**Clean Coal Technology**

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**Week-07**

**Lecture-32**

Hi, I am Professor Barun Kumar Nandi, welcoming you to the NPTEL online certification course on clean coal technology. We are in module 7, discussing emission control from combustion utilities. So, in this module, in lecture 2, I will be discussing pollution control from combustion utilities, with emphasis on the reduction of fly ash particles or capturing fly ash particles from the flue gas. Now, if we look at fly ash, it consists of ash particles that go into the atmosphere along with the flue gas.

So, if we examine the reasons for the generation of fly ash, we find that the particle size distribution of feed coal and fly ash particles is most important, as the particle coal particles burned in pulverized coal combustion are less than 75 microns, whereas in fluidized bed combustion, they range from 2 mm to 10 mm. Now, when these coal particles burn, their particle size reduces. So, this means that whatever the input coal particles are, even if they are less than 75 microns—or, say, 80% passing size is 75 microns—there can still be some coal particles of 30 to 40 microns. So, when these coal particles burn, their size reduces.

As a result, the fly ash particles will have a smaller size. So, the particle size distribution of input or feed coal particles and fly ash particles are closely correlated. If feed coal particles have a larger size, it is expected that fly ash particles will also have some larger size. And if feed coal has a smaller size or lower size, the product fly ash particles will also have a smaller size. For example, if we consider only the theoretical aspect, like assuming that 'less than 75 microns' means 80% of particles are below 75 microns, and if we assume for calculation purposes that coal particles contain 30% ash, That means after combustion, it is expected that the residual coal particles should be 30 percent of the size compared to the original coal particle, or from the original coal particle of 75 microns, as 70 percent is combustible material. Those will be reduced, so there will be simply a 70 percent reduction in the diameter of the ash particle. So, it is expected that the residual coal particle after combustion, or ash particle, will be of 22.5 micrometers. However, in actuality, this size will be much smaller. It will not be 22.5 micrometers; it will be much smaller than that. The reason is that the distribution of mineral matter in coal is not uniform. If we see this coal particle, which has a diameter of 75 microns, So, in this 75-micron coal particle, there are some locations where mineral matters are present. So, if we see these black particles corresponding to the mineral matter, these are the locations where mineral matters are available. Whereas the residual part, this entire part, is the combustible part of this coal. So, whenever these coal particles get burned, the ash particle will have the same size as these black particles. It is like a theoretical way. So, these coal particles, depending on the distribution of mineral matter and hydrocarbons, how they are mixed, if they are localized in some particular location, the particle size will be increased. Or, if they are distributed well across the entire coal particle, then only this one particle will form ash, which can have a size of maybe five microns or even one micrometer. So, what we can conclude is that, depending on the ash percentage of coal as well as the distribution of mineral matter and hydrocarbons in the coal, the ash particles produced after combustion will always have a much smaller size compared to the coal particle size. Since, in reality, the distribution of mineral matter is not uniform, most of the ash particles are less than 10 microns or even as small as 1 micron. Typically, cyclone separators, bag filters, ESPs (electrostatic precipitators), and different types of settling chambers are used to capture or reduce this. They are typically used to capture this particular matter from the flue gas.

So, what is important? Composition of mineral matter is important. And this mineral matter or fly ash may damage the corresponding equipment. Any equipment whatever is used there. Now if we see particularly with the fly ash particles. How their particle size will be? How it will be? How this particle size and their properties may be? If you say it is a 30% ash coal, so if we go for simple calculations, the produced ash particle will have 22.5 micron. But in actual, as their distribution of mineral matter and hydrocarbons are different, in reality they will be less than 10 micron or less than 5 microns.

If the ash percentage of the coal is on the lower side, like if we are using 20% ash coal or if we are using 15% ash coal, in such case, it is expected that the ash particles generated in the flue gas, they will be much smaller in size. As that overall, there will be 70 to 80% reduction in a coal particle size during combustion as 80% is the combustible matter whereas only 15 to 20% is the mineral matter. Ash in the feed coal is on the lower side, so fly ash will have lower size as particles. So, in such case all the particles may be on the 5 micron or even in the 1-micron range whereas if we are burning high ash coal it is expected that that fly ash will be of the bigger size. So, this is the general theory or general assumptions but may vary from coal to coal as it entirely depends on the distribution of mineral matter in the coal. So, it entirely depends on the distribution of mineral matter whether these mineral matters are very well distributed at each and every point or they are accumulated in some of the locations inside the coal particles if they are located at some of the if they are concentrated at some of the locations in the coal particles then ash particles will be of bigger size if they are distributed very well.

Even they can be less than 1 micron or some micron-sized particles also. Second is that their distribution is also important, as the mineral matter composition is also important, as we have discussed in the previous class. If this mineral matter contains heavy metals like high molecular weight metals, then in such cases, they will mostly report to the bottom ash. As the particle density will be on the higher side, it is possible that they will go to the bottom ash, not with the fly ash. So typically, fly ash will contain lightweight metal oxides in most cases, or they will be very simple oxides, not accumulating in bigger shapes. So, depending on the size of these fly ash particles, we have to use different types of particulate matter removal equipment like cyclone separators, bag filters, ESPs, settling chambers, and others, depending on the actual particle size distribution of the fly ash particles, as well as the temperature inside the reactor or the temperature of the flue gas, as well as the number of particles to be separated. So, all these factors decide what type of separation equipment we should use because all this separation involves some cost. to the plant. Some of the equipment only has installation costs, and some may have installation as well as operating costs. So, if these operating or installation costs are on the higher side, it will not be profitable at all or not economical at all for the plant to install such equipment.

So, in such cases, they cannot use coal or ultimately their plant has to shut down. Because of strict environmental guidelines. So, the major equipment or mostly used equipment in fly ash capture or reduction of fly ash particles from the flue gas is the cyclone separator. So, these cyclone separators are used to separate heavy particles from any fluid medium. So, in the case of air purification or air, these air cyclones are used where dust particles will enter from this point, so this will be the typical dimensions of the entry point of the cyclone separator, which can be of this cross-sectional shape.

It may be in a rectangular shape, a square shape, a cylindrical shape, or a circular shape. So, the shape of these entry points can vary for different types of cyclones. So, in this cyclone, the particles move in this way. So, they will have a fixed number of turns inside this, and depending on the gravitational force as well as the centrifugal force, these heavy particles, larger particles, or particles with higher density typically settle at the bottom, which we refer to as the dust or dirt particles here, whereas the clean air, after the removal of all ash particles, can be obtained from the top of this cyclone.

So, if we observe the entry point and others, as in this second picture, they enter here. So, there is no short circuit between this entry point here. So, it is like different points, and this particular exit point extends from the center to a greater depth. So, it is not like that. These particles will not simply come and go out there. So, any type of short-circuiting between the inlet air and outlet air is not possible. It is not like that. They will not simply come and go there. So, this is not the case. All the coal particles must go there and travel a specific number of turns.

Then, depending on the gravitational force as well as the centrifugal force, this will Fly ash particles will get separated at the bottom, where we can collect the dust here, and we can get clean air or air with fewer dust particles, depending on the separation efficiency of the cyclone at the top of this cyclone separator. So, if we see, cyclone separator primarily works on the centrifugal force, so the main driving forces are for the cyclone separator, the centrifugal force is F equals M into V squared by R. So, m corresponds to the mass of the particles or fine particles, v corresponds to the velocity of these particles, and r corresponds to the radius of the cyclone. So, r corresponds to the radius of the cyclone, v corresponds to the velocity of the particles or velocity of the air, and m corresponds to the mass of the cyclone.

Individual mass of the fine particles. So, the mass of particles m again depends on the density of the particle as well as the size of the particle, as this mass is the major factor which determines the separation efficiency, typically We can get a higher amount of mass, or mass will be on the higher side, if the density of ash particles is higher or if the size of the particles is larger. So, overall mass is linked with the density of the particle as well as 4 by 3 pi d cube, which is the volume. It depends on the density of the particle as well as the volume of the particles. If we assume that particles are spherical in shape, the formula will be 4 by 3 pi d cube.

So, d will be the diameter of the particles. So, overall, if we see that to get a higher amount of F, like if we want to create a higher amount of centrifugal force, that means if we want a high value of M or a high value of M, That is possible if m is increased, meaning m varies with the mass of coal particles, which is also linked with the mass as mass is linked with the diameter of the coal particle. So, effectively, it is proportional to the diameter of the coal particle. So, if the dust particle has a bigger size, in such a case, the generated centrifugal force will be on the higher side if the density of particles is the same. So, for the same density of particles, if the particle diameter or particle size is larger, they will face a higher amount of centrifugal force. So, they will be easily separated as the bottom particle.

So, in this case, here we will get the bigger-sized particles here, where D will be on the higher side, whereas the D will be on the lower side; they will be coming as the top product. So, based on the diameter of these fly ash particles, they will get separated. If the diameter of the particles is on the higher side, they will report to the bottom and will be collected as the dust particles or dirt particles, and if the diameter of the particles is on the lower side, they will go along with the clean air. So, this is the main driving force for the separation in the cyclone separator. The second parameter is the velocity of the air. So, if the entry air velocity is on the higher side, that means if we increase the velocity of this air, the centrifugal force will be on the higher side. If the centrifugal force is on the higher side, that means it is also proportional to the velocity. If we use high-velocity air, then the separation efficiency of the cyclone separator will be on the higher side. If the velocity of the air is low, the separation efficiency will be on the lower side. So, in such a case, all the particles, the fly ash particles, will go to the top as clean air. And the third parameter is the radius of the cyclone.

That is the radius here. This is the radius of the cyclone. If the radius of the cyclone is on the smaller side, then it will have a bigger centrifugal force. So, in such a case, it will have a higher centrifugal force. In such a case, the separation efficiency of the cyclone will be increased.

If we use a bigger diameter cyclone, in such a case, the generated centrifugal force will be less. So, F is proportional to 1 by R. So, for a bigger size cyclone separator, the efficiency will be less. If we use a smaller size cyclone separator, the efficiency will be high. So, for bigger size particles, as they have higher centrifugal force, they will be collected with higher efficiency at the bottom of the cyclone separator, whereas the smaller size particles will have lower separation efficiency, as they have a lower amount of centrifugal force.

They easily go to the top part of the cyclone along with the flue gas. And the same thing will happen if the density of the particles changes, like if their particle diameter is the same but their density is different. For example, some particles can have a specific gravity of 1.3, while others can have a specific gravity of 1.7. So, the 1.7 particles of the same size will go to the bottom as bigger size particles, they will be collected with the dust particles, whereas the lightweight particles will go to the top along with the flue gas. Similarly, the bigger the cyclone diameter, the lower the centrifugal force. So, it will have lower separation efficiency. So, if we see in general, bigger size particles will have higher separation efficiency, and smaller size particles will have lower separation efficiency. And if we see the actual collection efficiency of the cyclone, this is the main parameter which is considered or which is calculated from the cyclone separator.

This collection efficiency is typically the mass of ash particles which goes to the bottom. That amount of coal particles or amount of high ash particles goes to the bottom. They are called the collection efficiency. Like, if we are supplying 100 kg of dust particles and we are getting 30 kg dust particles here, then the separation efficiency is 30 by 100 into 100, meaning it has 30 percent separation efficiency. So, in this way, the separation efficiency is calculated, which is an important parameter for selection or to find whether the cyclone separator will be useful or not. If the cyclone separator has good separation efficiency, that means out of the 100 ash particles, if most of the particles are collected at the bottom, that means the cyclone is removing 30%, 40%, or 50% of the dust particles at the bottom.

So, its collection efficiency is very high. But if only five percent or ten percent goes to the bottom part, then its separation efficiency is on the lower side. So, we always assess the performance of the cyclone separator based on the first parameter, which is the collection efficiency—that means the mass percentage of ash particles collected at the bottom of the cyclone. The second parameter, which is important, is the cut diameter. What is this cut diameter? That means the particle size of the flue gas which will be collected with 50% collection efficiency. So, if we consider the collection efficiency and the cut diameter.

So, cut diameter, specifically, is the particle size. So, the cut diameter unit will be in the range of the unit will be micrometer. So, the cut diameter corresponds to the micrometer for those particles which will be collected with 50% separation efficiency. So, if we discuss this picture in particular detail, the dust particles will never have the same size. So, even in the dust particles, depending on the distribution of feed coal, there will be different distributions of particle size—like some particles can be 2 microns, some can be 10, and some can be 50 microns in size. So, there will always be some distribution of particle sizes. So, if I say there are some 10-micron particles—like if we are sending 100 kg of dust particles—out of this 100 kg, there can be 5-micron particles, maybe 10 kg, whereas there can be 10-micron particles, maybe 15 kg. So, we have to see how much of the 5-micron particles are collected here.

Because as this diameter of the particle changes whatever this theory is telling is that as this the mass changes. linked with the diameter of the particle. So, if bigger size particle is there so particle will have better separation efficiency that means it is always expected that if there is

5-micron particle and 10-micron particles are there. More amount of 10-micron particle will report here and less amount and 5-micron particle will be less but here most of the particle will be of the 5 microns. So, we have to see for which particle size, if you are using, getting 10 kg of that particle size, if we are getting at least 5 kg of particle or 50% of that particular corresponding size is reporting to the bottom of the cyclone. So, this cut diameter means that particular size, that means cyclone separator will be able to separate particularly 5-micron particles. will be goes to the bottom.

So, in such case, if they are efficiently reviewing 50 percent of the 5-micron particles. So, obviously, for 10-micron particles, it will have 60 to 70 percent values. For 100-micron particles, it will, all the particles will be going to the bottom. So, in the opposite way, if 5 micron is the cut diameter, that means 50 percent particles will go to the bottom that has particle size of 5 micron so if particle size is of 4 microns so more than 50 percent particle will go to the top in the clean air, whereas less amount of 4 microns particle will go to the bottom. So, this cut diameter gives an indication about the what will be the separation efficiency for smaller size and bigger size particle. If cut diameter is having 10 microns. So, any particle less than 10 micron more than 50% of those particles will go to the clean air in the top. Whereas less than 10-micron particles will go to the bottom.

As their separation efficiency will be less. So, these two major parameters are used: collection efficiency and cut diameter. They are deeply correlated with the particular distribution of ash particle size. So, if we see the theoretical formula for cut diameter or Dpc, it is like 9 into viscosity into a parameter B, which corresponds to the inlet width. That means whatever the width of this inlet is there, so from this unit we will get the parameter length and width. So that value is part of this B. It will have 2πN, where N corresponds to the number of turns, like number of turns means it is going for 1 turn, 2 turns, 3 turns, 4 turns. So, if any dust particle is entering there, how much time it will collide with the wall of the cyclone separator. So how many rotations it will take. That is called the number of effective turns. Its value is typically 5 to 10.

For some of the cyclones, it can be 5, maybe 6 or 7. So its value typically comes from 5 to 10. It is calculated from different formulas used in fluid mechanics. So, from that, we can get this number of effective turns. Then Vi is the inlet gas velocity. If the gas velocity is on the higher side, that means the gas velocity is higher. So, the particle will have much more centrifugal force. So, the separation efficiency will be on the higher side. So, the cut diameter will be on the lower side if the separation efficiency is higher, that means even the smaller size particles can also be separated with good efficiency. So, in such cases, the cut diameter of that cyclone will be less. That's why this velocity term is there, and there are two terms: the density of the particle as well as the density of air or gas. So, these are the main formulas which are used to assess the cut diameter of a cyclone. So, this cut diameter of a cyclone typically depends on the inlet gas velocity, cyclone diameter, particle density, and viscosity of air.

So, if we see the standard dimensions of any cyclone, it will have values like this for B. Like whatever this entry path is, it will have some dimensions like B and W, length and width. So, it will have this parameter, which is known as B. There will also be some outlet diameter of the cyclone, which will be like D, and there will be an outlet diameter at the bottom, which will also have some dimension. It will have the length of the first part of the cyclone or cylindrical parts. This length is the length of the conical path or conical part of the cyclone. This is the main diameter of the cyclone separator, and this is the particular height at which this entry point is located. From up to what distance this entry point is located. So, like this, we will get B and W, and this height will be the height of that entry path from the top, at how much distance it is entered there. This is the diameter of the exit at the top, the diameter of the entry at the bottom, the diameter of the cyclone, and this is the length corresponding to the main cyclone.

The cylindrical path, this is the path for the conical part. Now, all these dimensions are typically fixed. They are all correlated if they are like a standard cyclone. If it is a standard cyclone, these parameters are linked with the diameter. Like this is the diameter D.

So, this L will be like 2D, this will be like L will be like 2D, this L will also be like 2D, this will be like D by 2. So, all these diameters are generally fixed by standard dimensions or manufacturing in case of if it is the standard cyclone. If it is the non-standard cyclone, these diameters can be of different values. Why these dimensions are important? Because the entire

Flow directions or flow path of this gas and dust particles depends on the cyclone diameter. If any part of the cyclone is exceptionally high or low, then their particulate matter separation efficiency will be different. like if we make this part so much long whether as if we make this part only in smaller distance. So accordingly, number of turns used in this formula like if we change the different dimension. So, this number of effective turns it will get changed Number of this B value will get changed and eventually this inlet gas velocity will also get changed because this inlet gas velocity is in the range of the meter per second. It is the linear gas velocity.

Typically, gas velocity is calculated. as the volumetric gas velocity meter cube per second whereas this inlet gas velocity in the range of meter per second. So, if we give a very narrow entry path obviously due to action like and nozzle of a gas flow pipeline or acting like a venturi So, there we will have some pressure drop as well as increase in the velocity of this gas particle. If the velocity of this gas is increased, so in such case separation efficiency will get increased. So, all these parameters depend on these dimensions of this cyclone.

So, whenever we utilize any of this cyclone, we have to think about the standard dimensions of the cyclone separator. So, if we see the overall cases, the overall cost of a cyclone separator is less as there is no such operating cost involved. And there is only some installation cost involved. So, once we install the cyclone, there are no such moving parts.

Neither are there any very big motors or other components that will consume electricity or others. So effectively, there is zero operating cost. Maybe some pump or compressor may or may not be required, depending on the desired flue gas velocity. If the flue gas velocity is on the higher side, which originates from the primary airflow rate. So, if that is sufficient, it can separate very efficiently. And if it is not sufficient, we may have to add some compressor or similar equipment to get the desired velocity of the gas, and it can efficiently separate the bigger-sized ash particles. As we can see from this formula, the 50 percent cut diameter is very big. If we use a bigger-sized ash particle, for bigger-sized particles, their centrifugal force will be on the higher side, and so they will be efficiently separated from the flue gas very efficiently. And if the particle size is very small, their separation efficiency will be on the lower side. So, if we see the separation efficiency, it will be very high if particle sizes are more than 10 microns, but they will be low if the particle size is less than 5 microns. Typically, cyclone separators work very well for bigger-sized particles of 10 microns, 15 microns, or like this. And their separation efficiency is poor if their diameter is lower, meaning that the 50 percent cut diameter or Dpc parameter will be around 9 or 10 microns for most cyclone separators if normal velocity of air is used for the flue gas. If we increase the velocity of air or if we modify the dimensions of the cyclone, this can change. But in general, cyclone separators separate fly ash particles of 10 microns and above very efficiently, but their efficiency will be less, like this cut diameter, and collection efficiency will not be high if particle sizes are 5 microns or less. So overall, it can efficiently separate bigger-sized ash particles. That's why they are mostly suitable if their particle size is more than 10 microns. So, if fly ash particle size is above 10 microns, their efficiency will be very high. Another advantage is that it can operate even at higher temperatures. This is one of the major reasons why cyclone separators are mostly used in air purification. In all the units, we can make this cyclone separator using ceramic. Using metal or any other suitable material depending on the melting point of that particular material. If we use a ceramic-made cyclone separator, it can go up to 1500 degrees centigrade. If you are using any stainless steel, copper, or aluminum metal, we can easily operate it up to 800–900 degrees centigrade. So, it can separate fly ash particles from the flue gas even at high temperatures. As it is high-temperature flue gas, many common equipment may not be able to withstand this high temperature. So, that is the particular case compared to other cyclone separators where only low-temperature air is used.

So, cyclone separators can efficiently separate dust particles even at higher temperatures. Only the material of construction has to be changed accordingly. A particular advantage is that it can reduce most of the bigger-sized ash particles. Even if the cyclone separator has poor efficiency for smaller-sized particles. But if we see the particle size distribution of ash particles. If there is the cut diameter here.

And they can remove this mass percentage. Which can have 60% of total ash particles. So even, it can separate bigger-sized particles. But if those particles contribute about 60% of total particles, those particles can easily be separated or collected without any major operating cost.

So remaining unit or other unit has to separate only remaining 30 to 40% of ash particles. So, they can efficiently separate even at lower operating cost. So, in the later stage, Typically, the main part, main job or main purpose of the cyclone separator is that to reduce the major load on the next equipment like bag filter or ESP. These bag filter or ESP are typically having higher operating cost.

There are many other limitations. So, if cyclone separator can remove these ash particles or bigger size ash particles without any major operating cost even at high temperature, that reduces a lot of burden on the high cost or costly equipments like ESP or bag filters or others. So, they are very much cost effective and mostly used in all the thermal power plant as the primary or preliminary equipments to remove or reduce the dust particles if it can it particularly removes the bigger size ash particles. So that only finer size ash particle goes to the next unit, so that the load of the next unit is reduced significantly and overall operating cost of the plant is very less. So overall if we see the cyclone separator it is a very much effective instruments in fly ash capture and that's why all the thermal power plants used at least one cyclone separator in their circuit. Some of the cases they may increase the number of cyclones. As this efficiency of the cyclones are depend on the diameter of this cyclone like if this diameter of the cyclone is different So efficiency of the cyclone can get changed like this parameter if the diameter of the cyclone is different. So, in some of the cases power plant use multiple cyclones in parallel to meet the desired capacity. Like we cannot use a very bigger size cyclone if diameter of the cyclone is increased, efficiency decreased. So, to avoid that, in most of the cases, a bunch of cyclones are used in parallel.

Like whatever the airflow rate is coming, it is divided into 10, 15, 20, or 30 different cyclones of smaller diameters. A smaller diameter cyclone will have higher efficiency, and many cyclones in parallel can handle the desired airflow rate without reducing the pressure drop inside the cyclone. If the pressure drop inside the cyclone is on the higher side, that means air will accumulate there. In such cases, carbon dioxide concentration inside the combustor will increase and reduce combustion efficiency.

So, if we see the cyclone separator, it doesn't have any major pressure drop or only a very minor pressure drops. They can be placed as multiple units or in parallel to handle higher airflow rates as well as in smaller diameters to ensure higher efficiency. So overall, this cyclone separator is very efficient and very cost-effective for the separation of larger coal particles. The cyclone separator is mostly used in fuel bed combustion as well as fluidized bed combustion, which removes most of the dust particles and at least some of the dust particles in pulverized coal combustion, where particle size or ash particle size is around 10 microns or similar. So, it can remove at least some amount of dust particles from pulverized coal combustion.

So, if there is any fault in the efficiency of the cyclone separator, we have to consider this theory: whether the ash particle has high density or a certain diameter. So, we have to consider all these parameters to see if any error is reducing the efficiency of the cyclone separator. So, overall, the cyclone separator is a very good and cost-effective equipment for capturing fly ash particles from coal-fired thermal utilities.

Thank you.