CHAPTER 8

AIR POLLUTION PROBLEMS

8.1. THE PROBLEMS OF AIR POLLUTION - AN OVERVIEW.

Air pollution control is applying a wide range of remedies, and alternative technology is playing a more important role in air pollution control than in water pollution control. Alternative technology is often employed as a result of increasingly stringent legislation, e.g. the setting of lower threshold levels for lead in gasoline, sulphur in fuel and carbon monoxide in exhaust gases.

Air pollution problems can be considered in terms of the effect on climate, or local or regional effects caused by toxicity of particular pollutants. The principles of air pollution problems were discussed in Part A; this chapter outlines the technology now available for air pollution control. The methods employed are classified according to the problems they solve.

This chapter covers the control of particulate pollution, carbon dioxide, carbon hydride and carbon monoxide and sulphur dioxide problems, nitrogenous gas pollution and industrial gaseous pollution.

- P.8.1. The methods used in air pollution control can also be classified according to the technology applied:
 - 1. By changing the distribution pattern of the pollution. This method could, in principle, be used to solve all local and regional air pollution problems, but it has found its widest application in particulate pollution.
 - 2. By using alternative technology to eliminate the problem.
 - 3. By removing the pollutants. Distinction should be made between particulate control technology and gas and vapour control technology.

Emission is the output from a source of pollution. It might be indicated as mass or volume per unit of time or per unit of production. If it is given as a concentration unit, e.g. mg per m^3 , it is also necessary to know the number of m^3 discharged per unit of time, or the number of m^3 polluted air produced per unit of production.

Imission is the input of pollutants to a given area. It might be indicated as mg per m^2 and time for particulate matter or as a concentration unit for gaseous pollutants.

Correspondingly, legislation will distinguish between emission standards and air quality standards respectively (see 8.6.1. for

further details).

Particulate control technology is discussed in sections 8.2.5 - 8.2.10 in context with particulate pollution, although this technology has also found application for the control of other pollutants.

Gas and vapour technology is dealt with under problems of industrial air pollution, but it has also found application in other areas.

8.2. PARTICULATE POLLUTION.

8.2.1. Sources of particulate pollution.

When considering particulate pollution, the source should be categorized with regard to contaminant type. **Inert particulates** are distinctly different from **active solids** in the nature and type of their potentially harmful human health effects. *Inert particulates comprise solid* airborne material, which does not react readily with the environment and does not exhibit any morphological changes as a result of combustion or any other process. Active solid matter is defined as particulate material which can be further oxidized or *which reacts chemically* with the environment or the receptor. Any solid material in this category can, depending on its composition and size, be more harmful than inert matter of similar size.

A closely related group of emissions are from **aerosols**, which are droplets of liquids, generally below 5 μ m. They can be oil or other liquid pollutants (e.g. freon) or may be formed by condensation in the atmosphere.

Fumes are condensed metals, metal oxides or metal halides, formed by industrial activities, predominantly as a result of pyrometallurgical processes; melting, casting or extruding operations.

Products of incomplete combustion are often emitted in the form of particulate matter. The most harmful components in this group are often those of **particulate polycyclic organic matter** (PPOM). These materials are homologues and derivatives of benz-a-pyrene.

Natural sources of particulate pollution are sandstorms, forest fires and vulcanic activity. The major sources in towns are vehicles, combustion of fossil fuel for heating and production of electricity, and industrial activity.

The total global emission of particulate matter is in the order of 10⁷ t per year.

8.2.2. The particulate pollution problem.

Particulate pollution is important with regard to health. The toxicity and

the size distribution are the most crucial factors.

Many particles are highly toxic, such as asbestos and those of heavy metals such as beryllium, lead, chromium, mercury, nickel and manganese. In addition, it must be remembered that particulate matter is able to absorb gases, so enhancing the effects of these components. In this context the **particle size distribution** is of particular importance, as particles greater than 10 μ m are trapped in the human upper respiratory passage and the specific surface (expressed as m² per g of particulate matter) increases with I/d, where d is the particle size. The adsorption capacity of particulate matter, expressed as g adsorbed per g of particulate matter, will generally be proportional to the surface area.

Table 8.1 lists some typical particle size ranges.

TABLE 8.1Typical particle size ranges

	μm
Tobacco smoke Oil smoke Ash Ammonium chloride smoke Powdered activated carbon Sulphuric acid aerosols	$\begin{array}{rrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrr$

However, *size* as well as *shape* and *density* must be considered. Furthermore, particle size has to be determined by two parameters: the mass median diameter, which is the size that divides the particulate sample into two groups of equal mass, i.e. the 50 percent point on a cumulative frequency versus particle size plot (see the examples in Fig. 8.1); and the geometric standard deviation, which is the slope on the curve in Fig. 8.1. It can be found from:

$$\beta = \frac{Y_{84.1}}{Y_{50}} = \frac{Y_{50}}{Y_{15.9}}$$
(8.1)

where the subscript numbers refer to the particle diameters at that percentage on the distribution plot. From the plot is found, in this case:

$$\beta = \frac{7.2}{1.7} = \frac{1.7}{0.4} = 4.25$$
 (8.2)

The particle size also determines the settling out rate of the particulate matters. Particles with a size of 1 μm have a terminal velocity of a few

metres per day, while particles with a size of 1 mm will settle out at a rate of about 40 m per day. Particles that are only a fraction of 1 μ m will settle out very slowly and can be in suspension in the atmosphere for a very long time.



Fig. 8.1. Particle diameter (log scale) plotted against the percentage of particles less than or equal to indicated size.

8.2.3. Control methods applied to particulate pollution.

All three classes of control methods mentioned in section 8.1 are applied to particulate pollution. Legislation has been introduced in an attempt to reduce particulate pollution. In only few cases, however, has the legislation effected a change to alternative technology.

P.8.2. Particulate control technology can offer a wide range of methods aimed at the removal of particulate matter from gas. These methods are: settling chambers, cyclones, filters, electrostatic precipitators, wet scrubbers and modification of particulate characteristics.

Table 8.2 summarizes these six technological methods, including their range of application, limitations, particle size range and the efficiencies

achieved in general use also.

Particulate pollution is also controlled by modifying the distribution pattern. This method is described in detail in the next paragraph.

		-										
Device	Ο pa si: (μ	otimum article ze m)	O co tra (g	ptimum incen- ation m ⁻³)	Ten ture itat (°C)	npe l ior	im- is	Air sis (m	re- tance m H ₂ O)	Eff (%	icie by	ncy weight)
Settling chambers	>	50	>	100	-30	to	350	< 2	25		< 5	0
Centrifuges	>	10	>	30	-30	to	350	<	50-100		< 8	0
Multiple centrifuges	>	5	>	30	-30	to	350	<	50-100		< 9	0
Filters	>	0.3	>	3	-30	to	250	>	15-100		> 9	9
Electrostatic precipitators	>	0.3	>	3	-30	to	500	< 2	20		< 9	9
Wet scrubbers	>	2-10	>	3-30	0	to	350	>	5-25		< 9	95-99

TABLE 8.2

Characteristics of particulate pollution control equipment

8.2.4. Modifying the distribution patterns.

Although emissions, gaseous or particulate, may be controlled by various sorption processes or mechanical collection, the effluent from the control device must still be dispersed into the atmosphere.

P.8.3. Atmospheric dispersion depends primarily on horizontal and vertical transport.

The horizontal transport depends on the turbulent structure of the wind field. As the wind velocity increases so does the degree of dispersion and there is a correspondingly decrease in the ground level concentration of the contaminant at the receptor site.

The emissions are mixed into larger volumes, of air and the diluted emission is carried out into essentially unoccupied terrain away from any receptors. Depending on the wind direction, the diluted effluent may be funnelled down a river valley or between mountain ranges. Horizontal transport is sometimes prevented by surrounding hills forming a natural pocket for locally generated pollutants. This particular topographical situation occurs in the Los Angeles area, which suffers heavily from air pollution.

The vertical transport depends on the rate of changes of ambient temperature with altitude. The dry adiabatic lapse rate is defined as a decrease in air temperature of 1°C per 100 m. This is the rate at which, under natural conditions, a rising parcel of unpolluted air will decrease in temperature with elevation into the troposphere up to approximately 10,000 m. Under so-called isothermal conditions the temperature does not change with elevation. Vertical transport can be hindered under stable atmospheric conditions, which occur when the actual environmental lapse rate is less than the dry adiabatic lapse rate. A negative lapse rate is an increase in air temperature with latitude. This effectively prevents vertical mixing and is known as inversion.



Fig. 8.2. Stack gas behaviour under various conditions. A) Strong lapse (looping), B) Weak lapse (coning), C) Inversion (fanning), D) Inversion below, lapse aloft (lofting), E) Lapse below, inversion aloft (fumigation).

These different atmospheric conditions (U.S.DHEW 1969) are illustrated in Fig. 8.2, where stack gas behaviour under the various conditions is shown. Further explanations are given in Table 8.3.

TABLE 8.3Various atmospheric conditions

Strong lapse (looping)	Environmental lapse rate > adiabatic lapse rate
Weak lapse (coning)	Environmental lapse rate < adiabatic lapse rate
Inversion (fanning)	Increasing temperature with height
Inversion below lapse aloft (lofting)	Increasing temperature below, app. adiabatic lapse rate aloft
Lapse below, inversion aloft (fumigation)	app. adiabatic lapse rate below, increasing temperature aloft



Fig. 8.3. Distribution of emission from stack of different heights under coning conditions. A) height 0 m, B) height 50 m, C) height 75 m.

Fig. 8.3 illustrates the distribution of material emitted from a stack at three different heights under coning conditions. The figure demonstrates that

P.8.4. the distribution of particulate material is more effective the higher the stack.

The maximum concentration, C_{max} , at ground level can be shown to be approximately proportional to the emission and to follow approximately this expression:

$$C_{max} = k \frac{Q}{H^2}$$
(8.3)

where Q is the emission (expressed as g particulate matter per unit of time), H is the effective stack height and k is a constant.

The definition of the effective stack height is illustrated in Fig. 8.4 and it can be calculated from the following equation:

$$H = h + 0.28 * V_{s} * D_{s} [1.5 + 2.7 \frac{T_{s} - 273}{T_{s}} * D_{s}] (8.4)$$

where

 V_s = stack exit velocity in m per second D_s = stack exit inside diameter in m T_s = stack exit temperature in degree Kelvin h = physical stack height above ground level in m

H = effective stack height in m



Fig. 8.4. Effective stack height $H = h + \Delta h$.

These equations explain why a lower ground-level concentration is obtained when many small stacks are replaced by one very high stack. In addition to this effect, it is always easier to reduce and control one large emission than many small emissions, and it is more feasible to install and apply the necessary environmental technology in one big installation.

Example 8.1.

Calculate the concentration ratio of particulate material in cases A and B, given that the total emission is the same.

A: 100 stacks H = 25 m

B: 1 stack H = 200 m

Solution:

Ratio =
$$\frac{200^2}{25^2}$$
 = 64

8.2.5. Settling chambers.

Simple gravity settling chambers, such as the one shown in Fig. 8.5, depend on gravity or inertia for the collection of particles. Both forces increase in direct proportion to the square of the particle diameter, and the performance limit of these devices is strictly governed by the particle settling velocity.



Fig. 8.5. Simple gravity settling chamber.

The pressure drop in mechanical collectors is low to moderate, 1-25 cm water in most cases. Most of these systems operate dry but if water is added it performs a secondary function by keeping the surface of the collector clean and washed free of particles.

The settling or terminal velocity can be described by the following expression, which has general use:

$$V_t = (\partial_p - \partial) g \frac{d_p^2}{18\mu}$$
(8.5)

where

V, = terminal velocity

- $\partial_{\mathbf{p}}$ = particle density
- ∂ = gas density
- d_p = particle diameter
- μ = gas viscosity

This is the equation of Stokes' law, and is applicable to $N_{Re} < 1.9$ where $N_{Re} = d_p + V_t + \frac{\partial}{\mu}$ (8.6)

The intermediate equation for settling can be expressed as:

$$V_{t} = \frac{0.153 * g^{0.71} * d_{p}^{1.14} (\partial_{p} - \partial)^{0.71}}{\partial^{0.29} * \mu^{0.43}}$$
(8.7)

This equation is valid for Reynolds numbers between 1.9 and 500, while the following equation can be applied above $N_{Re} = 500$ and up to 200,000:

$$V_t = 1.74 (d_p * g - \frac{(\partial_p - \partial)}{\partial})^{1/2}$$
 (8.8)

The settling velocity in these chambers is often in the range 0.3-3 m per second. This implies that for large volumes of emission the settling velocity chamber must be very large in order to provide an adequate residence time ofr the particles to settle. Therefore, the gravity settling chambers are not generally used to remove particles smaller than 100 μ m (= 0.1 mm). For particles measuring 2-5 μ m the collection efficiency will most probably be as low as 1-2 percent.

A variation of the simple gravity chamber is the baffled separation chamBer. The baffles produce a shorter settling distance, which means a shorter retention time.

Equations (8.5) - (8.8) can be used to design a settling chamber, and this will be demonstrated by use of equation (8.5).

If it is assumed that (8.5) applies, an equation is available for calculating the minimum diameter of a particle collected at 100% theoretically efficiency in a chamber of length L. In practice, some reentrainment will occur and prevent 100% efficiency. We have:

$$\frac{v_t}{H} = \frac{v_h}{L}$$
(8.9)

where H is height of the settling chamber (m), L length of the settling chamber (m) and v_h is the horizontal flow rate (m s⁻¹).

Solving for v_t and substitution into equation (8.5) yields

$$\frac{v_{h} \cdot H}{L} = \frac{g(\partial_{p} \cdot \partial) d_{p}^{2}}{18\mu}$$

 $\partial_p >> \partial$ and this equation gives the largest size particle that can be removed with 100% efficiency in a settling chamber:

$$d_{p} = \left(\frac{-18\mu v_{h} * H}{Lg * \partial_{p}}\right)^{1/2}$$
(8.10)

A correction factor of 1.5 - 3 is often used in equation (8.10).

Example 8.2.

Find the minimum size of particle that can be removed with 100% efficiency from a settling chamber with a length of 10 m and a height of 1.5 m. The horizontal velocity is 1.2 m s^{-1} and the temperature is 75°C. The specific gravity is 1.5 of the particles. A correction factor of 2 is suggested.

Solution:

At 75°C, see appendix 8, μ is 2.1 • 10⁻⁵ kg m⁻¹ s⁻¹

$$d_{p} = \left(2\frac{18\mu v_{h} \cdot H}{1 \cdot g \cdot \partial_{p}}\right)^{1/2} = 2\left(\frac{-18 \cdot 2.1 \cdot 10^{-5} \cdot 1.2 \cdot 1.5}{9.81 \cdot 10 \cdot 1500}\right)^{1/2}$$

$$d_{p} = 96.2 \,\mu$$

8.2.6. Cyclones.

P.8.5. Cyclones separate particulate matter from a gas stream by transforming the inlet gas stream into a confined vortex. The mechanism involved in cyclones is the continuous use of inertia to produce a tangential motion of the particles towards the collector walls.

The particles enter the boundary layer close to the cyclone wall and loose kinetic energy by mechanical friction, see Fig. 8.6. The forces are involved: the centrifugal force imparted by the rotation of the gas stream and a drag force, which is dependent on the particle density, diameter, shape, etc. A hopper is built at the bottom. If the cyclone is too short, the maximum force will not be exerted on some of the particles, depending on their size and corresponding drag forces (Leith and Licht, 1975). If, however, the cyclone is too long, the gas stream might reverse its direction and spiral up the centre.



It is therefore important to design the cyclone properly. The hopper must be deep enough to keep the dust level low.

The efficiency of a cyclone is described by a graph similar to Fig. 8.7, which shows the efficiency versus the relative particle diameter, i.e. the actual particle diameter divided by D_{50} , which is defined as the diameter corresponding to 50 percent efficiency. D_{50} can be found from the following equation:

$$D_{50} = K^{*} \left(\frac{\mu D_{c}}{V_{c}^{*} \partial_{p}} \right)^{1/2}$$
(8.11)

where

 D_c = diameter of cyclone V_c = inlet velocity

- ∂_{p} = density of particles
- μ = gas viscosity
- K = a constant dependent on cyclone performance



Fig. 8.7. Efficiency plotted against relative particle diameter.

If the distribution of the particle diameter is known, it is possible from such a graph as in Fig. 8.7 to calculate the total efficiency:

$$eff_{T} = \sum m_{i} \cdot eff_{i}$$
 (8.12)

where

 m_i = the weight fraction in the i.th particle size range eff_i = the corresponding efficiency

The pressure drop for cyclones can be found from:

$$\Delta p = N * \frac{V_c^2}{2g}$$
 (8.13)

From equations (8.11) and (8.13) it can be concluded tabt higher efficiency is obtained without increased pressure drop if D_c can be decreased with velocity V_c maintained. This implies that a battery of parallel coupled

small cyclones will work more effectively than one big cyclone. Such cyclones batteries are available as blocks, and are known as multiple cyclones.

Compared with settling chambers, cyclones offer a higher efficiency for particles below $50\mu m$ and above 2-10 μm , but involve a greater drop.

Example 8.3.

Determine D_{50} for a flow stream with a flow rate of 7 m s⁻¹, when a cyclone with a diameter of 2 m is used and a battery of cyclones with diameters of 0.24 m are used. Air temperature is 75°C and the particle density is 1.5 g ml⁻¹. K can be set to 0.2. Find also the efficiencies for particles with a diameter of 5µm.

Solution:

1) $D_{50} = K \frac{\mu^* D_c}{v_c \cdot \partial_p} = 0.2 \frac{2.1 \cdot 10^{-5} \cdot 2}{7 \cdot 1500} = 12.7 \,\mu\text{m}$

2)
$$D_{50} = K \frac{\mu^* D_c}{v_c \cdot \partial_p} = 0.2 \frac{2.1 \cdot 10^{-5} \cdot 0.24}{7 \cdot 1500} = 4.4 \,\mu\text{m}$$

5 µm corresponds to a relative diameter of

2)
$$\frac{5}{4.4}$$
 = 1.14, the efficiency will be about 55% (see Fig. 8.7)

8.2.7. Filters.

Particulate materials are collected by filters by three mechanisms (Wong et al., 1956):

Impaction where the particles have so much inertia that they cannot follow the stream line round the fibre and thus impact on its surface (see Fig. 8.8).

Direct interception where the particles have less inertia and can barely follow the stream lines around the obstruction.

Diffusion, where the particles are so small (below $1\mu m$) that their

individual motion is affected by collisions on a molecular or atomic level. This implies that the collection of these fine particles is a result of random motion.



Fig. 8.8. Particle capture mechanism. A) Impaction. B) Direct interception. C) Diffusion.

Different flow patterns can be used, as demonstrated in Fig. 8.9. The types of fibres used in fabric filters range from natural fibres, such as cotton and wool, to synthetics (mainly polyesters and nylon), glass and stainless steel.

Some properties of common fibres are summarized in Table 8.4. As seen, cotton and wool have a low temperature limit and poor alkali and acid resistance, but they are relatively inexpensive. The selection of filter medium must be based on the answer to several questions (Pring, 1972 and Rullman, 1976):

What is the expected operating temperature?

Is there a humidity problem which necessitates the use of a hydrophobic material, such as, e.g. nylon?

How much tensile strength and fabric permeability are required? How much abrasion resistance is required?



Fig. 8.9. Flow pattern of filters.

Permeability is defined as the volume of air that can pass through 1 m^2 of the filter medium with a pressure drop of no more than 1 cm of water.

The filter capacity is usually expressed as $m^3 air per m^2$ filter per minute. A typical capacity ranges between 1 and 5 m^3 per m² per minute.

The pressure drop is generally larger than for cyclones and will in most cases, be 10-30 cm of water, depending on the nature of the dust, the cleaning frequency and the type of cloth.

In Fig. 8.10 the pressure drop is plotted against the mass of the dust deposit and as can be seen, the maximum pressure drop is strongly dependent on the cleaning frequency.

Properties of	nores				
Fabric	Acid res	Alkali istanc	Fluoride e	Tensile strength	Abrasion resistance
Cotton Wool Nylon Acrylic Polypropylene Orlon Dacron Teflon	poor good good good good good excellent	good poor good fair fair good good excellent	poor poor poor poor poor fair fair good	medium poor good medium very good medium good good	very good fair excellent good good yery good fair





Fig. 8.10. Pressure drop versus dust deposit. A) represents assistance of clean fabric.

There are several specific methods of filter cleaning. The simplest is *backwash*, where dust is removed from the bags merely by allowing them to collapse. This is done by reverting the air flow through the entire compartment. The method is remarkable for its low consumption of energy.

Shaking is another low-energy filter-cleaning process, but it cannot be used for sticky dust. The top of the bag is held still and the entire tube sheath at the bottom is shaken.

The application of *blow rings* involves reversing the air flow without bag collapse. A ring surrounds the bag; it is hollow and supplied with compressed air to direct a constant steam of air into the bag from the outside.

The pulse and improved jet cleaning mechanism involves the use of a high velocity, high pressure air jet to create a low pressure inside the bag and induce an outward air flow and so clean the bag by sudden expansion and reversal of flow. In some cases as a result of electrostatic forces, moisture on the surface of the bags and a slight degree of hygroscopicity of the dust itself, the material forms cakes that adhere tightly to the bag. In this case the material must be kept drier and a higher temperature on the incoming dirty air stream is required.

Filters are highly effecient even for smaller particles (0.1 - 2 m), which explains their wide use as particle collection devices.

8.2.8. Electrostatic precipitators.

The electrostatic precipitator consists of four major components:

- 1. A gas-tight shell with hoppers to receive the collected dust, inlet and outlet, and an inlet gas distributor.
- 2. Discharge electrodes.
- 3. Collecting electrodes.
- 4. Insulators.

The principles of electrostatic precipitators are outlined in Fig. 8.11.

P.8.6. The dirty air stream enters filter, where a high, 20-70 kV, usually negative voltage exists between discharge electrodes. The particles accept a negative charge and migrate towards the collecting electrode.

The efficiency is usually expressed by use of Deutsch's equation (see discussion incl. correction of this equation in Gooch and Francis, 1975):

$$(\frac{W^* I}{\partial^* v})$$

$$1 - n = e^{(8.14)}$$

where

n = the efficiency
 W = velocity of particles (migration velocity)
 i = effective length of electrode systems
 ∂ = distance between electrodes
 v = gas velocity

The migration velocity can be found from (see also Rose and Wood, 1966):

$$W = \frac{E_{o} \cdot E_{p} \cdot d_{p} \cdot C}{4\pi\mu}$$
(8.15)

where E_{o} = charging field strength Vm⁻¹

$$C = 1 + \frac{2.5 i}{d_p} + \frac{0.84}{d_p} \exp\left(\frac{0.435 d_p}{i}\right)$$

$$E_p = \text{collecting field Vm}^{-1}$$

$$I = \text{free path of gas molecules, m}$$

$$d_p = \text{particle diameter, m}$$

μ = particle gas viscosity, cp

This implies a relationship between migration velocity and particle diameter similar to the graph in Fig. 8.12 (see White, 1974, and Dismukes, 1975).



Fig. 8.11. The dust is precipitated on the electrode P. E has a high, usually negative voltage and emits a great number of electrons which give the dust particles a negative charge. The dust particles will therefore be attracted to P.

The operation of an electrostatic precipitator can be divided into three steps:

- 1. The particles accept a negative charge.
- 2. The charged particles *migrate towards the collecting electrode* due to the electrostatic field.
- 3. The collected dust *is removed from the collecting electrode* by shaking or vibration, and is collected in the hopper.



Fig. 8.12. A typical graph of migration velocity versus particle diameter.

Resistivity, r, is the specific electrical resistance measured in ohm m. It determines the ability of a particle to accept a charge. The practical resistivity can cover a wide range of about four orders of magnitude, in which varying degrees of collection efficiencies exist for different types of particles. Fig. 8.13 demonstrates the effect of resistivity on migration velocity.

The resistivity depends on the chemical nature of the dust, the temperature and the humidity.

Electrostatic precipitators have found a wide application in industry. As the cost is relatively high, the airflow should be at least 20,000 m³ h⁻¹; volumes as large as 1,500,000 m³ h⁻¹ have been treated in one electrostatic precipitator.

Very high efficiencies are generally achieved in electrostatic precipitators and emissions as low as 25 mg m⁻³ are quite common. The pressure drop is usually low compared with other devices - 25 mm water at the most. The energy consumption is generally 0.15-0.45 Wh m⁻³ h⁻¹.



Fig. 8.13. W versus log resistivity.

- Wet scrubbers. 8.2.9.
- A scrubbing liquid, usually water, is used to assist P.8.7. separation of particles or a liquid aerosol from the gas operational range for particle phase. The removal includes material less than 0.2 μ m in diameter to the largest particles that can be suspended in air.

Four major steps are involved in collecting particles by wet scrubbing. First, the particles are moved to the vicinity of the water droplets, which are 10-1,000 times larger. Then the particles must collide with the droplets. In this step the relative velocity of the gas and the liquid phases is very important: If the particles have an overhigh velocity in relation to the liquid they have so much inertia that they keep moving, even when they meet the front edge of the shock wave, and either impinge on or graze the droplets. A scrubber is no better than its ability to bring the particles directly into contact with the droplets of the scrubber fluid. The next step is adhesion, which is directly promoted by surface tension. Particles cannot be retained by the droplets unless they can be wetted and thus incorporated into the droplets. The last step is the removal of the droplets containing the dust particles from the bulk gas phase.

Scubbers are generally very flexible. They are able to operate under peak loads or reduced volumes and within a wide temperature range (Onnen, 1972).

They are smaller and less expensive than dry particulate removal

devices, but the operating costs are higher. Another disadvantage is that the pollutants are not collected but transferred into water, which means that the related water pollution problem must also be solved (Hanf, 1970).

Several types of wet scrubbers are available (Wicke, 1971), and their principles are outlined below:

1. **Chamber scrubbers** are spray towers and spray chambers which can be either round or rectangular. Water is injected under pressure though nozzles into the gas phase. A simple chamber spray scrubber is shown in Fig. 8.14.



Fig. 8.14. Chamber scrubber.

- 2. **Baffle scrubbers** are similar to a spray chamber but have internal baffles that provide additional impingement surfaces. The dirty gas is forced to make many turns to prevent the particles from following the air stream.
- 3. Cyclonic scrubbers are a cross between a spray chamber and a cyclone. The dirty gas enters tangentially to wet the particles by forcing its way through a swirling water film onto the walls. There the particles are captured by impaction and are washed down the walls to the sump. The saturated gas rises through directional vanes, which are used solely to impact rotational motion to the gas phase. As a result of this motion the

gas goes out though a demister for the removal of any included droplets.

4. Submerged orifice scrubbers are also called gas-induced scrubbers. The dirty gas is accelerated over an aerodynamic foil to a high velocity and directed into a pool of liquid. The high velocity impact causes the large particles to be removed into the pool and creates a tremendous number of spray droplets with a high amount of turbulence. These effects provide intensive mixing of gas and liquid and thereby a very high interfacial area. As a result reactive gas absorption can be combined with particle removal. The principles of this operation are demonstrated in Fig. 8.15.



Fig. 8.15. Principle of submerged orifice scrubber.

- 5. The ejector scrubber is a water jet pump (see Fig. 8.16). The water is pumped through a uniform nozzle and the dirty gas is accelerated by the action of the jet gas. The result is aspiration of the gas into the water by the Bernoulli principle and, accordingly, a lowered pressure. The ejector scrubber can be used to collect soluble gases as well as particulates.
- 6. The **venturi scrubber** involves the acceleration of the dirty gas to 75-300 m min⁻¹ through a mechanical constriction. This high velocity causes any water injected just upstream of, or in, the venturi throat to be sheared off the walls or nozzles and atomized. The droplets are usually 5-20 μ m in size and form into clouds from 150-300 μ m in diameter, depending on the gas velocity. The scrubber construction is similar to that of the ejector scrubber, but the jet pump is replaced by a

venturi constriction.

7. **Mechanical scrubbers** have internal rotating parts, which break up the scrubbing liquid into small droplets and simultaneously create turbulence.



Fig. 8.16. Principle of ejector scrubber.

- 8. Charged-droplet scrubbers have a high voltage ionization section where the corona discharge produces air ions (as in electrostatic precipitators; see 8.2.8). Water droplets are introduced into the chamber by use of spray nozzles or similar devices. The additional collection mechanism provided by the induction of water droplets increases the collection efficiency.
- 9. Packed-bed scrubbers have a bottom support grid, and an top retaining grid (see Fig. 8.17). The fluid (often water or a solution of alkali or acid) is distributed as shown in the figure over the top of the packed section, while the gas enters below the packing. The flow is normally counter current. Packed-bed scrubbers offer the possibility of combining gas absorption with removal of particulate material. The pressure drop is often in the order of 3 cm water per m of packing. If the packing consists of expanded fibre, the bed scrubber is known as a fibre-bed scrubber.

The packed-bed scrubber has a tendency to clog under high particulate

loading, which is its major disadvantage.

Common packings used are saddles, rings, etc., like those used in absorption towers.



Some important parameters for various scrubbers are plotted in Fig. 8.18, which demonstrates the relationship between pressure drop, energy consumption and D_{50} (the diameter of the particles removed at 50 percent efficiency).

8.2.10. Modification of particulate characteristics.

P.8.8. The human health hazards associated with particulate emission are directly related to the mass median diameter, the influence of which increases with the solubility and toxicity of the pollutant. Particle shape is another significant characteristic of particulate emission.



Fig. 8.18. Relationship between D_{50} , pressure drop (mm H_2O) and energy consumption. A: Packed-bed scrubber. B: Baffled scrubber. C: Venturi scrubber.

Although it is not important in electrostatic precipitators and has very little effecto on cyclone performance, it has a considerable effect on the choise of fabric filter - at least for some applications.

- P.8.9. Particles are conditioned merely to increase their size and thereby increase their ease of collection. Particle conditioning involves two principle mechanisms: agglomeration and condensation.
- P.8.10. Condensation can be achieved by adjusting the temperature of the water content of the gas phase.

The degree of particle growth obtained by condensation is dependent on four factors:

- 1. The number of nucleation centres.
- 2. The kinetics of particle nucleation. The surface forces and the character

of the material itself is of importance here. Such properties as surface tension, wetability, hydroscopicity and hydrophobicity effect the rate of particle growth.

- 3. The enlargement of the particles into droplets.
- 4. The degree of mixing between water and particles.

Condensation is carried out by bringing the gas close to the dew point. Saturation can be attained by spraying water into the gas by adding steam. Another possibility is to cool the gas to the dew point either by external cooling or by adiabatic expansion.

Prakash and Murray (1975) have reported on conditioning of process effluent containing talcum powder, under 5 μ m in diameter. By adding steam it was possible to reduce the emission by four to five times. Without conditioning the collection efficiency of particles smaller than 1 μ m was nil, while with steam injection a 99 percent collection efficiency of particles above 0.3 μ m was obtained.

P.8.11. Agglomeration of particles occurs in nature due to brownian motion.

The natural rate of agglomeration is, however, too slow under static or laminar flow conditions. If coagulation could be enhanced it would be possible to use a relative inexpensive control element for their removal. At present two techniques are used: **sonic agglomeration** (Dibbs and Marier, 1975) and **coagulation of charged particles**. The former method is more often used in practice. With this technique, particles need to be in insolation chambers for only a few seconds at intensities at 160-170 dB. Sonic aggregation can be *applied to any aerosol or solid particles*, but the energy requirement is relatively high and the high noise level must be eliminated by suitable insulation.

8.3. THE AIR POLLUTION PROBLEMS OF CARBON DIOXIDE, CARBON HYDRIDES AND CARBON MONOXIDE.

8.3.1. Sources of pollutants.

All types of fossil fuel will produce carbon dioxide on combustion, which is used in the photosynthetic production of carbon-hydrates. As such, carbon dioxide is harmless and has no toxic effect, whatever the concentration levels. However, since an increased carbon dioxide concentration in the atmosphere will increase absorption of infrared radiation, the heat balance of the earth will be changed (see Part A, section 2.4 for a detailed discussion).

P.8.12. Carbon hydrides are the major components of oil and gas, and incomplete combustion will always involve their emission. Partly oxidized carbon hydrides, such as aldehydes and organic acids, might also be present.

The major source of carbon hydride pollution is motor vehicles.

P.8.13. In reaction with nitrogen oxides and ozone they form the so-called photochemical smog, which consists of several rather oxidative compounds, such as peroxyacyl nitrates and aldehydes.

In areas where solar radiation is strong and the atmospheric circulation small, the possibility of smog formation increases, as the processes are *initiated by ultraviolet radiation*.

Typical concentration in American cities are shown in Table 8.5. Values from unpolluted areas are included for comparison.

TABLE 8.5

Typical concentrations in American cities (ppm) compared with values from a rural area

	Washing- ton	St. Louis	Phila- delphia	Denver	Chicago	Cincin- nati	Rural area
NO							
Annual average	0.04	0.03	0.06	0.04	0.10	0.004	0.1
Ma. 5 min. value	1.15	0.61	1.98	0.89	0.74	1.18	0.05
٥٥,							
Annual average	0.04	0.03	0.04	0.03	0.06	0.04	0.005
Max. 5 min. value	0.19	0.21	0.29	0.35	0.35	0.30	0.01
Carbon hydrides							
Annual average	2.4	3.0	2.5	2.4	2.8	0.6	0.05
Max. 5 mun. value	14.5	14.3	14.4	19.1	14.9	12.8	0.6
co							
Annual avearge	3	6	7	8	13	5	0.2
Max. 5 min. value	47	68	47	63	66	32	2

P.8.14. Incomplete combustion produces carbon monoxide. By regulation of the ratio oxygen to fuel a more complete combustion can be obtained, but the emission of carbon monoxide cannot be totally avoided.

Motor vehicles are also the major source of carbon monoxide pollution. On average, 1 litre of gasoline (petrol) will produce 200 litres of carbon monoxide, while it is possible to minimize the production of this pollutant by using diesel instead of gasoline.

The annual production of carbon monoxide is more then 200 million tons, of which 50 percent is produced by the U.S.A. alone.

In most industrial countries more than 85 percent of this pollutant originates from motor vehicles.

8.3.2. The pollution problem of carbon dioxide, carbon hydrides and carbon monoxide.

As mentioned carbon dioxide is not toxic, but its problem as a pollutant is related solely to its influence on the global energy balance. As this problem is rather complex it will not be dealt with here. For a comprehensive discussion, see Part A.

Carbon hydrides, partly oxidized carbon hydrides and the compounds of the photochemical smog are all *more or less toxic* to man, animals and plants. The photochemical smog *reduces visibility, irritates the eyes and causes damage to plants* with immense economical consequences, for example for fruit and tobacco plantations. It is also able *to decompose rubber and textiles*.

Carbon monoxide is strongly toxic as it reacts with haemoglobin and thereby reduces the blood's capacity to take up and transport oxygen. Ten percent of the haemoglobin occupied by carbon monoxide will produce such symptoms as headache and vomitting. A more detailed discussion of the relationship between carbon monoxide concentration, exposure time and effect is given in section 2.12. However, it should be mentioned here that smoking also causes a higher carboxyhaemoglobin concentration. An examination of policemen in Stockholm has shown that non-smokers had 1.2 percent carboxyhaemoglobin, while smokers had 3.5 percent.

8.3.3. Control methods applied to carbon dioxide, carbon hydride and carbon monoxide pollution.

Carbon dioxide pollution is inevitable related to the use of fossil fuels. Therefore, it can only be solved by the use of other sources of energy.

Legislation is playing a major role in controlling the emission of carbon hydrides and carbon monoxide. As motor vehicles are the major source of these pollutants, control methods should obviously focus on the possibilities of reducing vehicle emission. The methods available today are: 1. Motor technical methods.

2. Afterburners.

3. Alternative energy sources.

The first method is based upon the graphs shown in Fig. 8.19, where the relationship between the composition of the exhaust gas and the air/fuel ratio is illustrated. As seen, a higher air/fuel ratio results in a decrease in the carbon hydride and carbon monoxide concentration, but to achieve this better distribution of the fuel in the cylinder is required, which is only possible by construction of other gasification systems.



Fig. 8.19. Example of the relationship between the composition of exhaust gas and the air-fuel ratio. CH_x = carbon hydrides.

At present two types of afterburners are in use - thermal and catalytic afterburners. In the first type the combustible material is raised above its autoignition temperature and held there long enough for complete oxidation of carbon hydrides and carbon monoxide to occur. This method is used on an industrial scale (Waid, 1972 and 1974) when low-cost purchased or diverted fuel is available; in vehicles a manifold air injection system is used.

Catalytic oxidation occurs when the contaminant-laden gas stream is passed through a catalyst bed, which initiates and promotes oxidation of the combustible matter at lower temperature than would be obtained in thermal oxidation. The method is used on an industrial scale for the destruction of trace solvents in the chemical coating industry. Vegetable and animal oils can be oxidized at 250-380°C by catalytic oxidation. The exhaust fumes from chemical processes, such as ethylene oxide, methyl methacrylate, propylene, formaldehyde and carbon monoxide, can easily be catalytically incinerated at even lower temperatures.

The application of catalytic afterburners in motor vehicles presents some difficulties due to poisoning of the catalyst by lead. With the decreasing lead concentration in gasoline it is becoming easier to solve that problem, and the so-called double catalyst system is now finding a wide application. This system is able to reduce nitrogen oxides and oxidize carbon monoxide and carbon hydrides simultaneously.

Application of alternative energy sources is still at a preliminary stage. The so-called *Sterling motor* is one alternative, as it gives a more complete combustion of the fuel. Most interest has, however, been devoted to *electric vehicles*. Table 8.6 gives a survey of the suggested types of accumulator (battery). In spite of intensive research it is still a problem to produce an accumulator with a sufficiently high energy density to give the vehicle an acceptable radius action.

Fuel cells are able to produce electricity directly form fuel and Table 8.7 mentions the most realistic suggestions so far.

TABLE 8.6 Accumulator types

System	Energy density (Whkg ⁻¹)	Weight/effect ratio (KG kW ⁻¹)
Li - Cl	325	1.5
Zn - Air	130	14
Ag - Zn	110	2
Na - S	325	5
Pb-accumulator (conventional)	22	9

TABLE 8.7 Fuel cells

Fuel	Catalyst	Energy density (Whkg ⁻¹)	Weight/effect ratio (kg kW ⁻¹)	Volume/effect ratio (I kW ⁻¹)
Liquid, O ₂ and H ₂	Pt	2000	31	51
Air-Ammonium	Ni	1450	40	130
Liquid, air-carbon- hydrides	Pd-Ag	850	70	125

8.4. THE AIR POLLUTION PROBLEM OF SULPHUR DIOXIDE.

- 8.4.1. The sources of sulphur dioxide pollution.
- P.8.15. Fossil fuel contains approximately 2 to 5 per cent sulphur, which is oxidized by combustion to sulphur dioxide. Although fossil fuel is the major source, several industrial processes produce emissions containing sulphur dioxide, for example mining, the treatment of sulphur containing ores and the production of paper from pulp.

The total global emission of sulphur dioxide is approximately *80 million tons per year*, of which U.S.A. and Europe produce more than two-thirds. Emission figures for industrialized areas in Europe are given in Table 8.8.

TABLE 8.8SO2-emission in Europe (106 t)

	1965	1975	1985
France	2.3	2.7	3.3
Netherlands	0.9	1.3	1.9
Great Britain	6.4	5.5	5.3
Germany (West)	3.2	3.3	3.5
Scandinavia	1.0	1.7	2.5

The concentration of sulphur dioxide in the air is relatively easy to measure, and sulphur dioxide has been used as an indicator component. High values recorded by inversion are typical.

8.4.2. The sulphur dioxide pollution problem.

Sulphur dioxide is oxidized in the atmosphere to sulphur trioxide, which forms sulphuric acid in water. Since sulphuric acid is a strong acid it is easy to understand that sulphur dioxide pollution indirectly causes corrosion of iron and other metals and is able to acidify aquatic ecosystems (these problems have been covered in detail in section 4.7).

The health aspects of sulphur dioxide pollution are closely related to those of particulate pollution. The gas is strongly adsorbed onto particulate matter, which transports the pollutant to the bronchi and lungs. (The relationship between concentration, effect and exposure time has already been discussed in sections 2.12, 2.13 and 4.7).

In Sweden the corrosion problem is estimated to cost more than 200 million dollars per year.

8.4.3. Control methods applied to sulphur dioxide.

Clean Air Acts have been introduced in all industrialized countries during the last decade. Table 8.9 illustrated some typical sulphur dioxide emission standards, although these may vary slightly from country to country.

TABLE 8.9 SO ₂ -emission	standards
Duration	Concentration (ppm)
Month 24 h 30 min.	0.05 0.10 might be exceeded once a month 0.25 might be exceeded 15 times per month (1% of the time)

The approaches used to meet the requirements of the acts, as embodied in the standards, can be summarized as follow:

- 1. Fuel switching from high to low sulphur fuels.
- 2. Modification of the distribution pattern use of tall stacks.
- 3. Abandonment of very old power plants, which have higher emission.
- 4. Flue gas cleaning.

Desulphurization of liquid and gaseous fuel is a well known chemical engineering operation.

In gaseous and liquid fuels sulphur either occurs as hydrogen sulphide or can react with hydrogen to form hydrogen sulphide. The hydrogen sulphide is usually removed by absorption in a solution of alkanolamine and then converted to elemental sulphur. The process in general use for this conversion is the so-called Claus process. The hydrogen sulphide gas is fired in a combustion chamber in such a manner that one-third of the volume of hydrogen sulphide is converted to sulphur dioxide. The products of combustion are cooled and then passed through a catalyst-packed converter, in which the following reaction occurs:

 $2H_{p}S + SO_{p} = 3S + 2H_{p}O$

(8.16)

The elemental sulphur has commercial value and is mainly used for the production of sulphuric acid.

Sulphur occurs in coal both as pyritic sulphur and as organic sulphur. Pyritic sulphur is found in small discrete particles within the coal and can be removed by mechanical means, e.g. by gravity separation methods. However, 20 to 70 per cent of the sulphur content of coal is present as organic sulphur, which can hardly be removed today on an economical basis. Since sulphur recovery from gaseous and liquid fuels is much easier than from solid fuel, which also has other disadvantages, much research has been and is being devoted to *the gasification or liquefaction of coal*. It is expected that this research will lead to an alternative technology that will solve most of the problems related to the application of coal, including sulphur dioxide emission.

Approach (2) listed above has already been mentioned in 8.2.4, while approach (3) needs no further discussion. The next paragraph is devoted to flue gas cleaning.

8.4.4. Flue gas cleaning of sulphur dioxide.

When sulphur is not or cannot be economically removed from fuel oil or coal prior to combustion, removal of sulphur oxides from combustion gases will become necessary for compliance with the stricter air pollution-control laws.

The chemistry of sulphur dioxide recovery presents a variety of choices and four methods should be considered:

- 1. Adsorption of sulphur dioxide on active metal oxides with regeneration to produce sulphur.
- 2. Catalytic oxidation of sulphur dioxide to produce sulphuric acid.
- 3. Adsorption of sulphur dioxide on charcoal with regeneration to produce concentrated sulphur dioxide.
- 4. Reaction of dolomite or limestone with sulphur dioxide by direct injection into the combustion chamber.

8.5. THE AIR POLLUTION PROBLEM OF NITROGENOUS GASES.

8.5.1. The sources of nitrogenous gases.

Seven different compounds of oxygen and nitrogen are known: N_2O , NO, NO_2 , NO_3 , N_2O_3 , N_2O_4 , N_2O_5 - often summarized as NO_x . From the point of view of air pollution maily NO (nitrogen oxide) and NO_2 (nitrogen dioxide) are of interest.

Nitrogen oxide is colourless and is formed from the elements at high temperatures. It can react further with oxygen to form nitrogen dioxide, which is a brown gas.

P.8.16. The major sources of the two gases are: nitrogen oxide -

combustion of gasoline and oil; nitrogen dioxide - combustion of oil, including diesel oil. In addition, a relatively small emission of nitrogenous gases originates from the chemical industry.

The total global emission is approximately 10 million tons per year. This pollution has only local or regional interest, as the natural global formation of nitrogenous gases in the upper atmosphere by the influence of solar radiation is far more significant than the anthropogenous emission.

As mentioned above, the nitrogen oxide is oxidized to nitrogen dioxide, although the reaction rate is slow - in the order of 0.007 h⁻¹. However, it can be acclerated by solar radiation.

Nitrogenous gases take part in the formation of smog, as the nitrogen in peroxyacyl nitrate originates from nitrogen oxides, see Table 9.14 in 9.4.3. They are highly toxic but as the global pollution problem is insignificant, local and regional problems can partially be solved by changing the distribution pattern (see 8.2.4).

The emission from motor vehicles can be reduced by the same methods as mentioned for carbon hydrides and carbon monoxide. As illustrated in Fig. 8.19, the air/fuel ratio determines the concentration of pollutants in the exhaust gas. An increase in the ratio will reduce the emission of carbon hydrides and carbon monoxide, but unfortunately, will increase the concentration of nitrogenous gases. Consequently, the selected air/fuel ratio will be a compromise.

As mentioned in 8.3.3, a *double catalytic afterburner* is available. It is able to reduce nitrogenous gases and simultaneously oxidize carbon hydrides and carbon monoxide. The application of alternative energy sources will, as for carbon hydrides and carbon monoxide, be a very useful control method for nitrogenous gases at a later stage (see 8.3.3).

Between 0.1 and 1.5 ppm of nitrogenous gases, of which 10 to 15 per cent consists of nitrogen dioxide, are measured in urban areas with heavy traffic. As an example, Table 8.5 shows concentrations measured in North American cities. On average the emission of nitrogenous gases is approximately 15 g per litre gasoline and 25 g per litre diesel oil. About toxicity of nitrogenous gases, see section 2.12.

8.5.2. The nitrogenous gas pollution problem.

Nitrogenous gases in reaction with water form nitrates which are washed away by rain water. In some cases this can be a significant source of eutrophication (see 6.3.1). For a shallow lake, for example, the increase in nitrogen concentration due to the nitrogen input from rain water will be rather significant. In a lake with a depth of 1.8 m and an annual precipitation of 600 mm, which is normal in many temperate regions, the annual input will be as much as 0.3 mg per litre.

8.5.3. Control methods applied to nitrogenous gases.

The methods used for control of industrial emission of nitrogenous gases, including ammonia, will be discussed in the next paragraph, but as pointed out above industrial emission is of less importance, although it might play a significant role locally.

The emission of nitrogenous gases by combustion of oil for heating and the production of electricity can hardly be reduced.

8.6. INDUSTRIAL AIR POLLUTION.

8.6.1. Overview.

The rapid growth in industrial production during the last decades has enhanced the industrial air pollution problem, but due to a more pronounced application of continuous processes, recovery methods, air pollution control, use of closed systems and other technological developments, industrial air pollution has, in general, not increased in proportion to production.

P.8.17. Industry displays a wide range of air pollution problems related to a large number of chemical compounds in a wide range of concentrations.

It is not possible in this context to discuss all industrial air pollution problems, but rather to touch on the most important problems and give an overview of the control methods applied today. Only the problems related to the environment will be dealt with in this context.

A distinction should be made between air quality standards, which indicate that the concentration of a pollutant in the atmosphere at the point of measurement shall not be greater than a given amount, and emission standards, which require that the amount of pollutant emitted from a specific source shall not be greater than a specific amount (see also section 8.1).

P.8.18. The standards reflect, to a certain extent, the toxicity of the particular component, but also the possibility for its uptake.

Here the distribution coefficient for air/water (blood) plays a role. The more soluble the component is in water, the greater the possibility for uptake. For example, the air quality standard for acetic acid, which is very soluble in water, is relatively lower than the toxicity of aniline, which is almost insoluble in water.

Table 8.10 gives a survey of the most important air pollutants, the industrial emission source and the average emission per unit of production.

TABLE	8.1	0
Industri	al	emission

Production	Pollutant	Emission kg(t product) ⁻¹
Sulphuric acid	SO_2 $SO_3 + H_2SO_4$	10 -30 0.6 - 6
Hydrochloric acid	HCI CI SO2 SO3	0.7 - 1.0 0 - 0.1 2 - 3 0.2 - 0.9
Phosphoric acid	HF	0.1 - 0.2
Ammonium	SO2 SO3 NH3 NOx	40 - 56 0 - 0.4 0 - 0.06 0 - 0.5
Nitric acid	NO _x	10 - 25
Sodium hydroxide + chlorine	Hg Cl₂	0.002 - 0.035 0.005 - 0.02
Cellulose (sulphite) Cellulose (sulphate)	SO ₂ SO ₂	25 - 65 10 - 25
Steel and iron	particulate	2 - 20
Cement	particulate	0.5 - 5
Asphalt	particulate	0.1 - 0.5

8.6.2. Control methods applied to industrial air pollution.

Since industrial air pollution covers a wide range of problems, it is not surprising *that all three classes of pollution control methods* mentioned in section 8.1 have found application: modification of the distribution pattern, alternative production methods and particulate and gas/vapour control technology.

All the methods mentioned in 8.2.4 to 8.2.10 and 8.4 are equally valid for

industrial air pollution control.

It is not possible to mention here all alternative production methods that have found application in industry. Generally, it can be stated that a switch from dry to wet methods will often eliminate an air pollution problem, but at the same time create a water pollution problem. In each case it must be estimated which of the two problems it is most difficult or costly to solve properly.

- P.8.19. In gas and vapour technology a distinction has to be made between condensable and non-condensable gaseous pollutants. The latter must usually be destroyed by incineration, while the condensable gases can be removed from industrial effluents by absorption, adsorption, condensation or combustion. Recovery is feasible by the first three methods.
- 8.6.3. Gas absorption.
- P.8.20. Absorption is a diffusional process that involves the mass transfer of molecules from the gas state to the liquid state along a concentration gradient between the two phases.

Absorption is a unit operation which is enhanced by all the factors generally affecting mass transfer; i.e. *high interfacial area, high solubility, high diffusion coefficient, low liquid viscosity, increased residence time, turbulent contact between the two phases and possibilities for reaction of the gas in the liquid phase.*

This last factor is often very significant and an almost 100 per cent removal of the contaminant is the result of such a reaction. Acidic components can easily be removed from gaseous effluents by absorption in alkaline solutions, and correspondingly alkaline gases can easily be removed from effluent by absorption in acidic solutions. Carbon dioxide, phenol or hydrogen sulphide are readily absorbed in alkaline solutions in accordance with the following processes:

$$CO_2 + 2NaOH - 2Na^+ + CO_3^{2-}$$
 (8.17)

$$H_2S + 2NaOH - 2Na^+ + S^2 + 2H_2O$$
 (8.18)

$$C_{6}H_{5}OH + NaOH - C_{6}H_{5}O^{-} + Na^{+} + H_{2}O$$
 (8.19)

Ammonia is readily absorbed in acidic solutions:

 $2NH_3 + H_2SO_4 - 2NH_4^+ SO_4^{2-}$

TABLE8.11Absorberreagents

KMnO ₄	Rendering, polycyclic organic matter
NaOCI	Protein adhesives
Cl ₂	Phenolics, rendering
Na ₂ SO ₃	Aldehydes
NaOH	CO ₂ , H ₂ S, phenol, Cl ₂ , pesticides
Ca(OH) ₂	Paper sizing and finishing
H ₂ SO ₄	NH ₃ , nitrogen bases

Table 8.11 gives a more comprehensive list of absorber reagents and their application.

Absorption is the inverse process of air stripping and the theory for this unit process (see 6.2.4) is equally valid for the absorption process. By means of air stripping an water pollution problem becomes an air pollution problem, while the absorption transforms an air pollution problem into a water pollution problem. However, both processes open up possibilities for recovery. Gas absorbers and reactive scrubbers are quite flexible in application, dependable and can be highly effective. They have a large capacity at a reasonable pressure drop, are easy to install and are able to control gases and particulates. Their space requirements are usually favourable compared wiht alternative control methods.

8.6.4. Gas adsorption.

P.8.21. Adsorption is the capture and retention of a component (adsorbate) from the gas phase by the total surface of the adsorbing solid (adsorbent). In principle the process is the same as that mentioned in 6.3.3, which deals with waste water treatment; the theory is equally valid for gas adsorption.

Adsorption is used to concentrate (often 20 to 100 times) or store contaminants until they can be recovered or destroyed in the most economical way.



Fig. 8.20. Adsorption isotherms, at 20°C: (1) Pinene, (2) Methyl mercaptane, (3) Benzene, (4) Pyridine, (5) Isovaleric acid; at 40°C: (6) Isovaleric acid.

Fig. 8.20 illustrates some adsorption isotherms applicable to practical gas adsorption problems. These are (as mentioned in 6.3.3) often described *as* either Langmuir's or Freundlich's adsorption isotherms.

Adsorption is *dependent on temperature*, as illustrated in Fig. 8.21 (in accordance with the theory outlined in 6.3.3). There are four major types of gas adsorbents, the most important of which is activated carbon, but also aluminium oxide (activated aluminia), silica gel and zeolites are used.

The selection of adsorbent is made according to the following criteria:

- 1. High selectivity for the component of interest.
- 2. Easy and economical to regenerate.
- 3. Availability of the necessary quantity at a reasonable price.



Fig. 8.21. Typical relationship: desorption versus time at three different temperatures for butane on activated carbon. (Adsorption temperature 52°C).

- 4. High capacity for the particular application, so that the unit size will be economical. Factors affecting capacity include total surface area involved, molecular weight, polarity activity, size, shape and concentration.
- 5. *Pressure drop*, which is dependent on the superficial velocity, as illustrated in Fig. 8.22, where the relationship between the pressure drop and the superficial velocity is shown for different mesh sizes of granular activated carbon.
- 6. Mechanical stability in the resistance of the adsorbent particles to attrition. Any wear and abrasion during use or regeneration will lead to an increase in bed pressure drop.
- 7. *Microstructure* of the adsorbent should, if at all possible, be *matched to the pollutant* that has to be collected.
- 8. the temperature, which, as illustrated in Figs. 8.20 and 8.21, has a profound influence on the adsorption process.

As already mentioned **regeneration of the adsorbents** is an important part of the total process. A few procedures are available for regeneration:

- 1. Stripping by use of steam or hot air.
- 2. thermal desorption by raising the temperature high enough to boil off all the adsorbed material (see Fig. 8.21).
- 3. Vacuum desorption by reducing the pressure enough to boil off all the adsorbed material.
- 4. **Purge gas stripping** by using a non-adsorbed gas to reverse the concentration gradient. The purge gas may be condensable or non-condensable. In the latter case it might be recycled, while the use of a condensable gas has the advantage that it can be removed in a liquid state.
- 5. In situ oxidation, based on the oxidation of the adsorbate on the surface of the adsorbent.
- 6. Displacement by use of a preferentially adsorbed gas for the deadsorption of the adsorbate. The component now adsorbed must, of course, also be removed from the adsorbent, but its removal might be easier that that of the originally adsorbed gas, for instance, because it has a lower boiling point.



Fig. 8.22. Relationship between pressure drop (mm H_2O per m) and superficial velocity for two different grades of activated carbon. (1) coarse (2) fine at 1 atm. and 25°C.

Although the regeneration is 100 per cent the capacity may be reduced 10 to 25 per cent after several regeneration cycles, due to the presence of fine particulates and/or high molecular weight substances, which cannot be removed in the regeneration step.

A flow/chart of solvent recovery using activated carbon as an adsorbent is shown in Fig. 8.23 as an illustration of a plant design.



Fig. 8.23. Flow-chart of solvent recovery by the use of activated carbon.

8.6.5. Combustion.

P.8.22. Combustion is defined as rapid, high temperature gasphase oxidation. The goal is the complete oxidation of the contaminants to carbon dioxide and water, sulphur dioxide and nitrogen dioxide.

The process is often applied to control odours in rendering plants, paint and varnish factories, rubber tyre curing and petro-chemical factories. It is also used to reduce or prevent an explosion hazard by burning any highly flammable gases for which no ultimate use is feasible.

The efficiency of the process is highly dependent on temperature and reaction time, but also on turbulence or the mechanically induced mixing of oxygen and combustible material. The relationship between the reaction rate, r and the temperature can be expressed by Arrhenius' equation: $r = A * e^{-E/RT}$

where A = a constant, E = the activation energy, R = the gas constant and T = the absolute temperature

A distinction is made between combustion, thermal oxidation and catalytic oxidation, the latter two being the same in principle as the vehicles afterburners mentioned in 8.3.3.

QUESTIONS AND PROBLEMS.

- Calculate the maximum concentration (g m⁻³) at ground level for the following case: Emission: 20 g min⁻¹ k (constant): 0.2 min m⁻¹ Stable exit velocity: 2 m sec⁻¹ Stack exit inside diameter: 1.8 m Stack exit temperature: 600°K Stack height: 120 m
- Calculate the ratio in concentration of particulate matter in case A and B provided that the total emission is the same in the two cases:
 A: 2000 stacks H = 10 m
 B: 1 stack H = 250 m
- 3. Indicate a method to remove the following as air pollutants:1) ammonia, 2) hydrogen sulphide, 3) phenol, 4) hydrogen cyanide.
- 4. What is the energy consumption for a packed-bed scrubber treating 650 m³ min⁻¹ with a $D_{50} = 2\mu m$?
- 5. Compare the influence of SO_2 on the sulphur cycle and CO_2 on the carbon cycle.
- Would the total SO₂ emission on earth be able to change pH of the sea over a period of 100 years, if: a) the total SO₂ emission is constant at the present level, b) the total SO₂ emission increases 2% per year?
- Calculate the cost of activated carbon per day used for a 90% removal of 10 ppm (v/v) pyridine from 100 m³ air per hour. The temperature is 20°C. The cost of one kg activated carbon is US\$ 0.50.