Energy Conversion Technologies (Biomass And Coal)

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Lecture 20

Practice examples (Pyrolysis, Gasification)

Good morning everyone.

Welcome to this third lecture of module 4. In this lecture, we will practice few examples on thermochemical conversion processes. In that, first we will discuss one example on pyrolysis process that is mainly on heat and mass balance in the pyrolysis process. And then after, we will try to solve one more example that is on heat and mass balance in the gasification process followed by that we will discuss one example on the equivalence ratio. Equivalence ratio is one of the important concepts in combustion and the gasification process. So, here we will try to practice one example on the equivalence ratio as well. And at the end, we will practice one example on Fischer-Tropsch synthesis process. Let us begin with the first example, that is heat and mass balance in the pyrolysis process.

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Heat & Mass Balance in Pyrolysis

Example 1. A pyrolysis reactor is designed to process wood chips at a rate of 1000 kg/day. During the pyrolysis reaction, the feedstock is heated from an initial temperature of 25 °C to 500 °C. Calculate the amount of heat required to raise the temperature of the wood chips to the desired pyrolysis temperature. Assume a density 200 kg/m^3 and specific heat capacity of 1.5 kJ/kg·K for the wood chips. The reactor is a rotary kiln heated with fuel gas, gross calorific value 33.5 MJ/m^3. Estimate the quantity of fuel gas required, taking the overall efficiency of the furnace as 70%. Determine the necessary volume of the pyrolysis reactor to handle the daily throughput, if the residence time required for the pyrolysis process is 5 hr.

Solution:

Given data:

Mass of wood chips (m): 1000 kg/day

Initial temperature ($T_{initial}$): 25°C

Final temperature (T_{final}): 500°C

Specific heat capacity of wood chips (Cp): 1.5 kJ/kg·K

Here in this example, a pyrolysis reactor is designed to process wood chips at a rate of 1000 kg per day. And during this pyrolysis reaction, the feedstock is heated from initial temperature of 25 °C to 500 °C. And we need to calculate the amount of heat required to raise the temperature of the wood chips to the desired pyrolysis temperature that is up to 500 °C. Assume density of around 200 kg per meter cube and the specific heat of 1.5 kilojoule per kg degree Kelvin for the wood chips. The reactor is a rotary kiln heated with fuel gas and the gross calorific value is given as 33.5 megajoule per meter cube. And we need to estimate the quantity of fuel gas which is required and taking the overall efficiency of the furnace as 70 percent. And also, we need to determine the necessary volume of the pyrolysis reactor to handle the daily throughput, if the residence time required for the pyrolysis process is 5 hours. So, with this given data, we need to estimate the quantity of fuel gas which is required. Then again, we need to determine the necessary volume of the pyrolysis reactor to handle this daily throughput. And also, we need to calculate the amount of heat which is required to raise the temperature of the given feed material to the desired pyrolysis temperature. So, let us begin with the solution of this example. So here, if you see the given data is mass of wood chips 1000 kg per day. Initial temperature is given as 25 °C and the final temperature of the desired pyrolysis process is 500 °C. And the specific heat of wood chips is 1.5 kilojoule per kg degree Kelvin.

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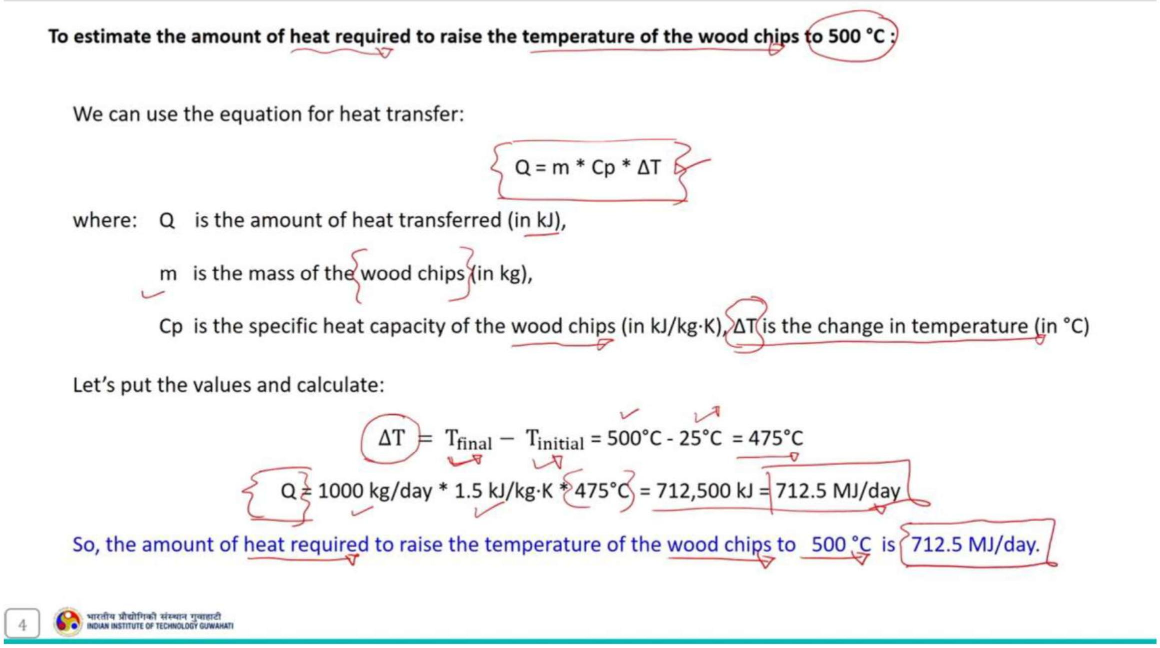

So, first we need to estimate the amount of heat which is required to raise the temperature of the wood chips to 500 °C. To do that, we can make use of this equation of heat transfer and this is very well-known equation, that is Q is equal to m Cp delta T,

$$Q = m * Cp * \Delta T$$

where Q is nothing but the amount of heat transfer in kilojoule and m is the mass of the feed. So, here the feed is the wood chips and Cp is the specific heat capacity of the given fuel material as here it is wood chips. So, the specific heat capacity of the wood chips is already given and delta T is the change in temperature in °C. And as we know the temperature of the wood chips need to be raised to around 500 °C whereas the initial temperature of the wood chips is also given. So, with the help of that we can estimate this value of delta T that is also termed as a temperature difference. So, let us put the value in this equation here.

$$\Delta T = T_{final} - T_{initial} = 500\ °C - 25\ °C = 475\ °C$$

$$Q = 1000\ kg/day * 1.5\ kJ/kg \cdot K * 475\ °C = 712{,}500\ kJ = 712.5\ MJ/day$$

So, this is change in temperature, the final temperature minus the initial temperature. Final temperature we know that is 500 °C minus the initial temperature that is 25 °C. If you take the difference of this, so this gives the delta T, that is difference in the temperature that is 475 °C. So, now once we substitute this given value in this above equation, then you can calculate the heat transfer. So, here the m is given as 1000 kg per day, specific heat is given as 1.5 and this is the value which we have just obtained from this equation. And if you just do this simple multiplication here, we will get the value in the form of 712.5 mega joule per day. And this is the amount of heat which is required to raise the temperature of the wood chips to 500 °C, and that is 712.5 mega joule per day.

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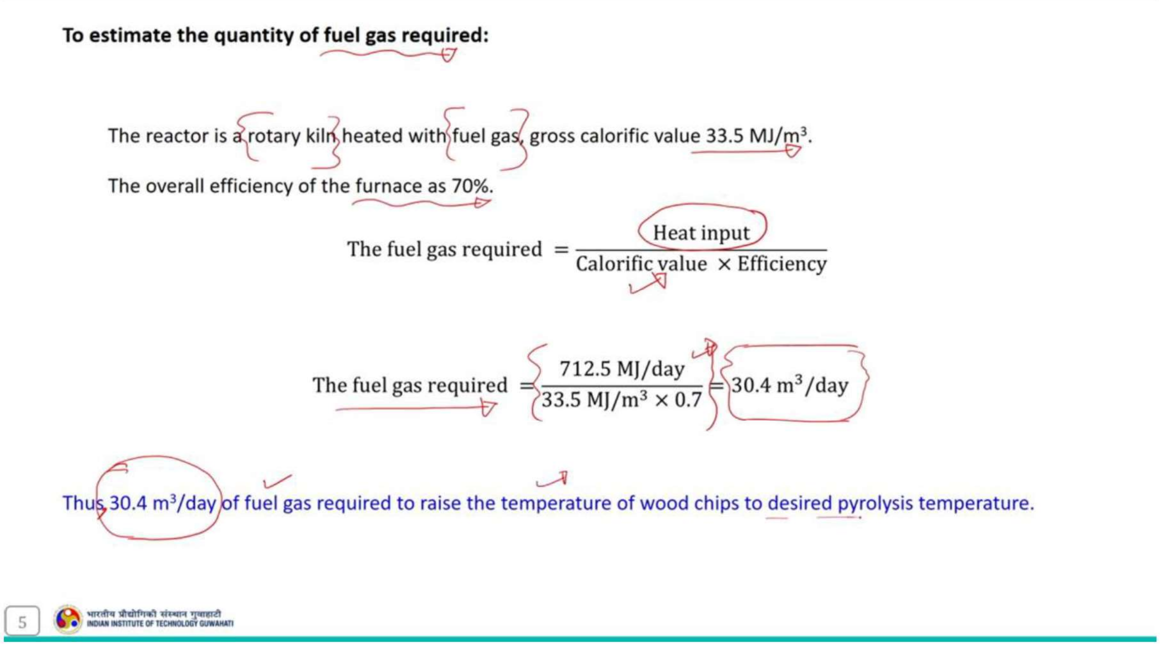

Next is we need to estimate the quantity of fuel gas which is required during this process. So, here as we know the reactor is of rotary kiln type and it is heated with this fuel gas and which has a gross calorific value of 33.5 mega joule per meter cube. And the overall efficiency of this reactor or we can term it as a furnace also is around 70 percent. So, the fuel gas required is heat input by its calorific value into the efficiency here.

$$\text{The fuel gas required } = \frac{\text{Heat input}}{\text{Calorific value } \times \text{Efficiency}}$$

$$\text{The fuel gas required} = \frac{712.5\ \text{MJ/day}}{33.5\ \text{MJ/m}^3 \times 0.7} = 30.4\ \text{m}^3/\text{day}$$

And as we know the heat input just we have estimated it is around 712.5 mega joule per day. And the calorific value is also given here and efficiency of the furnace is 70 percent. So, with the help of this given data, we can estimate the fuel gas which is required and it comes out to be around 30.4 meter cube per day. So, this much amount of the fuel gas is required per day to carry out this pyrolysis process. So, this indicate 30.4 meter cube per day of fuel gas is required to raise the temperature of the wood chips to desired pyrolysis temperature. And the desired pyrolysis temperature in this example is given as 500 °C.

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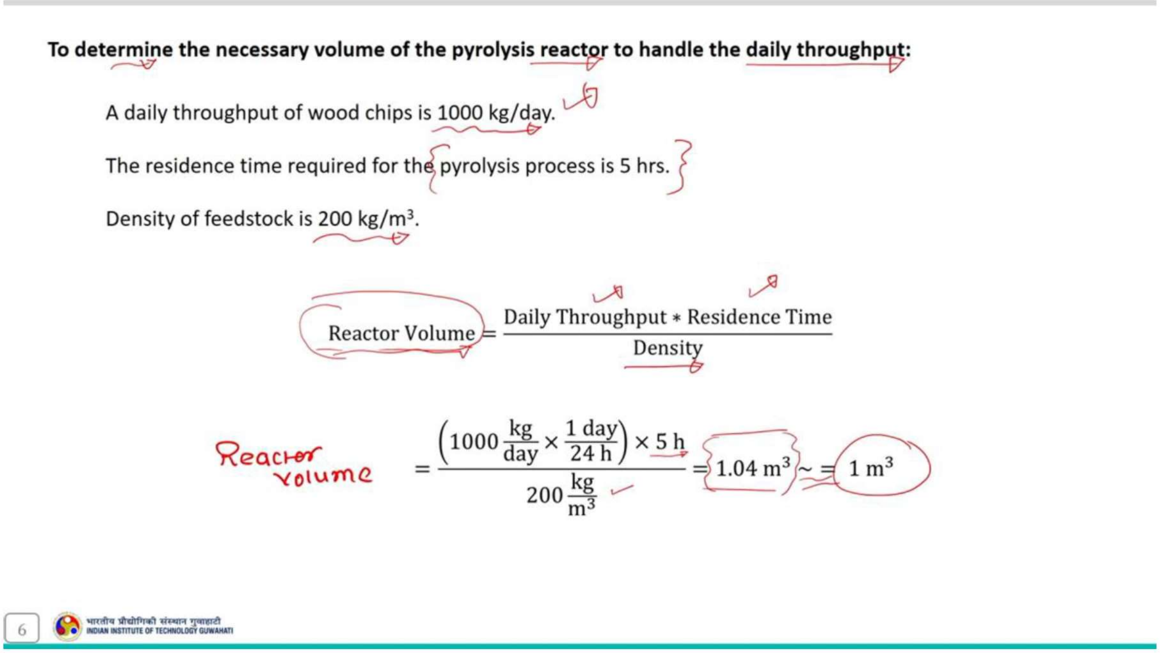

We need to determine the necessary volume of the pyrolysis reactor to handle the daily throughput. So, in this case, a daily throughput of wood chips is around 1000 kg per day. And the residence time which is required for this pyrolysis process is of 5 hours. And the density of the feedstock is given as 200 kg per meter cube. Now, we can estimate the necessary volume of the reactor which is required to handle this daily throughput.

$$\text{Reactor Volume} = \frac{\text{Daily Throughput} * \text{Residence Time}}{\text{Density}}$$

$$= \frac{\left(1000\,\frac{\text{kg}}{\text{day}} \times \frac{1\ \text{day}}{24\ \text{h}}\right) \times 5\ \text{h}}{200\,\frac{\text{kg}}{\text{m}^3}} = 1\ \text{m}^3$$

So, daily throughput as we know it is 1000 kg per day and its residence time is also known to us that is 5 hours and the density of the feedstock is also known. So, once we substitute this value here that is 1000 kg per day into we have just done this conversion here in terms of hour. Because the residence time which is required for this process is 5 hour and the density is 200 kg per meter cube. So, once you substitute this value here and do this simple multiplication and the division, we will get the final answer in the form of 1.04 meter cube and that is close to equal to 1 meter cube. So, that means the reactor volume that means the necessary volume of the reactor required to handle the daily throughput is 1 meter cube. And this is all about the heat and mass balance in the pyrolysis process. And with the help of that even we could able to estimate the necessary volume of the pyrolysis reactor which is required to handle the daily throughput of 1000 kg per day.

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Heat & Mass Balance in Gasification

Example 2. To perform the water-gas gasification reaction in an updraft gasifier, the required heat is provided by the combustion reaction by regulating the supply of oxygen and carbon. Calculate the amount of steam and oxygen required per kg of carbon to fulfil the needs of this gasification process. Assume that 40% additional heat is required for drying (inclusive of other losses).

Solution:

Water-gas gasification reaction used for gasification of carbon: $C + H_2O \rightarrow CO + H_2 - 131$ kJ/mol ....(1)

This endothermic reaction uses steam, where 131 kJ of heat is required for gasification of each mole of carbon.

In oxygen-deficient gasification conditions, partial combustion reaction (Eq. 2) is more likely to take place than the complete combustion reaction (Eq. 3)

$C + ½\,O_2 \rightarrow CO + 111$ kJ/mol ....(2)

$C + O_2 \rightarrow CO_2 + 394$ kJ/mol ....(3)

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Let us move on to the next example, that is on the concept of heat and mass balance in the gasification process. So, in this example, water gas gasification reaction is performed in the updraft gasifier and the heat required for this reaction is provided by the combustion reaction by regulating the supply of oxygen and carbon. And we need to calculate the amount of steam and oxygen required per kg of carbon to fulfill the needs of this gasification process. And here we need to make some assumptions that is 40% additional heat is required for drying operation and that is inclusive of other losses. So, with the help of this given information and the data given here we need to calculate the amount of steam as well as the oxygen required per kg of carbon to fulfill the needs of this gasification process. So, let us begin with the solution of this example.

$$C + H_2O \rightarrow CO + H_2 - 131 \text{ kJ/mol} \quad \text{..........(1)}$$

$$C + \tfrac{1}{2} O_2 \rightarrow CO + 111 \text{ kJ/mol} \quad \text{..........(2)}$$

$$C + O_2 \rightarrow CO_2 + 394 \text{ kJ/mol} \quad \text{..........(3)}$$

So, if you see here the water gas gasification reaction used for the gasification of carbon is given as like C plus H_2O and it will produce carbon monoxide along with the hydrogen as a gas. And if you see this particular term here, which indicates that this is the endothermic reaction. And it uses steam where 131 kilojoules of the heat are required for gasification of each mole of carbon. That means, this much amount of the heat needs to be supplied for the gasification of each mole of carbon. And since we know the concept of the gasification, the gasification is carried out in oxygen deficient environment. And the partial combustion reaction is more likely to take place than the complete combustion reaction in the gasifier. So, this particular equation that is 2, it represents the partial combustion reaction in the gasifier, where the carbon is partially combusted in oxygen deficient environment to form carbon monoxide. And along with this it releases this much amount of the energy. Because if you remember the combustion is an exothermic reaction and even the partial combustion is also exothermic process, it will release this much amount of energy. Similarly, when the carbon is completely combusted then it produces the stable product in the form of CO_2 along with that it releases this much amount of energy.

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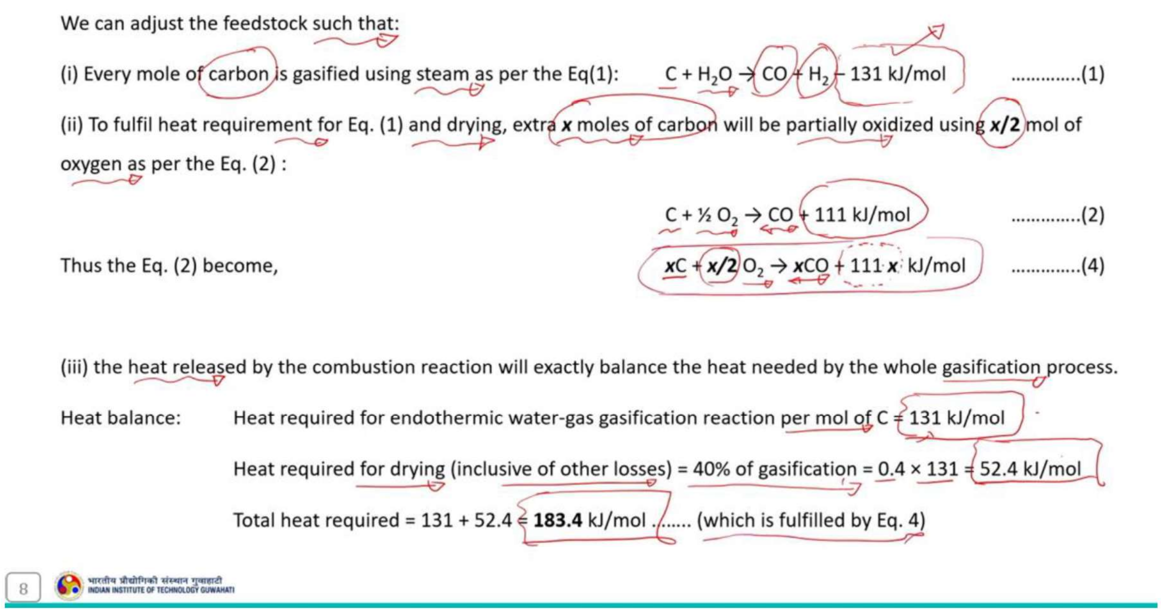

Now we can just adjust the feedstock in such a way that this every mole of carbon is gasified using steam and that is as per the equation 1 here. That is carbon is oxidized in presence of steam to produce carbon monoxide and hydrogen while this process requires this much amount of the energy. And to fulfill this heat requirement of equation 1, because as I mentioned this particular process, it may require this much amount of the energy. So, to fulfill this energy requirement of equation 1 and even the drying as mentioned in the example, so extra x moles of carbon will be partially oxidized using x by 2 moles of oxygen as per the equation 2, that we have just discussed in the previous slide. So, this is the equation number 2, if you remember that is partial combustion of carbon to produce carbon monoxide. And during this reaction it will release this much amount of energy. Now if you just represent this equation as per these extra moles of carbon, so you can simply write down the equation in this form.

$$xC + x/2\ O_2 \rightarrow xCO + 111\,x \text{ kJ/mol} \text{ ....(4)}$$

That is x mole of carbon will be partially oxidized using x by 2 moles of oxygen here to produce x mole of CO plus this much amount of energy into moles of carbon. And even as we know, the heat released by the combustion reaction will exactly balance the heat needed by the whole gasification process. So, if you just try to do this heat balance here, the heat which is required for endothermic water gas gasification reaction per mole of carbon is equal to 131 kilojoule per mole. Similarly, the heat which is required for drying, which is inclusive of the other losses is equal to 40% of the gasification. So, that is 40 percent of this value here, that is 0.4 into 131. And it comes out to be around 52.4 kilojoule per mole. So, the total heat required is summation of these two terms that is 131 plus 52.4. And it comes out to be around 183.4 kilojoule per mole. So, this requirement of the heat here is fulfilled by equation 4.

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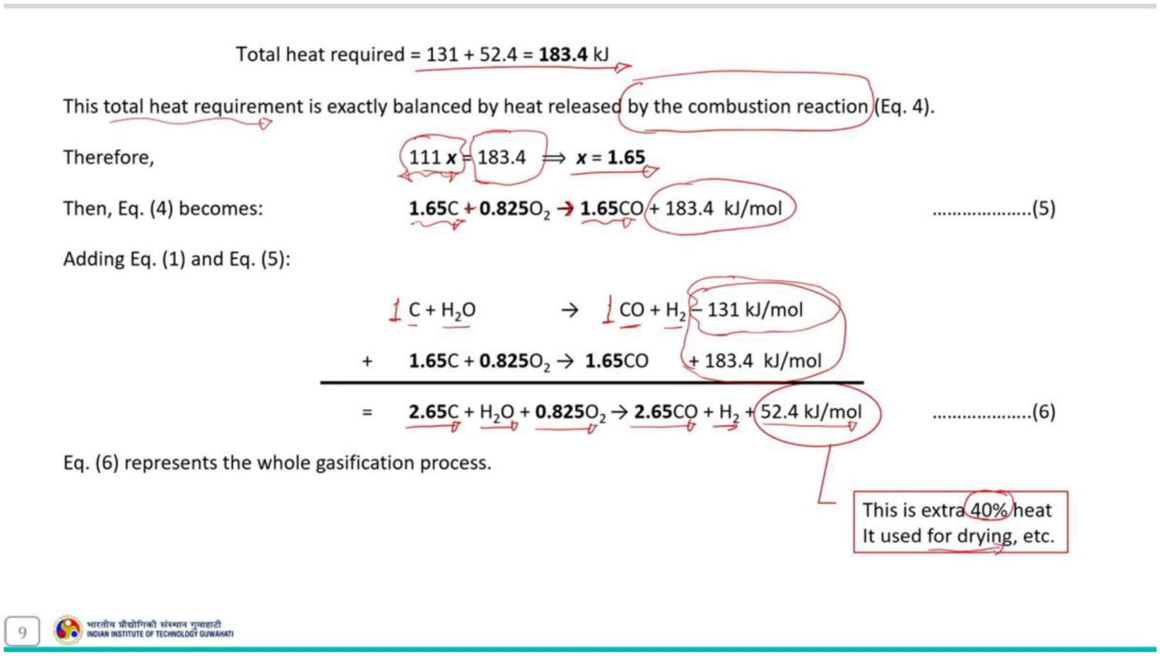

The total heat required as we have calculated it is around 183.4 kilojoule. And this total heat requirement is exactly balanced by heat released during the combustion reaction that is equation 4. So, as we know, this is the amount of energy which is released during this reaction as per the equation 4. And this is the amount of heat which is required for the process. So, if we equate these two terms here we can get the value of x. And once you substitute this value of x in equation 4 so the equation 4 modified in this form.

$$1.65C + 0.825O_2 \rightarrow 1.65CO + 183.4 \text{ kJ/mol} \qquad \ldots\ldots\ldots\ldots(5)$$

$$C + H_2O \rightarrow CO + H_2 - 131 \text{ kJ/mol}$$

$$+ \quad 1.65C + 0.825O_2 \rightarrow 1.65CO + 183.4 \text{ kJ/mol}$$

$$= \quad 2.65C + H_2O + 0.825O_2 \rightarrow 2.65CO + H_2 + 52.4 \text{ kJ/mol} \qquad \ldots\ldots\ldots(6)$$

That is 1.65 moles of carbon plus x by 2 that is 0.825 moles of oxygen produce 1.65 moles of carbon monoxide with this much amount of heat. Now, once we add the equation 1 and the equation 5, so equation 1 if you remember, that is water gas gasification reaction. C plus H_2O it produces CO plus H_2O, and it required this much amount of energy plus the equation number 5. So, after just adding these two equations so here we will have 1 mole of carbon plus 1.65. That will be equal to 2.65 moles of carbon H_2O plus 0.825 mole of oxygen. And it gives around again here 1 mole of carbon monoxide. So that will be 2.65 moles of carbon monoxide plus hydrogen. And once you do this calculation, it will be around plus 52.4 kilojoule per mole and this is what is the extra 40 percent heat used for drying. And this equation 6 it represents the whole gasification process.

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Whole gasification process: $\mathbf{2.65}C + H_2O + \mathbf{0.825}O_2 \rightarrow \mathbf{2.65}CO + H_2 + 52.4\ kJ/mol$ ....(6)

From Eq.(6),

Carbon gasified = 2.65 mol × 12 g/mol = **31.8** g of C

Steam required = 1 mol × 18 g/mol = **18** g of steam

Oxygen required = 0.825 mol × 32 g/mol = **26.4** g of oxygen

Thus, to calculate the amount of steam and oxygen required per kg of carbon:

Steam required = **18** g of steam / **31.8** g of C = 0.57 g_{steam}/g_{Carbon} = **0.57** kg_{steam}/kg_{Carbon}

Oxygen required = **26.4** g of Oxygen / **31.8** g of C = 0.83 g_{oxygen}/g_{Carbon} = **0.83** kg_{oxygen}/kg_{Carbon}

The whole gasification process is represented in this form here. So, from this equation 6 now we can calculate the amount of carbon which is gasified as we know 2.65 mole of carbon is taking part in the whole gasification process. and we know its molar mass that is 12 gram per mole. So, once you do this simple multiplication here it comes out to be around 31.8 gram of carbon. Similarly, we can calculate the steam required here that is 1 mole and this is the molar mass. So, once you do this multiplication it comes out to be around 18 gram of steam is required. And the oxygen which is required during this gasification process is around 0.825 into 32 that comes out to be around 26.4 gram of oxygen. So, since it has been asked to calculate the amount of steam and the oxygen which is required per kilogram of carbon during this gasification process. So, we can simply use this concept here and based on that we can estimate the steam required as well as the oxygen required per kg of carbon. Because we know the quantity of respective terms here which are taking part into this reaction. So, with the help of this given information we can estimate the amount of steam and the oxygen required per kg of carbon. So, first let us try to estimate steam required.

$$\text{Steam required} = 18 \text{ g of steam} / 31.8 \text{ g of C} = 0.57\ g_{steam}/g_{Carbon} = 0.57\ kg_{steam}/kg_{Carbon}$$

$$\text{Oxygen required} = 26.4 \text{ g of Oxygen}/31.8 \text{ g of C} = 0.83\ g_{oxygen}/g_{carbon}$$

$$= 0.83\ kg_{oxygen}/kg_{Carbon}$$

So, as we know it is 18 gram of steam which is required per gram of carbon, but here the carbon is around 31.8 gram. So, if you can simply divide this here, so it will be around 0.57 gram of steam is required per gram of carbon. And similarly, it is in the form of kilogram and the oxygen required will be around. Because we know this much amount of oxygen is required during this process and again the carbon amount is also we know. So, once you just take the division of these two it comes out to be around 0.83 gram of oxygen per gram of carbon and this is the respective amount in the kilogram. So, I hope now it is clear how to estimate the amount of heat which is required for the gasification process with the help of heat balance. And similarly, we can also estimate the amount of steam or the oxygen which is required for per kg of carbon during this gasification process.

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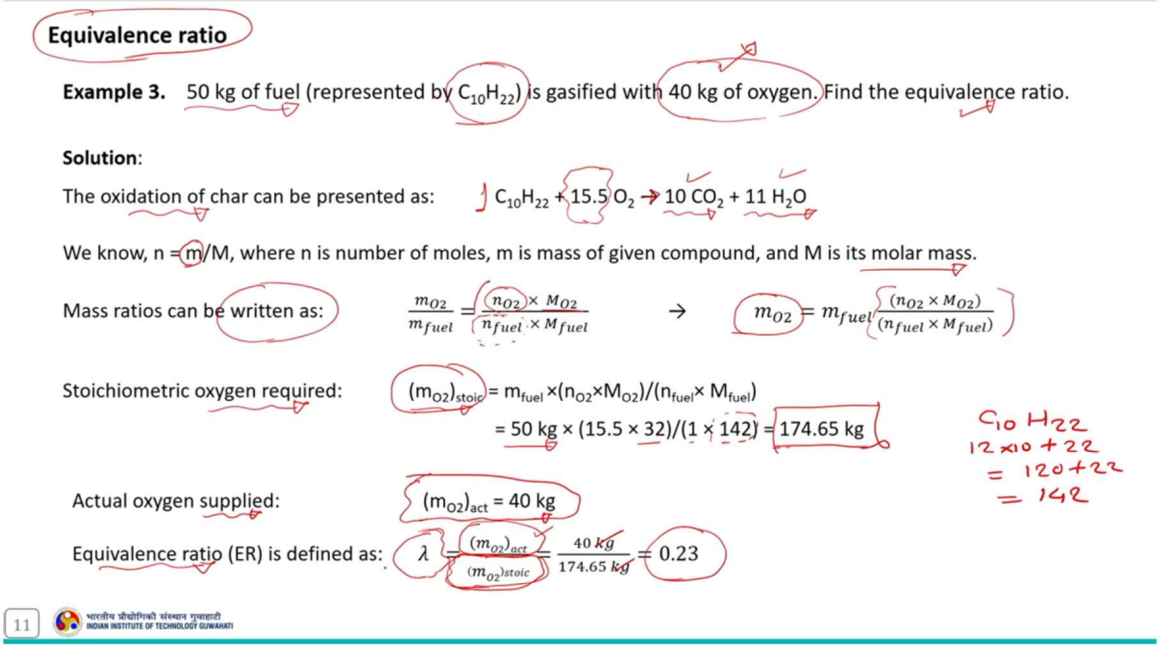

Now, let us move on to the next example, that is on equivalence ratio and this is one of the important concepts in the combustion as well as in the gasification process. So, here it is 50 kg of fuel which is represented by decane here. This is the fuel and it is gasified with 40 kg of oxygen. So, we need to find out the equivalence ratio for this particular feed and the amount of oxygen which is given here for this specific process. As we know, the fuel is decane, so we can just simply write down the oxidation of this particular reaction.

$$C_{10}H_{22} + 15.5\ O_2 \rightarrow 10\ CO_2 + 11\ H_2O$$

So, once you oxidize this particular fuel, it may produce 10 mole of carbon dioxide along with 11 moles of H_2O. And it may require around 15.5 mole of oxygen to achieve this conversion to produce 10 moles of CO_2 plus 11 moles of H_2O.

$$\frac{m_{O2}}{m_{fuel}} = \frac{n_{O2} \times M_{O2}}{n_{fuel} \times M_{fuel}} \quad \rightarrow \quad m_{O2} = m_{fuel} \frac{(n_{O2} \times M_{O2})}{(n_{fuel} \times M_{fuel})}$$

And we know this n is equal to m this is mass of the given fuel or you can say the feedstock. And this capital M is the molar mass. So, this mass ratio can be written in this particular form here, that is mass of oxygen by mass of fuel. And we know how to represent this mass of oxygen that is number of moles of oxygen into its molar mass. Similarly, this represent the number of moles of fuel into its molar mass. And if you have to just represent in this particular form that is mass of oxygen. Then you can just simply do this small rearrangement that is mass of fuel into this specific ratio here, so it gives us the mass of oxygen. Now, we can estimate this stoichiometric oxygen which is required from this particular mass ratio equation.

$$(m_{O2})_{stoic} = m_{fuel} \times (n_{O2} \times M_{O2})/(n_{fuel} \times M_{fuel})$$
$$= 50 \text{ kg} \times (15.5 \times 32)/(1 \times 142) = 174.65 \text{ kg}$$

That is mass of oxygen that is stoichiometric requirement of oxygen equal to the mass of fuel. So, mass of fuel is given as 50 kilograms into moles of oxygen that is 15.5 into is molar mass that is 32. And the mass of fuel here is 1 mole into its molar mass that is $C_{10}H_{22}$ that is 12 into10 plus 22. So, the final answer would be around 120 plus 22 which is equal to 142. So, this is the molar mass of decane and once you do this and once you do this simple calculation so the stoichiometric amount of oxygen required is around this much. But, since it is given that the actual oxygen supplied during this process is around 40 kilograms only. So, that is the actual oxygen which is supplied during this process.
So, with the help of this given information of stoichiometric amount of oxygen, which is required, and also the actual amount which is required for the gasification of this fuel. So, with the help of these two data we can calculate the equivalence ratio. And that is defined as the mass of actual oxygen which is required for the gasification process to the mass of oxygen is to be used in the stoichiometric equation.

$$\lambda = \frac{(m_{O2})act}{(m_{O2})stoic} = \frac{40\ kg}{174.65\ kg} = 0.23$$

And we know both these values. So, once you substitute these values here in this equation, so we can get the equivalence ratio as 0.23. Because as you know this is a gasification operation and it is carried out in the oxygen deficient environment. Therefore, the oxygen which is required at actual rate in the gasification process is only

40 kg. Whereas the stoichiometric oxygen which you have calculated for this given fuel is around 174.65 kg. But then once we use this stoichiometric amount of oxygen then it will be converted into a combustion process rather than the gasification. Because the gasification required oxygen deficient atmosphere to achieve the desired product. So, based on that this term here it indicates the actual oxygen which is required for the gasification process to that of the stoichiometric amount of the oxygen. Once you substitute these values here we will get the equivalence ratio for the specific fuel. And such kind of equivalence ratio can be calculated for various other fuels.

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Fischer–Tropsch synthesis

Example 4. For 1 kg of CO, calculate the hydrogen required to produce methane, butanol, and butane, respectively using Fischer–Tropsch synthesis. Also calculate the mass of the desired products.

Solution:

Molar masses: M_{CO} = 28.01 g/mol; M_{H2} = 2.016 g/mol; M_{CH4} = 16.042 g/mol; M_{C4H9OH} = 74.12 g/mol; M_{C4H10} = 58.12 g/mol

(a) Methane synthesis : $CO + 3H_2 \rightarrow CH_4 + H_2O$

From the stoichiometry of the reaction,

$$w_{H2} = w_{CO} \times (n_{H2} \times M_{H2})/(n_{CO} \times M_{CO}) = 1\ kg \times (3\ mol \times 2.016\ g/mol)/(1\ mol \times 28.01\ g/mol) = 0.2159\ kg$$

$$w_{CH4} = w_{CO} \times (n_{CH4} \times M_{CH4})/(n_{CO} \times M_{CO}) = 1\ kg \times (1\ mol \times 16.042\ g/mol)/(1\ mol \times 28.01\ g/mol) = 0.5727\ kg$$

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Let us move on to the next example, which is on the concept of Fischer-Tropsch synthesis process. So, here we need to calculate the mass of the desired products. Here in this example for 1 kg of carbon monoxide we need to calculate the hydrogen required to produce methane, butanol, and butane, using Fischer-Tropsch synthesis concept. And also, we need to calculate the mass of the desired products. So, let us begin with the solution of this example. Because the molar mass of carbon monoxide is this much. Similarly, the molar mass of hydrogen molar mass of butanol and molar mass of butane, the molar mass of methane is this much. So, let us first discuss about the methane synthesis where 1 mole of carbon monoxide reacts with 3 moles of hydrogen to produce 1 mole of methane and 1 mole of water.

$$CO + 3H_2 \rightarrow CH_4 + H_2O$$

So, from the stoichiometry of this particular reaction we can calculate the mass ratio here, that is the mass of hydrogen by the mass of carbon monoxide equal to the moles of hydrogen into the molar mass of hydrogen divided by the moles of carbon monoxide into the molar mass of carbon monoxide.

$$w_{H2} = w_{CO} \times (n_{H2} \times M_{H2})/(n_{CO} \times M_{CO})$$

$$w_{H2} = 1 \text{ kg} \times (3 \text{ mol} \times 2.016 \text{ g/mol})/(1 \text{ mol} \times 28.01 \text{ g/mol}) = 0.2159 \text{ kg}$$

$$w_{CH4} = 1 \text{ kg} \times (1 \text{ mol} \times 16.042 \text{ g/mol})/(1 \text{ mol} \times 28.01 \text{ g/mol}) = 0.5727 \text{ kg}$$

And here, if you see the mass of carbon monoxide is around 1 kg, that is on the mass basis, if you see here. And number of moles of hydrogen are around 3 and the molar mass of hydrogen is around 2.06 gram per mole. Number of moles of carbon monoxide is around 1 mole here and its molar mass is 28.1. So, with the help of this given data if you just do this simple multiplication and division we will get the respective amount of hydrogen. Similarly, once you try to calculate it for the methane so we can just simply calculate for the methane also here in this particular way. That is again 1 kg of CO is given here in the example. And just replacing the respective values from the given equation here, as well as from the molar mass values here, we will get the final answer in the form of 0.5727 kilogram. So, it indicates this much amount of hydrogen is required to produce this much amount of methane.

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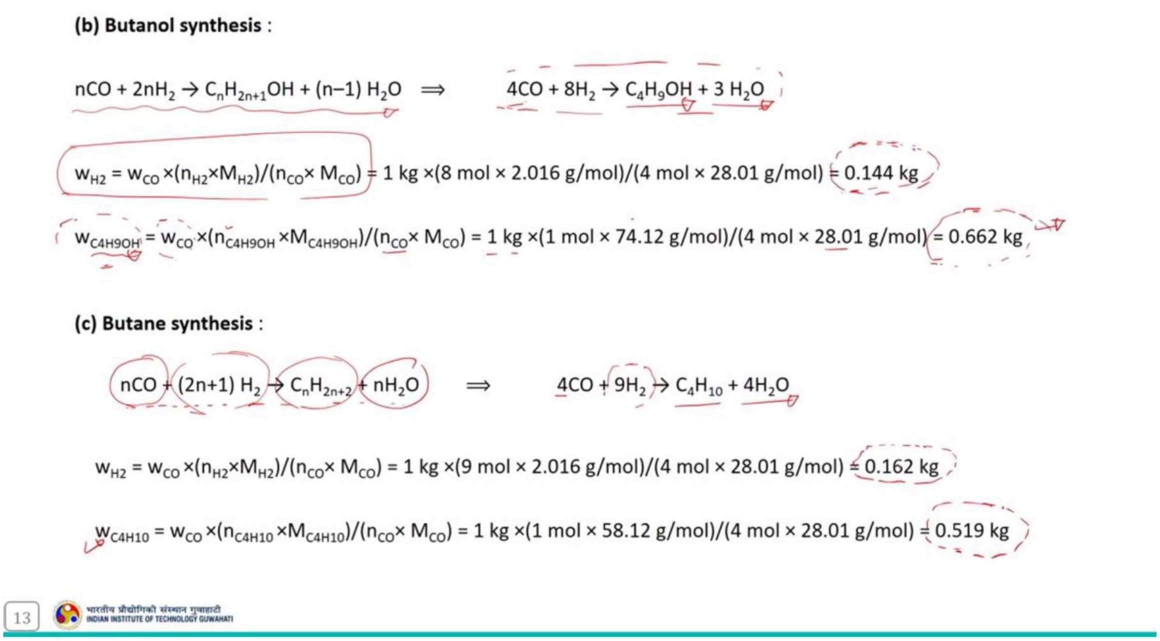

Similarly, for butanol synthesis we can represent the reaction in the generic form like this.

$$4CO + 8H_2 \rightarrow C_4H_9OH + 3\ H_2O$$

Where it is n mole of CO plus 2n moles of hydrogen once it reacts to form $C_nH_{2n+1}OH$ plus n minus 1 H_2O. So, now once we replace this n here, in the form of required moles to balance this reaction, so 4 moles of carbon monoxide once it reacts with 8 moles of H2, it forms butanol plus 3 moles of water. So, now for this stoichiometric reaction again, if you can write down the mass ratio for hydrogen and butanol then with the help of this above equation we will come to know the amount of hydrogen which is required to produce butanol.

$$w_{H2} = 1\ kg \times (8\ mol \times 2.016\ g/mol)/(4\ mol \times 28.01\ g/mol) = 0.144\ kg$$
$$w_{C4H9OH} = 1\ kg \times (1\ mol \times 74.12\ g/mol)/(4\ mol \times 28.01\ g/mol) = 0.662\ kg$$

So, here this is the amount of butanol which is getting produced for that we know 1 kilogram of carbon monoxide this is the given value and this indicates the moles of butanol. That is 1 mole into its molar mass divided by 4 moles of carbon monoxide into its molar mass. So, once you do this simple calculation it comes out to be 0.662. So, this indicates the amount of butanol which is getting produced and for which it required this much amount of hydrogen.

And in the similar line we can estimate for the butane synthesis as well. So, the general equation is represented in this form here it shows carbon monoxide once it reacts with the hydrogen it produces butane and water.

$$4CO + 9H_2 \rightarrow C_4H_{10} + 4H_2O$$

So, if you can just balance this reaction again 4 moles of carbon monoxide react with now 9 moles of hydrogen to produce butane and 4 moles of water.

Again, from this stoichiometric equation and with the help of the mass ratio equation, we can calculate the amount of hydrogen which is required to produce 1 mole of butane.

$$w_{H2} = 1\text{ kg} \times (9\text{ mol} \times 2.016\text{ g/mol})/(4\text{ mol} \times 28.01\text{ g/mol}) = 0.162\text{ kg}$$
$$w_{C4H10} = 1\text{ kg} \times (1\text{ mol} \times 58.12\text{ g/mol})/(4\text{ mol} \times 28.01\text{ g/mol}) = 0.519\text{ kg}$$

And similarly, we can calculate it for the butane as well and it comes out to be 0.519. So, it indicates that 0.162 kg of hydrogen is required to produce 0.519 kg of butane. I hope this is clear to all of you now how to do the mass balance in the pyrolysis process as well as in the gasification process as well as how to estimate the equivalence ratio required for the gasification operation. Similarly, we have also done the calculation for the specific product which is getting produced during the Fischer-Tropsch synthesis process. And the amount of hydrogen which is required to produce the specific product. And the example of similar type would be given in the assignment. Apart from that we can also practice some example just by changing the fuel. So, instead of decane now just go for the butane, propane, methane. And try to find out the equivalence ratio also for the specific fuel, if you are using in the gasification operation. As well as also try to find out the amount of hydrogen which is required to produce various other product using the Fischer-Tropsch synthesis concept.

So, with this we will stop here. And in the next lecture, which will be the first lecture of module 5, we will discuss about the biochemical conversion processes. In that we will discuss about the anaerobic digestion in landfills, landfill gas and biogas, bioconversion into biogas, single or two-stage anaerobic digestion process, wet and dry fermentation and integrated centralize co-digestion plant concept.

Thank you.