Air Pollution

1. Air and The Atmosphere

Atmosphere is the gaseous environment surrounding the earth.

Atmosphere consists of major 5 species of gases

Table 1. Composition of Background Air

Species	MW	Percent (dry air)
Nitrogen (N_2)	28	78.08
Oxygen (O_2)	32	20.95
Water (H_2O)	18	Varies
Argon (Ar)	40	0.93
Carbon dioxide (CO_2)	44	0.035

1.1 Structure of the Atmosphere

(1) Troposphere
(2) Stratosphere
(3) Mesosphere
(4) Thermosphere
(5) Exosphere
(6) Ionosphere

For environmental engineering, we are mainly concerned with the troposphere. However, the issue of stratosphere ozone depletion has emerged as a concern even though the stratosphere is outside of the region where life exists.

Viewed on a planetary scale, the troposphere is a thin blanket covering the earth's surface. For example, if the entire atmosphere were present as it is at the earth's surface ($P = 1$ atm, $T = 293$ K), it would be extend only 8.7 km less than the height of

Mt. Everest. If it were compressed to the density of water, it would cover the earth only to a thickness of 10 m.

Gases cool as their internal kinetic energy is transformed into the mechanical work of expansion. A typical rate of decrease of temperature with height throughout the troposphere is about 6.5 ^{o}C/km. Because the incoming solar intensity is greater near the equator than at the poles, the thickness of the troposphere varies from 5-6 km at the poles to 18 km at the equator.

2. Physical and Chemical Fundamentals

2.1 Ideal Gas Law

At the same temperature and pressure, different kinds of gases have densities proportional to their molecular masses.

$$\rho = \frac{1}{R} \cdot \frac{P \cdot M}{T}$$

where ρ = density of gas, kg/m^3;

P = absolute pressure, kPa;

M = molecular mass, g/mol;

T = absolute temperature, K; and

R = universal gas constant (= 8.3143 J/mol,K = 8.205 X 10^{-5} atm,m^3/mol,K).

Furthermore, since density is mass per unit volume,

$$\frac{1}{R} \cdot \frac{P \cdot M}{T} = \rho = \frac{M}{V_{unit}};$$

$$V = n \cdot V_{unit} \text{; and}$$

$$P \cdot V = n \cdot R \cdot T$$

where V_{unit} = the volume occupied by 1 mole of gas; and

V = the volume occupied by n moles of gas.

For example, at 273.15K and 101.325 kPa, 1 mol of an ideal gas occupies 22.414 L.

2.2 Dalton's Law of Partial Pressures

Total pressure exerted by a mixture of gases is equal to the sum of the pressures that each type of gas would exert if it alone occupied the container

$$P_t = P_1 + P_2 + P_3 + \ldots$$

where P_t = total pressure of mixture; and

P_1, P_2, P_3 = pressure of each gas if it were in container alone, that is, "partial pressure".

$$P_i = n_i \cdot \frac{R \cdot T}{V}$$

$$P_t = n_1 \cdot \frac{R \cdot T}{V} + n_2 \cdot \frac{R \cdot T}{V} + n_3 \cdot \frac{R \cdot T}{V} + \ldots = (n_1 + n_2 + n_3 + \ldots) \cdot \frac{R \cdot T}{V}$$

$$\frac{P_i}{P_t} = \frac{n_i}{n_t} = Y_i$$

where Y_i = mole fraction of the gas i.

2.3 Adiabatic (단열) Expansion and Compression

An adiabatic process is that

(1) takes place with no addition or removal of heat; and

(2) with sufficient slowness so that the gas can be considered to be in equilibrium at all times.

see Fig. 6-1 (p. 461)

(Heat added to gas) = (increase in thermal energy)
+ (external work done by or on the gas)

Since the left side of the equation is zero for the adiabatic process, the increase in thermal energy is equal to the work done. The increase in thermal energy is reflected by an increase in the temperature of the gas. Also, if the gas is expanded adiabatically, its temperature will decrease.

2.4 Units of Measure

Basic units in reporting air pollution data

1. micrograms per cubic meter ($\mu g/m^3$) : concentration
2. parts per million (ppm) : concetration
3. micron (μ) or micrometer (μm) : particle size

   see Fig. 6-2. (p. 464)

   Relative sizes of small particles (e.g., an average diameter of a hair is 80μm.)

ppm is a volume-to-volume ratio (ppm in water and solid is a mass-to-mass ratio.). Changes in T and P do not change the ratio of V of pollutant to V of air that contains it. Thus, it is possible to compare ppm readings from different places without any conversion.

Converting $\mu g/m^3$ to ppm

See example 6-1 (p. 463)

(Solution)

$$V_2 = V_1 \cdot \frac{T_2}{T_1} \cdot \frac{P_1}{P_2}$$

Using the relationship, we can calculate the volume of SO_2 occupied at 25°C and 103.193 kPa (V_2),

$$V_2 = 80\mu g \cdot \frac{1mol}{64.06g} \cdot \frac{1g}{10^6 \mu g} \cdot \frac{22.4l}{mol} \cdot \frac{(273+25K)}{273K} \cdot \frac{101.325kPa}{103.193kPa} = 3\times10^{-5} l$$

$$ppm = \frac{3\times10^{-5} l}{m^3} \cdot \frac{1m^3}{10^3 l} = 0.03\times10^{-6}$$

3. Air Pollution Perspective

3.1 Scales

(1) micro: indoor air pollution (e.g., construction materials, ventilation, naturally occurring radioactive materials, etc.)
(2) meso: ambient air pollutants (e.g., industrial and mobile sources, etc.)
(3) macro: ambient air pollutants over large distances and global impact (e.g., acid rain, ozone pollution, depletion of the ozone layer, global warming, etc.)

Our focus will predominately be on the meso-scale air pollution.

3.2 Impurities in Environmental Media (eg., Air or Water)

- Directly hazardous to human health (allergic reactions, short-term illnesses, chronic illnesses, acute toxicity, birth defects, cancer, and death)
- Aesthetic (including the taste, odor, color and clarity)
- Impact on the environment (e.g., carbon dioxide)
- Beneficial (e.g., Dissolved oxygen)

3.3 Toxic metals

- Lead

  Sources: pigments in paint, glazes of dishes, pipe in water distribution systems, gasoline additive

  Anemia (빈혈), kidney damage, high blood pressure, central nervous system effects, Probable human carcinogen.

- Mercury

  Sources: combustion of coal, manufacture of electrical components, production of chlorine and hydroxide, fungicide, additives to paints, amalgam of silver dental fillings

  Central nervous system dysfunction (역기능), paralysis (마비), blindness, birth defects, 미카마타 병.

- Cadmium

  Sources: metal plating, rechargeable batteries, smelting (제련), refining, mine drainage, industrial wastewater, corrosion of galvanized pipe in the water distribution system, etc.

  Cadmium's chemical similarity to zinc interferes with enzymes proper function.

  High blood pressure, kidney damage, lung tumors by inhalation, Probable human carcinogen.

- Chromium

  Sources: trace constituent of ordinary soils, coal burning, stainless steel

  Cr(III) is an essential trace nutrient in human, Cr(VI) causes a suite of adverse health effects. However, environmental standards do not distinguish among the oxidation states due to the possibility of conversion of Cr(III) to Cr(VI).

  Liver and kidney damage, internal hemorrhage (출혈), respiratory disorders, cancer.

3.4 Organic Impurities

- Formaldehyde (HCHO)

  Sources: A widely used industrial chemical, components in resins for bonding and laminating, preservative in cosmetics, manufacturing lacquers, dyes, and plastics, also can be formed in photochemical smog by degradation of other organics, byproduct of incomplete combustion and wood and tobacco smoke, and auto exhaust.

  Irritating to mucous membranes (점막) at low concentrations, nasal cancer in laboratory mice and rats, inconclusive evidence for human cancer.

- Chlorofluorocarbons (CFCs)

A family of chemicals that contain one or two carbon atoms attached to mix of chlorine, fluorine, and hydrogen atoms, e.g., CCl_3F, CCl_2F_2, $CHClF_2$, Working fluid in refrigeration units which replace ammonia and sulfur dioxide of which leakage cause hazardous conditions,

Sources: Refrigeration units (refrigerators, air conditions), aerosol propellants, foaming agents

CFCs are very little toxic. CFCs are very stable in environment and persist long enough in the atmosphere to be transported through troposphere into stratosphere. There, intense UV radiation decompose them and the liberated chlorine atoms act in a catalytic cycle, destroying ozone. Stratospheric ozone absorbing UV radiation from the sun.

- Benzene (C_6H_6)

  Sources: Octane-boosting component in gasoline, Solvent, by-product of the incomplete combustion of hydrocarbon fuels, tobacco smoke,

  Human carcinogen, leukemia (백혈병), Hodgkin's disease.

- Chlorinated solvents (Halogenated organics)

  Organic molecules that contain one or more halogen atoms (e.g., dichloromethane (CH_2Cl_2), trichloroethylene (C_2HCl_3), trichloroethane ($C_2H_3Cl_3$), tetrachloroethylene (PCE, perchloroethylene, C_2Cl_4)

  Sources: industrial applications, dry-cleaning, hazardous waste disposal sites

  Known or suspected human carcinogens

- Dioxin (e.g, 2,3,7,8-TCDD)

  A group of compounds that have a double aromatic ring structure coupled by two oxygen atoms (e.g., 2,3,7,8-tetrachlorodibenzo-*p*-dioxin)

  Sources: not produced intentionally, by-products in the manufacturing of some pesticides and during the combustions of plastics and chlorinated solvents, bleaching paper pulp with chlorine, relatively persistent in environment.

  One of the most highly toxic organic compounds, although the levels at which health effects occur are controversial,

- Polycyclic Aromatic Hydrocarbons (PAHs)

  PAHs (polycyclic aromatic hydrocarbons) or PNA (polynuclear aromatic compounds), is the presence of multiple benzene rings fused together.

  Sources: do not have significant industrial uses, formed by the incomplete combustion of hydrocarbon fuels (soot from diesel engines, smoke from wood fires, barbeques, or cigarettes), coal tar, wood and other biomass as a cooking fuel (especially for Benzo(a)pyrene ($C_{20}H_{12}$)).

  Benzo(a)pyrene ($C_{20}H_{12}$) is one of the first chemicals shown to be carcinogenic.

3.5 Radionuclides

- Atomic weapons
- Nuclear power station (mining, refining, transport, storage, use, and disposal)
- Medical purposes
- The greatest source of population exposure to ionizing radiation is not industrial, military, or medical uses, but rather the radionuclides that are naturally present in the environment, for example, ^{222}Rn.
- Radon is created constantly I all soil and earth base materials by the radioactive decay of radium. Most exposure to radon occurs indoors and the dominant source of indoor radon is the soil within a few meters of the building structure. Building materials and groundwater are also potential sources of indoor radon.
- Since radon is chemically inert, it does not pose a significant direct health threat. However, radon decay produces a series of three short-lived radio-isotopes whose inhalation does pose a direct health hazard, increasing the risk of lung cancer. When inhaled, they may deposit onto respiratory tissues and undergo further radioactive decay to ^{210}Pb.

3.6 Particulate Matter

Suspended particles

(1) decrease visibility

(2) disease transmission (suspended particles may be host to microorganisms.)

(3) transport and delivery of toxic materials (heavy metals and toxic organics are found in particulate form.)

(4) acute repiratory health effects (for airborne particulates)

Quantifying particulate matters in air

PM_x = particular matter smaller than x micrometers in aerodynamic diameter

e.g., Current air quality standards for particles are based on PM_{10}. The use of a second measure which focuses on $PM_{2.5}$ has been proposed.

4. Air Pollution Standards

4.1 Clean Air Act (CAA)

1970

Environmental Protection Agency (EPA)

by Stationary or Mobile sources

Human health or the Environment

National Ambient Air Quality Standards (NAAQS)

4.2 Standards

Standards : for the ambient air

(1) Primary standard : to protect human health with a “adequate margin of safety”

(2) Secondary standard : to prevent environmental and property damage

Criteria pollutants : health based criteria (see Table 6-1, p.465)

- CO, lead, NO_2, ozone, particulate matter (PM), SO_2

Hazardous air pollutants (HAPs)

- risk-based (Criteria pollutants are health-based.)
- National Emission Standards for Hazardous Air Pollutants (NESHAPs)
- 189 chemicals (asbestos, arsenic, benzene, beryllium, mercury, vinyl chloride, radionuclides, etc.)
- emission allowance based on MACT
- Maximum Achievable Control Technology (MACT) : include process change. Material substitutions, or air pollution control equipment

4.3 대기환경보전법

대기오염물질 배출허용기준

(H.W.) 우리나라 대기환경보전법과 미국의 CAA 비교 (예, Table 6-1)

5. Effects of Air Pollutants

reading assignment (6.4)

6. Origin and Fate of Air Pollutants

6.1 Carbon Monoxide (CO)

Natural sources : results from an intermediate step in the oxidation of CH_4

$$CH_4 + OH\cdot \rightarrow CH_3\cdot + H_2O$$

$$CH_3\cdot + O_2 + 2(hv) \rightarrow CO + H_2 + OH\cdot$$

Anthropogenic sources : motor vehicle, fossile fuel burning, industrial processes, solid waste disposal, etc (motor vehicles > 60%).

- No significant change in the global atmospheric CO level over the past 20 years.
- Anthropogenic contribution has doubled over the same time period.
  Potential reasons
  (1) Reaction with hydroxyl radical to form carbon dioxide
  (2) Removal by soil microorganisms

6.2 Hazardous Air Pollutants (HAPs)

Sources : fuel combustion, metal processing, petroleum and natural gas production and refining, surface coating processes, waste treatment and disposal processes, agricultural chemical production, and polymer and resin production, dry cleaning, electroplating (전기도금), etc.

(1) direct emissions
(2) chemical formation in the atmosphere

e.g., photolysis, chemical reactions with ozone, hydroxyl radicals, and nitrate radicals, etc.

6.3 Lead (Pb)

Natural sources : volcanic activity and airborne soil

Anthropogenic sources : Smelters (제련소), refining processes, incineration of lead-containing wastes, etc. (e.g., 70 to 80% of the lead which used to be added to gasoline was discharged to the atmosphere.)

6.4 Nitrogen Dioxide (NO_2)

nitrogen oxides

- nitrous oxide (N_2O)
- nitric oxide (NO)
- nitrogen dioxide (NO_2)

6.4.1 Natural sources

(1) bacterial action in the soil releases N_2O to the atmosphere

(2) In the stratosphere, atomic O reacts with N_2O to form NO. (the atomic O results from the dissociation of O_3.)

$$N_2O + O \quad \rightarrow \quad 2NO$$

6.4.2 Anthropogenic sources

Combustion : 96% of anthropogenic sources of nitrogen oxides

(1) At high temperature and pressure,

$$N_2 + O_2 \quad \rightarrow \quad 2NO$$

(2) No in turn reacts with O_3 or O to form NO_2.

(3) NO_2 is converted to NO_2^- or NO_3^- and then washed out by precipitation, HNO_3, and acid rain.

6.5 Photochemical Oxidants

- results from atmospheric reactions;
- are not directly attributable to either people or nature
- thus, “secondary pollutants”

for example, ozone (see Fig 6.6, p. 478: the attribute of ozone formation to the nitrogen dioxide photolytic cycle)

“photochemical smog”

6.6 Sulfur Oxides (SO_x)

- Primary pollutants : SO_2, SO_3, SO_4^{2-} from power plants, industry, volcanoes, and the oceans

- Secondary pollutants : SO_2 oxidized from H_2S which from biological decay process et. al.

$$H_2S + O_3 \quad \rightarrow \quad H_2O + SO_2$$

for example, the combustion of fossil fuels

$$S + O_2 \quad \rightarrow \quad SO_2$$

- The ultimate fate of SO_2 in the atmosphere is conversion to sulfate salts which accounts for acid rain.

(1) Catalytic oxidation

$$2SO_2 + 2H_2O + O_2 \xrightarrow{Catalyst} 2H_2SO_4$$

Catalysts : Fe^{3+}, Mn^{2+}, or NH_3 in the water droplets

(2) Photochemical oxidation

$$SO_2 + hv \quad \rightarrow \quad SO_2^*(photoexcited)$$

$$SO_2^* + O_2 \quad \rightarrow \quad SO_3 + O$$

$$SO_3 + H_2O \quad \rightarrow \quad H_2SO_4$$

6.7 Particulates (PM)

- Natural sources : sea salts, soil dust, volcanic particles, and smokes from forest fires, etc.
- Anthropogenic sources : fossil fuel burning, industrial processes, etc.
- Secondary sources : conversions of H_2S, SO_2, NO_x, NH_3, and hydrocarbons to particulates, e.g., H_2SO_4, NO_3^-, et al.
- Fate : removed from atmosphere as nuclei of raindrops or accretion to rain drops

7. Micro and Macro Air Pollution

7.1 Indoor Air Pollution

7.1.1 CO

- Acute effect of improperly operating furnaces
- Chronic effect of gas ranges, ovens, pilot lights, gas and kerosene heaters, and cigarette smoke (see, Tables 6-3, 4, p.482 and Fig. 6-7, p.483)
- Mainstream smoke vs. Sidestream smoke (see, Table 6-5, p.484)

7.1.2 Radon

- in dwellings not in the ambient air
- from geologic formations and construction materials
- Chapter 10.

7.1.3 VOCs (volatile organic compounds)

- Aldehydes, alkanes, alkenes, ethers, ketones, and PAHs (polynuclear aromatic hydrocarbons), et al.
- Formaldehyde : emitted by consumer products and construction materials (e.g., pressed wood products, insulation materials, textiles, and combustion sources)

7.1.4 Heavy metals

- Arsenic, cadmium, chromium, mercury, lead, and nickel
- generally from outdoor air, soil, and dust (however, lead and mercury can be generated from indoor painting)

7.2 Acid Rain

- The equilibrium pH of pure rainwater is about 5.6
- The rain of which $pH < 5.6$ = acid rain (effects on fish, tree, and soil propreties)
- Acid rain precursors and products (see Fig. 608, p.485)
- The effect of aid rain on the nature is still unclear.

7.3 Ozone Depletion

- O_3 in 20-40 km atmosphere provides a barrier to UV radiation
- generation of O_3 (see, Fig. 6-9, p.487)
- O_3 destruction by chlorofluoromethane (see, Fig. 6-10, p.487)
- Montreal Protocol (1987) : finally ban production of halon, CFCs, carbon tetrachloride, and methyl chloroform.
- However, it is anticipated that the peak chlorine levels will continue to rise until at least 2006 because of the long lifetimes of the chemicals.

7.4 Green House Effect

- CO_2 is transparent to shortwave UV, but absorb and emit longwave radiation.
- Other green house gases : CH_4, N_2O, CFCs
- GWP (global warming potential)
- Global warming (decrease heating costs, increase growing season for crops, and easier navigation in the arctic seas; however, drier conditions in some areas, adverse effects on buildings in the cold area, and increase the sea level which results in severity of flooding, damage to coastal structures, and sea water intrusion drier crop conditions)
- The effect of green house gases and the trend of global warming is still not clear.

8. Air Pollution Meteorology

8.1 Weather Map

Isobars : lines of constant pressure on the weather map (Fig. 6-11, p.492)

Direction of wind

- from the higher pressure to the lower pressure areas
- Wind direction would be perpendicular to the isobars
- However, due to the Coriolis effect (Fig. 6-12, p.493)

Wind speed

- A function of the steepness of the pressure surface

8.2 Stability

8.2.1 Stability

- The tendency of the atmosphere to resist or enhance vertical motion
- is related with both wind speed and the change of air temperature with height (i.e., lapse rate)
- unstable, neutral, and stable : See Fig. 6-13 (p.495)

(1) Neutral Stability

- Γ = dry adiabatic lapse rate (-1.00^{o}C/100m)
- ambient lapse rate = Γ, then neutral stability

(2) Unstable atmosphere

- when the ambient lapse rate is greater than Γ (e.g., -1.25^{o}C/100m)
- “superadiabatic”

(3) Stable atmosphere

- when the ambient lapse rate is smaller than Γ (e.g., -0.5^{o}C/100m)
- “subradiabatic” (isothermal, inversion)

8.2.2 Plume types

See Fig. 6-14 (p. 497)

8. 3 Terrain Effects

8.3.1 Heat island

- results from a mass of material, either natural or anthropogenic, that absorbs and reradiated heats at a greater rate than the surrounding area
- e.g., industrial complexes and large cities
- strong vertical convection currents above the heat island

8.3.2 Land/sea breezes

- see Figures 6.15, 16 (p.498, 499)

8.3.3 Valleys

9. Atmospheric Dispersion

9.1 Factors Affecting Dispersion of Air Pollutants

9.1.1 Source characteristics

- Effluent plume is (1) rising, (2) bending, and (3) move horizontally.
- The plume rise = *f*(upward inertia of the discharge gas, its buoyancy)
- Vertical inertia is related to the exit gas velocity and mass.
- Buoyancy is related to the exit gas mass relative to the surrounding air mass.
- Increasing the exit velocity or temperature will generally increase the plume rise.
- plume rise + physical stack height = “effective stack height”

9.1.2 Downwind distance

- The greater the distance between the point of discharge and a ground level receptor downwind, the greater will be the volume of air available for diluting the contaminants.

9.1.3 Wind speed and direction

- An increase in wind speed will decrease the plume rise due to the rapid bending. This leads increasing the pollutant's ground level concentration.
- An increase in wind speed will increase the rate of dilution of the plume, tending to lower the downwind concentrations.

9.1.4 Stability

- The more unstable the atmosphere, the greater the diluting power.

9.2 Dispersion Model

9.2.1 Gaussian dispersion model

Assumptions

(1) atmospheric stability is uniform;
(2) dilution of the gas stream can be described by the Gaussian or normal equation in both the horizontal and vertical direction;
(3) gas is discharged at the effective stack height;
(4) degree of dilution is inversely proportional to the wind speed;
(5) ground reflection.

Mathematical expression

$$\chi(x,y,0,H) = \left[\frac{E}{\pi \cdot s_y \cdot s_z \cdot u}\right] \cdot \left[\exp\left\{-\frac{1}{2} \cdot \left(\frac{y}{s_y}\right)^2\right\}\right] \cdot \left[\exp\left\{-\frac{1}{2} \cdot \left(\frac{H}{s_z}\right)^2\right\}\right]$$

where χ(x,y,0,H) = downwind concentration at ground level, g/m^3;
E = emission rate of pollutants, g/sec;
s_y, s_z = plume standard deviations, m; and
u = wind speed, m/sec.

H = effective stack height, m

$H = h + \Delta H$

where h = physical stack height, m; and

ΔH = plume rise, m.

Holland's formula for the plume rise,

$$\Delta H = \frac{v_s \cdot d}{u} \cdot \left[1.5 + \left\{ 2.68 \times 10^{-2} \times P \cdot \left(\frac{T_s - T_a}{T_s} \right) \cdot d \right\} \right]$$

where v_s = stack exit velocity, m/sec;

d = stack diameter, m;

P = atmospheric pressure, kPa;

T_s = stack temperature, K; and

T_a = air temperature, K.

Plume standard deviations

(1) see Figure 6-19, 20, p.504, 505);

(2) Martin' relationship

$$s_y = a \cdot x^{0.894}$$

$$s_z = c \cdot x^d + f$$

where x = in km;

s_y and s_z = in m; and

a, c, d, and f are in Table 6-7 (p.506)

10.Indoor Air Quality Model

Box Model (see, Fig. 6-22, p.509)

$$V \cdot \frac{dC}{dt} = Q \cdot C_a + E - Q \cdot C - k \cdot C \cdot V$$

where V = volume of box, L^3;

C = concentration of pollutant, M/L^3;

Q = rate of infiltration of air into and out of box, L^3/T;

Ca = concentration of pollutant in outdoor air, M/L^3;

E = emission rate of pollutant into box from indoor source, M/T; and

k = pollutant reaction rate coefficient, 1/T, (Table 6-8, p.510).

Solution for the steady-state (dC/dt =0),

$$C = \frac{Q \cdot C_a + E}{Q + k \cdot V}$$

Generally solution,

$$C_t = \frac{\frac{E}{V} + C_a \cdot \frac{Q}{V}}{\frac{Q}{V} + k} \cdot \left[1 - \exp\left\{-\left(\frac{Q}{V} + k\right) \cdot t\right\}\right] + C_0 \cdot \exp\left[-\left(\frac{Q}{V} + k\right) \cdot t\right]$$

If the pollutant is conservative (k=0), and the ambient concentration is negligible (C_a=0), the general solution is,

$$C_t = \frac{E}{Q} \cdot \left[1 - \exp\left\{-\left(\frac{Q}{V}\right) \cdot t\right\}\right]$$

11. Air Pollution Control of Stationary Sources

11.1 Gaseous Pollutants

11.1.1 Absorption

Mass transfer from a gas phase to liquid phase

(1) Diffusion of pollutant gas to the surface of the liquid;

(2) Transfer across the gas/liquid interface (dissolution, a partitioning);

(3) Diffusion of the dissolved gas away from the interface into the liquid.

Henry' law,

$$P_g \quad = \quad K_H \cdot C_{equil}$$

where P_g = partial pressure of gas in equilibrium with liquid, kPa;
K_H = Henry's law constant, kPa,m^3/g;
C_{equil} = concentration of pollutant gas in the liquid phase, g/m^3.

- If water is the solute, this limits the application, e.g., water/NH_3, water/Cl_2, and water/SO_2.

Spray chamber (Figure 6-23, p.512) :

- relatively inefficient
- can remove particulates

Absorption towers (Figure 6-24, p.512)

- more efficient
- plugged by particulate matter

11.1.2 Adsorption

- adsorbate vs. adsorbent
- The most common adsorbents are activated carbon, molecular sieve, silica gel, activated alumina, etc.
- Very effective for hydrocarbons
- Good for H_2S, SO_2, NO_2, etc.
- Inefficient at high temperature (vs. regeneration at that temperature)

Langmuir isotherm

$$W = \frac{a \cdot C_g^*}{1 + b \cdot C_g^*}$$

where W = amount of gas per unit mass of adsorbent, kg/kg;

a, b = constants (determined by experiments);

C_g^* = equilibrium concentration of gaseous pollutant, g/m^3.

Breakthrough (see Figure 6-27, p.520)

11.1.3 Combustion

Oxidizable gas, e.g., CO and hydrocarbons

None of the by-products of combustion should be toxic.

(1) Direct flame incineration

- for high energy concentration (> 3.6MJ/m^3)
- Otherwise, supplementary fuel or catalytic combustion

(2) Catalytic combustion

- Platinum of palladium compound on the ceramic bed

11.2 Flue Gas Desulfurization (FGD)

for limestone system,

$SO_2 + CaCO_3 \rightarrow CaSO_3 + CO_2$

for lime system,

$SO_2 + Ca(OH)_2 \rightarrow CaSO_3 + H_2O$

Finally, $CaSO_3 + 1/2O_2 \rightarrow CaSO_4$

11.3 Nitrogen Oxides

11.3.1 Prevention

Fuel NO_x : lower nitrogen content

Thermal NO_x : lower burning temperature and excess air

Natural gas (no nitrogen content) produces more NOx than coal due to the high burning temperature

11.3.2 Post-combustion

3 processes to convert NO_x to N_2

(1) Selective catalytic reduction (SCR)
  - catalyst bed (vanadium-titanium, or platinum-zeolite), NH_3
  - $NO_x + NH_3 \rightarrow N_2 + H_2O$

(2) Selective noncatalytic reduction (SNCR)
  - Urea (converted to NH_3) or NH_3
  - higher temperature is required than SCR

(3) Nonselective catalytic reduction (NSCR)
  - three-way catalyst

11.4 Particulate Pollutants

11.4.1 Cyclones (see Fig. 6-30, p.525)

- Particle size > 10μm
- Standard cyclone proportions (see Fig. 6-31, p.526)

Lapple's empirical equation

$$d_{0.5} = \left[\frac{9 \cdot \mu \cdot B^2 \cdot H}{\rho_p \cdot Q_g \cdot \theta}\right]^{1/2}$$

where $d_{0.5}$ = cut diameter, m (the particle size for which the collection efficiency is 50%);

μ = dynamic viscosity of gas, Pa•sec;

B = width of entrance, m;

H = height of entrance, m;

ρ_p = particle density, kg/m3,sec;

Q_g = gas flow, m3/sec;

θ = effective number of turns.

for the effective number of turns, θ

$$\theta = \frac{\pi}{H}\cdot\left(2\cdot L_1 + L_2\right)$$

where L_1, and L_2 are the length of the cylinder and cone, respectively.

- Using the ratio, $d/d_{0.5}$, the collection efficiency fo cyclone can be estimated (see Fig. 6-32, p.527).
- If the diameter of cyclone decreases, the efficiency?

  (answer) As the diameter of cyclone increases, the lengths of cylinder and cone are generally increases, too. Thus, θ increases, d0.5 decreases, and finally efficiency increases. However, the pressure drop also increases. So, multicones can be used to increase the efficiency without extra energy consumption.

11.4.2 Filters (see Fig. 6-33, p.528)

- Particle size < 5μm

(1) Deep bed filter : for relatively clean gases and low volume (e.g., air conditioning systems)

(2) Bag house (Fig. 6-33, p.528) : (e.g., vacuum cleaner)

Reverse-sir baghouse : gas into the inside of bag

Pulse-jet baghouse : with cage

- Bag materials : cost, temperature-, and chemical-resistance (life time = 1-5 yrs)
- Typical design criteria : the ratio of filter area to gas flow rate, 0.01 m^3/sec,m^2

11.4.3 Liquid scrubbing (see Fig. 6-34, p.530)

- wet, corrosive, or very hot

for the Ventury scrubber (Fig. 6-34, p.530)

$$\eta = 1 - \exp\left(-\kappa \cdot R \cdot \sqrt{\varphi}\right)$$

where η = efficiency;

κ = correlation coefficient, m^3 of gas/m^3 of liquid;

R = liquid flow rate, m^3/m^3 of gas;

φ = inertial impact parameter

$$\varphi = \frac{C \cdot \rho_p \cdot v_g \cdot (d_p)^2}{18 \cdot d_d \cdot \mu}$$

where C = Cunningham correction facotr;

ρ_p = particle density, kg/m^3;

v_g = speed of gas at throat, m/sec;

d_p= diameter of particle, m;

d_d = diameter of droplet, m;

μ = dynamic viscosity of gas, Pa•sec

$$C = 1 + \frac{6.21 \times 10^{-4} \times T}{d_p}$$

where T = temperature of gas, K.

11.4.4 Electrostatic precipitation (ESP) (see Fig. 6-35, 36, p.532, 533)

- dry and high
- 30-75 kV of direct current : negatively charged particles will stick to the plate.

(1) wire in tube (Fig. 6.35(a), p.532)

(2) wire and plate (Fig. 6.35(b), p.532)

- Gas flow is not stopped during cleaning

$$\eta = 1 - \exp\left(-\frac{A \cdot w}{Q_g}\right)$$

where A = collection area of plates, m^2;

w = migration velocity of particles, m/sec;

Q_g = gas flow rate, m^3/sec.

$$w = \frac{q \cdot E_p \cdot C}{6 \cdot \pi \cdot r \cdot \mu}$$

where q = charge, coulomb;

E_p = collection field intensity, volts/m;

R = particle radius, m;

C = Cunningham correction factor.

12. Air Pollution Control of Mobile Sources

(reading assignment)