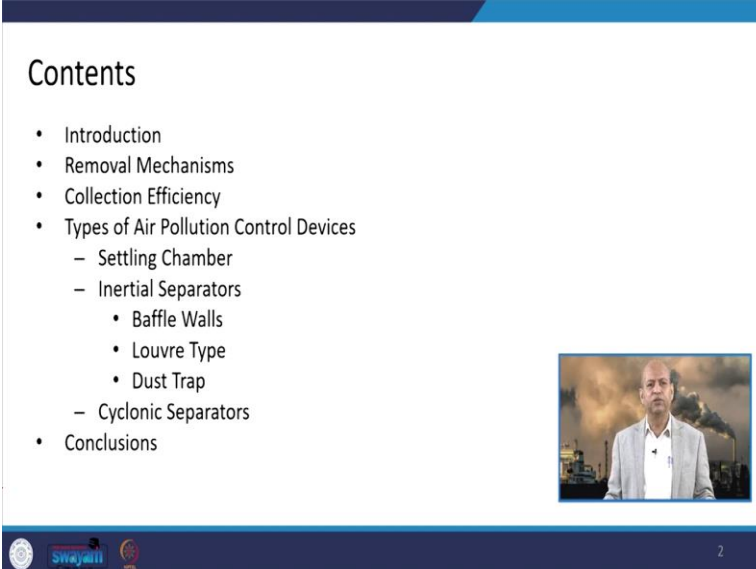


Air Pollution and Control
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Department of Civil Engineering
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Lecture 42
Air Pollution Control Devices- Part - 1


Hello, friends. You may recall last time we discussed about introductory part of air pollution control. Today we will discuss about air pollution control devices. And within that, first of all we will discuss like how to control particulate matters.


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 - Settling Chamber
 - Inertial Separators
 - Baffle Walls
 - Louvre Type
 - Dust Trap
 - Cyclonic Separators
- Conclusions




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So, in this lecture after introduction we will see these removal mechanisms, collection efficiency related issues, then types of air pollution control devices, for example, settling chamber or inertial separators like baffle walls related or louver type or dust trap kind of devices, separators, cyclonic separators and then we will conclude. And after in next lecture again we will continue, how to control the air pollution through these controlling devices. Well, so, in introduction, we can say that this control of their pollution is very important. And in a most effective way, if you want to control the pollution then it is better to control at the source itself.

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Introduction

- To control air pollution, the most effective methods are reduction at the source. One of these methods is by the **application of control equipment/devices**. Appropriate air-cleaning devices are required to collect the particulate pollutants.
- **Particulate pollutants** are a mixture of solid particles and liquid droplets found suspended in air and many of which can be hazardous. **Control devices** are installed at respective source to control particulate pollutants.
- Devices that remove particles from gas streams rely on one or more of the **pollutants removal mechanisms**.



Source: [Nathanson, J. A., 2019; www.epa.gov]

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And one of these methods which are prominent or effective to control the air pollution emissions is by the application of control equipment or devices at the source itself. And appropriate air cleaning devices are required to collect the particulate pollutants, because whenever there are a number of pollutants are emitted. So, as per the nature of the pollutant, whether it is particulate pollutant or gaseous pollutant we have to install some equipment or controlling devices.

So, today we will discuss about particulate pollutants, concentration, reduction or control of the particulate pollutant emissions basically. So, we will see how particulate matters of different sizes or different densities we can control. So, these control devices we will focus only on particulate matter concentration or collection basically.

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Pollutants Removal Mechanisms (1/2)

- Pollutants removal mechanisms are as follows:
 - ❖ **Gravitational Settling:** The particle-containing gas stream is introduced into a device or chamber where the particles settle under gravity.
 - ❖ **Centrifugal Impaction:** The gas is allowed to follow a circular path which causes the particulate to impact on the outer periphery of device.
 - ❖ **Direct Interception:** The particles having less inertia, barely follow the gas streamlines around the fiber and gets intercepted by the fibers.

The diagram illustrates three pollutant removal mechanisms:

- Centrifugal Impaction:** A circular path is shown with a particle of mass m moving at velocity v . The centrifugal force is labeled as mv^2/r .
- Gravitational Settling:** An aerosol particle of mass m is shown with a downward arrow indicating acceleration due to gravity g , and the force is labeled as mg .
- Direct Interception:** A barrier is shown with streamlines curving around it. Particles are shown being intercepted by the barrier.

Source: (<http://www.eng.utoledo.edu/>; M. N. Rao, H. V. N. Rao, 2007) Image Source: (K. Ardon-Dryer et al., 2015)


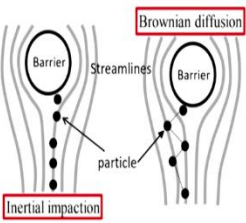
So, if you talk about like different pollutants removal mechanisms which are used for removal of these particulate pollutants, then basically we list like gravitational settling or centrifugal impaction or direct interception those kinds of things. So, in gravitational settling basically only the gravity, it acts like there is a mass of the aerosol or particles so gravity pulls and it settles down because of simple gravity. Then we can also mimic this pulling force or gravitational force by creating centrifugal force.

So, if you rotate by some device, the particulate matter, then there will be centrifugal force and it will strike to some surface and then there it will lose the velocity and it will be collected or we can also do like impaction through barriers, whenever we change the course or this direction of the flow, then what happens like these particles which are having mass so because of this momentum, they just go in a straight line. They do not quickly change the path right like the guests. So, they will have the tendency of striking to the particular that barrier and then again they can lose the velocity and they can be trapped or collected.

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Removal Mechanism (2/2)

- ❖ **Electrostatic Attraction:** The particle-containing gas stream is introduced into a device in which the particles are charged and then subjected to an electric field which causes them to migrate to one of the surfaces of the device, where they are held and collected.
- ❖ **Inertial deposition:** When a gas stream changes direction as it flows around an object in its path, suspended particles tend to keep moving in their original direction due to their inertia.
- ❖ **Brownian diffusion:** Particles suspended in a gas are always in Brownian motion. When the gas stream flows around obstacles, the natural random motion of the particles will bring them into contact with the obstacles, where they adhere and are collected.




Source: (<http://www.eng.utoledo.edu/>; M. N. Rao, H. V. N. Rao, 2007) Image Source: (K. Ardon-Dryer et al., 2015)

Then there may be another way like electrostatic attraction. Electrostatic attraction force is created by kind of ionization. So, we have different kinds of field, we have particles pass through so they get charged, and then on the opposite charge there is one device where they are collected, then they lose again the velocity and slides down. Inertial deposition can be there as these baffling kind of things maybe there or Brownian diffusion. So, ultimately, they get attached to some surface and slide down or get collected at the hopper at the bottom.

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Particulate Collection Efficiency

- The collection efficiency $\eta (D_p)$ of a device for particles of diameter D_p is expressed as:
$$\eta (D_p) = 1 - \frac{\text{number of particles of diameter } D_p \text{ per m}^3 \text{ of gas out}}{\text{number of particles of diameter } D_p \text{ per m}^3 \text{ of gas in}}$$
- The overall efficiency of the device based on particle number is:
$$\eta = 1 - \frac{\text{number of particles per m}^3 \text{ of gas out}}{\text{number of particles per m}^3 \text{ of gas in}}$$
- The collection efficiency based on particle mass η_m is defined as:
$$\eta_m (D_p) = 1 - \frac{\text{mass of particles of diameter } D_p \text{ per m}^3 \text{ of gas out}}{\text{mass of particles of diameter } D_p \text{ per m}^3 \text{ of gas in}}$$



Source: (M. N. Rao, H. V. N. Rao, 2007)

So, if we want to collect, then as an engineer we also want to know what the efficiency of collection is. So, in a general we can say, like this efficiency related to a particular, let us say, diameter particle D_p , if we want to calculate the collection efficiency of particulate pollution of the diameter D_p , then 1 minus number of particles of that diameter D_p only per cubic meter of the gas going out divided by the number of particles of diameter D_p only per cubic meter in the flow gas coming in. So, that is the simple relationship.

$$\eta (D_p) = 1 - \frac{\text{number of particles of diameter } D_p \text{ per m}^3 \text{ of gas out}}{\text{number of particles of diameter } D_p \text{ per m}^3 \text{ of gas in}}$$

$$\eta = 1 - \frac{\text{number of particles per m}^3 \text{ of gas out}}{\text{number of particles per m}^3 \text{ of gas in}}$$

$$\eta_m (D_p) = 1 - \frac{\text{mass of particles of diameter } D_p \text{ per m}^3 \text{ of gas out}}{\text{mass of particles of diameter } D_p \text{ per m}^3 \text{ of gas in}}$$

If you want to just the overall efficiency then rather than this particular diameter we consider number of all the particles. So, number of all the particles going out per cubic meter remember this and number of particles coming in so that division deducted from the 1 so that is the particular efficiency of overall efficiency.

If you want to see the collection efficiency based on particulate mass, this η_m (η_m) mass related, then it can be defined it like, defined like mass of particles of diameter D_p per cubic meter of gas going out divided by the mass of particles of diameter D_p per cubic meter of gas which is coming in that device. So, that is overall efficiency related relationship which we generally use, because it will be used later on to calculate the efficiency that is why we discussed just now about this.

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Types of Control Devices

- A list of common types of collection devices for aerosols (particulates) is as follows:

1. Settling Chambers
2. Inertial Separators
3. Cyclones
4. Filters
5. Electrostatic Precipitators
6. Scrubbers or Wet Collectors

Discussed in this lecture

Discussed in next lecture



Source: [M. N. Rao, H. V. N. Rao, 2007]

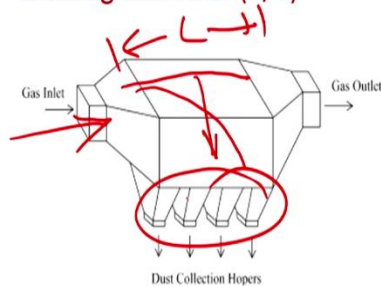


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Then if we talk what kind of devices are there which are available in industrial pollution control, so the list of common types of these air pollution control devices or collection devices of aerosols or particulate matter is like settling chambers or inertial separators or cyclones. These three types of devices we will discuss today. Then there are like bag house filters or filters, fabric filters, electrostatic precipitators or scrubbers or wet collectors they are known as we will discuss in the next lecture.

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Settling Chamber (1/7)



- It is the simplest type of equipment used for the collection of solid particulates.
- It consists of a chamber in which the carrier gas velocity is reduced to allow the particulates to settle out of the moving stream under the action of gravity.



Source: [www.epa.gov; M. N. Rao, H. V. N. Rao, 2007]

Image Source: [J. He, K. Chen, J. Xu et al., 2017]



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So, if we start our discussion on settling chamber that is the simplest device. Basically, this is simple chamber, length, width, height, so this kind of device. So, there is inlet, gas, lead and by

pollutants goes into this and it comes out of this particular outlet. So, there is a distance this length L, this has to be traveled by this gas particles, particles are there in the dirty gas and this particle has the mass so it has tendency due to gravity to go down.

So, when it travels to this distance this should be of such a speed or velocity that these particles comes down before going out through the outlet that is the fundamental thing very simple understanding we have to develop that it should be removed only then it will come down and we will remove from the hopper.

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Settling Chamber (2/7)


Principle (1/2)


- Assumes that the solids move along the chamber with the velocity of the gas and settle with Stoke's velocity.
- A particle entering the chamber at the top will be collected by the chamber, if its settling time is the same (or less than) the time the gas takes to pass through the chamber.

$$\frac{h}{V_s} = \frac{L}{V}$$

$$V_s = \frac{hV}{L} \quad \text{Eq.1}$$

- L = length of the chamber
- V = horizontal velocity of the carrier gas
- V_s = settling velocity of particulates
- h = height through which the particulates travel before settling down.





Source: (M. N. Rao, H. V. N. Rao, 2007) Image Source: (M. N. Rao, H. V. N. Rao, 2007)

So, this is the chamber, settling chamber of the length L and height h and this gas which is full of these particulate matters is going inside and this velocity of the gas is V simple V. And the Stoke's velocity of the particles, which takes it down is Vs. So, this Vs should be says that with this Vs this height will be traveled, this length of the height. For that particle this path is of the length height and this gas the path is length L. So, with V when this particle comes to this stage, this should basically come down.

$$\frac{h}{V_s} = \frac{L}{V}$$

So, that h divided by Vs equals L divided by V. So, the time taken by one particle which it travels from this point to this in the horizontal direction, in vertical direction it should have the velocity

of V_s and it should come down. So, that particular diameter of the particle we have to design for that how this V_s can be achieved so that it does not go out with the dirty gas rather it comes down. And this L is length of the chamber as you know, V is the horizontal velocity of the carrier gas and V_s settling velocity of particles and h is the height through which this particulate matter travels following the Stoke's velocity. So, this V_s is nothing but this hV divided by L . So, that way we can calculate the velocity.

$$V_s = \frac{hV}{L}$$

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Settling Chamber (3/7)

Principle (2/2)


- By Stoke's Law, ✓
- $V_s = \frac{g(\rho_p - \rho)D^2}{18\mu}$ ✓ Eq.2
- From Eq.1 and Eq.2, we get
- $D = \left[\frac{18Vh\mu}{Lg(\rho_p - \rho)} \right]^{1/2}$

- D = diameter of the particle
- g = acceleration due to gravity
- ρ_p = density of the particle
- ρ = density of the gas
- μ = viscosity of the gas

➤ From above equation we can calculate the **minimum size of the particle that can be removed** in a settling chamber.



Source: (M. N. Rao, H. V. N. Rao, 2007)


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This Stoke's law you can represent it by this V_s g into ρ_p (ρ_p) minus ρ D square divided by 18μ . So, D is the diameter of the particle, g is acceleration due to gravity as you know, ρ_p (ρ_p) is the density of the particles and ρ (ρ) is the density of the gas carrier, μ is viscosity of the gas. So, when we determine D using this equation, so you can just play with it and the square root of $18Vh\mu$ ($18Vh\mu$) divided by L into g ρ_p (ρ_p) minus ρ (ρ). So, that way this is the diameter which is basically the minimum size of the particle which can be removed in a settling chamber.

$$V_s = \frac{g(\rho_p - \rho)D^2}{18\mu}$$

$$D = \left[\frac{18Vh\mu}{Lg(\rho_p - \rho)} \right]^{1/2}$$

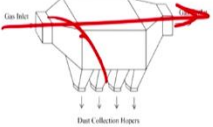

So, this will decide that this will be the minimum of size. Beyond that size they will have more than V_s . So, they will automatically come down. But this is the minimum size of the particle which will be removed almost completely. So, that will be the design parameter for settling chambers, like particulate matter of different size exist in the exhaust gas. So, we have to design the settling chamber to remove these particles which are mostly coarser particles, coarse sized particles and these are used for cleaning of the gas when it is passed through other instruments. So, that on those instruments load is less in comparison.

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Settling Chamber (4/7)

Important aspects (1/2)

- The **gas velocity** must be sufficiently low (less than about **3 m/s** to prevent re-entrainment of the settled particles; **less than 0.5 m/s** for good results.)
- To **minimize turbulence** and ensure **uniform velocity**, **curtains, rods, and wire mesh screens** may be suspended in the chamber.
- The **pressure drop** through the settling chamber is usually **small** and consists **mainly of entrance and exit losses**.

Source: (M. N. Rao, H. V. N. Rao, 2007) Image Source: (J. He, K. Chen, J. Xu et al., 2017)


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Then there are certain important aspects. So, like for example, the gas velocity must be sufficiently low. If it is more, if it is speedy, then short circuiting will be there and gas will directly pass through this taking the pollutants out. So, that is not effective. We want to calculate those particles. So, this gas velocity must be slow or it should not be more than 3 meter per second (m/s) and so that it can, otherwise it is speedy, it will short circuit as well as resuspension of the dust particles may also occur because of this high speed so that we have to avoid. Less than 0.5 meter per second is the velocity which gives very good results. So, 0.5 to 3 meter per second we have to maintain it.

Then to minimize the turbulence and ensure uniform velocity sometimes curtains or rods or wire mesh those kinds of things can be applied by suspension so that this inertia kind of things occur. And the pressure drop through the settling chamber is usually small, not most, not much and consists mainly of entrance and the exit losses only. So, that way it is very simple way.


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Settling Chamber (5/7)


Important aspects (2/2)

- Efficiency is improved if the height (h) to be traveled by the particles is less.
- Horizontal trays or shelves are incorporated in the chamber. The trays (plates) are fitted at about 1-3 cm height intervals.
- The increase in efficiency obtained by the insertion of horizontal trays is directly proportional to the number of trays.
- The minimum particle size which can be removed after installation of trays is about 10 μm .

$$D = \left[\frac{18 \mu u_t}{Lg(\rho_p - \rho)} \right]^{1/2}$$



Source: (M. N. Rao, H. V. N. Rao, 2007)


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Then if we talk about the efficiency then it can be improved by the height, improved in the terms of height as traveled by the, this particle. When efficiency is improved if the height traveled by the particle is less, otherwise there are other problems. So, this is less. So, diameter related to height can be calculated. Horizontal trays or shelves can be incorporated to reduce this height part, otherwise there will be large height. So, you can install more horizontal plates so that effective height can be reduced for several diameter particles.


And to this increase in efficiency obtained by these insertion of horizontal trays directly proportional to the number of trays, basically that efficiency can be covered by the number of trays. And the minimum particle size which can be removed after installation of these trays can be up to 10 micrometer, otherwise, generally it removes up to 40 micrometer or so. But by these manipulation of this settling chamber through horizontal trays etc. you can improve the efficiency in terms of the size of the particle so that you can remove even fine particles up to 10 micrometer which is PM₁₀ or RSPM, respirable suspended particulate matter.

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Settling Chamber (6/7)

Applications:

- Used to remove particulates **above 40 μm** in diameter. However, fine materials such as carbon black and various metallurgical fumes form agglomerates with enough mass to permit collection.
- Settling chambers are used widely to remove large solids particulates from natural draft furnaces, kilns, etc.
- Also used in process industries, like food and metallurgical industries, as the first step in dust control.
- Widely used as pre-cleaners for high-efficiency collectors.



Source: [M. N. Rao, H. V. N. Rao, 2007]

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So, this is used for removing the particulate matters of size equal to or more than 40 micrometer. For that, it is very good. And if you want to reduce further then you have to apply certain those original trays etc. Then these settling chambers are used widely to remove large solid particulate matters from natural draft furnaces, kilns, etc. And also, it is used in process industries like food and metallurgical industries as the first step to dust control, so that the load on the secondary device can be reduced significantly and it is widely used as pre-cleaners for high efficiency collectors.

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Settling Chamber (7/7)

Advantages:

- Low initial cost, Simple construction
- Low maintenance cost
- Low pressure drop
- Dry and continuous disposal of solid particulates
- It can be constructed out of almost any material
- Temperature and pressure limitations imposed only by material of construction used

Disadvantages:

- Large space requirements
- Relatively low particulate collection efficiency. (particularly of $\text{PM} < 50 \mu\text{m}$)
- Trays in multiple- tray settling chamber may warp during high temperature operations.



Source: (<https://www3.epa.gov/ttncaat1/dir1/fsetling.pdf>)

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Then there are advantages and disadvantages. In advantages that it is low initial cost, simple construction. The construction is very simple kind of chamber you can divide. But in terms of disadvantage it requires large space. So, in countryside it can be okay fine, but in urban areas it is difficult because land cost is much more.


When we go for another additional advantages that it requires very low maintenance, because there are no moving parts etc., low pressure drop is there, then dry and continuous disposal of solid particles can be achieved by these settling chambers and it can be constructed out of almost any material whether you construct by simple chamber of some metal or even bricks etc. that is also possible. Temperature and pressure limitations imposed only by material of the construction use. So, that way you can also control of which high temperature if you want to use then accordingly material of those valves can be used.

If you talk about the disadvantages, it requires large space. So, the land should be cheap in that particular location, otherwise it is not advisable. Then relatively low particles collection efficiency like beyond 40 micrometer or 50 micrometer if it is less than that then it is difficult to trap them unless we provide those horizontal trays etc. It is good for 40 or 50 micrometer. Then trays in multiple tray settling chambers may warp during high temperature. They can undulate. They can get D shaped kind of things. So, those are the issues with this settling chamber.

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Inertial Separators (1/10)

- Inertial Separator utilize the relatively greater **inertia of the dispersoid** to affect the particulate-gas separation.
- They employ a **continuous changes of direction** of the carrier gas stream **to exert the greater inertial effect** of the dispersoid.
- Types of Inertial or Impact Separators are:
 - ❖ Baffle Type Separator
 - ❖ Louvre Type Separator
 - ❖ Dust Traps



Source: (www3.epa.gov; M. N. Rao, H. V. N. Rao, 2007)

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Then we come to another device which is known as inertial separators. So, these inertial separators basically utilize the relatively greater inertia of the, these dispersoids, those fine particles to affect the particulate gas separation. And they employ continuous changes of the direction of the carrier gas stream to exert the greater inertial effect on the dispersoid or particles, because impact will be more if we changed its direction, we provide some baffle walls or those kinds of things. So, the types of inertial or impact separators can be like baffle type separators or louver type separators or dust traps.

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Inertial Separators (2/10)

Principle

- Greater inertia of the dispersoid is utilized.
- Assumes that the solids move along the chamber with the velocity of the gas gaining momentum and strikes the barrier and gets settles while the air changes the direction.



Source: (www3.epa.gov; M. N. Rao, H. V. N. Rao, 2007)

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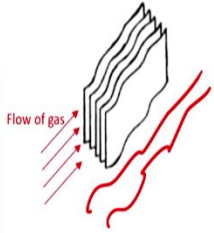
So, the principle, basically the inertia related, inertia when you change the direction by baffles etc. inertia occurs and they strike to the surface then they lose the velocity and slide down. And we, these solid moves along the chamber with the velocity of the gas gaining momentum and it strikes at the barrier and get settles down when air changes the direction because of losing the velocity.

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Inertial Separators (3/10)

Baffle Type Separators (1/3)

- The gas stream is made to follow a tortuous flow path, which is obtained by the insertion of **staggered plates** into the path of the gas stream.
- Gas is subjected to a **series of sudden changes of direction**, with the **resulting impaction** of the particles on solid surfaces.
- Suitable for removing particles larger than **20 μm** in diameter.



Source: (M. N. Rao, H. V. N. Rao, 2007) Image Source: (M. N. Rao, H. V. N. Rao, 2007)

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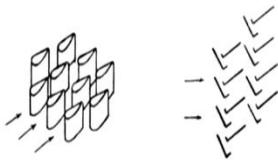
When we talk about baffle type separators, these kind of deformed kind of valves we take so the direction changes continuously and the suitable for removing particles larger than 20 micrometer in diameter. So, that way it is better if we compare with the settling chamber. So, certain change direction is to be ensured by these staggering kind of plates etc.

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Inertial Separators (4/10)

Baffle Type Separators (2/3)

- It is slightly **more expensive** to construct than a simple settling chamber, because of the interior works involved in fabricating and installing the baffles.
- High **impaction velocity** often leads to severe **abrasion**.
- **Efficiency** is dependent on the **degree of impaction** which occurs.



Different Types Of Baffle



Source: (M. N. Rao, H. V. N. Rao, 2007) Image Source: (M. N. Rao, H. V. N. Rao, 2007)

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Whenever this high impaction velocity often leads to severe abrasion, so those are the issues basically. Efficiency is dependent on degree of impaction which occurs. So, those things we have to ensure if we want to remove more particles.

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Inertial Separators (5/10)

Baffle Type Separators (3/3)

- Baffle chamber efficiency is a function of four variables:
 - ❖ Number of baffles
 - ❖ Length of baffles
 - ❖ Spacing of baffles
 - ❖ Configuration of the baffles



Source: [M. N. Rao, H. V. N. Rao, 2007]

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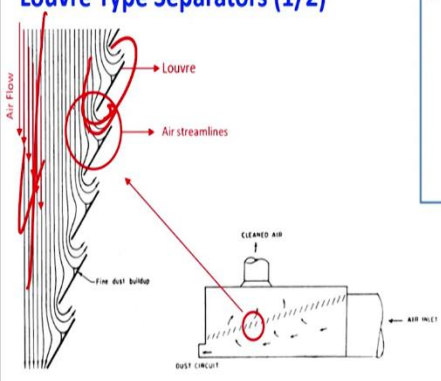
And these baffle chamber efficiency is a function of four variables basically, like number of papers we have provided, length of the baffle, spacing of the baffle, configuration of the baffles, the types etc. So, these things will influence the separation of the particles basically.

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Inertial Separators (6/10)

Louvre Type Separators (1/2)

- There is a series of louvres or impingement elements set at an angle to carrier gas stream so as to **cause a rapid reversal of the gas flow direction** and thereby cause the particulates to impinge on the louvres.



Source: [J. L. Smith JR., M. J. Goglia (1955); M. N. Rao, H. V. N. Rao, 2007]

Image Source: [J. L. Smith JR., M. J. Goglia (1955)]

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You can see like this louvre type of separators where these kind of louvers are installed. So, that there is the change of the velocity, like air is going like this, but nearer to these kind of insertions this air changes its velocity and then this it causes rapid reversal of the gas flow direction and thereby it causes the particulate matter to impinge on the louvers and lose the velocity and get

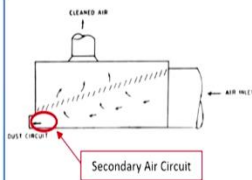

down in the hoppers basically. So, these type of, louver type of separators can operate at the velocity of like 12 to 15 meter per second at the inlet. So, that way you can have more efficiency. And its efficiency depends upon like closer spacing of these louvers which we have seen in the, these kind of configurations.

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Inertial Separators (7/10)

Louvre Type Separators (2/2)

- The impinged particles rebound back into the moving gas stream in the inlet chamber and are removed from the collector by a secondary air circuit.
- Efficiency depends on louver spacing (closer spacing producing higher efficiency).
- Operating velocities are of the order of 12-15 m/s at inlet.
- Suitable for removing particles larger than 30 μm in diameter.

Source: [J. L. Smith JR., M. J. Goglia (1955); M. N. Rao, H. V. N. Rao, 2007] Image Source: [M. N. Rao, H. V. N. Rao, 2007]

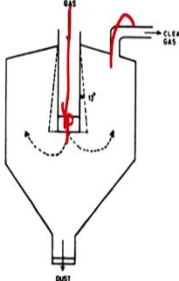

And it is suitable for removing particles larger than 30 micrometer. So, that way again it is better than the settling chambers, but baffle walls are better than these.

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Inertial Separators (8/10)

Dust Trap

- The dust-laden gas is introduced into a central pipe (cylindrical or tapered) and is made to change direction by 180°.
- Because of the inertia, dust settles in the conical chamber.
- Useful when dust loading is high ($> 100 \text{ g/m}^3$), and the quantity of gas to be handled is low.
- Gas velocity at inlet is about 10 m/s, and in the chamber, it is reduced to about 1 m/s.
- Collection efficiency is about 70% for particles greater than 30 μm .

Source: [M. N. Rao, H. V. N. Rao, 2007] Image Source: [M. N. Rao, H. V. N. Rao, 2007]


Then if we talk about the dust trap, like gas comes down and then it changed direction because the outlet is above so it will go 180°. So, in this change of the direction it again have this tendency of striking to the walls and losing the velocity and getting down and it is useful for dust loading when it is very high like 100 gram per cubic meter or so. And this gas velocity at the inlet is like 10 meter per second in the chamber and it is reduced about 1 meter per second afterwards. Then again collection efficiency is about 70 percent of the particles greater than 30 micrometer. So, it is comparable with those earlier one.

(Refer Slide Time: 19:31)

Inertial Separators (9/10)

□ Applications:

- Widely used for particulate removal in
 - Power Plants
 - Rotary Kilns
- It is sometimes used as a pre-cleaner.



Source: (M. N. Rao, H. V. N. Rao, 2007) Image Source: (M. N. Rao, H. V. N. Rao, 2007)

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Then the applications of these inertial separators can be widely it can be applied to the particulate matters removal like in power plants or rotary kilns or it is sometimes used as the pre-cleaner as settling chambers also use so that way also these are devices which can be used for pre-cleaner before better devices like ESP etc.

(Refer Slide Time: 19:57)


Inertial Separators (10/10)

Advantages:

- Simple and low cost of construction
- Simple to operate as it has no moving parts.
- Moderately low pressure drop for the degree of removal obtained.

Disadvantages:

- Clogging of the baffle, louver with a corresponding reduction in efficiency.
- Excessive abrasion because of high impact velocity.



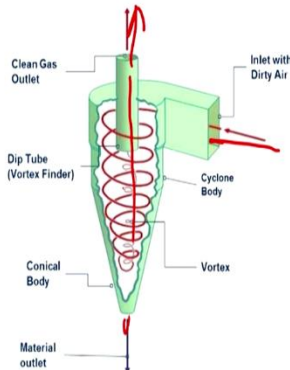
Source: [M. N. Rao, H. V. N. Rao, 2007] Image Source: [M. N. Rao, H. V. N. Rao, 2007]

24


Then advantages and disadvantages if you want to discuss about inertial separators then advantages are like it is again simple low-cost device and construction is also very easy, simple to operate as it has no moving parts, then moderately low pressure drop for the degree of removal obtained. But there are disadvantages like clogging of the baffle was louver with the corresponding reduction in efficiency occurs after some time. So, you have to clean that after some time. Then excessive abrasion because of high impact velocity also occurs. So, maybe you have to change those baffle walls or louver kind of structures.

(Refer Slide Time: 20:34)

Cyclonic Separators (1/19)



- It is a structure without moving parts in which the **velocity of an inlet gas stream is transformed into a confined vortex** from which **centrifugal forces** tend to drive the suspended particles to the wall of the cyclone body.



Source: [M. N. Rao, H. V. N. Rao, 2007] Image Source: [Krishnamoorthy, Sathish et al., 2018]

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Now, we come to the cyclonic separators. So, in cyclonic separators basically it is nothing but a structure without moving parts in which the velocity of an inlet gas stream is transformed into a confined vortex that circular motion from which centrifugal forces tend to drive the suspended particles to the wall of the cyclone body. So, like for example, this inlet is there and this gas goes downwards basically, it goes downwards in circular motion.

So, in circular motion because of centrifugal force and tangential force it restricts to the wall and loses its velocity and gets down to a hopper. Then when it goes up, because outlet is in this direction, so it goes up again, in circular motion it goes, there also again it is trapped and whatever remaining particles, smaller particles, they can be again give their velocity to zero and come down so that way cyclonic separators work.

(Refer Slide Time: 21:46)


Cyclonic Separators (2/19)

Principle (1/2)

- The collection of particulate depends on the generated centrifugal force, which in turn depends on:
 - Mass of The Particle (M_p)
 - Inlet Gas Velocity (v_i)
 - Radius of Cyclone (R)

➤ Centrifugal Force Generated, $F_c = M_p \frac{v_i^2}{R}$

- The design factor having the greatest effect on the collection efficiency is the cyclone diameter. For a pressure drop, smaller the diameter, higher is the efficiency, because centrifugal action increases with decreasing radius of rotation.



Source: (S. K. Garg, 2012; M. N. Rao, H. V. N. Rao, 2007)

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So, its principle basically have influence of the mass of the particles, inlet gas velocity or radius of the cyclone, because the centrifugal force generated is like this M_p into v_i square upon R , where mass of the particle is M_p and the radius of cyclone is R and the inlet gas velocity is the v_i . So, this particular relationship will work to get the particle separate from the cyclonic separators. And the design factor having the greatest effect on the collection efficiency is the cyclone diameter basically, this radius. For a pressure drop, smaller the diameter higher the efficiency, because centrifugal action increases with the decreasing radius of the rotation because it is in the denominator. So, that is the very simple thing.

$$F_c = M_p \frac{v_i^2}{R}$$


(Refer Slide Time: 22:25)

Cyclonic Separators (3/19)




Principle (2/2)

- The minimum diameter of a particle that can theoretically be completely separated from the gas stream is given by,
- $D_{p, \text{min.}} = \left[\frac{9\mu B}{\pi V N_t (\rho_p - \rho)} \right]^{1/2}$

- $D_{p, \text{min.}}$ = diameter of smallest particle that can be removed (cm)
- μ = viscosity of the fluid (poise)
- B = width of the cyclone inlet duct (cm)
- V = average inlet velocity (cm/s)
- N_t = number of turns made by gas stream in cyclone
- ρ_p = density of the particle (g/cc)
- ρ = density of fluid (g/cc)



Source: (M. N. Rao, H. V. N. Rao, 2007)




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The principle is again the minimum diameter, if you want to calculate for a particle that can theoretically be removed completely from the cyclonic separator then this is the relationship D_p can be calculated by this equation, $9\mu B$ ($9\mu B$) divided by $\pi V N_t \rho_p - \rho$ [$\pi V N_t (\rho_p - \rho)$], where D_p is the minimum diameter of the smallest particle which can be removed by this particular mechanism, μ is the viscosity of the fluid that is the gas or so, and the B width of the cyclone inlet duct when it is coming and then the V is the average inlet velocity, N_t is the number of turns made by gas stream in the cyclone when it comes down and go up, so ρ_p (ρ_p), density of the particle so is the density of the fluid.


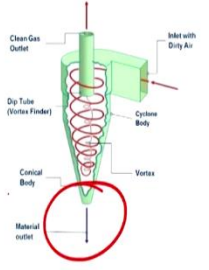
$$D_{p, \text{min.}} = \left[\frac{9\mu B}{\pi V N_t (\rho_p - \rho)} \right]^{1/2}$$

(Refer Slide Time: 23:14)

Cyclonic Separators (4/19)

Important aspects (1/6)

- It consists of a vertically placed cylinder that has an inverted cone attached to its base.
- The **particulate-laden gas stream enters tangentially** at the inlet point into the cylinder.
- The outlet pipe for the **purified gas** is a central cylindrical opening at the top.
- The **dust particulates are collected at the bottom** in a storage hopper.



Source: (M. N. Rao, H. V. N. Rao, 2007) Image Source: (Krishnamoorthy, Sathish et al., 2018)

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Important aspects like it consists of vertically placed cylindrical apparatus that has an inverted cone kind of attached to the base. And the particulate laden gas stream enters tangentially, at the inlet point here and then it goes down. And the dust particles are collected at the bottom in the storage hopper.


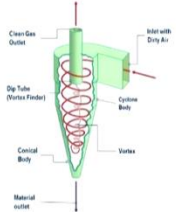
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Cyclonic Separators (5/19)

Important aspects (2/6)

- The gas path generally follows a **double-vortex**.
- First, the **gas spirals downwards** at the outer periphery of the cylindrical portion continues through the conical portion and reaches the bottom.
- The gas stream then **moves upwards in a narrower inner spiral**, concentric with the first and leaves through the outlet pipe.
- Due to the rapid spiraling movement of the gas, the dispersoid are projected towards the wall by the centrifugal force and then they drop by gravity to the bottom of the body, where they are collected in the storage hopper.

➤ During cyclonic separation, carrier gas rotational velocity exceeds several times the average inlet gas velocity.



Source: (www.epa.gov, M. N. Rao, H. V. N. Rao, 2007) Image Source: (Krishnamoorthy, Sathish et al., 2018)

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The gas path generally follows a double vortex. Once it comes down then it goes up inside. So, double part is there. So, that way there is a possibility of collection of smaller particles also. During


cyclonic separation carrier gas rotationally rotational velocity exceeds several times the average inlet gas velocity. So, that is the very important point for removal of these particles.

(Refer Slide Time: 24:07)

Cyclonic Separators (6/19)

Important aspects (3/6)

- Cyclone efficiencies are:
 - For particulates with dia. of the order of 10 μm , greater than 90% .
 - For particles with dia. higher than 20 μm , efficiency is about 95%.
- Can be operated at temp. as high as 1000°C, pressure 500 atm and can handle gas volumes ranging from about 0.85 to 700 m³/min.
- A 15% gas leakage can bring down the efficiency to virtually zero.



Source: (M. N. Rao, H. V. N. Rao, 2007)

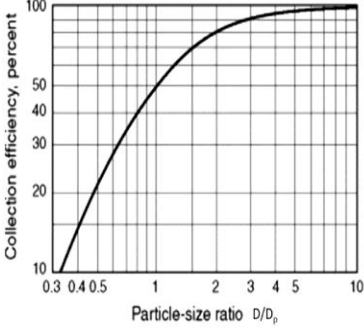
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So, cyclone efficiencies are like for particulates of the order of 10 micrometer also greater than 90 percent. A particles are of the size of 20 micrometer or so, then efficiency further increases 95 percent. So, coarser particles naturally mass is more, removal efficiency is more. And it can be operated at the high temperature like 1000 degrees Celsius, pressure of the 500 atmospheric pressure. It can handle gas volumes ranging from 0.85 to 700 cubic meter per meter minute. So, means good flow rate can we handled. A 15 percent gas leakage can bring down the efficiency to virtually zero. So, the leakage should not be there that is very important aspect in this case. So, wherever leakage it should be handled properly and promptly, otherwise efficiency will be drastically reduced.

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Cyclonic Separators (7/19)

Important aspects (4/6)



Particle-size ratio D/D_p	Collection efficiency, percent
0.3	10
0.4	20
0.5	30
1	50
2	75
3	85
4	90
5	95
10	100

- The cyclone collection efficiency can be determined using the graph based on the average particulate diameter (D) and the diameter of smallest particle that can be removed (D_p)



Source: [Ruth F. Weiner, Robin A. Matthews, 2003]

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In this graph the efficiency, collection efficiency depending upon the size of the ratio of the particle, this D and D_p , particulate diameter D and diameter of smallest particle that can be removed D_p . So, if it is like 10 up to 100 it can be removed. So, the ratio and you can decide the efficiency.

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Cyclonic Separators (8/19)

Important aspects (5/6)

- The collection efficiency increases if there is an increase in:
 - Dust particle size
 - Dust particle density
 - Gas inlet velocity
 - Inlet dust loading
 - Cyclone body length (number of gas revolutions)
 - Ratio of body diameter to gas outlet tube diameter
- The collection efficiency decreases if there is an increase in:
 - Gas viscosity or density
 - Cyclone diameter
 - Gas outlet diameter
 - Inlet width
 - Inlet area



Source: [M. N. Rao, H. V. N. Rao, 2007]

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Well, the important aspects like the collection efficiency increases, if there is an increase in like dust particle size or dust particle density or gas inlet velocity or inlet dust loading or cyclone body length, number of gas revolutions because it will ensure more gas revolutions, then ratio of the body diameter to the gas outlet tube diameter. And the collection efficiency decreases with the gas

viscosity or density or cyclone diameter or gas outlet diameter, inlet width or inlet area. So, these very kind of thumb rules. These aspects can be observed or taken care when we want to design cyclonic separators.

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Cyclonic Separators (9/19)

Important aspects (6/6)

Efficiency Range of Cyclones

Particle Size range (μm)	Efficiency percentage (%)	
	Conventional	High Efficiency
<5	<50	50-80
5-20	50-80	80-95
15-40	80-95	95-99
>40	95-99	95-99

- Based on efficiency, two classes of cyclones are Conventional and high efficiency cyclones



Source: [M. N. Rao, H. V. N. Rao, 2007]

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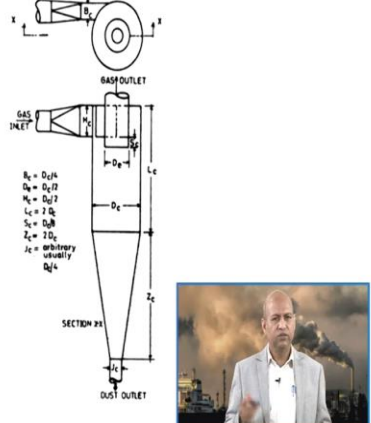
And then another set of important aspects are there like different size of the particles are there, less than 5 micrometer or 5 to 10, 15 to 40, more than 40. Efficiency, conventional and high efficiency kind of separators maybe there. So, in conventional like less than 5, less than 50 percent efficiency is there, high efficiency can ensure 50 to 80 also. And like 40 micrometer or so, 95 to 99 in conventional and in high efficiency also. So, that is the limit up to the 40, otherwise the basic thing is difference in this 5, 20 and 15, 40 that is the efficiency difference. And based on the efficiency, two classes of cyclones have been categorized like conventional and high efficiency.

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Cyclonic Separators (10/19)

Design parameters

- Cyclones are not sized from theory but are normally designed by set procedures one set of sizes of various parts is as follows:
 - $D_e = D_c/2$
 - $H_c = D_c/2$
 - $S_c = D_c/8$
 - $L_c = 2D_c$
 - $Z_c = 2D_c$
 - $B_c = D_c/4$
 - $J_c = D_c/4$



Source: [M. N. Rao, H. V. N. Rao, 2007] Image Source: [M. N. Rao, H. V. N. Rao, 2007]

If you want to see the design parameters basically, based on several design exercises or practices or observations there are certain relationship, empirical relationships which have been decided like this D_e equals D_c upon 2, Z_c equal equals D_c upon 2. So, these are the dimensions in this cyclonic separator cross section and those particular relationships are taken into consideration when we design so that become better or efficient way of designing.

- $D_e = D_c/2$
- $H_c = D_c/2$
- $S_c = D_c/8$
- $L_c = 2D_c$
- $Z_c = 2D_c$
- $B_c = D_c/4$
- $J_c = D_c/4$


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Cyclonic Separators (11/19)

Operating problems (1/3)

❑ Operating Problems:

- Three important operating problems associated with cyclones are:
 - ❖ Erosion
 - ❖ Corrosion
 - ❖ Material Build-up
- ❖ Erosion
 - Heavy, Hard, sharp-edged particles, in a high concentration, moving at high velocity in the cyclone, continuously scrape against the wall and can erode the metallic surface unless suitable materials are used.



Source: (M. N. Rao, H. V. N. Rao, 2007)

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Well, operating problems are there, like it can eroded by particulate matter because it strikes to the surfaces, corrosion maybe there if those gas, carrier gas is having like acidic content like SO₂ etc. then material build-up can be there at the inlet, outlet or some surfaces also. So, at some surfaces sometimes people use those kind of like rim kind of thing and it can be removed, otherwise regular cleaning is needed.


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Cyclonic Separators (12/19)

Operating problems (2/3)

❖ Corrosion

- It is a problem if the cyclone is operating below the condensation point when reactive gases are present in the effluent stream.
- The best solution to any corrosion problem in a cyclone is to keep the product above the dew point.
- If the gas and dust are corrosive at low temperatures, then perhaps the only alternative is to use a stainless alloy.



Source: (M. N. Rao, H. V. N. Rao, 2007)

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And corrosion-related means the carrier gas is taken into at the temperature where dew point is not achieved only then it would be better, otherwise corrosion problem may be there.

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Cyclonic Separators (13/19)

Operating problems (3/3)

- ❖ Material Build-up
 - Build-up of dust cake on the cyclone walls, especially around the vortex finder, at the ends of any internal vanes, and opposite the entry can become a severe problem. It occurs most frequently with hygroscopic dust.
 - In case the dust builds up on the wall of the cyclone cone, a simple solution is to pound on the cone with the sledgehammer.
 - Another solution is to hang chains inside; this works but reduces efficiency.
 - A better solution is to flange a section (provide rim) between the dust collecting hopper and the cyclone body. It can be removed periodically and scraped.



Source: [M. N. Rao, H. V. N. Rao, 2007]

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And metal build-up can be taken into consideration and it can be removed by this rim provision or by regular cleaning.

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Cyclonic Separators (14/19)

Applications (1/5)

- Control of gas-borne particulates in industrial operations such as cement manufacture, feed and grain processing, food and beverage processing, mineral processing, paper and textile industries, and wood working industries.
- Also used to separate dust in disintegration operations such as rock crushing, ore handling and sand conditioning in industries.
- Also used in the recovery of catalyst dusts in the petroleum industry, and in the reduction of fly ash emissions.
- Based on application two types are:
 - ❖ Multiple Cyclones
 - ❖ Cyclones in Series



Source: [M. N. Rao, H. V. N. Rao, 2007]

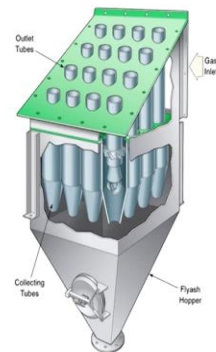
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Well, applications can be there in many cases, like it can be used as the multiple cyclones or cyclones in series depending upon what kind of pollution load is there.

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Cyclonic Separators (15/19)

Applications (2/5)



- Multiple Cyclones:
 - For higher efficiency at reasonable capacity, a battery of smaller cyclones operating in parallel is used in preference to a large single into. This battery of smaller cyclones is known as 'multiple cyclones.'



Source: [M. N. Rao, H. V. N. Rao, 2007]

Image Source: [www.babcock.com]



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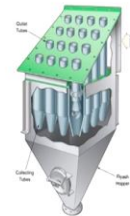
For example, to increase the efficiency in row and parallel rows as well as this kind of system maybe there where smaller cyclones can be put together and multiple cyclones we can call it so that more cyclones are available to remove the particles.

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Cyclonic Separators (16/19)

Applications (3/5)

- It consists of rows of parallel tubes about 25 cm in diameter, with a common inlet chamber, a common outlet plenum, and a common dust collection system.
- These chambers must be designed for a constant pressure drop in each, to avoid any channeling of the dirty gas to any particular single cyclone or group of cyclones.
- Used for cement clinkers, steel mill sinter and stone dust in quarry and asphalt operations.



Source: [M. N. Rao, H. V. N. Rao, 2007]

Image Source: [www.babcock.com]



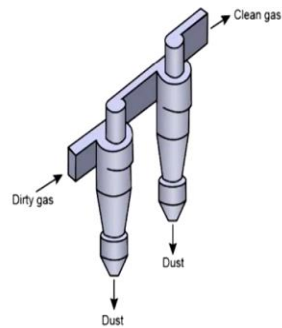
40

Well, this can consist of different rows two or more and depending upon their distance and collection efficiency can be calculated.

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Cyclonic Separators (17/19)

Applications (4/5)



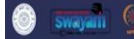
□ Cyclones in Series:

- To get the higher efficiency, cyclones are arranged in series, where the exit gas from the primary cyclone is allowed to enter in the secondary cyclone.



Source: [M. N. Rao, H. V. N. Rao, 2007]

Image Source: [nptel.ac.in]



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If we go into series only one after one then dirty gas goes to one particular this separator then cleaner gas goes to another separator that way you can ensure very high efficiency or very clean gas at the outlet depending upon how many cyclone separators you have installed in series basically.

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Cyclonic Separators (18/19)

Applications (5/5)

□ Cyclones in Series:

- The efficiency of two cyclone dust collectors operating in series is given by:

$$\eta = \eta_p + \eta_s(100 - \eta_p)$$

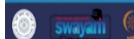
□ Advantages:

- Maintain a large degree of dust collection even if the primary cyclone plugs.
- More efficient (large particles by primary cyclone and smaller diameter by secondary cyclone)

- η = efficiency of the combination of both cyclones
- η_p = efficiency of the primary cyclones
- η_s = efficiency of the secondary cyclones (based on the inlet dust load in it)



Source: [M. N. Rao, H. V. N. Rao, 2007]



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So, if you want to calculate the efficiency in cyclones installed in series, then this is the simple formula like η equals η_p plus this η_s 100 minus η_p [$\eta = \eta_p + \eta_s(100 - \eta_p)$]. So, this is basically this η (η) efficiency of the combination of


both the cyclones, η_p is efficiency of the primary cyclone that is initially, then efficiency of the secondary cyclone based on the inlet dust load in it so that can be used.

$$\eta = \eta_p + \eta_s(100 - \eta_p)$$

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Cyclonic Separators (19/19)

<p>Advantages:</p> <ul style="list-style-type: none">• Low initial cost• Simple construction and operation• Low-pressure drop• Low maintenance requirements• Dry collection and disposal• Temperature and Pressure limitations are only dependent on the materials of construction• Relatively small space requirements	<p>Disadvantages:</p> <ul style="list-style-type: none">• Low collection efficiency for particles below 10 μm in dia.• Equipment is subjected to severe abrasive deterioration• Decreasing collection efficiencies for decreasing dispersoid concentrations in the gas stream.
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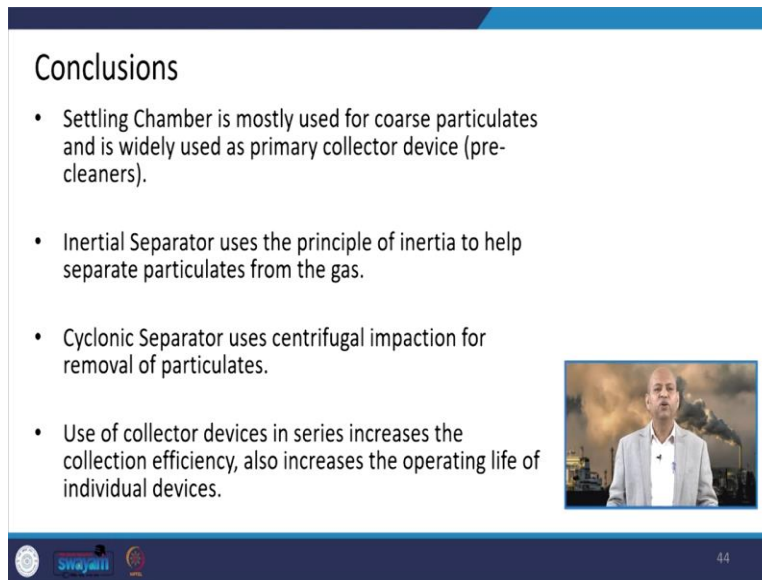
Source: (<https://www3.epa.gov/ttn/catc1/dir1/fcyclon.pdf>)

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Then advantages are like low cost, initial low cost, simple construction and operation, low pressure drop or low maintenance requirement, dry collection and disposal is very easy, temperature and pressure limitations are only dependent on the materials of the construction. So, that way you can have different kinds of metal if there are issues with the temperature. Relatively small space required, because vertical you can design it. So, horizontal space may not be a big problem which is a problem in the settling chamber.

Disadvantages like low collection efficiency for particles below 10 micrometer in diameter, equipment is subject to the severe abrasive deterioration and depending upon the particle size, its sharpness etc. then decreasing collection efficiency for decreasing dispersoid concentration in the gas system. So, those are the issues of the disadvantages.

(Refer Slide Time: 30:53)



Conclusions

- Settling Chamber is mostly used for coarse particulates and is widely used as primary collector device (pre-cleaners).
- Inertial Separator uses the principle of inertia to help separate particulates from the gas.
- Cyclonic Separator uses centrifugal impaction for removal of particulates.
- Use of collector devices in series increases the collection efficiency, also increases the operating life of individual devices.

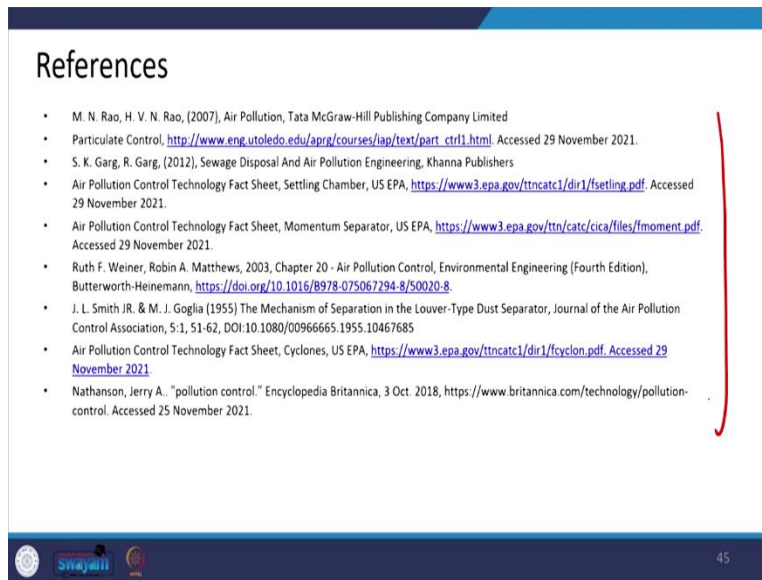
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Well, so, overall, we can say that the settling chamber is mostly used for coarser particles because it is very simple device. It works on gravitational force. So, there is no other external forces we are using. So, only coarse particles can be removed very efficiently and it is used that is why for primary collector devices before some other devices are placed.

Then inertial separator uses the principle of inertia as we have seen to help separate particulate from the gas. And cyclonic separators basically use this centrifugal impaction because of centrifugal force to remove the particulate matter.

And the use of collector devices in series increases the collection efficiency. It also increases the operational life of the individual devices. If some devices more problematic at the primary stage you can remove it, replace it so that you can increase the life of the other devices which are on the downward side. So, this is all for today's lecture on particulate matter collection devices. We will continue this lecture of air pollution control devices.

(Refer Slide Time: 32:03)



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So, these are the references for additional information. And thank you for your kind attention. See you again in the next lecture. Thanks again.