

Clean Coal Technology
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Hi, I am Professor Barun Kumar Nandi, welcoming you to the NPTEL online certification course on clean coal technology. In module 6, we are discussing various industrial coal combustion methods. In the previous class, I discussed fuel bed combustion and pulverized coal combustion. In this class, I will be discussing fluidized bed coal combustion. So, let's start lecture 3: fluidized bed combustion. Fluidized bed combustion is the process of combustion of solid fuel. In this process, solid fuel is fluidized for better combustion. So, if we see the fluidized bed combustion, first of all, we have to know what fluidization actually is. In this fluidization or fluidized bed combustion, typically coal particles are burned in bigger sizes, and a high airflow rate is used to fluidize these solid coal particles.

So, effectively, if we know that fluidization is the process in which granular materials are converted from a static solid state to a dynamic state, which acts as if they are in a fluid state. So, this fluidized bed is widely used in different applications, like fluidized bed gasification and fluidized bed drying. In this process, a solid fuel like coal is fluidized using pressurized air by placing the solid fuel in a bed that has some gaps for air to pass. and in the combustion system, typically, we can easily burn any low-grade fuel. Low-grade fuel means if it has a higher amount of ash percentage or a lower amount of fixed carbon. Such type of fuel can also be burned along with regular types of coal. Low-grade fuel is difficult to burn otherwise, like. This low-grade fuel cannot be burned in pulverized coal combustion as their ash percentage may be on the higher side or their fixed carbon or volatile material may be on the lower side, though it may take a lot of time for ignition. So, there will be a lot of difficulty if we burn coal. This low-grade fuel in a pulverized unit. So, such type of coal can also be easily burned in a fluidized bed combustion system. So, if we see what happens. In any of the fluidized bed combustion or what happens when we fluidize any of the solid materials. Like in this first picture, if we see, this is the location where fuel or any coal particle stays. And there we will have some openings like perforated plates or some grids, some grates, or similar grids. An arrangement will be there through which high-speed or high-pressure air can flow. So, through which high-pressure air can flow. And on top of this bed, there will be fuel like coal particles

and other types of materials. Now, what will happen if, normally, the velocity is very low? Like, if the velocity is almost zero or it is low, air is flowing through this. What will happen? So, whatever the air is there, in such a case, air will just pass through this. If air velocity is very low, then simply air will go and it will come out. If we burn this fuel, then it will be like the fuel bed combustion we have discussed in our previous classes. So, if the air velocity is very low or it is on the lower side, the air will just go there and easily pass through the porous structure of the fuel bed. But if we increase the velocity of the air, if we increase the velocity or if we increase the pressure of the air, then what will happen? Due to this velocity, whatever energy is available with the air, some of the coal particles will get some force, which will take this material toward the upper direction. So, if we see in a normal case, there will be some weight that corresponds to the mg that mass and gravitational force. Now, if from the opposite side, we can create or give some velocity or force, so that this material will start going upwards or it will just start lifting. So, if F equals the mg force, then it will just stay over this material. And when just F will be greater than mg , that means the applied force is just higher than this coal particle mass. So, in such a case, this coal particle will be lifted from its actual stationary bed and will go toward the upper direction. So, they will come into this state, meaning they will be floating in the atmospheric condition or the air inside this reactor. So, in such a condition, they will be almost in the air.

Like, it will be as if they are suspended in the air. Like any liquid medium, when we disperse some of the sand particles and others, they will stay in the liquid medium for some time. So, similar conditions will occur. So, these coal particles and other materials will remain in the air phase for some time. And if we further increase the velocity of the air, the particles will rise to a greater height. So, these particles will disperse further throughout the reactor in this manner. So, as the velocity of the gas increases, these particles will move upward and may fill the entire reactor. This is called the fluidization of the particles, meaning the solid particles have transitioned into a fluid state where the entire gas mixture contains a large quantity of solid particles. In the case of coal combustion, if these coal particles are heated to their ignition or burning temperature, such as around 900 degrees Celsius, then the coal particles will combust at this specific location. All the coal particles remaining in this location within the reactor but in this fluid state will burn or begin burning under these conditions if provided with adequate oxygen, air supply, temperature, and other requirements for combustion. In this case, combustion will occur under these specific conditions when the coal particles are fluidized inside the reactor. If we further increase the velocity, the coal particles may exit the reactor,

requiring a recovery system like a cyclone separator to return or recycle some of the coal particles or other materials. So, in the case of a fluidized bed, these processes occur. We must ensure or provide sufficient air velocity so that all coal particles reach this level without exceeding it.

On this side, if we make the particles go to this side, in such a case, coal particles may go out without any combustion. So typically, our requirement is that coal particles should reach this level, and if we want this level, then there should be some amount of or some cyclone separator or other particle recovery unit must be there. So typically, this condition is the Last condition when we can carry out the fluidization. But this is the best condition where we will carry out the fluidized bed combustion. Now, what is the advantage or other aspect of this fluidization? The advantage is that as these particles are staying in this air phase. So, in such a case, the surface area available for reactions or oxygen available for reactions will be much better. So, all the coal particles are staying in this fluidized state. So, all these coal particles will be able to burn at the same time. So, we can get a much higher heat release. At this condition, second is that. Whatever the moisture, Volatile material etc. Has to come out. So, from the entire coal, they will come out. So, we can get a much higher temperature compared to normal fuel bed combustion. In case of fuel bed combustion, we have carried out similar things, but the coal combustion happens in stages, not the entire coal. Whatever is charged burns at the same time. They burn in a sequential manner. So, we get a lower temperature in such cases. So in case of fluidized bed, all the coal particles present in this fluidized state, all the coal particles will be releasing moisture, releasing volatile material, and they will get burned at the same time. So, we can easily burn a higher quantity of material in this fluidized bed combustion. So, what are the other parameters which affect the fluidization? First of all is the particle size.

The coal particle size which will be used for this combustion and its density should be such that whatever the velocity of air is being used, those air velocities should be adequate to lift these particles from the surface to make them fluidized. Like for any coal particle, there is some mg force acting on it. So, what we need is that F should be at least equal to mg . Now, the mass of this particle also depends on the density of the particle as well as the diameter of the coal particles. So, this diameter and density of the particles are the main parameters to decide what velocity of air will be adequate to lift them.

Lifting from the normal stationary position and what will be the highest velocity we can use so that this coal particle does not go out of this reactor, thus preventing them from being released

into the atmosphere without any combustion. So, this is the major parameter considered in the case of fluidized bed combustion, where we have to decide the suitable particle size and their density. So that we can efficiently fluidize the particles, ensuring the air velocity is adequate to lift the particles from the fuel bed. The air flow rate should be controlled in such a way that no particle goes out of the combustor before burning. Now, at this point, if we see that the velocity of air here is very important. Because in any coal mixture or any crushed coal, there can be different sizes of coal available. Like whenever we crush the coal, there will always be some coal fines. Of 0.5 mm size, and there can be some coal particles maybe of 2 mm size, and there can be some bigger size coal particles maybe of 10 mm size or like this. So, if coal has different particle sizes, the corresponding velocity required for their fluidization will be of different values. So, if we use a very high value which will be able to lift the 10 mm coal particle. So, due to that high velocity of air, 2 mm or 0.5 mm coal particles will go out of the reactor.

Similarly, if we use air velocity corresponding to 2 mm size coal particles, in such a case, 10 mm particles will not get the desired force for fluidization, whereas 0.5 mm particles will also go out. So here, the selection of suitable size and the crushing efficiency will be very important so that all the coal particles are of similar size. There should not be significant variations in the coal particle size; otherwise, they will go out of the reactor. In such a case, we may have to create or use a very tall reactor so that even the fine particles can stay there. Maybe on the upper side so that they can get burned. So, when we design this fluidizer or fluidized bed combustor, we have to consider what particle size coal we will be burning, what will be the height of this fluidization, and what will be the air velocity required to achieve this fluidization. For how long will they stay there? This is also another parameter. Like, what will be the typical residence time—the desirable time we want these coal particles to stay there? Like, if these coal particles are staying there and they are not getting removed from the system. So, in such a case, there will be stagnation of coal as generated. So, we also have to ensure that whenever these coal particles get burned, they should get removed or they should go out of this reactor. This is easily maintained by the velocity of air. Like, whenever these coal particles get burned. So once these coal particles get burned, their combustible material will be removed, and whatever ash is there or mineral matter converted to ash will be removed. Broken into different sizes. As a result, their size will be on the lower side. So, if it is a 2 mm coal particle, after burning, the produced ash may be 0.5 mm or 0.2 mm. So, those coal particles can easily go out of this reactor. So, outside this reactor, we have to keep suitable particle collection equipment like cyclone separators and others, which will efficiently collect the fly ash as well as whenever

the gas burns, it should come out. The bottom is the second important parameter or advantage for this fluidized bed combustion or fluidized bed operation, as we can easily maintain the temperature of the reactor. Now, how is this important or what is the other purpose of this fluidized bed combustion?

In fluidized bed combustion, to maintain the desirable temperature of the reactor, some other bed material like sand or other materials is used—sandstone chips or similar inert materials are used as bed material and mixed with the coal particles. So, what is the purpose of these materials? They typically improve the heat transfer coefficient, easily remove the ash content from the surface of the coal, and help maintain the desirable temperature of the fluidized bed combustor. So, if we start from the previous slides, like fluidized bed combustion in its basic form, there are different designs of fluidized beds available. So, in its basic form, fuel particles are suspended in a hot, bubbling fluidized bed of ash and other particles—these are the other particles or bed materials typically used along with the coal. They are charged into the reactor, such as sand particles or limestone particles, through which high-velocity air or jets of air are blown to provide the oxygen required for combustion, or in the case of gasification, we call it fluidized bed gasification. So, there are three or four parameters or things to consider here: one is the use of inert material like sand, and the role of this sand or other inert material is to maintain the temperature of this reactor, as we are using inferior-quality coal or not good-quality coal. The temperature of this reactor can easily fall down, or if we use any good-quality coal, the temperature of the reactor may increase. So, in both cases, there will be significant variations in the temperature of the reactor. So to avoid this sudden change in the temperature profile inside the reactor, which is mostly seen in case of pulverized coal combustion, that if any coal property varies, in pulverized coal combustor there will be always some major changes in the fireball characteristics and temperature profile. So as here we are using the inferior type coal. So, such variations will be wide if we are not able to control the heat balance inside the reactor. So, to maintain the desirable amount of heat or so that in case of there is sudden increase in heat release sand particle will absorb some amount of heat they will store some amount of heat for few moments then it will easily maintain the temperature inside the reactor. Similarly, if there is some poor combustion, heat will be released from the sand particle, whatever heat is stored there. So, as a result, sand particle can easily maintain the desirable temperature of the combustor second purpose for this sand particle is that whatever the coal particle is there as in fluidized bed combustion we are bigger using bigger size coal there will be thick ash layer formed so whatever this ash layer is getting formed when some sand particles are there so they

will also have some abrasion or they will also have some collision with this coal particle and sand so during this collision sand particle will be able to easily remove the ash layer formed over the coal particle so that means whatever the ash is formed over the coal particles due to their high ash percentage those ash will be continuously removed by this sand particle so always coal particle will have exposure to its hydrocarbon or carbon content so always the rate of combustion will be on higher side it will not deteriorate significantly although it may have high as coal so sand particle does both the job maintain the temperature profile as well as it continuously removes the ash layer formed over the coal particle so that coal particle rate of combustion of coal particle remain constant throughout the its residence time inside the reactor so even the bigger size coal particle we can easily burn with constant heat rate that is the purpose of this fluidized bed combustion so sand particle acts as an very important part of this combustion process by continuously removing the ash layer formed over the coal particle.

Second is that we can also add limestone. Limestone like calcium oxide or calcium carbonate added different form. They are also added along with the coal particle. Now this limestone They can act like a sand particle whatever the job being done by the sand particle. Limestone can also do the same job by removing the ash layer over the coal particle as well as it can maintain the desirable temperature. Apart from that, major role of limestone is that it can release calcium oxide, which can easily react with sulfur dioxide to form calcium sulfate. So as a result, whatever sulfur is present in the coal, they will be trapped, they will be captured by this limestone during the combustion process. So effectively if we add limestone along with the sand particle and along with the coal, so this limestone will easily react with sulfur compounds present or released, SOX released during the combustion and they will easily trap all these sulfur emissions so that we can easily monitor the sulfur emission or we can easily control the sulfur emissions from the combustor so this will enable us to utilize or burn the high sulfur coal in this reactor like if even if the coal can have higher amount of sulfur we can utilize them or we can burn them in this fluidized bed combustor.

In case of pulverized bed combustor, this facility or this advantage was not there. We cannot add limestone on higher dose in pulverized combustor. That will create lot of other issues. But in fluidized bed combustor, we easily capture this sulfur oxides or SOX during the combustion process. So, this process is also known or we can consider it like during combustion cleaning of coal. What we have discussed in our very beginning of this lecture series that coal can be cleaned during combustion also or during utilization also. One was the pre-combustion or pre-utilization cleaning by conventional coal washing and other methods. By this fluidized bed

combustion or fluidized bed gasification, we can even capture the sulfur or reduce the sulfur during utilization. So, this is the major advantage or purpose of utilizing or burning coal in fluidized bed combustion. So overall, if you see, we add limestone and sand particles, and in the combustor, the resultant fast and intimate mixing of gas and solid promotes—as we are using high-velocity air—so there will be an increase in the oxygen concentration in the reactor, and there will be continuous removal of the ash layer over the coal particle, so there will be very fast chemical reaction between the coal particle and the ash. And as there is very good mixing of gas and solid particles, this promotes rapid heat release and chemical reaction within the bed. FBC plants are capable of burning even low-grade solid fuel. As we can see from this picture, unless any coal particle gets completely burned, and it becomes very lightweight so that the air velocity will take it out of the reactor like this—so before that, it will remain in the reactor. So, there is no shortage of residence time in this reactor, so all the coal particles will get their desirable residence time. If any coal particle gets burned immediately, it will convert into low-density ash particles and will be removed easily. If it is a bigger density or bigger-sized coal particle, it can stay there for much more time so that it can completely burn and then be removed from the reactor as an ash particle. So, we can easily burn low-grade solid fuel, particularly coal which is not suitable for pulverized combustion units. So those types of low-grade solid fuel, like low-calorific-value coal, high-calorific-value coal, or any coal having some problems with the volatile material and fixed carbon ratios, all these types of solid fuels can be burned inside this fluidized bed combustor. Those include different types of coal.

It can have coal waste, or reject coal, or coal which is released from different coal washers, which cannot be used in normal pulverized bed units. So different types of reject coal, like coal tailings released from the transportation units as well as from the oil agglomeration units, or high-ash coal released or reject coal released from the heavy-media cyclone separator, dense-media cyclone separators, and others. So, all types of coal which have some amount of calorific value. That means those type of coal may be outside normal gradation range. so, all types of coal irrespective of their calorific value they can be burned here and we can also add some woody biomass we can easily add different type of biomass which can be co-fired co-burned along with the coal so that we can get high efficiency and without necessity for expensive fuel preparation like pulverizing so if we see in case of fluidized bed combustion, we can burn bigger size coal particle. So, we may not need grinding of coal. We can burn coal even after just crushing to make it around 2 mm or 10 mm size.

So, we do not require any coal pulverizer which is mostly costly equipment and which needs big attention or major attention in thermal power plant whether this coal is very hard whether the HGI value of the coal is very different from that of design parameters. So, in case of pulverized coal combustion all these parameters are important particle density was very much important whether that will stay there and that will get their crushed and grinded within the desirable time. All these parameters were the major difficult parameters to control in pulverizer but in this fluidized bed combustor we don't need this pulverized unit. So we can save lot of money and lot of space in the thermal power plant if we are not pulverizing the coal and if we are using the fluidized bed combustion now for a given thermal duty Fluidized bed combustor are typically smaller size than their equivalent conventional furnace so and so may offer significant advantage over the latter in terms of cost and flexibility as we can we do not need any pulverizer unit so we may not need a very bigger environmental or environmental pollution control unit like ESP, cyclone separator there as we are burning coal in bigger particle. So, we can have much more compact and smaller plant but can have almost similar thermal efficiency. So, if we consider for a smaller capacity plant and where space is the limiting factor we can easily use fluidized bed combustion where we can use any type of coal irrespective of their combustion characteristics as well as their ash content and others we can easily burn them in fluidized bed combustor. So, this is the typically what we see in case of fluidized bed combustor like in previous picture from the bottom side hot air is passed through this fluidizer and there are some distributor plates though these distributor plates ensure that air is always passed through all to the entire reactor not making any channeling effect. So that entire air will pass through a small area. So entire air will pass to the entire reactor that is the purpose of these distributor plates. So, in such case this air will leave the coal particle at this shape so there can have bubbles there can have heat these are the heat absorbing units or boiler tubes present in other direction. So, this entire coal particle will combustion will occur at this stage where coal particle will be in the fluidized form and we can add coal and dolomite like limestone and dolomite are used to capture sulfur emissions, etc. From this other side, so that all these materials can also be in a fluidized state. We can add some amount of steam if required for gasification and other such needs. We can get the ash from here and easily obtain the flue gas, which will be used in producing steam and other purposes. These are the typical characteristics of materials we can use, like coal. Coal is typically used in fluidized bed combustion and is burned in the combustion chamber.

We can add limestone or dolomite, depending on availability. They are used to remove the sulfur generated from the gases in the fuel during combustion. It removes all the SO_x released by the combustion, captures it, and converts it into the corresponding sulfate salts, either calcium sulfate or magnesium sulfate. By removing the sulfur during the combustion process, it reduces the emission of harmful gases like SO_x into the combustor. They also need some bed material or sand, which is used to optimize the fluidization process. It is mixed with coal, ash, and limestone for a better fluidization process. At the start of the combustor cycle, ash is typically not present in the bed, but after some time, ash will be generated. Some quantity of ash will always remain in the bed to maintain the reactor's desirable temperature. There are different types or variations of this reactor. One is atmospheric fluidized bed combustion units or bubbling bed fluidized bed combustion.

Second is circulating fluidized bed combustion, or CFBC for short. There can be pressurized fluidized bed combustion, or PFBC. So, that means they can be AFBC, CFBC, or PFBC in different models or variations. In general, we use larger coal particles of 2 to 10 mm. The exact size depends on the design and other parameters, such as whether the air velocity will be adequate to lift a 2 mm particle or a 10 mm particle. So, there is no grinding involved in this process. This entire combustion process occurs at around 900 degrees centigrade. We burn this coal, or combustion of coal occurs, at around 900 degrees centigrade. Since we are using 900 degrees centigrade, the chances of ash fusion and other consequences are minimized. We can also capture SO_x gases simultaneously using limestone.

Fluidized beds reduce the amount of sulfur emissions in terms of SO_x. We can better maintain the temperature since bed material is used. Some ash is also recycled or remains there for a longer time. So, we can easily maintain or control the temperature of this bed. So, even if we use inferior quality coal, it can easily maintain the desired temperature around 900 or 850 degrees centigrade, as per design. As bed material can store some amount of energy, they can basically buffer the temperature variation. There is adequate residence time available for the combustion of coal. All the coal particles get their desirable residence time, whether they have a higher amount of volatile material or a higher amount of fixed carbon, or they have a lower amount of volatile material. So, irrespective of their combustion characteristics, their mineral matter percentage, etc., all will get their desirable residence time, so the probability of unburnt carbon even for high-ash coal, we can reduce it. Recirculation of unburned coal particles is also there. Even if some coal particles go out without proper combustion, there is an arrangement of a cyclone separator in most of the designs.

So, they recycle these unburned carbon particles, so that the chances of unburned carbon particles being released to the environment and fuel loss are reduced. So typically, limestone is used to capture sulfur dioxide, but we can also add dolomites and other materials which can capture sulfur oxides during combustion. And it allows more efficient heat transfer from the boiler to the water, as the temperature is always constant, we can easily maintain the temperature. The temperature we can easily control and maintain. So, whatever the desirable heat release rate required for power production, we can easily maintain it.

Since this allows coal particles to burn at a much lower temperature. As it is burning coal at a much lower temperature, around 850 or 900 degrees centigrade. The chances of NOx generation are less or typically zero. However, burning at low temperature may cause some unburned volatile material and unburned hydrocarbons to remain, which may need a higher temperature for burning. In coal, there can be some hydrocarbons which are not reacted or not burned at low-temperature combustion, so they may need a higher temperature for burning. So those compounds may remain there; this is one of the drawbacks or negative aspects, like if coal has very complex hydrocarbons and they are those for those hydrocarbons.

Their temperature required for burning is above 1000 degrees centigrade. So, those hydrocarbons will not burn properly. So, it may release some hydrocarbons that are not properly burned. These FBC boilers can burn other types of fuel also, like biomass, or we can use coal washery rejects, tailings—all these types of coal can be burned. So, whatever the wastage from the coal washeries or coal preparation plants is there, all types of materials can be burned here in these combustion units even at this temperature, which makes for a very profitable operation for the coal washeries, particularly eliminating the various issues of storage and disposal of high-ash reject coal.

Thank you.