Clean Coal Technology

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Week-10

Lecture-46

Hi, I am Professor Barun Kumar Nandi, welcoming you to the NPTEL online certification course on clean coal technology. Now, we will start Module 10. Here in this module, we will be discussing different types of reactors used during coal gasification. So, these are the contents of this module, where we will be discussing fixed bed, moving bed, fluidized bed, entrained bed gasifiers, as well as product gas cleaning and energy utilization, removal of H2S, ammonia, tar, and other impurities from the syngas. So, let us start Lecture 1 by discussing updraft and downdraft gasifiers.

Now, if we see the gasification reactions we have discussed in our previous lectures. During gasification, different types of reactions happen. There are some combustion reactions, water gas reaction, Boudouard reaction, hydro-gasification reaction, water-gas shift reactions, and methanation reactions. So, all these reactions can happen, or some of the reactions may or may not happen, depending on the reactor design, how the coal or the organic feedstock and the reactants like air or steam are reacted in the reactor. Depending on all these phenomena, some reactions may happen, and some may not. If some reactions happen, accordingly, the product gas composition or syngas composition will be different. For example, if we see in the case of a normal gasification reactor, in the first stage drying of coal or drying of the feedstock happens. During this drying stage, the moisture content present in the feedstock or coal gets removed. This happens if the temperature is around 100 degrees Celsius. So, whenever this feedstock or coal is heated or comes into contact with some hot air or hot reactor medium around 100 degrees Celsius, the moisture present in the coal will get released from the coal surface. So, as a result, this moist feedstock, under the action of heat, will lose the water molecules. So, it will create a dry feedstock, as well as some water molecules will be released. Now, after this heating at 100 degrees Celsius, when the coal gets further heated to around 300 degrees and above—so by that temperature, when it is more than 300 to 400 degrees Celsius—in that temperature range, the coal will start losing its volatile material. So, whatever volatile materials are present, they will be released.

So, this is very similar to that of deep volatilization temperature or ignition temperature in case of combustion that I have studied earlier. So, as your condition can be that oxygen may be present or may not be present, typically we call it like a pyrolysis stage. where devolatilization of the feedstock happens. So in by this reaction the hydrocarbon under the action of heat we release some of the volatile material or VM rich gases and residue coal we call it like char because at this char here only the fixed carbon and ash content will be there. In the previous stage moisture has been removed, in this reaction we have removed the VM or volatile material. So, residue will be the fixed carbon as well as the mineral matter or ash. That's why it is called char, so this char may contain some volatile material depending on the temperature but broadly it's called the char as a general nomenclature. So, this reaction pyrolysis will happen when the coal reaches temperature around 300 to 350 degree or 400 degrees centigrade and if the reactor has some of So during the reactor if some oxygen gas is available then it can go for combustion reaction as well as but if there is no oxygen is there. So, in general it will go for the pyrolysis reaction releasing volatile material at char and if oxygen is there at the same location volatile material will catch fire and it will ignite.

So, this is the stages happens when we heat the coal at initial stages and then it will go for the different type of solid gas heterogeneous reaction that is reaction of the char and the reactant medium as well as there can have reactions between the volatile material as well as the reactant medium. So, depending on the gas composition or what type of gas present at that particular location of the reactor there can have some combustion reaction if oxygen is available where we can have this C plus O2 CO2 reaction. There can have the water gas reaction where coal will react with the steam to produce carbon monoxide and hydrogen. There can have outward reaction where the carbon or coal will react with carbon dioxide, to produce carbon monoxide. There can have hydro gasification or methane reaction where carbon will reach react with hydrogen to produce methane and there can also have some gas-gas reaction like the volatile material reacting with the gases as well as the produced carbon dioxide, carbon monoxide, hydrogen, they can react with the other gases like water gas shift reaction which contains CO plus H2O to produce carbon dioxide and H2O. And there can have methane plus H2O which produce carbon monoxide and H2O.

So, all these chemical reactions may happen or may not happen depending on the temperature as well as the gas present in that any particular location. That means in the particular zone if any oxygen concentration is high it can go for this reaction. However, if at that location oxygen concentration is not there or oxygen is not present then it can go for this reaction or it can. go for this reaction if coal is there but carbon dioxide is present there is neither steam neither oxygen in such case these reactions may happen as well as if hydrogen concentration is higher this may happen. So, all these reactions can happen depending on the reactor type of reactor how this gas that means the feed oxygen or air along with steam is interacting with the coal as well as what is the nearby temperature of the reactor because some of the reactions are sensitive to the temperature as we have discussed in our previous module.

So, all these reactions may happen or may not happen. Some reactions may happen; some reactions may not occur depending on the feedstock condition. If the feedstock allows that some of the volatile material is released and they can react for gas reaction. So, it is entirely depended on the feedstock as well as the design of reactor. Typically, these are the two different types of reactors is used or the two types of design of reactor is used in gasification, although there is other type of reactor is also available.

So, in general, we can categorize them as broadly two, but there can have three or four also. First one is like an updraft reaction and reactor and second one is the downdraft reactor. What is this updraft reactor? As coal is a solid material, it cannot move by its own. So typically, in all the reactor, we charge coal from the top side or from this side we charge coal here.

So, if we assume that coal will charge from here, it will naturally go free fall from top to bottom. So, in most of the cases, coal is charged from the top as coal charge from the bottom is not possible here. So, in most of the cases, coal particles are charged from the top. And air which is the reactant or air or steam this air or steam or any other gases whatever is there they can be charged either from the bottom or again they can be charged from the top side itself. So, they can charge either from top or from the bottom if they are charged from the bottom that means this air is going upwards that's why it is called the updraft reactor where the gas flows towards the upward direction in this case, gas flows toward the downward direction. That's why they are called the downdraft gasifier. It may not be exactly from the top. It can be nearby side locations or these locations also.

But overall, these gases are going downwards. That's why they are called the downdraft gasifier. also, in some of the cases we can call it like an depending on the direction of flow of coal and the gases we can also call it like a co-current gasifier or counter current gasifier if like in this case coal is going in this direction gas is also going in this direction. So, they are going in a co-current in the same direction they are moving but in this direction coal is going at this direction and gas is going at this particular direction. So, they are the counter current direction in the opposite direction this flow of gases as well as the coal particles are there. Their major difference between all these two reactors is that their reaction zone and the corresponding reactions will be different in both the cases.

Like in this case whatever we have seen in our previous slide like this slide if we see. This reaction first reaction is the drying reaction then pyrolysis reaction. So, these reactions will happen like coal particles are entered here it is entering at atmospheric condition like 30 degrees centigrade. So, at this entering position it may have some moisture. So here at this zone it will get dried.

So, that is why this zone is called the drying zone and further it will go for the pyrolysis where temperature will increase certainly in the higher temperature. So, here temperature may be near by 100 degrees centigrade, in this location temperature may be 300 or 400 degrees centigrade and further these two zones, it may have the reduction zone or it can have the oxidation zone depending on the flow and mass flow rate of the oxygen. Like if oxygen is entering here, so oxygen concentration at these locations will be high and here they will react with the other gases. So entire oxygen is expected that they will be consumed here.

So, at these locations there will not have any amount of oxygen. So, if at this location there is no oxygen is there, so in such case this reaction will not happen rather this reaction will happen in the reduction zone if oxygen is there, like at this particular zone You can have this reaction is possible. So similarly in the other cases it will have the drying zone here as oxygen is also entering here. So, in this pyrolysis zone itself combustion may starts. So after just after pyrolysis zone there can have the oxidation zone is also possible that just after the pyrolysis coal may get burned, it will get oxidized but in this zone as oxygen is not there. After this drying zone, it will have pyrolysis zone, then reduction zone will be there. So, this difference of the zone will be there depending on the direction of oxygen as well as the availability of oxygen in the reactor.

As during this gasification, we are not providing adequate amount of oxygen. So, there will always be having these two zones, different zone is available. One will be oxidation zone; one will be reduction zone. So, just after the entering point of the reactor, it will have the drying zone of the coal particle then it will go for the pyrolysis or deep volatilization zone and further it can have either reduction zone or oxidation zone or other zone depending on the availability of oxygen and direction of oxygen and coal flow.

So accordingly, if we see that all these reactions happen in two different ways. In the first cases whatever the field stock we are charging it can have coal or it can have biomass. At these cases in case of A it is the upward direction where air is supplying from this bottom of this reactor and coal is charged from the top. So, in case in this case what will happen coal particle will pass through this zone one where that temperature will be around 100 degrees centigrade that means whenever in inside the reactor coal will reach around 100 degrees centigrade it will release the moisture content present in this coal. So, coal will get dried it will get highly porous after removal of moisture So this zone is called the drying zone and after this drying zone this coal will enter to the further high temperature reactor where temperature can be around 300 degrees centigrade. So in the first zone temperature is around 100 degree centigrade here if that location where temperature will be around 300 degree centigrade here coal pyrolysis or de-volatilization will occur that means whatever the volatile materials are present in this coal that will start releasing from the coal surface once this volatile material is released from the coal we can have volatile material can have all these compounds like different type of hydrocarbon, nitrogen gas, methane gas, tar, other particles, H2S, NH3 all they may be released at this zone because they are all the constituents of the volatile material typically coal volatile material contains different type of low molecular hydrocarbon. So, whatever the hydrocarbons are there they can be either tar toluene, benzene or ammonia or H2S or other type of gases whatever is released during this pyrolysis stage or during this volatilization stage, those gases will be released at this particular location. So, this zone will have all these gases. Further it will enter here as its coarse particle move downwards at this zone 3, In this case it will be having the reduction zone why this reduction zone here because oxygen is entering or air is entering at this stage, so entire this oxygen will react at this zone 4. So, whatever the oxygen is there that will react with the coal particle or coke particle or tar particle present at this zone. So, it will react with this feedstock here and it will reach very high temperature 1300 to 1400 degree centigrade. So, at this temperature all will produce carbon dioxide, carbon monoxide as well as water molecule may split to H2. H2O and steam. So, they will produce all the oxidation reaction will happen at this stage because the air is separate from the bottom. So, at this location oxygen concentration is high.

So, whatever the hydrocarbons are there either hydrocarbon gases or the coal or char particle they will go for the oxidation reaction at this location. zone and all the oxygen will be consumed here. So, when these gases reach to this zone at this particular zone there is no oxygen is available. So, it will go for the different type of reduction reaction where carbon monoxide carbon dioxide and others will react individually there with their coal particle. So, at this zone it will have the shortage of oxygen it will be the reduction zone. So, all the reduction reaction will happen in this zone and as a result temperature of this zone will be little bit less like 900 degree or 800 degrees centigrade or similar temperature. Whereas in the oxidation zone depending on the gas composition as well as the input air temperature it will have the high temperature zone will be there and further air it will go as it is releasing entire heat at this zone 3. after it release the entire at zone 3 it will go there. So here it will have the low temperature air will be there, that's why here pyrolysis of the coal particle occur and here it will have the only moisture will be there. So the air whatever is going out from this reactor at this particular location if we see this air will constitute the moisture content present in coal because that will be at the last stage from the coal moisture is getting released, so some amount of moisture will be there in this coal as well as some of the volatile material will also be there because some of the volatile material may not get adequate temperature as here temperature is 300 degree centigrade if their reaction takes at higher temperature those volatile material will not getting reacted here. So, they will be part of this product at here. So, in such case this product gas will have the gasified product like CO, CO2, H2 as well as the components of volatile material of the coal as well as the moisture content present in coal. So, all these material in the gas phase will be part of the product gases from this reactor and here at this particular zone if we see at the bottom of the reactor as the temperature is excessively high, nearby 1400-1300 degree centigrade, so as releasing or as going up the reactor, it will also have the similar temperature of 1400 degree centigrade.

So, depending on this temperature, ash may be in the fused, it may be in the liquid phase or it may be in solid phase, but it will take significant amount of heat from this reactor itself. So, depending on the exact temperature of the reactor as well as the ash fusion temperature of the ash, this ash may be in the liquid phase or may be in the solid powder stage. If we see the other picture, when we go for the downdraft reactor, like if we charge both the coal particle as well as the air particle here, initially they will go for drying here. Because at this temperature zone, coal will be releasing moisture so it will have the moisture will be there. So whatever moisture are there that means they will be converted to steam and they will enter the pyrolysis zone where the temperature is around 300 degrees centigrade.

So, during this pyrolysis zone volatile material will also be getting released. from the coal surface. So entire volatile material as well as the moisture it will go to the zone 3 where it will go for oxidation. So, in this oxidation zone all the volatile material or its components as well as steam and oxygen because oxygen is also available from the top. So, they will react and they will create the oxidation zone at this location. So as a result in this zone temperature will be also on the higher side may be 1400 degree centigrade and further this coal particle will go there and gases will go there but at this zone particularly entire oxygen will be consumed there is no amount of oxygen is there, So it will go for the reduction reaction accordingly the reduction zone it will have carbon monoxide, hydrogen, steam, carbon dioxide, methane, ethane, some amount of tar if it has not been burned may be there or if it has been released from the reduction zone. It may be there some fly ash particle will be there H2S, ammonia will also be there and in this zone temperature of ash will be obviously on the lower side. It will not be exactly like molten here but here it may not melt because it is coming to the reduction zone temperature will be on the lower side. So, depending on the type of reactor, reactor design, where we are feeding the oxygen, we are feeding the coal, how they are interacting the flue gas composition at this particular zone and in this particular zone it will be different. So, in some cases concentration of carbon monoxide will be on higher, in some cases concentration of hydrogen will be on higher side, in some cases the presence of tar and other organic impurities may be higher and in some cases presence of tar and other computers may be on the lower side and this is the typical reactor design if we see from the top side we charge the coal. So, in this zone is typically called the drying zone further this zone is called the pyrolysis zone. Then it will be the combustion zone reduction zone and in this case also Here also we can charge it like in different way also. So, there are different types of reactors is there. So, product gas composition, temperature, energy efficiency that will vary depending on the feedstock as well as the reactor design.

Now if we see in details about the down draft reaction like in the case of B that coal is charged from here air is charged from here the it is obviously called a co-current reaction that air as well as the that means gasified medium gasifying medium air steam as well as the coal is going in a same direction the gasification agent enter gasifier at the certain heights below the top. So that it can exactly from top or it can enter from Some nearby top locations also and it mixed with the pyrolysis gas product which flow downwards in a partial parallel with the solids. And that can have solids, it can have char, it can have ash or it can have unburned coal also. through the oxidation and gasifying zone.

The drying and pyrolysis zone lies above the oxidation zone and they are maintained at the required temperature by condition of the heat generated from the combustion of pyrolysis vapor including the tar is also will be as part of this zone which is entering at this particular location.

And these gases leaving the oxidation zone they mainly constitute of CO_2 and H_2O. After this oxidation zone in there it will that means at this particular zone entire char it will be converted to carbon dioxide because concentration of oxygen is extremely high. So, it will mostly constitute carbon dioxide steam. It may have some amount of hydrogen and other and there will be less amount of carbon monoxide and further this oxidation zone whenever enter to this reduction zone where oxygen will not be there then this carbon dioxide will be converted to carbon monoxide that will happen in this particular zone.

This gas temperature decreases due to occurrence of endothermic gasification reaction to a up to a level at which no further reaction takes place. So, at this zone temperature will be extremely high, but further at this zone when it doesn't enter the reduction zone as temperature is falling. So, some of the reduction reaction will takes place and some reduction reaction may not take place depending on the temperature because all the reduction reaction are Many of them are in the endothermic nature, they will absorb heat. So, temperature in the reduction zone will be on the lower side.

And if we see the updraft gasifier, in case of updraft gasifier, it is one of the oldest and the simplest design people use. Updraft gasifier, they can further be classified at different design like fixed bed gasifier, fluidized bed gasifier, circulating fluidized bed gasifier. They are all the different types of updraft gasifier are there. Here the gasifying medium like air, oxygen, steam they travel upward while the weight of the fuel they move downwards. Thus, there will be some counter current mode is there.

The product gas leaves from the top or nearby the top at this position or at this position. location it will near by the top as well as the air enters at this point. So, in this case updraft gasifier gaseous medium enters the bed to a grid or the distributor where it meets with the hot bed of ash. So, in such case in the from the bottom side it will enter after contacting with the hot ash. So, some amount of heat available in the hot ash it will collect and this air get preheated from the ash. So as a result, it will recover some amount of heat from the hot ash. As a result, the temperature of the released ash will be on the lower side and energy efficiency of that particular plant will be on the higher side. This ash drops to the grate which is often made moving by rotating or reciprocating any type of suitable mechanical arrangement especially in the large unit to facilitate the ash discharge. Feedstock material is first introduced in the drying zone at the top and followed by the pyrolysis zone and the reduction zone and finally the unconverted solid passes through the combustion zone as we have seen in the previous plots. In the combustion zone, solid charcoal combusts producing heat and which effectively transfer to the solid particles. during counter current flow rising gas and descending solids and in the gasification system contamination of substantial amount of tar is the major problem in updraft gasifier as we have seen in these reactions also like from this zone air is enter here. So, at this air it directly gets contact with the ash and it enters in the combustion zone. So, in the combustion zone all the tar and other material will get converted but whatever the material released at this zone because coal is charging from the top, so in such case whatever is VM is released at this stage or at this stage here also. So those components will not get adequate temperature for further reaction to convert into the carbon monoxide or other hydrogen gases, hydrocarbon rich gases. So as a result, tar and similar complex materials which are present in coal as part of volatile material, they may not get the desirable temperature for conversion. So as a result, these gases will always have some amount of contamination with the tars and others. And this is the temperature distribution we can see. In this steam and air enter here, it passes through this ash, collects some amount of temperature.

This is the oxidation zone where the temperature is extremely high. Further, the reduction zone can be divided into the primary reduction zone, secondary reduction zone, and then the pyrolysis zone, sometimes called the distillation zone because the solid-state distillation of coal occurs here. It releases volatile material. These are the different types of reactions if we divide them stage-wise. Here, the air enters, and this is the ash zone. In this oxidation zone, all the carbon dioxide reacts to produce carbon monoxide, and other reactions occur. This also happens in the primary reaction zone. In the secondary reaction zone, these reactions have already occurred, and heat flows in this reaction. As a result, you will get producer gas here, which will contain some volatile material from the flue gas. Additionally, there is another design called the cross-draft reactor. In this reactor, air enters from this side, and the gas exits from the other side, while coal, biomass, or other feedstock enter from this side. The entire reaction occurs particularly in this zone-wise manner. Whenever coal or other feedstock enters here, it first enters the drying zone and comes into contact with the air.

The entire coal will dry here and then proceed to the pyrolysis zone, where the temperature is maintained. The temperature will be somewhat high here, and then it will move to the combustion zone, where the temperature will be even higher. Finally, it will enter the reduction zone, and the gases will exit. These designs depend on the type of feedstock to be gasified. In the case of a cross-draft gasifier, they are mostly used for feedstock with high carbon content. If the carbon content is significantly higher—meaning the feedstock contains more carbon and less hydrogen or mineral matter—this design works very well. Charcoal classification results in very high temperatures, around 1500 degrees Celsius or higher, in the oxidation zone. This can cause material problems if the oxidation zone is kept nearby. With high carbon content, it can lead to extremely high temperatures, damaging the sidewalls and other reactor components. Controlling the temperature is very difficult, which is why in this zone, the entire the oxidation zone is kept inside it, and by this heat present in the oxidation zone, it can easily facilitate the pyrolysis of the feedstock. So, if the carbon content or carbon percentage of the feedstock is significantly higher, for such cases, pyrolysis happens only at higher temperatures, not at lower temperatures. So, it requires high temperatures for pyrolysis as well. So, we have to create high temperatures in this oxidation zone on this side. So that this heat can further radiate and transfer to the nearby coal particles or carbon-rich feedstock.

So that they can be heated to higher temperatures, undergo pyrolysis, and react here. In the cross-draft gasifier, thermal insulation against high temperatures is provided by the fuel itself. So, the major purpose of this cross-draft gasifier is to heat the feedstock to significantly higher temperatures because their activation energy for reaction is significantly higher. All this carbon-rich feedstock will not react easily with oxygen or steam.

So, they must be heated to high temperatures. As a result, in this reactor, the fuel or feedstock is used as the insulating material along the entire side of these reactors, so they will get heated and protect the nearby refractory walls of the reactors from exposure to high temperatures. While the high temperature will be absorbed by the coal particles. And that will enter the oxidation zone and the reduction zone.

The advantage of the system is that it can operate on a very small scale and can be operated easily. A disadvantage of the cross-draft gasifier is its minimal tar conversion because its length is very short, and the temperature of this reactor just outside the main combustion zone is very low. So, there can always be a problem with tar formation because they cannot convert this tar into gasifying products. Consequently, it also needs high-quality charcoal, which will have a very low quantity of hydrogen. So, overall, if we compare, there are three different designs available: the downdraft gasifier, the updraft gasifier, which moves in this direction or that direction, as well as the cross-draft. So, different designs exist, and there can be different reaction zones depending on the reactor design. So, overall, if we see, gasification can be done through either a downdraft gasifier, an updraft gasifier, or a cross-draft gasifier, depending on the type of feedstock you want to gasify. If it is normal coal or high-volatile coal, we can use the downdraft or updraft gasifier. High-carbon-containing materials like anthracite coal or any petroleum refinery-based feedstock must be processed through the cross-draft gasifier. Similarly, if some amount of biomass is present, we have to ensure that this biomass material gets adequate time for reaction.

Accordingly, we change the draft of this reactor so that it can also be co-gasified along with the coal. So, it entirely depends on the feedstock, whether we are using pure coal, a coal-biomass mixture, or any other feedstock. So, the sequence of reactions is different in different regions, as the concentration of oxygen varies depending on the draft or location where we introduce the oxygen. So, the reaction can be the sequence of reactions can be different, and hence the design may be modified as per requirement. So, depending on the feedstock characteristics, what product we want in the syngas—whether we need a high hydrogen-rich product, a high carbon-rich product, or a high carbon monoxide-rich product—we can accordingly modify the reactor either as a downdraft, updraft, or cross-draft gasifier. The chemical composition and yield of gas can vary based on the reactor design, and the product gas may contain impurities or undesirable gases depending on the reactor design. If these undesirable gases pass into the combustion zone or are released at the last moment, the product gas may contain different types of impurities, such as H2S, ammonia, or other similar gases released from coal as well as biomass. Whether these gases pass through the reduction zone or not determines if they can be converted into other products or if they lack the opportunity or suitable temperature to react with the gas medium and convert. Accordingly, the product gas may have a different composition, and we certainly need to clean these gases. It is compulsory to remove all tar and other undesirable gases. The temperature profile of the reactor will also vary: in some reactors, the highest temperature is at the bottom, while in others, it is in the middle or central part of the reactor. So, if the reactor's temperature at the endpoint is extremely high, there is a probability of heat loss through sensible heat or latent heat from the bottom ash, as well as heat loss from the exit.

So, from syngas, we may also have to recover waste heat to maintain overall energy efficiency or thermal efficiency. So, the exit gas temperature and exit ash temperature will also depend on the reactor design we are using, and accordingly, further units must be placed for either heat recovery or removal of fly ash particles, unburned carbon particles, or impurities like ammonia, tar, H2S, HCN, or other gases, etc.

Thank you.