Energy Conversion Technologies (Biomass and Coal)

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Lecture 29

Combustion Process (Biomass and Coal)

Good morning everyone.

Welcome to this third lecture of module 7. So, here in this lecture we will practice example on the important topics covered in this module that is stoichiometry of combustion reaction equivalence ratio and excess air calculation. So let us begin with the first example.

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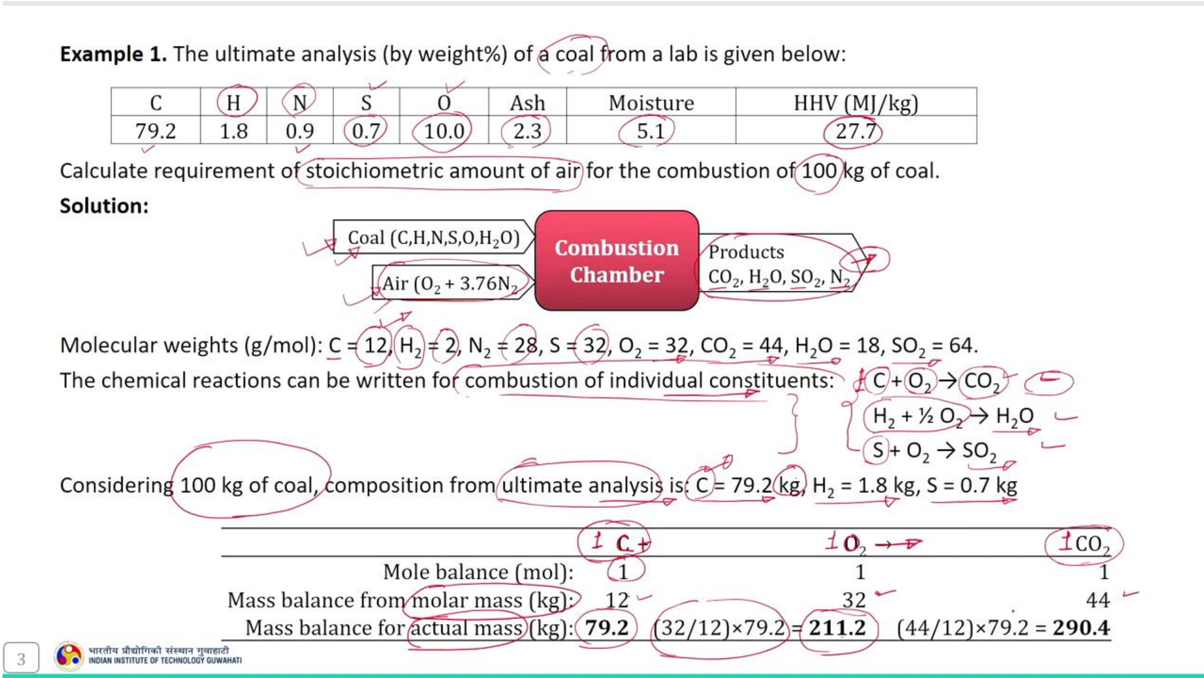

So in this example the ultimate analysis of coal is given that is carbon 79.2 percent, H 1.8 percent, N 0.9, S 0.7 and O 10 percent. Ash is given as 2.3% and while the moisture is 5.1% in the given coal sample and the high reading value it is given as 27.7. So, based on this given data we need to calculate the requirement of stoichiometric amount of air required for the combustion of 100 kg of coal sample. Let us begin with the solution of this example.

So, in this example, we need to calculate the stoichiometric amount of air required for the complete combustion of the given coal sample to produce the product. Now, if you see the product composition here, so here in this composition, there is no oxygen here which indicates that the complete combustion of the fuel and the complete utilization of the oxidizer in the combustion process. So, now here the molecular weight of this component here that is carbon is 12, in terms of hydrogen it is 2, nitrogen 28, S sulphur that is 32, oxygen, carbon dioxide water and sulphur dioxide. So, now the chemical reaction it can be written for the combustion of the individual constituents in the given sample. If you recollect our discussion in one of the lecture of the module 1, we discussed this concept of chemical reaction for the combustion of individual constituents in a given fuel sample.

And as we discussed there the carbon, hydrogen and sulfur are the main constituents which takes parts in the combustion process. And it gets oxidized to produce product in the form of carbon dioxide, hydrogen it forms H_2O and the sulfur it get oxidized to form sulfur dioxide. And considering here the 100 kg of coal sample composition from the ultimate analysis is given here that is carbon 79.2 kg, hydrogen 1.8 kilogram and sulfur is 0.7 kilogram. So, based on this given information, we can write down the mole balance and the mass balance for these 3 reactions. So, first let us try to write the mass balance and the mole balance for first reaction that is carbon oxidized to form carbon dioxide. So, from the mole balance here, the 1 mole of carbon from this reaction that is 1 mole of carbon is oxidized in presence of 1 mole of oxygen to produce 1 mole of carbon dioxide. Now, the mass balance from the molar mass that is on kilogram basis.

So, see as we know the carbon it is 12. So, here also we have represented this reaction that is carbon plus oxygen, it produces carbon dioxide. And here the 1 mole of carbon is oxidized in presence of 1 mole of oxygen to produce 1 mole of carbon dioxide and the mass balance from this molar mass that is based on the kilogram. So, carbon here it is 12 as we know from this values here oxygen 32 and carbon dioxide is 44. So, the mass balance for actual mass on kilogram basis that is because we know the carbon from the ultimate analysis of the given coal sample is 79.2 kilogram. And hence the amount of oxygen required to completely oxidize this carbon can be calculated using this small calculation here because since we know the 1 mole of carbon required 1 mole of oxygen to completely oxidize and form the 1 mole of CO_2. And the mass balance from the molar mass it is 12 for carbon and it is 32 for the oxygen. And mass balance for the actual mass in kilogram here it is 79.2 kilogram of carbon. So, based on that the amount of oxygen required would be around 211.2 kilogram that is 32 by 12 into 79.2. And similarly the carbon dioxide mass balance can also be calculated from this actual mass of 79.2 kg of carbon that is 44 by 12 into 79.2 which comes out to be around 290.4.

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	H_2 +	½ O_2 →	H_2O
Mole balance (kg/kmol)	1	½	1
Mass balance from molar mass (kg)	2	32/2= 16	18
Mass balance for actual mass (kg)	1.8	(16/2)×1.8= **14.4**	(18/2) ×1.8= 16.2

	S +	O_2 →	SO_2
Mole balance (kg/kmol)	1	1	1
Mass balance from molar mass (kg)	32	32	64
Mass balance for actual mass (kg)	0.7	(32/32)×0.7= **0.7**	(64/32)×0.7= 1.4

Total stoichiometric oxygen required = 211.2 + 14.4 + 0.7 = 226.3 kg

Oxygen already present in 100 kg coal (given) = 10 kg

Additional oxygen required = 226.3 – 10 = 216.3 kg oxygen

The quantity of dry air required (air contains 23% oxygen by wt.) = 216.3/0.23 = 940.4 kg air

Therefore, stoichiometric (theoretical) amount of air required for the combustion of 100 kg of coal is 940.4 kg.

Similarly, we can represent the mass balance for actual mass for the above reaction that is hydrogen reacts with oxygen to form H_2O. So, mole balance here 1 mole of hydrogen oxidized in presence of half a mole of O_2 produces 1 mole of H_2O. The mass balance from the molar mass here it is 2 and since we know the molar mass of oxygen is 32. And since only half of this mole of oxygen is utilized to oxidize the hydrogen so it is 32 by 2 equal to 16 and it produces 1 mole of water that is 18. So, now based on this molar mass, we can calculate the mass balance for the actual mass in kilogram and it is 1.8 kilogram of hydrogen. It requires around 14.4 kilogram of oxygen to produce 16.2 kilogram of water. And here again the calculations are done in the similar way as we have done in the previous case that is carbon which is getting oxidized in presence of oxygen to form CO_2.

And in the similar line the sulfur is oxidized to produce sulfur dioxide. So, again here the 1 mole of sulfur is oxidized with 1 mole of oxygen to produce 1 mole of sulfur dioxide. And the mass balance from the molar mass that is on kilogram basis, it is 32 for sulfur, oxygen 32 and sulfur dioxide it is 64. So, the mass balance for actual mass that is 0.7 kg which is known from the ultimate analysis of the given coal sample.

So, the 0.7 kg of sulfur required around 0.7 kg of oxygen because equal moles and produces around 1.4 moles of sulphur dioxide. So, from these three mass balance equation for the actual mass we can calculate the total stoichiometric oxygen which is required for the combustion process that is 211.2. Which is mass balance for the actual mass of carbon which oxidizes in presence of oxygen to produce carbon dioxide and that is 211.2 and for hydrogen it is 14.4 and for sulphur it is 0.7.

So, once you take the summation of these three values it comes out to be 226.3 kilogram. So, that is the total stoichiometric oxygen which is required for the combustion process. So, this is the total stoichiometric oxygen required for the combustion of given coal sample. The oxygen which is already present in the 100 kg of fuel is given in this example. So, if you just recollect here the oxygen is given as 10 percentages. So, the additional oxygen which is required for this combustion of the given coal sample is 226.3 and minus this 10 because this is the oxygen which is already present in 100 kg of coal. So, the additional oxygen which is required is around 216.3 kilogram of oxygen. Because the total stoichiometric oxygen required for the combustion of the given coal sample is 226.3.

However, the 10 kg of oxygen is already present in the given coal sample. So, only the additional oxygen which is required for the oxidation or the combustion of the given coal sample need to be supplied for the complete combustion of the fuel and that is around 216.3 kg of oxygen. So, now based on this the quantity of dry air which is required can also be calculated because we know air contains around 23 percent of oxygen and that is by weight and this is the amount of oxygen which is required for the combustion of the given coal sample. So, based on these two values we can estimate the quantity of dry air which is required.

So, that is 216.3 divided by 0.23 that is air contains 23 percent of the oxygen by weight and once we calculate these value it comes out to be 940.4 kilogram of air. So, for combustion of 100 kg of coal it requires around 940.4 kg of air according to this stoichimetry of combustion reaction.

And in case if the pure oxygen is used for the combustion process, then the additional oxygen which is required for the combustion of this given coal sample is 216.3 kg of oxygen is required for the complete combustion of the given coal sample. Because the 10 kg of oxygen is already present in the coal sample. Therefore, the stoichiometric or we can also say the theoretical amount of air which is required for the combustion of 100 kg of coal is 940.4 kg.

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Example 2. Consider the stoichiometric combustion of dry redwood at 1 atmosphere. The ultimate analysis of redwood is 53.8% C, 5.9% H, 40.3% O, <0.1% N, and <0.1% S (by weight). Find :

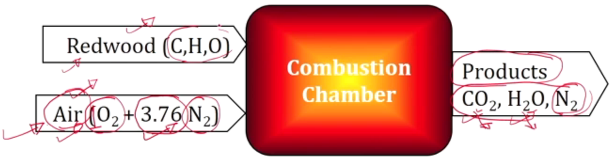
(i) stoichiometric amount of air for the combustion of redwood,

(ii) fuel–air mass ratio,

(iii) composition of the products on a mass basis, and

(iv) theoretical CO_2% in dry flue gas by volume.

Solution:



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So, in the similar line we can also estimate the stoichiometric amount of air required for the combustion of the redwood. So, this is another example also we can estimate the fuel to air mass ratio for the given fuel sample and composition of the product on mass basis. And once we know the composition of the product on mass basis, then you can also calculate the theoretical carbon dioxide percentage in dry flue gas by volume considering the stoichiometric combustion of dry redwood at 1 atmospheric pressure. The ultimate analysis of the redwood is given as 53.8% carbon dioxide, 5.9% hydrogen, 40.3% oxygen and close to around 0.1% nitrogen and similarly is the sulfur and this composition is given by weight percent.

So, based on this given data we need to find out the stoichiometric amount of air for the combustion of the redwood, fuel to air mass ratio, composition of the product on mass basis as well as the theoretical carbon dioxide percentage in a dry flue gas. So, here this schematic it represents the combustion of redwood which consists of chemical formula that is CHO and it is combusted in presence of oxidizer that is air.

So, in this case the fuel and the oxidizer are completely oxidized to form product that is carbon dioxide H_2O and nitrogen. If you recollect our discussion in the previous lecture, we discussed about this concept of composition of the air that means it contains 1 mole of oxygen and 3.76 moles of nitrogen. So, here 1 mole of oxygen is accompanied by 3.76 moles of oxygen if the air is used as an oxidizer during the combustion process.

So, if you look at this product composition here, it contains carbon dioxide and H_2O along with the nitrogen. And among this product, carbon dioxide and H_2O are the oxidized products of the carbon and the hydrogen. So, we will just try to write down this mass balance or the molar balance terms for carbon, hydrogen and the oxygen.

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(i) To determine stoichiometric amount of air for the combustion of redwood:

Using 100 kg of fuel as a basis for calculation.

	m (kg)	M (kg/kmol)	n (kmol)	Normalized moles
C	53.8	12	4.48	1.00
H	5.9	1	5.90	1.32
O	40.3	16	2.52	0.56

The stoichiometric equation for given biomass becomes:

$$CH_{1.32}O_{0.56} + 1.048\,(O_2 + 3.76\,N_2) \rightarrow CO_2 + 0.66\,H_2O + 3.94\,N_2$$

$$C_aH_bO_c + \left(a + \frac{b}{4} - \frac{c}{2}\right)(O_2 + 3.76\,N_2) \rightarrow a\,CO_2 + \left(\frac{b}{2}\right) H_2O + 3.76\left(a + \frac{b}{4} - \frac{c}{2}\right) N_2$$

So, now let us first determine the statometric amount of the air which is required for the combustion of redwood. So, from the ultimate analysis we know the carbon, hydrogen and the oxygen percentage that is by mass. Because as we are considering 100 kg of fuel as a basis for the calculation. So, the carbon content in the fuel is around 53.8, H is 5.9 and oxygen is 40.3 and the molecular weights is 12 for H1 and O it is 16. So, based on this given information if you can just find out the number of moles that is in the form of kilo moles. So, it is simply 53.8 divided by 12 and it comes out to be around 4.48. Similarly, for H it is 5.9 and for O it is 40.3 divided by 16 and it comes out to be around 2.52. So, if you try to normalize these moles on the basis of carbon content in the given field sample which comes out to be around 1 here that means 4.48 divided by 4.48 which is 1, and for hydrogen it is 5.90 divided by 4.48 which comes out to be around 1.32 and for O it is 0.56.

So, based on these given moles in the feed material the stoichiometric equation for the given sample can be written in this form that is carbon which is 1 mole H 1.32 O 0.56 and it is combusted in presence of air. So, this indicates the air that is mixture of oxygen and nitrogen and produces CO_2 0.66 moles of H_2O and 3.94 moles of nitrogen. And to balance this equation it require around 1.048 moles of air to completely combust this biomass to produce CO_2, H_2O and nitrogen as a product of given composition. And if you recollect our discussion in the previous lecture we represented the combustion equation for the biomass that is with oxygen or without oxygen. So, this is the equation if the biomass contains oxygen in its composition it requires these many moles of air to completely combust this fuel to produce CO_2, H_2O and nitrogen as a product. So, let us try to write the mass balance for the given stoichiometric equation.

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Mass balance for above stoichiometric equation:

	$CH_{1.32}O_{0.56}$ +	$1.048\ (O_2 + 3.76\ N_2)$ →	CO_2 +	$0.66\ H_2O$ +	$3.94\ N_2$
Mole balance (kg/kmol):	1	1.048	1	0.66	3.94
Mass balance (kg):	12+1.32+0.56×16 = 22.28	1.048×4.76×28.85 = 143.92	1×44 = 44	0.66×18 = 11.88	3.94×28 = 110.32

Thus, stoichiometric air required for the combustion of redwood = 143.92/22.28 = 6.46 kg/kg of redwood .

(ii) To find fuel-to-air ratio:

Stoichiometric fuel-to-air mass ratio: $FAR_{sto} = FAR_{sto} = \left(\frac{m_{fuel}}{m_{air}}\right)_{sto} = 22.28 / 143.92 = 0.155$

(iii) To find composition of the products on a mass basis:

Total mass of products: $\sum m_{products} = m_{CO2} + m_{H2O} + m_{N2} = 44 + 11.88 + 110.32 = 166.2$ kg

Composition of the products on a mass basis: $y_i = m_i / \sum m_{products}$

$y_{CO2} = 44/166.2 = 0.265$

$y_{H2O} = 11.88/166.2 = 0.072$

$y_{N2} = 110.32/166.2 = 0.664$

So, since we know the fuel is oxidized in presence of air, to produce CO_2, H_2O and nitrogen as a product. So, from the mole balance 1 mole of fuel is oxidized using 1.048 moles of air to produce 1 mole of carbon dioxide, 0.66 mole of H_2O and 3.94 mole of nitrogen. So, if you write down the mass balance here, so the carbon that is 12 plus 1.32 into 1 plus 0.56 into 16 that is molar mass of oxygen here and it comes out to be around 22.28. Similarly for the air it is 1.048 into 4.76 into 28.85 that is molar mass of air we are considering as 28.85 or sometimes you may find that we are considering it as a round of figure that is 29 and it comes out to be around 143.92. Similarly, for carbon dioxide it is 1 into 44 that is molar mass of carbon dioxide and for water it is 0.66 into 18 that is 11.88 and for nitrogen it is 3.94 into 28 which comes out to be around 110.32. So, thus the stoichiometric air which is required for the complete combustion of redwood is 143.92 divided by 22.8 that is mass of air divided by the mass of fuel and it comes out to be around 6.46 kg of air per kg of fuel that is redwood here in this case.

So, to find the fuel to air ratio for the given sample, the stoichiometric fuel to air ratio can be calculated using this correlation. That is mass of fuel by mass of air and that is the stoichiometric quantity. So, we know the mass of the fuel that is 22.28 as per this stoichiometric equation and the mass of fuel is 143.28. So, it comes out to be around 0.155. So, the stoichiometric field to air mass ratio for the given sample comes out to be around 0.155. Similarly we can find out the composition of the product on mass basis because the total mass of the product we know that is mass of CO_2, mass of water and mass of nitrogen.

So, here it is 44 plus 11.88 plus 101.32 and if you take the summation of these three terms it comes out to be around 166.2 kilogram. So, the composition of the product on the mass basis can be calculated using these equations that is for CO_2 it is mass of the individual component that is mass of CO_2 divided by the total mass of the product that is 166.2 and it comes out to be around 0.265. Similarly, for H_2O it is 11.88 that is the mass of water in the product divided by the total mass of the product is 166.2. And it comes out to be around 0.072 and similarly is the nitrogen it is around 0.664. And this gives the composition of the product on mass basis.

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(iv) To determine theoretical CO_2% (by volume) in dry flue gas:

Theoretical composition of flue gas (by mole): CO_2 = 1 mole

H_2O = 0.66 mole

N_2 = 3.94 mole

Theoretical CO_2% (by volume) in dry flue gas = (moles of CO_2)/(total dry gas moles) × 100

= 1/(1+3.94) × 100

= 20.24%

So, next is the theoretical carbon dioxide percentage by volume in dry flue gas. And since we know the composition of the flue gas that is a theoretical composition of the flue gas which contains 1 mole of CO_2, 0.66 mole of H_2O and 3.94 mole of nitrogen. So, this is the theoretical composition of the flue gas, which we have calculated from the stoichiometric equation of the given fuel sample.

So, this theoretical carbon dioxide percentage by volume in dry flue gas, it is ratio of moles of carbon dioxide in a flue gas divided by the total dry gas moles. And here if you try to take the note of this term this is a total dry gas mole. So, in that case we need to exclude the H_2O in this term and hence we can take the summation of only CO_2 plus nitrogen and exclude moisture or the water vapor in the flue gas. And the moles of CO_2 we know it is 1 mole and total dry gas moles excluding H_2O is 1 plus 3.94 and it comes out to be around 20.24. So, the theoretical carbon dioxide percentage in dry flue gas is around 20.24 percent.

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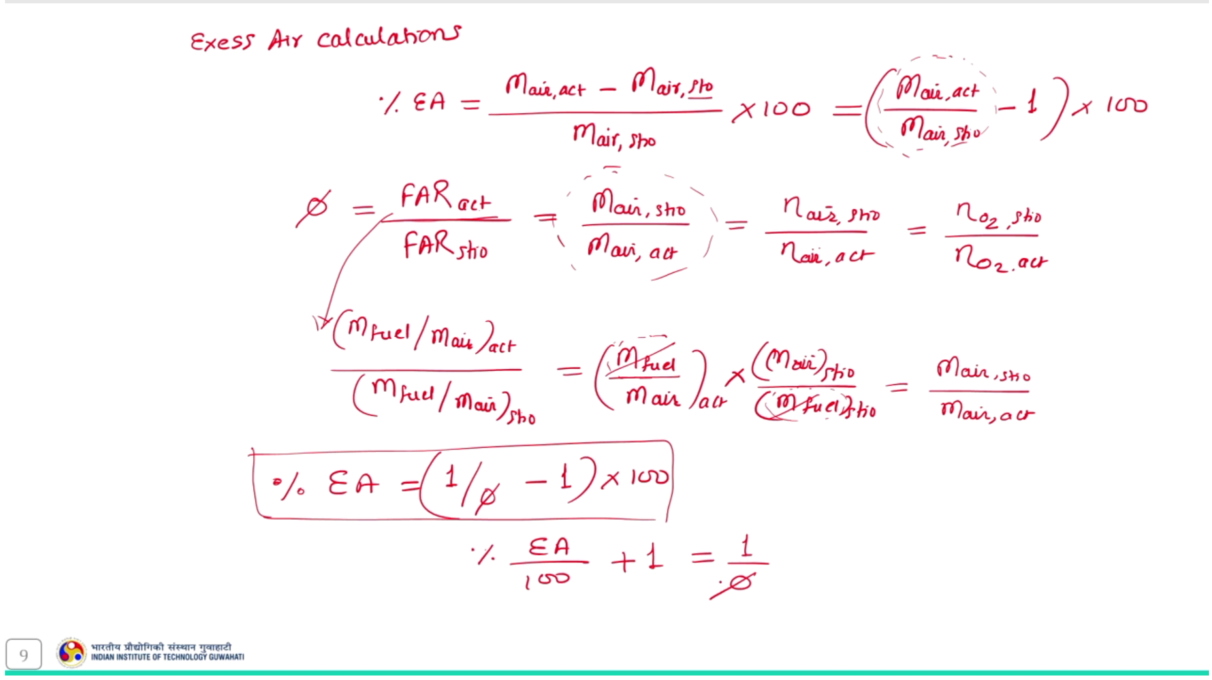

So, if you recollect in the previous lecture we discussed one important concept that is excess air calculation. So, in that if you recollect the percentage excess air was represented in the form of following equation. That is percentage excess air equal to mass of air that is actual minus that is mass of air stoichiometric quantity divided by mass of air again the stoichiometric quantity into 100.

And so, just by separating this term here, it can be represented in the form of mass of air that is actual divided by mass of air stoichiometric quantity minus 1 into 100. Similarly, the equivalence ratio represented as fuel to air ratio that is actual by fuel to air ratio stoichiometric quantity equal to mass of air stoichiometric quantity divided by mass of air actual equal to the moles of air that is a stoichiometric quantity again by moles of air actual. And if we represent in the form of oxygen, so here it is moles of oxygen by moles of oxygen actual quantity. And this here it is basically if you try to expand this term that is fuel to air ratio actual. So, we can represent this fuel to air ratio actual as mass of fuel by mass of air that is actual divided by mass of fuel by mass of air stoichiometric quantity.

So, if you just rearrange these terms, so it is mass of fuel by mass of air actual into, it will just become reverse, it will be mass of air stoichiometric quantity by mass of fuel stoichiometric quantity. So, in this case now if you see this mass of the fuel which is same here that is for actual or maybe you can say for the stoichiometric. So, the final equation it comes out to be mass of air that is stoichiometric quantity by mass of air that is the actual quantity required for the combustion process. And in this equation here if you substitute this term from the equivalence ratio, so this percentage excess air can be represented in the form of 1 by phi minus 1 into 100 because phi equal to mass of air stoichiometric quantity by mass of air actual quantity.

So here it is just reversed of this term. So that is why it is 1 by phi minus 1 into 100 and that gives us the percentage excess air. And if you simply rearrange this equation, so we can write down percentage excess air by 100 plus 1 is equal to 1 by phi.

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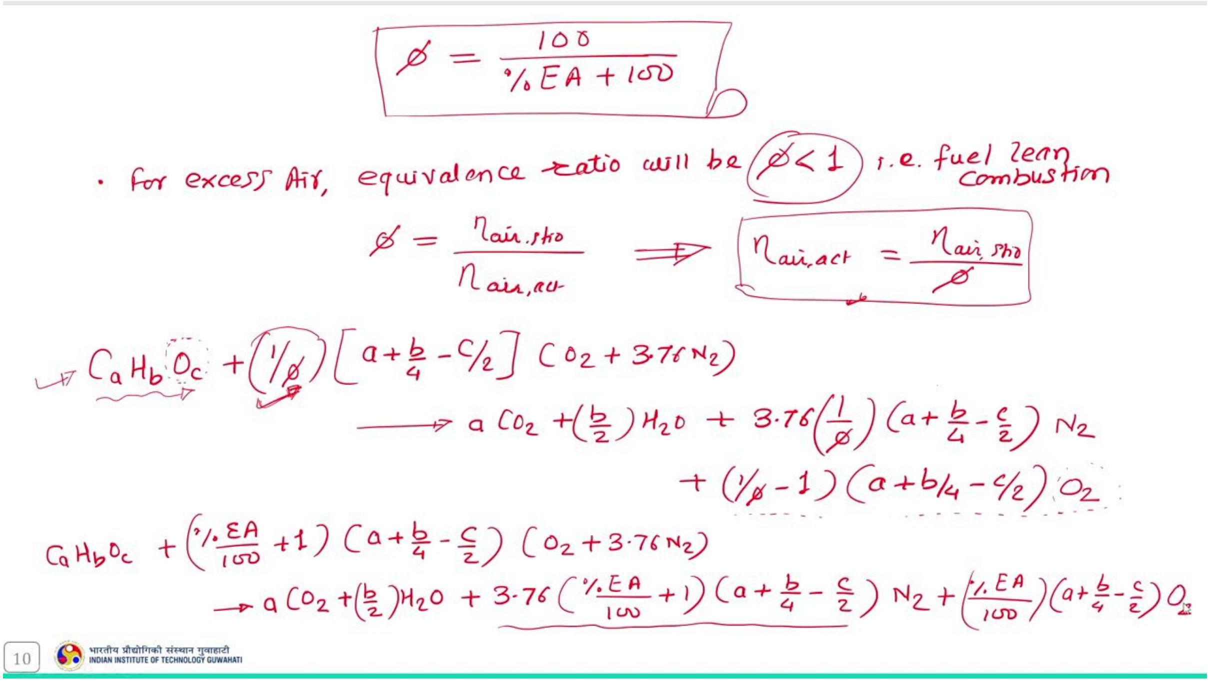

And then this phi equal to 100 divided by percentage excess air plus 100. So, this gives us the equivalence ratio say for excess air, this equivalence ratio will be less than 1 and that is why it is termed as fuel lean combustion.

Thus from the above equation that is the equation of the equivalence ratio. So, from this equation we can represent the equivalence ratio as moles of air statuette quantity by moles of air actual quantity and if you just rearrange this that is actual is equal to divided by phi. So, we can use this term to write the general stoichiometric combustion reaction equation for a solid fuel that is plus 1 by phi into a plus b by 4 minus c by 2 into oxygen plus 3.76 moles of nitrogen, and which gives a moles of CO_2 plus b by 2 moles of H_2O plus 3.76 moles into 1 by phi into these many moles of nitrogen plus these many moles of oxygen.

And this is applicable when the product flue gas contains oxygen in its composition. And if you recollect, we discussed this equation in the previous lecture where the oxygen is already present in the given solid fuel. So, now if you substitute 1 by phi term from this equation here, then the modified equation would be plus so instead of 1 by phi. We will write percentage excess air by 100 plus 1 into a plus b by 4 minus c by 2 into this composition of air. That is oxygen plus 3.76 moles of nitrogen and it gives a moles of CO_2 plus these many moles of H_2O plus 3.76 into excess air by 100 plus 1 into a plus b by 4 minus c by 2. So, these many moles of nitrogen percentage excess air by 100 into a plus b by 4 minus c by 2 into oxygen.

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∴ In exhaust gas, the ratio of mole fractions betn CO_2 & O_2 is,

$$\frac{x_{CO_2}}{x_{O_2}} = \frac{a}{\left(\frac{\%EA}{100}\right)\left(a + \frac{b}{4} - \frac{c}{2}\right)}$$

$$\frac{\%EA}{100} = \frac{a}{\left(a + \frac{b}{4} - \frac{c}{2}\right)\left(\frac{x_{CO_2}}{x_{O_2}}\right)}$$

$$\%EA = \frac{a}{\left(a + \frac{b}{4} - \frac{c}{2}\right)\left(\frac{x_{CO_2}}{x_{O_2}}\right)} \times 100$$

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So, now in the exhaust gas the ratio of mole fractions between CO_2 and O_2 is that is mole fraction of CO_2 by mole fraction of O_2 equal to so mole fraction of CO_2 we know that is a from the above stoichiometric equation and the mole fraction of O_2 is percentage excess air by 100 into a plus b by 4 minus c by 2. That is this term here which indicates the mole fraction of O2 in the exhaust gas. So, now after rearranging this equation so percentage excess air by 100 will be equal to a plus b by 4 minus c by 2 into mole fraction of CO_2 by mole fraction of O_2.

And hence the percentage excess air will be equal to a by small fraction of O_2 into 100. So, with the help of this equation, we can calculate the percentage excess air required for the combustion of given fuel. So, to understand this concept of percentage excess air calculation, let us try to practice one example on this concept.

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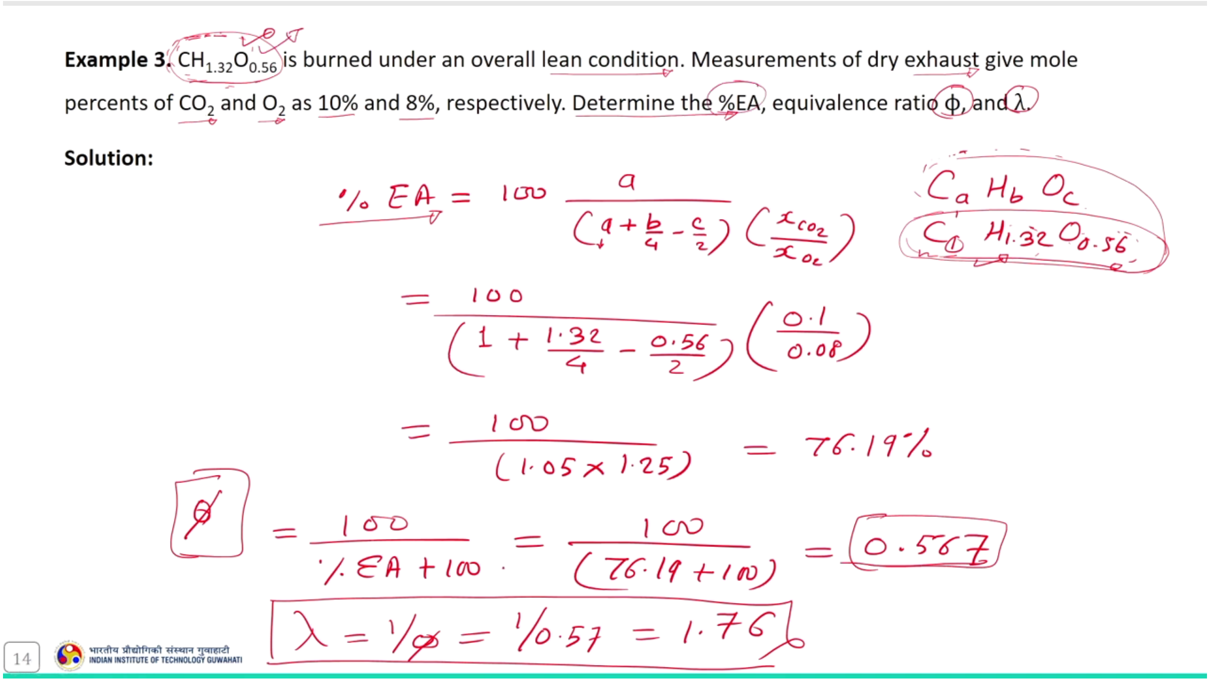

So, in this example the given fuel is burned under an overall lean condition. Measurements of dry exhaust give mole percents of carbon dioxide and oxygen as 10 percent and 8 percent respectively. So, with help of this given data we need to estimate the percentage excess air as well as the equivalence ratio for the given fuel.

So, since we know the percentage excess air is represented as 100 into a by a plus b by 4 minus c by 2 into mole fraction of CO_2 by mole fraction of oxygen. And that is equal to 100 divided by this a here is 1 plus 1.32 by 4 minus 0.56 by 2. The given fuel is represented in the form of C1 H1.32 and oxygen 0.56. In general the solid fuel that is biomass or coal is represented in the form that is C, H and O. And here in this example the fuel given here is represented in the form of C1 H1.32 and O 0.56. So, correspondingly a here is 1, b 1.32 and c

0.56. So, we can use these values to calculate the percentage excess air which is required for the burning of this fuel. So after substituting the value of a, b and c from this given fuel as well as the molar fraction of CO_2 and O_2 in the exhaust stream that is 0.1 divided by 0.08. So, it comes out to be around 100 divided by 1.05 into 1.25 and that is 76.19%.

Similarly the equivalence ratio phi can be estimated using this correlation that is 100 divided by percentage excess air plus 100 which is equal to 100 divided by 76.19 plus 100 and it comes out to be around 0.567. And similarly this equivalence ratio is also represented as lambda which is equal to 1 by phi and it comes out to be around 1.76.

So, this is about the calculation of the percentage excess air which is required for the combustion of given fuel. So, in the next lecture that will be the first lecture of module 8, we will discuss the integrated energy system and concept of integration of the energy system.

Thank you.