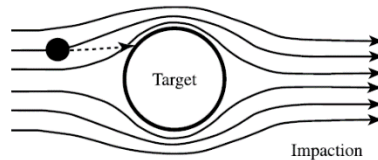


Model Answer

1. Define the following terms: Aerodynamic diameter, polluted air, Troposphere, Smog, Particulate matters, Outdoor air pollution, terminal settling velocity, impaction, Temperature lapse rate, and fumigation. (10)
 - a- Aerodynamic particle size: is defined as the diameter of a sphere of unit density (1 g/cm^{-3}) which has the same terminal settling velocity in air as the particle under consideration.
 - b- Polluted air: the clean air in addition to foreign materials (pollutants) as SO_2 , CO or with non-normal composition as when CO_2 concentration exceeds standard level.
 - c- Troposphere: The first and lowest of the atmospheric layers is called the “troposphere”.
 - d- Smog: type of air pollution that contains two groups of pollutants; Smoke and fog referring to smoky fog as that detected in London (1952) and Loss- Anglos (1943).
 - e- Particulate matter: any finely divided liquid or solid substance including smoke, dust, or some forms of fine mist and is entrained in effluent gas streams or suspended in ambient air.
 - f- Outdoor air pollution: Pollutions from outdoor services and environmental mixings, such as: transportation-automobiles, industries-refineries, atomic energy plant-nuclear, and community activities-cleaning of streets.
 - g- Terminal settling velocity: is the flow velocity at which the particle weight force is balance by the flow drag force, so for flow velocity beyond this value the particle will settle while for higher values particle will be carried by the flow.
 - h- Impaction: is a flow-particle interaction mechanism in which large particles moving toward the target have mass, and so momentum that tends to cause particle motion in a straight line toward the target. As the gas streamlines bends around the target, the particle will leave (is separated) from carried streamline



- i- Temperature lapse rate: the rate of change of air temperature with altitude. It is an important factor regarding air stability, its normal (adiabatic state) value is $-1 \text{ }^\circ\text{C}/100 \text{ m}$.
 - j- Fumigation: is the sudden return of pollutants emitted into atmosphere back to the earth.
2. Volume Conversion to Standard Conditions: A volume of 20 m^3 was drawn from a spirometer at 20°C and 700 mm Hg . What was the standard volume drawn, based on EPA reference conditions for atmospheric sampling and monitoring? (10)

$$\text{For ideal gases, } V_2 = V_1 \frac{P_1 T_2}{P_2 T_1}$$

where:

$V_2 =$ Volume at condition 2, m^3

$V_1 =$ Volume at condition 1, 20 m^3

$P_2 =$ pressure at condition 2, 700 mm Hg

$P_1 =$ pressure at condition 1, 760 mm Hg

$T_2 =$ temperature at condition 2, 293 K

$T_1 =$ temperature at condition 1, 298 K

Thus V_2 will be 18.7 m^3 .

3. What are: (10)
 - a. the main strategies of air pollution control,
 - b. the major principles for particulate removing,
 - c. the combustion techniques to reduce NO_x emissions,
 - d. the main approaches for pollution control.
 - e. The different purposes of dust collection process.

- a) generally there are two strategies to control air pollution; namely long and short-term strategies. Long-term control strategies involve an authorized set of measures to be adopted over a long period (many years). For long-term control, a typical objective might be to reduce to a specified value the expected number of days per year that the maximum hourly average concentration of a certain pollutant exceeds a given value. Short-term control involves shutdown and slowdown procedures suitable for short time testing (from hours to several days) under impending adverse meteorological conditions. An example of a short-term strategy is the emergency procedures for fuel substitution by coal-burning power plants when SO₂ concentrations reach certain levels. The goal of short-term control is ordinarily to keep the maximum concentration of a certain pollutant below a given value on that particular day. In figure below, requirements and the elements of a comprehensive regional air pollution control strategy, including both long- and short-term measures are illustrated.
- b) The principles used in many practical devices to control particulate emissions include:
1. Electrostatic Precipitation (particle obstruction)
 2. Fabric Filters (particle obstruction)
 3. Venturi Scrubbers (particle obstruction and gravity forces)
 4. Cyclones (enhancement of centrifugal forces)
 5. Settling Chambers (enhancement of gravity forces)
- c) Realization of combustion techniques: A variety of combustion control techniques can be realized to reduce the peak flame temperature; reduce the oxygen concentration in the primary flame zone, or to promote reconverting NO_x back into nitrogen and oxygen.
- d) Air pollution can be controlled by performing different approaches, such as
1. Regulations on auto industry
 2. Fines to enforce bans; Incentives for reduction
 3. Switch from high sulfur coal to low sulfur coal
 4. Switch to oil, gas, wind, solar, nuclear power
 5. “Scrubbers” on smoke stacks to remove sulfur after use
- e) The purposes of dust collection process include:
1. Air-pollution control, as ash removal from power-plant flue gases
 2. Equipment-maintenance reduction, as in filtration of engine-intake air or pyrites furnace-gas treatment prior to its entry to a contact sulfuric acid plant
 3. Safety- or health-hazard elimination, as in collection of siliceous and metallic dusts around grinding and drilling equipment and in some metallurgical operations and flour dusts from milling
 4. Product-quality improvement, as in air cleaning in the production of pharmaceutical products and photographic film
 5. Recovery of valuable product, as dusts from dryers and smelters
 6. Powdered-product collection, as in pneumatic conveying; the spray drying of milk, eggs, and soap; and the manufacture of high-purity zinc oxide and carbon black
4. Determine the SO₂ concentrations at the centerline of the plume and at a point 60 meters to the side and 20 meters below the centerline of plume emitted from a factory’s chimney. The chimney emits 20 g/s of SO₂ at height (includes plume rise), Wind speed = 3 m/s. At distance of 1 km downstream, the standard deviation of wind direction in the horizontal and vertical directions are taken to be 30 m and 20 m, respectively. (10)

$$Q = 20 \text{ g/s of SO}_2$$

$$u = 3 \text{ m/s (u)}$$

$$\sigma_y \text{ and } \sigma_z \text{ are 30 m and 20 m}$$

$$y = 0 \text{ and } z = H$$

$$C(x) = \left(\frac{Q}{2\pi u \sigma_y \sigma_z} \right) \exp\left\{ -0.5 \left(\frac{H}{\sigma_z} \right)^2 \right\} \exp\left\{ -0.5 \left(\frac{y}{\sigma_y} \right)^2 \right\}$$

So reduces to:

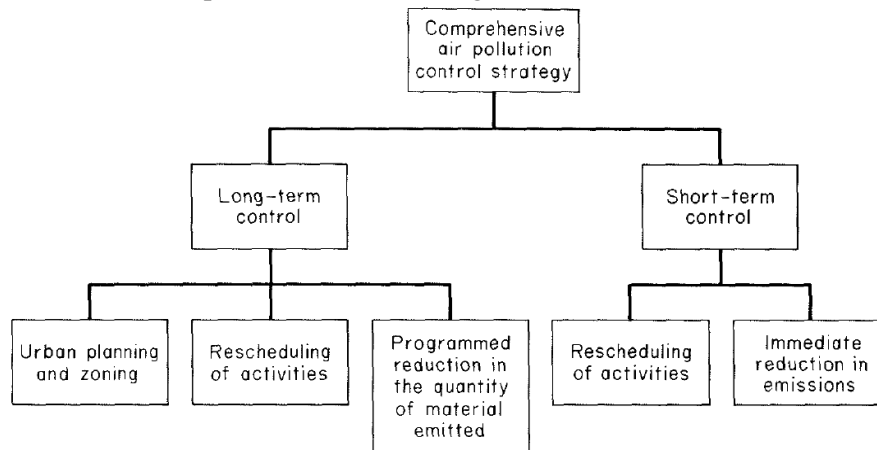
$$C(x, 0, 0) = \frac{20 \text{ g/s}}{2(\pi \cdot 3 \cdot 30 \cdot 20)} = 0.00177 \text{ g/m}^3 = 1770 \mu \text{ g/m}^3 \text{ at centerline y and Z are 0}$$

$$C = (0.00177 \text{ g/m}^3) \cdot (\exp^{-2.5}) = 0.000145 \text{ g/m}^3 \text{ or } 145.23 \mu \text{ g/m}^3 \text{ at 20 and 60 meters}$$

5. State with details a comparison between

(10)

- a. smog formation at London on 1952 and that at Los Angeles on 1943,
 - b. long-term and short-term air pollution control strategies,
 - c. atmospheric layers,
 - d. Different sizes and compositions of particulate matters,
 - e. physisorption and chemisorption.
- a. The two groups of pollutants were detected in two types of smogs (Smog = Smoke+fog):
- 1- **London type smog** (1952) comes from coal smoke combining with the water vapor and liquid water in cool, humid or foggy air. In this case burning of many coal resources in stagnant humid air lead to the formation of acidic rains ($SO_2 + H_2O \rightarrow H_2SO_4$)
 - 2- **Los Angeles** and other urban areas over the world (1943 and verified 1951) comes from auto exhaust pollutants (CO, NO_x, and ROG- reactive organic gas from unburned gasoline), primarily (we will see later that there is a significant "stationary" source). Emissions of NO_x, ROG into sunny atmosphere will lead to formation of O₃ and NO₂ due to photochemical reactions.
- b. long-term and short-term air pollution control strategies



Requirements for long-term planning

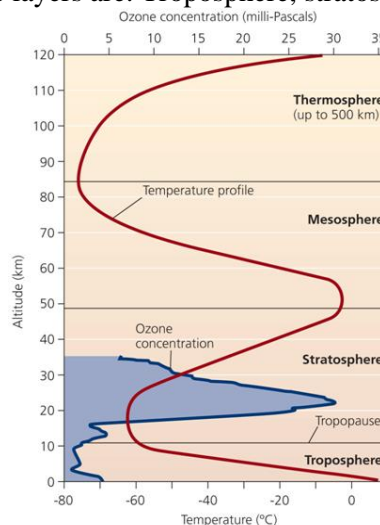
- Air quality objective
- Airshed model (dynamic or static)
- Survey of control techniques and their costs
- Meteorological probabilities

Requirements for real-time control

- Air quality objective
- Dynamic model
- Rapid communications
- Strict enforcement of measures

c. Atmospheric layers

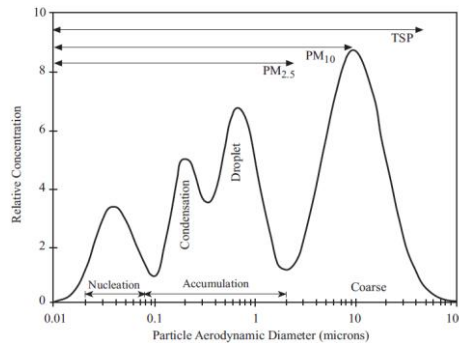
The atmosphere is layered in to four distinct zones of contrasting temperature due to differential absorption of solar energy. The four atmospheric layers are: Troposphere, stratosphere, mesosphere, and thermosphere.



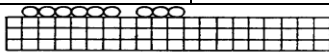
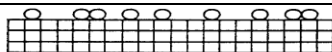
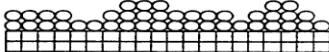
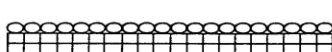
- **Troposphere** is the bottommost layer adjacent to earth's surface up to about 16 km where most weather events occur and containing over 80% of the total atmospheric air. Other characteristics of troposphere:
 - Air for breathing, weather and all live activities occur in this layer

-
- Temperature declines with altitude
 - Contains water vapor, gases and dust
 - The residence time of particle in the troposphere is short due to rain, gravity, air movement
 - Mixing time is rapid due to wind or turbulence
 - Limiting mixing between troposphere and the layer above it
 - **Stratosphere** extends from the tropopause up to about 50 km. Air temperature in this zone is stable or even increases with higher altitude. Although more dilute than the troposphere, the stratosphere has a very similar composition except two important components: water and ozone (less than one hundred of that in the troposphere). Recently discovered decreases in stratospheric ozone over the Antarctica. The earth would be exposed to increasing amount of dangerous UV rays if these trends continue. This will lead to:
 - Higher rate of skin cancer
 - Problem with eyes (Cataract, conjunctivitis etc.)
 - Genetic mutations
 - Crop failures &
 - Disruption of important living organismsOther characteristics of stratosphere
 - There is no water vapor nor dust
 - Drier and less dense, with little vertical mixing
 - Colder in its lower regions
 - Contains UV radiation-blocking ozone, 17-30 km above sea level
 - Amount of ozone vary depending on location and season; lowest above the equator and increase towards the poles, increased markedly between fall and spring
 - Mixing time is lower, so Pollution entering in this region tends to remain long time due to low mixing
 - **Mesosphere** extends above the stratosphere (from 50 to 80 km), temperature diminishes again (up to -80°C) creating the mesosphere (middle) layer. Other characteristics of mesosphere:
 - Extremely low air pressure
 - Temperatures decrease with altitude
 - **Thermosphere** is the top layer extending from altitude of 80 km up to 500 km containing highly ionized gases and very high temperature due to high solar and cosmic radiations. Other characteristics of thermosphere
 - Emit visible light
 - There is no sharp boundary that marks the end of the atmosphere
 - Pressure and density decreases gradually approaching the vacuum conditions of interstellar space
 - The composition gradually merges with that of interstellar space (mostly of H_e and H₂)
- d. Different sizes and compositions of particulate matters,
- 1- The "nucleation" range (also termed "ultrafine particles") consists of particles with diameters < 0.08 μm that are emitted directly from combustion sources or that condense from cooled gases soon after releases to the atmosphere. The lifetime of particles in the nucleation range is usually less than 1 hour because they rapidly coagulate with larger particles or serve as nuclei for cloud or fog droplets.
 - 2- The "accumulation" range consists of particles with diameters between approximately 0.08 and 2 μm. These particles result from the coagulation of smaller particles emitted from: 1) combustion sources; 2) the condensation of volatile species; 3) gas-to-particle conversion; and 4) finely ground dust particles. The nucleation and accumulation ranges constitute the "fine particle size fraction." Particles in this size range account for the majority of sulfuric acid, ammonium bisulfate, ammonium sulfate, ammonium nitrate, and organic and elemental carbon. The accumulation range consists of at least two sub-modes. Existence of sub-modes is based on measurements of chemically specific size distributions in several different urban areas; one peak centered at approximately 0.2 μm as a "condensation" mode, while the other occurs at 0.7 μm.
 - 3- The "coarse" range consists of particles with size > 2 or 3 μm; they result from grinding activities and are dominated by material of geological origin. Pollen and spores also inhabit the coarse particle size range, as do ground up trash, leaves, and tires. Coarse particles at the low end of the size range also occur when cloud and fog droplets form in a polluted environment, then dry out after having scavenged other particles and gases. The peak of the coarse mode may shift between approximately 6 and 25 μm. A small shift in

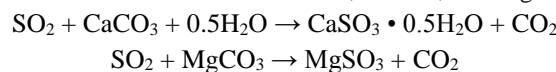
the 50 percent cut-point of a PM₁₀ sampler has a large influence on the mass collected because the coarse mode usually peaks near 10 μm.



e. Physisorption and chemisorption

Physisorption	chemisorption
Van der Waals forces between molecules multilayer adsorption predominates at low temperatures occurs rapidly reversible heat of adsorption < 40 kJ/mol	Chemical bond (stronger than Van der Waals bonds) monolayer chemical adsorption decreases at low temperatures activation energy involved irreversible heat of adsorption > 80 kJ/mol
Early stage of adsorption 	
Later stages 	

6. Consider a wet limestone scrubber for controlling SO₂ emissions with the flue gas of 460 m³/Sec at 1 atm and 150°C containing 3000 ppm SO₂. Determine how much limestone is required per year to remove 90% of inlet SO₂. The limestone supplier reported that analytical data showed that the limestone contains 94.5 wt % CaCO₃, 1.5wt%MgCO₃ and 4.0 wt % of inert material. The actual limestone consumption rate is usually 110% of the theoretical requirement. The overall reactions between SO₂, CaCO₃, and MgCO₃ are balance as follows: (10)



The equation shows that 1 mole of SO₂ requires 1 mole of CaCO₃ and 0.5 mole of H₂O or 1 mole of MgCO₃. Determine the amount of SO₂. Assume that the flue gas behaves as ideal gas at pressure 1 atm, thus the gas law can be applied to the scrubber inlet flue gas:

$$n/V = P/RT = 101.325 / (8.314 \times 423) = 0.0288 \text{ kmole/m}^3$$

$$\text{SO}_2 \text{ at the scrubber inlet} = 3000 \times 460 \times 0.0288 / 1,000,000 = 0.04 \text{ kmol/Sec}$$

Determine the SO₂ removal requirement

Under current NSPS regulation, the scrubber system must remove 90% of the inlet SO₂ for this high sulfur coal case.

$$\text{The amount of SO}_2 \text{ to be removed by the scrubber system} = 0.04 \times 3600 \times 90\% = 130 \text{ kmol/h}$$

Calculate the amount of limestone required

The theoretical limestone requirement depends on the amount of SO₂ to be removed. Since 1 mole of SO₂ requires 1 mole of alkalinity (as CaCO₃ and MgCO₃):

$$\text{The theoretical alkalinity requirement} = 130 \text{ kmol/h}$$

$$\text{The actual alkalinity consumption rate} = 130 \times 110\% = 142.6 \text{ Kmol/h}$$

The limestone supplied contains 94.5 wt % CaCO₃ (molecular weight 100.09) and 1.5 wt% MgCO₃ (molecular weight 84).

$$\text{The alkalinity in each 100 kg of limestone} = 100 \times 94.5\% / 100 + 100 \times 1.5\% / 84 = 112.4 \text{ kmol}$$

$$\text{The total amount of limestone consumed} = (142.6 / 112.4) \times 100 = 126.8 \text{ kg/h}$$