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 4, we will discuss coal combustion fundamentals. So, in this Lecture 3, we will continue our discussion on coal combustion, particularly focusing on identifying the combustion characteristics of coal. To identify the combustion characteristics of coal, we typically analyze the burning profile of coal. Now, what is this burning profile of coal?

So, this profile provides information about how these hydrocarbons react with coal, and how they respond to temperature and oxygen presence in the combustor. So, this analysis is used to gather information about the combustion behavior of solid fuels like coal, biomass, coke, and others. So, in these experiments, coal is typically heated in an oxidative environment, starting from ambient temperature to higher temperatures at a specific heating rate. What happens during this experiment is that, due to the action of heat under oxidative conditions, coal mass loss occurs. As we heat the coal from its surface, different materials are released, such as moisture, volatile materials, and other thermal decomposition products, since it is in an oxidative condition. Some oxidation reactions also occur in parallel. So, if we measure at what temperature and under what conditions this moisture loss, thermal decomposition of coal, and oxidation occur, we can identify specific temperatures that represent different types of hydrocarbons, mineral matters, pore structure, porosity, and their overall contribution to the combustion process. We can identify all these important temperatures and other details from this profile. So, for this purpose, a highly sensitive balance is used. About 10 mg of coal is taken, allowing us to measure the exact amount of mass loss. Here, a sensitive balance means it measures in the range of 10 micrograms or even beyond that.

Even at the nanogram level in some of the sophisticated equipment. So, we take samples of a 10 mg coal sample. And from this 10 mg coal sample, we also measured in the fourth, fifth, and sixth digits at the gram level, so that we can identify any mass loss corresponding to 1 microgram, 5 micrograms, 10 micrograms, etc. So, we measured the mass loss even at the microgram level. So, any thermal decomposition, any minor mass loss, can be identified by this balance. As we are identifying those mass losses, we can easily correlate that mass loss with the temperature of the combustor or this instrument. So, we can get information that at this particular temperature, This mass loss has started, which means that mass loss temperature represents some thermal decomposition, moisture loss, or oxidation reactions that have started with the coal sample. So, we typically measure the mass loss profile of the coal samples along with variations in temperature and time in parallel. This will give us important information about the mass loss profile as well as the chemical reactions happening with the coal sample. So, what we do in this analysis is take a very small quantity of coal sample, around 10 mg, and in this small crucible, we create a very small amount of height. Why is there only a 10 to 12 mg coal sample? If we take a higher amount of coal samples, like if we fill it with a higher mass, such as around 50 mg of coal sample, what will happen? As the thickness of these coal sample layers in this crucible will be on the higher side, there will be an impact on the layer and diffusion of this coal sample, diffusion of oxygen, carbon dioxide gas, all these things, as we have discussed in our previous class, like the shrinking core model. They will impact the exact combustion behavior or reaction kinetics. To avoid all these effects of the ash layer, because once this coal is burned, after a certain time, it will form an ash layer of this thickness.

So, this top layer will have some ash layer. So, through this ash layer, oxygen has to pass, and carbon dioxide, hydrogen gases, or water molecules have to come out. So, this ash layer will play an important role. During this analysis, which will create a barrier in getting the exact temperature and other conditions to carry out these reactions. That's why in this sample—that's why in this experiment—only 10 to 15 mg or 12 mg, a very small quantity of coal sample, is taken. So that the height of this coal sample is not significantly higher. We should not take coal samples beyond 20 mg or 25 mg. Second is the coal particle size. As we want to analyze the exact thermal decomposition and thermal decomposition kinetics of this coal sample, we should take very small or very fine coal particles again to avoid any of the impact of the shrinking core model and ash layer, whatever we have studied there, to avoid any impact coming from the ash layer on the coal particle. So, to avoid this, typically a coal sample of 75 micrometers or less—less than 75 micrometers—up to what extent we can do grinding or we can prepare the coal samples at this size, it is done. So, this finer size coal sample of about 10 to 12 mg is taken in any particular possible and they are placed in a heater. where it will be heated in that equipment and it is connected with a magnetic suspension spring balance. So that any weight change we can measure it by this balance at this location, which is connected to the computer and sophisticated software. So, any mass loss or any change in mass loss will be immediately recorded in this computer software. So, any mass loss profile what is happening at any particular temperature or any particular condition, we can easily identify from that software and we can easily identify indirectly the coal combustion characteristics or coal reaction kinetics. If we are doing this analysis in the presence of oxygen, we call it combustion analysis. If we are doing this experiment in inert conditions like in the presence of nitrogen gas or any of the inert gases like argon, helium, etc., we call it pyrolysis analysis or thermal decomposition analysis. So, if in this or similar equipment, we can do or we can identify many important parameters which represent the coal reaction kinetics and its reaction behavior. So, this, during this, as chemical reaction is linked with the types of hydrocarbon present in coal when Coal has different types of hydrocarbons, as we have already discussed. It will react; individual hydrocarbons will react with oxygen at their molecular levels, and at the same time, other mineral matter surface areas and other parameters will have an impact. So overall, any reaction happening with coal is indirectly linked or has an indirect correlation with the hydrocarbons and other mineral matter percentages present in coal. So, any mass loss profile we record indirectly represents the hydrocarbons' combustion characteristics or reaction kinetics. So, in pilot scale or plant scale, when we actually burn coal, it is expected that coal will burn within a very specific or very short time. Exact combustion in any thermal power plant or combustor occurs under different conditions. In a thermal power plant boiler, the temperature is already raised to 1000 or 1200 degrees centigrade, and coal is burned or fed into the combustor at that temperature.

So, coal typically gets a very short time—4 to 5 milliseconds or 4 to 5 seconds—depending on the design. A very small amount of time is given for coal particles to heat, burn, finish burning, and generate ash. All these phenomena occur within the shortest span of time, but that reaction will happen based on the individual coal characteristics, hydrocarbon characteristics, as well as other parameters. So, whatever characteristics it shows in this analysis will be there, but in a different way. So, these coal properties will always be linked with the source and the types of hydrocarbons.

So, even on a larger scale, if any coal particle has a higher mass percentage, it will burn slowly and take longer time to burn—that is already a proven concept. So, the rate of combustion for different coals will vary, as coal has different hydrocarbon structures and other factors. And we can easily identify those differences from this analysis. So, this combustion profile is linked with hydrocarbons reacting with oxygen or indirectly with different types of hydrocarbons present, as well as mineral matter in the coal. So, it is essential to supply a particular type of coal, known as the design coal. That means for that type of coal, any particular burner or boiler was designed. When any boiler is designed, we use its coal properties, like what is the ash percentage, what is the volatile material percentage, and what is the gross calorific value. Considering all these parameters, the boiler is designed, and its dimensions are fixed based on all these input parameters. So, to get the best combustion result from the boiler, we should use design coal or that coal properties for which the boiler has been designed. So, in such a case, it will give very accurate combustion and can maintain the steam quality in thermal power plants, temperature in cement plants, and others. It will generate zero unburned carbons or hydrocarbons, as we are using coal in the burner which has been designed for that coal.

So, in this analysis, when we analyze the burning profile of coal, it is known as thermogravimetric analysis, well known as TGA. This is a thermogravimetric analysis which plots the mass versus time. So, this mass versus time plot shows the mass percentage versus time as well as temperature, as we are using a fixed heating rate of 10 degrees centigrade per minute. So, whether we measure the temperature, mass, or time, both can be represented on the same scale. That means it starts from 30 degrees centigrade or atmospheric condition. It will go up to higher temperatures as per our choice. Typically, coal combustion analysis temperature around 700 to 800 degrees centigrade is adequate. So, in the computer software, we measured both time and the temperature of the furnace, and it is a very small furnace heated electrically through the much more sophisticated instruments. So, if we plot on the x-scale, we plot the mass percentage of coal. Suppose we have taken 10 mg or 12 mg of coal; we convert it to the mass percentage, meaning your mass is at 100 percent. So, at 100 percent mass percentage, coal combustion will start heating the coal from the atmospheric temperature, maybe at 25 degrees centigrade or 30 degrees centigrade.

So, from that temperature its combustion will start will try to heat that coal. So, this blue curve here it presents the mass loss versus time or M versus T plots. At the same time, we can also get another plot that is the rate of mass loss or we can say the Dm versus Dt. That is, we can also create the DM/DT plot, that is the differential thermogravimetric analysis. So, this represents the DM/DT versus again temperature, that is in this axis, whereas this plot is M versus time or temperature. So, this plot is, TGA plot is actually M versus T, whereas the DTG plot is DM/DT versus temperature. So, in the both case, if we measure simply the mass loss If we identify the mass loss, what happening at individual temperature, we can identify how this mass loss is happening. And that represents the different type of decomposition, mass loss, corresponding to the thermal decomposition, chemical reaction, etc. And if we measure the rate of mass loss, we can identify at what temperature mass loss is increasing. And what temperature the rate of mass loss is finished. That means we can identify at what temperature some chemical reaction is occurring and what temperature only some minor mass loss is there due to moisture loss and others. So, all these parameters we can identify through this equipment. well known as the thermogravimetric analyzer. TGA-DTG analysis or we can also do the differential scanning calorimetric analysis in coal. As in the differential scanning calorimetric or in the DSC analysis we measure the heat release as heat release measurement is also linked with the

Chemical reactions in the coal. So, we can also analyze the differential scanning calorimetry analysis, which can give the same or similar results. In these TGA experiments, when we perform this analysis, we take about 10 to 12 mg of coal and analyze their rate of mass loss and other factors. If we observe these plots, what we can see is that It will start from 100% of coal, now 100% mass. Now, depending on the types of moisture present, if that moisture is released at very low temperatures or at very high temperatures, even at 50 degrees centigrade, we can see that there is a certain mass loss of about 2 to 3%. So, initial mass loss occurs around 100 degrees centigrade here. These correspond to the mass loss, these correspond to the moisture mass loss, meaning any water molecules or moisture present in the coal. Typically, they will be released from the coal surface as we heat the coal. Later, it will continue in a steady manner, meaning the mass loss will remain almost in the same range. After a certain time, we can see that after this temperature, some rapid mass loss begins. So, if we observe this point, it means In the case of coal, moisture is released at 100 degrees centigrade. If we increase the temperature from 100 degrees to 150, 200 degrees centigrade, 250 degrees centigrade, what will happen? At a certain particular temperature, volatile materials will try to release from the coal surface. As these volatile materials are released from the coal surface, there will be some mass loss from the coal.

So, this initial mass loss was due to moisture loss, but at higher temperatures around 250 or 300 degrees centigrade, some mass loss will begin and continue. This continuation of mass loss indicates that something is happening inside the coal, for which it is losing some mass. Typically, if we correlate this with real-time observations, volatile materials are released from the coal surface. This temperature corresponds to the initiation of devolatilization of coal or the release of volatile materials from coal. Now, once the volatile materials start releasing from the coal surface, after a certain time when the concentration of volatile materials is high, they will catch fire. So, once they catch fire, maybe at this point, we can see that the coal has So, it has started the main oxidation reaction, and the coal has started burning. When coal is burning here, both volatile material loss will occur, as well as volatile material plus fixed carbon, which will all be converted to CO2 and other gases. So that means at this temperature, coal combustion has started. So, this temperature is known as the ignition temperature, where coal combustion started, and then it will have a very sharp mass loss because, by this chemical reaction or combustion reaction, both volatile material and fixed carbon—or we can say the hydrocarbons—are reacting with oxygen, forming carbon dioxide and H2O, and leaving the coal surface. So, it will result in rapid mass loss from the coal surface. It will continuously go on, and after a certain time, at this point, we can see that almost no mass loss is occurring, meaning the combustible materials there have finished burning. So, there is no more combustible material left. That means their combustion has finished, and it has almost become a very flat curve here, meaning no more weight loss is happening.

Whatever thermal decomposition or chemical reaction was supposed to happen has finished. So, that temperature is known as the burnout temperature, where combustion has finished. In between, at some rate, we can find that at this position, the rate of reaction is extremely high. That means the rate of mass loss is at its highest value. That temperature is known as the peak temperature. And the value we get from this DTG curve is known as the peak combustion rate, or at this rate, coal can be burned at a much higher rate. So, if we analyze them in detail and if we can identify all these different temperatures—like if we say Ti or ignition temperature—this ignition temperature is where we can say that the rate of mass loss is just above 1% per minute. So, if we start at the initial part of this coal, there is some mass loss occurring. So, the initial mass loss is due to the devolatilization of coal. That means from that mass loss where it has started maybe 0.1 weight percentage per minute or 0.2 weight percentage of minutes. So, at that mass loss where it is less than 1%. Here combustion has not started but volatile material started releasing from that coal. So that is not the ignition temperature. So, for ignition temperature theoretical concept is that where it will concept 1 percentage per minute that is the world recognized value where it will cross 1 percentage per minute that means in the DTG curve, it is started from 0 percentage, it is crossing 1 percentage per minute that means this pink curve. If we see at this value it is started really crossing 1 percentage per minute. So, this point is identified as the ignition temperature where value is less than 1, crossing 1 percentage per minute that means it is exceeding 1 percentage per minute. Below 1 percentage per minute any mass loss is due to the loss of volatile material. So that volatile material loss does not mean that combustion has been started. Their combustion is yet to start from the coal surface that is known as the devolatilization temperature. So, this temperature ignition is started, so if you analyze the further DTG curve at this point it has reached the highest mass loss that means from minus one percent it has started to two percent, three percent, four percent, five percent etc. So, this rate of mass loss at some temperature coal is burning at much rapid rate. So why this coal is burning at this rapid rate that means entire hydrocarbon has started reacting with oxygen, it has started burning and coal is releasing energy at that particular temperature. So, if this rate is value is significantly higher means coal can be burned at much higher rate. If this DTG value is on lower side like if DTG value is at 2 that means coal is burning its highest rate but that highest rate value is less And if this DTG value is like 20 or 30, that means coal is burning, entire coal is burning within shorter span of time. So, it can release much higher amount of energy. Because this DTG max means it is the mass percentage.

If we multiply with the GCV value, we will get the rate of heat release. So, 2 percentage of coal is burning with calorific value this, that will give that kilocalorie per minute. So peak combustion rate represents at what rate it can burn at how quickly this coal can burn or how slowly this coal can burn and corresponding temperature is known as the peak temperature. Similarly, after this coal combustion is finished as coal has started Almost coal combustion is finished and it reached that entire combustible material is that. So, that TF or this temperature.

So, this TF is known as the burnout temperature where rate of mass loss again reduces below 1 percentage per minute. So, initially from 1 percentage rate of mass loss will increase. reach its peak temperature and again it will decrease. As there is no more combustible materials are there or combustible material combustion is getting finished with time. So, at this certain temperature it will again come back to below 1% and ultimately it will reach to 0%. So, this temperature is known as the burnout temperature.

So, if we overall see this ignition temperature, peak temperature, peak combustion rate or DTG max value here and burnout temperature. These all represents types of hydrocarbons and their reaction kinetics. when they are present in coal. So, this represents the entire contribution from volatile material, fixed carbon, mineral matter, whatever their combined role during combustion is there, those we can identify by this burning profile. So, if we see stage by stage, initially coal will lose moisture, which typically happens around 100 degrees centigrade. Around 300 degrees centigrade, and for some coal, it may go up to 400 degrees centigrade. Coal will start releasing volatile material. This volatile material easily catches fire and makes the primarily fixed carbon component of the coal react. That means the purpose of this ignition or the purpose of this volatile material is to burn itself and provide the necessary activation energy. for coal combustion. After coal combustion begins, it starts burning, and we will see a major mass loss and major energy loss, which we can observe from this temperature. So, if we discuss one by one, what is the role of ignition temperature? Ignition temperature is that during the heating of coal after moisture loss around 100 degrees centigrade, further heating causes the release of volatile hydrocarbons. or low molecular weight hydrocarbons from the coal structure. So, those volatile materials can be released as they are directly present in the fuel or. they are released by the action of heat through thermal cracking.

So, such released volatile materials, as they are in the gas phase, easily mix with oxygen and catch fire. Once the concentration of volatile material exceeds certain limits—if the volatile material concentration is very low, it will not catch fire unless it crosses some particular limits, some mass percentage values. So, they will not catch fire. So, for that purpose, there are two different points: ignition temperature and devolatilization temperature. So, once this concentration of volatile material exceeds some value, the volatile material catches fire and releases some amount of heat. So that the entire fuel or remaining amount of coal gets the necessary activation energy for combustion, and the entire fixed carbon starts burning. So, once this fixed carbon starts burning, coal combustion will continue. So, ignition temperature indirectly represents the entire role. or entire contributions from the hydrocarbon types in respect to ignition, as well as other mineral matter, surface area, etc. So, their combined role and joint role are represented by this ignition temperature. So, if this ignition temperature is on the higher side, that means. If the ignition temperature is on the lower side, that means if the Ti value is less, then it has a higher amount of VM presence in that particular fuel. If VM is on the higher side, the ignition temperature will always be low. But if volatile material is less, that means volatile material released from the coal surface will occur at a higher temperature, either by thermal cracking or as present. So, it will ignite at a much higher temperature. So, if the ignition temperature is low, the fuel will easily ignite, meaning the coal will easily ignite. If this volatile material is on the higher side, in such cases, the ignition temperature will be low.

Similarly, if we see the significance of peak temperature, peak temperature represents the temperature at which fuel combustion occurs at the highest rate. That means at highest rate at what rate fuel can get burned. Like kg of fuel, it is burning within some unit time or minute. So how much at highest rate what rate any fuel can burn. So that will identify by the rate of mass loss. If any coal is burning very rapidly in such case its rate of combustion is high. So, in such case its rate of mass loss is also will be on higher side. So, this DTGmax value represents the highest possible maximum rate of chemical reaction. If any fuel burns at high rate that means it can release most of the energy or calorific value available with this fuel that is whatever the energy is there. that can release this entire amount of energy at their temperature. So, this DTG max indirectly represents the rate of chemical reaction or rate of combustion of that particular fuel. If any fuel releases highest amount of energy at lower temperature that means any fuel is releasing energy at much lower temperature that means it will burn easily and entire combustion can be occur at much lower temperature. So that can sometimes be very hazardous and that can be a fire prone material or fire prone fuel that it may cause some accident. We know such material as the highly inflammable fuel. Like if we compare like coal and any of the liquid fuel like petrol or diesel or other fuel. So, all these liquid fuel burn at highest rate or higher rate even at much lower temperature.

That's why they are called highly inflammable fuel. But coal does not burn very rapidly at lower temperatures. That's why it is very safe for storage as well as transportation. Similarly, if any fuel ignites at a much higher temperature, if it ignites at a much higher temperature, that means it will not easily catch fire. If it does not easily catch fire, that means it is safe to store and safe to transport. But when we see it in terms of a combustor, it will be difficult to ignite, so we have to work hard to get it to ignite, like mixing it with other types of fuel or other things. So, in a real-time combustor, it may not ignite at all or it may ignite at a later stage. So, it may create some unburned carbon and other things. So mostly, fixed carbon combustion is responsible for getting the peak temperature of the coal. Now, once combustion is entirely completed, we can see that the residual fuel is very less. So, in such a case, the rate of combustion again falls below 1 mass percentage per minute. That means it represents that all the combustible material has been burned. And only some minor quantity of combustible material may be there, or whatever the mineral matter is there. Now they are starting decomposition or they are starting to decompose at that particular temperature. So, this temperature is known as the burnout temperature. So, if any hydrocarbons are highly flammable, this entire combustion will finish at a much lower temperature. So, if hydrocarbons are easily getting burned, we will get that burnout temperature at much lower temperature. hydrocarbons reacts very slowly. It is not burning very rapidly. Typically, this burnout temperature will be on the higher side. So, fuel will take much more time for the combustion.

So, overall, if we see all these parameters, ignition temperature, peak temperature, burnout temperature and peak combustion rates, all these parameters, they indirectly represent the Combined contribution of hydrocarbons, combustible as well as mineral matter present in any of the fuel. If ignition temperature is high, if ignition temperature is very high, that means coal will ignite at much higher temperature. So, if coal ignites at much higher temperature, that means in real time combustor, it will start ignition late. So, in actual boiler, it will cause delayed ignition time. Although temperature is different is from the actual boiler. So, although this ignition temperature is different in case of actual boiler where boiler temperature is already 1000 degree centigrade whereas in case of TGA analysis, we are heating them at 200 to 50 degree whatever at lower temperature but this ignition temperature characteristics it will show there. So, in case of actual boiler it will ignite but it will ignite delayed like if coal get burnt within 5 seconds but it may ignite after 3 seconds after remaining 3 seconds at higher temperature it may start ignition. If volatile material on higher side, it will ignite within 1 second or 1.5 second. So, this ignition temperature represents the ignition characteristics. Similarly, if the peak burnout temperature is on the higher side, that means fuel will end burning.

At a much longer time. That means it will take a long time to finish burning. That means whatever hydrocarbons are there, they are not very reactive in nature. So, they will react slowly, and it will take a long time. That means in a real-time boiler. It may not complete burning within these 5 seconds. It may need 10 seconds or 15 seconds of time. So, in a real-time boiler, it may not have such a long time. That means if a boiler is designed for a coal residence time of 5 seconds or 6 seconds, but if any coal particle needs 10 seconds to finish burning. So, in such a case, each coal particle will not get adequate time for burning. And it will precipitate or fall to the bottom of this combustor as unburned carbon mixed along with the bottom ash. So, in such a case, fuel or coal will not burn properly. Similarly, if the DTGmax value is on the higher side, DTGmax represents the highest reaction rate possible from the coal. So, if any fuel has hydrocarbons that are highly reactive in nature, all the hydrocarbons may react within a short span of time. So, in such a case, it will release most of the energy within a short span of time and can reach a very high temperature. But if DTGmax is on the lower side, that means hydrocarbons are there, but they are not very reactive, so the rate of reaction is on the lower side. so they will release energy but they will energy at much lower rate so if DTG max value is higher most of the energy will be released at short span of time and if this DTG max value is exceeding some limit, so it may create some excessive temperature. Like in boiler, we may need only temperature up to 1200 degree centigrade. But if entire coal gate burns at very smaller time, DTG max value is higher. Temperature may exceed 1500 or 1600 degree centigrade.

So, at that exceeding high temperature, entire boiler, refractory, boiler tubes and other equipment, they may get damaged or they may have faced some thermal action of heat or they may get some cracking or other. So DTGmax value also should match with the design. So DTGmax value if it is on very much lower value like coal is burning but it is burning very slower rate. In such case we will get heat out of it but that heat may not be able to maintain the desirable temperature required for utilization. So, if DTGmax value of any coal is very less, we can use them for the domestic applications. If DTGmax value is in the medium range, we can use them in the small scale application.

If DTGmax value is on higher side, we can use them in the boiler for heating or getting some very higher temperature. But if DTGmax value is very high, we cannot use it directly we have to take some other precautions like blending with other type of fuel or we have to take additional precautions to control the temperature of the boiler. So overall what we can get it that all these burning profile parameters this all four parameters in combined ignition temperature, peak temperature, peak combustion rate and burnout temperature. They combined represents the burning characteristics or reaction characteristics of that coal. So, if we can identify this temperature, we can indirectly characterize coal in terms of their reactivity. If coal is highly reactive or non-reactive, what is the difference or temperature gap between the ignition temperature and peak temperature? What difference is there between peak temperature and burnout temperature? All these temperature differences represent That means, they represent hydrocarbons or mineral matter composition, their porosity, and etc. Their entire characteristics we can identify by this analysis. Individually, hydrocarbon analysis and mineral matter analysis are difficult. So, in most cases, this analysis is done. And if we can analyze all these parameters, we can assess the coal reactivity—how they will burn, how they will react in a real-time boiler.

Thank you.