Clean Coal Technology

Prof. Barun Kumar Nandi
Department of Fuel, Minerals and Metallurgical Engineering
IIT ISM Dhanbad

Week-04

Lecture-17

Hi, I am Professor Barun Kumar Nandi, welcoming you to the NPTEL online certification course on clean coal technology. We are discussing coal combustion fundamentals in module 4. Now, I will be discussing lecture 2 on coal combustion. In coal combustion, the shrinking core model is widely used to express or assess coal combustion with respect to the ash composition or ash material. In the case of the shrinking core model, typically, as we all know, air or oxygen reacts with the external surface of the coal. In coal combustion, as we know, if we take freshly available coal, initially, air or oxygen—typically oxygen—reacts, but sometimes we supply air. So, air or oxygen reacts with or starts reacting with the coal at the surface. A few moments later, some ash forms over the coal surface as combustion progresses. Here, the coal combustion hydrocarbons react with oxygen, and CO_2 and other gases are released. Very soon, outside this layer, a thin ash layer will form. How does this ash layer form?

As the hydrocarbons or combustibles are released from this surface, at $T = 0$, it will have this condition. But after some time, maybe $T = 2$ or 5, whatever, after some time, the hydrocarbons present on the external surface of the coal will react, releasing CO_2, H_2O, and other gases as per the composition of the hydrocarbons or coal. They will release and convert to the gaseous phase, leaving the surface. So, basically, the product gases will release, and oxygen will enter. Once this happens and some time passes, the external surface hydrocarbons leave the coal structure, and only the mineral matter, which is converted to ash, will remain or be retained on the surface of the coal particle.

So, few moments later ash is formed. Now, this ash layer formed outside the coal structure. So, at t equals to 0, at t equals to 0, it will have this structure. But after certain times, few moments later, it will form an ash layer over these coal particles. Now, what is the composition or what is the properties of that ash?

That depends on the mineral matter composition and how and after decomposition of mineral matter to ash, what is their present state like presence of silica, alumina, etc. Those will be staying at this layer of this ash. So, after this time what will happen? When now further coal combustion goes, now this fresh oxygen which wants to enter at this surface like initially there was no ash layer across this coal particle but once this coal combustion has been started there is a formation of ash layer over this. Now this oxygen or air the it has to pass through this or it has to pass through this ash layer. Initially oxygen or air it was directly getting contact with the surface of the coal; it was easily reacting with the hydrocarbons. Now, after some time, this ash layer has been formed. So, these newly fresh oxygen molecules need to pass through this ash layer. So, whatever ash has been formed, depending on the properties of this ash, it has to pass through this ash layer so that it can again contact with this inside coal.

So, this ash layer will form and inside this coal particle, there will be unburned coal particle present there. So, fresh oxygen or air has to pass or has to diffuse through this ash layer. So, after certain time, this reaction will be controlled by this diffusion. If rate of diffusion of this oxygen to this through this ash layer is high coal will easily react, if rate of diffusion through this ash layer is slow rate of combustion or rate of reaction will slow down. Similarly, whatever the product gases has been formed after this reaction. So, after oxygen pass through this layer it has faced some resistance due to the diffusion and due to the layer of ash formation. So already it is rate of oxygen supply is getting slowed down compared to the freshly coal. So already the rate of supply of oxygen is getting slowed down as layer has been formed. So, it is reacting at much slower rate at this point but after certain times also whatever the Product gases like carbon monoxide, carbon dioxide, H_2O and other gases, whatever is the product of combustion is there or even it is same thing is applicable in case of gasification also or other chemical reactions also. So, whatever the product of this chemical reaction is there, they also has to return or they has to come out of this coal surface through this ash layer. So, if we see oxygen, It is facing difficulty or it is facing resistance from the ash layer as well as product CO_2.

It is also facing difficulty or it is also facing diffusion or resistance from the ash layer to come out. So, both freshly new oxygen as well as the combustion product gases like CO_2, H_2O, SO_2, they also needs to pass through this ash layer in the opposite direction or reverse reaction. So, rate of combustion or rate of chemical reaction or rate of energy release that will be again dependent on the rate of diffusion of gases.

At what rate these gases are going inside this coal particle through the ash layer. As well as at what rate these gases are coming out from the coal surface through this gas layer. So, this entire ash layer will control the rate of chemical reaction. if this ash layer is supportive it is not creating any resistance to the diffusion of both the gases rate of reaction will continue as like it is a freshly available coal or if it is creating resistance or it has some negative impact that it will not allow it has some opposite action with the oxygen gases or it may have affinity to the co2 gases. So that concentration of co2 is increasing inside this. All these aspects will impact or they say they will affect the rate of combustion. So hence combustion rate it will slows down gradually. So, at initial time, whatever the rate of combustion was there, or rate of heat release, rate of chemical reaction, whatever we say, whatever that rate of reaction was there, that was initially will be on higher side. But as time goes on, this rate of chemical reaction or rate of combustion will slow down gradually. Because as combustion is going on, much more quantity of ash is getting formed so this thickness of this ash layer is getting increased and it will increase as combustion going on. So, rate of reaction will slow down how that means if initially it was like 10 kg per second, it will become 5 kg per second, maybe 2 kg per second, 1 kg per second and it can take lot of time. So, if we plot like rate of reaction initially rate of reaction will be high then it will slow down in this way. So, rate of reaction it will take longer time to complete the combustion. Complete combustion means we are discussing about coming to at this particular phase where it will completely convert to ash particle. So, it will take lot of time to complete the combustion and if we doesn't give this sufficient time for completion of combustion there will have some unburned carbon particle like this image. This image represents the unburned carbon or unburned coke particles or unburned hydrocarbons in the fuel particles. So, as time goes on, the rate of chemical reaction will slow down, and it will take longer for combustion. If we do not provide adequate time for combustion, there will always be some possibility of unburned hydrocarbons. And if we consider the rate of reaction, the rate of reaction depends on the hydrocarbon composition. We have already discussed earlier what the hydrocarbon composition is—that there may be different types of hydrocarbons present. Individual hydrocarbons react with oxygen.

So, the hydrocarbons will react. So, the rate of hydrocarbon—what hydrocarbon is inside this coal particle and what hydrocarbon is present outside this coal particle— So, their individual hydrocarbons will decide the rate of reaction. The composition of ash will decide the rate of diffusion or the rate of supply of oxygen, as well as the back diffusion or release of combustion product gases like CO_2, CO, H_2O, and others. So, if we continue, whatever we can observe is that the combustion of high-ash coal, if we see, will be extremely difficult or relatively slow or very difficult because if we say high-ash coal, that means the formation of the ash layer will be thick. If coal has a higher amount of ash, that means the residue left after combustion will be a higher percentage. So, the thickness of the ash layer will increase rapidly. Thus, the rate of combustion or the rate of chemical reaction will be relatively slow. With an increase in ash percentage, this rate of reaction due to diffusion—I am discussing only diffusion because this entire reaction will become diffusion-controlled—that initially, it can be kinetically controlled by different types of hydrocarbons present in coal. But after some time passes, this entire reaction will become diffusion-controlled. A diffusion-controlled reaction means the rate of diffusion or the rate of supply of product gases, as well as the feed rate of supply of feed gases and the back diffusion of product gases. They will decide the rate of chemical reaction.

So, this diffusion control means that diffusion rate of oxygen is slow, means oxygen is not going inside the coal particle through this ash layer, rate of reaction will get slow. So, this for high ash coal particle, it will become extremely slow chemical reaction as the ash layer properties, what is the composition of ash. they will decide whether this combustion will go at higher rate or combustion will go at slower rate. One is the thickness if ash layer is very highly thick, rate of diffusion will get slow down as driving force is getting decreased. So, first parameter is if ash layer thickness is high. That means if it is a high ash coal, its rate of reaction will be slow.

If it is a low ash coal, residue left will be less after combustion. Thickness will be less. So, it depends on the thickness of the ash layer. Second parameter is the porosity. Whatever the ash is formed after the combustion, if this ash is highly porous or they are non-porous. As we have seen in the previous module that in the scanning reactor microscopy or SEM images, it shows that different density coal particle has the different surface structure, surface morphology, some of the coal particle has higher porosity in terms of ash layer and some ash layer was less porous. So, entirely this porosity of this ash layer, if that pores are highly that ash layer is highly porous. What is their pore volume if the pore volume or pore size is very smaller then oxygen may not go there or even if oxygen goes there CO2 may not come out easily as the molecular volume of this oxygen is smaller. It has lower molecular weight whereas carbon dioxide. It has 44 molecular weight, it is molar or molecular volume is on the higher side. So, depending on the porosity, pore volume, pore structure on that of this ash layer rate of combustion or rate of reaction will get varied. So, this is the entirely depends on the thickness and porosity.

These two material or these two properties affects mostly whether their thickness is higher or lower or they are highly porous or non-porous. That makes that barrier in diffusion of oxygen. That means there creates problem in entry of oxygen as well as exit of combustion gases. Third one is the mineral matter composition. If it has some silica, alumina, iron, copper or sodium, potassium, calcium, they will also impact because they may have affinity to the oxygen or they may have affinity to the carbon dioxide or any of the product gases. Like if they have any affinity to the oxygen, oxygen will be absorbed in the mineral matter layer itself. So, oxygen will not go further to the Unburnt carbon left in the coal. Similarly, if they are repelling material, they will not allow oxygen to go there. So, in such case, mineral matter composition will impact. If in the opposite way, if there is some mineral matter which is very much favourable to the oxygen diffusion. so, in such case rate of combustion will remain same that it will not create any problem. So, it entirely depends on the ash layer properties like ash layer properties is acting large and extra barrier level and extra layer of resistance. So, if the ash layer is allowing this diffusion or oxygen, carbon dioxide gases to go out, come in easily, so it will rate of reaction, impact and all these parameters. So, all these parameters will decide or control the diffusion of all the gases. So, all these thickness, porosity, mineral matter composition, their affinity, all these are respect to all the gases like CO2, O2 and other all the gases. If we observe pulverized coal combustion, where combustion occurs for fine coal particles of less than 75 microns. So, in the case of 75-micron or smaller particles, as the particle size decreases, the layer thickness becomes very small. Thus, it will burn very easily without any major impact from the ash layer. However, if we burn coal particles of a larger size, such as 10 mm, the thickness of the ash layer will be significantly high. Therefore, it will take a lot of time for complete combustion. In contrast, if the particle size is reduced to 75 microns, it will take less time. The difference is that 75 microns refers to this size, while 10 mm refers to this size coal particle. Thus, the larger the coal particle size, the more time it will take for combustion, whereas smaller coal particles will require less time for complete combustion.

The combustion rate or energy release rate depends on the diffusion rate of gases through the ash layer. The rate at which combustible materials burn and release energy entirely depends on the diffusion rate of these gases through the ash layer. Here, if we examine the effect of different coal particle sizes on combustion, for instance, burning coal of 75-micron size, which has a very low ash layer thickness, it will burn within a very short span of time. It may burn within 4 milliseconds, 5 milliseconds, or even 3 to 4 seconds. However, if we take a larger coal particle size, such as 10 mm or 100 mm, they will take a lot of time. Since they take a lot of time, effectively from the start to the end of combustion, it may take an infinite amount of time. Thus, they will take a lot of time. In real-time, this may take 3 hours, 4 hours, or even 10 hours for complete combustion. In contrast, very fine coal particles will burn within a very short amount of time or almost immediately. Now, what is their specific impact on coal combustion?

We can use this parameter in other way like if we want or intentionally we want that lower heat release rate if we want. Like for domestic applications where heat is required for longer time but at lower rate. When we burn this coal for cooking purpose and other purpose. We do not need higher amount of energy. We need lower amount of energy which is sufficient for cooking foods and others. But we need that this oven will work for longer 3 hours, 4 hours or even for 6 to 7 hours. So, in such case we use bigger size coal particle. As their rate of combustion is higher, we use their bigger size coal particle. Whereas where we want faster heat release rate, like in thermal power plant, we use smaller size coal particle. So, this ash layer thickness, ash layer property, it is not that they are always bad. We have to utilize them in our proper way. So that we can use the coal as per our requirement of different industries where we need smaller quantity of heat but heat to be available for longer span of time like same 1 kg of coal if we want to burn it across 10 minutes or if we want to burn it across 10 hours. So, if we want to burn it for 10 hours, we will use a bigger size coal particle so that their ash layer thickness or ash layer impacts the coal combustion, coal burn at much lower rate. And if we want that they should burn at faster rate, we should use the smaller size coal particles. Also, if we see that What is the role of this GCV? Particularly, if we see GCV represents, it is the unit in kilocalorie per kg. Kilocalorie per kg means the total amount of energy released per unit mass of coal. So, a certain amount of heat will be released with a certain mass of coal. But here, it does not mention the rate of reaction—whether coal is burning at a faster rate or a slower rate. So, this has another role. It will show how much energy we can get after burning this coal—that is the gross calorific value. But if we see all these ash layer properties and others, there is another parameter's impact: the heat release rate. That is heat release per unit time or heat release per minute—kilocalorie per minute or kilocalorie per second, whatever. So, the rate of heat release depends on the coal composition or coal properties, their ash layer properties, and the coal size we are burning. So, the rate of heat release is important when we utilize the coal and want to maintain a certain heat release rate or a certain temperature inside the boiler or any of the utilities. Where the rate of heat release plays an important role, we have to consider the rate of combustion or the chemical kinetics of this combustion.

So, this is most important when we want to maintain a certain temperature inside any of the thermal utilities, like in a thermal power plant boiler. If we want to produce a certain amount of steam at a particular temperature, pressure, etc., we have to maintain that temperature. Coal should burn and release a certain amount of heat. So, in such cases, the heat release rate or kilocalorie per minute is important, which depends on the ash layer properties and the entire ash layer characteristics—the coal particle size, at what size they are getting burned, and how much resistance they are facing. From this ash layer, all factors decide the rate of combustion. If we want a slower rate of combustion where the rate of heat release is not so important, but only that the heat is released at a smaller rate, then GCV is important. Burning 1 kg of coal will give this amount of energy, but we can control the rate of heat release from that coal. So, in such cases, the overall gross calorific value is important, not the rate of heat release. So, what we can understand or get from this entire shrinking core model is that. Whenever we burn any coal particle, as it has some ash layer or mineral matter, an ash layer will always form. This ash layer will create an additional barrier that reduces the rate of diffusion of oxygen as well as product gases like carbon dioxide, water, sulfur dioxide, etc. So, after a certain time, the properties of this ash layer will determine the reaction rate. So, a coal particle of bigger size will take a lot of time or may even take infinite time to burn. Whereas coal of smaller size will take less time to burn.

So, if we want to ensure that coal gets completely burned without any unburned carbon. Because this condition means there is unburned carbon, whereas this condition indicates complete combustion. So, if we want complete combustion to take place for this coal, we should reduce the size of the coal particle as much as possible, within technical feasibility. And if coal has a lower ash percentage, the ash layer formed during combustion will not create any problem. Such coal can be burned even at a bigger size.

So, if coal has a higher amount of ash, it needs to be ground or reduced to the smallest possible size. To ensure complete combustion, if we use any bigger-sized coal particle, there is always some possibility that coal will have unburned carbon. So, to ensure complete combustion, coal is always ground, pulverized, and reduced to the smallest possible size before combustion. Similarly, in gasification or other similar chemical reactions. Typically, fine coal particles are burned, not bigger-sized coal particles, in any reaction like combustion or gasification. It is always preferable to use smaller-sized coal for chemical reactions, and bigger-sized coal is not preferred. If we use bigger-sized coal, the rate of heat release will be slow.

The possibility of unburned carbon and other issues will be there. So, we may not be able to get the desired amount of energy available or energy released from the coal. At any particular rate. So, if we use bigger-sized coal particles, the heat release rate will be less. There will be a possibility of unburned carbon, as well as the temperature of the combustor, which will always be less. If we use coal particles of 75 microns in pulverized coal combustion units, we can easily get a temperature of 1200 to 1300 degrees centigrade. Whereas, in fluidized bed combustion, where we use bigger-sized coal particles, it is very difficult to cross even a temperature of 1000 degrees centigrade. So, in those units, in the case of fluidized bed combustion, the temperature is less as the amount of energy available decreases. As the rate of energy release from the coal is on the lower side. So, when we discuss the gross calorific value and the utilization of this coal in thermal power plants, we have to ensure that if coal has a higher amount of ash, we should grind it to a smaller size possible, and if we think about the other way, grinding to a smaller size for high-ash coal is also difficult because high-ash coal will have higher hardness (HGI value) or be very hard. It will damage the crusher, grinder, and other equipment. So, it is very difficult to utilize any high-ash coal. If we see low-ash coal, they are typically soft in nature. We can grind them easily, and we can easily burn them, but if we see high-ash coal, their handling, crushing, and grinding are all difficult, as well as their combustion or their rate of reaction, which is also on the lower side. So, in an overall way, this shrinking core model tells us that if we use high-ash coal, you have to be ready for different types of difficulties. So, when we utilize coal, some coal may have a higher amount of ash, but it may have a very good GCV. Now, that is a very contradictory condition.

If coal has very good amount of GCV, but if it has higher amount of ash available. So, if higher amount of ash is available, coal will get burned at much slower rate, but it may have higher GCV. So, this entire calorific value, it will be released through a long span of time, which may be or may not be the desirable condition to utilize. If it has a high GCV coal and high ash coal, so that will be very much suitable for the domestic applications or low temperature application where lower heat release rate is required. But that coal will not be suitable for high temperature application where higher heat release rate is required. Similarly, if we think about the bigger size coal particle, if it is burned in a pulverizer, whatever the residence time it is getting or whatever the space time it has, that means for high as coal, its space time will be on the higher side. If the reactor or the combustor does not allow to have such higher amount of space time, so it may not get adequate time for burning. So, it will be creating unburned carbon in the ash or in the fly ash. Whereas if it is the low ash coal, probability of getting unburned carbon in the ash, either in the bottom ash or in the fly ash will be less. So, by considering shrinking core model, what we have to do is that we have to identify suitable type of coal. If it is a high as coal, we have to reduce the size to finer and finer and finest possible, so that it will burn properly without creating any unburned carbon in the ash, either it is a bottom ash or in the bottom. fly ash. If it is a lower ash coal particle. Still, we can use it at much bigger size without producing any significant of amount of ash either in bottom ash and fly ash. So bigger size coal particle if it is of high ash coal it is very difficult to utilize it must be grinded and crushed. Accordingly, if it is a low ash coal, we can use it even at bigger size or even at the smaller size.

Thank you.