulse-jet baghouse, a short burst (30 to 120 milliseconds) of compressed ambient air is directed down through the venturi from an orifice in a manifold pipe above the casting. The air pressure, usually at 620–690 kPa (90–100 psi), is released by a solenoid valve actuated by a timer. As this air jets through the venturi, it induces backward flow of cleaned air from the exit manifold, and a ripple forms in the top of each bag being cleaned, which snaps the cloth away from the cage, and displaces the dust layer. The duration of the compressed air pulse must last long enough to allow the fabric to ripple down the length of the bag to the bottom, cleaning the entire bag surface as it goes. (Often the bottom third of the bag is not cleaned very well.) The volume of ambient air used for the cleaning pulses is about one-half to one percent of the volumetric flow of the gas being filtered (4).

Frequency of cleaning is set to limit the pressure drop (that ΔP experienced just before cleaning) to some maximum desired level, often 1–2 kPa (4–8 in. H_2O).

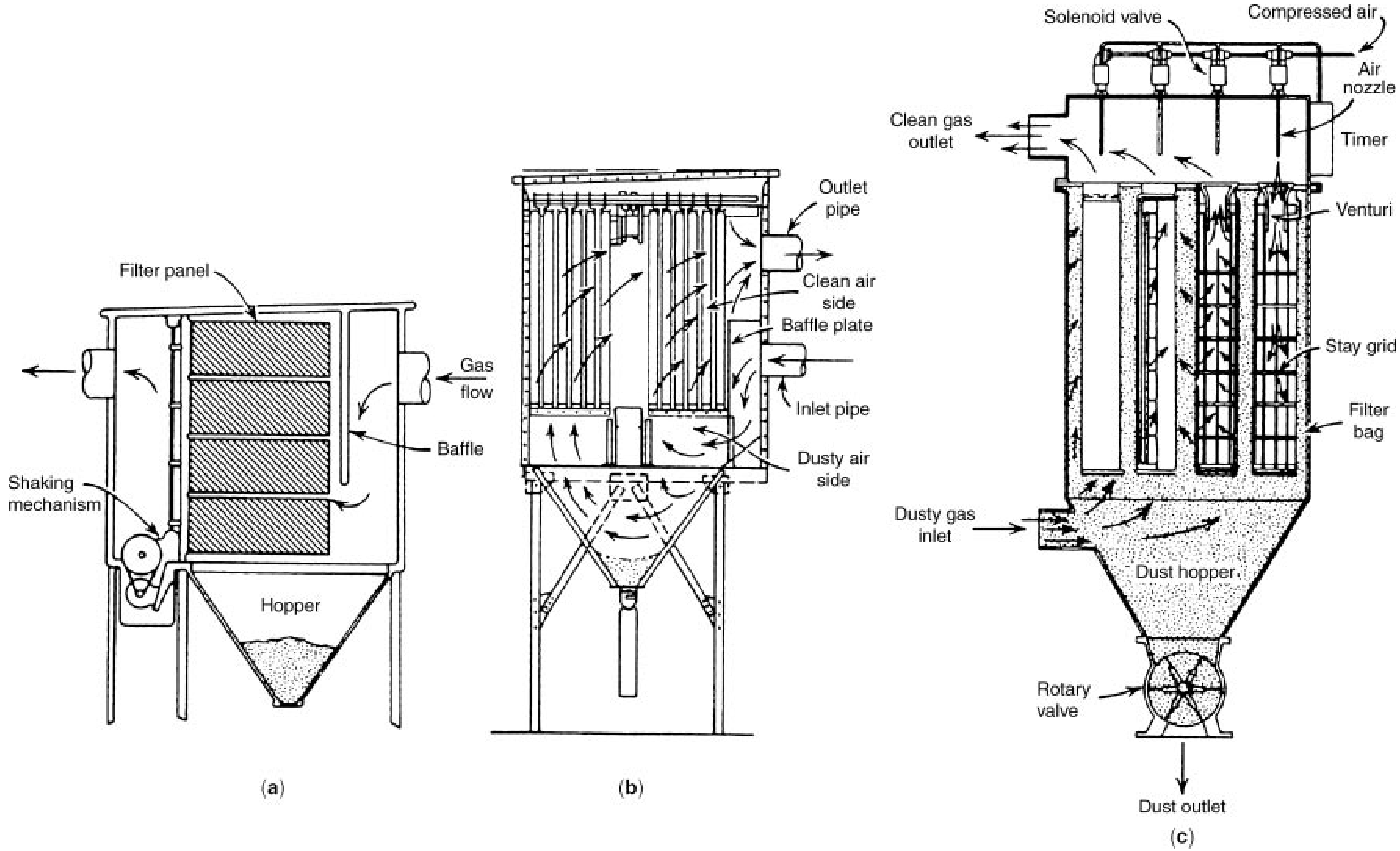


Fig. 16. Types of Baghouses: (**a**) shaker (panel); (**b**) shaker (bags); (**c**) pulse-jet; (**a**) and (**c**) from Ref. 58 (courtesy of Academic Press, (**b**) courtesy of Wheelabrator-Frye).

The degree of cleaning can be adjusted somewhat by changing the pressure of the compressed air or the duration of the pulse. For efficient dust collection, it is desireable to leave a light dust layer on the bag surface and for long bag life, a minimum number of cleaning cycles is preferred. Since some bags in the compartment are filtering while some are being cleaned, any re-entrainment of the dust is followed by re-deposition on bags remaining in the filtering operation. Dust re-deposition is an appreciable problem even at low filtering velocities; it becomes considerably worse as high filtering velocities are approached (59).

Reverse-air or backflow bag filters are rather similar in appearance to shaker filters except that the shaking mechanism is eliminated. The bags are clamped to a tube sheet at the bottom and are closed at the upper end with a metal cap from which they are suspended. Dirty gas enters below the tube sheet and passes upward through the bag. When the bag cleaning cycle begins, the flow of dirty gas is shut off, and a fan forces cleaned gas backward through the bags. A series of rings, sewn into the bags at intervals, prevent the complete collapse of the bag under the reverse-flow conditions. Dust dislodged by the backflow falls down through the bag to a dust hopper below the tube sheet. The quantity of back-flush gas is usually sufficient to produce a reverse-flow superficial velocity of 0.5–0.6 m/min through the bag. Woven fabrics are generally used for reverse-flow bag filters. The small reverse-flow pressures generally used would be insufficient to back-flush felt bags. The principal application for reverse-flow cleaning is in bag-houses using glass-fiber bags that handle gas at temperatures above 150°C such as boiler flue gas containing flyash. Bag collapse and re-inflation must be sufficiently gentle that excessive flexing is not applied to the glass fiber fabric. Advanced cleaning methods include sonic horns (4); these low frequency but high energy horns help dislodge the dust from the fabric without flexing the bags.

Filtration Mechanism. Baghouses are among the most efficient of all PM control technologies. The filtration process is not simply sieving by the fabric since filter fabric pore size is much larger than the particles collected. The efficiency of a new bag for fine dust particles is quite low until the bag fibers and interstices are coated with collected dust. A used bag always has higher collection efficiency than a new one because the entrapped dust particles reduce the effective pore size. A pre-coat of coarser particles serves as a support for finer ones and filter efficiency drops momentarily if the bag cleaning is too thorough. Pressure drop through a cleaned, dust-impregnated bag may be as high as ten times that of a new bag with no dust on it. General particle collection mechanisms, such as direct impingement, inertial impaction, gravity settling, Brownian diffusion, and electrostatic attraction, apply in initial bag coating.

Design Considerations. Baghouse efficiency for a well-designed system is almost always greater than 99%; indeed the most common source of particulate loss is through bag leaks, defects, or gaps where the bags attach rather than through direct penetration of the fabric. Because of this, there are no good equations for predicting collection efficiency. However, the proper selection of operating and design parameters ensures a high efficiency. The superficial filtering velocity (also called the air-to-cloth ratio) is an important design parameter for baghouses, and is defined simply as the volumetric flow rate of gas divided by the net cloth area. The net cloth area is the area of fabric left on line even when one compartment is down for cleaning. The other design and operating parameter of importance is pressure drop. Both will be addressed in the following paragraphs.

The superficial filtering velocity is given by:

$$V_{N-1} = Q/A_{N-1} \tag{11}$$

where:

V_{N-1} = superficial filtering velocity based on net cloth area, m/min
Q = gas flow rate through the baghouse, m^3/min
A_{N-1} = net cloth area (area in N−1 compartments), m^2

To achieve high efficiency filtering, one must: select an appropriate fabric to handle the type of particulate matter (PM), the concentration of PM in the gas, and the gas temperature and chemical characteristics; pick the "right" value for filtering velocity; calculate the fabric area needed to achieve the desired velocity with the given gas flow rate; and configure the baghouse with the right number of compartments.

The first steps in the design of a fabric filter are to select the fabric and the filtering velocity, which is based on particle and gas characteristics. These steps are facilitated by the use of Tables 9 and 10.

After selecting the fabric and baghouse type, the calculation of fabric needed is simply done by solving eq. 11 for A_{N-1}. Note that if the baghouse type is pulse-jet, then there are no compartments to be shut off during cleaning, and the net cloth area is the same as the gross cloth area. If, however, the baghouse type is a shaker or reverse-air, then the number of compartments must be determined. This is done using Table 11.

As mentioned earlier, pressure drop is an important parameter. Forcing a high volume of gas through a high pressure drop requires substantial work and results in high operating costs (electricity to run the fan). The decision of how frequently to clean the bags is primarily made based on not exceeding some

Table 9. **Maximum Recommended Filtering Velocities in Baghouses**[a]

	Maximum filtering velocity, m/min	
	Type of baghouse	
Types of dust	Shaker, reverse air	Pulse-jet
activated charcoal, carbon black, detergents	0.46	1.7
aluminum oxide, fertilizer, iron ore, lime, fly ash, dyes, paint pigments	0.61	2.3
bauxite, ceramics, chrome ore, flour, flint, glass, gypsum, cement, plastics	0.69	2.7
asbestos, limestone, quartz, silica	0.84	3.0
cork, feeds and grains, marble, salt	0.95	3.5
leather, paper, tobacco, wood	1.07	4.0

[a] Ref. 4.

Table 10. **Chemical Resistance and Maximum Temperatures of Fabrics**[a]

Fabric	Chemical resistance		Maximum temperature, °F
	Acid	Base	
Dynel	good	good	160
cotton	poor	good	180
wool	good	poor	200
nylon	poor	good	200
polypropylene	excellent	excellent	200
Orlon	good	fair	260
Dacron	good	fair	275
Nomex	fair	good	400
Teflon	excellent	excellent	400
glass	good	good	550

[a] Ref. 4.

maximum desired pressure drop. Equations relating power to gas flow rate and pressure drop using typical units and metric units are shown below:

$$W_F = \frac{Q\,\Delta P}{\eta} \tag{12}$$

where:

W_F = power drawn by fan, kw
Q = gas flow rate, m^3/s
ΔP = pressure drop, kPa
η = fan and motor efficiency, dimensionless

or

$$W_F = \frac{k\,Q\,\Delta P}{\eta} \tag{13}$$

Table 11. **Number of Compartments as Function of Net Cloth Area**[a]

Net cloth area, m^2	Number of compartments
<372	2
372–1115	3
1115–2324	4–5
2324–3718	6–7
3718–5577	8–10
5577–7436	11–13
7436–10225	14–16
10225–13943	17–20
>13943	>20

[a] Ref. 4.

where:

W_F = power drawn by fan, HP
Q = gas flow rate, ft^3/s
ΔP = pressure drop, in H_2O
η = fan and motor efficiency, dimensionless
k = units conversion factor, 0.0001575 (HP-min)/(ft^3-in. H_2O)

Equations to predict the pressure drop through a baghouse can be developed from Darcy's law (4). The total pressure drop is composed of contributions from the structure, the fabric, and the dust layer, but essentially it is due to the layer of dust that builds up on the fabric. Often, the pressure drop relationship is determined by pilot studies or previous experience with the particular dust. It is a quadratic function of the filtering velocity, and a linear function of the dust loading and the time between cleanings, as follows:

$$\Delta P = K_1 V + K_2 L V^2 t \tag{14}$$

where:

K_1, K_2 = constants related to gas viscosity, permeability of fabric and dust layer, thickness of fabric, and bulk density of dust layer
L = dust loading (mass concentration of dust in gas)
t = time

The filter drag model linearizes the above relationship as follows:

$$S = K_1 + K_2 W \tag{15}$$

where:

S = filter drag = $\Delta P/V$
W = areal dust density = LVt

The above equations can be used to determine the maximum pressure drop to be expected when operating a compartmented baghouse, or for calculating the running time between cleanings. Methods for obtaining values for K_1 and K_2 from pilot-plant data, and for using the above equations in the design of a compartmented baghouse are described elsewhere (4).

For pulse-jet baghouses, methods to predict pressure drop are largely empirical. Based on data from 35 pulse-jet baghouses operating on coal flyash, the following empirical equation has been proposed (60):

$$\Delta P = 1.7V + / - 40\% \tag{16}$$

where:

ΔP = flange-to-flange pressure drop, in. H_2O
V = filtering velocity, ft/min

Example Problem. A pulse-jet baghouse is to be specified to filter 600 m^3/min of air containing limestone dust. The gas temperature is 300°F. Calculate the number of bags required if each bag is 2 meters long and 15 cm in diameter.

Solution. From Tables 9 and 10, choose Nomex fabric and a filtering velocity of 3.0 m/min. The fabric area is

$$A = 600\,\mathrm{m}^3/\mathrm{min}/3.0\,\mathrm{m}/\mathrm{min} = 200\,\mathrm{m}^2$$

The area of one bag is equal to the surface area of a cylinder, or

$$A_{\mathrm{bag}} = \pi(0.15)\,2.0 = 0.94\,\mathrm{m}^2$$

The number of bags required is calculated from:

$$\mathrm{No.\,bags} = 200\,\mathrm{m}^2/0.94\,\mathrm{m}^2/\mathrm{bag} = 213\,\mathrm{bags}$$

Note that arranging these bags in a rectangular pattern to fit a baghouse structure that could be transported to the site may result in a slightly different number of bags (eg, an arrangement of 20 rows of 11 bags per row would require 220 bags).

7.4. Wet Scrubbers.

Devices that collect particles by contacting the dusty gas with water are called wet scrubbers. Although they can act like gas absorbers and remove a substantial fraction of soluble gaseous pollutants, their main function is to remove particulate matter. These devices can be classified by their contacting mechanism and by their power consumption. Wet scrubber efficiency can vary, but high-energy venturis, for example, can be highly efficient even on small particles. Capital costs can be very reasonable, but the cost of water and sludge treatment can be substantial in some areas.

The advantages of wet scrubbers are that they can handle flammable and explosive dusts, provide some degree of gaseous pollutant control, collect wet mists, neutralize corrosive gases and dusts, and provide cooling of hot gases. Disadvantages include the potential for corrosion of the metal, potential water pollution problems, may freeze in cold climates, may produce a visible plume due to condensation, and may require expensive disposal of the waste sludge.

Description. Spray chamber scrubbers operate on the principle of the particles colliding with droplets of water as the gas flows though the chamber. The predominant mechanisms include inertial impaction, direct interception, and diffusion or Brownian motion. The flow pattern can be countercurrent vertically (the gas flows up while the water drops fall down), cross-flow (the gas flows horizontally) or cyclonic (the gas flows in spirals) (see Fig. 9). The difference is that when the gas contains a lot of particles, the scrubbers must be open, and generally can not have plates or packing. In all cases, as the PM being carried in the gas collides with water drops, the particles are collected, and the much larger water drops are then separated (by gravity or centrifugal force) from the air stream. The amount of water used is in the range of 1 to 3 mass units of water for each mass unit of air.

Most spray chambers are low energy devices, and hence the efficiency of collection is fairly low, especially for small particles. The power used in scrubbing can come from gas pressure drop, water being sprayed out of nozzles at high velocities, or from both. Semrau (61–63) proposed a contacting power principle for correlation of dust-scrubber efficiency: the efficiency of collection is proportional to power expended, and more energy is required to capture finer particles. Furthermore, the correlation is not general because different parameters are obtained for differing emissions being controlled by different devices. However, in many wet scrubber situations for constant particle-size distribution, Semrau's power law principle can be applied, especially for interpolating or extrapolating data for an existing scrubber:

$$N_t = \alpha P^{\gamma} \tag{17}$$

where:

N_t = number of contacting units
P = total contacting power
α, γ = constants that depend on gas, particle size distribution, and device

Venturi scrubbers are higher energy and therefore more efficient devices than spray chambers. The higher energy usually manifests itself in a higher gas pressure drop through the device; in general, a higher pressure drop in a scrubber means a higher collection efficiency. Venturis operate on the principle of a fast-moving gas (velocities of 100 m/s are not uncommon) atomizing and accelerating liquid droplets into the gas flow. Particles collide with the newly formed droplets, and are captured when the droplets are later separated from the gas. High-energy venturis can have very high pressure drops, and may require special fans to move the air. Table 12 gives some typical applications of wet scrubbers.

Scrubber Efficiency Equations. Scrubber collection efficiency can vary over a wide range depending on particle size and power input. The penetration for particles of diameter *d* is just the fractional efficiency subtracted from one, as shown by equation 18. The overall penetration can be obtained by integrating over the particle size distribution.

$$Pt_d = 1 - \eta_d \tag{18}$$

Table 12. **Industrial Applications of Wet Scrubbers**

Type of scrubber	Pollution source	Flow rate, acfm	Pressure drop, in. H_2O
Venturi, high energy	haz. waste incin.	1000–100,000	45–50
Venturi, high energy	medical waste	500–50,000	45–50
Venturi, medium energy	lime sludge kiln	2000–100,000	18–30
Venturi, low energy	lime slaker	500–20,000	6–12
spray tower	pulp and paper dust	500–30,000	4–8
packed tower	chem. plant gas	50–60,000	3–20

where:

η_d = fractional collection efficiency for particles of diameter d.

For spray chambers, the penetration as given in (64–66) is related to the liquid-to-gas ratio, the droplet size, the droplet terminal settling velocity, the height of the scrubber, and the target efficiency of a single droplet. Equations 19 and 20 are given for counter current vertical spray chambers and cross-flow horizontal spray chambers, respectively.

For counter current vertical spray chambers:

$$Pt_d = \exp - (0.75\,(L/G)\,V_{td}\,Z\,\eta_d)/(r_d(V_{td} - V_G)) \tag{19}$$

For cross-flow horizontal spray chambers:

$$Pt_d = \exp - (0.75\,(L/G)\,Z\,\eta_d)/(r_d) \tag{20}$$

where:

L/G = liquid-to-gas ratio, based on volume flows, dimensionless
V_{td} = terminal settling velocity of droplet, cm/s
Z = height of scrubber contact zone, cm
η_d = droplet target efficiency, defined below
r_d = droplet radius, cm
V_G = superficial gas velocity in scrubber, cm/s

The single droplet target efficiency is estimated from:

$$\eta_d = (K_p/(K_p + 0.7))^2 \tag{21}$$

where:

K_p = an impaction parameter that depends on properties of the particle, the gas, and the droplet.

The impaction parameter (64) is defined as:

$$K_p = \frac{\rho_w d_{\mathrm{a}}^2 V_{p,d}}{9\,\mu_{\mathrm{G}}\,d_{\mathrm{d}}} \tag{22}$$

where:

d_{a} = particle aerodynamic diameter, cm
ρ_w = density of water, g/cm^3
$V_{p,d}$ = particle velocity (relative to droplet), cm/s
μ_{G} = gas viscosity, poise
d_{d} = droplet diameter, cm

Single droplet target efficiencies are shown in Figure 17, and spray chamber performance curves are displayed in Figure 18.

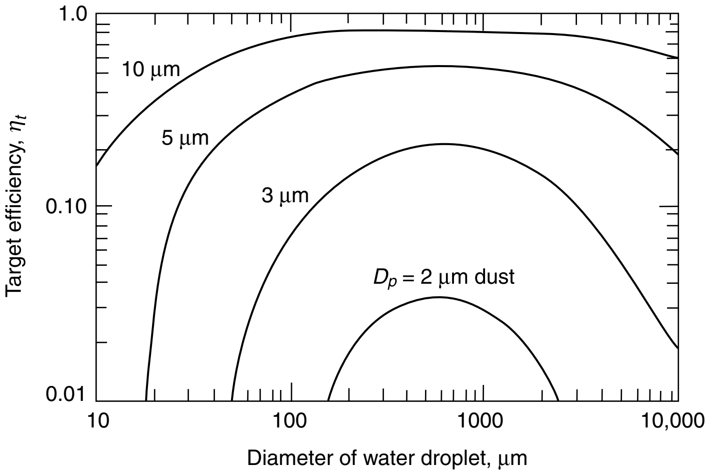
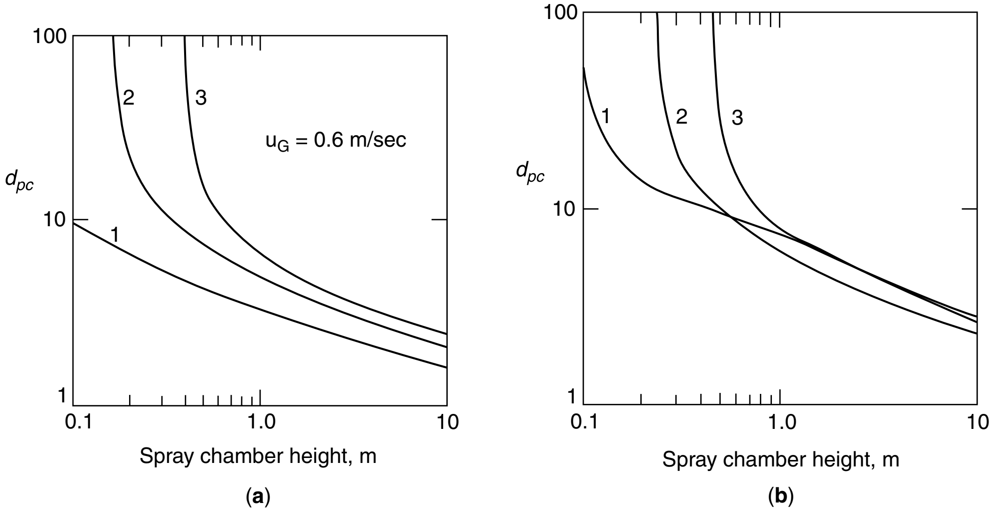


Fig. 17. Single droplet target efficiency in gravity spray tower. Courtesy of McGraw-Hill, Inc.

Venturi scrubbers are more efficient and consume more power (in the form of gas pressure drop) than spray chambers. For venturis, the penetration as given in reference 66 is related to many of the same parameters as for spray chambers, and is given by the following equation:

$$\begin{aligned}Pt_d = {} & \exp[(L/G)(V_{\mathrm{G}}\,d_{\mathrm{d}})\{-0.7 - K_p\,f + 1.4\ln((K_p\,f + 0.7)/0.7) \\ & + 0.49/(0.7 + K_p\,f)\}/55\mu_{\mathrm{G}}K_p]\end{aligned} \tag{23}$$



(a) (b)

Fig. 18. Performance cut diameters for spray towers: (**a**) vertical counterflow; (**b**) horizontal cross-flow. Liquid–gas ratio is 1 m^3 of liquid/1000 m^3 of gas. Drop diameter: curve 1, 200 µm; curve 2, 500 µm; curve 3, 1000 µm. U_G = 0.6 m/s. Ref. 64. Courtesy of *J. APCA*.

where:

f = empirical factor ($f = 0.25$ for hydrophobic particles; $f = 0.50$ for hydrophilic particles), and all terms have been defined previously in eqs. 19–22.

8. Control of Mobile Source Emissions

Mobile sources include cars, trucks, buses, motorcycles, bulldozers, trains, airplanes, boats, and all other things (on-road and nonroad) that move and emit air pollutants. Emissions from mobile sources include all the usual pollutants, but the three that are emitted in the largest quantities are carbon monoxide, nitrogen oxides, and volatile organic compounds. Particulate matter (PM) is an important pollutant from diesel engines, and so can be of serious concern for on-road large trucks and buses, and for non-road construction equipment. Mobile source pollution is a world-wide problem; every large city in the world has traffic congestion and serious air pollution problems. In the United States, over the last 30 years, improvements in individual vehicle emission factors (EFs) has been so great that it has offset the growth in vehicle miles traveled (VMT), and total emissions (the product of EF and VMT) have gone down (see Figure 19). However, in recent years, the improvements have been leveling out, and total emissions are forecast to start to rise. In many other countries, emissions controls are not as strict as in the U.S., and motor vehicle emissions per VMT are much larger. If economic development in China and India continues at their recent extremely rapid rates, motor vehicle emissions in those countries will grow very significantly over the next twenty years.

8.1. Engine and Exhaust Controls. Fuel is injected into an engine, mixes with air, ignites (initiated by a spark in a gasoline engine or via compression in a diesel engine), and burns very rapidly. The rapidly expanding combustion gases provide the force to drive the engine and thus the vehicle. An idealized chemical equation for the stoichiometric combustion of the gasoline component octene is shown below:

$$C_8H_{16} + 12\,O_2 + 45.1\,N_2 \rightarrow 8\,CO_2 + 8\,H_2O + 45.1\,N_2$$

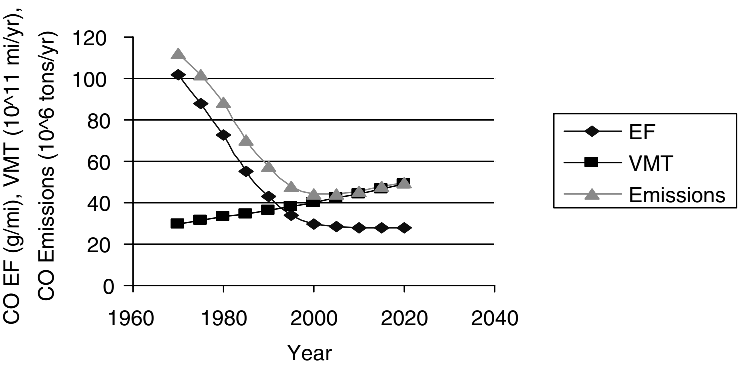


Fig. 19. Trends in VMT and emissions growth in VMT overshadows improvements in EFs by 2010.

Note that in this equation, the octene is burned completely with 100% efficiency. The amount of oxygen is exactly that needed to burn the carbon completely to carbon dioxide and the hydrogen to water. Furthermore, the nitrogen gas (which comes along with the oxygen in air) is shown as being totally inert. In reality, hydrocarbon fuels are not burned completely, some of the carbon forms CO rather than CO_2, so we must use slightly more air than the stoichiometric amount, and some of the nitrogen reacts with some oxygen to produce NO_x. The incompletely burned hydrocarbon fuel fragments and/or by-products are VOCs, and along with the CO and the NO_x, comprise the pollutants that exit the engine.

The air/fuel ratio plays a very large role in how much of each pollutant is formed, as shown in Figure 20. The stoichiometric ratio (SR = actual air/fuel ratio divided by theoretical air/fuel ratio) for gasoline is about 15:1, and as can be seen, NO_x is maximized at SR that are slightly above 1.0, while CO and hydrocarbons are emitted at much larger rates when the SR drops below 1.0. Gasoline engines can emit CO, VOCs and NO_x simultaneously. Diesel engines operate at higher compression ratios, and much higher air/fuel ratios, and CO and hydrocarbon emission factors (EFs) are relatively low, but NO_x EFs are significantly higher compared with gasoline engines. In use on actual roads, many variables can influence the EFs. These include: engine load, acceleration rates, roadway grade, air conditioning usage, time since engine start, ambient temperature,

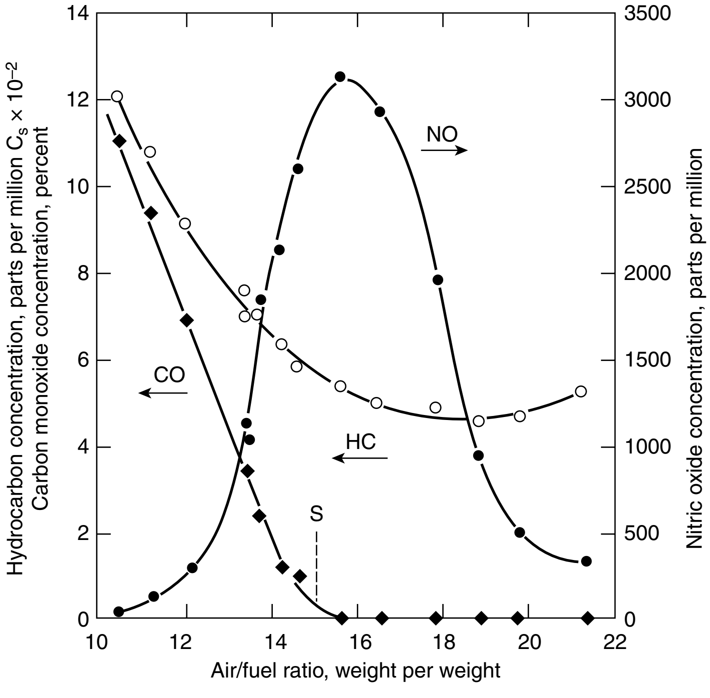


Fig. 20. Effect of air/fuel ratio on pollutants. Adapted from Ref. 67. Reproduced with permission from Ref. 4.

age of the vehicle and its state of repair, and others. In addition, the effects of different fuels and impurities in the fuels can be very significant.

Cars today are much, much cleaner than cars of the early 1970s. Much can be said for better fuel injection, and for precise (computer) control of the air/fuel ratio. Current practice is to control the actual ratio to about 0.98–0.99 of the SR. This is accomplished by an on-board computer that measures a number of variables (including the oxygen in the exhaust gases), and adjusts the air inlet rate accordingly. This prevents excessive NO_x while not forming too much hydrocarbons and CO. Fuel injection and newer cylinder designs add swirl to the incoming air to improve micromixing of the air and fuel. A more recent innovation is the extra-lean-burn engine that accomplishes a staged combustion in one combustion chamber (68). Other automotive control features include exhaust gas recirculation, spark timing, compression ratio, carbon canisters, and the PCV valve. Of course, all equipment must be maintained properly to work effectively.

However, the best known automotive pollution control device is the catalytic converter. This device is an exhaust gas clean-up device that simultaneously oxidizes CO and hydrocarbons while it reduces NO_x. Its effectiveness is enhanced by the engine controls mentioned above, but it is the device that allows newer cars to meet such tight pollution control standards. Precise air/fuel ratio control is required (see Figure 21). The catalytic converter is designed to allow the exhaust gas to pass through small channels with very little pressure drop. The pollutants adsorb momentarily on a catalyst (platinum and palladium supported on aluminum oxide) and react. The diesel engine equivalent is called a trap-oxidizer, since there is a much higher concentration of PM in diesel exhaust, which takes longer to oxidize.

8.2. Fuels. Fuels can have a big effect on emissions, and switching fuels is a viable pollution control measure. Gasoline is a blend of many different hydrocarbon fuels, as is diesel fuel (although diesel components are slightly heavier

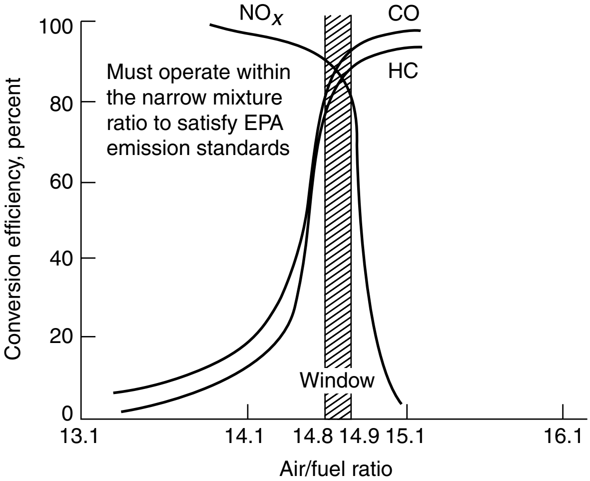


Fig. 21. Precise control of air-to-fuel ratio is required for good pollution. Adapted from Ref. 69. Reproduced with permission from Ref. 4.

than gasoline components). Different components burn differently and the fuels are blended to meet industry specifications. The Reid Vapor Pressure (RVP) is a measure of the volatility of gasoline, and a higher RVP is required for good engine start-up in the winter. However, with higher RVP, the gasoline has more of a tendency to evaporate, releasing hydrocarbon vapors into the air. One regulatory control measure that has been used by the U.S. EPA to help control ozone is to require a much lower RVP in the summer than in the winter. This reduces the emissions of VOCs, both from evaporation and from engine emissions. For areas that have a winter-time CO problem, EPA has required that some oxygenates (such as ethanol or MTBE) be blended in with gasoline. Having an oxygen molecule in the fuel helps to complete the combustion, and reduce CO formation. Thus, seasonal fuel programs can be an effective air quality management tool, regionally or nationally.

Impurities also greatly affect emissions; sulfur is one good example. Sulfur in fuel leads directly to more SO_2 emissions. But in addition, sulfur can temporarily poison catalytic converters, and can lead indirectly to more PM emissions. In the U.S., gasoline is highly refined and no longer has much sulfur in it. However, diesel fuel does. The U.S. EPA has promulgated new regulations for diesel fuel that will drop the sulfur content from about 500 ppm to 15 ppm in 2007 for on-road diesel, and in 2010 for nonroad diesel. This should greatly reduce both the sulfur oxides and the particulate matter from diesels.

In very recent years, high prices for petroleum fuels have spurred great interest in so-called alternative fuels and alternate technologies. The “new” fuels include ethanol, biodiesel, and hydrogen, and the new technologies include fuel cells, hybrids, and pure electric vehicles. Electric vehicles have batteries that must be recharged with electricity produced at power plants, so one might argue that one is simply displacing pollution. But often, the power plants are well-controlled, and the net result is a reduction in total air pollution. Fuel cells use a fuel (such as hydrogen) to combine at low temperature with oxygen to produce electricity on-board the vehicle. Hybrid vehicles have both gasoline and electric motors, and use regenerative braking and other techniques to recharge their batteries. Although still dependent on gasoline, they get substantially better gas mileage than regular engine cars, and thus reduce pollution emissions per mile. Fuel cell technology is still not commercial, but hybrid cars are a reality today.

Ethanol is an interesting fuel in that it comes from corn or other crop that can be grown domestically, thus reducing our dependence on foreign oil. In addition, it is “carbon-neutral,” meaning that the CO_2 emissions that come from burning ethanol simply replace the CO_2 that was absorbed in growing the corn to make the ethanol. Ethanol can be mixed with gasoline in low percentages and used in all cars today. E-85 is a blend of 85% ethanol and 15% gasoline that can be run in so-called flex-fuel vehicles, of which there are dozens of models being manufactured today by all the big automakers. The country of Brazil utilizes mostly ethanol in all of its cars, and has successfully weaned itself from dependence on foreign oil. However, there is still much debate over the efficacy of ethanol (its net energy effects), and its contributions to other air pollutants.

The most interesting alternative fuel today is biodiesel. Biodiesel is a domestic, renewable fuel for diesel engines derived from natural oils like soybean oil, or used cooking oils, and which meets certain fuel specifications. Like ethanol it is carbon neutral. Biodiesel can be mixed in any concentration with petroleum-based diesel fuel for use in existing diesel engines with little or no modification to the engine. It is produced by a chemical process (called trans-esterification) which is a reaction of the vegetable oil (or animal fats) with methanol in the presence of sodium hydroxide to produce mono-alkyl esters and glycerin. The glycerin is removed from the oil, and can be sold as a by-product. Biodiesel is not the same thing as raw vegetable oil. The American Society for Testing Materials has developed a technical standard-ASTM D 6751 (70) that requires that biodiesel meet a number of technical specifications which allows it to be blended into petroleum diesel in any proportion. A biodiesel blend is a mixture of biodiesel fuel meeting ASTM D 6751 with petroleum-based diesel fuel, designated BXX, where XX represents the volume percentage of biodiesel fuel in the blend. (For example, B20 is 20% biodiesel and 80% petroleum diesel.)

What makes biodiesel so interesting now is that it can be produced in large quantities from current soybean (or other) crops, and can displace petroleum diesel gallon for gallon with no ill effects on diesel equipment. The economics of biodiesel can be quite compelling with petroleum diesel above $3.00/gallon. In addition, biodesel emits substantially less pollution than petroleum diesel, and there are no arguments about its overall net energy effects.

8.3. Other Steps. In metropolitan areas, there are a number of other steps that can be and are being taken to reduce air pollution from mobile sources. After a car leaves the manufacturing plant, the operation and maintenance of the vehicle pollution control equipment becomes the responsibility of the individual owner. Thus, local and state governments have had to come up with many air resource management strategies. These air quality management steps are not end-of-pipe pollution control technologies, but deserve mention here anyway.

Since total emissions are the product of emission factors times VMT, anything that can be done to reduce VMT will reduce air pollution. Many urban areas have underutilized transit systems, and a very good first step is to try to get more drivers out of their vehicles and onto transit. In addition, many areas promote bicycling and walking as a way of commuting shorter distances. Bicycle "stations" (places where bike commuters can safely store their bikes and even shower before going to their offices) are being built in urban areas both in Europe and in the U.S. New trends in land development are trying to reduce home-to-work commute distances, and locate residential, employment, and commercial areas close to each other. Vehicle inspection and maintenance (I/M) programs are ways that some states or counties ensure that vehicles are being maintained in good working order, and meet certain minimum emission standards. Computerized signal timing to improve traffic flow and reduce idling time has been used to reduce air pollution in downtown areas of cities, and electronic toll collection has had the same effect on toll roads.

9. Odor Control

An objectionable odor can be defined as the human perception of a "bad smell." A "smell" is the reaction of a human being to the stimulation of olfactory sensory neurons, located in the mucous membranes high in the nasal cavity, by molecules of an odorous substance. As odor molecules impact the receptors in the nasal membranes, the olfactory neurons are excited and send signals to the brain. This can occur at extremely low concentrations of the odorous molecules. It is thought that there are seven primary smell stimulants (71): (*1*) Camphorous, (*2*) musky, (*3*) floral, (*4*) peppermint, (*5*) ethereal, (*6*) pungent, and (*7*) putrid.

Human reaction to odor depends on many variables, including the odor detectability (concentration in air), intensity (strength of perception), and character or hedonic tone (associations in the person's mind with past experiences that make this odor pleasant or unpleasant) (71). Being as odor perception involves humans, there can be a wide range of perceptions and reactions to the same concentration of an odorous gas.

Many odorous compounds are known, and *detection thresholds* (the lowest concentration of the compound that can be detected by 50% of people) have been determined for some of them. The *recognition threshold* is the point at which odor can be identified (this is significant because observers will not complain until the recognition threshold is exceeded) (72). Odors are a major concern for wastewater treatment plants, landfills, composting operations, and agricultural operations (eg, cattle feedlots, hog or poultry farms, etc). Table 13 lists some odorous compounds that have been identified in wastewater, and gives their odor detection thresholds. Many of these same compounds have been found at landfills and other sources. Odor control involves any process that results in a more acceptable perception of smell, whether as a result of dilution, removal or destruction of the offending substance, counteraction, or masking.

There are no federal regulations for odors *per se*; mostly such regulations are at the state or local level. Scholars suggest that odor entered common law as possible trespass or nuisance; an odor wafting from one property to another was considered trespass. If sufficient evidence can be demonstrated, common law holds that the property owner who is the recipient of the odor has suffered a wrong (73). Today, odors are typically regulated as nuisances, and regulations are set by state and local governments often citing the right of "comfortable enjoyment of life and property"(73).

9.1. Odor Measurement. Both static and dynamic measurement techniques exist for odor. The objective is to measure odor intensity by determining the dilution necessary so that the odor is imperceptible or doubtful to a human test panel. That is, a given sample of odorous air is diluted with enough odor-free air to reach the detection threshold. Compliance with odor laws is determined by modeling, or by off-site or site-boundary sampling and dilution to threshold (D/T) measurements.

An odor unit (o.u.) has been widely defined as 0.0283 m^3 (1 ft^3) of air at the odor detection threshold. It is a dimensionless unit representing the quantity of odor which when dispersed in 28.3 L (1 ft^3) of odor-free air produces a positive response by 50% of panel members. The number of odor units (odor concentration) is the number of cubic meters that one cubic meter of odorous gas will occupy when diluted with air to the odor threshold.

The "concentration" of odors is determined by a panel of people who are exposed to various dilutions of the odorous air (since odors are subjective, it is

Table 13. **Odorous Compounds Found in Wastewater**[a]

Compound name	Formula	Molecular weight	Odor description	Odor threshold, ppm (v/v)
acetaldehyde	CH_3CHO	44	pungent, fruity	0.067
acetic acid	CH_3COOH	60	sour	1.0
allyl mercaptan	CH_2CHCH_2SH	74	disagreeable, garlic	0.0001
ammonia	NH_3	17	pungent, irritating	47
amyl mercaptan	$CH_3(CH_2)_4SH$	104	unpleasant, putrid	0.0003
benzyl mercaptan	$C_6H_5CH_2SH$	124	unpleasant, strong	0.0002
n-butyl amine	$CH_3(CH_2)NH_2$	73	sour, ammonia	0.080
crotyl mercaptan	$CH_3(CH)_2CH_2SH$	88	skunklike	0.00003
dibutyl amine	$(C_4H_9)_2NH$	129	fishy	0.016
diisopropyl amine	$(C_3H_7)_2NH$	101	fishy	0.13
dimethyl amine	$(CH_3)_2NH$	45	putrid, fishy	0.34
dimethyl disulfide	$(CH_3)_2S_2$	94	decayed vegetables	0.0001
dimethyl sulfide	$(CH_3)_2S$	62	decayed cabbage	0.001
diphenyl sulfide	$(C_6H_5)_2S$	186	unpleasant	0.0001
ethyl amine	$C_2H_5NH_2$	45	ammonialike	0.27
ethyl mercaptan	C_2H_5SH	62	decayed cabbage	0.0003
hydrogen sulfide	H_2S	34	rotten eggs	0.0005
indole	$C_6H_4(CH)_2NH$	117	fecal, nauseating	0.0001
methyl amine	CH_3NH_2	31	putrid, fishy	4.7
methyl mercaptan	CH_3SH	48	rotten cabbage	0.0005
phenyl mercaptan	C_6H_5SH	110	putrid, garlic	0.0003
propyl mercaptan	C_3H_7SH	76	unpleasant	0.0005
pyridine	C_5H_5N	79	pungent, irritating	0.66
skatole	C_9H_9N	131	fecal, nauseating	0.001
thiocresol	$CH_3C_6H_4SH$	124	skunky, irritating	0.0001
thiophenol	C_6H_5SH	110	putrid, garliclike	0.00006
trimethyl amine	$(CH_3)_3N$	59	pungent, fishy	0.0004

[a] Reproduced with permission from Ref. 4.

important to get the perceptions of a number of people). Development of a panel is essential because of differences in individual sensitivity to compounds causing taste and odor problems. Panels should be diverse in age, gender, ethnicity, etc which are statistically representative of population.

There are two types of odor panels: expert and consumer (72). The differences are (*1*) Experts are trained and have increased sensitivity. Fewer panelists are required, and they are all familiar with the testing protocol. (*2*) Consumers may be required to choose by comparison of two samples, and are often only expected to determine whether multiple samples are different or not. A consumer panel is useful to determine detection threshold (detects a difference but cannot characterize difference).

Selection of people to participate in an odor panel should reflect the type of information or measurement required, eg, for evaluation of an alleged neighborhood odor nuisance, the test subjects should be representative of the entire neighborhood.

Static Dilution Methods. With the static method, a known volume of odorous sample is diluted with a known amount of nonodorous air, mixed, and presented statically (quiescently) to the test panel. The ASTM D1391 syringe dilution technique is the best known of these methods and involves preparation of a 100-mL glass syringe of diluted odorous air which is allowed to stand 15 min to assure uniformity. The test panel judge suspends breathing for a few seconds and slowly expels the 100-mL sample into one nostril. The test is made in an odor-free room with a minimum of 15 min between tests to avoid olfactory fatigue. The syringe dilution method is reviewed from time to time by the ASTM E18 Sensory Evaluation Committee, who suggest and evaluate changes. Instead of a syringe, a test chamber may be used which can be as large as a room (74,75).

Dynamic Dilution Methods. In the dynamic method, odor dilution is achieved by continuous flow. Advantages are more accurate results, simplicity, reproducibility, and speed. Devices known as dynamic olfactometers control the flow of both odorous and pure diluent air, provide for ratio adjustment to give desired dilutions, and present multiple, continuous samples for test panel observers at ports beneath ventilation hoods.

9.2. Odor Control Methods. Absorption, adsorption, and incineration are all typical control methods for gaseous odors; odorous particulates are controlled by the usual particulate control methods. However, a gas carrying odorous particulates may still require gaseous odor control treatment even after the particulates have been removed. For oxidizable odors, wet absorption combined with oxidation of the odorous compounds using such oxidants as hydrogen peroxide, ozone, chlorine, and $KMnO_4$ has been practiced; vapor phase oxidation (either thermal or catalytic) has also been employed. Odor control for such facilities as rendering plants (76), spent grain dryers (77), pharmaceutical plants (78–80), and cellulose pulping has been reviewed (81,82). Odor control at a wastewater treatment plant in Orange County, Florida, was being accomplished (but not consistently well) by a chlorine-caustic scrubber, but that was replaced by a biofiltration unit with excellent results (83). The odor-control performances of activated carbon and permanganate-alumina for reducing odor level of air streams containing olefins, esters, aldehydes, ketones, amines, sulfide, mercaptan, vapor from decomposed crustacean shells, and stale tobacco smoke have been compared (84). Activated carbon produced faster deodorization in all cases. Activated carbon adsorbers have been used to concentrate odors and organic compounds from emitted gases, producing fuels suitable for incineration (85). Both air pollution control and energy recovery were accomplished.

9.3. Air Pollution Dispersion Modeling for Odor Impacts.

Air pollution dispersion modeling is a very useful function. It allows the prediction of concentrations of gaseous and particulate matter pollutants far downwind of where they were emitted. Many improvements in model sophistication have been made in the past decade, but oftentimes model accuracy is still somewhat limited. Furthermore, it is known that models are imperfect representations, and that modeling is expensive and time consuming. Some may question the use of models, and prefer “real data” from monitoring instruments. Instruments are very sophisticated, and can be deployed in many locations to measure the concentrations that result from the totality of emissions from vehicles and large industrial sources. Why not avoid those uncertainties, and put all our efforts into measuring “the real world?”

Despite its shortcomings, modeling is *essential*. There are several reasons why modeling must be conducted. First, it is impossible to measure the impact from a facility that will be built in the future. Yet, it is necessary to have a reasonable estimate of that impact before the facility can be constructed. Modeling allows this. Second, comprehensive measurement programs could be 1000 times more expensive than modeling. Third, modeling is the only practical approach when there are many sources, and when the isolation of the potential effects of just one source is wanted. Finally, modeling may not be 100% accurate, but it is precise (reproducible). Thus modeling provides an impartial and reproducible tool for assessing and comparing various alternatives. However, one should always keep in mind the limitations of modeling, and use good judgment in interpreting the results of any modeling study.

Modeling in odor control is used to determine maximum impact distances or conversely, the minimum distances downwind from odor sources that residential areas can be located. There are two common models used for this task. The first is the Gaussian plume model, Industrial Source Complex-Short Term, Version 3 (ISCST3) (86). This dispersion modeling program estimates hourly average downwind concentrations of many pollutants, based on steady-state conditions. However, it has difficulty in predicting odor impacts, which are inherently very short-term concentrations. The other model used for odor impact studies is CALPUFF (87), which is a nonsteady state air emission modeling system, capable of modeling sub-hourly time steps.

In a comparison study of the two models, CALPUFF fairly accurately predicted average downwind odor concentrations while ISCST3 underestimated values compared to field measurements (88). However, both models failed to predict peak odor concentrations (88). In another modeling study, applied to landfills, a methodology was proposed to model methane production rate and dispersion, and based on the ratio of various trace chemical species, an odor index was calculated. By comparing the predicted trace chemical concentrations with the odor detection limits, the odor strength at a specific distance could be evaluated (89).

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