How the Air We Breathe Deteriorate?

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Abstract:
Every day we consume around 12 kg of air[1]. This indicates that even a small amount of air pollutants (in unit of µg/m^3) can have huge impact on our health. The concentration of air pollutants not just depends on emission rate from source, but also on prevailing weather conditions. The article explains the mechanism which increases the amount of air pollutants in ambient air.

Introduction:

Clean and healthy air is one of the important ecosystem services provides by natural ecosystems. Recently, these services are declining to degradation and destruction of natural ecosystems like forests, mangroves, grasslands etc. Let's discuss about the causes of decline of our air quality. We would also try to understand how air pollutant affects our health and how can we reduce the air pollutants to a level which does not harm us.

What is air pollution?

As per the Air (Prevention and Control of Pollution) Act, 1981, air pollution is said to exist if the levels of gases, solids, or liquids present in the atmosphere are high enough to harm humans, other organisms, or materials. So, any substance gas, liquid or solid present in atmosphere, which affects our health or affects the health of animals and plants or deteriorates buildings or materials, is termed as air pollutant.

Case Study: Donora Smog, 1948

Now let's discuss about major air pollution episode which leads to formation environmental laws related to air pollution in many countries.

Donora is situated near Pittsburg at bank of Monongahela River in US. On October 26, 1948 the there was a dense fog in Donora. At that time the town's population was 13,000 and it was an industrial town. The two big industries one steel plant and one zinc reduction plant was successfully running in the town which supported the US economy during World War II by supplying galvanized iron articles like barbed fences, nails and sheets.

The fog was not unusual for the town's peoples at that time as it generally occurred in morning and lifted till noon when Sun arose. But, the fog of Tuesday, 26-Oct-1948 lasted for five days. The coal used in steel plant had high concentration of sulfur, while zinc reduction plant was using sulfur laden ore for extracting zinc metal. These two operations were releasing large amount of sulfur dioxide in atmosphere of the town. Due to above persisting fog on Wednesday and Thursday people started to smell pungent sulfur dioxide in air. On Friday morning physicians of the town received call from elderly and asthmatics for difficulty in breathing. However, till evening of Friday even young adults also started to call physicians for suffering from headache, stomach pain and nauseating feeling. On Saturday 10 am first death was reported and by afternoon 20 more peoples were died due to unknown disease. The owners of mills were sure this is nothing to do with operation in their plant, which was plausible as plant had been running for many decades. Fortunately, Sunday was holiday and plant operation was halted, mercifully rain also arrived on Sunday which cleared the atmosphere. But still it killed 50 more people in the next month and 6000 peoples in the town of 13,000, got sickened.

Later investigation found that generation of sulfate particles and their accumulation including the sulfur dioxide (source the source of sulfate particles) due to anticyclone, resulted in so many causalities.[2], [3]

Industrial Smog:

The incident which occurred in Donora is called industrial or sulfurous smog. The similar smog also occurs in London in 1952 and recently found in our country and China. The Donora smog incident explains us that air pollution depends on two factors weather conditions and emission rate of air pollutants. The industrial smog are characterized by particulate matter (PM, vide infra) of size (0.2 to 0.9 μm) which disperse visible light and causes the disappearance of blue sky. The particulate matter could be sulfate or nitrate particles.

Photochemical Smog:

As the application of petroleum products and natural gas replaced the use of more polluting coal, the incidences of industrial smog were minimized. However, the rapid of use petroleum products as transportation fuel, resulted in new type of smog which first occurred in Los Angles, US. This is cured in clear sunny day, in contrast to industrial smog which mostly formed during foggy weather. A severe photochemical smog incidence turns sky orange, which is different from grayish white sky observed during industrial smog.

Many secondary air pollutants are formed during incidence of photochemical smog. Let's try to understand mechanism of photochemical smog formation. As photochemical smog is formed by reaction of nitrogen oxides and volatile organic compounds (VOC), we would first discuss what major airs pollutants are.[4]

Major air pollutants:

The major pollutant whose safe level is given by Central Pollution Control Board of India is given below:

- Carbon Monoxide
- Nitrogen oxides
- VOC
- Ozone
- Sulphur oxides
- Suspended Particulate Matter

Carbon monoxide: It is toxic gas which is generated during combustion of hydrocarbon in low amount of oxygen. The complete combustion of hydrocarbon produces mainly CO_2 and H_2O, but incomplete combustion results in formation CO.

CO forms stronger bond with hemoglobin than O_2 and stops the ability of blood to supply O_2 to various tissues of our body. Impact of CO on our health depends on how much carboxyhemoglobin is formed in the blood after staying in environment possessing CO.

The percentage of carboxyhemoglobin generated in our blood is given by following expression:

$$\%\mathrm{COHb} = \beta(1 - e^{-\gamma t})[\mathrm{CO}] \quad (1)$$

Here, β = 0.15% per ppm of CO

γ = 0.048 per hr (hour)

[CO] = concentration of CO in ppm.

From above equation 1 it is clear that impact of CO depends on not just concentration of CO in atmosphere, but also on how much time we spend in polluted atmosphere.

Nitrogen oxides: There is seven nitrogen oxides is known in literature, but from air pollution perspective two are important, nitric oxide NO and nitrogen dioxide NO_2. There are two sources of nitrogen oxides. It is generated by direct reaction of N_2 and O_2 (Eq. 2) in IC engines where temperature is above approximately 800^{o}C. This is called thermal NOx.

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

Other source is nitrogen contained in fuels, which is converted to NOx during combustion and called fuel NOx. Most of nitrogen oxides emitted in the form of nitric oxide NO from the source. It is readily converted to NO_2 after its emission in atmosphere (Eq. 3).

$$2NO + O_2 \rightarrow 2NO \quad (3)$$

NO was found to have no adverse impact on health at concentration present in atmosphere. NO is an important gasotransmitter in our body, it is also released by macrophages (part of immune system) to kill engulfed pathogens. However, NO_2 irritate our lungs (induce bronchitis, pneumonia) and reduce its capacity for respiratory infections.

Volatile organic compounds (VOC): VOC are mostly non toxic organic compounds emitted from evaporation of fuels and solvents used in paints, varnishes and industrial processes. These are also emitted in atmosphere due to incomplete combustion of fuels. VOC are listed as air pollutants as these react with NOx in the presence of sun light and generate photochemical smog. Let's understand mechanism of photochemical smog formation.[5]

Mechanism of formation of photochemical smog:

NO_2 is brown colored photoactive gas responsible for reddish brown color of photochemical smog. It is broken down by photons of sun light and created a NO_2-NO-O_3 cycle (Eq. 4-6).

$NO_2 + h\nu \rightarrow NO + O$ (4)

$O_2 + O \rightarrow O_3$ (5)

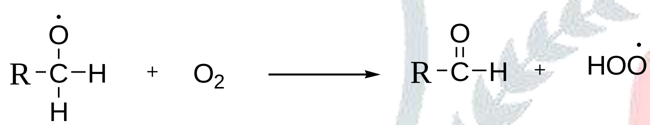
$O_3 + NO \rightarrow NO_2$ (6)

In this cycle initially generated NO_2 leads to formation of ozone O_3 which broken down by NO. As per experiments in done laboratory smog chamber, this cycle does not produce O_3 concentration which is harmful to humans. It is introduction of hydrocarbons (VOC) which disturb the above cycle and increases the concentration of O_3 in atmosphere, as shown below.

$R\text{-}CH3 + OH^{\cdot} \rightarrow R\text{-}CH_2^{\cdot} + H_2O$ (7)

$R\text{-}CH_2^{\cdot} + O_2 \rightarrow R\text{-}CH_2\text{-}O\text{-}O\cdot$ (8)

$R\text{-}CH2\text{-}O\text{-}O\cdot + NO \rightarrow R\text{-}CH2\text{-}O\cdot + NO2$ (9)



(10)

$HOO\cdot + NO \rightarrow NO_2 + OH\cdot$ (11)

Equations (9) and (11) explain that NO which destroys O_3 is consumed, while NO_2 increases due to presence of hydrocarbon and NOx both in atmosphere. It increases O_3 concentration in atmosphere. It also leads to generation of lachrymatory aldehydes and ketones in atmosphere which created irritation in our eyes during incidence of photochemical smog (Eq. 10). Hydroxyl free radicals which are naturally present in atmosphere are important species to clean our atmosphere. These radicals convert the pollutants entering in our atmosphere to CO_2, H_2O or water soluble compounds (H_2SO_4, HNO_3 etc.). Now the aldehyde formed in photochemical smog further react with hydroxyl free radicals and oxygen to generate peroxyacyl free radical which react with nitrogen dioxide and form eye irritant peroxyalkyl nitrate (Eq. 12-14), for R=CH3 it is called peroxyacetyl nitrate (PAN). Aldehydes, ketones, PAN and O_3 which are formed during photochemical smog are collectively called photochemical oxidants. Severity of photochemical smog is measured in terms O_3 present in atmosphere.

$RCHO + OH\cdot \rightarrow RCO\cdot + H2O$ (12)

$RCO\cdot + O_2 \rightarrow RC(O)OO\cdot$ (13)

$RC(O)OO\cdot + NO_2 \rightarrow RC(O)OONO_2$ (14)

Particulate matter and its impact on health:

Particulate matters are fine particles solid or liquids dispersed in atmosphere, also called aerosol. Depending on size particulate matter are classified as PM_{10} and $PM_{2.5}$. The examples of particulate matter are dust (dispersion of solids in air), fumes (formed by condensation of vapor), mist, fog (water dispersed in air) and smoke (carbonaceous matter dispersed in air). Only particulate matter having size in the range 0.4 μm to 10 μm are harmful to us. As particulate matter above diameter 10 μm are easily stopped at upper respiratory tract and those below 0.5 μm follow the air path when we inhale the air and returns back when we exhale the air back. However PM having diameter in the range 0.5 μm to 10 μm enters our lungs when we inhale, but mostly does not come back from lungs settle inside lungs by sedimentation.

Depending on size particulate matter are classified as PM_{10} and $PM_{2.5}$. The PM having size between 2.5 µm to 10 µm are referred as PM_{10}, while PM having diameter 0.5 to 2.4 µm are referred as $PM_{2.5}$. $PM_{2.5}$ are more injurious to health than PM_{10} as they can enter to alveoli sacks of our lungs and may inflame the lung tissues . The cytokines released due to lung inflammation was also found to damage the brain leading to dementia and Alzheimer disease. The damage to lung tissue also affects functioning of cardiovascular system (due to decrease of lung function) leading to cardiac disorders like congestive heart failure and non fatal heart attack. It also aggravates asthma, and irritation of air ways. Soot and smoke also contain polynuclear aromatic hydrocarbon (PAH), many of them such as benz[a]pyrene is known human carcinogen.[6]

Air pollution and meteorology:

Air pollution is not just depends on emission rate from source, but it also depends on prevailing weather condition. One of the weather condition which traps air pollution during no horizontal wind flow is temperature inversion. Now what is temperature inversion? Normally as me move to higher altitude temperature declines, so high mountain peaks mostly covered with snow. Rate of decrease of temperature with altitude is called lapse rate. Theoretically lapse rate for dry is 9.76 °C/km i.e. temperature decline by approximately 10 °C temperature as me moves 1 km above in atmosphere. Temperature inversion occurs when instead of decline of temperature it rises as we moves up.

The hot exhaust gases coming out from tailpipes and smoke stacks of industrial plants, move up (because these are less dense that surrounding air) they get cools down as they expand due to decline of pressure in upper atmosphere. If the ambient air temperature remained less than the moving up exhaust gases, these gases containing pollutant will move up continuously. However, due to temperature inversion moving up exhaust gases encounter hot air in upper atmosphere, which bounce them back to ground surface. Or warm upper air works as lid for vertical dispersion of air pollutants. Temperature inversion generally occurs during winter months as land cools fast than upper atmosphere. The temperature inversion becomes more significant in valley as cool air over mountain surface rolls down in the valley.

Air pollution prediction and its control measure:

We can predict the concentration of air pollutants for a given emission rate and prevailing weather condition. A simple method is Gaussian plum model for the point source (Fig. 5). Point source is generally a smoke stake of an industrial plant. Highway is regarded as line source, while an industrial complex having many industries could be regarded as an area source. For a point source as per Gaussian plume model concentration of pollutant C(x, y) at point (x, y) could be:

$$C(x, y) = (Q/\pi.u_H.\sigma_z.\sigma_y).\exp(-H^2/2\sigma_z).\exp(-y^2/2\sigma_y) \qquad (15)$$

Here,

C(x, y) = concentration at ground-level at the point (x, y), µg/m^3

x = distance directly downwind, m

y = horizontal distance from plume center line

Q = emission rate of pollutants, µg/s

H = effective stack height, m

u_H = average wind speed at the effective height of the stack, m/s

σ_y = horizontal dispersion coefficient, m

σ_z = vertical dispersion coefficient, m

From equation 15, it is clear that the concentration of pollutant is dependent of emission rate from source and weather condition since value of dispersion coefficients σ_y and σ_z depends on weather condition or stability of atmosphere (temperature inversion makes the atmosphere stable). Since we cannot control the stability of atmosphere, we may control the air pollution (maintain air pollutants at safe level) by controlling emission rate Q. It could be done either using improved technologies for combustion or simply removing the air pollutants from exhaust gases. Other option is restricting the operation of pollution source like implementing even-odd formula or temporarily stopping the industrial operation.

Summary:

Two types of severe air pollutions industrial smog (or just smog) and photochemical smog are formed from reactions of primary pollutant emitted from various sources in atmosphere. Concentrations of air pollutants depend not on rate of emission from source, but also on prevailing weather condition. Temperature inversion is one of the important weather phenomenons responsible for trapping air pollutants generated in atmosphere. We may model the concentration of air pollutants using Gaussian plume model and its extensions. This helps us in not exceeding air pollution above safe level. Air pollution could be controlled either inherently safe technologies for combustion or manufacturing or using efficient scrubber for removing air pollutants from air. If nothing is available then we can temporarily stop the operation of polluting source.

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