Air Pollution and Control
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Lecture 44
Air Pollution Control Devices: Part – 3

Hello, friends. So, these days we are discussing about Air Pollution Control devices. And in that series we have already discussed the devices which are used for capturing or controlling the particulate matter. And today we will start about the devices which are used for capturing the gaseous pollutants. So, in two parts we discussed about air pollution control of particulate matter, now in two parts we will discuss about gaseous pollutant control techniques. So, today we will discuss like adsorption, absorption and biofiltration and then we will conclude.

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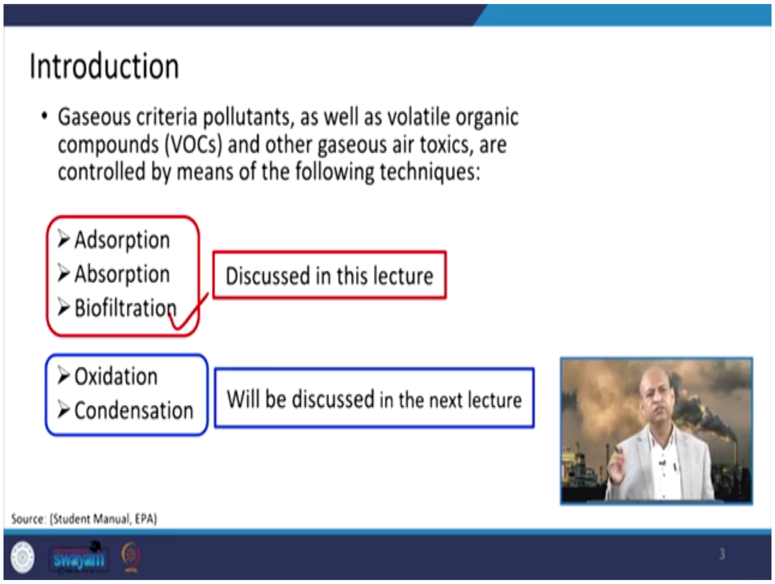

Introduction

- Gaseous criteria pollutants, as well as volatile organic compounds (VOCs) and other gaseous air toxics, are controlled by means of the following techniques:

➢ Adsorption
➢ Absorption
➢ Biofiltration

Discussed in this lecture

➢ Oxidation
➢ Condensation

Will be discussed in the next lecture

Source: (Student Manual, EPA)

So, when we talk about gaseous pollutants, how to capture them, so whether it is criteria pollutants of gaseous nature or volatile organic compounds that is VOCs or other gaseous toxic, air toxic all these are controlled by means of the following techniques and which can be listed like adsorption, absorption, biofiltration. So, these three today we will discuss. Then there are oxidation and condensation, so that we will discuss in the next lecture.

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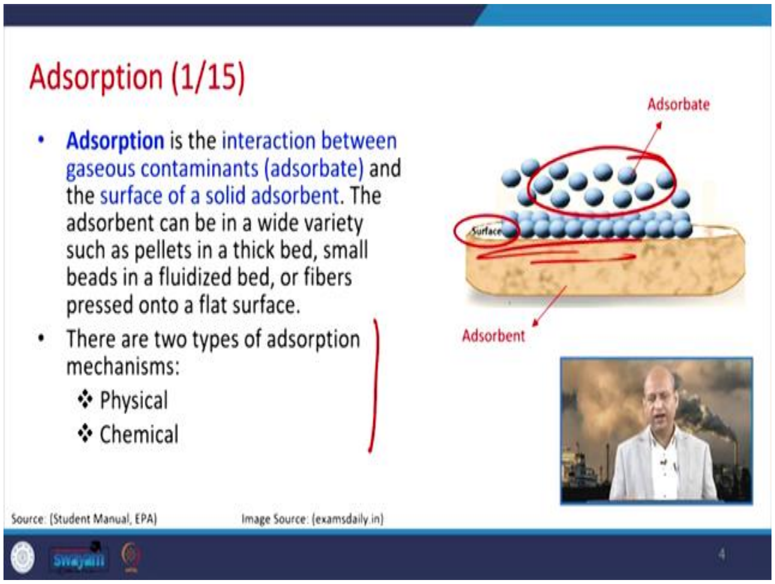

Adsorption (1/15)

- **Adsorption** is the interaction between gaseous contaminants (adsorbate) and the surface of a solid adsorbent. The adsorbent can be in a wide variety such as pellets in a thick bed, small beads in a fluidized bed, or fibers pressed onto a flat surface.
- There are two types of adsorption mechanisms:
  - ❖ Physical
  - ❖ Chemical

Source: (Student Manual, EPA) Image Source: (examsdaily.in)

So, when we talk about adsorption, so this adsorption is nothing but basically it occurs because of interaction between gaseous contaminants or pollutants that we call it as adsorbate, and the surface of a solid adsorbent. So, that is the basically interaction or the process of that interaction is the adsorption. So, the adsorbent can be in a wide variety of these materials like pellets in a thick bed or small beads in fluidized beds or fiber pressed onto a flat surface.

So, basically two mechanisms are used in adsorption, one is physical, other one is chemical. So, this is adsorbate which is captured or which is deposited or chemically adhered and this is the surface area, this is the adsorbent where they stick to it. So, this phenomenon could be like physical process or chemical process.

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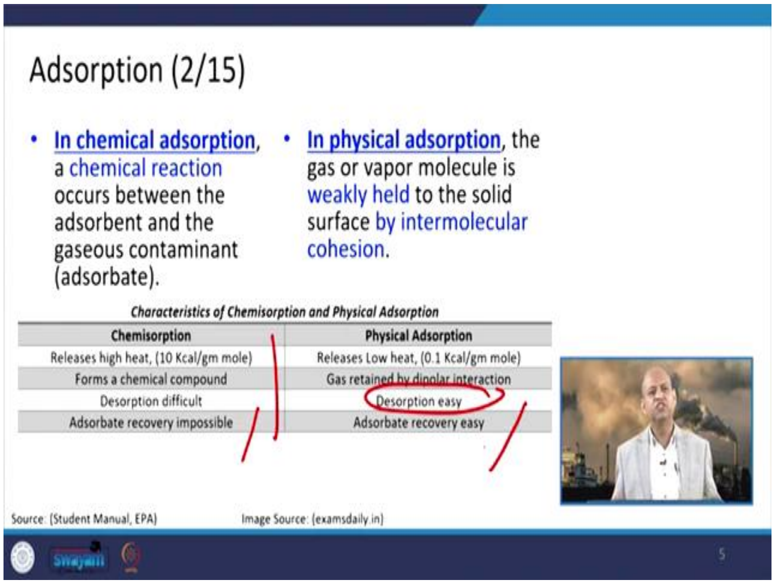

Adsorption (2/15)

- **In chemical adsorption**, a chemical reaction occurs between the adsorbent and the gaseous contaminant (adsorbate).
- **In physical adsorption**, the gas or vapor molecule is weakly held to the solid surface by intermolecular cohesion.

Characteristics of Chemisorption and Physical Adsorption

Chemisorption	Physical Adsorption
Releases high heat, (10 Kcal/gm mole)	Releases Low heat, (0.1 Kcal/gm mole)
Forms a chemical compound	Gas retained by dipolar interaction
Desorption difficult	Desorption easy
Adsorbate recovery impossible	Adsorbate recovery easy

Source: (Student Manual, EPA) Image Source: (examsdaily.in)

In chemical adsorption process basically, a chemical reaction occurs between this adsorbent and the gaseous contaminant or the adsorbate. And in physical process what happens, the gas or vapor molecules is weakly held on to the solid surface by intermolecular cohesion. So, the characteristics when we talk about this chemisorption or physical absorption, so like in chemisorption or chemical adsorption this releases high heat, this chemical process, because of chemical process like 10 kilocalorie per gram of the mole.

And in physical adsorption basically releases low heat like 0.1 kilocalorie per gram of mole. If we talk about like it forms chemical compounds, this gas is retained by dipolar interaction. It does not change its state or nature. In chemical process, chemical adsorption, this can form some sort of chemical compound. And desorption is difficult means it is very difficult to get back that particular adsorbate which has been absorbed chemically. And this desorption is easy, means you can get again if you want to resource recovery is to be done then this is the physical adsorption is a good process. Then in chemical process adsorbate recovery impossible and adsorbate recovery is easy in this physical process. So, that is the consequence basically.

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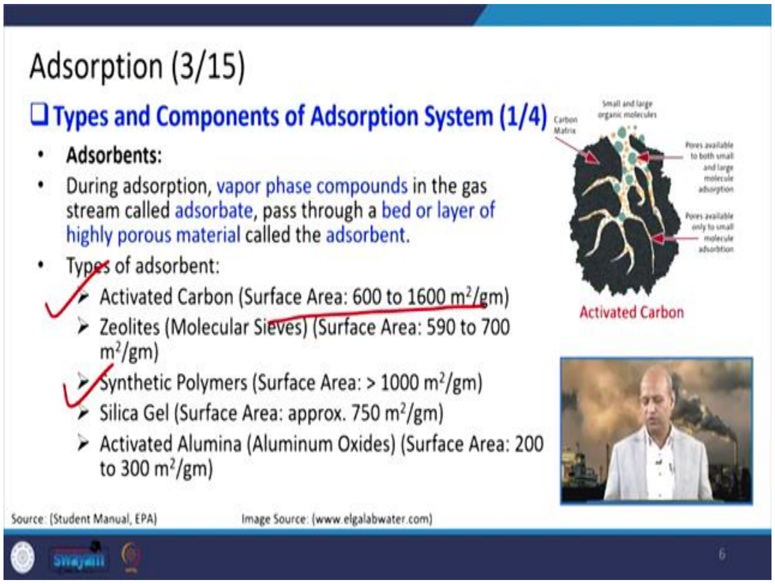

Adsorption (3/15)

❑ Types and Components of Adsorption System (1/4)

- **Adsorbents:**
- During adsorption, vapor phase compounds in the gas stream called adsorbate, pass through a bed or layer of highly porous material called the adsorbent.
- Types of adsorbent:
  - Activated Carbon (Surface Area: 600 to 1600 m^2/gm)
  - Zeolites (Molecular Sieves) (Surface Area: 590 to 700 m^2/gm)
  - Synthetic Polymers (Surface Area: > 1000 m^2/gm)
  - Silica Gel (Surface Area: approx. 750 m^2/gm)
  - Activated Alumina (Aluminum Oxides) (Surface Area: 200 to 300 m^2/gm)

Source: (Student Manual, EPA) Image Source: (www.elgalabwater.com)

Now, if we look into like types and components of this adsorption system, then basically when we talk about adsorbents, which kind of adsorbents are available, so during this adsorption process basically these upper phase compounds in the gas stream which is called adsorbate, as we have already discussed, this passes through a bed or layer of the highly porous material, which is called as adsorbent.

So, the porosity is something which is very helpful to give the characteristic of adsorbent. So, the types of absorbent depending upon their porosity we can see different materials like activated carbon which is the excellent adsorbent basically, because the surface area is very high 600 to 1600 square meter per gram. See the activity carbon surface area is very high. So, the lot of porosity exists there and this lot of surface area is there where gases and other things can stick to or this cohesion can occur.

Then zeolite if you talk, these molecular sieves, they have also good surface area, but it does not go beyond 700, 590 to 700 square meter per gram of the mole. Synthetic polymers the surface area is around more than 1000 square meter per gram. So, this is also a good in that sense. It is comparable to the activated carbon. When we talk about the silica gel, it has again surface area similar to zeolite like 750 square meter per gram also. Activated alumina is also another adsorbent which is aluminum oxide and, but its surface area available for this adsorption process is not more than 200 to 300 square per gram. So, that way activated carbon is the best sort adsorbent.

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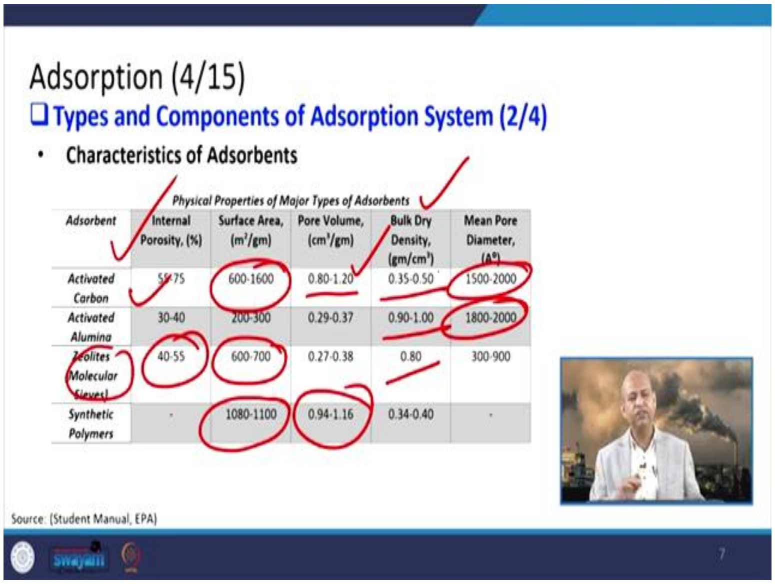

Adsorption (4/15)

❑ Types and Components of Adsorption System (2/4)

- **Characteristics of Adsorbents**

Physical Properties of Major Types of Adsorbents

Adsorbent	Internal Porosity, (%)	Surface Area, (m^2/gm)	Pore Volume, (cm^3/gm)	Bulk Dry Density, (gm/cm^3)	Mean Pore Diameter, (A°)
Activated Carbon	55-75	600-1600	0.80-1.20	0.35-0.50	1500-2000
Activated Alumina	30-40	200-300	0.29-0.37	0.90-1.00	1800-2000
Zeolites (Molecular Sieves)	40-55	600-700	0.27-0.38	0.80	300-900
Synthetic Polymers	-	1080-1100	0.94-1.16	0.34-0.40	-

Source: (Student Manual, EPA)

When we see different physical properties or characteristics of these major type of adsorbents like this is the list of the adsorbent and here are internal porosity. So, the maximum porosity is of the activated carbon as we have seen because of this surface area. Then zeolite is the second one in that sense 40 to 55. Third one is activated alumina. But the surface area basically, even if surface area again synthetic polymers have 1080 to 1100, 600 to 1600 is activated carbon depending upon its quality and 600 to 700 zeolite molecular sieves which we have already seen.

Pore volume maximum like 0.8 to 1.20 cubic centimeter per gram in case of activated carbon, then the second one is this one 0.94 to 1.16. So, it is comparable. Activated carbon and synthetic polymers are almost same in terms of pore volume. When we talk about the bulk dye density, so the activated carbon has 0.35 to 0.5 gram per cubic centimeter, activated alumina has 0.9 to 1. So, this is maximum in that sense, after that this zeolite 0.80 or so.

Then we talk about the mean pore diameter, so the maximum is basically of this activated alumina and the second one is the activated carbon. So, that way different physical properties, which influence behavior of this adsorption process in totality.

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Adsorption (5/15)

❑ Types and Components of Adsorption System (3/4)

- **Adsorption Systems**
- Nonregenerative Adsorption Systems
- The adsorbent bed is discarded as it approaches saturation with the contaminant and is termed nonregenerative.
- Designed for odor control and other low contaminant concentration applications (<10 ppm).

Source: (Student Manual, EPA)

When we see about this adsorption system, non-regenerative adsorption system basically, so these are the absorbent bed which are discarded when it approaches saturation with the contaminant and is termed as non-regenerative. We cannot regenerate it. So, we have to discard it after saturation state is there. If regeneration is possible, then we can regenerate it and reuse it again. But that is not possible in case of non-regenerative type of adsorption systems. And they are designed basically for odor control or some low contaminant concentrations applicable like less than 10 ppm or so.

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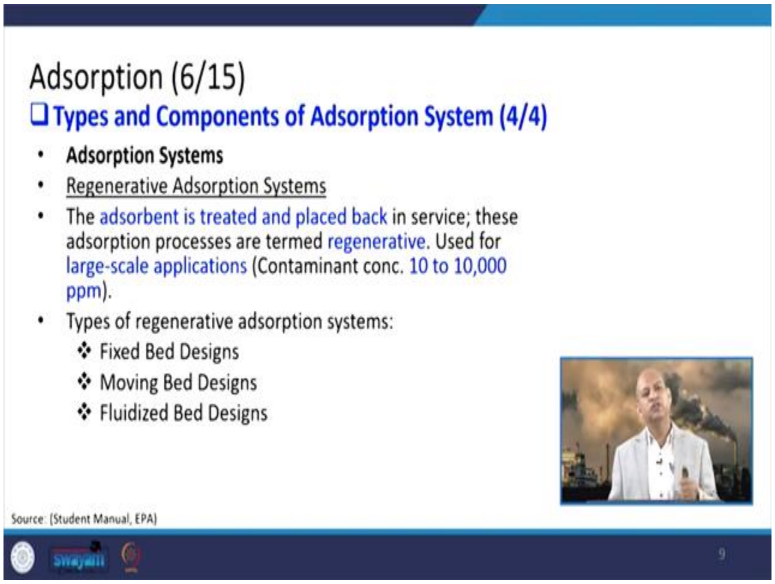

Adsorption (6/15)

❑ Types and Components of Adsorption System (4/4)

- **Adsorption Systems**
- Regenerative Adsorption Systems
- The adsorbent is treated and placed back in service; these adsorption processes are termed regenerative. Used for large-scale applications (Contaminant conc. 10 to 10,000 ppm).
- Types of regenerative adsorption systems:
  - ❖ Fixed Bed Designs
  - ❖ Moving Bed Designs
  - ❖ Fluidized Bed Designs

Source: (Student Manual, EPA)

Well, when we talk about regenerative adsorption systems, so adsorbent is treated and placed back in service after regeneration. So, these adsorption process are termed as regenerative because of this property and this can be used for large scale applications like contaminant of high concentration 10 to 10,000 ppm or so. Then types of regenerative adsorption systems further can be subdivided in terms of like fixed bed designs or moving bad designs or fluidized bed designs.

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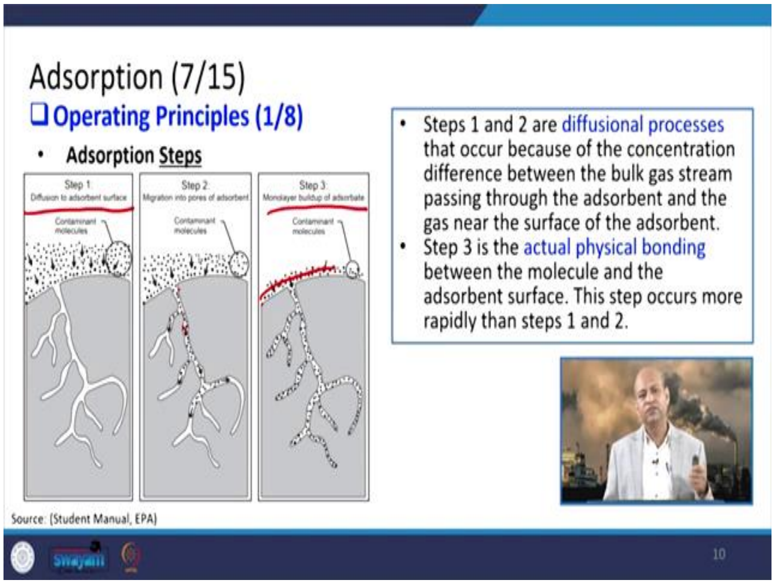

Adsorption (7/15)

❑ Operating Principles (1/8)

- **Adsorption Steps**

- Steps 1 and 2 are diffusional processes that occur because of the concentration difference between the bulk gas stream passing through the adsorbent and the gas near the surface of the adsorbent.
- Step 3 is the actual physical bonding between the molecule and the adsorbent surface. This step occurs more rapidly than steps 1 and 2.

Source: (Student Manual, EPA)

Like operating principles if we discuss, the adsorption steps are basically in these three figures it is shown like Step 1 diffusion to absorb surface. So, diffusion occurs at the adsorb surface and contaminant molecules are visible here. Then the migration into pores, the secondary stage is these molecules start to migrate into the pores which are available in these adsorbents. Then this monolayer buildup of adsorbent at the, means the pores are packed and this kind of layer starts to build-up at the surface.

So, these Step 1 and Step 2 are diffusional processes that occur because of the concentration difference between the bulk gas stream passing through the adsorbent and the gas near the surface of the adsorbent. And the Step 3 is the actual physical bonding between the molecules and the absorbent surface. So, this step occurs more than, rapidly than Step 1 and 2. The third stage is kind of having the fastest speed.

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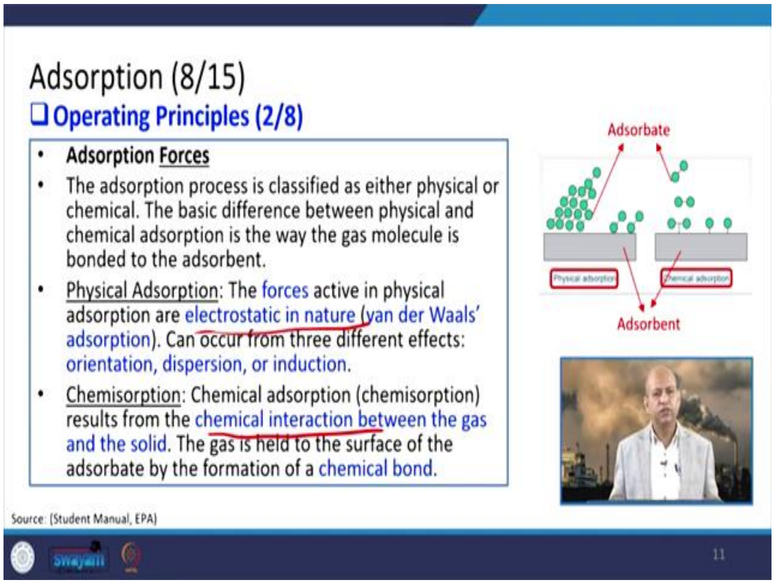

Adsorption (8/15)

❑ Operating Principles (2/8)

- **Adsorption Forces**
- The adsorption process is classified as either physical or chemical. The basic difference between physical and chemical adsorption is the way the gas molecule is bonded to the adsorbent.
- Physical Adsorption: The forces active in physical adsorption are electrostatic in nature (van der Waals' adsorption). Can occur from three different effects: orientation, dispersion, or induction.
- Chemisorption: Chemical adsorption (chemisorption) results from the chemical interaction between the gas and the solid. The gas is held to the surface of the adsorbate by the formation of a chemical bond.

Source: (Student Manual, EPA)

When we see like absorption forces, which are responsible for this adsorbent and adsorbate sticking together, so this is basically electrostatic nature in physical adsorption. In chemical, this is the chemical interaction between the gas and the solid. So, both these two things are different in that sense in fact. So, these adsorption forces of physical adsorption and chemical, this chemisorption has different way, because the physical adsorption uses this electrostatic force kind of thing and in chemical absorption, chemical interaction occurs basically.

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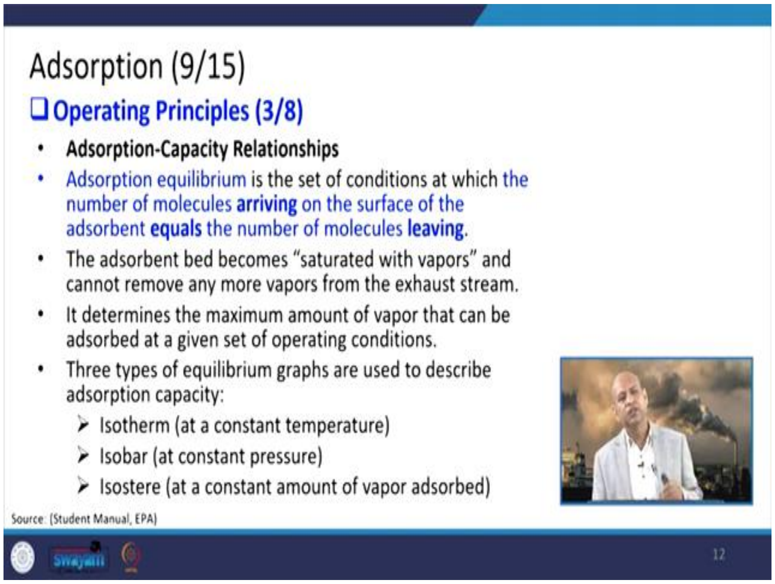

Adsorption (9/15)

❑ Operating Principles (3/8)

- **Adsorption-Capacity Relationships**
- Adsorption equilibrium is the set of conditions at which the number of molecules **arriving** on the surface of the adsorbent **equals** the number of molecules **leaving**.
- The adsorbent bed becomes "saturated with vapors" and cannot remove any more vapors from the exhaust stream.
- It determines the maximum amount of vapor that can be adsorbed at a given set of operating conditions.
- Three types of equilibrium graphs are used to describe adsorption capacity:
  - Isotherm (at a constant temperature)
  - Isobar (at constant pressure)
  - Isostere (at a constant amount of vapor adsorbed)

Source: (Student Manual, EPA)

Then the capacity, the adsorption capacity relationships again depend upon equilibrium. So, adsorption equilibrium is the set of conditions at which the number of molecules arriving at the surface of the adsorbent equals to the number of molecules leaving, so that kind of steady state equilibrium state has to be achieved and the adsorbent bed become saturated with the vapors and cannot remove any more vapors from the exhaust system that kind of state happens to be there. It determines the maximum amount of vapor that can be adsorbed at a given set of operating conditions and three types of equilibrium graphs are used to describe these absorption capacity basically, like isotherms or isobars and isostere.

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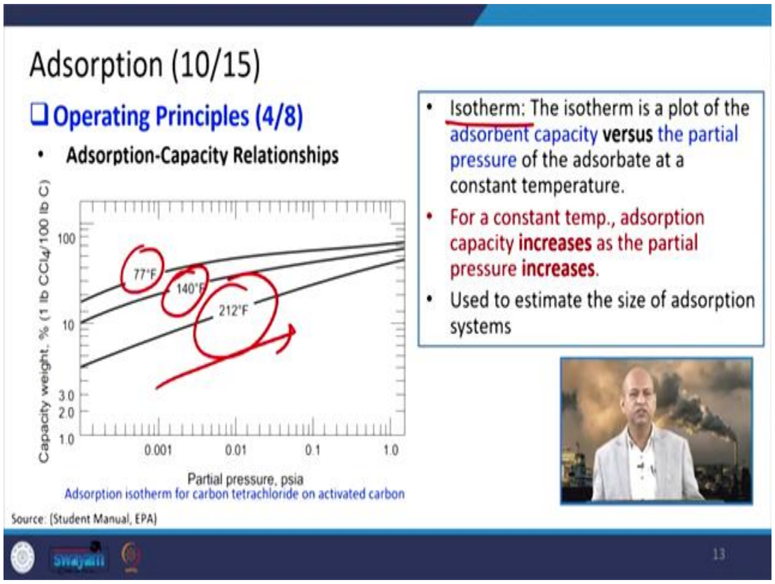

Adsorption (10/15)

❑ **Operating Principles (4/8)**

- **Adsorption-Capacity Relationships**

Adsorption isotherm for carbon tetrachloride on activated carbon

Source: (Student Manual, EPA)

- Isotherm: The isotherm is a plot of the adsorbent capacity **versus** the partial pressure of the adsorbate at a constant temperature.
- For a constant temp., adsorption capacity **increases** as the partial pressure **increases**.
- Used to estimate the size of adsorption systems

So, these are the partial pressure versus this capacity weight. So, when we talk about isotherms these, isotherm is a plot of the adsorbent capacity versus the partial pressure as it is shown in the figure. Though the title is not shown in the figure, but basically this is the isotherm. And for a constant temperature basically this adsorption capacity increases as the partial pressure increases. The partial pressure increases so the capacity also increases with the fixed temperature whether it is 212 or 140 means whatever temperature you take if it is constant then with respect to the partial pressure the capacity of adsorption also increases.

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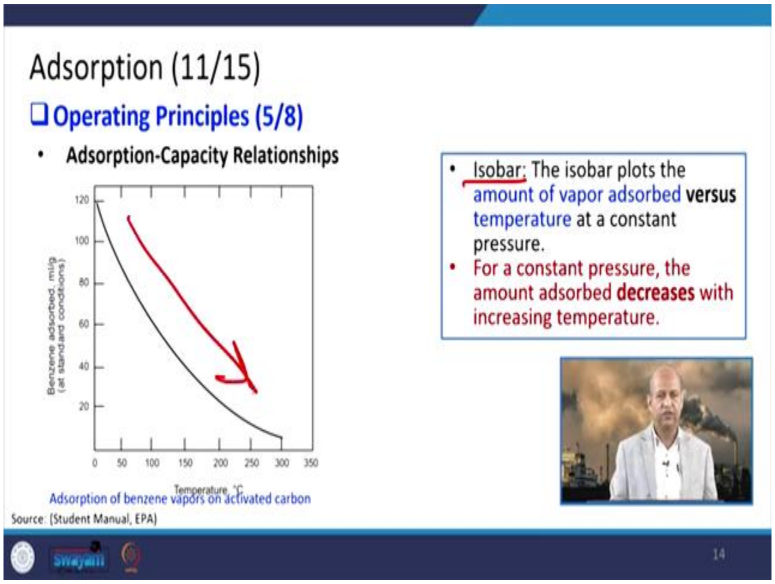

Adsorption (11/15)

❑ Operating Principles (5/8)

- **Adsorption-Capacity Relationships**

Adsorption of benzene vapors on activated carbon

Source: (Student Manual, EPA)

- Isobar: The isobar plots the amount of vapor adsorbed **versus** temperature at a constant pressure.
- For a constant pressure, the amount adsorbed **decreases** with increasing temperature.

When we talk about isobar, when this pressure is constant, in that case, when you increase the temperature, this adsorption decreases. The capacity of the adsorption decreases. It decreases like this. So, that is you know kind of inversely proportional or so.

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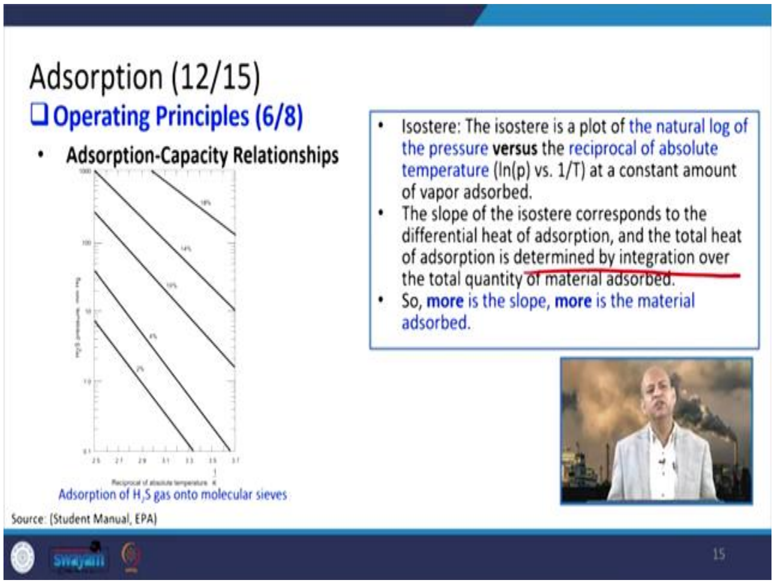

Adsorption (12/15)

❑ Operating Principles (6/8)

- **Adsorption-Capacity Relationships**

Adsorption of H_2S gas onto molecular sieves

Source: (Student Manual, EPA)

- Isostere: The isostere is a plot of the natural log of the pressure **versus** the reciprocal of absolute temperature (ln(p) vs. 1/T) at a constant amount of vapor adsorbed.
- The slope of the isostere corresponds to the differential heat of adsorption, and the total heat of adsorption is determined by integration over the total quantity of material adsorbed.
- So, **more** is the slope, **more** is the material adsorbed.

When we talk about these isosteres, these are the plots of the natural log of the pressure versus the reciprocal of the absolute temperature. So, again the slope of the isostere corresponds to the differential heat of the adsorption and the, this total heat of adsorption is determined by the integration over the total quantity of the material which is adsorbed. So, more is the slope more is the material which can be adsorbed.

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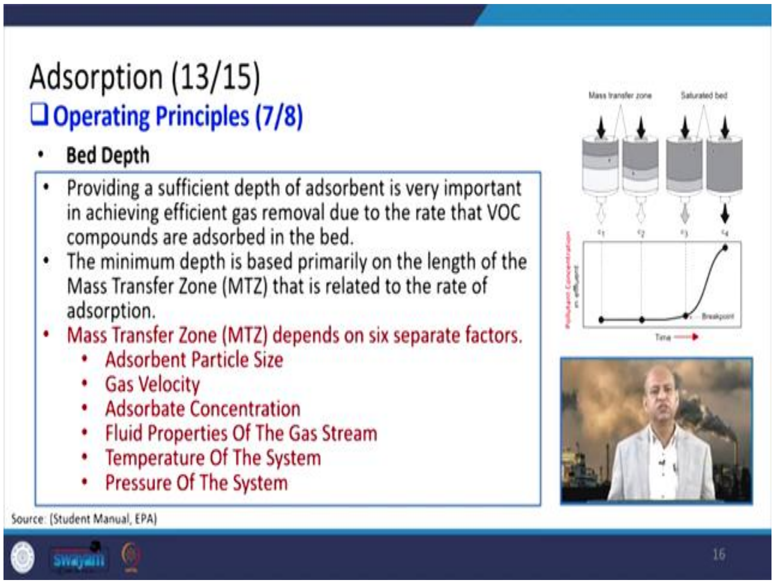

Adsorption (13/15)

❑ Operating Principles (7/8)

- **Bed Depth**
  - Providing a sufficient depth of adsorbent is very important in achieving efficient gas removal due to the rate that VOC compounds are adsorbed in the bed.
  - The minimum depth is based primarily on the length of the Mass Transfer Zone (MTZ) that is related to the rate of adsorption.
  - Mass Transfer Zone (MTZ) depends on six separate factors.
    - Adsorbent Particle Size
    - Gas Velocity
    - Adsorbate Concentration
    - Fluid Properties Of The Gas Stream
    - Temperature Of The System
    - Pressure Of The System

Source: (Student Manual, EPA)

Well, when we talk about the bed depth, so the sufficient depth has to be there of the adsorbent, because it is important for achieving the efficient gas removal mechanism. And because like you want to remove these VOCs etc. so this particular principle has to be taken into account. The minimum depth is based primarily on the length of Mass Transfer Zone, MTZ and that is related to the rate of adsorption.

And this Mass Transfer Zone or MTZ basically depends on six separate factors which are like adsorbed particle size or gas velocity or adsorbate concentration, fluid properties of the gas stream, temperature of the system and pressure of the system all these factors really govern the efficiency of this adsorption process.

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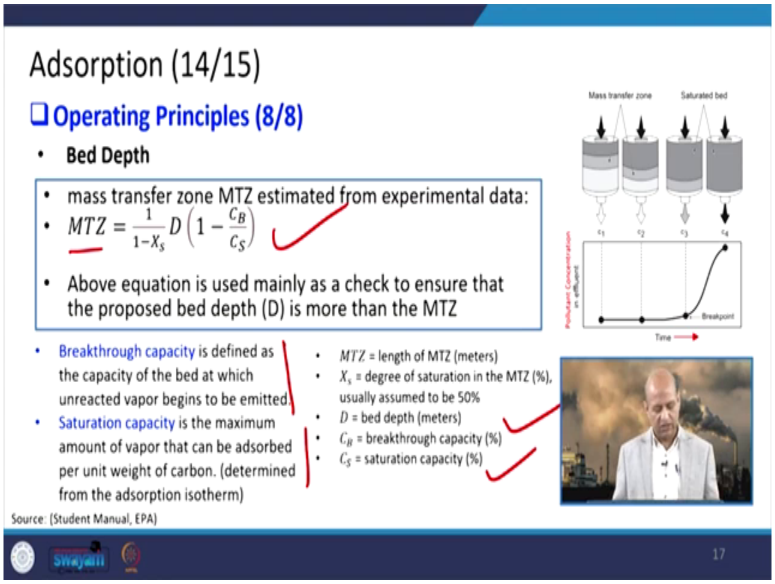


Adsorption (14/15)

❑ Operating Principles (8/8)

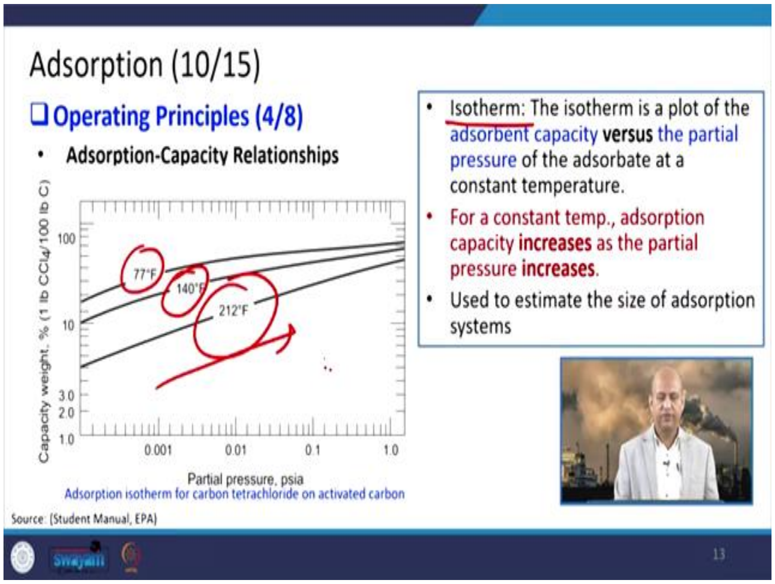
- **Bed Depth**

- mass transfer zone MTZ estimated from experimental data:
- $MTZ = \frac{1}{1-X_s} D\left(1 - \frac{C_B}{C_S}\right)$
- Above equation is used mainly as a check to ensure that the proposed bed depth (D) is more than the MTZ

- Breakthrough capacity is defined as the capacity of the bed at which unreacted vapor begins to be emitted.
- Saturation capacity is the maximum amount of vapor that can be adsorbed per unit weight of carbon. (determined from the adsorption isotherm)

- MTZ = length of MTZ (meters)
- X_s = degree of saturation in the MTZ (%), usually assumed to be 50%
- D = bed depth (meters)
- C_B = breakthrough capacity (%)
- C_S = saturation capacity (%)

Source: (Student Manual, EPA)



Adsorption (10/15)

❑ Operating Principles (4/8)

- **Adsorption-Capacity Relationships**

Adsorption isotherm for carbon tetrachloride on activated carbon

- Isotherm: The isotherm is a plot of the adsorbent capacity **versus** the partial pressure of the adsorbate at a constant temperature.
- For a constant temp., adsorption capacity **increases** as the partial pressure **increases**.
- Used to estimate the size of adsorption systems

Source: (Student Manual, EPA)

So, bed depth if you want to calculate basically this is the empirical relationship which can be used like MTZ equals 1 upon 1 minus X_s D into 1 minus C_B upon C_S $[1/(1-X_s)\ D(1-C_B/C_S)]$. C_B is breakthrough capacity in percentage, C_S is saturation capacity in percentage, MTZ already given length of the MTZ here acts as degree of saturation.

$$MTZ = \frac{1}{1-X_S} D\left(1 - \frac{C_B}{C_S}\right)$$

So, this breakthrough capacity is basically defined as the capacity of the bed at which unreacted vapor begins to be emitted. And the saturation capacity is the maximum amount of vapor that can be adsorbed per unit weight of the activated carbon determined from the adsorption isotherm. From this we can determine these values.

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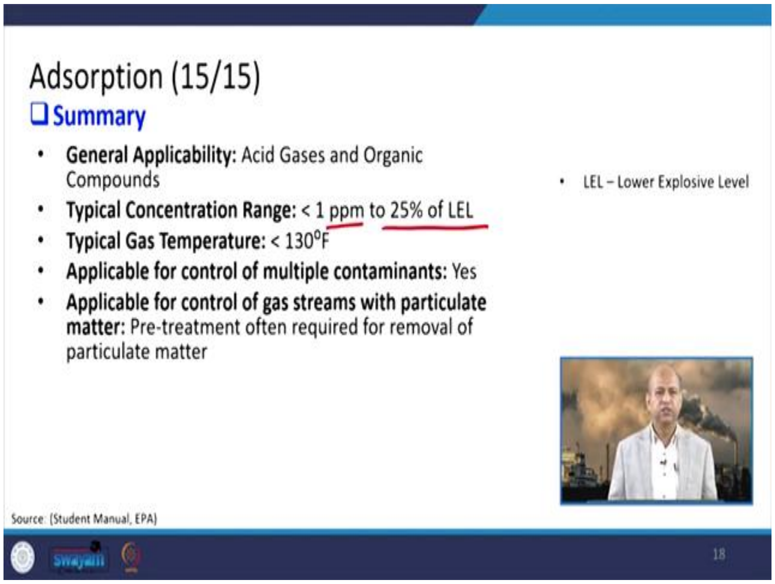

Adsorption (15/15)

❑ Summary

- **General Applicability:** Acid Gases and Organic Compounds
- **Typical Concentration Range:** < 1 ppm to 25% of LEL
- **Typical Gas Temperature:** < 130^{o}F
- **Applicable for control of multiple contaminants:** Yes
- **Applicable for control of gas streams with particulate matter:** Pre-treatment often required for removal of particulate matter

- LEL – Lower Explosive Level

Source: (Student Manual, EPA)

So, in summary, we can say the adsorption summary can be like general applicability of adsorption is like acid gases and organic compounds can be removed by these adsorption process. So, the typical concentration range can vary like it can be less 1 ppm and up to 25 percent of LEL. LEL is Lower Explosive Level. So, that range can be easily handled.

And the typical gas temperature which it can handle is said to be like less than 130-degree Fahrenheit. It can be applicable for control of multiple contaminants that is possible and the applicable for control of gas streams with particulate matter. So, the pretreatment often required for removal of the particulate matter in that case basically.

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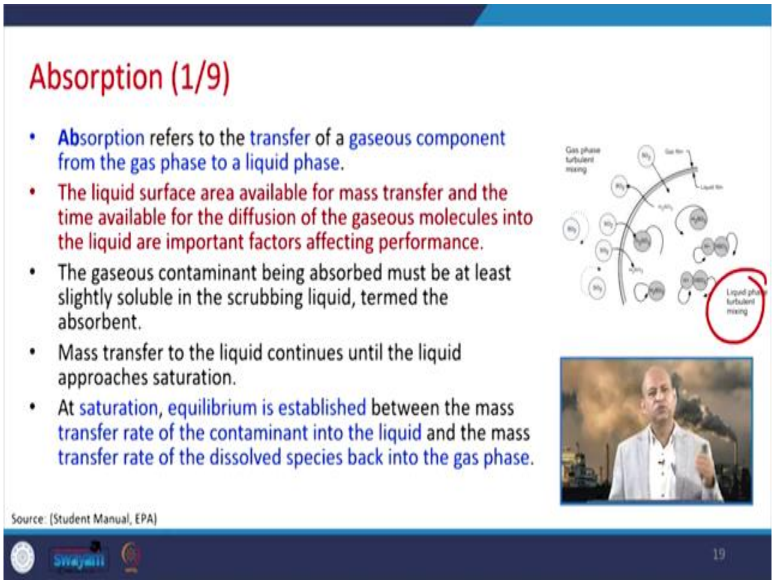

Absorption (1/9)

- **Ab**sorption refers to the transfer of a gaseous component from the gas phase to a liquid phase.
- The liquid surface area available for mass transfer and the time available for the diffusion of the gaseous molecules into the liquid are important factors affecting performance.
- The gaseous contaminant being absorbed must be at least slightly soluble in the scrubbing liquid, termed the absorbent.
- Mass transfer to the liquid continues until the liquid approaches saturation.
- At saturation, equilibrium is established between the mass transfer rate of the contaminant into the liquid and the mass transfer rate of the dissolved species back into the gas phase.

Source: (Student Manual, EPA)

Now, if we go for absorption, so adsorption is over, now we go for absorption, both are thing, two different things. Adsorption means at the surface, absorption means like liquid or so. So, absorption refers to the transfer of gaseous components from the gas phase to the liquid phase basically like these gases are there, SO_2 or so. So, they go into the liquid and there is a liquid film and ultimately this liquid phase turbulent mixing can be there for removal purpose and the liquid surface area available for mass transfer and that time available for the diffusion of the gaseous molecules into the liquid are basically important to factors affecting the performance of the system.

And the gaseous contaminant being absorbed must be at least slightly soluble in the scrubbing liquid, otherwise it would not possible, termed to the absorbent. The mass transfer to the liquid continues until the liquid approaches the saturation level. And at saturation equilibrium is established between the mass transfer rate of the contaminate into the liquid and the mass transfer rate of the dissolved species back into the gas phase. So, up to that stage this process can go that saturation level is achieved at certain point of time.

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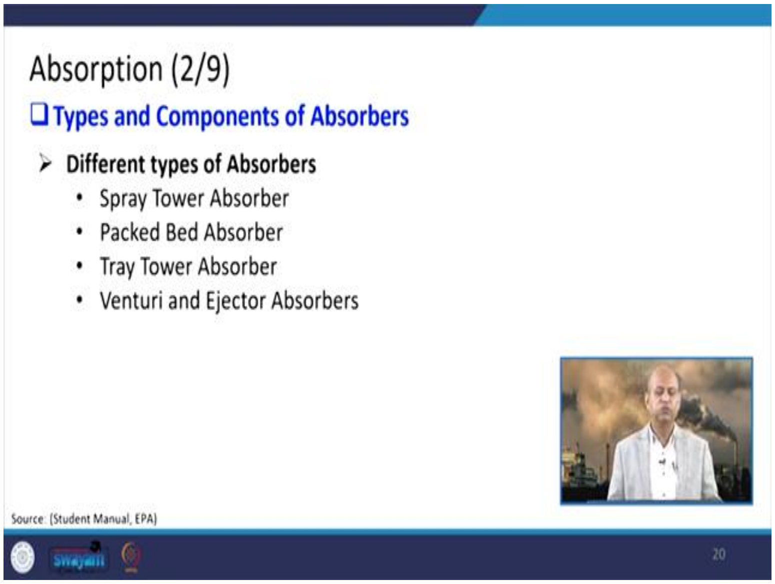

Absorption (2/9)

❑ Types and Components of Absorbers

- **Different types of Absorbers**
  - Spray Tower Absorber
  - Packed Bed Absorber
  - Tray Tower Absorber
  - Venturi and Ejector Absorbers

Source: (Student Manual, EPA)

Different types of components of absorbers are like spray tower absorbers or packed bed absorbers or tray tower absorbers or venturi and ejector absorbers. Some of them already we discussed during second part of the particulate matter removal if you recall.

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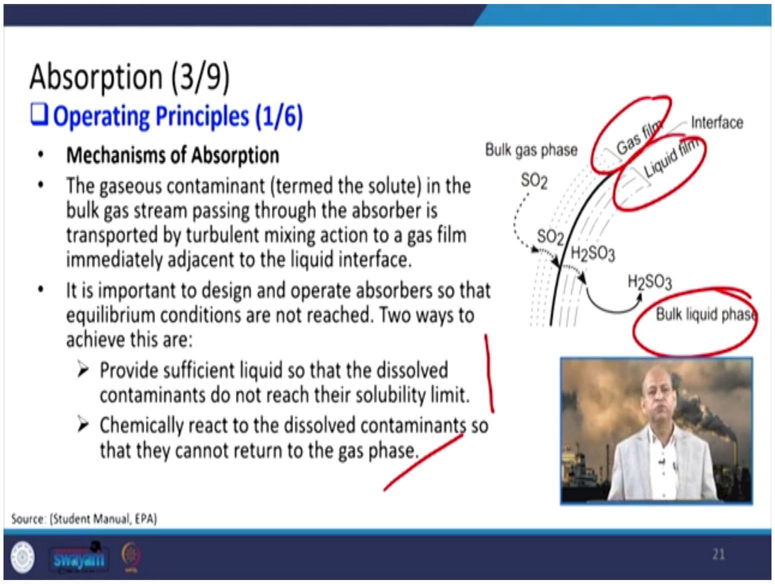

Absorption (3/9)

❑ Operating Principles (1/6)

- **Mechanisms of Absorption**
- The gaseous contaminant (termed the solute) in the bulk gas stream passing through the absorber is transported by turbulent mixing action to a gas film immediately adjacent to the liquid interface.
- It is important to design and operate absorbers so that equilibrium conditions are not reached. Two ways to achieve this are:
  - Provide sufficient liquid so that the dissolved contaminants do not reach their solubility limit.
  - Chemically react to the dissolved contaminants so that they cannot return to the gas phase.

Source: (Student Manual, EPA)

Then we can have this mechanism of absorption. So, this gas film is there, liquid film is there, and then bulk liquid phase is there. So, this is the particular important design and operation part. This provides sufficient liquid so there the dissolved contaminants do not reach their solubility limit. And chemically it can react to the dissolved contaminants so that they cannot return to the gas phase. So, that is why it is important when we are designing and we are operating that absorbers so that the equilibrium conditions are not reached so that we can remove more and more of the required those pollutants.

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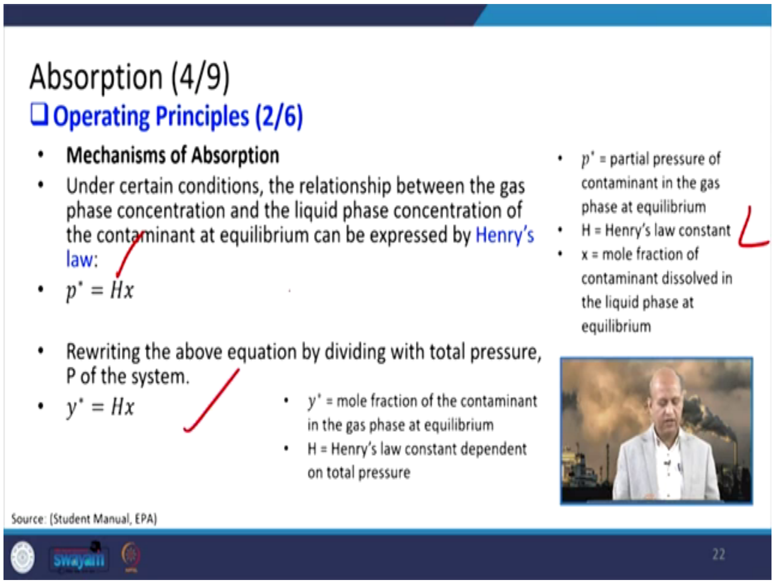

Absorption (4/9)

❑ Operating Principles (2/6)

- **Mechanisms of Absorption**
- Under certain conditions, the relationship between the gas phase concentration and the liquid phase concentration of the contaminant at equilibrium can be expressed by Henry's law:
- $p^* = Hx$

- p^* = partial pressure of contaminant in the gas phase at equilibrium
- H = Henry's law constant
- x = mole fraction of contaminant dissolved in the liquid phase at equilibrium

- Rewriting the above equation by dividing with total pressure, P of the system.
- $y^* = Hx$

- y^* = mole fraction of the contaminant in the gas phase at equilibrium
- H = Henry's law constant dependent on total pressure

Source: (Student Manual, EPA)

Well, these mechanisms of absorption basically the relationship between this gas phase concentration and the liquid phase concentration as you know it is governed by Henry's law. here p* equals Hx. The partial pressure of the contaminant in the gas phase of equilibrium, Henry’s law constant, Hx, mole fraction of the contaminant dissolved in the liquid phase at the equilibrium. So, we can use this particular relationship to see how much it can be removed by this process of absorption.

$$p^* = Hx$$

$$y^* = Hx$$

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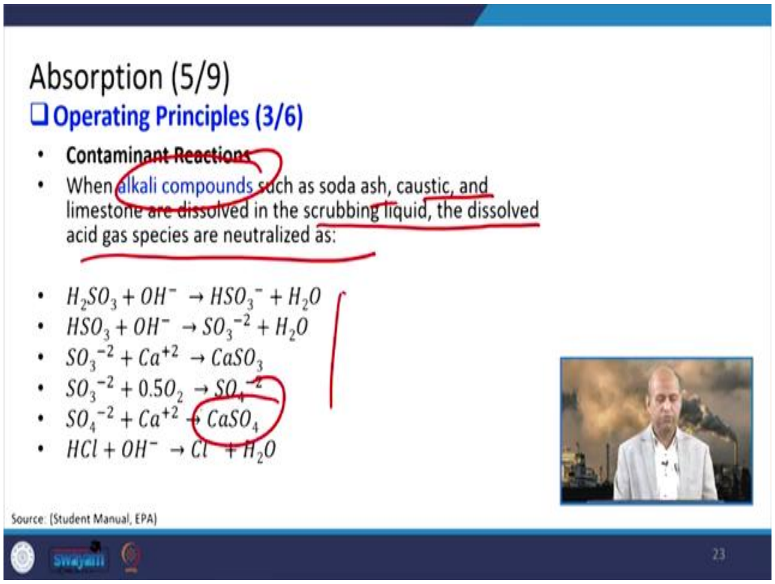

Absorption (5/9)

❑ Operating Principles (3/6)

- **Contaminant Reactions**
- When alkali compounds such as soda ash, caustic, and limestone are dissolved in the scrubbing liquid, the dissolved acid gas species are neutralized as:
- $H_2SO_3 + OH^- \rightarrow HSO_3^- + H_2O$
- $HSO_3 + OH^- \rightarrow SO_3^{-2} + H_2O$
- $SO_3^{-2} + Ca^{+2} \rightarrow CaSO_3$
- $SO_3^{-2} + 0.5O_2 \rightarrow SO_4^{-2}$
- $SO_4^{-2} + Ca^{+2} \rightarrow CaSO_4$
- $HCl + OH^- \rightarrow Cl^- + H_2O$

Source: (Student Manual, EPA)

When we talk about like alkali compounds in contrast to the acidic such as soda ash, caustic and limestone etc. so the scrubbing liquid, the dissolved acid gases species are neutralized in this process basically. So, the alkali compound is to be used for that purpose. And like calcium sulfate can be produced in that particular process.

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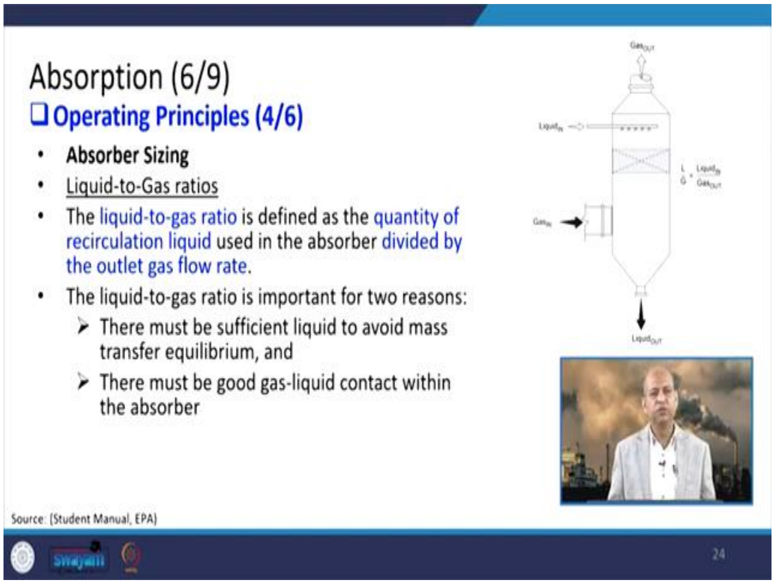

Absorption (6/9)

❑ Operating Principles (4/6)

- **Absorber Sizing**
- Liquid-to-Gas ratios
- The liquid-to-gas ratio is defined as the quantity of recirculation liquid used in the absorber divided by the outlet gas flow rate.
- The liquid-to-gas ratio is important for two reasons:
  - ➢ There must be sufficient liquid to avoid mass transfer equilibrium, and
  - ➢ There must be good gas-liquid contact within the absorber

Source: (Student Manual, EPA)

Then the size if we look into liquid to gas ratios basically that determines the size of the particular this device. So, the liquid to gas ratio is defined as the quantity of recirculation liquid used in the absorber divided by the outlet gas flow rate. So, the liquid to gas ratio is important for two reasons like there must be sufficient liquid to avoid mass transfer equilibrium and there must be good gas liquid contact within the absorber so that determines the size of the particular the system.

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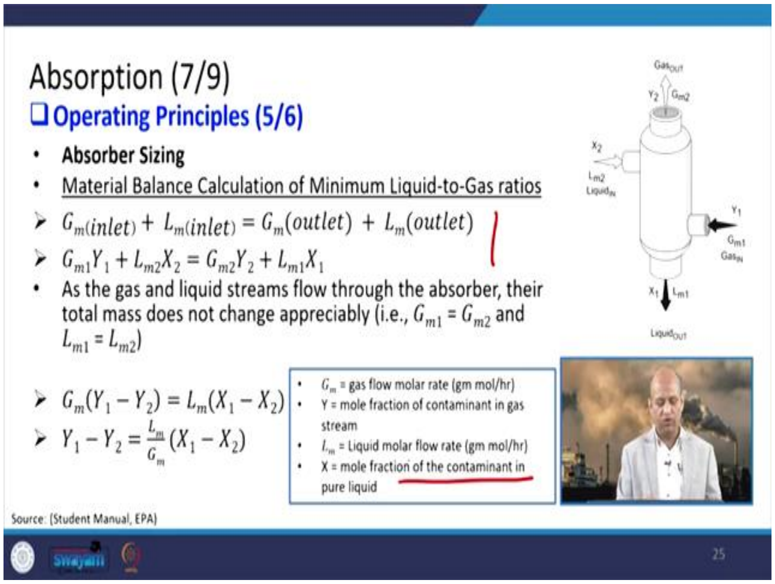

Absorption (7/9)

❑ Operating Principles (5/6)

- **Absorber Sizing**
- Material Balance Calculation of Minimum Liquid-to-Gas ratios

➢ $G_{m(inlet)} + L_{m(inlet)} = G_m(outlet) + L_m(outlet)$

➢ $G_{m1}Y_1 + L_{m2}X_2 = G_{m2}Y_2 + L_{m1}X_1$

- As the gas and liquid streams flow through the absorber, their total mass does not change appreciably (i.e., $G_{m1} = G_{m2}$ and $L_{m1} = L_{m2}$)

➢ $G_m(Y_1 - Y_2) = L_m(X_1 - X_2)$

➢ $Y_1 - Y_2 = \frac{L_m}{G_m}(X_1 - X_2)$

- G_m = gas flow molar rate (gm mol/hr)
- Y = mole fraction of contaminant in gas stream
- L_m = Liquid molar flow rate (gm mol/hr)
- X = mole fraction of the contaminant in pure liquid

Source: (Student Manual, EPA)

Well, again, this material balance calculation minimum liquid to gas ratios can be seen here with these empirical relationships, where this gas flow, molar rate, mole fraction of contaminant in gases stream or liquid molar flow rate, mole fraction of the contaminant in the pure liquid all these parameters are to be used for calculation purposes.

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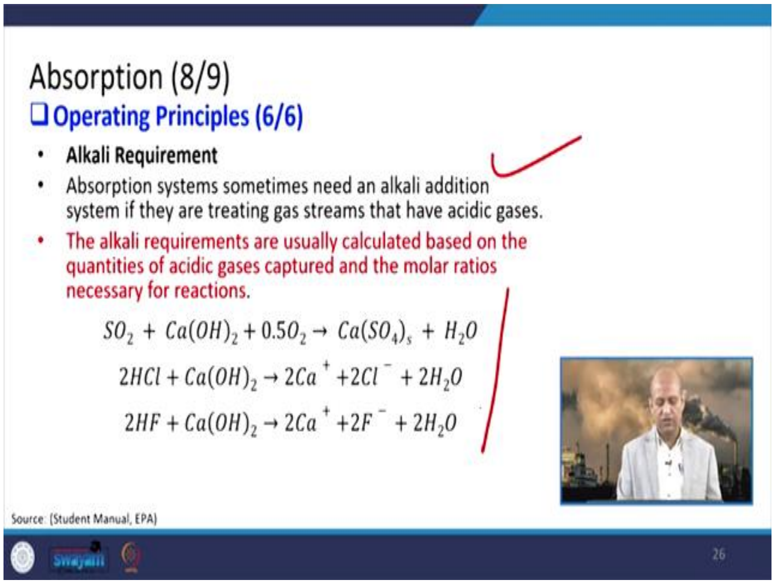

Absorption (8/9)

❑ Operating Principles (6/6)

- **Alkali Requirement**
- Absorption systems sometimes need an alkali addition system if they are treating gas streams that have acidic gases.
- The alkali requirements are usually calculated based on the quantities of acidic gases captured and the molar ratios necessary for reactions.

$$SO_2 + Ca(OH)_2 + 0.5O_2 \rightarrow Ca(SO_4)_s + H_2O$$

$$2HCl + Ca(OH)_2 \rightarrow 2Ca^+ + 2Cl^- + 2H_2O$$

$$2HF + Ca(OH)_2 \rightarrow 2Ca^+ + 2F^- + 2H_2O$$

Source: (Student Manual, EPA)

Then this alkali requirement basically when we talk about absorption systems they sometimes need alkali additions as we have seen if we are removing these acidic gases. So, these alkali requirements are usually calculated based on the quantities of the acidic gases which need to be captured. So, these molar ratios necessary for reactions can be used in these particular equations and you can determine that quantity.

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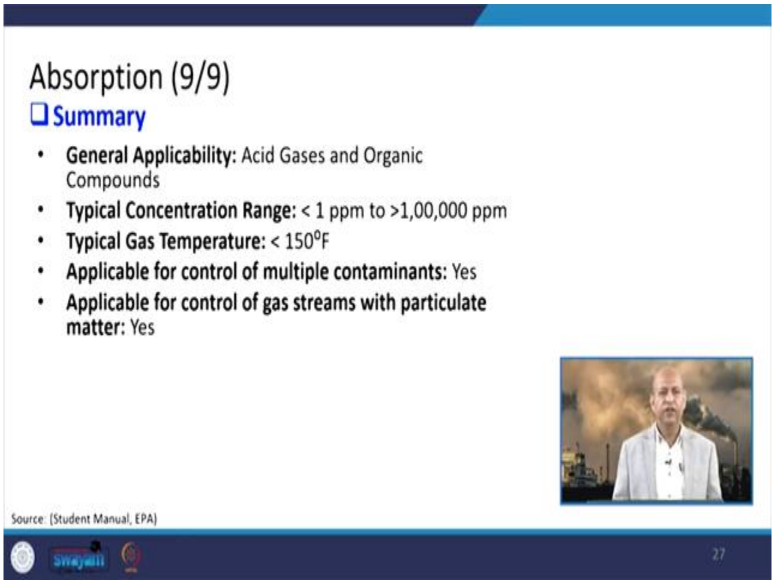

Absorption (9/9)

❑ Summary

- **General Applicability:** Acid Gases and Organic Compounds
- **Typical Concentration Range:** < 1 ppm to >1,00,000 ppm
- **Typical Gas Temperature:** < 150^{0}F
- **Applicable for control of multiple contaminants:** Yes
- **Applicable for control of gas streams with particulate matter:** Yes

Source: (Student Manual, EPA)

In summary, for the absorption we can say that this is applicable for removal of acid gases, organic compounds. And the concentration again 1 ppm to 100,000 ppm it can go. Wide range is there. So, that is wonderful thing in that sense. Less than 150-degree Fahrenheit temperature typically we go for. And then this is applicable for control of multiple contaminants. And yes, it is applicable for control of gas systems with particulate matter that is possible because of this scrubbing process. So, that is advantage, double advantage of this particular process.

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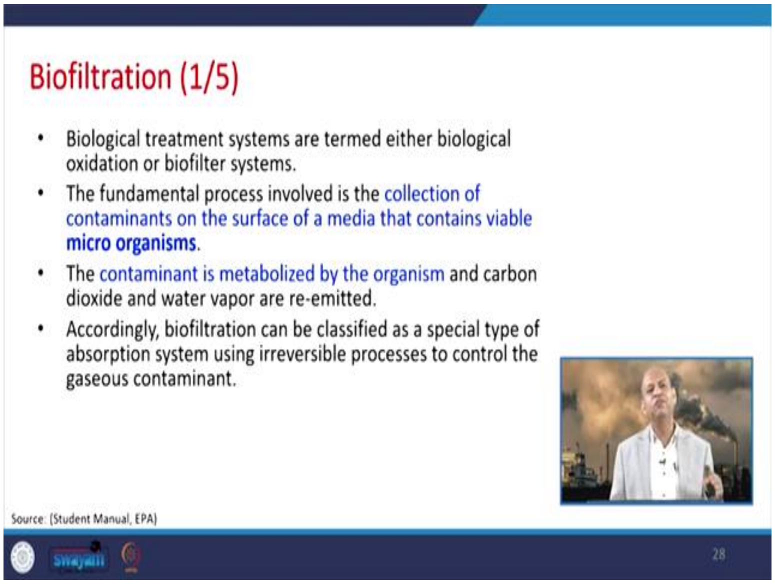

Biofiltration (1/5)

- Biological treatment systems are termed either biological oxidation or biofilter systems.
- The fundamental process involved is the collection of contaminants on the surface of a media that contains viable **micro organisms**.
- The contaminant is metabolized by the organism and carbon dioxide and water vapor are re-emitted.
- Accordingly, biofiltration can be classified as a special type of absorption system using irreversible processes to control the gaseous contaminant.

Source: (Student Manual, EPA)

Now, the third one we come to the biofiltration basically. So, the biological treatment systems which are termed either biological oxidation or biofilter systems, the fundamental process involved in this particular process is a collection of these pollutants on the surface media of which contains viable microorganisms some surface media has to be there where microbes can, microorganisms can grow basically. The layer can be of microorganisms there.

The contaminant is metabolized by these organisms and the carbon dioxide and vapor, water vapor are emitted into that process. So, that way they can remove those particular contaminants or pollutants. And accordingly, this biofiltration can be classified as a special type of absorption system using irreversible processes to control the gaseous contaminants because those gaseous contaminants will be like food for those microorganisms which are there in this particular system.

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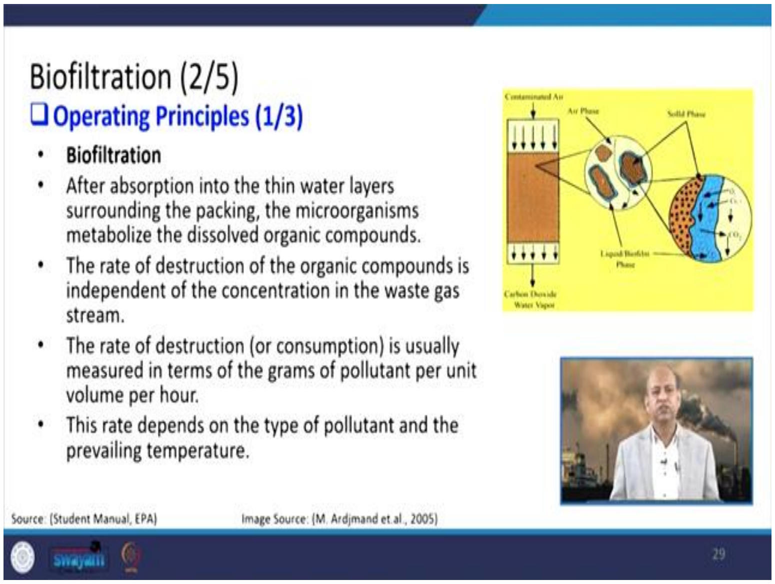

Biofiltration (2/5)

❑ Operating Principles (1/3)

- **Biofiltration**
- After absorption into the thin water layers surrounding the packing, the microorganisms metabolize the dissolved organic compounds.
- The rate of destruction of the organic compounds is independent of the concentration in the waste gas stream.
- The rate of destruction (or consumption) is usually measured in terms of the grams of pollutant per unit volume per hour.
- This rate depends on the type of pollutant and the prevailing temperature.

Source: (Student Manual, EPA)

Image Source: (M. Ardjmand et al., 2005)

Well, when we talk about operating principles, so this after absorption into the thin water layers surrounding those packing materials which are the habitats for microorganisms, the metabolic system occurs there. So, they are dissolved organic compounds which are the food of those microorganisms and the rate of destruction of the organic compounds which is available that is independent of the concentration in the waste gas stream, because that is governed by the number of microorganisms basically, and their kinetics. The rate of destruction or consumption is usually measured in terms of the grams of pollutant per unit volume per hour and this rate depends on the type of pollutant and the prevailing temperature only.

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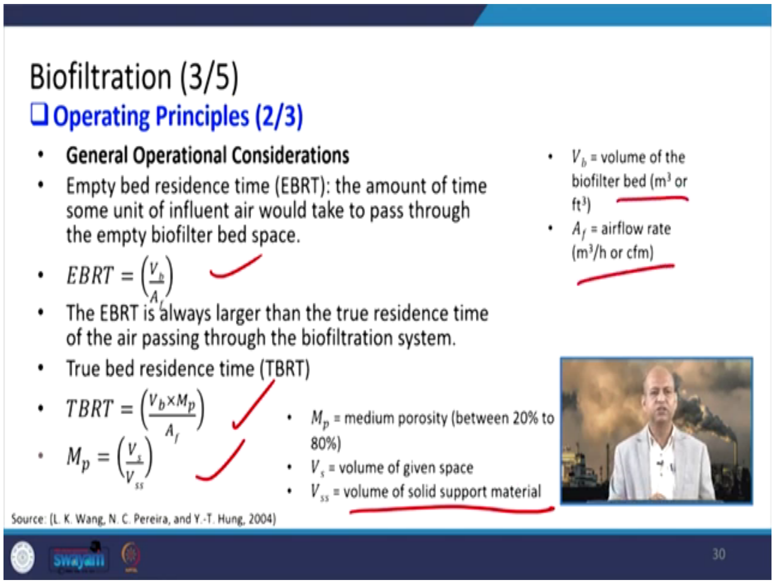

Biofiltration (3/5)

❑ Operating Principles (2/3)

- **General Operational Considerations**
- Empty bed residence time (EBRT): the amount of time some unit of influent air would take to pass through the empty biofilter bed space.
- $EBRT = \left(\frac{V_b}{A_f}\right)$
- The EBRT is always larger than the true residence time of the air passing through the biofiltration system.
- True bed residence time (TBRT)
- $TBRT = \left(\frac{V_b \times M_p}{A_f}\right)$
- $M_p = \left(\frac{V_s}{V_{ss}}\right)$

- V_b = volume of the biofilter bed (m^3 or ft^3)
- A_f = airflow rate (m^3/h or cfm)

- M_p = medium porosity (between 20% to 80%)
- V_s = volume of given space
- V_{ss} = volume of solid support material

Source: (L. K. Wang, N. C. Pereira, and Y.-T. Hung, 2004)

Then if we go into this operating principle for the general operation considerations, so the Empty Bed Residence Time (EBRT) or the True Residence Time (TBRT) they can be calculated by these relationships, where medium porosity between 20 percent to 80 percent, volume of given space, volume of solid support, then volume of the biofilter bed and airflow rate all these parameters have to be considered for these relationships.

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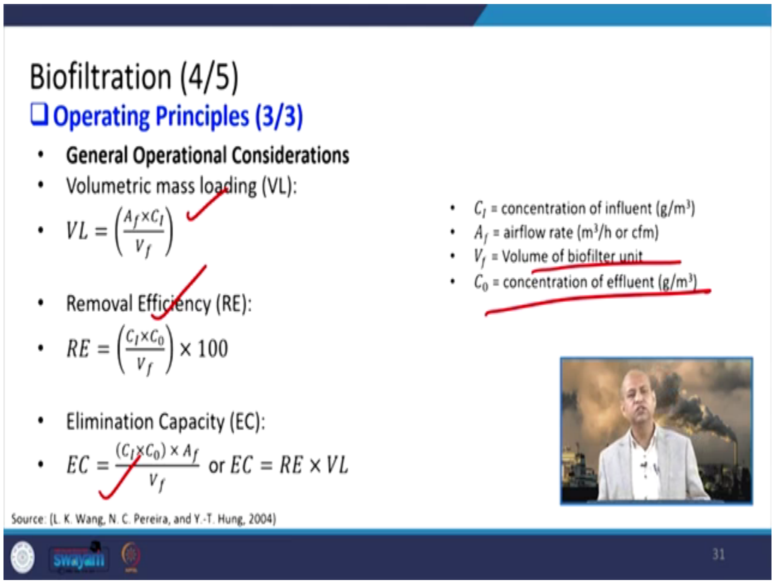

Biofiltration (4/5)

❑ Operating Principles (3/3)

- **General Operational Considerations**
- Volumetric mass loading (VL):
- $VL = \left(\frac{A_f \times C_I}{V_f}\right)$
- Removal Efficiency (RE):
- $RE = \left(\frac{C_I \times C_0}{V_f}\right) \times 100$
- Elimination Capacity (EC):
- $EC = \frac{(C_I \times C_0) \times A_f}{V_f}$ or $EC = RE \times VL$

- C_I = concentration of influent (g/m^3)
- A_f = airflow rate (m^3/h or cfm)
- V_f = Volume of biofilter unit
- C_0 = concentration of effluent (g/m^3)

Source: (L. K. Wang, N. C. Pereira, and Y.-T. Hung, 2004)

Well, when we talk about volumetric mass loading, then this A_f into C_I divided by V_f, where C_I is concentration of influent, A_f air flow rate, V_f volume of the biofilter unit, C_0 concentration of effluent where this is used for removal efficiency calculations. Elimination capacity can be calculated by this empirical relationship. So, all these you know relationships are there depending upon these variables which are available in the system which we can measure and accordingly we can determine the systems efficiency.

$$VL = \left(\frac{A_f \times C_I}{V_f}\right)$$

$$RE = \left(\frac{C_I \times C_0}{V_f}\right) \times 100$$

$$EC = \frac{(C_I \times C_0) \times A_f}{V_f} \text{ or } EC = RE \times VL$$

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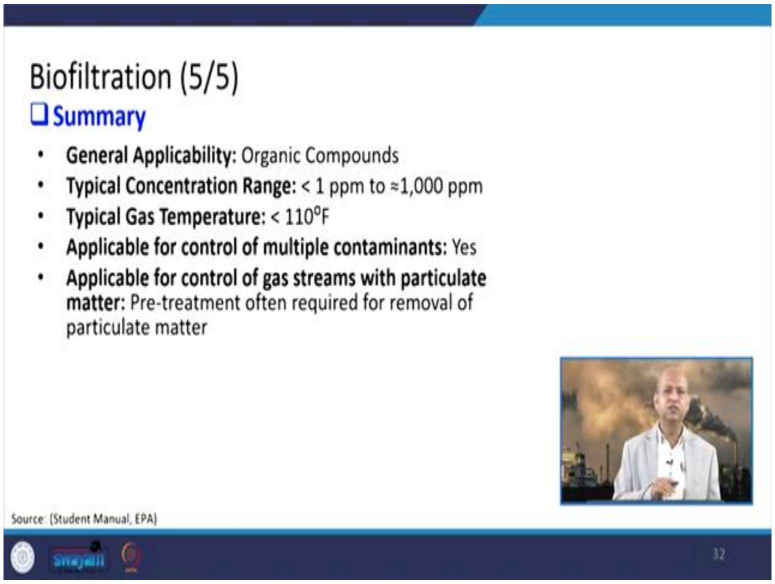

Biofiltration (5/5)

❑ **Summary**

- **General Applicability:** Organic Compounds
- **Typical Concentration Range:** < 1 ppm to ≈1,000 ppm
- **Typical Gas Temperature:** < 110^0F
- **Applicable for control of multiple contaminants:** Yes
- **Applicable for control of gas streams with particulate matter:** Pre-treatment often required for removal of particulate matter

Source: (Student Manual, EPA)

Well, in summary of the biofiltration we can say that it is applicable for organic compounds removal basically. And the typical concentration range 1 ppm to 1000 ppm it can go but, means the range is not as wide as of the absorption if you can remember. Typical gas temperature around 110 degree Fahrenheit applicable for control of multiple contaminants, yes, it is possible, and applicable for control of gas streams with particulate matters.

Pretreatment often required for removal of the particulate matter like adsorbent. So, absorbance in absorption, this was not the limitation, but in adsorption and biofiltration, you have to first remove the particulate matter only then gases component will be removed efficiently. So, that remember, please remember that difference.

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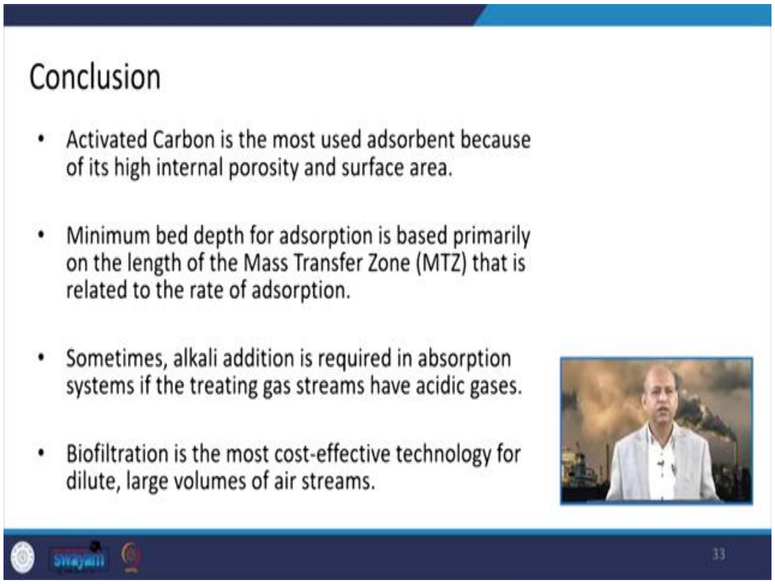
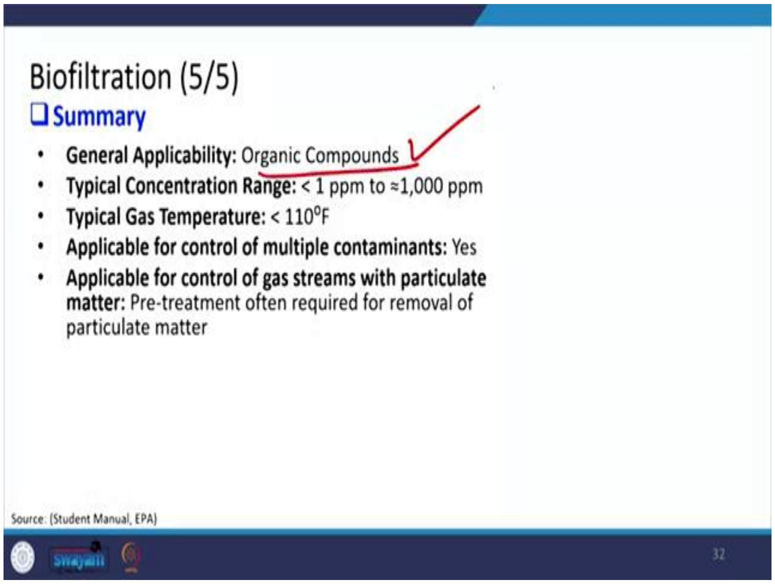


Conclusion

- Activated Carbon is the most used adsorbent because of its high internal porosity and surface area.
- Minimum bed depth for adsorption is based primarily on the length of the Mass Transfer Zone (MTZ) that is related to the rate of adsorption.
- Sometimes, alkali addition is required in absorption systems if the treating gas streams have acidic gases.
- Biofiltration is the most cost-effective technology for dilute, large volumes of air streams.



Biofiltration (5/5)

❑ **Summary**

- **General Applicability:** Organic Compounds ✓
- **Typical Concentration Range:** < 1 ppm to ≈1,000 ppm
- **Typical Gas Temperature:** < 110°F
- **Applicable for control of multiple contaminants:** Yes
- **Applicable for control of gas streams with particulate matter:** Pre-treatment often required for removal of particulate matter

Source: (Student Manual, EPA)

In conclusion, we can say that the activated carbon is the most used adsorbent because of the high internal porosity and high surface area where they can capture the gases, those pollutants. Minimum bed depth for the adsorption is based primarily on the length of the mass transfer zone that is related to the rate of adsorption. And sometimes these alkali addition is required in adsorption systems if we are treating the gas streams which are having acidic gases. And biofiltration is the most cost-effective technology for dilute large volumes of air stream serving these organic compounds as we have discussed like this. So, this is all for today. In next lecture we will discuss about oxidation and condensation processes to remove these gaseous contaminants or pollutants.

(Refer Slide Time: 26:52)

References

- Student Manual, Control of Gaseous Emissions, 2000, US EPA, Air Pollution Training Institute (APTI), EPA_APTI-415
- L. K. Wang, N. C. Pereira, and Y.-T. Hung, 2004, Handbook of Environmental Engineering, Volume 1: Air Pollution Control Engineering, The Humana Press, Inc., Totowa, NJ
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This is the reference list. You can go through at your free time to have more information about these processes which we have already discussed. So, thank you for your kind attention and see you in the next lecture. Thanks again.