Fuels, Refractory and Furnaces

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Lecture No. # 10

Principles of Combustion: Concepts and illustrations

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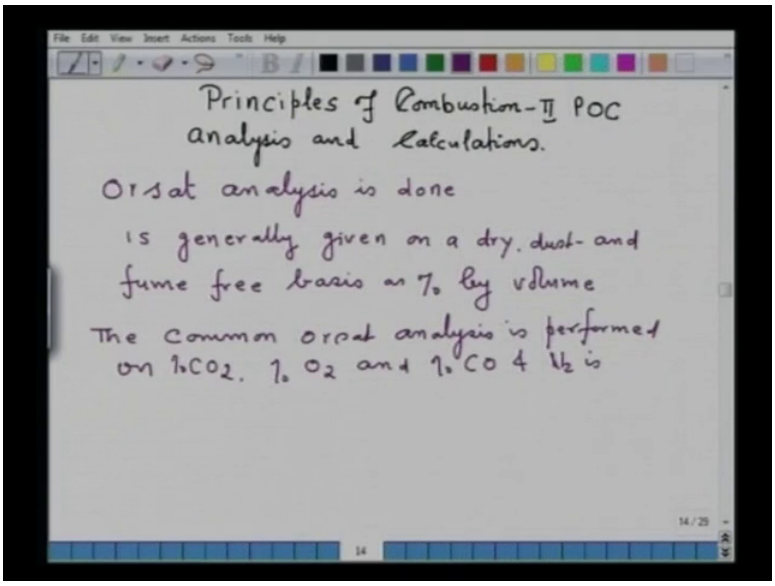

Today, I will talk on principles of combustion second, where I will be dealing with the analysis of products of combustion, in short, I have written POC. In the combustion calculation, the analysis of products of combustion is important. The calculations on combustion can be done on several ways. If we are given with the products of combustion, say, its analysis, then, we can make several calculations like, the amount of products of combustion, like amount of air, if we know the composition of coal, or liquid fuel, or gaseous fuel.

So, in analyzing the products of combustion, in fact, Orsat analysis is done, Orsat analysis is done, to report the percentage composition of the products of combustion. Now, this, the Orsat analysis is generally, is generally given, or expressed on a dry, dust and fume free basis, as percentage by volume, and are given in terms of molecular species, comprising the product of combustion. So, what is important is that, the Orsat analysis of the products of combustion is given on dry basis; that is a very very important, that you should understand, while performing the calculations on combustion.

The Orsat analysis reports volume percentage directly. The common Orsat analysis, the common Orsat analysis is performed, say on C O 2, percent O 2 and percent C O and nitrogen is determined by difference from 100. So, in fact, in the Orsat analysis, there are three or four bottles are filled with the different solutions; a certain amount of products of combustion is taken in a glass bulb, and the gas amount is passed through a solution and the amount of the gas which is absorbed, that is reported in terms of its volume percentage.

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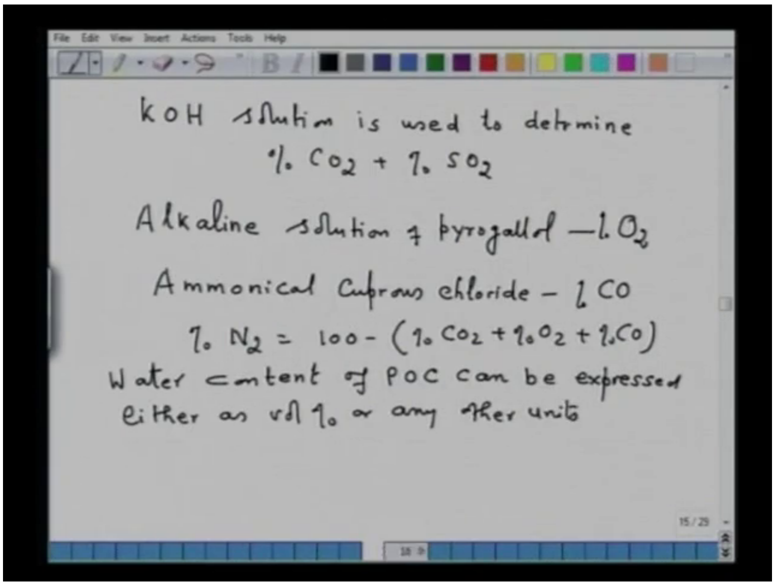

So, that means, the various solutions which are used, say K O H solution is used to determine percentage C O 2, plus percentage S O 2. Now, that is also very important that, in the Orsat analysis, K O H solution absorbed both C O 2 and S O 2, and whatever percentage that you get, that is reported in terms of percentage C O 2; but while making the carbon balance, if the coal contains carbon and sulfur both, then this, then the Orsat analysis means that, carbon in coal, plus sulfur in coal, that is equal to carbon in C O 2, as reported in the Orsat analysis; because Orsat analysis does not give separately the percentage S O 2; that point should be remembered; that is very very important while performing the combustion calculation. Once again, I will say that, the percentage S O 2 is not separately reported in the Orsat analysis. It is reported along with carbon dioxide, because K O H solution, it absorbs both.

Then, an alkaline solution, then, an alkaline solution of pyrogallol, it measures percentage oxygen. Then, ammonical, ammonical cuprous chloride, this measures percentage carbon monoxide. So, percentage nitrogen is determined from plus percentage C O. I am writing here only percentage C O, though it is implied that, it contains percentage C O 2 plus percentage S O 2 both, but the Orsat analysis gives you percentages C O 2; percentage S O 2 is not separately reported. So, that is how the Orsat analysis is done. Now, few important things, that must be remembered while solving the problems. First of all, in majority of the combustion calculation, the POC analysis is given in terms of Orsat analysis; that is, the Orsat analysis of POC is so, so, so. It is to be remembered that, Orsat analysis is always on the dry basis. It does not report anything about the water content, or moisture content of the product of combustion. It is on dry basis; that point is to be noted. Point number two. S O 2 content of the products of combustion is not reported separately; it is embedded in carbon dioxide. So, while performing a balance, one has to take care that, the Orsat analysis of C O 2, it contains the contribution of carbon as C O 2 and sulfur as S O 2, in the products of combustion; these two things are important.

Now, say, water content of products of combustion, water content of products of combustion. Now, this products of combustion, they are also called (( )) gas. So, I mean interchangeably, one can use either products of combustion, or fuel gas; both have the same meaning. In the problems you can have the products of combustion analyses as follows, or the fuel gas analyses for C O 2, S O 2, whatever the case may be. So, they can be used; both have the same meaning; they are the combustion product of any fuel. So, water content of POC is, can be expressed, it can be expressed, either as volume percent, or any other units.

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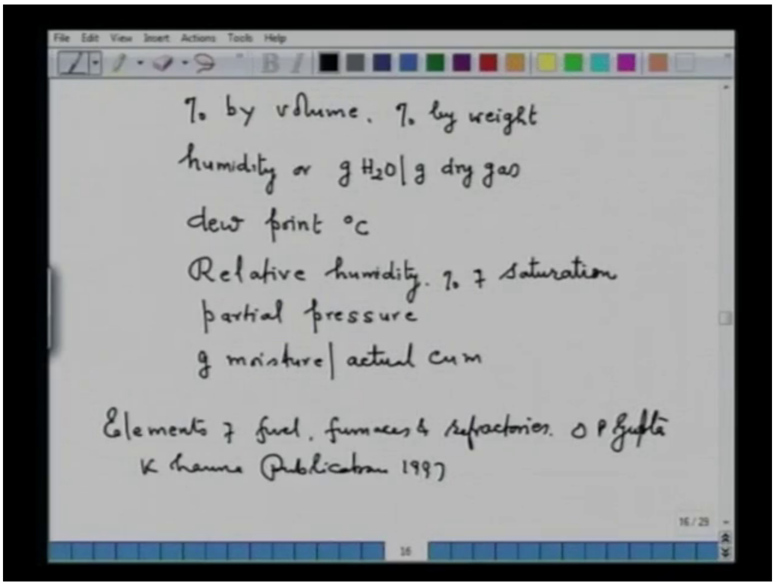

As I am giving here, for example, it may be report, reported on the percentage by volume, or for that matter, can be reported, percentage by weight; then, it can also be reported humidity, in terms of humidity, or gram H 2 O per gram dry gas; can also be reported this way. It can also be reported in terms of dew points; dew points in degree Celsius. Dew point is a temperature, at which water vapor begins to condense. Now, this dew point calculation is again a very important part of the calculation, because the condensation of water content in the fuel gas, or products of combustion, is very important. For if the water condenses during exit of the POC, then, it may spoil the entire stake part of it, because water will condense, and suppose, S O 2 is present in the fuel gases, it will react with H 2 O and then, it will form H 2 S O 4.

So, what I want to say is that, the dew point, or the temperature at which water begins to condense, that is a very important calculation in case of product of combustion. It will also be reported in terms of relative humidity, relative, relative humidity, or percentage of saturation. Then, it can also be reported in terms of partial pressure, report in terms of partial pressure, following the Dalton's law of pressure, which is, the total pressure is equal to the sum of partial pressures of each component of the products of combustion. Then, we can also report in terms of, for example, gram moisture, gram moisture per actual cubic meter. So, these are the various ways, in which the water content of the products of combustion can be expressed, in a particular problem. Now, for details on the Orsat analysis, you can also consult the book, say, Elements of fuels, furnaces and refractories, by say O P Gupta; this is Khanna Publication, 1997. However, there are, other books are also there; you can consult any of the books.

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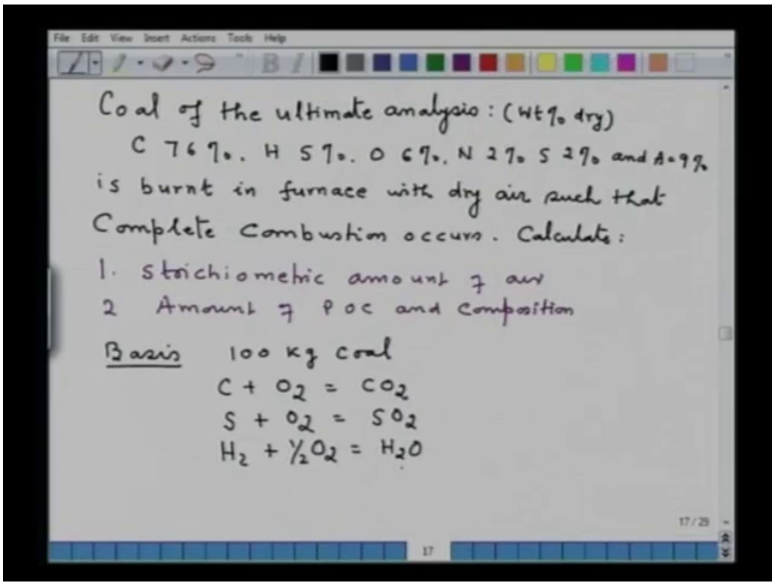

Now, let me illustrate this, by taking an example. What I do, let me take a problem, say coal of the ultimate analysis, coal of the ultimate analysis is given, say carbon 76 percent, hydrogen 5 percent, oxygen 6 percent, nitrogen 2 percent and sulfur 2 percent and ash is 9 percent. Now, this analysis is given on weight percent, weight percent in dry basis. This is the analysis of coal, that is given to us. Now, this particular coal is burnt in a furnace with dry air, such that complete combustion occurs, such that complete combustion occurs. Now, you have to calculate, to calculate stoichiometric amount of air, stoichiometric amount of air and calculate the amount of POC and composition. Now, in order to proceed with the calculations, one has to do elemental balance. It is again a material balance type of problem. So, one has to do material balance, say, carbon balance, sulfur balance, oxygen balance, nitrogen balance and hydrogen balance. And, from the balance, one can find out the unknown values. Now, as regards the calculation on a stoichiometric amount of air, this means that, one has to write down the stoichiometric equations; that is, stoichiometrically balanced equations and from the balanced equations, one can find out the amount of air; that is one important thing.

So, we can also say, in several ways, we can say, either find out the stoichiometric amount of air, or we can also say, find out theoretical amount of air, or we can also say, find out air for complete combustion. All the three has same meaning; that means, you have to calculate the amount of air for complete combustion, whether it is said as calculate theoretical amount of air, or calculate stoichiometric amount of air, or calculate air for complete combustion. So, that is one important thing over here. Now, let us calculate stoichiometric amount of air. So, the first thing, you have to take the basis. Now, here, you are free to choose the basis. You can choose the basis 1 kg coal, 100 kg coal, or 1000 kg, whatever you like. So, what I am doing, I have chosen the basis, say, let us take it 100 kg coal. Now, I will write down the stoichiometric reactions. And, the stoichiometric reactions, in case of this particular problem, I have to write down those equations, where the components are being combusted.

So, here, the carbon will combust; hydrogen will combust, and sulfur will combust. So, write down the reaction, C plus O 2, that is equal to C O 2; S plus O 2, that is equal to S O 2; H 2 plus half O 2, that is equal to H 2 O; that is what the meaning of stoichiometric amount of air, or stoichiometric combustion, or theoretical air, or air for complete combustion; because the products of combustion for complete combustion, is well defined. And carbon, on complete combustion, can give only C O 2. Had these not been given, that the, to find out the amount of air, then, simultaneously it has to be told, what is the C O - C O 2 ratio. So, that is an important issue. For combustion, the product of complete combustion of carbon is very clear; there is no doubt, it is the C O 2. So, these are the stoichiometric reactions. One can interpret these ways, the 1 kg mole carbon takes 1 kg mole oxygen and gives 1 kg mole of C O 2. 1 mole of sulfur, 1 mole of oxygen gives you 1 mole of S O 2. Similarly, 1 mole of hydrogen requires half mole of oxygen and gives you 1 mole of H 2 O.

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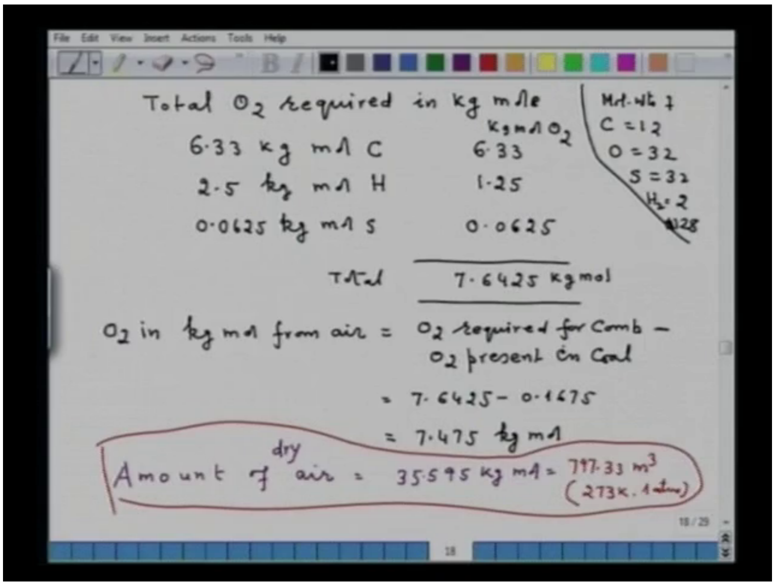

So, from these stoichiometric equations, one can find out the, the total oxygen required, total O 2 required, and we find out in kg mole. Now, total oxygen required would be the oxygen required for carbon to C O 2, for sulfur to S O 2, for hydrogen to H 2 O. So, total oxygen required will be, say, I will be needing 6.33 kg mole is carbon, because 76 by 12, that is, 6.33 kg mole of carbon. We will be needing 6.33, say in kg mole oxygen. From this stoichiometric reactions, one mole carbon, one mole oxygen; so, 6.33 kg mole of carbon will need 6.33 kg mole of oxygen. Similarly, 2.5 kg mole of hydrogen will need 1.25 kg mole of oxygen, from this stoichiometric reaction. Similarly, 0.0625 kg mole of sulfur will need 0.0625 kg mole of oxygen. Now, I can also give, I use the molecular weight of carbon, that is equal to 12; oxygen that is 32; sulfur 32, hydrogen as 2, nitrogen, I will be using 28. So, these are the things, that I am using over here.

So, coming back, now. So, the total moles of oxygen that is required, the total moles of oxygen that is required, the sum total, it will come 7.6425 kg mole. So, that much amount of kg mole is required. Now, note, in the problem, the coal also contains oxygen. So, one has to do the oxygen balance; that means, the O 2 in kg mole from air, that will be required, that will be equal to oxygen required for combustion minus O2 present in coal; O 2 present in coal, because that amount of oxygen which is present in the coal, that is already available to you. So, if you do minus, then, you get the oxygen from air. So, that will be equal to 7.6425, you have to convert the percentage oxygen, divide by 32, minus 0.1675. So, oxygen in kg mole required from air, that will be equal to 7.475 kg mole.

Now, remember, this oxygen in kg mole from air, that is, in fact, it is from the dry air, because air does not contain any moisture. So, if the air is dry, then, the composition of air is very clear, that we will be using in solving the problem; O 2 21 percent and nitrogen is 79 percent, I think all of you know. Then, from here, I can find out now, the amount of air. Take your calculator and calculate the amount of air; how will you calculate? 21 percent oxygen, 79 percent nitrogen; so, that means, one mole of air, or 4.76 moles of air contains 1 mole of oxygen and 3.76 moles of nitrogen. So, if I divide this 7.475 by the oxygen percent in air, that is equal to 21 percent, then, I will be getting the amount of air. So, the amount of air will be equal to 35.595 kg mole. This is the amount of dry air; simply 7.474 divided by 0.21, we will get 35.595 kg mole and that will be also equal to 797.33 meter cube. Mind you, you have to express here, temperature and pressure; and the temperature is at 273 Kelvin and pressure is 1 atmosphere.

So, this is, in fact, the answer for the stoichiometric amount of calculation of air. So, remember, while doing the calculation on stoichiometric amount of air, you should not forget the oxygen content of coal, and that oxygen content, you have to subtract it from the oxygen required for combustion; only that much amount of oxygen, you are required to supply to the air. So, that is an important thing. It is, in fact, a elemental balance. Now, let us calculate amount of POC and their composition. I will also try to, I will also try to explain the various basis in which the analysis of POC can be expressed.

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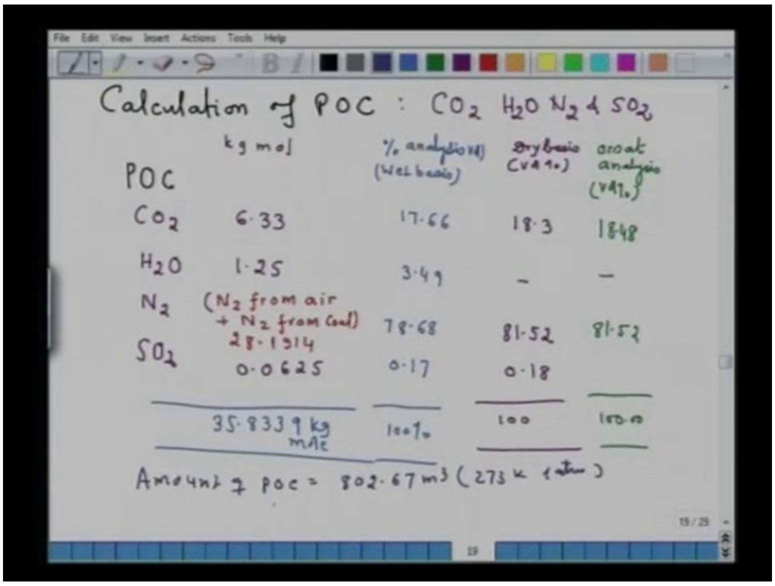

Next is the calculation of POC. Calculation of POC. Now, if you see this stoichiometric reaction, the POC will consist of C O 2, H 2 O, N 2 and S O 2. Now, if you see the reaction, you can immediately calculate the amount of POC that is being formed. You note again, from the stoichiometric reaction which I have written, C plus O two is equal to C O 2. 1 mole of carbon will give you 1 mole of C O 2. So, if you have 6.33 kg mole of carbon, we will be getting 6.33 kg mole of C O 2; it is a straight forward calculation. If you have 0.0625 kg mole of sulfur, we will be getting 0.0625 kg mole of S O 2. So, it is straight forward calculation in terms of the stoichiometrically balanced equation, because stoichiometric balanced equation always says, 1 kg mole of reactant that we give you, say, in the case of carbon plus oxygen, 1 kg mole carbon will give you 1 kg mole of C O 2.

So, let me write down, now, here, say, POC, I will just try to make a table. The POC, and then, first I put it here, in kg moles, kg mole. So, let us take POC, say C O 2; then, H 2 O; then, nitrogen, and then S O 2. So, straight away, we can calculate 6.33 kg mole of carbon. What will be the kg mole of C O 2? Can you answer? The kg mole of C O 2 will be 6.33 kg mole. What will be the kg mole of H 2 O? Half, that is 1.25 kg mole. Now, be careful while determining the kg mole of nitrogen in products of combustion; because kg mole of nitrogen in products of combustion will consist of two components; one is nitrogen from air, plus nitrogen from coal; do not forget; that is important. Though the amount of nitrogen in coal is very small, but that is considered to be a conceptual error, and you should be taking note of that; that is the nitrogen. In fact, it is a nitrogen balance; nitrogen from coal, plus nitrogen from air, that will be equal to nitrogen in products of combustion. So, that is the way you will be determining. So, you can find out the kg mole of both. So, it will come to be equal to, 28.1914 is the kg mole of nitrogen in products of combustion. S O 2 is straight forward; that is 0.0625. So, if I sum total it, then, sum total is coming 35.8339 kg mole.

Now, we can determine the percent analysis on weight basis; or, that means, whatever we have received, that is the analysis that I am reporting; what I have to do, I have to simply divide the amount of C O 2, by the total amount, the amount of H 2 O, by the total amount, and so on, and I will be getting the percentage here. They are only volume percent, remember, percentage analysis by volume. So, here, it will be 17.66; here, it will be 3.49; here, it will be 78.68; and here, it will be equal to 0.7. So, this total is again 100 percent. Now, I can also report this analysis on dry basis; that means, analysis of POC on dry basis. Of course, it is volume percent. So, on dry basis, to do that and if you do, the analysis comes 18.3, 81.52, and S O 2 is 0.18 and that again makes 100. That is how you will be doing the, or expressing the analysis of POC on dry basis.

Now, another important thing is, suppose, you perform an Orsat analysis of the products of combustion; say, you have burned in a furnace; you have taken the products of combustion and you want to analyze this by using Orsat analysis. Then, what will be the percentage composition that you will be reporting, after performing the Orsat analysis? So, let us calculate here, now, the Orsat analysis. With that, I mean, we are now calculating the percentage composition of the products of combustion, as if we have performed Orsat analysis. Remember, this is also on the volume percent, but after performing the Orsat analysis. So, here, it will be 18.48 percent and here, 81.52 percent. So, that will be again equal to 100. Now, you have noted here, that, on the dry basis, the volume of C O 2 was 18.3, where Orsat analysis, it will become 18.48; what does it mean? As I said that, separate S O 2 analysis is not done, in case of Orsat analysis. So, what I have done, I have added 18.3 and 0.18; that becomes 18.48. So, the Orsat analysis in a problem will be in terms of, in this particular case, 18.48 percent C O 2 and 81.52 percent nitrogen. We can calculate now, amount of POC in meter cube. So, the amount of POC in meter cube, that will be equal to 802.67 meter cube, again at 273 Kelvin and 1 atmospheric pressure.

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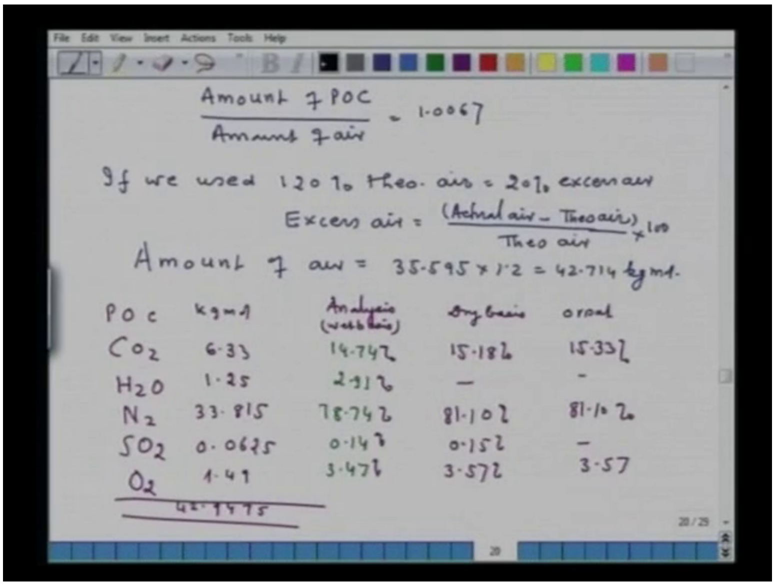

Now, it is interesting to have a ratio of amount of POC upon amount of air, and in this case, it comes to be equal to 1.0067. I will tell you afterwards, the implication of this. Now, suppose now, if we use, suppose, if we use 120 percent theoretical air, that has become equal to 20 percent excess air. So, one can define excess air, that is equal to actual air minus theoretical air, upon theoretical air. So, remember, excess air is always expressed on theoretical air. So, if we use 120 percent theoretical air, then, amount of air, amount of air would be straight away, 35.595 into 1.2, that is equal to 42.714 kg mole. So, that is how we can determine the amount of air.

Now, when excess air is being used, then again, the products of combustion and their composition, everything changes. So, if you want to determine the products of combustion, same way. So, I will write here POC, which is having C O 2, H 2 O, nitrogen, S O 2. Now, since I am using the excess air, so, the POC will consist of excess O 2, that will also be there in POC. So, again, I can calculate the kg mole. About the C O 2, it will remain the same; nothing will change. That is also important thing, you should note that, whether we use theoretical air, or excess air, the amount of carbon oxide cannot change it; because 1 mole carbon takes 1 mole oxygen and makes 1 mole C O 2. Similarly, H 2 O also, same 1.25. Now, nitrogen will be, you have to add, you have to take 79 percent of the amount of air, that will go as nitrogen, because now, you are using 120 percent theoretical air. So, point or 79 point or 79 percent of 42.714, plus, do not forget to add the nitrogen from coal. So, total, it becomes 33.815. S O 2 is 0.0625 and O 2, you can find out from the total amount of air you have, 42.714; you know the stoichiometric amount of air; if you multiply by 0.21, that will be the amount of excess oxygen; and that comes as 1.49. So, the total has become now, 42.9475.

Now, I can determine the, the analysis, again on weight basis; of course, volume percent. So, here, it will be 14.74, 2.91, 78.74, 0.14 and 3.47; the total again, it becomes 100. So, if I do on dry basis, I am performing the same calculation, which I have done earlier. So, dry basis, it will be 15.18; it will be 81.1 nitrogen; 0.15 and 3.57; total again becomes 100. So, I have performed Orsat analysis. Then, the analysis will be 15.33; of course, they are all in percentage; they are all in percentage; 15.33 percent; 81.10 percent and 3.157 percent; again it makes 100.

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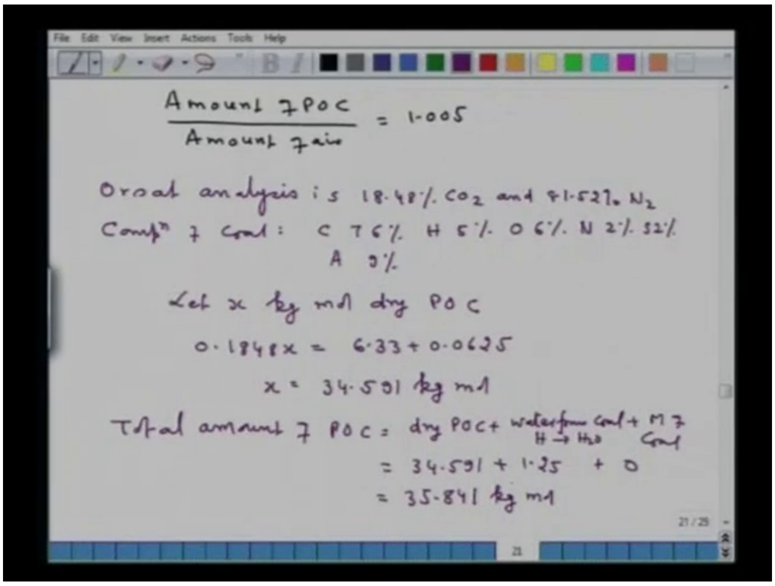

So, if I now determine the, the so called ratio, the amount of POC upon, say, amount of air, that becomes equal to 1.005; slightly here and there a bit affected. Now, this is how, this particular problem can be tackled. Now, imagine, a problem is given, where you are given the Orsat analysis. So, I formulate the problem in a different way; I go from the reverse engineering; that is, the products of combustion analysis is given and you have to find out the amount of POC. So, let us take, let us formulate the problem. Let us say that, now the Orsat analysis is given; say, Orsat analysis is 18.48 percent C O 2 and 81.52 percent of nitrogen. This is the Orsat analysis; the products of combustion is this one, and this has been obtained by combusting coal in dry air. The composition of coal is given; composition of coal, carbon

76 percent, hydrogen 5 percent, oxygen 6 percent, nitrogen 2 percent, sulfur 2 percent and ash is 9 percent. Now, you have to calculate the amount of POC.

Now, since Orsat analysis is given, this is on the dry basis. So, let us see that, let us consider, let x kg mole dry POC. We will do the carbon balance. So, carbon balance will tell us 0.1848 x, that will be equal to 6.33, that is the carbon of the coal, plus 0.0625. So, what my objective was to illustrate that, when the Orsat analysis is given, and when you make the carbon balance, then, you have to consider the carbon and sulfur of the coal. So, if you do that, then, the value of x, that is equal to 34.591 kg mole. Now, mind you, this is the dry. So, the total amount of POC, total amount of POC, that will be equal to dry POC, plus water from coal, say, that is H to H 2 O, plus moisture of coal. Now, in this particular problem, the dry POC, we have find out 34.591, water from H 2 O of coal, that you determined earlier 1.25, moisture is 0. So, the amount of POC we are getting is 35.841 kg mole. Now, this 35.841 is approximately similar to the amount of POC that is produced on using the stoichiometric amount of air. Now, remember, this calculation has been done on taking the stoichiometric amount of air. So, 35.841kg is the amount of POC.

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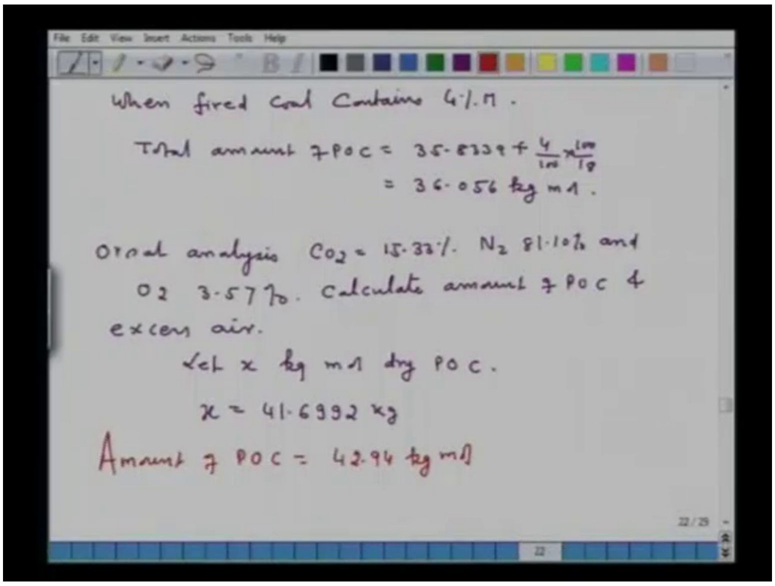

Now, in certain problems, when fired coal contains, say, 4 percent moisture; same, same problem, when the coal is fired, contains 4 percent moisture, burned with the stoichiometric amount of air; then, you have to find out again, the total amount of POC; so, in there, just I have done; m of coal, I have taken as 0. So, now, m will also be introduced. So, total amount of POC would be, total amount of POC would be, 35.8339 plus 4 upon 100 into 100 upon 18. So, that will be equal to 36.056 kg mole. So, that is how, you will be determining the so called, amount of POC, from Orsat analysis.

So, now, we can take another version of the problem, where it is given, say, Orsat analysis, C O 2, that is equal to 15.33 percent; nitrogen 81.10 percent and oxygen is 3.57 percent. This is the Orsat analysis given. Then, you have to calculate, calculate amount of POC, and excess air. Now, mind you, if the POC contains oxygen, that means, on theoretical front, or on theoretical calculation, this means, the decombustion has occurred with the excess amount of air, unless otherwise mentioned. So, in this particular case, excess air…Now, here, I am using the coal of the same composition, which you have used in the previous problem. So, I am not writing. So, again, we will determine, let us say, x kg mole, let x kg mole dry POC. Again, do the carbon balance. So, from carbon balance, you will be getting x; that will come out to be equal to 41.6992. Now, remember, while doing the carbon balance, you have to take carbon and sulfur both, and that, you have to equate with the POC C O 2; that is an important thing. So, the amount of POC now, amount of POC now, again the same dry POC, plus water of coal, plus moisture; since moisture is equal to 0 here, so, we add both, and we will be getting 42.94 kg mole, amount of POC dry, when excess air is used. So, that is what the problem. Now, we have to calculate excess air. Now, as I told you that, the excess air is calculated by calculating the actual air minus theoretical air, divided by theoretical air.

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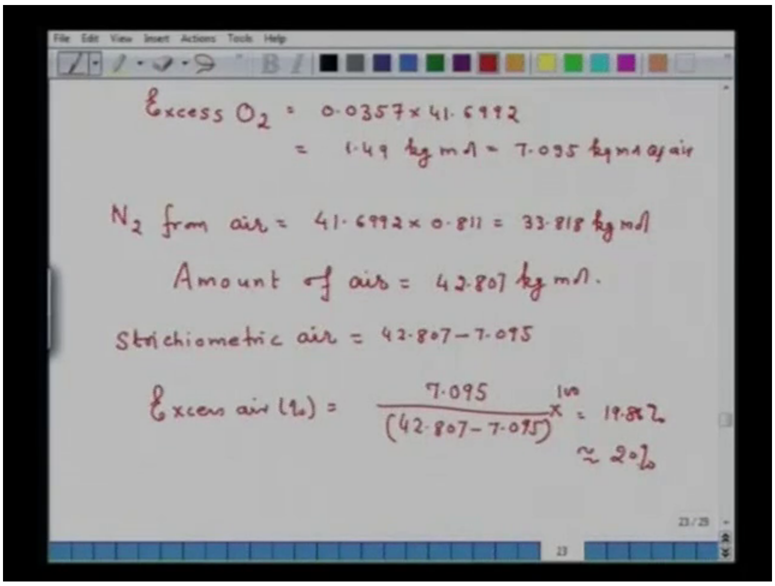

So, first I will calculate excess oxygen. I will calculate excess oxygen and the excess oxygen will be equal to, 0.0357 as given in the Orsat analysis. The total amount of, say, the dry POC, we have determined 41.6992. So, that comes equal to 1.49 kg mole and that is equal to 7.095 kg mole of air, of air. You have to divide by 0.21; you will get that much amount of air. So, we have got now, this is excess oxygen. Now, in order to find out, in order to report the percentage excess air, one has to determine the theoretical amount of air; also, one has to determine the nitrogen from air. For, what is the amount of nitrogen from air, then and then, you will find out the actual amount of air, because whatever nitrogen that is present in the POC, it has come solely from the air; because you have subtracted the nitrogen content of coal also. So, the nitrogen from air, nitrogen from air, that will be equal to 41.6992 into 0.811, that will make 33.818 kg mole; that will make 33.818 kg mole. So, amount of air, how much? You divide by 0.79, because 79 percent is nitrogen content of dry air; remember, we are using dry air. So, amount of air will be equal to 42.807 kg mole.

Now, what will be the stoichiometric amount of air? Can anybody tell me? The stoichiometric amount of air, actual air minus excess air, that is the stoichiometric amount of air. So, that will be 42.807 minus 7.095, that is the stoichiometric amount of air. Now, excess air in percent, that will be equal to excess 7.095 divide by 42.807 minus 7.095; because this is stoichiometric amount of air into 100 and that makes 19.86 percent and that is approximately 21, 20 percent. And, as in this particular problem, I have used 120 percent air, that is 20 percent air. So, we are, approximately we are also getting the 20 percent air.

So, what I have illustrated you is, today, the formulation of combustion problem can be done in several ways. Either the coal composition is given, or analysis of POC is given, and then, Orsat analysis is given, and then, you have to perform the calculation. So, I have tried to illustrate, the formulation of problem and the calculation method by taking the same composition of coal and burned with stoichiometric amount of air and excess amount of air, how one can do the combustion calculation. The basis is to do elemental balance and keep track of the elemental balance, from whichever sources the element is entering, you have to take into account, and you will be getting the answers, and you will also be feeling good.