Clean Coal Technology

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Lecture-24

Hi, I am Prof. Barun Kumar Nandi, welcoming you to the NPTEL online certification course on Clean Coal Technology. We are discussing the effects of coal properties on their combustion characteristics in Module 5. We have already discussed the effects of volatile material, fixed carbon, mineral matter, moisture, coal particle density, particle size, etc. on their combustion characteristics. So, in this lecture, I will be discussing the effect of primary air and secondary air on the combustion characteristics.

So let us start Lecture 4 on the role of primary air and secondary air. Now, if we see the overall combustion process of any fossil fuel, air or oxygen is required. So, this air and oxygen react with hydrocarbons to produce carbon dioxide, other hydrocarbons, moisture, and other gases, as well as releasing energy. So, for the combustion process, some air is always required. So always some amount of air is required for the combustion process. Now the first question here is whether we will supply the entire oxygen at once or supply the oxygen in two or three different stages so that the total oxygen is split into two or three different locations. So, this is the starting point where we get the concept of primary air, secondary air, and in some cases, tertiary air. So primary air basically means the air initially supplied with the fuel. That means along with the fuel, some amount of oxygen is supplied and fuel and oxygen mixture get reacted, fuel get burned. at later as some of the other locations of the reactor or combustor we supply some additional amount of oxygen or remaining amount of oxygen. So that oxygen is known as the secondary oxygen or even if it is supplied at some third location in the reactor it is known as the tertiary oxygen Now why this concept of primary, secondary and tertiary air is there? So, this concept is like if we have 100% oxygen is required, we may give it like 50% as the primary air and may be remaining 50% as the secondary air. Or we may again split this 50% as secondary air to either 30% as secondary air and remaining 20% as the tertiary air.

Now why this concept of secondary and tertiary air is there? This concept comes from the last earlier principle of chemical reaction. What this principle of any chemical reaction calls is that or the inference is that if any chemical reaction is at equilibrium level that if some reactant A plus B they are at equilibrium making C plus D. So, whether this reaction will go in forward direction or at backward direction, like whether A plus B will make product C plus D or C plus D will revert back to raw material A and B. That means this equilibrium whether shift towards the product side or towards the reactant side, that depends on the changes in the pressure, temperature, concentration of the product or reactant. Like if reaction is happening like A plus B making C plus D, and if we remove C continuously from the system, so in such case A plus B will allow us from C plus D. So, reaction will go in the forward direction. So, either C or D, any of this product if we remove continuously, or if we take out from the system, so reaction will go in the forward direction. In the opposite way, if concentration of C and D is increased, that means whatever the products are there, they are not getting removed from the system. They are again in the same system. So, reaction will again come back to the backward direction. So, it will again form A plus B. So, this shift whether we will be reducing the concentration of c plus d or we will keep concentration of a plus b on the higher side that means if concentration of a plus b is on the higher side it will always go in forward direction to make it c plus d or if c plus d concentration is on the higher side it will make a plus b so these changes is Happens in real time chemical reaction through change of partial pressure or total pressure. As this partial pressure for gas phase, it represents the concentration of gases.

So, if the partial pressure of C and D if it is reduced or if we modify the temperature or if we change the concentration of either products or reactant like A plus B or C and D, if we change any of this concentration of this reactant, this reaction will shift to the forward direction or it will go to the backward direction to offset any of these changes. So, reaction will always try to be in equilibrium So, if we removing or reducing the concentration of AB or if we are reducing the concentration of C or D, that will decide whether reaction will go in forward direction or backward direction. So, if we see in case of coal combustion, typical reaction is like C plus O2 equals to CO2. So, this is actually a two-step reaction. At first stage, C plus O2 C plus O2, it makes carbon monoxide. And in the second stage, carbon monoxide further reacts with oxygen to make carbon dioxide. So, we can consider carbon plus oxygen making carbon dioxide.

This reaction is a two-stage reaction. In the first stage, it produces carbon monoxide. In the second stage, carbon monoxide again reacts with oxygen to make carbon dioxide. And similarly, whatever the other hydrocarbons are present like any other hydrocarbon, methane, ethane, whatever. So, in all those hydrocarbons also they will again react in the same way.

So, during initial stage of coal combustion as different volatile materials are released from the coal surface they may have hydrocarbon structure or volatile material composition like this hydrogen, methane, ethane etc. That means for them also reaction is like it is like from coal. It is creating VM. So, if we are not removing volatile material from the coal, it will not go in the forward direction. It will come back to the backward direction to make this coal. So, for this case also, the same reaction or same theory is applicable. So, during de-volatilization and after release of volatile material, their combustion, for all of them, the same Le-Chatelier's principle is applicable. As coal is a solid material and the products are in the gas phase. So, this is the major difference where we see or we apply the Le Chatelier's principle in other cases or other application. In case of coal combustion as we have seen that coal is a solid material.

So, the feed is in the solid phase, whereas the products are in the gas phase. So, we can think like solid plus oxygen makes some gaseous product and gaseous products like CO_2 plus H_2O. So, in such a case, what happens? If we remove or reduce the concentration of gas, that means any of the product gases, either CO_2 or H_2O, or even during volatilization like methane, hydrogen, whatever is there. If they are removed from but they are released from the system, from the combustion chamber, the reaction will go in the forward direction. If they are not removed from the system, the system will achieve some equilibrium where coal will not react further or no hydrocarbons or carbon dioxide will be produced. If it is a compact or complete system where no products are being released or no additional oxygen is added. So, in the case of coal combustion, what happens is, once we add oxygen and provide the desirable temperature, at this temperature, once coal is heated, it will release hydrocarbons and as oxygen is present, it will initially produce carbon monoxide. So once all these hydrocarbons are released and carbon monoxide is also produced, if all these products leave the reactor or the location of that reactor, then all the products will leave the coal surface because they are in the gaseous phase. Once coal is heated all these hydrocarbons will be released from the coal structure and they will be released and leave the coal surface. So, this reaction will always go in the forward direction. Similarly, any of the carbon material will also form carbon monoxide. So, this first reaction always goes in the forward direction. So, in such a case, coal will always be the excess reactant and supplied oxygen will be the limiting reactant. So, whatever the amount of coal is there or whatever concentration of oxygen we are giving we may give 200 percent additional oxygen or we can give concentrated or high pressurized oxygen but at the reactant surface where reaction is happening always coal immediately it will convert it to gas phase and if we allow that gases to go out they will always go. So, at the first instance always their oxygen will be in the limiting reactant and entire coal will be converted to this volatile rich material as well as the carbon monoxide. So, they are they will not go for the second reaction like first reaction is C plus O2 to make it CO and in the second case CO plus O2 to make it CO2. So, at this fast reaction happenings entire CO leaves the combustion surface coal surface and it comes to the gas phase. So, if these gases are removed from the system entire coal will be converted to carbon monoxide. So, they will not go for secondary reaction or making it CO plus O2 CO2 hence Always oxygen will be on the limiting reactant and supplied coal will be on the excess reactant. So, at the first stage or initial stage entire coal will be converted to carbon monoxide.

In real time reaction it may takes only very few milliseconds or very one or two seconds but this will actually happen. So hence produce CO and other gases they do not get adequate oxygen or to further convert it to the go for the further reaction. So whatever oxygen is there, we are supplying it near the coal surface. All the oxygen will be consumed to make it carbon monoxide. So there will never be adequate oxygen to make it carbon monoxide to carbon dioxide for the second reaction or further reaction. So, any reaction where carbon monoxide and other hydrocarbons are produced, typically those are known as the gasification reaction. We will discuss them in next or future modules. So, for further combustion of carbon monoxide and other hydrocarbon rich gases, oxygen needs to be supplied at a later stage. So, if we want that carbon monoxide will again react with oxygen. We have to supply oxygen at a later stage, not at the same location along with the coal. So, oxygen needs to be supplied at a later stage. That's why, that means either in multiple locations in the boiler. In the boiler or in the combustor, we have to supply this oxygen at two different phases. Maybe at the initial phase, we supply 50 to 60% of the oxygen, and the remaining requirement of oxygen, we have to supply at some other location to ensure that all the carbon monoxide and all the hydrocarbon gases which have been released from the coal, get complete combustion. So, oxygen supplied initially is known as the primary air, and if it is supplied at a later stage depending on location, we can call it secondary air or tertiary air. So, the purpose of this primary air is primarily to ignite the fuel and burn it. So initially, the purpose of this primary air for coal, it will be only to ignite the fuel and convert it to or bring it to the gaseous phase, make the fuel ignite and burn it. And after this primary air is there, there will always be some amount of unburned hydrocarbon gases as well as carbon monoxide gases. So, the supply of secondary air ensures that no unburned fuel gases, that is in the gas phase, or any other carbon monoxide gas, are released from the combustor. They get burned in the reactor, and typically we can see such supply of primary air and secondary air in any of the gaseous fuel or liquid fuel burners. And in some cases, sometimes they are required, and they may not be required because, in the case of gaseous fuel, mixing is uniform. But still, whatever the household combustion equipment we see, there is always a supply of primary air and secondary air, like if we see the normal LPG gas burner we use in our domestic applications. Just below the burner where LPG comes from the cylinder.

From here, LPG gas comes from the cylinder. It enters here, and along with this, there is some opening. As this LPG comes at high speed, it will directly enter here. So, no LPG gas will go there. But at this point, at this location, we can always find there are some holes which supply this primary air. So, any oxygen supplied in any of the gas oven at this location, they are known as the primary air. This primary air mixed with the LPG gases, they get well mixed here and reach to the burner head. So, in the burner head, they will get burned and release heat and from the burner surface, we always supply secondary air that's why in all of the burner gas oven burner we can find some stand is there. So, purpose of giving this stand over this burner is to make supply of secondary air through natural convection if we not allow any of the secondary air to come here gas oven will not burn properly or it will create so much smoke or carbon source for particles below our cooking vessel. So, this secondary air purpose here is that whatever the fuel supplied through this main origin and here primary air mix it makes that entire fuel and oxygen get properly mixed. So that they reach in the burner level burn sheet and may produce some low molecular weight gases carbon monoxide gases etc., which needs to be further burned by the helps of secondary air similarly if we see similar type of other combustor like in coal combustion units here we can see from this point coal is charged and here we supply the air. So, this is the point we supply coal and supply air. They get burns here and after this coal gets burned they release some flame. So, to ensure that any gas releasing at this position does not or they should completely get combust burnt, always some secondary air they are supplied at this location and depending on the coal properties may be here if required tertiary oxygen or tertiary air also needs to be supplied.

So, we can see from bottom of this location we are supplying primary air. We can supply primary air from this side also. From other location we have to supply. We cannot supply complete air from the bottom here. So here if we see we cannot supply the entire amount of oxygen only from this of these sources even through at higher space higher speed if we even if we give the compressed air here entire coal will immediately convert it to carbon monoxide. So, they will get immediately gasified converted to carbon monoxide and other hydrocarbon gases and they will at high speed they will get released. So, whatever the flue gas will go it will contain carbon monoxide. So that's why, to ensure that no carbon monoxide is present, we have to supply secondary air at some other location. So, this is the role of primary air and secondary air, and in some cases, we can also find that we always need some amount of excess air. What is this excess air? Typically, if we burn any fuel with oxygen, we supply theoretically, based on the stoichiometry of the fuel—like the amount of carbon, hydrogen, sulfur, etc., present—how many moles of sulfur, how many moles of hydrogen are there. Based on that calculation, we determine that for a certain amount of coal, like one kg of coal, it may need 2 kg of air. So that is the theoretical requirement, which is determined based on the elemental analysis, or what we call the CHNSO analysis. So, for any fuel, this ultimate analysis is carried out. To determine the percentage of carbon, hydrogen, nitrogen, sulfur, and oxygen present. So, what will be the amount of oxygen required for combustion to convert all carbon into carbon dioxide?

Here, in this stoichiometric calculation, we assume that carbon is converted to carbon dioxide, hydrogen is converted to steam or moisture, and sulfur is converted to sulfur dioxide. Typically, we do not consider nitrogen to react. We assume that it will be released as nitrogen gas because the reaction between oxygen and nitrogen typically occurs at much higher temperatures. So, if we operate this combustor at a much lower temperature, we can assume that no NOx formation will occur. So, typically, this reaction is not possible. We consider that this nitrogen will not react. But in reality, it may react or may not react depending on the conditions or temperature of the combustor. So, typically when we do the stoichiometric calculation, we calculate the amount of carbon, hydrogen, and other materials present and accordingly determine We make calculations like what is the amount of oxygen required. So, for making carbon dioxide, what is the amount of oxygen required. So, oxygen is used for combustion purposes along with the supplied air. So, based on the stoichiometric calculation like C plus O2 equals CO2. So, what is the mass of oxygen and carbon available? What is the mass in moles of oxygen and carbon available? So, how much oxygen is required?

Similarly, for H plus O2, we also calculate the amount of sulfur available. So, how much oxygen is required to burn sulfur dioxide? A similar approach is used for H2 plus O2 to make it. So, we consider all these things and calculate the amount of oxygen required. So, we calculate this oxygen requirement based on the stoichiometric calculation.

Like for unit mass of kg of fuel, we consider kg mole because this chemical reaction happens on a mole basis, not on a mass basis. Like 1 mole of oxygen and 1 mole of carbon, they react.

Not 1 kg of carbon and 1 kg of oxygen. This reaction happens in terms of moles. That is either in kg mole or in gram mole. So we calculate what is the mole of oxygen required for the calculation. And typically, fuel oxygen is deducted from the total oxygen requirement. But in most cases, this percentage or amount of fuel available is very less. Compared to the supplied oxygen. So, we may neglect it or may not neglect it. For accurate calculation, we should consider the oxygen available in the fuel. But if we go for a rough calculation, this oxygen available from the fuel, we may neglect. So, this is our choice whether we will consider it or not consider it. So, from the oxygen requirement, whatever is available, we convert it to the air requirement. So that air requirement conversion is done by considering that air has 21% oxygen by volume and 23% oxygen by mass. So, if we are doing calculation based on volume basis, we should consider that 21% oxygen is available for volume. If we are considering on mass basis, we can consider like that there is 23% is there. Again, here if we want exact calculation we may consider the exact value may be 21.1 or 23.2 whatever the exact value is there. So, this air exact that this air is the exact air required for combustion will know as the 100% air. So based on all this calculation whatever the oxygen requirement is there. That is the corresponding exact theoretical or stoichiometric oxygen required or stoichiometric air required. This is known as the 100% air required for the combustion process. Now, the actual scenario is that as coal is extremely heterogeneous fuel, coal is not a homogeneous fuel. So, always... coal and air mixture it is always in gas and solid phase. So, it is never uniform because coal is in solid phase and air or oxygen supplied is in gas phase always this solid particle will be dispersed or suspended in this air. So, there can have some zone where concentration of oxygen will be less and there will be more amount of coal particles are there.

On the other zone there can be less amount of coal particles are there as they are in suspension they are never uniform. This scenario is much better in case of liquid fuel and in case of gas combustion or gaseous fuel combustion this is completely we can use that all the gases will be mixed properly. So as there is some zone where less amount of oxygen is there now what will be the actual scenario is there If there is some zone where coal particle amount is more compared to their oxygen concentration. So maybe some zone is there where coal particle dispersal there may be that 10 particles per meter cube. Where in the other zone location may be 20 particles per meter cube. So any location where less amount of oxygen is there and more amount of coal particles are there.

So in that particular zone. Oxygen is the limiting reactant. So whatever coal is there will not be converted to carbon dioxide; it will be converted to carbon monoxide, whereas in the other zone, there can be excess oxygen, so all the coal particles will be converted to carbon dioxide, and there will be additional oxygen there. So In the first case, we find that there are some unburned coal particles or some carbon monoxide. In the second case, the other zone will have all the coal particles consumed, but some oxygen is in excess. So, as this zone has some excess fuel, there will always be some unburned fuel. This unburned fuel may be carbon particles, coal particles, carbon monoxide, or hydrocarbons—whatever. So, effectively, there will be some unburned fuel in the system. Whatever effort we use, there is always this possibility because the dispersion of oxygen and coal particles will never be uniform. So, there will always be some zones where excess oxygen is present, whereas in other zones, less oxygen is present, which will result in unburned fuel particles or unburned fuel gases. So, to avoid such phenomena and ensure that all coal particles get at least the required amount of oxygen (while some may get additional oxygen), we have to ensure that all coal particles get the required oxygen as per their stoichiometry. So, we always have to supply some additional oxygen, known as excess air. So, this excess air requirement is always there to ensure that there will be no zone where oxygen concentration is insufficient—that is, to ensure the fuel gets adequate oxygen for combustion and there is no unburned fuel, unburned carbon, or any hydrocarbons, etc., whether in the ash (bottom ash or fly ash) or in the flue gas. So, if there is any unburned carbon, unburned hydrocarbons, or fuel left in the ash or flue gas, that means it is a wastage of fuel. We are paying the cost of the fuel, so if it is not properly burned, it is not being properly utilized. So, that is effectively a loss of fuel. As well as all these unburned carbons and hydrocarbons, they will create environmental pollution because they can include harmful hydrocarbon gases that cause pollution. So, to ensure that complete combustion happens with adequate oxygen, so that no coal particle or no particular zone remains. So, that there is no zone where there will be a lack of oxygen. So, that is why this excess air is typically supplied as secondary or tertiary air. So, initially we may supply the required amount of air for combustion.

At a later stage, as we have seen in the previous picture, we may supply this excess air to ensure that combustion gets completed or there is no unburned fuel, unburned carbon, or any other residue. So, these are typically supplied as secondary air or tertiary air. Now, typically for coal, as it is a solid and gas mixture, we always have to use a higher side of excess air. So, typically for coal, the excess air supplied is around 20%.

For liquid fuel, there is better mixing, and some evaporation occurs. So, for liquid fuel, it is around 10% or lower, and even for gaseous fuel, we can supply maybe 5% excess air, which is adequate. Here, we have to keep in mind that whenever we are supplying excess air, excess air contains around 80% inert gases like nitrogen. Because air contains 21% or 23% oxygen, and the remaining is nitrogen. So, whatever the remaining part is, that means about 18% of the gas is inert gas nitrogen. So, this nitrogen does not take part in any of the chemical reactions. But it takes the latent heat because the flue gas will be released at a higher temperature. Depending on the heat recovery system, it may release typically on the lower side, maybe around 150 degrees centigrade or 100 degrees centigrade. In some cases, it may release even at 300 or 400 degrees centigrade. Typically, if we consider nitrogen, nitrogen enters the system at atmospheric conditions, maybe at 25 degrees centigrade, whereas it exits the system at 150 degrees centigrade or higher. So, it will take the latent heat, that heat corresponding to the mass of nitrogen gas, its specific heat capacity—it can be Cp or Cv depending on the condition—and the temperature difference: the temperature at which it enters and the temperature at which it exits the system. This amount of heat will always be lost to the flue gas, as nitrogen is an inert gas. It does not take part in the reaction but takes away the sensible heat required for its heating. That is the temperature difference between the inlet and outlet. But we cannot avoid it. We cannot avoid that—we cannot not supply any nitrogen or not supply excess air. So, to ensure that no amount of hydrocarbons or fuel is lost, we always have to supply excess oxygen or excess air. But we can keep a close eye or closely monitor the concentration of oxygen, carbon monoxide, etc. in the flue gas, so that we can ensure there is complete combustion in the system and no fuel loss occurs. So, we always have to supply some amount of air, which is additional air known as the excess air in the system.

So, if we summarize air, So, the last point is that for excess air, there will always be some oxygen remaining. For example, whatever the 20% excess air we are sending. So, in the reaction, 20% of the oxygen will not be consumed. In the reaction, only 100% of the oxygen will be consumed. So, whatever excess oxygen is there will also absorb the latent heat. So, for oxygen requirement, only 100% is needed. So, in the actual reaction, only 100% of the oxygen will be consumed. So, as we are supplying 20% extra or 120% air, this 20% is oxygen. It will be part of the flue gas, along with 120% of the corresponding nitrogen. It will also be part of the flue gas. So, if we supply a very high amount of additional oxygen, it will cause heat loss through these gases. Typically, this amount of excess oxygen is always monitored closely to ensure that the heat losses due to the sensible heat from this excess air or oxygen are minimized. So, to summarize overall, starting from primary air as well as secondary air, typically the primary air's purpose is to ignite the coal as it. In the first stage, always coal will be converted to any of the gaseous phase nearby location. So, maybe it is converted to carbon monoxide or any other hydrocarbon gases, which will as it is released from the combustor without converting it to the carbon dioxide or the final product. So, always there is a need to supply oxygen at that later stage of the oven or burner or the combustor which is known as the primary air and here it is known as the secondary air and in some cases we may have to supply the tertiary air. So primary air and secondary air ensure that whatever the volatile materials or whatever the combustibles are released from the combustion they get adequate residence time or adequate oxygen for combustion if we supply entire oxygen at one place. So, all the oxygen will be consumed only to convert fuel to a nearby gaseous phase and it will release as that in case of gaseous phase as if we get it from the Le-Chatelier's principle. So that is the main theory we get it from the Le-Chatelier's principle. That whenever any CO is formed, it will go out. It will not wait that it has to stay for more time to convert it to CO2. So, this reaction will never happen. If we want to ensure that this reaction happens, we have to supply oxygen at later stage, not just nearby the coal surface.

So, purpose of the secondary air is to ensure that there are no unburned hydrocarbons released to the flue gas. So, it is mandatory that any combustor system should have supplied oxygen at two different phases. Major oxygen in the primary air and some of the oxygen as the secondary air. And to ensure that all the coal particles get burned properly. As their mixing of fuel and air is not uniform, and since there is some probability that their mixing is not uniform, we always have to supply some amount of excess air. So, this excess air percentage is typically lower in the case of gaseous fuel, whereas this excess air percentage will be higher if we are using any solid fuel like coal or biomass.

Thank you.