Air Pollution and Control
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Lecture 45
Air Pollution Control Devices: Part – 4

Hello, friends. You may remember that we have already discussed in three lectures regarding controlling particulate matters and gaseous pollutants also. So, today will be the last lecture on these controlling devices especially on gaseous pollutants.

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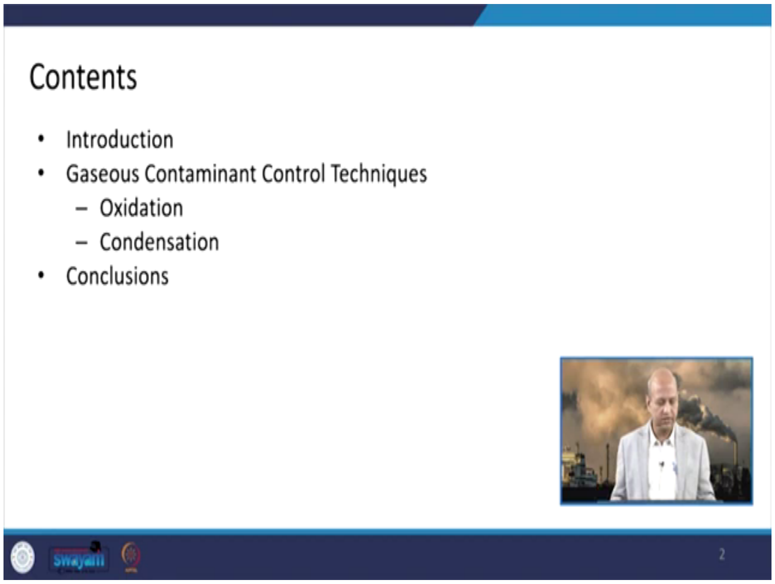

Contents

- Introduction
- Gaseous Contaminant Control Techniques
  - Oxidation
  - Condensation
- Conclusions

So, today's lecture contents include like, we will see what we have covered so far and what we will do in this lecture. So, today's focus will be on gaseous contaminant control techniques based on oxidation and condensation.

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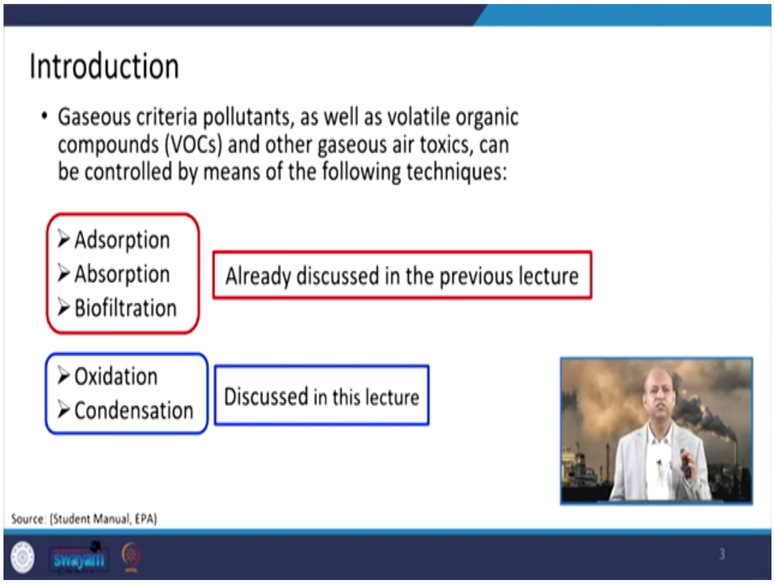

Introduction

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

  - Adsorption
  - Absorption
  - Biofiltration

Already discussed in the previous lecture

  - Oxidation
  - Condensation

Discussed in this lecture

Source: (Student Manual, EPA)

So, we have already discussed adsorption, absorption and biofiltration related devices which have been used for gaseous pollutants control or capturing, because these gases criteria pollutants or like VOCs and even gaseous air toxics they can easily be controlled by these techniques, like adsorption, absorption, biofiltration, oxidation and condensation. So, three of these adsorption, absorption and biofiltration in the last lecture we have covered. Today we will focus on oxidation and condensation.

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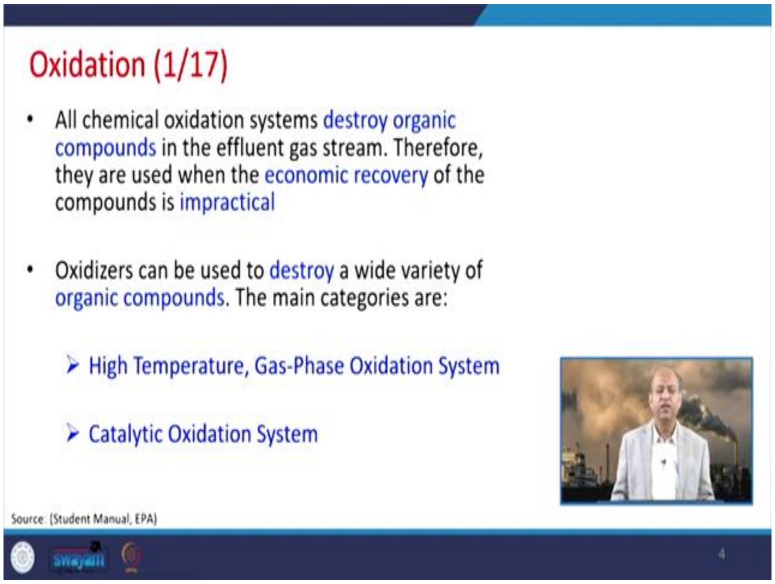

Oxidation (1/17)

- All chemical oxidation systems destroy organic compounds in the effluent gas stream. Therefore, they are used when the economic recovery of the compounds is impractical
- Oxidizers can be used to destroy a wide variety of organic compounds. The main categories are:
  - High Temperature, Gas-Phase Oxidation System
  - Catalytic Oxidation System

Source: (Student Manual, EPA)

So, let us see what the oxidation is basically. So, all chemical oxidation systems are really for destroying organic compounds in the effluent gases stream which comes out of after some combustion process or burning process of the fuel. So, that is why they are used when the economic recovery of the compounds is impractical, otherwise we try to recover the resources, whether it is some chemical compound or something like that. So, the oxidizers can be used to destroy a wide variety of organic compounds. And the categories, the broad or main categories within this oxidation process are high temperature gas phase oxidation systems and catalytic oxidation systems.

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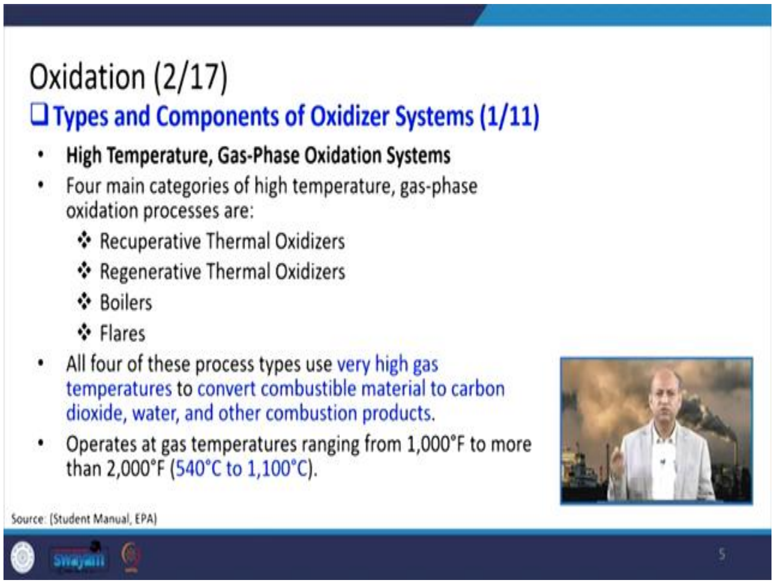

Oxidation (2/17)

❑ Types and Components of Oxidizer Systems (1/11)

- **High Temperature, Gas-Phase Oxidation Systems**
- Four main categories of high temperature, gas-phase oxidation processes are:
  - ❖ Recuperative Thermal Oxidizers
  - ❖ Regenerative Thermal Oxidizers
  - ❖ Boilers
  - ❖ Flares
- All four of these process types use very high gas temperatures to convert combustible material to carbon dioxide, water, and other combustion products.
- Operates at gas temperatures ranging from 1,000°F to more than 2,000°F (540°C to 1,100°C).

Source: (Student Manual, EPA)

And these high temperature or gas phase oxidation systems are, can be divided into four main categories basically, like recuperative thermal oxidizers, regenerative thermal oxidizers, boilers and flares. And all these four processes can be used for controlling or destroying very high gas, at very high gas temperature those gases pollutants and they can convert combustible materials to carbon dioxide.

Because when complete oxidation occurs basically what happens, the carbon dioxide, water and other combustion products are really produced by this particular combustion process or oxidation process and it can operate at a range of temperature basically like 540 degrees centigrade to 1100 degree centigrade. So, this gas temperature range is also important because only up to that temperature if we can operate the system, then it will be able to oxidize all these kinds of pollutants which are possible to burn and oxidize fully so that it can be converted into carbon dioxide and water vapor ultimately.

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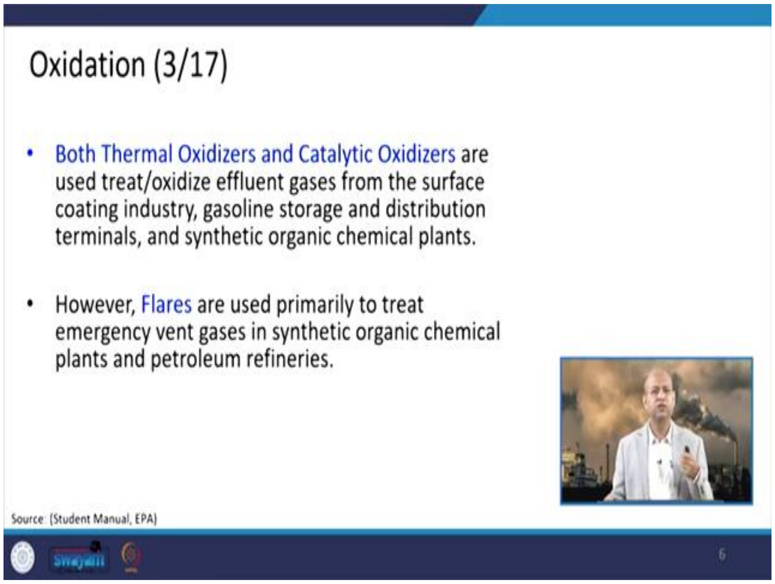

Oxidation (3/17)

- Both Thermal Oxidizers and Catalytic Oxidizers are used treat/oxidize effluent gases from the surface coating industry, gasoline storage and distribution terminals, and synthetic organic chemical plants.
- However, Flares are used primarily to treat emergency vent gases in synthetic organic chemical plants and petroleum refineries.

Source: (Student Manual, EPA)

Well, these both thermal oxidizers or catalytic oxidizers are used to treat or oxidize effluent gases or exhaust gases from the surface coating industry or gasoline storage industry or distribution terminals or synthetic organic chemical plants basically. So, there are some vapors or some those effluent gases which need to be controlled, otherwise they will go to the atmosphere and they will create several other problems according to their chemical characteristics.

However, flares, burning, the flares are used primarily to treat emergency vent gases in synthetic organic chemical plants or petroleum refineries, because it is not practical to recover that so it is better to, those vapors, those fuel vapors or fumes to burn them directly. In the flares technology, we do that particular burning kind of process.

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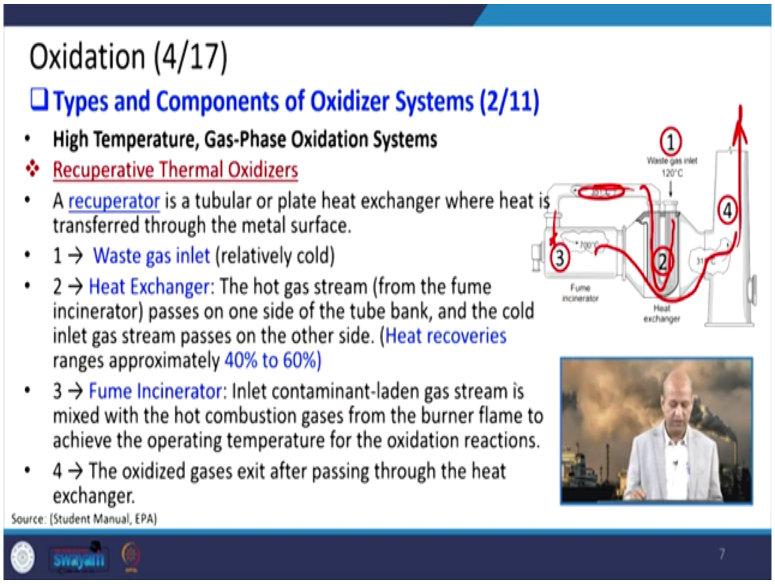

Oxidation (4/17)

❑ Types and Components of Oxidizer Systems (2/11)

- **High Temperature, Gas-Phase Oxidation Systems**

❖ Recuperative Thermal Oxidizers

- A recuperator is a tubular or plate heat exchanger where heat is transferred through the metal surface.
- 1 → Waste gas inlet (relatively cold)
- 2 → Heat Exchanger: The hot gas stream (from the fume incinerator) passes on one side of the tube bank, and the cold inlet gas stream passes on the other side. (Heat recoveries ranges approximately 40% to 60%)
- 3 → Fume Incinerator: Inlet contaminant-laden gas stream is mixed with the hot combustion gases from the burner flame to achieve the operating temperature for the oxidation reactions.
- 4 → The oxidized gases exit after passing through the heat exchanger.

Source: (Student Manual, EPA)

Well, when we talk about this recuperative thermal oxidizers in this figure it is shown like waste gas inlet at around 120 degrees Celsius, which is much colder than the system of this oxidizing system. So, it goes into this particular system and it passes through heat exchange that particular chamber where exchange of the heat is there so that the higher heat of those burning gases goes to this waste gas inlet then it is again taken after this heating process when temperature increases, it is taken around like 351 degrees Celsius, it goes to this chamber where it is burning or oxidizing happening. So, it is around 700 degrees Celsius where it is oxidized or burned and it goes again and then it comes out of this exit, this pipe.

So, the waste gas inlet basically relatively cold this one and then it goes to the heat exchanger system and around heat recovery of 40 percent to 60 percent happens. So, that is another advantage. When these burned gases pass through then they are taking lots of heat with them. So, the heat recovery happens in this heat exchanger system, part of this particular system. At the higher temperature when this waste gas is taken to this chamber fume incinerator basically, so there it is burned or oxidized completely and then it is taken to the exhaust pipe. So, the fume incinerator is very important in that sense. And then these oxidized gases exit after passing through the heat exchanger basically. So, at the point of heat exchanger, they exchange the heat from higher temperature to the lower temperature.

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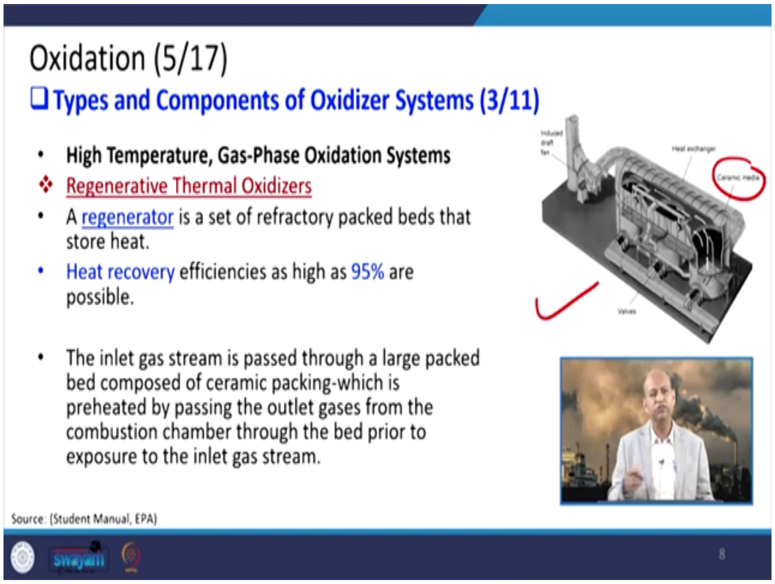
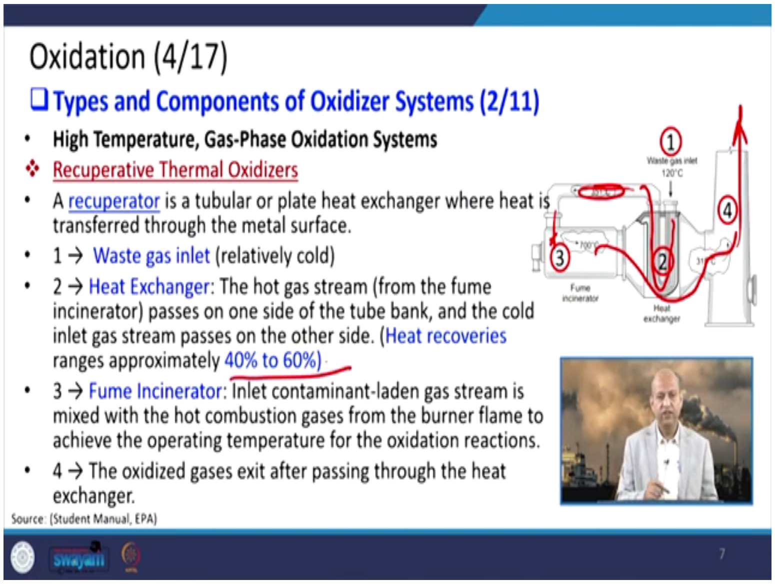


Oxidation (5/17)

❑ Types and Components of Oxidizer Systems (3/11)

- **High Temperature, Gas-Phase Oxidation Systems**
- ❖ Regenerative Thermal Oxidizers
- A regenerator is a set of refractory packed beds that store heat.
- Heat recovery efficiencies as high as 95% are possible.
- The inlet gas stream is passed through a large packed bed composed of ceramic packing-which is preheated by passing the outlet gases from the combustion chamber through the bed prior to exposure to the inlet gas stream.

Source: (Student Manual, EPA)



Oxidation (4/17)

❑ Types and Components of Oxidizer Systems (2/11)

- **High Temperature, Gas-Phase Oxidation Systems**
- ❖ Recuperative Thermal Oxidizers
- A recuperator is a tubular or plate heat exchanger where heat is transferred through the metal surface.
- 1 → Waste gas inlet (relatively cold)
- 2 → Heat Exchanger: The hot gas stream (from the fume incinerator) passes on one side of the tube bank, and the cold inlet gas stream passes on the other side. (Heat recoveries ranges approximately 40% to 60%)
- 3 → Fume Incinerator: Inlet contaminant-laden gas stream is mixed with the hot combustion gases from the burner flame to achieve the operating temperature for the oxidation reactions.
- 4 → The oxidized gases exit after passing through the heat exchanger.

Source: (Student Manual, EPA)

Well, regenerative thermal oxidizers are there, another set of regenerators. So, these regenerator is a set of refractory packed beds that store heat basically in direct way. So, this is heat exchanger and ceramic media is used for this exchanging of the heat. They are first, they take the heat into that and then they keep the sheet for longer period and these are the walls to control. So, this is the particular device where heat recovery efficiency as much as 95 percent are possible in this particular kind of regenerative thermal oxidizers.

It was only 40 to 60-degree heat recovery, but here now up to 95 percent you can recover the heat. So, even heat when it is wasted to the atmosphere, it is also kind of wasting the energy. If you can recover the heat in the process then it is basically we are helping the environment, otherwise you might have heard about heat island impact those things happen because of these kind of extra heat which goes to the atmosphere. The contribution is there I mean to say.

The inlet gas stream is passed through a large packed bed composed of ceramic packing that is shown here and which is preheated by passing the outlet gases which has a lot of heat from the combustion chamber and through the bed prior to the exposure to the inlet gases stream so that we heat exchange is possible.

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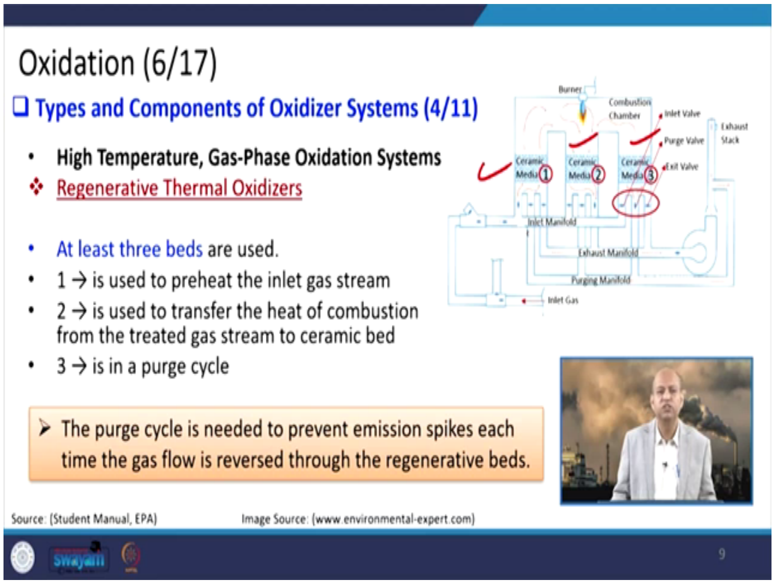

Oxidation (6/17)

❑ Types and Components of Oxidizer Systems (4/11)

- **High Temperature, Gas-Phase Oxidation Systems**
- Regenerative Thermal Oxidizers

- At least three beds are used.
- 1 → is used to preheat the inlet gas stream
- 2 → is used to transfer the heat of combustion from the treated gas stream to ceramic bed
- 3 → is in a purge cycle

➢ The purge cycle is needed to prevent emission spikes each time the gas flow is reversed through the regenerative beds.

Source: (Student Manual, EPA) Image Source: (www.environmental-expert.com)

So, in this particular device there are at least three beds required for the complete process. The first one is used to preheat the inlet gas stream basically. Here first, second and third all these have ceramic media and they can exchange the role also and this is the exhaust gas ultimately.

Second is used for transferring the heat of the combustion from the treated gas stream to ceramic bed. So, the treated gas means the burned gas or oxidized gas. So, it has a lot of heat. So, that heat is taken by these ceramic bed media, ceramic media that bed layers is there, lot of pebbles are there.

And in this purge cycle happens in the third one and they can change the role. So, the purge cycle is basically needed to prevent emission spikes, each time the gas flow is reversed through the regenerative beds, because then beds are regenerated in that sense when they are changing the rules.

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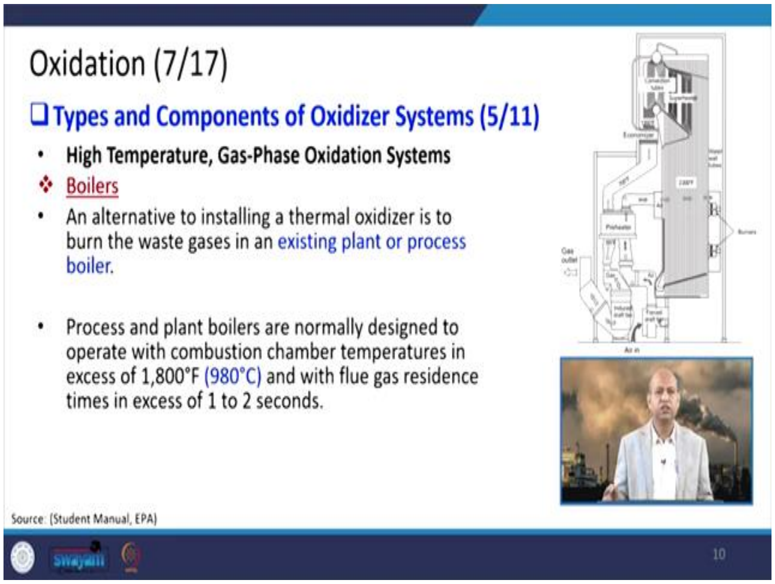

Oxidation (7/17)

❑ Types and Components of Oxidizer Systems (5/11)

- **High Temperature, Gas-Phase Oxidation Systems**

❖ Boilers

- An alternative to installing a thermal oxidizer is to burn the waste gases in an existing plant or process boiler.
- Process and plant boilers are normally designed to operate with combustion chamber temperatures in excess of 1,800°F (980°C) and with flue gas residence times in excess of 1 to 2 seconds.

Source: (Student Manual, EPA)

The third one is boilers basically. So, this is one another alternative to installing a thermal oxidizer and which is like burning the waste gases as the fuel. Like these are the burners and this is the gas outlet and air goes inside this. So, that way these inlet gases which are kind of we can use as the fuel and they are burnt.

So, some calorific value is recovered by this particular process of oxidization or the burning and this process and the plant boilers are normally designed to operate with the combustion chamber temperatures in excess of around 980 degrees Celsius and with flue gas residence times in excess of 1 to 2 seconds. So, within that small period that particular heat exchange happens in that particular device.

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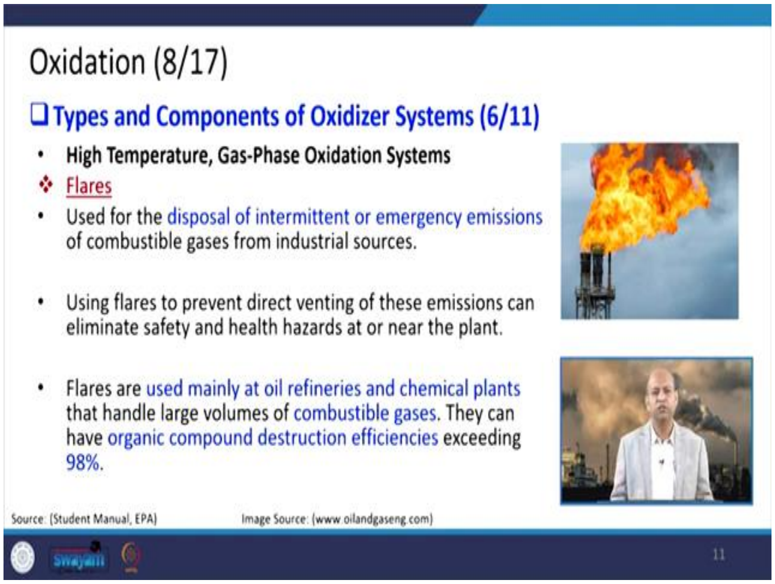

Oxidation (8/17)

❑ Types and Components of Oxidizer Systems (6/11)

- **High Temperature, Gas-Phase Oxidation Systems**

❖ Flares

- Used for the disposal of intermittent or emergency emissions of combustible gases from industrial sources.
- Using flares to prevent direct venting of these emissions can eliminate safety and health hazards at or near the plant.
- Flares are used mainly at oil refineries and chemical plants that handle large volumes of combustible gases. They can have organic compound destruction efficiencies exceeding 98%.

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

Well, flares are there. These are used for disposal of intermittent or emergency emissions of combustible gases from industrial sources which are not economical to recover basically. So, using flares to prevent direct venting of these emissions can eliminate the safety issues or health hazards which can be because of these toxic gases which can come out of these exhaust pipes.

So, flares are used mainly at the oil refineries and chemical plants that handle large volumes of combustible gases. And if we do not, in a controlled way, this is a controlled way of burning them, oxidizing them. If, otherwise if we emit into gases at some places if concentration is very high then it can catch fire or there may be other dangerous situations also. So, they can have organic compound destruction efficiency exceeding 98 percent. So, that way it is quite efficient way of doing away with these gases. But of course, we do not recover in that particular process. We just burn it. Even we are not recovering heat here.

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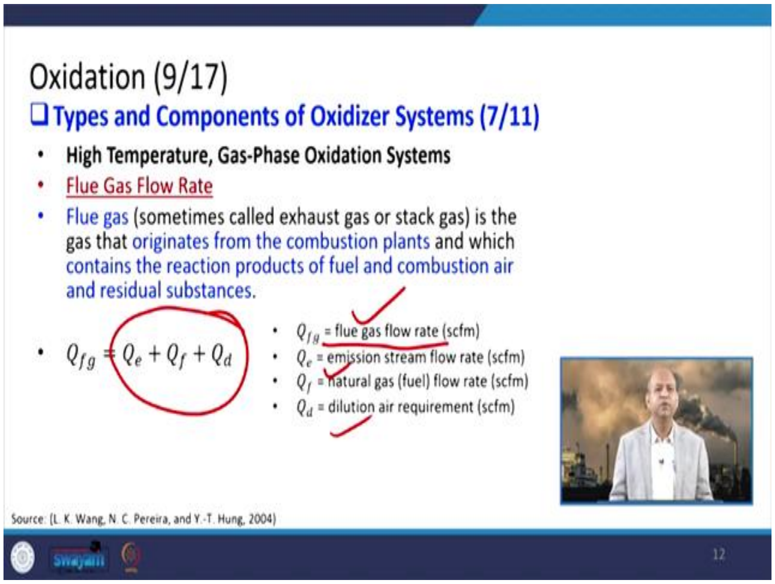

Oxidation (9/17)

❑ Types and Components of Oxidizer Systems (7/11)

- **High Temperature, Gas-Phase Oxidation Systems**
- Flue Gas Flow Rate
- Flue gas (sometimes called exhaust gas or stack gas) is the gas that originates from the combustion plants and which contains the reaction products of fuel and combustion air and residual substances.
- $Q_{fg} = Q_e + Q_f + Q_d$
  - Q_{fg} = flue gas flow rate (scfm)
  - Q_e = emission stream flow rate (scfm)
  - Q_f = natural gas (fuel) flow rate (scfm)
  - Q_d = dilution air requirement (scfm)

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

Then when we talk about flue gas flow rate like how to design those particular instruments? So, there are certain parameters which are important to know about like the flow rate. So, the flue gas flow rate maybe there, emission stream flow rate can be there, natural gas flow rate, dilution air time, requirement all these, this emission, natural gas and dilution air time requirement these are basically making the total flue gas flow rate so that we should know.

This flue gas sometimes also called like exhaust gas or stack gas is the gas which is originated from the combustion plants and which contains the reaction products of the fuel and combustion air and residual substances so they are waste gases. So, we need to know these flow rates to design the particular device.

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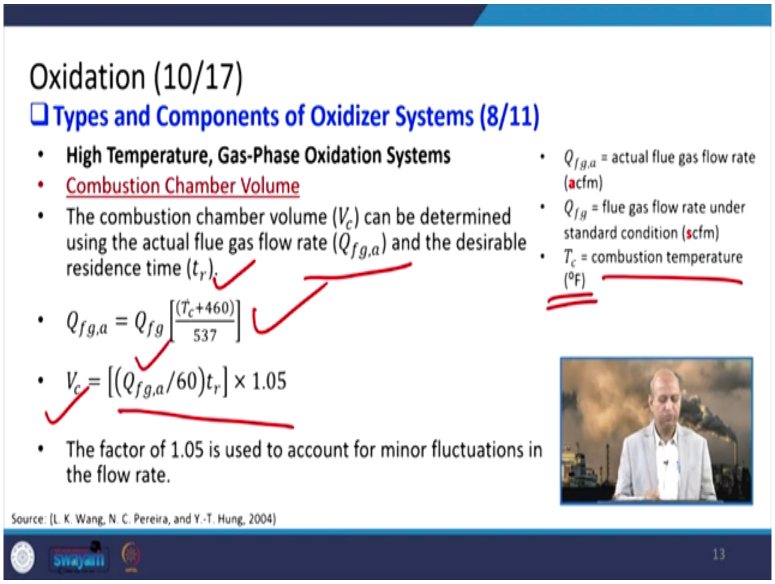

Oxidation (10/17)

❑ Types and Components of Oxidizer Systems (8/11)

- **High Temperature, Gas-Phase Oxidation Systems**
- Combustion Chamber Volume
- The combustion chamber volume (V_c) can be determined using the actual flue gas flow rate ($Q_{fg,a}$) and the desirable residence time (t_r).
- $Q_{fg,a} = Q_{fg}\left[\frac{(T_c+460)}{537}\right]$
- $V_c = \left[(Q_{fg,a}/60)t_r\right] \times 1.05$
- The factor of 1.05 is used to account for minor fluctuations in the flow rate.

- $Q_{fg,a}$ = actual flue gas flow rate (acfm)
- Q_{fg} = flue gas flow rate under standard condition (scfm)
- T_c = combustion temperature (°F)

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

So, combustion chamber volume we need to know before designing the combustion chamber. So, how to know the volume? So, the combustion chamber volume can be determined using the actual flue gas flow rate and the desirable residence time. So, residence time t_r and this is the actual flue gas flow rate. So, this is the empirical relationship which is used. T_c is here combustion temperature which is known and because it is in Fahrenheit so we can convert into Celsius, then this V_c is the combustion chamber volume which can be computed by using this particular formula.

$$Q_{fg,a} = Q_{fg}\left[\frac{(T_c + 460)}{537}\right]$$

$$V_c = \left[(Q_{fg,a}/60)t_r\right] \times 1.05$$

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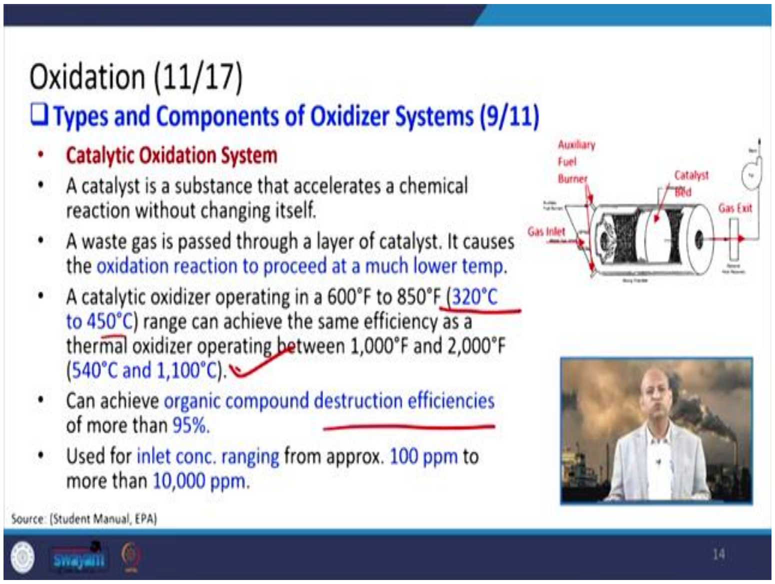

Oxidation (11/17)

❑ Types and Components of Oxidizer Systems (9/11)

- **Catalytic Oxidation System**
- A catalyst is a substance that accelerates a chemical reaction without changing itself.
- A waste gas is passed through a layer of catalyst. It causes the oxidation reaction to proceed at a much lower temp.
- A catalytic oxidizer operating in a 600°F to 850°F (320°C to 450°C) range can achieve the same efficiency as a thermal oxidizer operating between 1,000°F and 2,000°F (540°C and 1,100°C).
- Can achieve organic compound destruction efficiencies of more than 95%.
- Used for inlet conc. ranging from approx. 100 ppm to more than 10,000 ppm.

Source: (Student Manual, EPA)

Well, catalytic oxidation system is another way, means we have seen the oxidizing systems and then catalytic oxidation system where catalyst, the substance which accelerates the chemical reactions about the, without changing itself. So, the waste gas is passed through a layer of the catalyst and it causes the oxidation reaction to proceed at a much lower temperature that is the advantage of this catalytic bed where we pass through the gas and it passes through this catalytic bed and at lower temperature we can have this oxidation of these gases then gas exit is there. Auxiliary fuel burners are also there.

So, it can achieve basically this catalytic oxidizing operation system it operates around 320 degree to 450 degrees Celsius. So, this is much lower than the oxidizing device which we have seen which operate in the range of 540 degrees Celsius to 1100 degrees Celsius. So, that way this catalytic oxidation system is much advantageous in that sense. It can achieve organic compound destruction efficiency even more than 95 percent. So, that is another advantage. And it is used for inlet concentration ranging from approximately 100 ppm to 10,000 ppm. So, that way range is also very good depending upon different industries.

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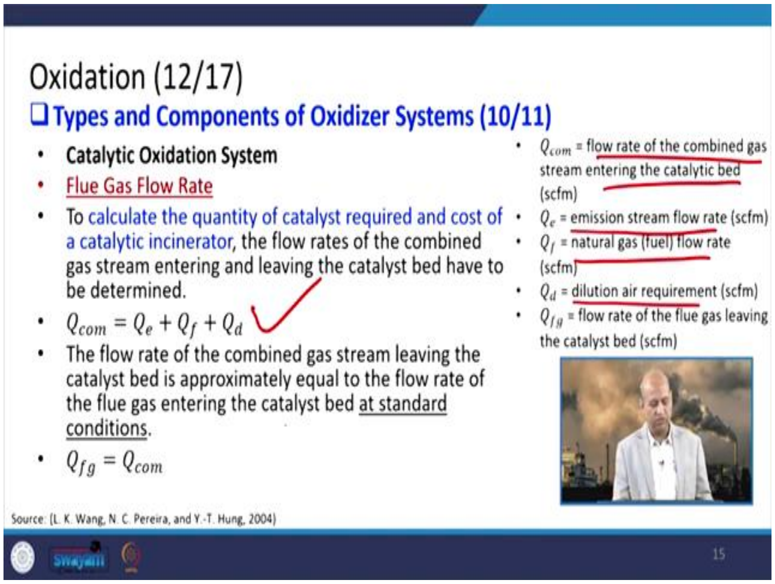

Oxidation (12/17)

❑ Types and Components of Oxidizer Systems (10/11)

- Catalytic Oxidation System
- Flue Gas Flow Rate
- To calculate the quantity of catalyst required and cost of a catalytic incinerator, the flow rates of the combined gas stream entering and leaving the catalyst bed have to be determined.
- $Q_{com} = Q_e + Q_f + Q_d$
- The flow rate of the combined gas stream leaving the catalyst bed is approximately equal to the flow rate of the flue gas entering the catalyst bed at standard conditions.
- $Q_{fg} = Q_{com}$

- Q_{com} = flow rate of the combined gas stream entering the catalytic bed (scfm)
- Q_e = emission stream flow rate (scfm)
- Q_f = natural gas (fuel) flow rate (scfm)
- Q_d = dilution air requirement (scfm)
- Q_{fg} = flow rate of the flue gas leaving the catalyst bed (scfm)

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

Well, when we talk about the flue gas flow rate, when we want to design the system, thenb for calculation purpose again this Qe + Qf + Qd that is emission stream flow rate, natural gas flow rate and dilution air requirement in the same unit so that constitute the flow rate of the combined gas stream which is entering to the catalytic bed. So that we can calculate by this. And we also assume that which is the flow rate of the incoming gas is equal to the outgoing after the catalytic bed. So, that is the way of calculation.

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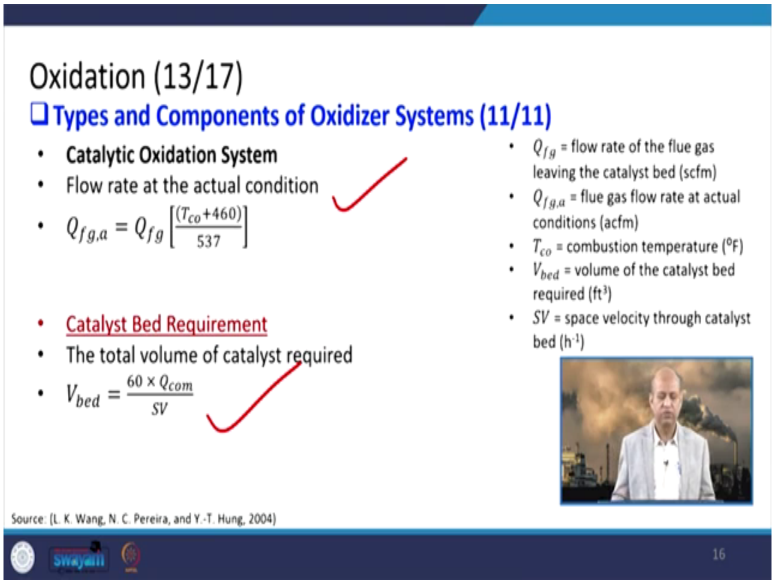

Oxidation (13/17)

❑ Types and Components of Oxidizer Systems (11/11)

- Catalytic Oxidation System
- Flow rate at the actual condition
- $Q_{fg,a} = Q_{fg}\left[\frac{(T_{co}+460)}{537}\right]$

- Catalyst Bed Requirement
- The total volume of catalyst required
- $V_{bed} = \frac{60 \times Q_{com}}{SV}$

- Q_{fg} = flow rate of the flue gas leaving the catalyst bed (scfm)
- $Q_{fg,a}$ = flue gas flow rate at actual conditions (acfm)
- T_{co} = combustion temperature (⁰F)
- V_{bed} = volume of the catalyst bed required (ft^3)
- SV = space velocity through catalyst bed (h^{-1})

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

Then we also know this flow rate at the actual condition. So, again similar equation is used which we have seen in oxidation. Then we can calculate this volume of the catalytic system. So, that way these are the parameters which we should remember which are used for designing purposes basically.

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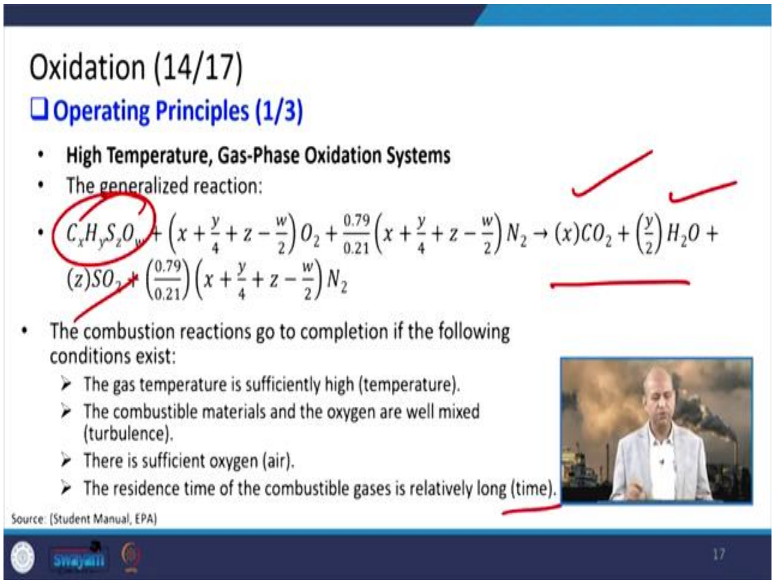

Oxidation (14/17)

❑ Operating Principles (1/3)

- **High Temperature, Gas-Phase Oxidation Systems**
- The generalized reaction:
- $C_xH_yS_zO_w + \left(x + \frac{y}{4} + z - \frac{w}{2}\right)O_2 + \frac{0.79}{0.21}\left(x + \frac{y}{4} + z - \frac{w}{2}\right)N_2 \rightarrow (x)CO_2 + \left(\frac{y}{2}\right)H_2O + (z)SO_2 + \left(\frac{0.79}{0.21}\right)\left(x + \frac{y}{4} + z - \frac{w}{2}\right)N_2$
- The combustion reactions go to completion if the following conditions exist:
  - ➢ The gas temperature is sufficiently high (temperature).
  - ➢ The combustible materials and the oxygen are well mixed (turbulence).
  - ➢ There is sufficient oxygen (air).
  - ➢ The residence time of the combustible gases is relatively long (time).

Source: (Student Manual, EPA)

And high temperature gas phase oxidation systems which we are talking into this particular general form then this is the basic oxidation when we convert it into CO_2, S_2O basically and some if sulfur products are there in this particular fuel, so that SO_2 will also be there and some other products of the nitrogen related. So, the gas temperature is sufficiently high which is very important for the combustion reactions to go for completion, complete oxidation for that we need the gas temperature adequately high.

So, temperature is one variable. Another is turbulence, because it ensured the combustible materials and the oxygen should be well mixed. So, the turbulence must be adequate. Similarly, there is sufficient oxygen we have to ensure, so air must be there, proper flow of the air must be there. The residence time of the combustible gases is relatively long so that the whole system gets into this oxidation process the completion occurs. So, the time is also issue. The time, air, turbulence and temperature all these factors we have to ensure that they are there for the complete combustion.

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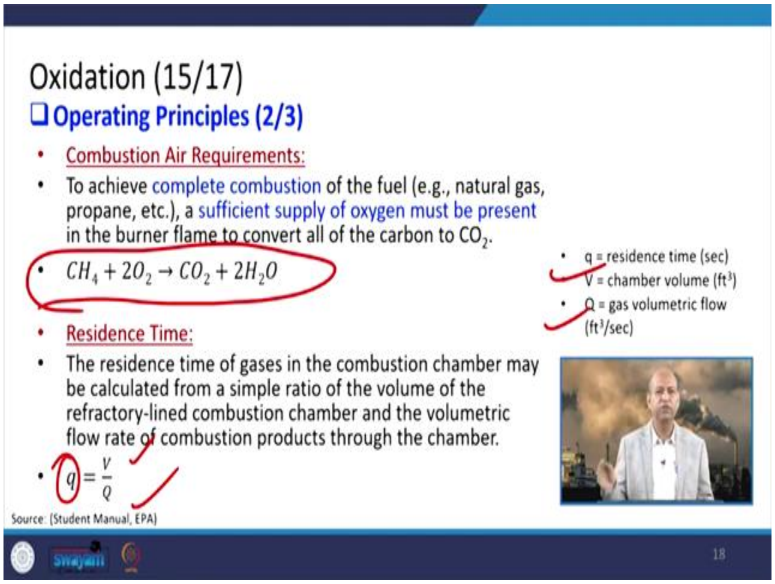

Oxidation (15/17)

❑ Operating Principles (2/3)

- Combustion Air Requirements:
- To achieve complete combustion of the fuel (e.g., natural gas, propane, etc.), a sufficient supply of oxygen must be present in the burner flame to convert all of the carbon to CO_2.
- $CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$
- Residence Time:
- The residence time of gases in the combustion chamber may be calculated from a simple ratio of the volume of the refractory-lined combustion chamber and the volumetric flow rate of combustion products through the chamber.
- $q = \frac{V}{Q}$

- q = residence time (sec)
- V = chamber volume (ft^3)
- Q = gas volumetric flow (ft^3/sec)

Source: (Student Manual, EPA)

Then what happens like for example to achieve the complete combustion the sufficient supply of oxygen goes for like this oxidation system like methane if it is there. So, when complete oxidation occurs then CO_2 is there and water is there, water vapor is there. And how to calculate the residence time that can be calculated with the chamber volume and the gas volumetric flow rate. So, V/Q. So, this is the residence time Q. Some authors use T, R some use Q so that we do not get confused. This is the concept is very simple that the volumetric chambers volume divided by gas volumetric flow rate can give you the residence time.

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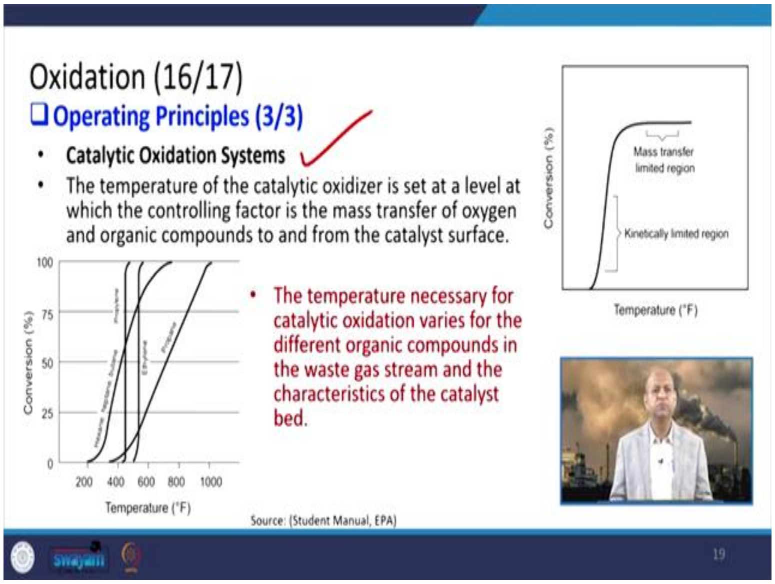

Oxidation (16/17)

❑ Operating Principles (3/3)

- **Catalytic Oxidation Systems**
- The temperature of the catalytic oxidizer is set at a level at which the controlling factor is the mass transfer of oxygen and organic compounds to and from the catalyst surface.

- The temperature necessary for catalytic oxidation varies for the different organic compounds in the waste gas stream and the characteristics of the catalyst bed.

Source: (Student Manual, EPA)

This operating principles, so in the catalytic oxidation systems the temperature of the catalytic oxidizer is set at a level at which the controlling factor is the mass transfer of oxygen and organic compounds to and fro the catalytic surface and we have to remember the temperature necessary for catalytic oxidation varies for the different organic compounds in the waste gas stream and the characteristics of the catalytic bed. So, depending upon the gas which we want to oxidize at the catalytic oxidation system and it is temperature and other properties. Those things we have to keep in mind.

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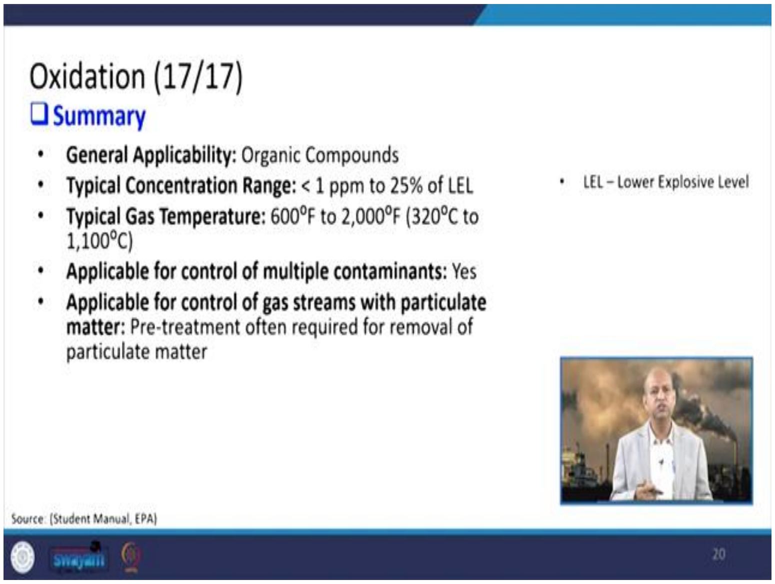

Oxidation (17/17)

❑ **Summary**

- **General Applicability:** Organic Compounds
- **Typical Concentration Range:** < 1 ppm to 25% of LEL
- **Typical Gas Temperature:** 600°F to 2,000°F (320°C to 1,100°C)
- **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 that this oxidation system can work for organic compounds and it can typically the concentration range for which we use it so it is 1 ppm to 25 percent of lower explosive level and it can 320 degree to 1100 degrees Celsius that can be there depending upon whether we are using this catalytic or thermal system. It can be applicable for controlling multiple contaminants because the range of the handling with the temperature range as well as other ranges are quite larger.

Applicable for control of the gas streams with particulate matter is also and pretreatment often required for removal of particulate matter, then it is possible to use this system, otherwise with particulate matters like scrubbers we could use. In this system we do not want this particulate matter, otherwise system efficiency will not work properly. So, the particulate matter with the pretreatment we can remove and then let us oxidize the gas or burn the gas that way this system is good for.

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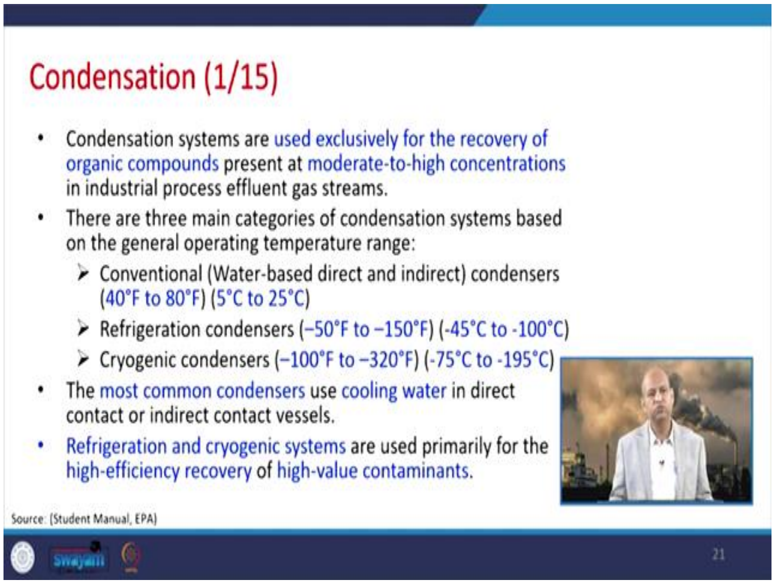

Condensation (1/15)

- Condensation systems are used exclusively for the recovery of organic compounds present at moderate-to-high concentrations in industrial process effluent gas streams.
- There are three main categories of condensation systems based on the general operating temperature range:
  - Conventional (Water-based direct and indirect) condensers (40°F to 80°F) (5°C to 25°C)
  - Refrigeration condensers (–50°F to –150°F) (-45°C to -100°C)
  - Cryogenic condensers (–100°F to –320°F) (-75°C to -195°C)
- The most common condensers use cooling water in direct contact or indirect contact vessels.
- Refrigeration and cryogenic systems are used primarily for the high-efficiency recovery of high-value contaminants.

Source: (Student Manual, EPA)

Now, next is condensation. So, condensation system basically like condensation means to reduce the temperature and recover something which is in the vapor form so that we can convert into liquid form. So, the condensation systems is used for exclusively for the recovery of organic compounds present at moderate to high concentrations in the industrial processes in effluent gas systems and which are of kind of valuable, means they are expensive to buy. So, it is better to recover them rather than releasing them into the atmosphere.

So, there are three main categories of condensation systems based on the general operating temperature range like 5 degrees to 25 degrees Celsius. This is conventional waste based direct or indirect. And the condensers of other type are like refrigeration condensers or cryogenic condensers. So, they have different ranges, like refrigeration condenser has the range of –45 degrees Celsius to –100 degree Celsius and this cryogenic condenser can have –75 to –195 degrees Celsius and for normal temperature like 5 to 25 we do conventional kind of thing, but their efficiency will vary.

The most common condensers use cooling water in direct contact or indirect contact vessels and the refrigeration and cryogenic systems are used primarily for the high efficiency recovery of high value contaminants. When they are variable then we have to recover them rather than releasing them into the atmosphere because it will be economical to recover them.

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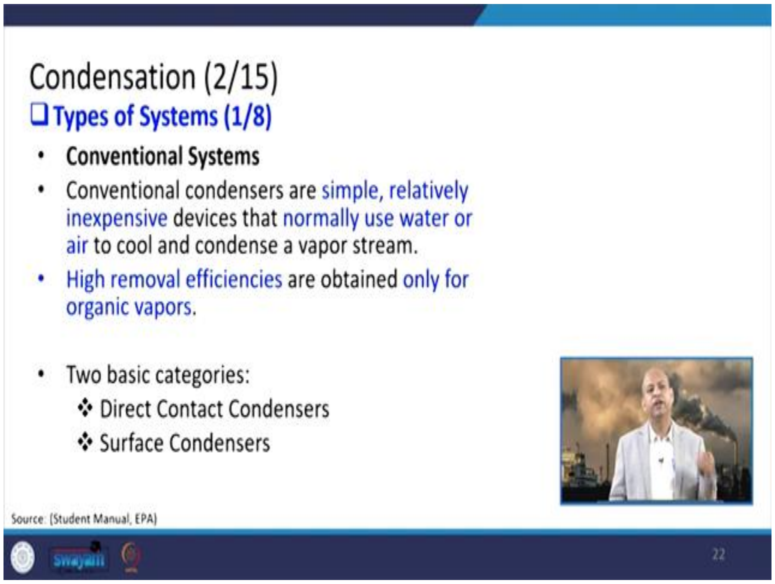

Condensation (2/15)

❑ Types of Systems (1/8)

- **Conventional Systems**
- Conventional condensers are simple, relatively inexpensive devices that normally use water or air to cool and condense a vapor stream.
- High removal efficiencies are obtained only for organic vapors.
- Two basic categories:
  - ❖ Direct Contact Condensers
  - ❖ Surface Condensers

Source: (Student Manual, EPA)

Well. So, types of these systems could be like conventional system as we have just discussed. So, conventional condensers are simple, relatively inexpensive devices and normally use the water or air to cool and condense a vapor stream. So, the high removal efficiencies are obtained only for organic vapors. Two basic categories of this particular conventional system could be like direct contact condensers or surface condensers.

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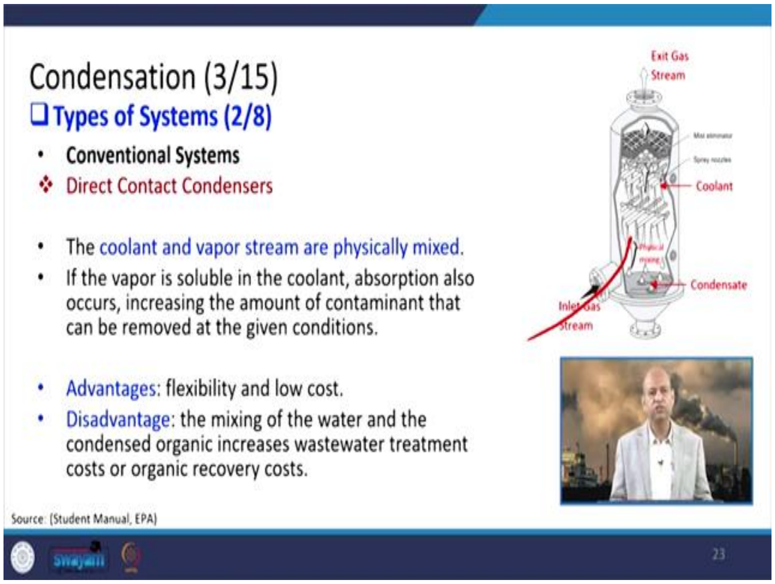

Condensation (3/15)

❑ Types of Systems (2/8)

- **Conventional Systems**
- ❖ Direct Contact Condensers

- The coolant and vapor stream are physically mixed.
- If the vapor is soluble in the coolant, absorption also occurs, increasing the amount of contaminant that can be removed at the given conditions.

- Advantages: flexibility and low cost.
- Disadvantage: the mixing of the water and the condensed organic increases wastewater treatment costs or organic recovery costs.

Source: (Student Manual, EPA)

So, the direct contact condensers, this coolant is there. So, coolant kind of spray is there and this inlet gas system goes. So, as you have seen in scrubbers the same system is here. And then because of temperature difference, this below dew point the vapors get condensed. So, in this particular process the coolant and vapor stream are physically mixed that is why it is known as the direct contact condenser.

If the vapor is soluble in the coolant or absorption like in water it occurs, then increasing the amount of contaminant that can be removed at the given conditions. Advantages are like they are flexible and very low-cost kind of system. Disadvantage because like mixing in the water then it is creating the wastewater stream. So, we are converting one pollutant into another one. So, wastewater treatment cost is to be added into that system of this organic recovery cost.

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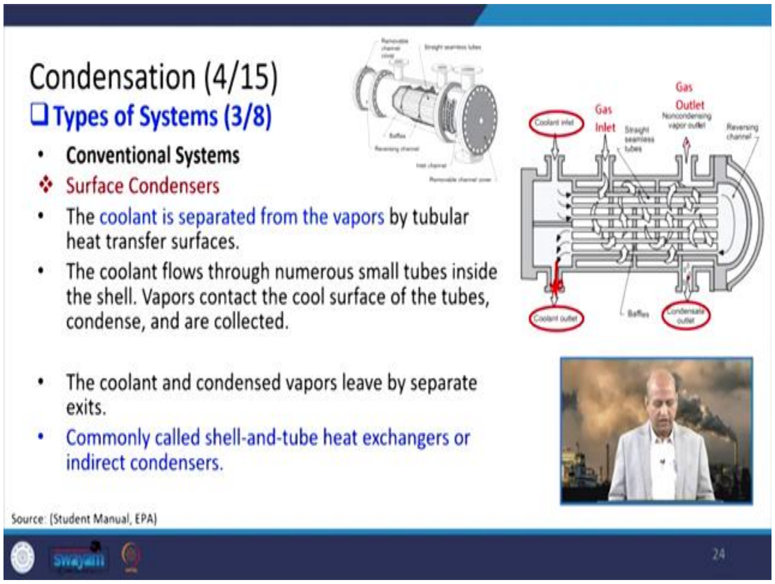

Condensation (4/15)

❑ Types of Systems (3/8)

- Conventional Systems

❖ Surface Condensers

- The coolant is separated from the vapors by tubular heat transfer surfaces.
- The coolant flows through numerous small tubes inside the shell. Vapors contact the cool surface of the tubes, condense, and are collected.
- The coolant and condensed vapors leave by separate exits.
- Commonly called shell-and-tube heat exchangers or indirect condensers.

Source: (Student Manual, EPA)

Then if we talk about surface condensers then this gas inlet is there and these coolant outlets and this condensate outlet is there and gas outlet is there, gas inlet is there, coolant inlet can be there. So, this coolant passes through those surfaces get cooled and in direct contact they do not come coolant and this gas, because through pipes it goes through the system. So, the coolant is separated from the vapors by these tubes kind of system, tubular heat transfer surfaces.

The coolant flows through numerous small tubes inside the shell, these tubes are there. And vapors contact the cooled surface of those tubes and condense and then convert it into liquid portion and then it is collected. So, the coolant and condensed vapors leave by separate exits. This coolant exit and this is condensate outlet because they have separate you know flow regimes. And the commonly called like shell and tube heat exchanger or indirect condensers because of this process of indirect recovery.

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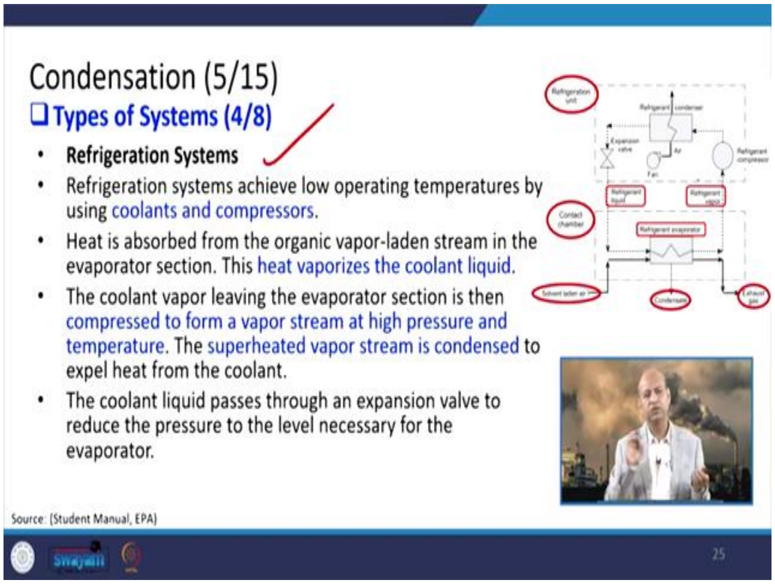

Condensation (5/15)

❑ Types of Systems (4/8)

- **Refrigeration Systems**
- Refrigeration systems achieve low operating temperatures by using coolants and compressors.
- Heat is absorbed from the organic vapor-laden stream in the evaporator section. This heat vaporizes the coolant liquid.
- The coolant vapor leaving the evaporator section is then compressed to form a vapor stream at high pressure and temperature. The superheated vapor stream is condensed to expel heat from the coolant.
- The coolant liquid passes through an expansion valve to reduce the pressure to the level necessary for the evaporator.

Source: (Student Manual, EPA)

Then we come to this refrigeration system. The refrigeration systems achieve low operating temperatures by using coolants and compressors. So, the heat is absorbed from the organic vapor laden stream because they are hot in the, this operation section. That heat vaporizes the coolant liquid. And the coolant vapor leaving the operator section is then compressed.

And then superheat vapor stream is condensed to expel the heat from the coolant. So, that system is shown in this particular schematic diagram you can go through. And the coolant liquid passes through an expansion wall to reduce the pressure to the level necessary for the operator. So, that can be controlled by depending upon what kind of vapor it is.

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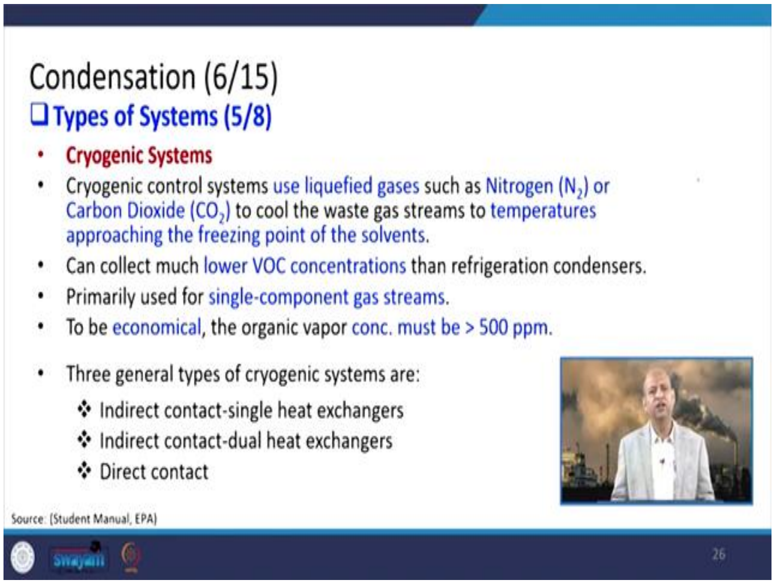

Condensation (6/15)

❑ Types of Systems (5/8)

- **Cryogenic Systems**
- Cryogenic control systems use liquefied gases such as Nitrogen (N_2) or Carbon Dioxide (CO_2) to cool the waste gas streams to temperatures approaching the freezing point of the solvents.
- Can collect much lower VOC concentrations than refrigeration condensers.
- Primarily used for single-component gas streams.
- To be economical, the organic vapor conc. must be > 500 ppm.
- Three general types of cryogenic systems are:
  - ❖ Indirect contact-single heat exchangers
  - ❖ Indirect contact-dual heat exchangers
  - ❖ Direct contact

Source: (Student Manual, EPA)

When we talk about cryogenic systems, so cryogenic control systems use liquefied gases such as nitrogen or carbon dioxide to cool the waste gas stream to temperature approaching the freezing point of the solvent so that they can be condensed. So, this can collect much lower VOC concentrations then refrigeration condensers if we compare.

Primarily used for single compound gases streams. And to be economical, the organic vapor concentration must be more than 500 ppm, otherwise of course it can go for low concentration but it depends basically. Then three general types of cryogenic systems are there, like indirect contact single exchanger or indirect contact dual heat exchanger, indirect contact single heat exchanger and indirect contact dual heat exchanger and the third one is direct contact.

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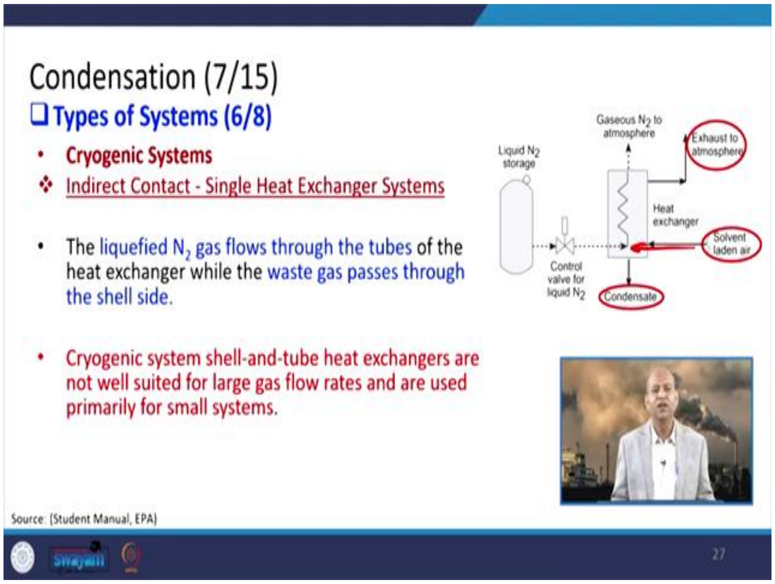

Condensation (7/15)

❑ Types of Systems (6/8)

- Cryogenic Systems

❖ Indirect Contact - Single Heat Exchanger Systems

- The liquefied N_2 gas flows through the tubes of the heat exchanger while the waste gas passes through the shell side.

- Cryogenic system shell-and-tube heat exchangers are not well suited for large gas flow rates and are used primarily for small systems.

Source: (Student Manual, EPA)

So, that way we can see this indirect contact single heat exchanger in this particular system, where this liquid nitrogen storage is there and control valve so that you can control the flow rate of this liquid nitrogen, then it passes through this particular system gaseous nitrogen to the atmosphere and this solvent laden air gas goes to this and then it condensate because it converted to liquid it goes down and exhaust to atmosphere can be there those gases.

So, the liquefied nitrogen basically it flows through the tubes of the heat exchanger while the, this waste gas passes through the shell side. Then cryogenic system shell and tube heat exchangers are not well suited for the large gas flow rates and are used primarily for a small system. So, that is the limitation of this particular system.

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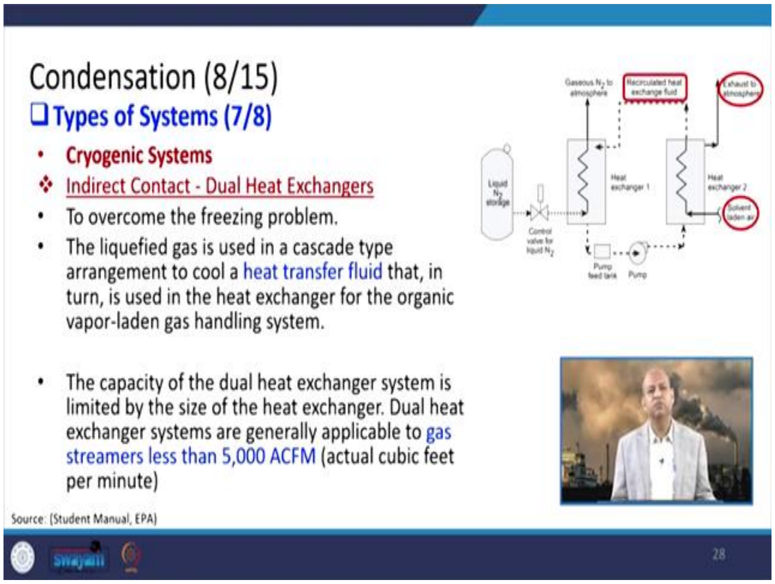

Condensation (8/15)

❑ Types of Systems (7/8)

- Cryogenic Systems

❖ Indirect Contact - Dual Heat Exchangers

- To overcome the freezing problem.
- The liquefied gas is used in a cascade type arrangement to cool a heat transfer fluid that, in turn, is used in the heat exchanger for the organic vapor-laden gas handling system.
- The capacity of the dual heat exchanger system is limited by the size of the heat exchanger. Dual heat exchanger systems are generally applicable to gas streamers less than 5,000 ACFM (actual cubic feet per minute)

Source: (Student Manual, EPA)

When we talk about the indirect contact dual heat exchangers, so basically this is used for overcoming the freezing problems. So, there are two chambers there. So, the liquefied gas is used in this case in a casket type arrangements to cool a heat transfer fuel that in turn is used to heat exchanger for the organic vapor laden gas handling the system and the capacity of the dual heat exchanger system is limited by the size of the heat exchanger and dual heat exchanger systems are generally applicable for the gases streams like less than 5000 actual cubic feet per minute. So, that is again the limitation of this particular system.

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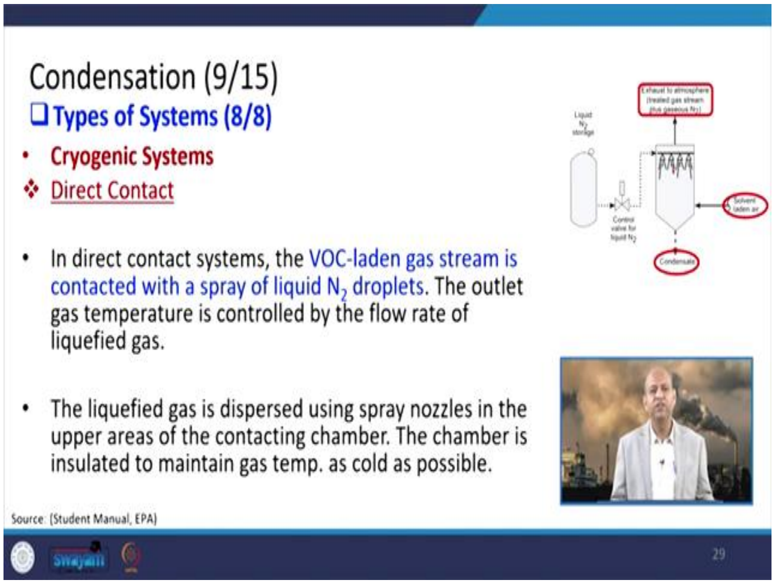

Condensation (9/15)

❑ Types of Systems (8/8)

- Cryogenic Systems

❖ Direct Contact

- In direct contact systems, the VOC-laden gas stream is contacted with a spray of liquid N_2 droplets. The outlet gas temperature is controlled by the flow rate of liquefied gas.
- The liquefied gas is dispersed using spray nozzles in the upper areas of the contacting chamber. The chamber is insulated to maintain gas temp. as cold as possible.

Source: (Student Manual, EPA)

When we talk about the direct contact of cryogenic systems, then again this is similar to the, this scrubber kind of thing. So, here it is coming into the direct contact. Solvent goes this particular liquid gas is there. So, it is in this particular system then exhaust gas goes afterwards there but the liquefied those vapors which we want to extract that goes like a condensate. So, in direct contact system the VOC laden gas stream is contacted with the spray of liquid nitrogen droplets.

So, droplets have larger surface, they come into contact and cools down those vapors which we want to collect as a condensate. So, the outlet gas temperature is controlled by the flow rate of the liquefied gas and the liquefied gas is dispersed using spray nozzles like spray. And in this upper areas of the contacting chamber, the chamber is insulated to maintain the gas temperature as cold as possible so that this condensation process is not disturbed by the outer temperature.

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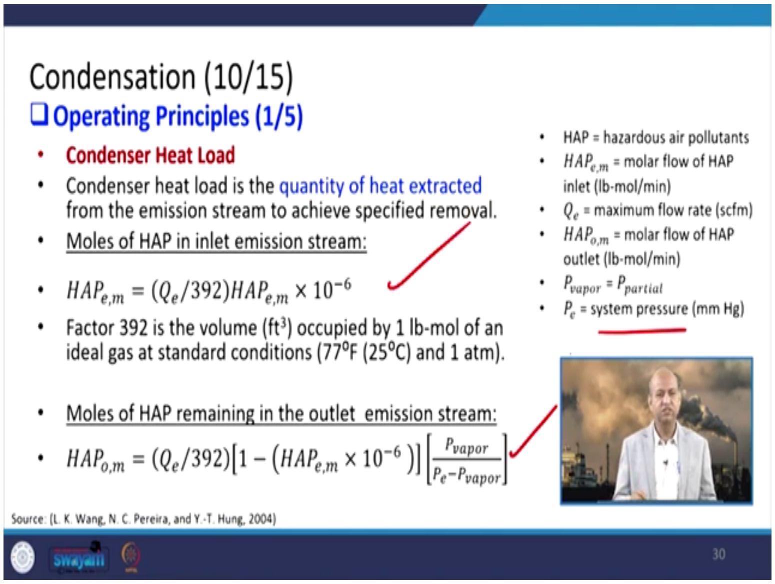

Condensation (10/15)

☐ Operating Principles (1/5)

- **Condenser Heat Load**
- Condenser heat load is the quantity of heat extracted from the emission stream to achieve specified removal.
- Moles of HAP in inlet emission stream:
- $HAP_{e,m} = (Q_e/392)HAP_{e,m} \times 10^{-6}$
- Factor 392 is the volume (ft^3) occupied by 1 lb-mol of an ideal gas at standard conditions (77°F (25°C) and 1 atm).
- Moles of HAP remaining in the outlet emission stream:
- $HAP_{o,m} = (Q_e/392)\left[1 - \left(HAP_{e,m} \times 10^{-6}\right)\right]\left[\frac{P_{vapor}}{P_e - P_{vapor}}\right]$

- HAP = hazardous air pollutants
- $HAP_{e,m}$ = molar flow of HAP inlet (lb-mol/min)
- Q_e = maximum flow rate (scfm)
- $HAP_{o,m}$ = molar flow of HAP outlet (lb-mol/min)
- $P_{vapor} = P_{partial}$
- P_e = system pressure (mm Hg)

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

When we want to go for design aspect then we have to see like molar flow of the these hazardous air pollutants, maximum flow rate, molar flow of the HAP outlet, then this partial pressure and the vapor pressure, system pressure all these things in these empirical relationships which are there for calculating moles of the hazardous air pollutants in the inlet emission stream and to calculate most of the HAP remaining the outlet emission streams. So, these are the particular relationships which we use.

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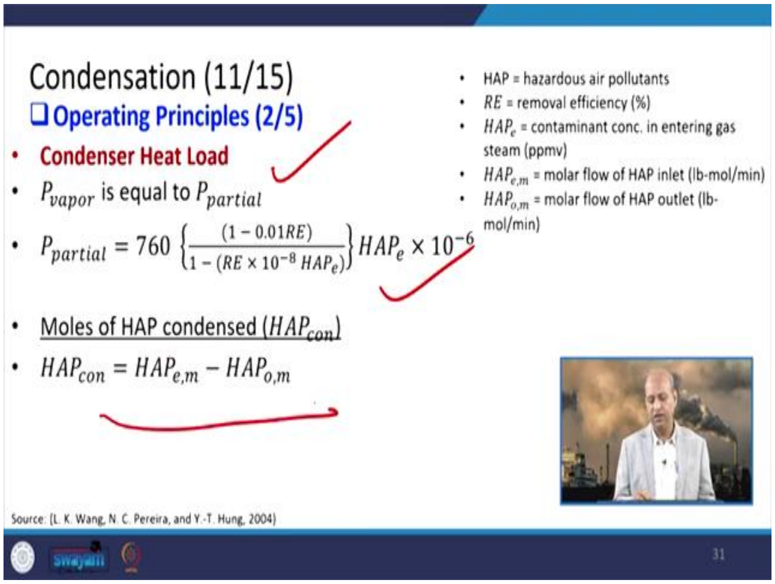

Condensation (11/15)

❑ Operating Principles (2/5)

- **Condenser Heat Load**
- P_{vapor} is equal to $P_{partial}$
- $P_{partial} = 760 \left\{ \frac{(1 - 0.01RE)}{1 - (RE \times 10^{-8}\, HAP_e)} \right\} HAP_e \times 10^{-6}$
- Moles of HAP condensed (HAP_{con})
- $HAP_{con} = HAP_{e,m} - HAP_{o,m}$

- HAP = hazardous air pollutants
- RE = removal efficiency (%)
- HAP_e = contaminant conc. in entering gas steam (ppmv)
- $HAP_{e,m}$ = molar flow of HAP inlet (lb-mol/min)
- $HAP_{o,m}$ = molar flow of HAP outlet (lb-mol/min)

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

Similarly, the condenser heat load if you want to calculate then P_{vapor} is equal to $P_{partial}$ this pressure of the vapor P_{vapor} and this partial pressure. So, this is again estimated by using this empirical relationship and ultimately moles of hazardous air pollutants condensed is calculated by this particular relationship.

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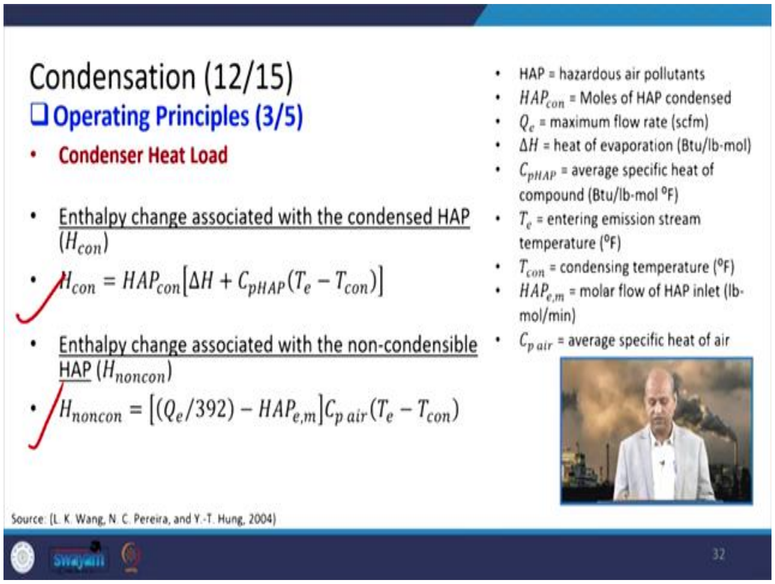

Condensation (12/15)

❑ Operating Principles (3/5)

- **Condenser Heat Load**

- Enthalpy change associated with the condensed HAP (H_{con})
- $H_{con} = HAP_{con}[\Delta H + C_{pHAP}(T_e - T_{con})]$
- Enthalpy change associated with the non-condensible HAP (H_{noncon})
- $H_{noncon} = [(Q_e/392) - HAP_{e,m}]C_{p\,air}(T_e - T_{con})$

- HAP = hazardous air pollutants
- HAP_{con} = Moles of HAP condensed
- Q_e = maximum flow rate (scfm)
- ΔH = heat of evaporation (Btu/lb-mol)
- C_{pHAP} = average specific heat of compound (Btu/lb-mol °F)
- T_e = entering emission stream temperature (°F)
- T_{con} = condensing temperature (°F)
- $HAP_{e,m}$ = molar flow of HAP inlet (lb-mol/min)
- $C_{p\,air}$ = average specific heat of air

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

Well, when we talk about this enthalpy change associated with this condensed hazardous air pollutant system and enthalpy change associated with the non-condensable HAP then also there are certain relationships which can be used where temperatures and other parameters which you can know here like T is entering emission extreme temperature, T_{con} is $T_{condensing}$ the condensing temperature all these terminologies are used here for calculation purpose.

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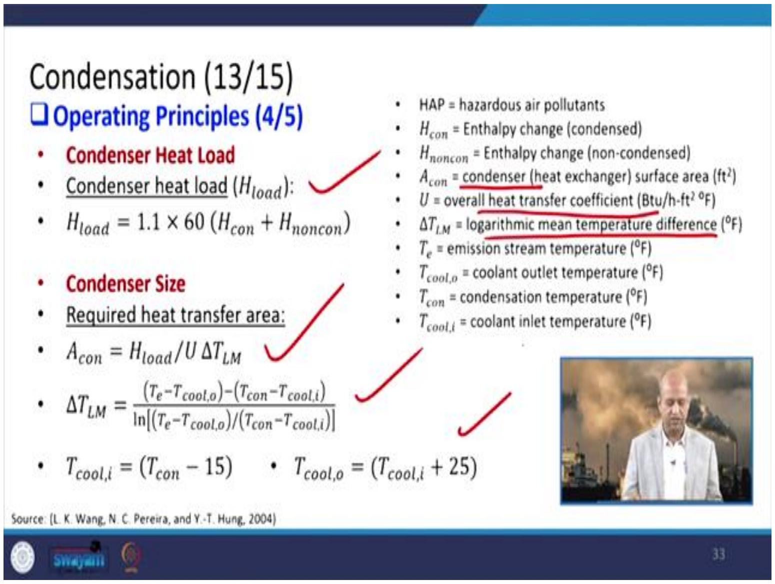

Condensation (13/15)

☐ Operating Principles (4/5)

- **Condenser Heat Load**
- Condenser heat load (H_{load}):
- $H_{load} = 1.1 \times 60\ (H_{con} + H_{noncon})$

- **Condenser Size**
- Required heat transfer area:
- $A_{con} = H_{load}/U\,\Delta T_{LM}$
- $\Delta T_{LM} = \dfrac{(T_e - T_{cool,o}) - (T_{con} - T_{cool,i})}{\ln[(T_e - T_{cool,o})/(T_{con} - T_{cool,i})]}$
- $T_{cool,i} = (T_{con} - 15)$
- $T_{cool,o} = (T_{cool,i} + 25)$

- HAP = hazardous air pollutants
- H_{con} = Enthalpy change (condensed)
- H_{noncon} = Enthalpy change (non-condensed)
- A_{con} = condenser (heat exchanger) surface area (ft^2)
- U = overall heat transfer coefficient (Btu/h-ft^2 °F)
- ΔT_{LM} = logarithmic mean temperature difference (°F)
- T_e = emission stream temperature (°F)
- $T_{cool,o}$ = coolant outlet temperature (°F)
- T_{con} = condensation temperature (°F)
- $T_{cool,i}$ = coolant inlet temperature (°F)

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

Similarly, the condenser heat load can be calculated and then how much area is needed of the condenser, this condenser heat exchanger surface area, because only then we will be able to design the particular system, how much area is needed, how many tubes will be required for ensuring that much area. So, this area can be calculated by H load this condenser heat load divided by U delta TL and U is here, overall heat transfer coefficient and that delta TLM is logarithmic mean temperature difference. So, that way you can use these empirical relationships to estimate these parameters.

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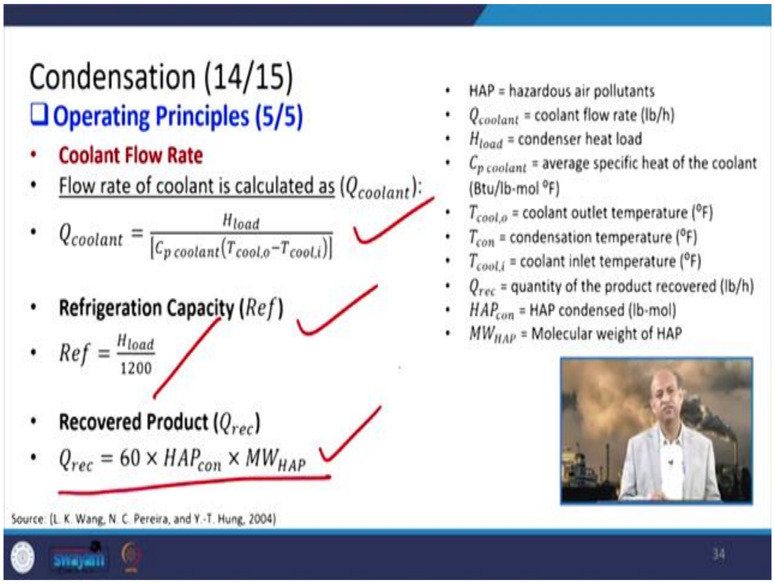

Condensation (14/15)

❑ **Operating Principles (5/5)**

- **Coolant Flow Rate**
- Flow rate of coolant is calculated as ($Q_{coolant}$):
- $Q_{coolant} = \frac{H_{load}}{[C_{p\,coolant}(T_{cool,o} - T_{cool,i})]}$
- **Refrigeration Capacity** (Ref)
- $Ref = \frac{H_{load}}{1200}$
- **Recovered Product** (Q_{rec})
- $Q_{rec} = 60 \times HAP_{con} \times MW_{HAP}$

- HAP = hazardous air pollutants
- $Q_{coolant}$ = coolant flow rate (lb/h)
- H_{load} = condenser heat load
- $C_{p\,coolant}$ = average specific heat of the coolant (Btu/lb-mol °F)
- $T_{cool,o}$ = coolant outlet temperature (°F)
- T_{con} = condensation temperature (°F)
- $T_{cool,i}$ = coolant inlet temperature (°F)
- Q_{rec} = quantity of the product recovered (lb/h)
- HAP_{con} = HAP condensed (lb-mol)
- MW_{HAP} = Molecular weight of HAP

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

Ultimately, we flow rate of the coolant is calculated like this and refrigeration capacity can be calculated by H_{load} /1200. Recovered product can be estimated by this relationship.

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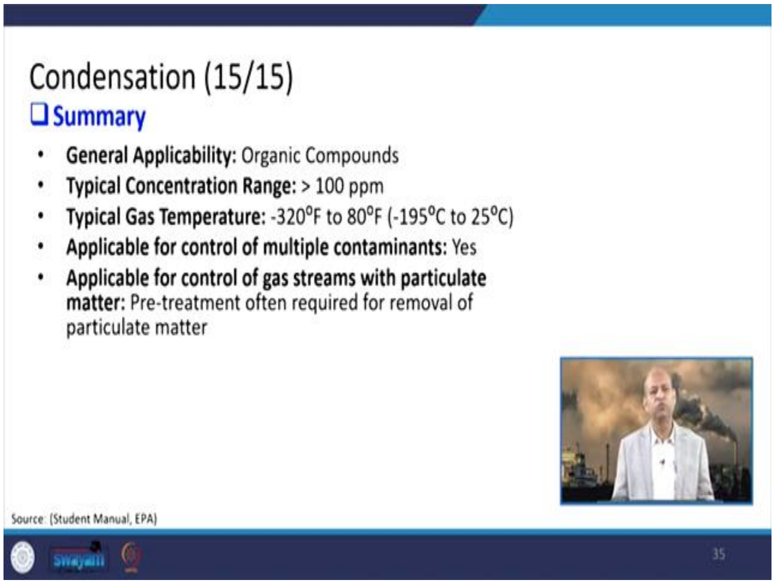

Condensation (15/15)

❑ **Summary**

- **General Applicability:** Organic Compounds
- **Typical Concentration Range:** > 100 ppm
- **Typical Gas Temperature:** -320°F to 80°F (-195°C to 25°C)
- **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)

So, in summary we can say that these condensers are very good for recovering the organic compounds and typical, this concentration range for them is more than 100 ppm then it is efficient to recover them. And the typical gas temperature is around –195 degree Celsius to 25 degrees Celsius as per the system. And it can be applicable for controlling multiple pollutants and pretreatment is required for removal of particulate matter for efficient way of working of the condenser system. So, that it work only for that gas, otherwise it would be difficult or the efficiency will be reduced and system may also be disturbed.

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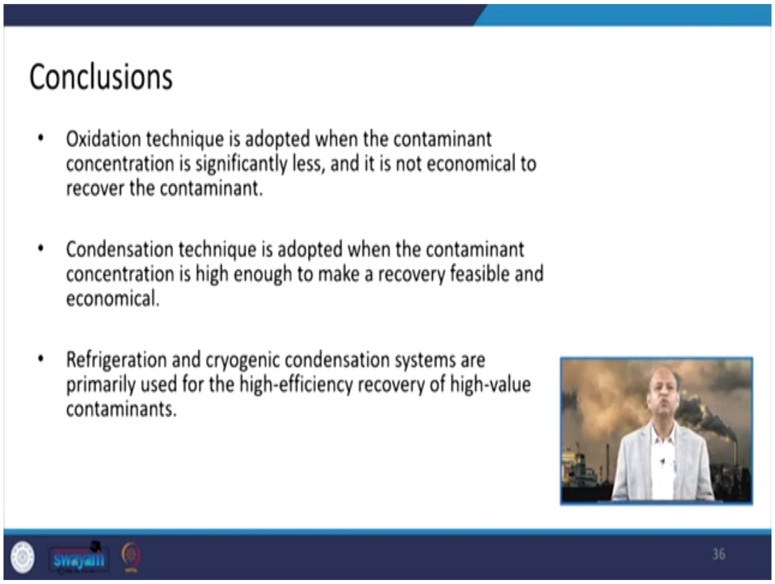

Conclusions

- Oxidation technique is adopted when the contaminant concentration is significantly less, and it is not economical to recover the contaminant.
- Condensation technique is adopted when the contaminant concentration is high enough to make a recovery feasible and economical.
- Refrigeration and cryogenic condensation systems are primarily used for the high-efficiency recovery of high-value contaminants.

Well, this is all for today. So, in conclusion, we can say that the oxidation techniques which are adopted when the contaminant concentration is significantly less and it is not economical to recover the contaminant so oxidation is used, burning is used in simple words. Condensation technique is used when contaminant is precious or has value so that we can recover it or recovery is feasible and economical. Then refrigeration and cryogenic condensation systems are primarily used for the high efficiency recovery of high value contaminants.

So, that way now it is clear I hope that oxidation for which particular organic compounds we would like to use and condensation for which kind of vapors or these organic compounds which we will, we would like to use. And refrigeration and cryogenic condensation will be used primarily for high efficiency recovery of high value contaminants so that efficiently we can recover them because they are precious in that sense, valuable in that sense. So, this is all for today and that way we have covered for lectures on controlling these, controlling devices for removing particulate matters and removing gaseous air pollutants.

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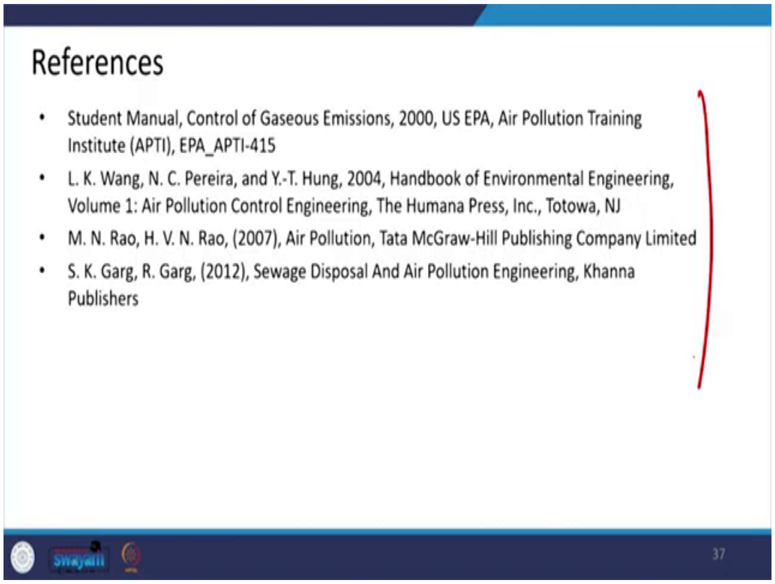

References

- 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
- M. N. Rao, H. V. N. Rao, (2007), Air Pollution, Tata McGraw-Hill Publishing Company Limited
- S. K. Garg, R. Garg, (2012), Sewage Disposal And Air Pollution Engineering, Khanna Publishers

So, this is all for today. This is the reference for your additional information which you can go at leisure time. So, thank you for your kind attention and see you in the next lecture. Thanks again.