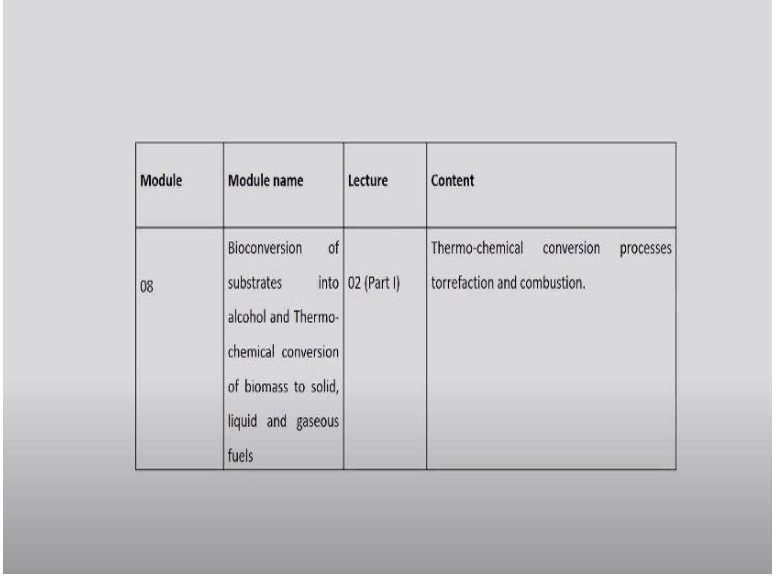
Renewable Energy Engineering: Solar, Wind and Biomass Energy Systems
Prof. Vaibhav V. Goud and Dr. R. Anandalakshmi
Department of Chemical Engineering
Indian Institute of Technology - Guwahati

Lecture - 27
Thermo-Chemical Conversion of Biomass to Solid, Liquid and Gaseous Fuels

Good morning everyone, welcome to Part 1 of lecture 2 under module 8. So, in this lecture, we will discuss about the thermo-chemical conversion processes, like torrefaction and combustion.

(Refer Slide Time: 00:36)



Module	Module name	Lecture	Content
08	Bioconversion of substrates into alcohol and Thermo-chemical conversion of biomass to solid, liquid and gaseous fuels	02 (Part I)	Thermo-chemical conversion processes torrefaction and combustion.

So, if you recall our discussion in the previous lecture, we initiated our discussion about the thermo-chemical conversion techniques. So, then we will discuss about the basics of these particular techniques, whereas, in this particular lecture, we will discuss about these individual techniques in detail. So, first let us see about the torrefaction.

(Refer Slide Time: 01:00)

Torrefaction:

Torrefaction is a thermochemical process carried out in an inert or limited oxygen environment. In this process biomass is slowly heated to within a specified temperature range and retained there for a stipulated time such that it results in near complete degradation of its hemicellulose content while maximizing mass and energy yield of the solid product.

- Typical temperature range for this process is between 200 °C and 300 °C.
- Temperature above this would result in extensive devolatilization and carbonization of the polymers both of which are undesirable for torrefaction.
- Also, the loss of lignin in biomass is very high above 300 °C. This loss could make it difficult to form pellets from torrefied products.
- Moreover, fast thermal cracking of cellulose causing tar formation starts at temperature 300 – 320 °C.
- Thus, upper limit of torrefaction temperature fixed as 300 °C.

So, torrefaction is a thermo-chemical conversion process carried out in inert or limited oxygen environment. So, in this process, biomass is slowly heated to within a specified temperature range. So, here the temperature ranges specified and it retained there for a stipulated time period. So that it results in near complete degradation of the hemicellulose fraction presenting the biomass sample.

And while it maximises the mass and energy yield of the solid product. So, this is how the torrefaction processes convert the biomass into a solid product. So, in this particular process, the temperature range is between 200 to 300 degree C. So, there is a very narrow temperature ranges there for the torrefaction process, because in this particular case, if the temperature it goes above this specified limit, then what happens is like, it results in the extensive devolatilization and carbonization of the polymers.

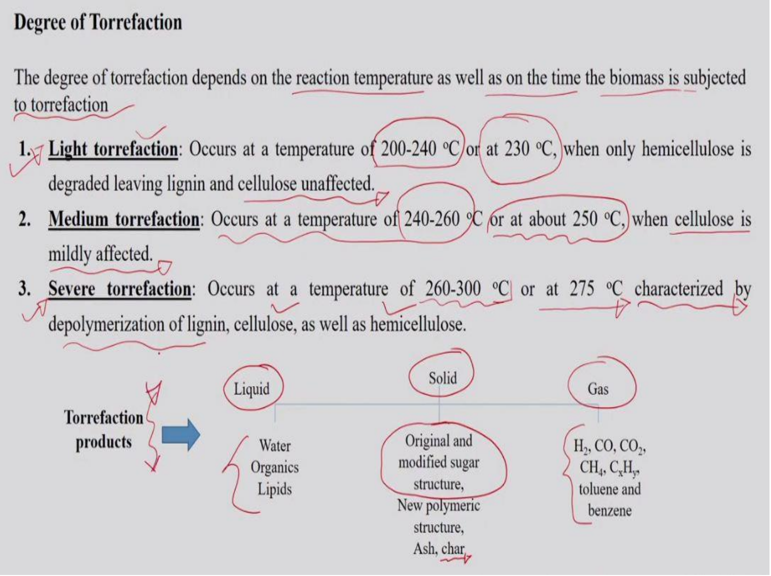
And both these particular steps are undesirable for the solid product formed during the torrefaction process. Moreover, the loss of lignin in biomass is also very high if the temperature it goes beyond 300 degrees C. And if the loss of lignin is relatively high, then it makes it difficult to form the pellet from the product produced by this torrefaction process. Why it is so? Because the lignin in the biomass itself is act as a binder and then it binds the solid particles to form a solid pellets on the lignin.

In case, if the lignin is volatilized or maybe the lignin is not present in the torrefied product, then the formation of such a strong or the solid pellets is difficult. Moreover, if you see, the fast thermal cracking of the cellulose fracture, it forms the tar and as a result, this tar formation, it started in the temperature range of 300 to 320 degrees C, there are also very small or narrow ranges there for the cellulose degradation.

And if this particular temperature it shoots up relatively to a higher range, then what happens is like, there was degradation of the cellulose tars and then it started the tar formation and that is the reason the upper limit of torrefaction temperature it is fixed as 300 degrees C. And hence, that is the reason that the torrefaction process also has a very small and narrow temperature range.

The torrefaction is an important stage in the whole process as the bulk of depolymerization happens in this particular process and that is why it is called as a important stage. Moreover, depolymerization of the biomass, it also takes place in a specific temperature range and also required a specific time period to allow these depolymerization to occur, that is the reason the degree of torrefaction is very important, so, that it can be carried out in a specific temperature range and the material is allowed to retain or a specific time period in torrefaction process.

(Refer Time Slide: 04:19)



So, now, let us try to understand what is this degree of torrefaction is. The degree of torrefaction here if you see, it depends on the reaction temperature as well as on the time when the biomass is subjected to the torrefaction process. And it is shown here in the 3 different ways. For example, the light torrefaction process, so, it occurs in the temperature range of 200 to only 240 degree C.

So, to be precise here, it carries out in the temperature range of around 230 degrees C when only hemicellulose fraction of the biomass is getting affected, whereas the lignin and cellulose component remains unaffected during this particular process. That is why it is called as a light torrefaction process. And that is also called as a light degree of torrefaction.

Whereas, if you see the medium degree of torrefaction process here, so, in this case, this process occurs in the temperature range of 240 to 260 degrees C and exactly if you say it is about 250 degree C. So, in this process cellulose is mildly get affected and that is why it is called as a mild torrefaction process or mild degree of torrefaction. Last is the severe torrefaction process.

In this case, the temperature is between 260 to 300 degrees C or if you say the specific value it is 275 degrees C is a specific temperature which is maintained during the severe torrefaction process. So, it characterised by if you see, in this case, depolymerization of the lignin, cellulose as well as the hemicellulose fraction of the biomass compound. And that is the reason as I said, the narrow temperature range of the torrefaction is very crucial to get the efficient quality of the solid product.

Now, if you see the torrefaction product in this case, it gives the product in the form of solid, liquid and gas fraction. So, in the case of liquid if you see, it is mainly a water organic repeats and if you talk about the solid proton obtained during this process, it is mostly a original and the modified sugar structure and new polymeric structure along with the ash and char.

Whereas, the gases produced during these processes if you see, it is the composition of these gases along with this also it forms a toleune in the benzene. This is how the torrefaction production of solid takes place in this case, the process is more toward the formation of the solid product. So, now, once you understand this degree of torrefaction process, now, let us try to compare the torrefaction process with the carbonization because the torrefaction as well as the carbonization process is more or less similar.

But, there is an important difference between these 2 processes. Similarly, if you just try to compare these 2 processes with the pyrolysis process as well, so, you can easily differentiate between the torrefaction process, carbonization and the pyrolysis process. So, let us see the important difference between these 3 processes.

(Refer Time Slide: 07:23)

Difference between carbonization, pyrolysis, and torrefaction

The most important difference between pyrolysis, carbonization, and torrefaction lies in their product motivation

Torrefaction	Carbonization	Pyrolysis
Maximize energy and mass yields with reduction in (O/C) and (H/C) ratios	Maximize FC and minimize HC content of the solid product	Maximize its liquid production
Torrefaction retains most of it, driving away only the early volatilized low energy dense compounds and chemically bound moistures	Carbonization drives away most of the volatiles	Complete devolatilization
Torrefaction require relatively slow rates of heating	Carbonization require relatively slow rates of heating	It relies on fast pace of heating to maximize the liquid yield
It tries to avoid oxygen as well as combustion	Carbonization takes place at higher temperatures with a certain level of oxygen	Pyrolysis takes place at higher temperature and utilizes partial oxygen to provide the thermal energy needed for this process
The process has very narrow temperature range i.e. 200 – 300 °C	High temperature (> 300 – 600 °C) destructive distillation process	Thermally decomposes sample by heating above 300-400 °C

Carbonization produces more energy dense fuel than torrefaction, but it has a much lower energy yield

If you look at the torrefaction process here, it maximises the energy and mass yields with reduction in the O/C and the H/C ratios. So, what is the O/C? Its nothing but the oxygen to carbon ratio and H/C is the hydrogen to carbon ratio. Whereas in case of carbonization process, it maximises the fixed carbon content and it minimises the hydrocarbon content of the solid product.

While pyrolysis process, it maximises its liquid production and that is what is the pyrolysis process is known for, it maximises the liquid production to produce the bio-oil. Now, another important difference between the torrefaction and the carbonization process is, it retains most of the volatile and driving away only early volatilized low energy dense compounds and chemically bound moisture. Whereas, in case of the carbonization process, it drives away most of the volatiles which are present in the biomass.

Whereas, in case of pyrolysis, it is a complete devolatilization process. So, this is how is the major difference between the torrefaction, carbonization and pyrolysis process. If you look at another difference here, it is in the form of the torrefaction process, it requires relatively slow heating rate. And that is so, with the carbonization process also, it requires slow heating rate to get the solid product.

Whereas, in case of the pyrolysis process, the fast pace heating of the material is required to achieve the maximum liquid yield and that is what is mentioned here, that it requires fast pace heating of the sample, so that it can maximise the liquid yield in terms of the product.

Moreover, in this particular process, it tries to avoid the oxygen as well as the combustion during the process.

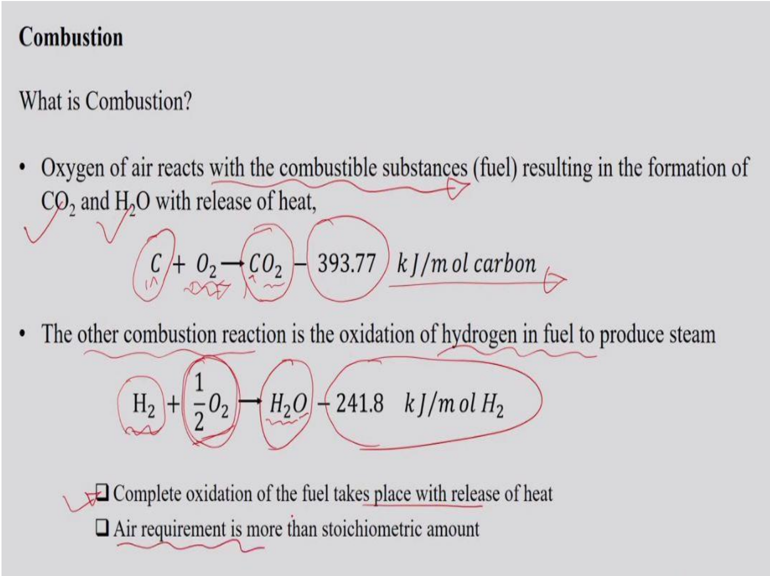
Whereas carbonization, it takes place at a higher temperature and with certain level of the oxygen. Whereas in case of pyrolysis, it takes place at higher temperature and utilises the partial oxygen, so that it can supply the energy which is required for the process. So, this is the important difference again between these 3 processes. Moreover, the temperature range which is mentioned for the torrefaction processes, it will narrow that is in between 200 to 300 degrees C.

Whereas the carbonization process is carried out above a temperature of 300 degrees C and it goes up to even 600 degree C. Similarly, the pyrolysis process, it decomposes the material and the heating is about 300 to 400 degrees C, it also goes up to 600 degrees C as well. So, this is how the important difference between the torrefaction, carbonization and the pyrolysis process.

And one important difference between the torrefaction and the carbonization process is, the carbonization process, it produces more energy dense fuel than the product produced by the torrefaction process, but it has much lower energy yield. And that is what is the important difference between the carbonization and torrefaction. So, now, let us discuss about another thermo-chemical conversion technique that is combustion.

So, thermo-chemical conversion process which is widely used at a commercial scale to produce the energy from the biomass is nothing but the combustion process and this is one of the most widely used commercial process, where it utilizes the biomass to produce the energy. And in this particular process, the oxygen reacts with the combustible substances.

(Refer Slide Time: 10:54)



And it results in the formation of 2 stable product in the form of C O 2 and H 2 O along with it also produces the heat. If you see here the reaction which is shown here on the slide, this particular C, it represents the carbon content in the combustible solid fuel or maybe the liquid fuel, it undergoes the combustion in presence of oxygen and it produces the compound which is called as a oxidised compound C O 2.

And it releases significant amount of the energy, this is kilojoules per mole of the carbon. So, when one mole of the carbon is burned in adequate air or the oxygen supply, then it produces around 393 kilojoules amount of energy along with the C O 2 and H 2 O as a product. So, when we see this particular reaction, this is called as stoichiometrically balanced reaction, because here if you see the one mole of C is reacting with the one mole of oxygen.

And then it is producing one mole of the C O 2, the carbon in the product is also getting balanced in the carbon reactor and the oxygen here in the product is also getting balanced with the oxidising agent which we have supplied for the oxidation purpose. So, this is called as a stoichiometrically balanced equation and it is balanced on the basis of mole balance of the component.

Now, the other combustion reaction, which happens in the combustion process, because of the oxidation of the hydrogen in the fuel to produce the steam. So, if you again see this reaction, this is the hydrogen. It undergoes the combustion to produce water as a product that is H 2 O in the form of steam, here H 2 O is in the form of gas and then it produce around this much amount of the energy per mole of the hydrogen combusted in the combustion chamber.

So, this is also mole balance reaction, which is we can see a stoichiometrically balanced equation. Because here, if you see the one mole of hydrogen, which is reacting again with the 0.5 moles of the oxygen, it produces around H_2O, that is again the same. So, one mole of oxygen is coming out from the product and here also the same and it releases significant amount of the energy.

So, now, this combustion reaction, you know, need to be balanced stoichiometrically to understand that whether the reaction is happening in the proper air to fuel ratio or not. So, what is meaning of the air fuel ratio that we will discuss in the subsequent slides. So, for the complete combustion of the fuel, it takes place with a significant amount of release of the energy.

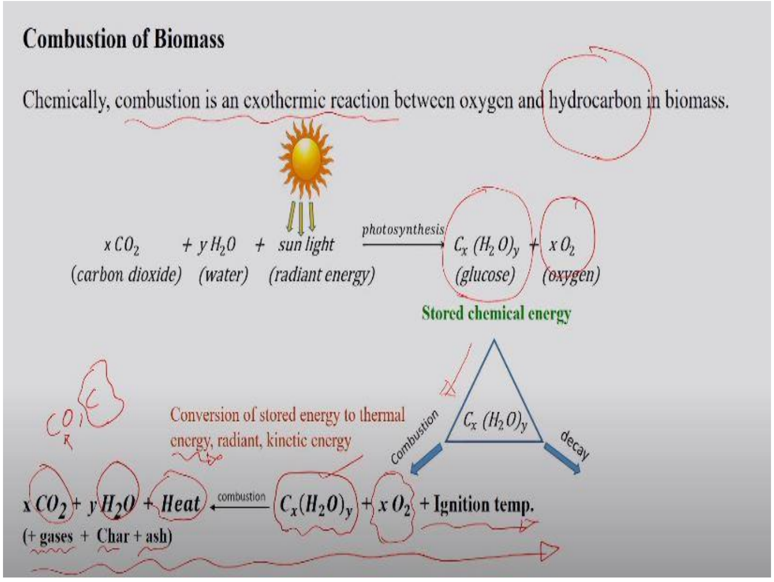
Apart from that the air requirement is more than the stoichiometric requirement for the oxidation reaction. And that is what I mentioned in the cases like all these equations or the reactions are balanced stoichiometrically to understand that the complete combustion of the solid fuel or the liquid fuel is taking place in the combustion unit, that is why it is producing the oxidised product in the form of CO_2 and H_2O.

But in practice, it may not be so, because in practice, the oxygen required may be excess of the stoichiometric requirement and that is a reason the particular stoichiometric equation need to be balanced for the actual combustion process as well, just to find out what is the amount of oxygen or the oxidation medium is required to allow the complete combustion to take place in the combustion chamber.

Let us discuss about the combustion of the biomass. So, before we discuss about the combustion of biomass, let us spend some time to understand that how this carbohydrate formation is taking place in the biomass or you can see in the land material. This particular part, we already discussed in one of the lecture. So, I am just repeating here once again, just to make you aware that once biomass is formed in the form of the carbohydrate molecules.

These particular carbohydrate molecules, it undergoes the combustion process and as a result, it forms the stable oxidised compound.

(Refer Slide Time: 14:49)



Chemically, the combustion is an exothermic reaction between the oxygen and hydrocarbon in biomass. So, how this hydrocarbon formation takes place in the biomass? Because during the growth of the plant, it absorbs the C O 2 from the environment and water also, along with that the radiant energy which is supplied in the form of solar radiation, it also takes part into the photosynthesis process.

Whereas, the chlorophyll also present in the photosynthesis process by which it converts into a carbohydrate molecule, which we represented here in the form of the glucose and along with that it also produces the oxygen molecule and the carbohydrate molecules which formed during this photosynthesis process, it stores the chemical energy in the form of the chemical bond in this carbohydrate molecule.

And the chemical energy which is stored in these carbohydrate molecules, it can be released by the combustion process. So, once these carbohydrate molecules undergo the thermo-chemical conversion process by the combustion mechanism, it release significant amount of the energy along with the radiant and the kinetic energy.

So, if you see here one simple example of the reaction scheme, this represents the carbohydrate molecule obtained from the biomass and this is the oxidising medium, which is here shown as a oxygen and with some ignition temperature, the combustion of the carbohydrate molecule takes place and it produce around x moles of C O 2, y moles of H 2 O and a significant amount of the heat.

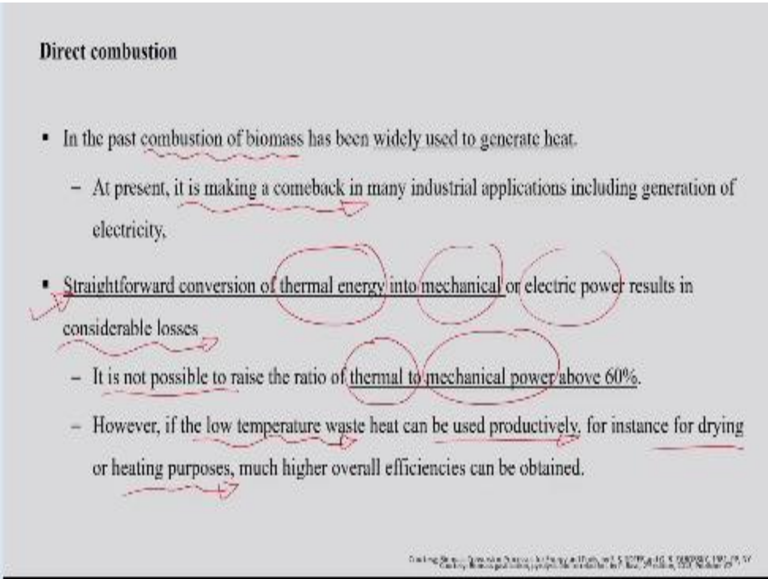
Apart from that it also produces some other gases, char and ash. And that is what I said earlier, if the combustion process is not a complete combustion, so, in that case, it may produce even CO and C as the product along with the C O 2 and H 2 O because the CO which is formed here, it is a product of the incomplete combustion. So, this CO it may react again with the oxygen to form the C O 2 and this char, it may further undergo the oxidation process to form the C O 2.

So, likewise, these particular kinds of products may form in practice, whereas, in theoretical we always considered it as the ideal condition and we considered that the entire fuel presenting the combustion chamber is getting oxidised forming C O 2 and H 2 O as a product along with that it also releases significant amount of the energy, but in practice it may not be.

So, because there may be some uncombusted carbon present in the product along with that it may also release certain amount of the CO, which is a partly combustion mixture of the gas. So, this CO as I said, it can further undergo the oxidation reaction to form the C O 2. So, likewise, the combustion reaction need to be balanced based on the oxidising medium used for the oxidation purpose in the combustion unit.

So, once you understand this concept of the combustion of the biomass, now, let us try to see how this direct combustion of the biomass is taking place.

(Refer Slide Time: 17:45)

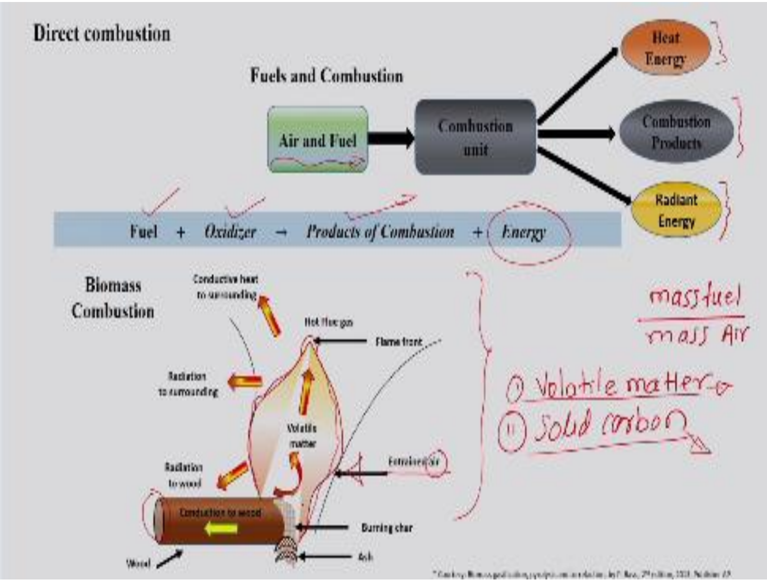


For example, in the past, the combustion of the biomass has been widely used to generate the heat and this is the regular practice in the past to generate the heat by combusting the biomass and this combustion process now is making a comeback in the many manufacturing industries to produce the electricity by combusting the biomass as a fuel.

And the straightforward combustion of thermal energy into the mechanical energy or the electrical energy results in the considerable losses during this particular process, because, it is not possible to raise the ratio of thermal to mechanical power above 60%. But, if the low temperature waste heat produced during this particular process can be used effectively for the drying and heating purposes.

So, much higher overall efficiency can also be obtained. So, for that reason, the heat produced during this particular process needs to be effectively utilised for the drying and the heating purposes. So, that the overall high efficiency of the process can be obtained. So, this is the direct combustion of the biomass. Now, if you see the direct combustion process here, the fuel and air mixture is burned in the combustion unit to produce significant amount of the heat energy.

(Refer Slide Time: 19:07)



Along with that it also produces the combustion product and radiant energy. So, air fuel ratio mixture is nothing but mass of fuel to mass of air ratio. So, this mixture of fuel and the air it oxidised or burned in the combustion chamber to produce heat energy, combustion product in the radiant energy. The simple equation which is represented here is, fuel in presence of the oxidising medium either oxygen which is a pure oxygen and the air.

It gives combustion product along with the energy and they are also represented in the previous slide as well that combustion of carbon in presence of the oxygen it gives C O 2 as a completely oxidised product along with the significant amount of the energy. Now, if you remember our discussion in one of the lecture regarding the combustibles of the solid carbon, so, the combustibles of the solid carbons are shared into 2 groups that is volatile matter and the combustible solid carbon present in the fuel.

Whereas, in this case the share of the volatile matter present in the wood is typically high. Whereas, the share of the solid combustible metal presenting in the wood is relatively low. So, 80% of the energy of the wood generally originates from the combustion of the volatile matter or burning of the volatile matter. Whereas, 20% of the energy it originates from the combustion of the burning of the solid carbon fuel present in the wood sample.

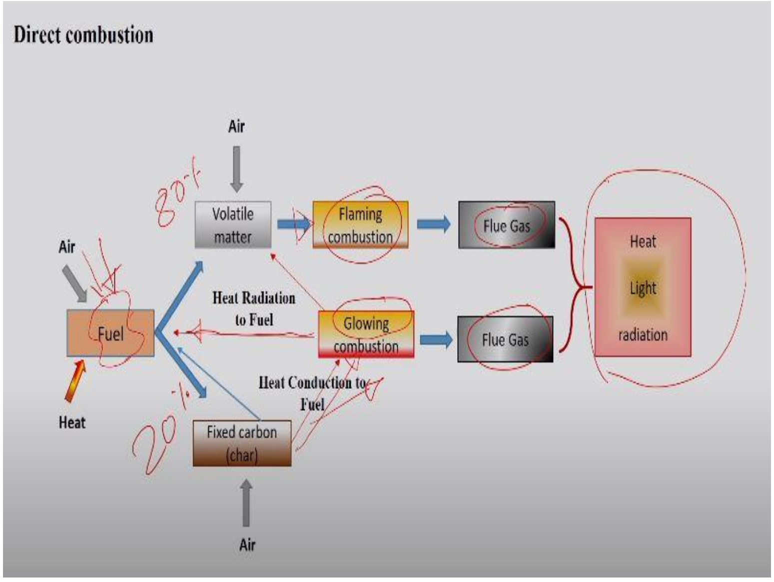
And this is what the difference between the combustion of the volatile matter and the combustion of the solid carbon present in the fuel. So, if you just try to understand this concept in more elaborate way, let us see the example of the burning of the word sample here. So, it is burned in presence of the oxidising medium that is here.

So, during combustion as I mentioned, the volatile component in the solid fuel, it burns rapidly in presence of the oxidising medium and these volatile components are nothing but the aromatic hydrocarbon long and the short chain hydrocarbon compound in the solid fuel. So, once this combustion takes place, first this volatile matter rapidly takes part in the combustion process in presence of the oxidising medium and then it forms this kind of the flaming behaviour in the combustion unit.

And because of this, it also transferred the radiant energy to the wood along with that it also transferred the radiant energy to the surrounding and some forms of the conductive heat transfer also takes place in the surrounding medium here. Whereas, the solid carbon which is present in the wood, it takes part in the glowing combustion process, whereas, the volatile matter present in the solid represents the flaming combustion behaviour.

So, let us try to understand these 2 concepts in more detail we are using this particular schematic.

(Refer Slide Time: 22:21)

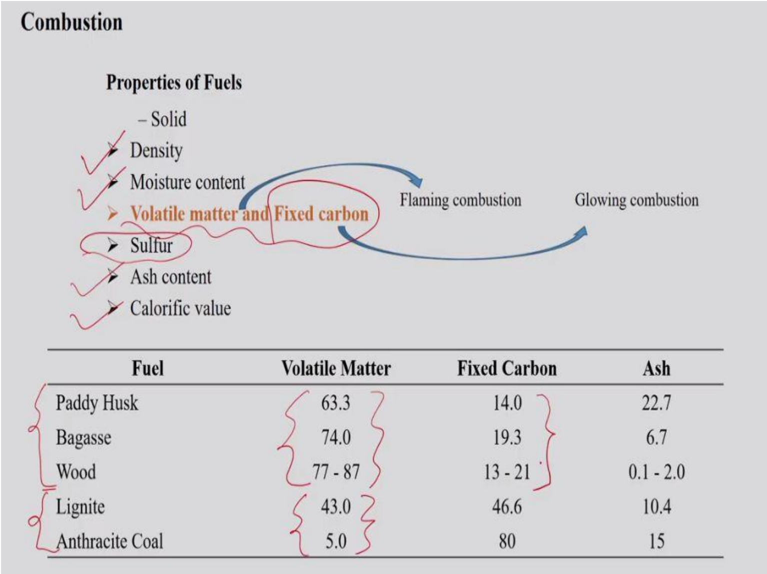


So, if you see here the fuel, which is again the solid fuel, which is ignited in presence of the oxidising medium here. So, the solid fuel as I mentioned, it mainly consists of 80% of the volatile matter and 20% of the solid carbon present in the wood sample, then it undergoes the combustion process as a result, the volatile matter it burn by the flaming combustion behaviour.

Whereas, the fixed carbon present in the Wood, it burns with the glowing combustion behaviour and at the end it produces the flue gas as the product. While during this combustion, the radiant energy produced, it will get transfer some of the energy to the fuel wood. Whereas, some of the energy will get transferred to the surrounding, along with that some heat conduction will also happen to fuel, if it is a solid fuel.

As we have discussed the solid fuel example here, so, some heat conduction also happens to the fuel and then the product output is in the form of the heat, light and the radiation energy. So, this is how the combustion of the wood takes place in the combustion unit.

(Refer Slide Time: 23:35)



Fuel	Volatile Matter	Fixed Carbon	Ash
Paddy Husk	63.3	14.0	22.7
Bagasse	74.0	19.3	6.7
Wood	77 - 87	13 - 21	0.1 - 2.0
Lignite	43.0	46.6	10.4
Anthracite Coal	5.0	80	15

So, now, once you understand this particular combination of the wood sample, now, let us try to understand that how the properties of the combustion of the fuel is important. Why? Because if you are considering the combustion fuel as a solid, then the properties in the form of density, moisture content, volatile matter and the fixed carbon content is also important in this case apart from that the sulfur content.

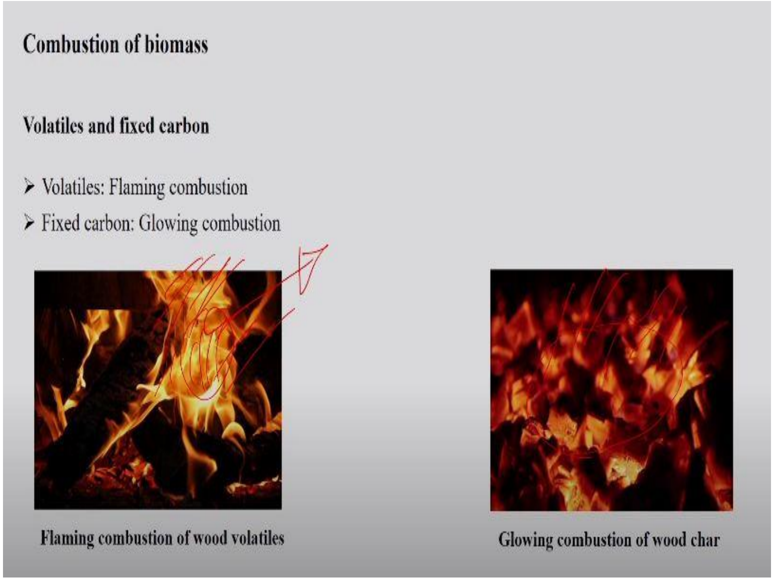
But most of the biomass does not have the sulfur but there are some few specific biomasses samples are there, where it can find certain trace of the sulfur component as well along with that it also depends on the ash and the calorific value of the biomass. Why it is so? Because, if you look at this particular table here, it represents the fuel in the form of wood sample and then the fossil fuels.

Now, if you just look at the biomass samples, the volatile matter contained in the biomass sample is significantly high. That is in the range of say, for example, here you can see the range here. Whereas, the volatile matter contained in the lignite and the anthracite coal if you see, it is relatively low compared to that of the biomass. While the fixed carbon contained if you try to see in this table, it is relatively less in the wood sample that is a biomass simple while the fixed carbon content in the coal is significantly high.

And that is the reason, if the coal contains significantly higher amount of the volatile matter then it is beneficial for the ignition and the combustion process. Why? Because of the presence of high volatile matter in the combustion process and in the coal simple, it relatively takes part in the combustion process and as a result, it will form the complete oxidised product of the carbon and even it will release significantly lower level of NOx during the combustion process.

And that is what the importance of the volatile matter in the solid fuel during the combustion process, because, as I mentioned, the volatile matter within the solid, it contributes to the flaming combustion. Whereas, the fixed carbon contained in the solid fuel, it contributes to the glowing combustion process. Once you understand this combustion of the solid fuel, the flaming combustion and the glowing combustion is represented with the small pictures here.

(Refer Slide Time: 25:49)

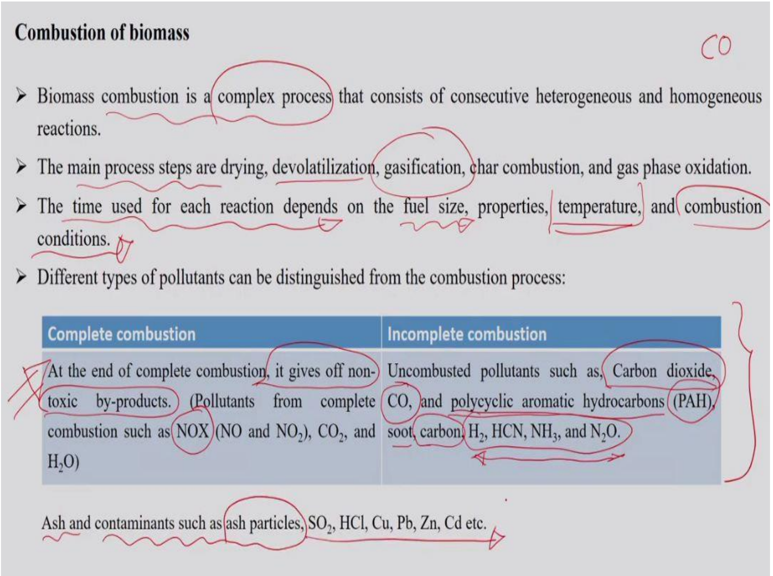


So, if you see the first picture, it represents the flaming combustion. So, this kind of flames are formed because of the presence of more volatile matter in the wood sample or you can say the solid fuel sample. Whereas, if the fixed carbon content is high, then this kind of glowing combustion appears in the combustion chamber. So, there will not be any flame because the volatile matter contained in this particular sample is relatively less.

So, as a result, the formation of the flame will not happen in this particular process, because the volatile matters as I mentioned, they rapidly burn in presence of the oxygen. So, if the volatile matter content is relatively high, so, obviously, the burning of the volatile matter will happen at a faster rate, as a result, there will be a formation of the flame. If the volatile matter content is less, what happens in that case is like such formation of the flame will not happen.

So, this is how is the difference between the flaming combustion and the glowing combustión. I think it is very much clear from these 2 picture now.

(Refer Slide Time: 26:48)



The biomass combustión, it is a complex process and that consists of the heterogeneous and homogeneous reaction. Why it is a homogenous reaction? As I said, because when the biomass combustion is taking place in the combustion unit, so, there will be some incomplete combustion will happen in the chamber. As a result, it may release CO as a gas. So, this CO which is a highly oxidising agent, it can oxidise in presence of oxygen to produce again the C O 2 as a product.

So, the reaction of CO with oxygen, it is a gaseous reaction, whereas, the combustion of the solid and the char which are produced during the process with the oxidising medium, that is a heterogeneous reaction that is a solid gas heterogeneous reaction. So, likewise, the biomass combustion, it is a very complex process where heterogeneous as well as the homogeneous reaction appears consecutively and then it will lead to a product.

The main process steps in this particular combustion process are drying, devolatilization of the material, then the gasification followed by the char combustion and in the gas phase oxidation. And as the reason I mentioned, the gas phase oxidation is nothing but again the homogeneous reaction. Because both the gases are reacting in the same medium that is a gaseous medium, that is why it is called as a homogeneous reaction of the gaseous mixture.

And the time used for each reaction, it depends on the fuel size, properties of the fuel, the temperature selected and the combustion conditions. This is how this particular process it varies, it varies from the fuel to fuel as well as from the solid fuel from coal to the biomass as well. Because it all depends on the fuel size, which is used for the combustion purpose. Along with that, it also depends on the properties of the solid fuel which is used for the combustion purpose.

As I mentioned earlier, it all depends on the volatile matter and the fixed carbon content in the solid fuel, the temperature which is used for the combustion purpose is also very important and the combusion condition. So, now, once you try to see these parameters is that need to be used very effectively to have the complete combustion of the solid fuel in the combustion unit.

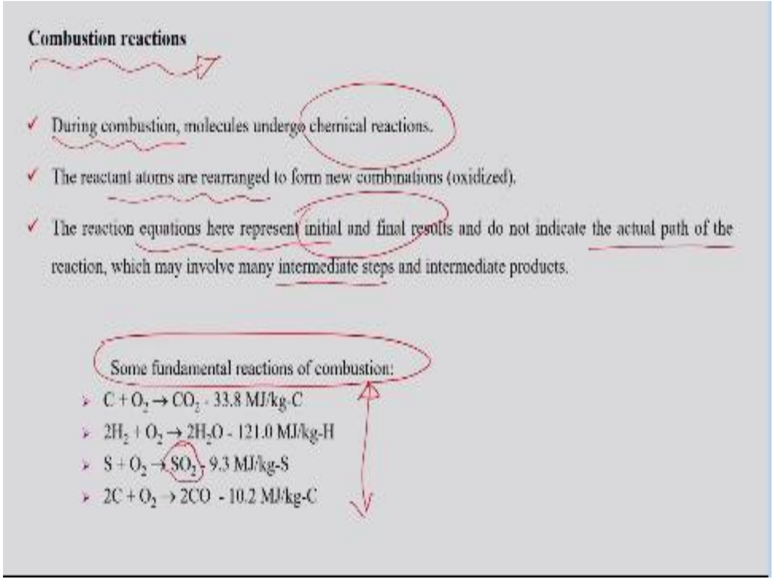
In case if these kind of conditions are not maintained properly, then different types of pollutants are generated from the complete and incomplete combustion process. So, now, let us see the difference between the complete and the incomplete combustion and the pollutant release from the complete and incomplete combustion process. So, if you see this particular table, we already discussed in one of the lecture.

So, in case of complete combustion, if the sufficient amount of oxygen is supplied during the reaction, the complete combustion will take place. As a result, it gives out the non-toxic product in the form of C O 2 that is a completely combustion product and the H 2 O again which is a completely combusted product along with the NOx that is NO in NO 2.

Whereas, in case of the incomplete combustion, because of the incomplete combustion of the solid fuel in the combustion unit, it gives up some polluting product that is in the form of, it may form carbon dioxide, which is a completely combusted product. Along with that it also formed the CO and polycyclic aromatic hydrocarbons that is called as a PAH and soot particle unconverted carbon will be there along with that the composition of the gas heading in this particular range will also get formed during the incomplete combustion of biomass.

And this is how is the difference between these 2 processes. So, in practice, we try to ensure that the reaction will reach to a complete combustion. So, this kind of polluting gases can be avoided during the combustion process. Apart from that, it also forms ash and contaminants such as ash particle and the range of this kind of product as well. So, this is how is the difference between the incomplete and the complete combustion.

(Refer Slide Time: 30:54)

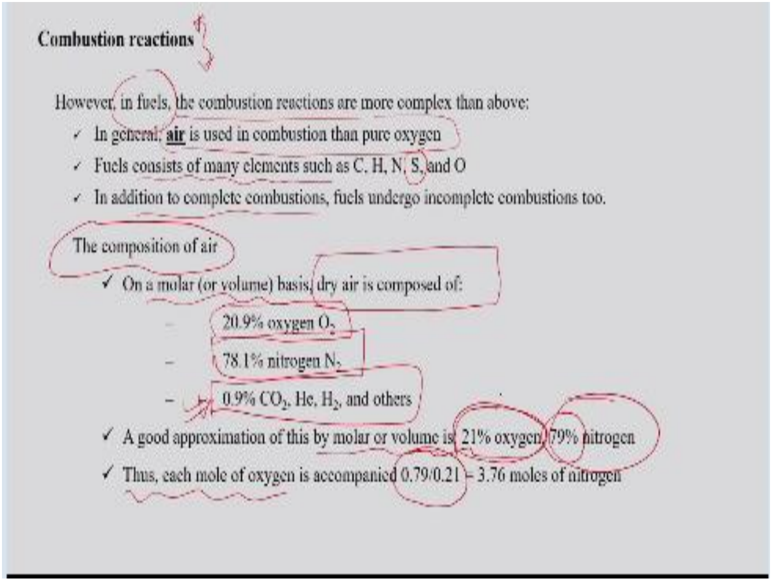


So, once you understand this difference between the complete and incomplete combustion, so, now, let us try to understand the combustion reactions taking place during the combustion of the solid fuel. For example, if you see here during combustión, the molecules it undergoes the chemical reaction and the reactant atoms are rearranged to form new combination that is the oxidised product in the form of CO 2 or the H 2 O.

And the reaction equation here, it represents only the initial and the final results only and do not indicates the actual part of the reaction, it may involve some intermediate steps and the formation of some intermediate product as well. So, some fundamental reaction of the combustion mechanisms are shown here in the form of formation of the CO 2 and the H 2 O if the sulphur content is high in the solid fuel.

Take an example of the coal, if the sulphur content is relatively high in the coal, then it also releases this particular gas. So, these are some fundamental reactions of the combustion process.

(Refer Slide Time: 31:58)



Now, after understanding the fundamental reaction of the combustion process, let us try to understand this particular reaction in some more elaborate way. For example, if the combustion reaction is occurring in presence of the oxygen as an oxidising medium, then the product formation will be in the form of only CO 2 in the H 2 O. Whereas, if the air mixture is used for the combustion purpose, then along with the CO 2 and the H 2 O, the nitrogen will also come out as it is from the combustion chamber.

As per the ideal condition as we consider that the nitrogen is not reacting in the process. So, it will come out as it is without reacting into the combustion process. So, that will also add to the product along with that, it may also form some other products which are present in the hydrocarbon component of the solid fuel. So, if the air is used as the oxidising agent, so, in that case, the combustion reactions are more complex, because the air is used in combustion than the pure oxygen.

And if the air is used, though it will be accompanied by the nitrogen as well. Moreover, the fuel also consists of many elements such as carbon, hydrogen, nitrogen, sulphur and the oxygen. The sulphur is presenting some of the biomass only, not all the biomass has the sulphur component, but, if it is a coal, then obviously, it will have the sulphur in its composition and then it will lead to a SO 2 as a product because of the complete combustion again.

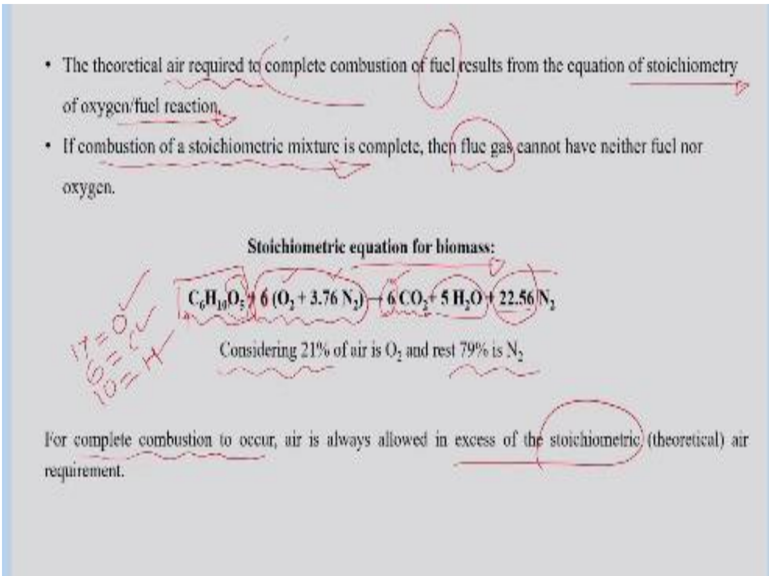
And in addition to the complete conversion, as I mentioned earlier, this point also, fuel also undergoes the incomplete combustion and that is what we have discussed in the previous slide that it may happen, so, in the practice that the fuel also undergoes the incomplete combustión. As a result, it will form the uncombusted product during the reaction. So, the composition of air if you just try to see for the combustion purpose, so, it mostly consists of on the molar volume basis is that is a dryer which is composed of 21%.

So, we are represented here is like exact composition 20.9. So, it will present here like 20.9% oxygen, 78.1% is the nitrogen and remaining is traces of the other gases. For the good approximation purpose, we use molar volume of oxygen as 21 and nitrogen has 79. So, we neglect the traces of other gases during the psychometric balance or during the approximation.

And thus, each mole of oxygen if you see here, it is accompanied by approximately 0.79 divided by 21 because, there is a 79% of the nitrogen is accompanied by the 21% of the oxygen. So, in this case, oxygen is only the oxidising medium whereas, in ideal condition we considered that the nitrogen is not taking part into the reaction. So, it will come out as it is from the combustion chamber.

As a result, it is accompanied by around 3.76 moles of the nitrogen, so, one mole of oxygen is accompanied by around 3.76 moles of the nitrogen, if air is used as the oxidising medium.

(Refer Slide Time: 35:03)



So, now, based on this particular discussion, if we just try to find out the theoretical air, which is required for the complete combustion of the fuel to take place and it results from the equation of stoichiometric of oxygen fuel reaction. So, once you try to balance this particular equation, then you can easily find out theoretically, the amount of oxygen which is required for the complete combustion of the fuel.

If combustion of a stoichiometirc mixture is complete, then in that particular case the flue gas cannot have either a fuel or oxygen because we term it as a complete combustion. As a result, there will not be any incomplete product formation will take place. As a result, there will not be any oxygen which is left out in the combustion chamber, which is coming out as it is not oxidising the fuel.

As the result, if the oxygen is not coming on as it is, that means fuel is also getting completely oxidised in the combustion chamber and hence, fuel also will not come out from the combustion chamber as a product. So, if we just try to balance, one small stoichiometric equation of the biomass here, if you just try to see here, this represents the carbohydrate content of the biomass.

It is reacting with the oxygen. This represents the air composition in the form of oxygen and 3.76 moles of the nitrogen. So, as I said, one mole of oxygen it is accompanied by 3.76 moles of the nitrogen and for this particular complete reaction to happen, 6 moles of the air or we can say the air mixture is required for the complete combustion to take place and it will form 6 moles of CO 2, this many moles of wáter.

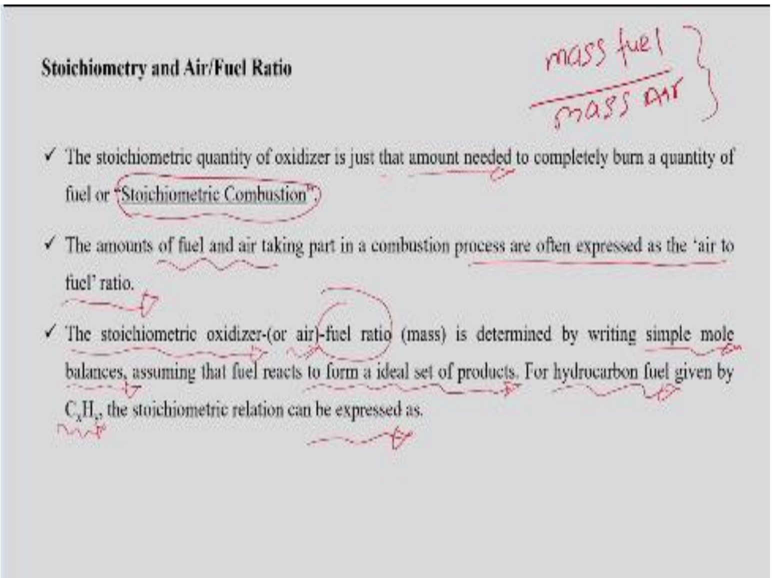
And if you simply multiply 6 into 3.76, these many moles of nitrogen are coming out as it is from the combustion chamber without reacting into the combustion chamber. So, now, if you just try to balance the carbon in this equation, so, initially there are 6 carbon in the carbohydrate. As a result 6 carbon dioxide molecules are coming out from the combustion chamber as a product.

And the air mixture, it contains 6 moles of the oxygen and remaining moles of the nitrogen. So, 6 moles or oxygen already here and oxygen is already available in the hydrocarbon fuel also. So, these also need to be taken into account during the mole balance. If you see here, we have total 5 plus 12 that is 17 oxygen carbón, 6 and then hydrogen if you just count, we have 10 hydrogen in the reactant side.

So, we have to just balance these moles in the product as well. So, as a result, we got 6 carbon in the product, 10 hydrogen also in the product. Now, we have to just balance the oxygen. So, 6 into 2 that is 12 and 5 oxygen that means 17 oxygen. So, this is the stoichiometrically balanced equation and so, it is called as a stoichiometric equation for the complete combustion of the biomass.

And considering here, the oxygen has 21% in the air mixture and 79% is nitrogen. But in practice for complete combustion to takes place, air is always required in excess of the stoichiometric amount to ensure that the complete combustion of the solid fuel or the liquid fuel is taking place in the combustion chamber and that is the reason we always try to ensure that the excess air is available in the oxygenation chamber to allow the complete combustion of the fuel to take place.

(Refer Slide Time: 38:53)

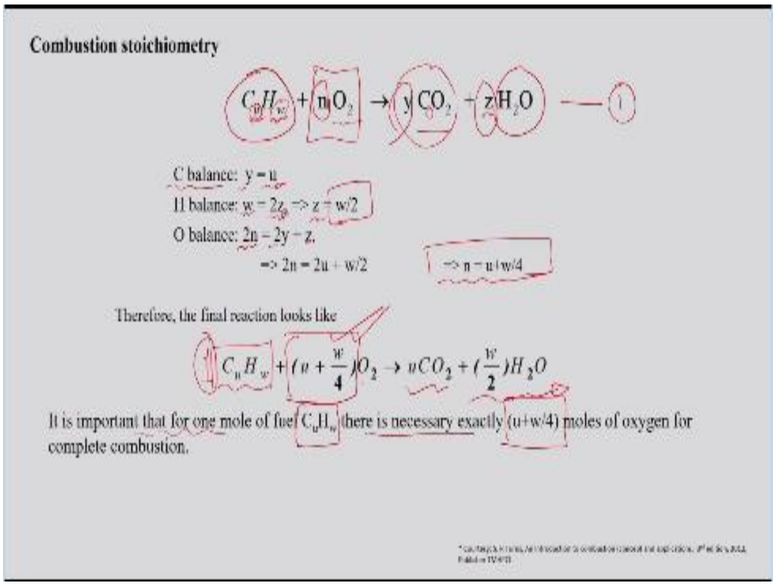


So, now, based on this particular stoichiometric, if we just try to discuss the stoichiometric in the air fuel ratio as I mentioned, the air fuel ratio is nothing but the mass of fuel to the mass of air that is called as a fuel to air ratio or we can also termed as the air to fuel ratio in other terms. So, the stoichiometric quantity of the oxidizer, which is required for the complete burning or quantity of the fuel that is termed as a stoichiometric combustion.

And this amount of fuel and air which are taking part in the combustion process are often expressed as air to fuel ratio. And that is what I mentioned here is like, this is very important to understand that how the particular combustion of the fuel air misture is taking place in the combustion chamber. The stoichiometric oxidizer that is either oxygen or the air to fuel ratio is determining by writing the simple mole balance equation.

And assuming that the fuel reacts to form ideal state of product, so, for example purpose, let us take one example of the hydrocarbons fuel, which is normally represented in the form of C x and H y and the stoichiometric relation for this particular fuel can be expressed in the following way. So, let us see how to express this particular hydrocarbon fuel in the stoichiometric way to have the complete combustion of this particular fuel in the combustion chamber.

(Refer Slide Time: 40:39)



So, if you see here the combustion stoichiometry of a hydrocarbon fuel, so, it is represented as C u H w. So, this is the hydrocarbon, which is available for the combustion purpose and it is oxidised using the pure oxygen and the number of moles of oxygen required is mentioned here and then it gives y moles of CO 2 and then z moles of H 2 O as a product. So, if you just try to first balance the carbon, hydrogen and oxygen in the reaction.

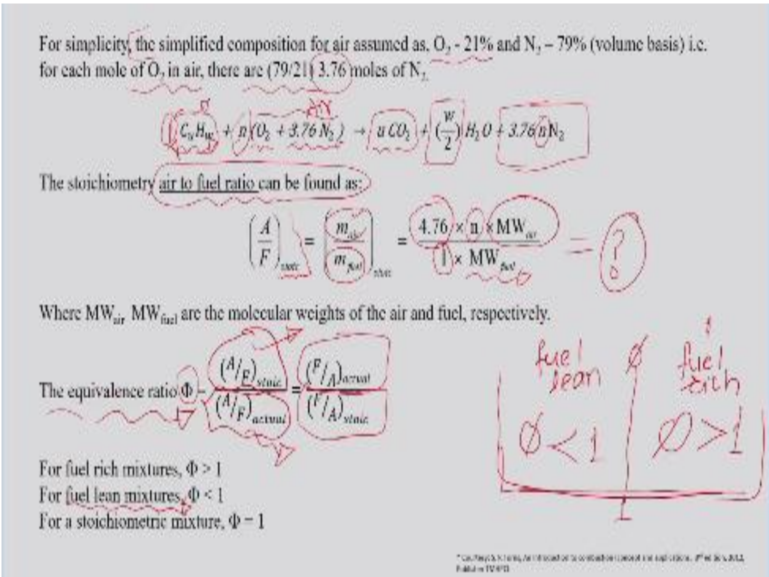
So, for balancing the carbon if you see here, there is this many atoms of carbons are there. So, y is equal to u, there is no other carbon which is getting formed during this particular reaction. Apart from that, if you just try to balance the hydrogen again. So, this is the hydrogen which is present in the hydrocarbon and it is forming z moles of H 2 O. So, if you just try to balance this, so, this w is equal to 2 z that is twice of z moles and hence, z can be written in the form of w by 2.

So, this is a simple mole balance of the hydrogen also, we are done and now, for the oxygen if you see here, the 2 n and then we have 2 y in the product along with the 1 z as well right. So, this is the mole balance, you can say for the oxygen. Now, just simply by this equation, and we will get the equation in the form of n is equal to u plus w by 4.

So, if we just substitute this value in the previous equation, that is equation 1 suppose here, it forms, this is a hydrocarbon, it requires this much moles of oxygen to form the stable compound and to have the complete combustion of the fuel in the combustion chamber. Or I would say the other term is like, this much moles of oxygens are required to completely oxidised the hydrocarbon fuel to produce the CO 2 and H 2 O as a component along with the significant amount of the heat.

So, it is important here that for 1 mole of fuel that is represented here as like this, there is a necessary exactly to have, this many moles of oxygen for the complete combustion. So, this is one of the simple way to represent this that for this 1 mole of hydrocarbon fuel, it requires this many moles of the oxygen. So, that the complete combustion of the fuel will take place in the combustion chamber.

(Refer Slide Time: 43:22)



So, based on this, we can easily find out like how to calcúlate, now, the air to fuel ratio for the specific solid fuel. Why it is required, because as I mentioned, when we are burning of fuel in the oxidising medium, so, it is an air fuel mixture now. So, as a result, the air fuel mixture is getting oxidised in the combustion chamber and forming oxidise product along with a significant amount of the heat.

When this particular combustion process is taking place in the combustion unit, so, the combustion process it all depends on the supply of the oxygen in the combustion chamber. If the supply of the oxygen in the combustion chamber, if it is not sufficient, then it may lead to incomplete combustion. If the supply of oxygen is relatively high, then it will have complete combustion along with that it may also add some oxygen in the product as well because the supply of the oxygen is in surplus.

So, as a result, to have the complete combustion process and to balance the equation that is called a stoichiometric equation, the exact amount of the oxygen also can be calculated from the mole balance of the fuel and that is termed as a stoichiometric equation or stoichiometric oxygen which is required for the combustion purpose and based on that the amount of the excess air required for the combustion purpose also can be calculated that is called as the air to fuel ratio.

And if this particular issue is calculated for the stoichiometric equation, similarly, for the actual process, it can also be calculated considering the same fuel. So, that is called as a equivalence ratio which is the ratio of the stoichiometric quantity of the air to fuel ratio divided by the air to fuel ratio which is actually required for the combustion of the solid fuel in the combustion chamber.

So, before discussing on the equivalent ratio, let us first discuss about the what is mean by the air to fuel ratio. So, for simplicity purpose, if you just simplify the combustion of the fuel in presence of the air, then as I mentioned, it will be having 21% of the oxygen and it will be accompanied by the 79% of the nitrogen if the air is the oxidising medium and for that reason, each mole of oxygen in air is accompanied by 3.76 moles of the nitrogen.

So, if you just replace this particular equation in the form of now, hydrocarbon fuel and instead of using the oxygen as the oxidising agent, here we are considering oxygen plus a component nitrogen molecules in the air. So, this is a air mixture now and this many moles of air are required for the combustion process to occur or I would say for the complete combustion of the fuel to takes place.

It will results into u moles of CO_2, w by 2 moles of H_2O that balance we already done in the previous slide and 3.76, n is the moles of nitrogen just multiply 3.76 into n. So, this many moles of nitrogen will come out as it is from the combustion unit. So, now, if we just try to find out the air to fuel ratio for this stoichiometric balance equation.

So, air to fuel ratio stoichiometrically that is why it is mentioned here the stoichiometrically, it is calculated as the mass of air, this is a mass of air and that is the reason if you remember in the previous slide, I wrote the ratio as even feel to air ratio as mass of fuel to the mass of air, because, here we are considering the balance of the equation in terms of the mole balance or you can say the volume basis, but while calculating the air to fuel ratio, we are calculating in terms of the mass ratio.

So, we need to convert this particular moles into the mass first. So, if you talk about the mass of air and in the mass of fuel, which is stoichiometric quantity, which is required for the complete combustion to take place. So, the mass of air is now here is like 3.76 moles of nitrogen, 1 mole of the oxygen that is equivalent to 4.76 into n.

This is the moles of air which is required for the combustion and molecular weight of the air divided by the moles of fuel that is a hydrocarbon here it is 1, so, 1 into molecular weight of the fuel that is a hydrocarbon in the particular equation. So, once you multiply these value, you will get here the air to fuel ratio for the particular stoichiometric equation that is a mole balance equation, which you have set for the specific hydrocarbon in the form of this.

So, this is the exact quantity of the air mixture, which is required for the complete combustion of this fuel to produce CO_2 and the H_2O as a product that is why it is called as a stoichiometric air to fuel ratio. Similarly, in practice or you can see an actual the amount of oxygen which is required for the combustion, it may be high or even it may be lesser than the stoichiometric amount. It all depends on the properties of the fuel as we have discussed in the previous slide.

So, if the actual amount of the air which is required for the combustion purpose is even higher or lower than the stoichiometric amount, then this particular amount is represented by the equivalence ratio and it is the ratio of air to fuel ratio of stoichiometric amount to the air to fuel ratio of the actual reaction. And if you just rearrange this, it will lead to a form of like fuel to air ratio that is actual to the fuel to air ratio stoichiometrically required for the complete combustion to takes place.

Let us try to understand this concept in more simpler way. For example, if the equivalence ratio is 1. In that case, what happens is like, the fuel to air ratio which is required for the actual reaction, it is same as that of the fuel to air ratio which is required for the stoichiometric equation as well. That is the reason here, the phi is equal to 1 that means the exact amount of oxygen is required for the combustion of the specific amount of the fuel.

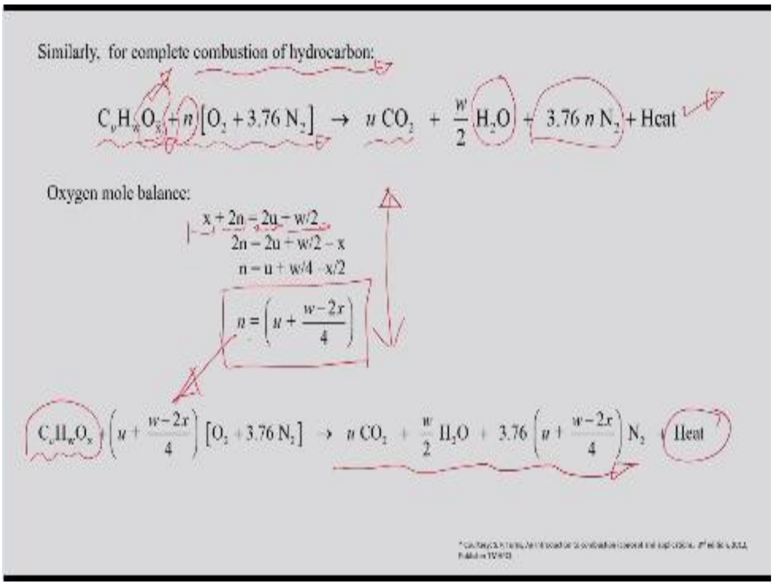
And it is also matching with the stoichiometric quantity of the fuel requirement as well as the oxygen requirement for the combustion purpose. In case, if this particular phi value, if it is less than 1, in that case, what happens is like, it is considered as the fuel lean mixture, because from this ratio if you just try to see the phi value is less than 1. What does it mean?

The fuel which is available for the combustion purpose is less than that of the oxygen which is available for the combustion purpose. So, it is called as a fuel lean mixture or in the other term it is called as a oxygen rich or oxidizer rich mixture. Now, in other way, if this particular phi, if it is greater than 1, then in that case, we just try to substitute the value which is greater than 1 here, in that case, it may happen.

So, that the fuel which is available for the oxidising purpose in the combustion unit, which is significantly higher than the oxygen which is supplied for the combustion purpose or the air which is supplied for the combustion purpose. That is why it is called as a fuel rich mixture. Whereas, here it is a fuel lean that means lower amount of the fuel is available for the combustion purpose whereas, the oxygen is higher and other words we can term it as a oxidizer rich mixture.

Whereas, in this case, the fuel is available in the significantly higher amount than that of the oxidizer which is supplied in this particular combustion unit, as a result, it is called a fuel rich mixture or in other word is a oxygen or oxidizer lean mixture. So, it is very much clear now, how to find out the fuel reach and fuel lean mixture from the particular equation.

(Refer Slide Time: 51:41)



So, now, after understanding the concept of the solid fuel combustion in the combustion chamber, let us try to extend our discussion for the combustion of the hydrocarbon which is another kind of hydrocarbon, but it also has a oxygen in its composition. Whereas, if you see the previous example, there, we have seen that it is a pure hydrocarbon where there is no oxygen present in the hydrocarbon as a solid fuel.

Whereas, in this case, the hydrocarbon, it also contains the oxygen in its composition. And when you are burning this particular fuel in the same amount of the air mixture, it produce CO 2, this many moles of CO 2 and H 2 O along with nitrogen as a product. And also it releases a significant amount of the heat. But in this case, while balancing the oxygen, we need to take into account oxygen which is present in the solid fuel as well.

Then only we will come to know the exact oxygen which is required for the combustion purpose and it also matches to the stoichiometric balance of the oxygen in the equation. So, if you try to see here, now, this equation and if you just try to balance again the moles of carbon, hydrogen and oxygen, so, we already done this exercise in the previous slide. So, I will just do here for the oxygen just to make you understand that if there is oxygen present in the solid fuel itself.

So, how to balance the moles of oxygen in the reaction. So if you see here, there is a x mole of oxygen which is already present in the solid fuel and then we have 2 moles of oxygen in the air mixture, which is resulting into the 2 moles of oxygen which is getting combined with

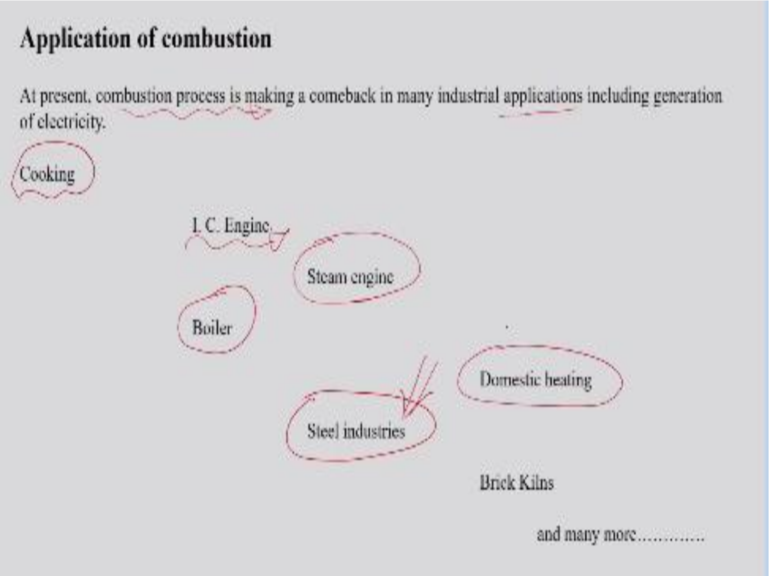
C to form CO 2 and then w by 2. Again, it is coming from the H 2 O. So, once you balance this and then calculate the value, we will get the n in the form of u plus w minus 2 x by 4.

So, this is nothing but the moles of air which is required, if the oxygen is present in the solid fuel. So, this is slightly different than the previous mole balance equation, because in that case, there was no oxygen present in the hydrocarbon fuel. Now, simply just subsidies n value into the equation here. So, you can see, there this is the hydrocarbon fuel and these many moles of air which is required for the complete combustion to takes place.

And it will lead to a product and then amount of the heat. So, this is called a stoichiometrically balance equation for the hydrocarbon where the oxygen is present in the hydrocarbon fuel itself. So, once you understand this stoichiometric balance or the mole balance of the components stoichiometrically, then you can find out the air to fuel ratio for any kind of fuel either it can be a methane, propane, butane or gasoline one. You can easily find out the air to fuel ratio.

So, after learning the combustion process, now, let us discuss about the application of this combustion process.

(Refer Slide Time: 54:40)

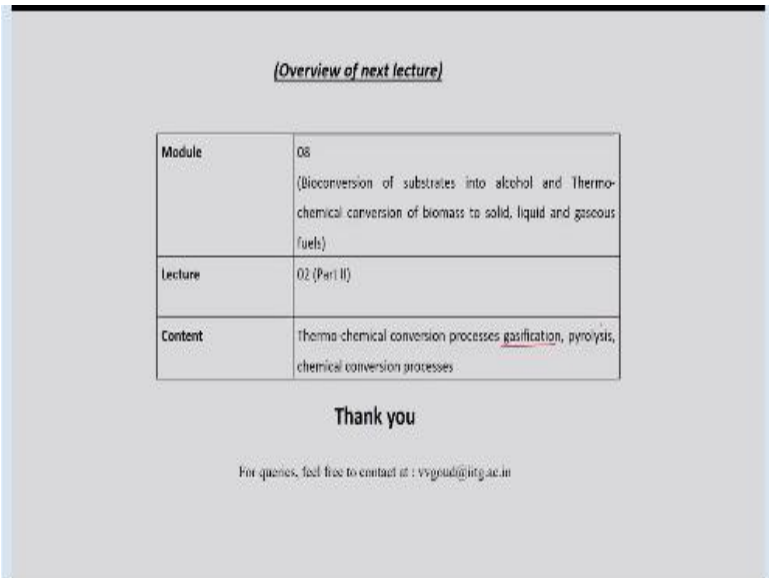


For example, as I mentioned, the combustion process is making a comeback in many industrial application, including the generation of the electricity. So, apart from this production of electricity, the combustion process also has application in the this particular fuel, it also has application in the IC engine that is a combustion of fuel in the engine, boiler that is a combustion of the solid fuel to produce the heat and the subsequently the heat produced from the boiler can be used as a process it for the manufacturing purpose.

Apart from that, it can be also used to produce the steam and in the steam engine. Steel industries where significantly higher temperature is required, so, the combustion process is widely used in the steel industries. Apart from that the domestic heating which is a very well known example and brick kilns. Apart from that there are many more applications are there for this particular technique.

So, now, in this particular lecture, we learn about the torrefaction as well as the combustion process in detail. So, in the next lecture, we will discuss about the other thermo-chemical processes like gasification, pyrolysis and chemical conversion process.

(Refer Slide Time: 55:56)



Thank you. Regarding this lectura, if you have any doubt, so, feel free to contact me at vvgoud@iitg.ac.in.