Part II Wastegas Engineering

9 Control of Primary Particles

9.1 Wall Collection Devices

The first three types of control devices we consider--gravity settlers, cyclone separators, and electrostatic precipitators--all function by driving the particles to a solid wall, where they adhere to each other to form agglomerates that can be removed from the collection device and disposed of.

9.1.1 Gravity Settlers

It is an old, unsophisticated device that must be cleaned manually at regular intervals. But it is simple to construct, requires little maintenance, and has some use in industries treating very dirty gases, e.g., some smelters and metallurgical processes.

Gravity settlers have little practical industrial use because they are ineffective for small particles.

At even modest velocities and common radii, the centrifugal forces acting on particles can be two orders of magnitude larger than the gravity forces. For this reason centrifugal particle separators are much more useful than gravity settlers.

There are many other variants on the centrifugal collector idea, but none approaches the cyclone in breadth of application. These devices are simple and almost maintenance-free. Because any medium-sized welding shop can make one, the big suppliers of pollution control equipment, who have test data on the effects of small changes in the internal geometry, have been unwilling to make these data public.

When it is used to separate solids from liquids it is generally called a hydroclone.

If gravity settlers and centrifugal separators are devices that drive particles against a solid wail, and if neither can function effectively (at an industrial scale) for particles below about 5 μm in diameter, then for wall collection devices to work on smaller particles, they must exert forces that are more powerful than gravity or centrifugal force. The electrostatic precipitator (ESP) is like a gravity settler or centrifugal separator, but electrostatic force drives the particles to the wall.

The basic idea of all ESPs is to give the particles an electrostatic charge and then put them in an electrostatic field that drives them to a collecting wall. This is an inherently two-step process. In one type of ESP, called a two-stage precipitator, charging and collecting are carried out in separate parts of the ESR. This type, widely used in building air conditioners, is sometimes called an electronic air filter. However, for most industrial applications the two separate steps are carried out simultaneously in the same part of the ESP.

Figure 9.2 shows in simplified form a wire-and-plate ESP with two plates. The gas passes between the plates, which are electrically grounded (i.e., voltage = 0). Between the plates are rows of wires, held at a voltage of typically -40 000 volts. The power is obtained by transforming ordinary alternating current to a high voltage and then rectifying it through some kind of solid-state rectifier.

On the plates the particles lose their charge and adhere to each other and the plate, forming a "cake."

Solid cakes are removed by rapping the plates at regular time intervals with a mechanical or electromagnetic rapper that strikes a vertical or horizontal blow on the edge of the plate.

Some of the cake is always re-entrained, thereby lowering the wastegas flowrate whereas enhancing the removal efficiency of the system.

If the collected particles are liquid, e.g., sulfuric acid mist, they run down the plate and drip off.

9.2 DIVIDING COLLECTION DEVICES

Filters and scrubbers divide the flow into smaller parts where they can collect the particles.

Two types of filters, surface filters and depth filters, are commonly used in air pollution control.

9.2.1 Surface Filters

The filter is a membrane (sheet steel, cloth, wire mesh, or filter paper) with holes smaller than the dimensions of the particles to be retained.

Although industrial air filters rarely have holes smaller than the smallest particles captured, they often act as if they did. The reason is that, as fine particles are caught on the sides of the holes of a filter, they tend to bridge over the holes and make them smaller. Thus as the amount of collected particles increases, the cake of collected material becomes the filter, and the filter medium (usually a cloth) that originally served as a filter to collect the cake now serves only to support the cake, and no longer as a filter.

This cake of collected particles will have average pore sizes smaller than the diameter of the particles in the oncoming gas stream, and thus will act as a sieve for them. The particles collect on the front surface of the growing cake. For that reason this is called a surface filter.

One may visualize this situation with a screen having holes 0.75 in. (1,91 cm) in diameter. We could collect a layer of Ping-Pong balls easily on this screen. Once we had such a layer, we could then collect cherries, which, by themselves, could pass through the holes in the screen but cannot pass through the spaces between the Ping-Pong balls. Once we have a layer of cherries, we could put on a layer of peas, then of rice, then of sand.

The two most widely used designs of industrial surface filters are shown in Figs. 9.13 and 9.14. Because the enclosing sheet metal structure in both figures is normally the size and roughly the shape of a house, this type of gas filter is generally called a baghouse. The design in Fig. 9.13, most often called a shake-deflate filter, consists of a large number of cylindrical cloth bags that are closed at the top like a giant stocking, toe upward.

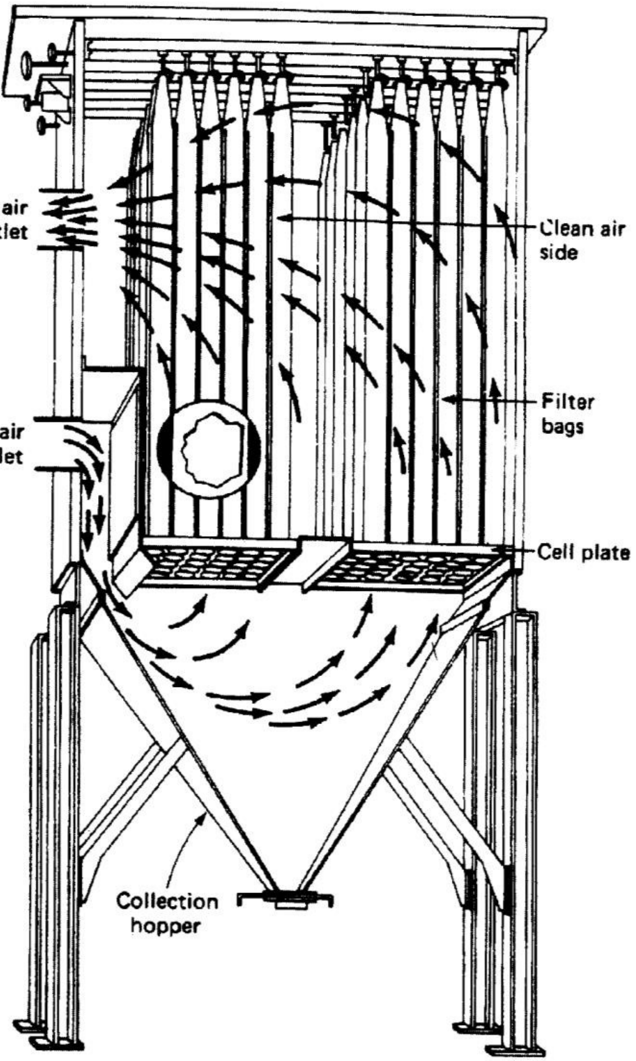


FIGURE 9.13
Typical industrial baghouse of the shake-deflate design. (Courtesy of Wheelabrator Air Pollution Control, Inc.)

- *Fig. 9-4 Typical industrial baghouse of the shake-deflate design*

These are hung from a support. Their lower ends slip over and are clamped onto cylindrical sleeves that project upward from a plate at the bottom. The dirty gas flows into the space below this plate and up inside the bags. The gas flows outward through the bags, leaving its solids behind. The clean gas then flows into the space outside the bags and is ducted to the exhaust stack or to some further processing.

For the baghouse in Fig. 9.13 there must be some way of removing the cake of particles that accumulates on the filters. Normally this is not done during gas-cleaning operations, instead the baghouse is taken out of the gas stream for cleaning. When the gas flow has been switched off, the bags are shaken by the support to loosen the collected cake.

A weak flow of gas in the reverse direction may also be added to help dislodge the cake, thus deflating the bags.

Often metal rings are sewn into filter bags at regular intervals so that the bag will only partly collapse when the flow is reversed.

Typically, for a major continuous source like a power plant, about five baghouses will be used in parallel, with four operating as gas cleaners during the time that the other one is being shaken and cleaned. Each baghouse might operate for two hours and then be cleaned for 10 minutes; at all times one baghouse would be out of service for cleaning or waiting to be put back into service.

Fig. 9-14 Typical industrial baghouse of the pulse-jet design

The other widely used baghouse design, called a pulse-jet filter, is shown in Fig. 9.14. In it the flow during filtration is inward through the bags, which are similar to the bags in Fig. 9.13 except their ends open at the top. The bags are supported by internal wire cages to prevent their collapse.

Just after the cleaning the control efficiency will be less than just before the next cleaning, but the average efficiency meets the legal control requirements.

9 .2.2 Depth Filters

Another class of filters, widely used for air pollution control, does not form a coherent cake on the surface, but instead collects particles throughout the entire filter body. The examples are the filters on filter-tipped cigarettes and the lint filters on many home furnaces.

Such filters are often used where the particles to be caught are fine drops of liquids that are only moderately viscous.

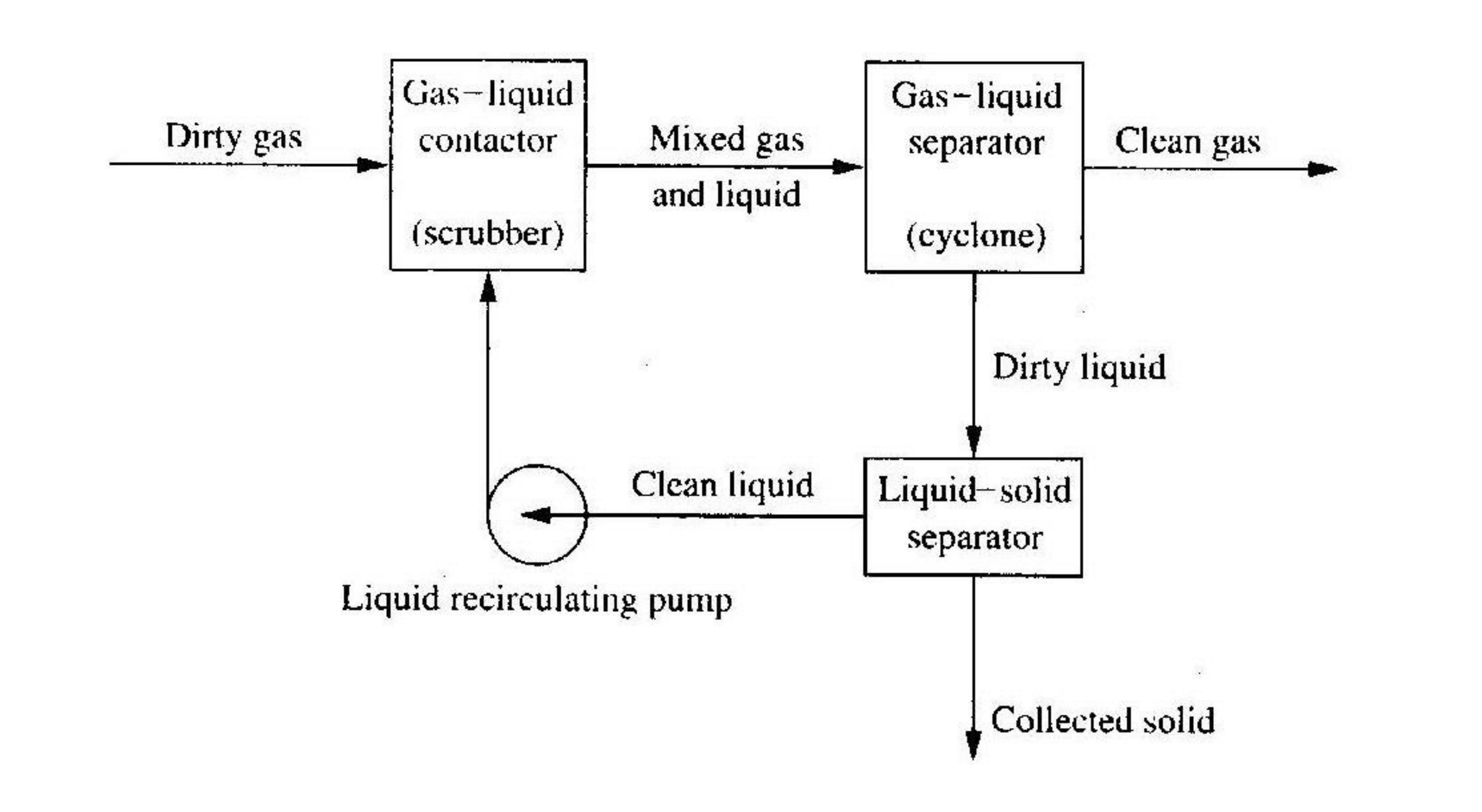
The most widespread air pollution control use of depth filters is in the collection of very fine liquid drops, sulfuric acid mist, produced in sulfuric acid plants.

One brand uses the trade name Demister. This kind of device is also used for cleaning the air of industrial clean rooms or hospital surgical suites and in personal protection dust masks. The filters are thrown away when they have collected enough particles that their pressure drop begins to increase.

9.2.4 Scrubbers for Particulate Control

Scrubbers effectively divide the flow of particle-laden gas by sending many small drops through it.

A complete scrubber has several parts, as sketched in Fig. 9.20.



- ***Fig. Component parts of a scrubber installation***

If possible, the engineer should try to save money by finding a place where the contaminated water stream can be recycled inside the plant without first removing the solids.

Obviously, if there is no good way to deal with the contaminated water stream, then the scrubber has merely changed an air pollution problem into a water pollution problem.

9.3 Choosing the Collectors

In choosing a primary particle collection device one must consider the size of the particles to be collected, the required collection efficiency, the size of the gas flow, the allowed time between cleanings, and details of the nature of the particles. The following rules of thumb may be helpful:

1. Small or occasional flows can be treated by throwaway devices, e.g., cigarette and motor oil filters, in which the collected particles remain in the device. Large and steady flows require collection devices that operate continuously or semicontinously, and from which the collected particles can be removed continuously or semicontinuously.

2. Sticky particles (e.g., tars) must be collected either on throwaway devices or into a liquid, as in a scrubber or cyclone, filter, or wet ESP whose collecting surfaces are continually coated with a film of flowing liquid.
3. Particles that adhere well to each other but not to solid surfaces are easy to collect. Those that do the reverse often need special surfaces, e.g., Teflon-coated fibers in filters that release collected particles well during cleaning.
4. Electrical properties of the particles are of paramount importance in ESPs, and they are often significant in other control devices where friction-induced electro-static charges on the particles can aid or hinder collection.

5. For nonsticky particles larger than about 5 μm, a cyclone separator is probably the only device to consider.
6. For particles much smaller than 5 μm one normally considers ESPs, filters, and scrubbers. Each of these can collect particles as small as a fraction of a micron.
7. For large flows the pumping cost makes scrubbers very expensive; other devices are chosen if possible.
8. Corrosion resistance and acid dew point must always be considered.

9.4 SUMMARY

1. Gravity settling chambers, cyclones, and ESPs work by driving the particles to a solid wall where they form agglomerates that can be collected. These three devices have similar design equations.
2. Filters and scrubbers divide the flow. They have different design equations from

   wall collection devices and from each other.

3. Both surface and depth filters are used for particle collection. Surface filters are used to collect most of the particles in a heavily laden gas stream. Depth filters are mostly used for the final cleanup of air or gas that must be very clean or for fine liquid drops, which coalesce on them and then drop off.

4. To collect small particles, a scrubber must have a very large relative velocity between the gas being cleaned and the liquid drops. For this reason co-flow scrubbers are most often used. The venturi scrubber is the most widely used type of co-flow scrubber.

10 Control of Volatile Organic Compounds

10.1 Introduction

Volatile organic compounds (VOCs) are liquids or solids that contain organic carbon (carbon bonded to carbon, hydrogen, nitrogen, or sulfur, but not carbonate carbon as in $CaCO_3$ nor carbide carbon as in CaC_2 or CO or CO_2), which vaporize at significant rates. VOCs are probably the second-most widespread and diverse class of emissions after particulates.

VOCs are a large family of compounds some (e.g., benzene) are toxic and carcinogenic. The principal concern with VOCs is that they participate in the "smog" reaction and also in the formation of secondary particles in the atmosphere. These latter are mostly in the fine particle size range. Some VOCs are powerful infrared absorbers and thus contribute to the problem of global warning.

10.2 VOCs

VOCs are those organic liquids or solids whose room temperature vapor pressures are greater than about 0.01 psia (0.0007 atm) and whose atmospheric boiling points are up to about 500°F (260°C), which means most of these organic compounds with less than about 12 carbon atoms.

A lighted cigarette produces a gaseous mixture of high-boiling organic compounds; when this mixture is cooled on leaving the cigarette it forms a smoke of fine particulate droplets.

In common usage it would often be grouped with the hydrocarbons.

Hydrocarbons are only slightly soluble in water, so we can normally separate liquid HCs from liquid water by simple phase separation and decantation. However, the water left behind often contains enough dissolved hydrocarbon that it cannot be discharged to the sewer or natural body of water without additional treatment.

Polar VOCs, which almost all contain an oxygen or nitrogen atom in addition to carbons and hydrogens (alcohols, ethers, aldehydes and ketones, carboxylic acids, esters, amines, nitriles) are much more soluble in water. This difference in solubilities makes the polar VOCs easier to remove from a gas stream by scrubbing with water, but harder to remove from water once they dissolve in it.

10.3 CONTROL BY CONCENTRATION AND RECOVERY

10.3.1 Adsorption

Adsorption means the attachment of molecules to the surface of a solid. In contrast, absorption means the dissolution of molecules within a collecting medium, which may be liquid or solid. Generally, absorbed materials are dissolved into the absorbent, like sugar dissolved in water, whereas adsorbed materials are attached onto the surface of a material, like dust on a wall. Absorption mostly occurs into liquids, adsorption mostly onto solids.

Industrial face masks of activated carbon are worn by workers exposed to solvents, as in paint spraying or solvent cleaning. The worker's lungs suck the air in through thin beds of activated carbon, contained in replaceable cartridges on the face mask. When the activated carbon is loaded (i.e., the solvent begins to come through into the worker's breathing space) the cartridge of activated carbon is discarded and a fresh one installed.

10.3.2 Absorption (Scrubbing)

If we can find a liquid solvent in which the VOC is soluble and in which the remainder of the contaminated gas stream is insoluble, then we can use absorption to remove and concentrate the VOC for recovery and re-use, or destruction. The standard chemical engineering method of removing any component from a gas stream--absorption and stripping--is sketched in Fig. 10.15. If we can find a liquid solvent in which the gaseous component we wish to selectively remove is much more soluble than are the other components in the gas stream, the procedure is quite straightforward.

The feed gas enters the absorber, which is a vertical column in which the gas passes upward and the liquid solvent passes downward. Normally, bubble caps, sieve trays, or packing is used in the interior of the column to promote good countercurrent contact between the solvent and the gas. The stripped solvent enters the top of the column and flows countercurrent to the gas.

The loaded solvent, which now contains most of the component we are removing from the gas, passes to the stripper, which normally is operated at a higher temperature and/or a lower pressure than the absorber.

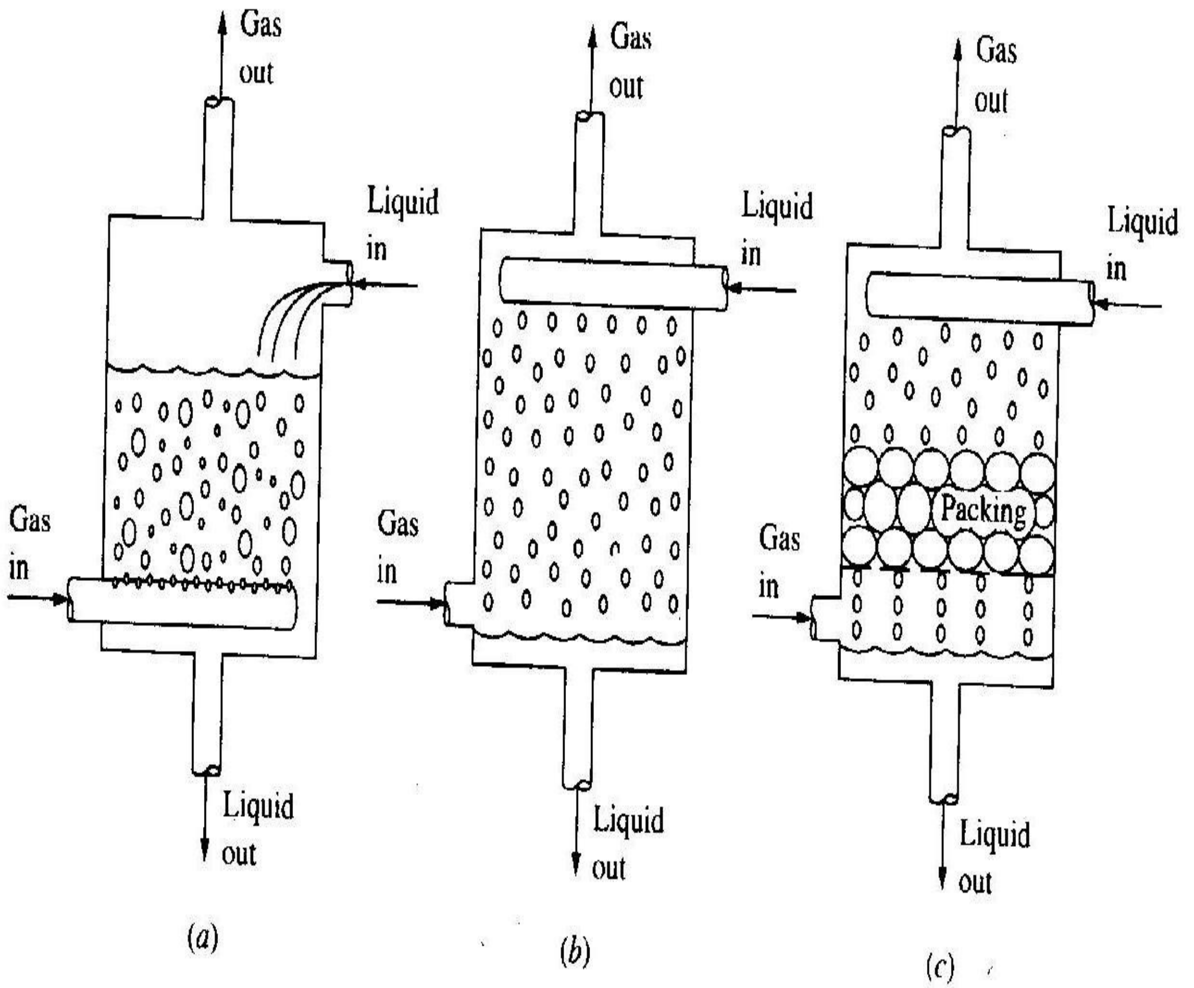


FIGURE 11.4

- ***Fig. Three plausible arrangements for scrubbing a gas with a liquid: (a)bubbler;(b)spray chamber;(c)packed***

In Fig. 10.15 the separated component is shown leaving as a gas for use, sale, or destruction. In some cases it is condensed and leaves as a liquid. The stripped or lean solvent is sent back to the absorber column. Very large absorption-stripping systems often use tray columns, but the small ones used in most air pollution control applications use internal packings.

1. It must afford reasonable solubility for the material to be removed, and, if this material is to be recovered at reasonable purity, it must not dissolve and thus carry along any of the other components of the gas stream.
2. In the absorber, the gas being treated will come to equilibrium with the stripped solvent. The vapor pressure of the solvent, at absorber temperature, must be low enough that if the cleaned gas is to be discharged to the atmosphere, the emission of solvent is small enough to be permissible. Some solvent is lost this way; the cost of replacing it must be acceptable. If the solvent is water this is not a problem (unless we need the gas to be dry for its next use), but for other solvents this can be a problem.

3. At the higher temperature (or lower pressure) of the stripping column, the absorbed material must come out of solution easily, and the vapor pressure of the solvent must be low enough that it does not contaminate the recovered VOC. If the solvent vapor pressure in the stripper is too large, one may replace the stripper by a standard distillation column (combination stripper and rectifier) to recover the transferred material at adequate purity.
4. The solvent must be stable at the conditions in the absorber and stripper, and be usable for a considerable time before replacement.
5. The solvent molecular weight should be as low as possible, to maximize its ability to absorb. This requirement conflicts with the low solvent vapor pressure requirement, so that a compromise must be made.

10.4 Biological Oxidation (Biofiltration)

As discussed above, the ultimate fate of VOCs is to be oxidized to CO_2 and H_20, either in our engines or furnaces, or incinerators, or in the environment. Microorganisms can also oxidize the VOCs contained in gas or air streams.

The typical biofilter consists of the equivalent of a swimming pool, with a set of gas distributor pipes at the bottom, covered with several feet of soil or compost or loam or other carriers in which the microorganisms live. The contaminated gas enters through the distributor pipes and flows slowly up through soil, allowing time for the VOC to dissolve in the water contained in the soil, and then to be oxidized by the microorganisms that live there.

Typically these devices have soil depths of 3 to 4 ft, void volumes of 50%, upward gas velocities of 0.005 to 0.5 ft/s, and gas residence times of 15 to 60 s. They work much better with polar VOCs, which are fairly soluble in water (see Sec. 10.2) than with HCs whose solubility is much less. The microorganisms must be kept moist, protected from conditions that could injure them, and in some cases given nutrients. Because of the long time the gases must spend in them, these devices are much larger

In spite of these drawbacks, there are some applications for which they are economical, and for which they are used industrially.

10.5 SUMMARY

1. VOCs are emitted from a wide variety of sources and have a wide variety of individual components, each with its own properties. We use VOCs mostly as petroleum-based fuels and solvents. The majority of our VOC emissions come from fuel and solvent usage, transportation, and storage.
2. The control alternatives are prevention, concentration and recovery, or oxidation.
3. Some of these control options can also be used for non-VOC emissions, e.g., incineration for odor control of H_2S, adsorption for SO_2 or mercury vapor, and leakage control for any process source.

11 Control of Sulfur Oxides

The control of particulates and VOCs is mostly accomplished by physical processes (cyclones, ESPs, filters, leakage control, vapor capture, condensation).

Some particles and VOCs are chemically changed into harmless materials by combustion.

Control of sulfur oxides and nitrogen oxides is largely chemical rather than physical.

Sulfur and nitrogen oxides are ubiquitous pollutants, which have many sources. SO_2, SO_3, and NO_2 are strong respiratory irritants that can cause health damage at high concentrations.

These gases also form secondary particles in the atmosphere, contributing to our PM_{10} and $PM_{2.5}$ problems and impairing visibility. They are the principal causes of acid rain.

11.1 The Elementary Oxidation-Reduction Chemistry Of Sulfur And Nitrogen

Both sulfur and nitrogen in the elemental state are relatively inert and harmless to humans. Both are needed for life; all animals require some N and S in their bodies. However, the oxides of sulfur and nitrogen are widely recognized air pollutants. The reduced products also are, in some cases, air pollutants.

Both hydrogen sulfide and ammonia are very strong-smelling substances, gaseous at room temperature (-60° C and -33° C boiling points, respectively), and toxic in high concentrations. (High concentrations due to accidental releases often cause fatalities. These occur in the production and use of ammonia as a fertilizer and refrigerant and in the production and processing of "sour" gas and oil, which contain hydrogen sulfide.).

In the atmosphere NO_2 and SO_3 react with water to form nitric and sulfuric acids, which then react with ammonia or any other available cation to form particles of ammonium nitrate or sulfate or some other nitrate or sulfate. These particles, generally in the 0.1 to 1-μm size range, are very efficient light-scatterers. They are significant contributors to urban PM10 and PM2.5 problems. They are the principal causes of acid deposition and of visibility impairment. NO and NO_2 also play a significant role in the formation of O_3.

11.1 Dry systems

The solids handling and wet sludge handling and disposal difficulties that are integral to wet throwaway processes induced engineers to develop dry throwaway processes that would have fewer corrosion and scaling difficulties and would produce a waste product much easier to handle and dispose of. All of these systems inject dry alkaline particles into the gas stream, where they react with the gas to remove SO_2.

The SO_2-containing particles are then captured in the particle collection device that the plant must have to collect fly ash (most often a baghouse, sometimes an ESP). If successful, this approach eliminates the problems with disposal of wet scrubber sludge and all the difficulties involved with the wet limestone process. It increases the volume of dry solids to be disposed of, but that is considered a less difficult problem. The flow diagrams for such systems are sketched in Fig. 11.7.

The first two call for the injection of powdered limestone or lime into the boiler. In the high-temperature part of the furnace the limestone would convert to lime, so that either way the active reagent would be CaO. The desired reaction is

$$CaO + SO_2 \dashrightarrow CaSO_3$$

$CaSO_3$ would then oxidize to $CaSO_4$. In principle this should work, but most tests have shown that to get high SO_2 collection efficiencies one must put a large excess of lime or limestone into the system, thus increasing reagent costs, increasing the load on the particle collector, and increasing the volume of solid wastes to be disposed of. However, if one uses more reactive (and much more expensive) $NaHCO_3$ or Na_2CO_3, the collection efficiency is much better, mostly because of the much higher chemical reactivity of these sodium salts.

Mass transfer between gases and solids is much less well understood than that between gases and liquids, so that the design of these devices is much more heavily dependent on test and empiricism than is the design of systems like that in Fig. 10.15.

11.2 Regenerative systems

Table 11.4 shows an entirely different category of systems. In these some kind of absorbent or adsorbent is used to capture SO_2 from the flue gas. Then in some separate device or set of devices the adsorbent or absorbent is regenerated to produce a flow of relatively pure SO_2 or H_2SO_4.

Recently, work has begun on regenerative processes that will simultaneously capture both SO_2 and NOx. These systems have not yet advanced to commercial scale, but they may have a major role in future air pollution control.

11.3 SUMMARY

1. SO_2 emissions from human activities are mostly due to the combustion of sulfur-containing fossil fuels and the smelting of metal sulfide ores.
2. The overall control strategy for SO2 emissions is to convert the sulfur to $CaSO_4 \cdot 2H_2O$ and return it to the ground in some kind of landfill, or use it to make wallboard.

3. For liquid or gaseous fuels containing reduced sulfur, the most common approach
is to use catalytic processes to convert the contained sulfur to H_2S, remove that by
scrubbing the gas with a weakly alkaline solution, convert the H_2S to elemental
sulfur by the Claus process, and either sell that sulfur for sulfuric acid production or place it in a landfill.

4. For metal sulfide ore smelting, which produces waste gases with 4 percent or more SO_2, the common approach is to convert that SO_2 to sulfuric acid.

5. For coal (or high-sulfur oil) used in a large power plant, the most common approach is to burn the coal and then treat the plant's exhaust gas (typically containing about 0.1 percent SO_2) with limestone or lime in a forced-oxidation wet scrubber or a spray dryer, to convert SO_2 to $CaSO_4 \cdot 2H_20$, which will then go to a landfill or a wallboard plant.

6. Other alternatives are being explored, some in large-scale demonstrations. They may replace those just listed in the future.