Model Answer

1. Define the following terms: Stok's diameter, Advective inversion, meteorology, thermosphere, air pollutants, Smog, Particulate matters, indoor air pollution, sorption, and fumigation. (10)

a- Stokes's equivalent diameter, d_s is the spherical diameter of equivalent particle having the same volume (V) and the same terminal settling velocity (See figure below). In this case d_s is calculated as: $d_s = \sqrt[3]{(6V/\pi)}$.

b- Advective inversion is a type of thermal inversion formed when warm air moves over a cold surface or cold air. For example, when a hill range forces a warm land breeze to follow at high levels and cool sea breathes flows at low level in the opposite direction.

c- Meteorology is the study of air quality depending on the dynamics of the atmosphere.

d- 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.

e- Air pollutants - airborne substances that occur in concentrations high enough to endanger the health of people and animals, to harm vegetation and structures, or to have undesirable effect on a given environment

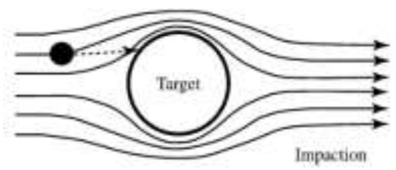
f- Smog: type of air pollution that contains two groups of pollutants; Smoke and fog referring to smoky fog as that detected in London (1952) and Loss- Anglos (1943).

g- 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.

h- Indoor air pollution: Pollutions from indoor sources, including the occupants and their activities (e.g. smoking, cooking, vacuuming), heating appliances, furnishings, building materials and penetration of contaminated air from outdoors.

i- Sorption is a pollutant removing/selection method combines both adsorption and absorption.

j- 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



2. The nitrogen oxides measured for coal powered power plant (where the reference oxygen concentration is 6%) is measured to be 200 ppm at condition of 250 °C and 95 kPa when 60% excess air was used. As per Egyptian law, the maximum NOx consideration shall not exceed 500 ppm at NPT. State if this power plant is environmentally compatible with Environmental Law or not? (10)

For carbon combustion with 40% excess air

$$C + 1.6(O_2 + 3.76N_2) \rightarrow CO_2 + 0.6O_2 + 6.016N_2$$

Thus the measured O2 is determined to be:

$O_2 = \frac{0.6}{1+0.6+6.016} = 7.88\%\ by\ Vol.$

The corrected NOx concentration is determined from:

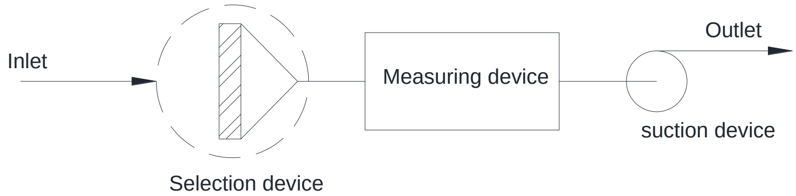
$$NO_{x,Corrected} = NO_{x,Mes}\frac{O_{2,Ref} - 21}{O_{2,Mes} - 21}\frac{T_{Mes}}{273}\frac{1}{P_{Mes}} = 400\frac{6-21}{7.88-21}\frac{273+250}{273}\frac{1}{0.95} = 461\ ppm$$

Thus the mentioned plant need the installation of control devices to reduce emitted NOx.

3. What are: (10)

   a. the main components of sampling train and its main features,
   b. the exhaust gas treatment methods for control of NO_x emissions,
   c. the major SO_2 removing processes,
   d. The purposes of dust collection process.

a) The simple sampling system consists of:
   1. Collection device or selection device to collect the proper of predefined component from the gas stream
   2. Measuring device that will measure the flow rate of selected pollutants only
   3. Suction device as blower, fan, or pump to pull the gases throughout the overall sampling system.



An effective sample line will satisfy the following criteria:

1- impart no change in concentration of the component of interest;
2- remove components or agents such as condensed moisture and dust, which could interfere with the analysis;
3- be reliable, with low maintenance requirements; and
4- be able to withstand the elements, wildlife and vandals.

b) Exhaust gases treatment techniques provide a chemically reducing (i.e., reversal of oxidization) substance to remove oxygen from nitrogen oxides. Examples include Selective Catalytic Reduction (SCR), which uses ammonia, Selective Non-Catalytic Reduction (SNCR) that use ammonia (NH3) or urea (H2NCONH2) to reduce NOx to nitrogen and water, and Fuel Reburning. Non-thermal plasma, an emerging technology, when used with a reducing agent, chemically reduces NOx; these methods are briefly described below.

   1- **Selective Noncatalytic Reduction (SNCR):** The overall reactions using ammonia as the reagent are:

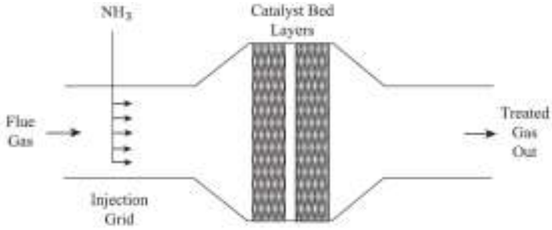
$$2NH_3 + 2NO + 1/2O_2 \leftrightarrow 2N_2 + 3H_2O \qquad 850 – 1050°C$$

$$2NH_3 + 2NO + O_2 + H_2 \leftrightarrow 2N_2 + 4H_2O \qquad 700\text{-}850 °C$$

$$4NH_3 + 5O_2 \leftrightarrow 4NO + 6H_2O$$

   In a typical application, SNCR produces about 30 to 50% NO_x reduction. For larger reduction levels SNCR system is replaced by SCR system. But the capital costs of SNCR may be lower than an SCR system

   2- Selective Catalytic Reduction (SCR): An SCR system consists primarily of an ammonia injection grid and a reactor that contains the catalyst be; as simplified in figure below with the following system of reactions leading to reduction of NO_x in an SCR system:



   SCR systems are capable of reducing NO_x up to 90%. In the common power- generation application of gas-fired turbines, less than 5 ppm NO_x at 15% O_2 can be achieved.

3- **Low-Temperature Oxidation with Absorption:** NO_x can be removed at low-temperature by its oxidation to highly soluble N_2O_5 that can be absorbed in a wet absorption tower. Ozone is used as the oxidizing agent for the reactions:

$$NO + O_3 \rightarrow NO_2 + O_2$$

$$NO2 + O_3 \rightarrow N_2O_5 + O_2$$

$$N_2O_5 + H_2O \rightarrow HNO_3$$

This technique able to remove up to 99% of NO_x, in some facilities may be there an acidic absorber for SO_2 control, so only the ozone generation and injection systems will be added. A possible disadvantage for some facilities would be additional nitrate in the wastewater discharge, since NO_x is removed in the form of nitric acid.

4- **Catalytic Absorption:** This system utilizes a single catalyst for removal of both NO_x and CO. First, NO, CO, and hydrocarbons are oxidized to NO_2 and CO_2. Then NO_2 is absorbed in a coating of potassium carbonate on the catalyst. The process can operate effectively at temperatures ranging from 150 to 350°C. Significant advantages of this process include the simultaneous removal of CO, hydrocarbons, and NO_x to very low levels, and the lack of ammonia storage and emissions. Less than 2 ppm NO_x has been demonstrated when used in conjunction with other NO_x control technologies.

c) the methods used to remove SO2 emissions from flue gases:

1- **Wet limestone.** The process flow sheet for the wet limestone scrubbing process. Particulate removal is typically done upstream by electrostatic precipitator or baghouse, but can be done downstream or as an integral part of the absorber.

2- **Wet soda ash or caustic soda.** A simplified process flow sheet for a wet soda ash or caustic soda scrubber. Particulate removal is typically done upstream of the absorption tower. Wet soda ash or caustic scrubbing is simpler than wet limestone scrubbing, since the reagent and the waste products are water soluble. There are no slurries or solid waste products to handle. At the same time, very high acid gas removal efficiency can be obtained. A common application for wet soda ash or caustic scrubbing is catalyst regeneration for fluid catalytic crackers in the refinery industry.

3- **Lime spray drying.** The simplified lime spray dryer process flow sheet. The optimum temperature is maintained by control of the approach-to-adiabatic saturation (approach). This is the difference between the spray dryer exit temperature and the adiabatic saturation temperature.

4- **Circulating lime reactor.** Simplified process flow sheets for circulating lime reactors using quicklime (similar can be used for hydrated lime). The circulating lime reactor process is similar to the spray drying process, but has one significant difference: reagent regeneration. In this system a much larger quantity of solids can be recycled from the particulate collectors to the reactor. The larger solids recycle produces two advantages. First, it enhances reagent utilization by providing additional gas–solid contact time with additional passes of solids through the reactor. Second, the recycled solids provide surface area to absorb moisture and scour the walls of the reactor vessel.

d) 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. A factory emits 20 g/s of SO_2 at height H=60 m (includes plume rise) when wind speed (u) is 3 m/s, at a distance of 1 km downstream, $\sigma_y$and σ_z are estimated to be 30 m and 20 m. What are the SO2 concentrations at the centerline of the plume and at a point 60 meters to the side and 20 meters below the centerline? (10)

Q = 20 g/s of SO_2

u = 3 m/s (u)

σ_y and σ_z are 30 m and 20 m

y = 0 and z = H

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

So reduces to:

C(x, 0, 0) = (20 g/s) / 2(pi*3*30*20) = 0.00177 g/m^3 = 1770 μ g/m^3 at centerline y and Z are 0

C = (0.00177 g/m^3) * (exp. $^{-2.5}$) = 0.000145 g/m3 or 145.23 μ g/m3 at 20 and 60 meters

5. State with details a comparison between (10)
   a. Terminal and curvilinear settling velocities,
   b. The impact of meteorological and topographical aspects on pollution of environment,
   c. atmospheric layers,
   d. damage cost and control cost,

a. For a spherical particle under Stokes's law, which is generally valid for the aerosol in the ambient atmosphere, the drag force is:

$$F_D = 3\pi\mu d_p V_p \text{, for Re < 1}$$

This relation is based on the following assumptions:

- rigid spherical particle
- Stokes's law or inertial force is much smaller than viscous force
- continuum fluid
- free flow with neglected wall effects
- the density of air is constant or low Mach number flow
- steady state flow

At terminal settling velocity, the drag force is equal to the gravitational force

$$3\pi\mu d_p V_p = \frac{(\rho_p - \rho)\pi d_p{}^3 g}{6} \text{ and } V_p = V_{sT}\text{, thus}$$

$$V_{sT} = \frac{(\rho_p - \rho) d_p{}^2 g}{18\mu} \text{ As } (\rho_p >> \rho) \text{ then } V_{sT} \approx \frac{\rho_p d_p{}^2 g}{18\mu}$$

where:

V_P = particle velocity (m/s),

ρ_P = particle density (kg/m^3)

ρ = fluid density (kg/m^3)

d = particle diameter (m),

g = gravitational acceleration (9.81 m/s^2)

μ= fluid viscosity (kg/m·s)

In case of curvature path or when a particulate-laden gas stream is made to flow in a circular manner within a cylinder, as shown below. Inertial force that is applied in a spinning gas stream is often termed centrifugal force. The movement of particles due to inertial force in a spinning gas stream is estimated using the same procedure described for terminal settling velocity due to gravitational force. Accordingly the particle will be in rest when the centrifugal force balances the drag force:

$$F_C = F_D \text{ where } F_C = m_p V_t^2 / R = \pi d_p^3 \rho_p V_t^2 / 6R \text{ and } F_D = 3\pi\mu d_p V_p$$

$$\text{thus } V_p = \frac{(\rho_p - \rho) d_p^{\,2} V_t^2}{18 \mu R}$$

where

FC = centrifugal force

V_t = tangential velocity of the gas

d_p = physical particle diameter

V_p = radial particle velocity

m_p = mass of the particle

R = radial position of the particle

ρ_p = particle density

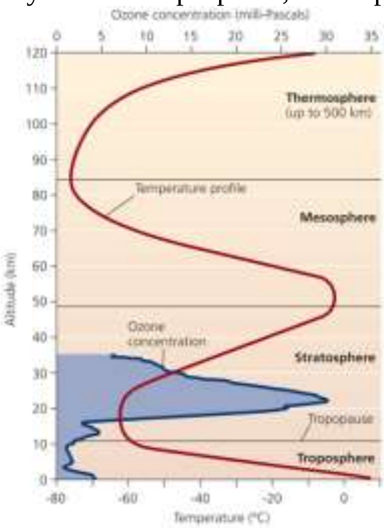
μ = gas viscosity

b. Meteorology aspects include **Temperature lapse rate, atmospheric stability and wind speed.** The ease with which pollutants can disperse vertically into the atmosphere is largely determined by the rate of change of air temperature with altitude. For some temperature profiles the air is stable, that is, air at a given altitude has physical forces acting on it that make it want to remain at that elevation. Stable air causes the dispersion and dilution of pollutants. For other temperature profiles, the air is unstable. In this case rapid vertical mixing takes place that leads to the increase of air quality. The atmosphere conditions is called super adiabatic, when its stability is normal and parcel of air pollutions will be warmer and less dense than the surrounding environment, so while raising, it cools at the adiabatic rate. As a result, it becomes more buoyant and tends to continue it's up ward motion. This vertical motion is enhanced by buoyancy; such an atmosphere is called unstable. In the unstable atmosphere the air from different altitudes mixes thoroughly. This is very desirable from the point of view of preventing pollution, since the effluents will be rapidly dispersed throughout atmosphere. The wind velocity profile is affected by the surface roughness and time of the day. During the day, thermal turbulence or eddies set up convective currents are caused due to solar heating, so that turbulent mixing is increased.

Topographical aspects include large bodies of water providing see breeze (having the thermal inertia of the water and can cause a slower temperature change than the nearby land) and the mountain - valley wind. In this case the air tends to flow down the valley at night Valleys are cooler at higher elevation and the driving force for the airflow result from the differential cooling. Similarly, cool air drains off the mountain at night and flows in to the valley. Both the sea breeze and the mountain valley wind are important in meteorology of air pollution. Large power stations are often located on ocean costs or adjacent to large lakes. In this case the stack effluent will tend to drift over the land during the day and may be subjected to fumigation.

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 organisms

Other 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

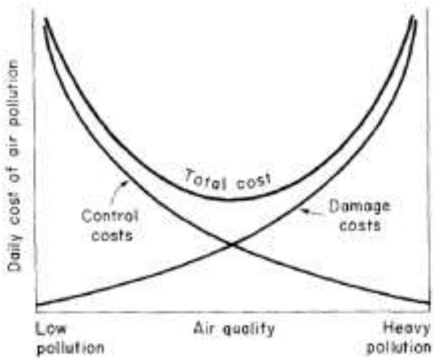
• **Mesosphere** extends above the stratosphere (from 50 to 80 km), temperature diminishes again (up to -80°C) creating the mesosphere (middle) layer. Other characteristics of mesosphere:
- Extremely low air pressure
- Temperatures decrease with altitude

• **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 H_2)

d. A logical inclination is to use total cost as the criterion by which to evaluate alternative air pollution reduction policies. The total cost of air pollution control can be divided into a sum of two costs:

1. **Damage costs**: the costs to the public of living in polluted air, for example, tangible (real) losses such as crop damage and deteriorated materials and intangible losses such as reduced visibility and eye and nasal irritation
2. **Control costs**: the costs acquired by emitters (and the public) in order to reduce emissions, for example, direct costs such as the price of equipment that must be purchased and indirect costs such as induced unemployment as a result of plant shutdown or relocation

Figure below shows qualitative form of these two costs and their sum as a function of air quality; poor air quality has associated with it high damage costs and low control costs, whereas good air quality is just the reverse. Cost/benefit principles indicate that the optimal air quality level is at the minimum of the total cost curve. The key problem is: How do we compute these curves as a function of air quality? Consider first the question of quantifying damage costs



Total cost of air pollution as a pollution sum of control and damage costs.

6. A settling chamber is installed in a small heat plant. Determine the overall collection efficiency of the settling chamber to collect particulate matters up to 100 μ, hence state the particle size at which the effective collection efficiency is 100%. The chamber dimensions are width = 3.3 m, height = 1 m, and length = 4.5 m and the volumetric flow rate of contaminated air stream = 2 m^3/sec. Assuming the flue gas dynamic viscosity of 1.8×10^{-5} $kg.m^{-1}.s^{-1}$, particle specific gravity = 2.65, and the the standard conditions = 25 ° C, 1 atm. (10)

For, settling chamber the collection efficiency is determined from:

$$\eta = \left[\frac{g\rho_p BL}{18\mu Q}\right] d_p^2$$

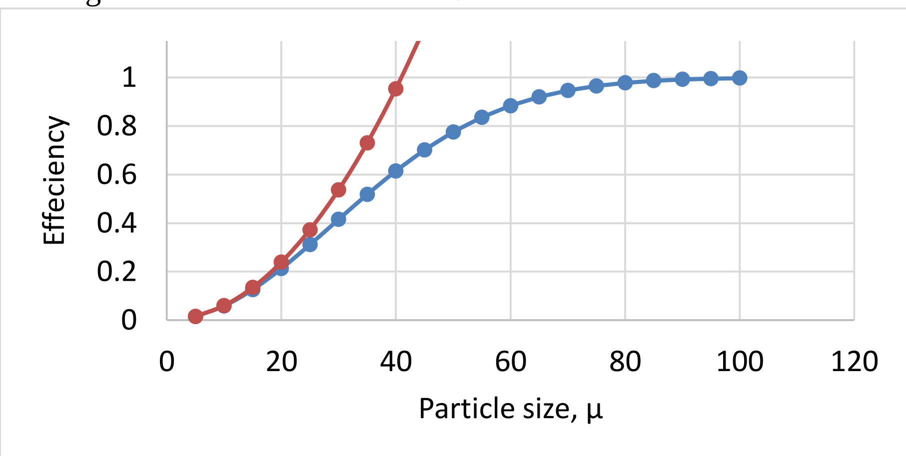
The effective efficiency is calculated from:

$$\eta_{eff} = 1 - \exp[-\eta]$$

Using the previous relation to draw variation of eefecicncy with particle size, the following table is produced:

D, μ	Efficiency	Effective eff.	D, μ	Efficiency	Effective eff.
5	0.014894	0.014783	55	1.802153	0.835057
10	0.059575	0.057835	60	2.144711	0.882898
15	0.134044	0.125449	65	2.517057	0.919303
20	0.238301	0.212035	70	2.91919	0.946023
25	0.372346	0.310884	75	3.351111	0.964955
30	0.536178	0.41502	80	3.81282	0.977914
35	0.729798	0.517993	85	4.304316	0.98649
40	0.953205	0.614496	90	4.8256	0.991978
45	1.2064	0.700727	95	5.376672	0.995377
50	1.489383	0.774488	100	5.957531	0.997414

Plotting data of this table to receive:



Best wishes, Ali M.A. Attia