**Fuels, Refractory and Furnaces**
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**Lecture No. # 11**
**Materials balance in combustion**

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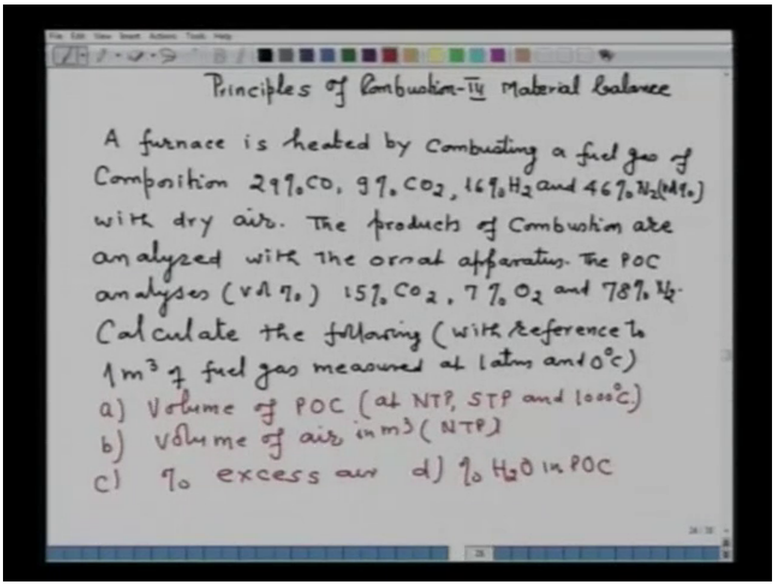


Today, we will be solving some problems, some combustions, the principles of combustion, material balance. Let me write problem for you. You read the problem carefully and then, we both will solve together, this particular problem. So, I write the problem for you. A furnace is heated by combusting, by combusting a fuel gas, of composition 29 percent C O, 9 percent C O 2, 16 percent hydrogen and 46 percent nitrogen. Mind you, the composition of gases is always given in volume percentage, unless otherwise stated. Hence, these percentages are also on volume percent, with dry air. When we say dry air, the air has a composition, 79 percent nitrogen and 21 percent oxygen.

The products of combustion, the products of combustion are analysed with the Orsat operator. And, as all of you know that, whenever analysis of the product of combustion is given, or is done by Orsat operators, then, analysis is always on dry basis. So, this point is to be noted that, Orsat analysis gives the analysis of P O C, or products of combustion on dry basis. So, as such, the analysis, so, the P O C analysis, or P O C analyses, again the analysis is on volume percent, 15 percent C O 2, 7 percent O 2, and 78 percent nitrogen. Calculate the following, with reference to 1 meter cube of fuel gas, measured at 1 a t m and 0 degree Celsius; that is N T P, normal temperature and pressure. You have to calculate the following: a, calculate the volume of P O C. Now, report the volume of P O C at N T P, S T P and 1000 degree Celsius. Second, or b, volume of air, volume of air in meter cube, again at N T P; c, percent excess air and d, percentage H 2 O in P O C.

So, I will give you some time. You read the problem carefully, and then, attempt to solve the problem with me. I hope, you must have read the problem by now. Take your calculator out, and begin to solve the problem with me. So, the first thing is, to represent, as I said, the input and output, that is, whatever is given in the problem, in a box; a box, for example, representing a furnace. This particular representation, and solving the problem, it is helpful in that, you are writing everything which is given in the problem, in the form of input and output. So, all the information which is given in the problem, is before you to solve the problem. That means, you do not need to read the problem, all the time. So, this is typically, all material balance problem are solved this way, or you may develop your own technique to solve this problem; that is ok. So, I will be proceeding to solve the problem, by reporting all the inputs and outputs in the form of a block diagram.

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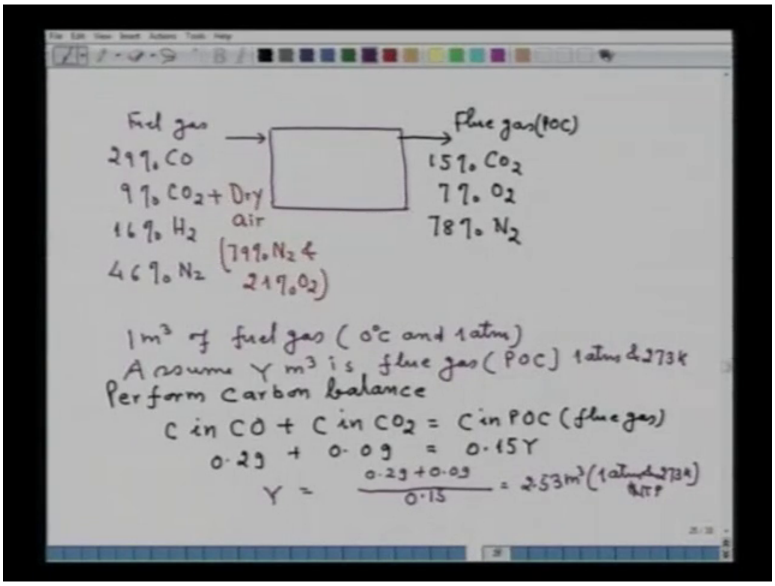

So, this is a block diagram. So, here, a fuel gas of composition, say 29 percent C O, 9 percent C O 2, 16 percent H 2 and 46 percent nitrogen is given to us. Now, this particular fuel gas is burned with dry air. A dry air has the composition of 79 percent nitrogen and 21 percent oxygen; that is what is given to us. Then, in the output, say we have flue gas; note the difference between, fuel gas is something which burns and flue gas is the product of combustion. You can also write down the product of combustion, or you can also write flue gas, whatever is comfortable with you. So, flue gas are also called P O C and it is given a 15 percent C O 2, 7 percent oxygen and 78 percent nitrogen, that is given to us. And, we have to calculate; the first calculation we have to do, is the volume of P O C. So, in order to calculate the volume of P O C, let us assume 1 meter cube of fuel gas, that is the basis of calculation, and this is at 0 degree Celsius and 273 and 1 atmospheric pressure; that is what given to us. Now, we have to calculate the volume of P O C.

Assume, y meter cube is flue gas or products of combustion, which is at 1 atmosphere and 273 Kelvin; that is what we are assuming for calculation. Now, as I said, in order to calculate the volume of flue gas, or volume of products of combustion, we have to do carbon balance. So, as such, I will be making the carbon balance. So, let us perform, you perform along with me, perform carbon balance. To perform carbon balance, you can write down in words, carbon in C O, plus carbon in C O 2; that is, what is present in the fuel gas, and that should be equal to carbon in P O C, or flue gas; both are the same thing. I may use this term interchangeably. So, they represent the same; you can call products of combustion, or you can call flue gas. So, you have to make this particular carbon balance; if there are no losses of carbon, is given in the problem. So, whatever carbon is being input, that carbon has to come out. So, if we perform this balance, there are several ways to perform balance; you can perform this balance on the basis of kg, kg mole, or meter cube.

So, I will perform on the kg mole basis, because the mole percent and volume percent, they are the same. So, I can put it now, straight away, 0.29 plus 0.09; that is in carbon mole, since C O 2, that is equal to 0.15 y. So, straight away, I get now, y, that is equal to 0.29 plus 0.09 upon 0.15 and this comes to be equal to 2.53 meter cube. And, mind you, our basis was, this value is at 1 atmospheric pressure and 273 Kelvin. It is also called, in a standard physics book N T P, normal temperature and pressure. Now, it is also being asked to calculate the volume of P O C at STP.

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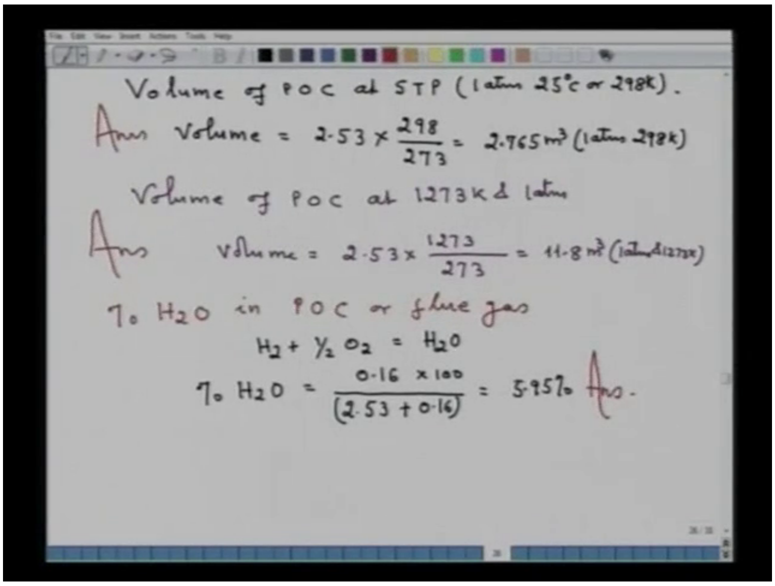


So, volume of P O C at S T P, volume of P O C, P O C or, or the flue gas at S T P; now, S T P represents 1 atmospheric pressure and 25 degree Celsius, or 298 Kelvin. So, the volume of P O C here, that will be equal to 2.53 into 298 upon 273, and that is equal to 2.765 meter cube. This volume is at 1 a t m and 298 Kelvin. Now, the problem also says to report the volume of P O C at 1000 degree Celsius, also at 1 atmospheric pressure. So, volume of P O C at 1273 Kelvin which is equal to 1000 degree Celsius and 1 a t m pressure, that is equal to…So, this volume will be equal to 2.53 into 1273 upon 273 and this is equal to 11.8 meter cube. This is at 1 a t m and 1273 Kelvin. So, this is the answer. This is also the answer and earlier was also the answer. So, why I asked you to calculate, particularly at 1273 Kelvin, is to appreciate the fact that, the gases expand on heating, which all of you know. Now, you note from here that, there is approximately five times increase in the volume of products of combustion, than what it was at 0 degree Celsius and 1 atmospheric pressure. So, what does it imply? It implies that, while designing the fuel fire furnaces, it is the volume of P O C at that particular temperature is very important, because once you combust, the volume of P O C will increase. So, accordingly, the cross section area for the flow passage of the P O C has to be designed.

So, let us take the next, we have to find out, percentage H 2 O, percentage H 2 O in P O C or flue gas. It does not matter, which order you calculate, which order it is given, as long as you report all, what is being asked to you. So, percentage H 2 O is very straight forward. The reaction is H 2 plus half O 2, that is equal to H 2 O. So, straight away the percentage H 2 O, that will be equal to 0.16, this is the k g mole of H 2, and same as H 2 O. Now, here, you have to divide it by the total volume of P O C or flue gas. So, total volume of flue gas would be dry volume plus volume of H 2 O. So, dry volume at 0 degree and 1 atmosphere, we had determined as 2.53. To this, we add, 0.16, that is the volume of H 2 O and if we multiply by 100, then, we get percentage H 2 O is 5.95 percent. So, this is the answer. So, Orsat analysis gives, on dry basis, that is what it is given. Now, the moisture content is 5.95 percent. Now, next, we have to find out volume of air.

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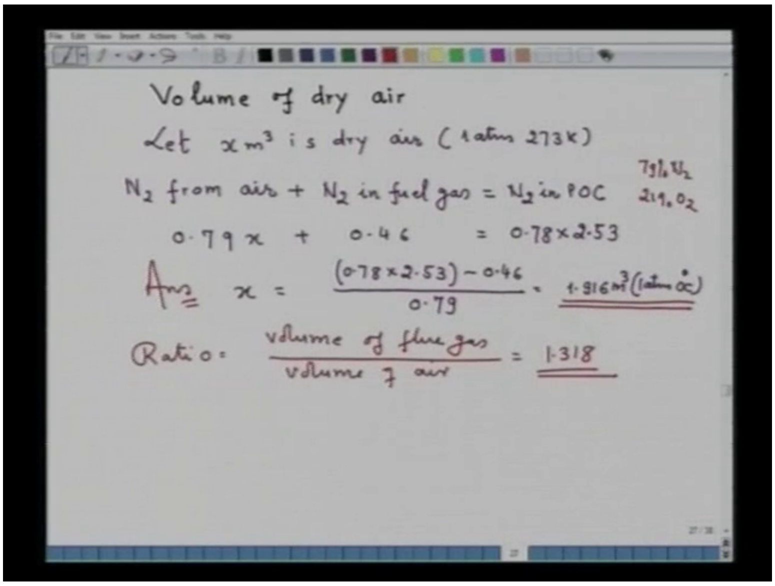


Next, we have to find out volume of, let us say, dry air; volume of dry air. Now, in finding out the volume of dry air, as I have said, what we have to do? Do you recall? From the earlier lectures, on gasification, or on carbonization, where I said that, if we want to determine the volume of dry air, you have to do nitrogen calculation; you can argue, sir, oxygen balance can also be done, but remember, oxygen is reactive. So, where it has reacted you do not know, and it is liable to commit the mistake. So, if you take nitrogen balance, then, you are safe; because nitrogen is inert and it does not react with anything. So, whatever nitrogen is in, same nitrogen will be out. So, nitrogen balance is always very safe, in order to find out the amount of air. So, we will do the nitrogen balance.

Now, before that, let us consider, let x meter cube is air, or dry air, and we are representing at 1 a t m and 273 Kelvin. Now, we have to do the nitrogen balance, and nitrogen balance is, say, nitrogen from air; do not forget to add nitrogen from fuel gas, because 46 percent nitrogen is also there in the fuel gas; so, plus nitrogen in fuel gas, that is equal to, in this particular problem, nitrogen in P O C. From all sources, you have to consider the input, and from all sources, you have to consider the output. So, if you make this particular balance, now, nitrogen from air; you know, the composition of air; 79 percent nitrogen and 21 percent is the oxygen. So, I can straight away write down, 0.79 x plus 0.46, that should be equal to nitrogen in P O C, is given, say 0.78 and into 2.53, 2.53 is the volume of dry P O C at N T P. So, from straight away I can solve the value of x. The value of x would be equal to 0.78 into 2.53 minus 0.46 divided by 0.79. Now, you can just take a calculator and solve it and the value will be coming approximately equal to 1.9176 meter cube at 1 a t m and 0 degree Celsius. So, that is what the volume of air in this particular…This is the answer for volume of air. Now, it is interesting to develop a (( )), the ratio between volume of air and volume of flue gas.

So, to find out the ratio, we calculate, for example, ratio, say volume of flue gas upon volume of air; it is just to get a feel, though it is not given in the problem, because from the solution of the problem, you should also analyse it and see, whether you can get some feel about the ratios of different inputs and outputs. Of course, in this particular case, the ratio would also depend upon, what is the composition of fuel gas. But in this particular case, the ratio is equal to 1.318. It is just a information, which may help in some case.

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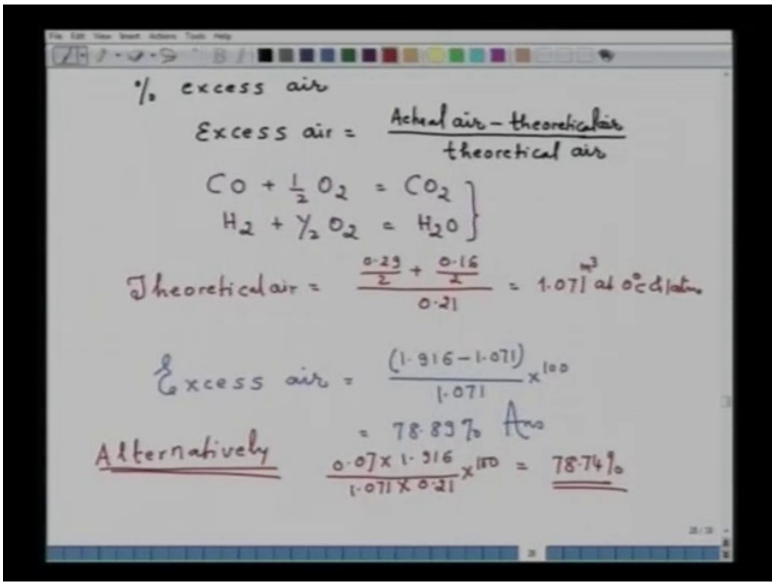

Now, next, we have to calculate the percentage excess air. We have to calculate now, percent excess air. Now, as you know, the percent excess air, or excess air, that is equal to actual air minus theoretical air upon theoretical air; or you can calculate anyway; you can also calculate actual oxygen minus theoretical oxygen, divide by theoretical oxygen; because they are, air and oxygen, nitrogen, they are interconnected; 1 mole of oxygen is equal to 3.76 moles of nitrogen; or, 1 mole of oxygen is carried by 4.76 moles of air. So, they are all interrelated. It depends on whichever way you define; whether you define excess air by, on the basis of air, or on the basis of oxygen. It just becomes the same. Now, you can calculate. Now, first, you have to calculate theoretical air. So, actual amount of air we have already calculated; that is 1.916 meter cube. Now, what you have to calculate, is the theoretical air.

Now, you recall what is meant by theoretical air? The theoretical air always means, the air required for complete combustion; that is the clear cut meaning of theoretical air, or air for complete combustion. The clear cut meaning that, you have to calculate the amount of air which is required for complete combustion; or the stoichiometric amount of air; all have the same meaning. So, in this particular case, if you have to calculate theoretical air, then, what you have to consider? You have to consider the following reactions. The reactions are C O plus half O 2, that is equal to C O 2 and H 2 plus half O 2, that is equal to H 2 O. These are the two reactions which are responsible for combustion. So, straightaway we see, 1 mole of C O, half mole of oxygen, 1 mole of H and half mole of oxygen, that is theoretical oxygen. So, we can calculate now, the theoretical air; the theoretical air, that will be equal to 0.29 upon 2 plus 0.16 upon 2; you have to divide by 0.21, and this is equal to 1.071, again, at 0 degree Celsius and 1 atmosphere, because, or 1.071, of course meter cube, because the volume of gases without mentioning pressure and temperature, it has no value.

Now, we can calculate the excess air. Now, we can calculate excess air and the excess air would be, you know, 1.916 is the actual amount of air, minus 1.071 is the theoretical amount of air; if you divide by 1.071, that is the theoretical air, into 100, because excess air is always referred with respect to the theoretical amount of air. So, this excess air, in this particular case, it comes out to be equal to 78.89 percent and that is the answer for the excess air in percent. Now, in another way, this excess air can also be calculated. Now, if you see the volume of, or the Orsat analysis of flue gases or products of combustion, if you look, you know that, products of combustion, it contains 7 percent oxygen. So, this 7 percent oxygen means, it is the so called excess oxygen that is present in the flue gas, which has come from the amount of air which was being supplied. So, we can also calculate now, in this way, reverse, if you know the, that the percentage of oxygen into P O C, then, alternatively, only in this particular problem, you can calculate; had there been C O in the products of combustion, then probably, different method is to be adopted.

So, alternatively, the excess air can be calculated from, because you have 0.07 is the percentage oxygen, into 1.916 is the volume of P O C; if we divide it by 1.071 is the volume of theoretical air; you have to find out now, the theoretical oxygen. So, multiply it by 0.21 and multiply by 100. So, this gives you around 78.74 percent. So, from the both the methods, we get, in the earlier method we got excess air 78.79 percent; here, we are getting 78.74 percent. So, slight difference; that may be the analysis, or round off error. So, what I mean to say is that, from both methods, the excess air can be calculated; either from the products of combustion, because the excess oxygen in the products of combustion, it is due to the excess air; but when the products of combustion contains carbon monoxide also, then, you have to consider the oxygen required for C O, and then, you have to calculate. So, this is about the, this particular problem. Now, I can give you one problem, so that, you can solve the particular problem on your own, and this problem is self assessment problem.

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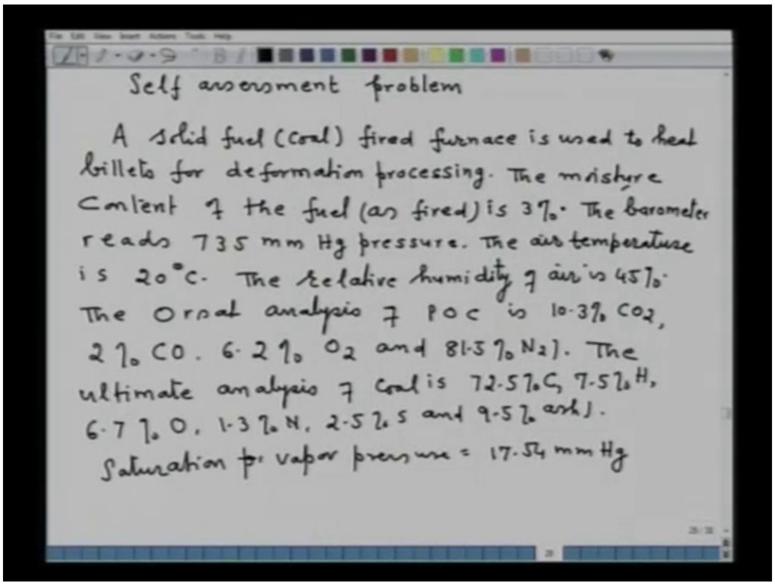


Self assessment problem; you have to solve yourself. I will write down the problem for you. A solid fuel, a solid fuel, for example coal, a solid fuel fired furnace is used to heat billet for deformation processing. You know, for deformation processing, you heat the billet to 1000, or

1200 degree Celsius, so that, the deformation is done easily. The moisture content of the fuel, the moisture content of the fuel as fired, is 3 percent. The barometer reads 735 millimeter mercury pressure; the air temperature is 20 degree Celsius; the relative humidity, the relative humidity of air is 45 percent. Mind you, here, air is not dry, as compared to the previous problem. Here, air is humid and the relative humidity is 45 percent. The Orsat analysis of P O C, the Orsat analysis of P O C is 10.3 percent C O 2, 2 percent C O, 6.2 percent oxygen and 81.5 percent nitrogen. The ultimate analysis of coal, the ultimate analysis of coal…Now, you remember, as I said, the ultimate analysis is given, always on the dry basis. So, the ultimate analysis of the coal is 72.5 percent carbon, 7.5 percent hydrogen, 6.7 percent oxygen, 1.3 percent nitrogen, 2.5 percent sulphur and 9.5 percent ash. The problem is complete.

Now, given, a solid fuel fired furnace; coal analysis is known; the coal when fired contains 3 percent moisture; the barometer reads 735 millimeter of mercury; that means, there is, it is not 760 millimeter, but 735 millimeter; air temperature is given; the relative humidity is given, and it is also given, the saturation, the vapour pressure of air, or vapour pressure of moisture at the temperature and pressure, that is, the saturation vapour pressure; vapour pressure at saturation, or saturation vapour pressure, that is equal to 17.54 millimeter mercury; that means, air at most can contain 17.54 millimeter mercuric pressure, the amount of moisture.

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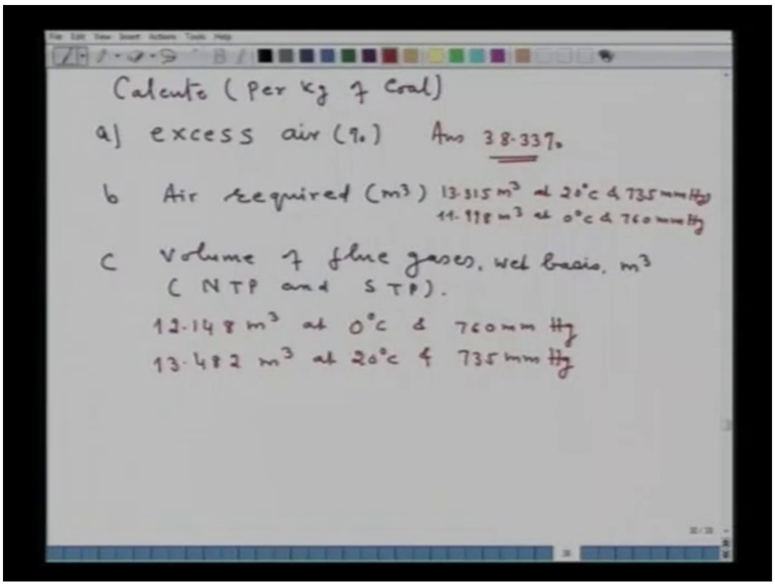

What you have to calculate, so, calculate per kg of coal…Now, for your information, the analysis of solid fuel is always given on weight percent. So, you have to calculate per kg of coal, a, excess air; of course, in percent; b, you have to calculate air required, of course, in meter cube; c, you have to calculate volume of flue gases; volume of flue gases, or product of combustion, weight basis in meter cube at N T P, and S T P; that is what you have to calculate. Now, as I already illustrated one problem, I expect you to give the answer. So, when you calculate, you can match. Now, in order to calculate the excess air, all of you know, first of all, you have to calculate the volume of P O C; from volume of P O C, you have to do nitrogen balance and you can find out the actual amount of air; because excess air is the actual amount of air minus theoretical air upon theoretical air, into 100. So, once you find out the actual amount of air, then, you have to find out the theoretical amount of air, as it is required for complete combustion. If you do all this things, then, the excess air, for this problem, it comes to be, the answer for this would be, 38.33 percent is the answer.

Again, if you calculate volume of air, now remember, you have to calculate at N T P and S T P; do not forget to take into account that, air is moist. So, volume of air, that will be 13.315 meter cube at 20 degree C and 735 millimeter mercury and it is also 11.998 meter cube at 0 degree C and 760 millimeter mercury. You can also calculate the volume at 25 degree C and 760 millimeter mercury, where it is just a matter of conversion. Then, you have to find out the volume of flue gases. Now remember, the volume of flue gas, as I said earlier also, is the volume of dry volume, plus H 2 O, due to reaction between hydrogen and oxygen, plus moisture of the fuel. So, if you perform, then, the volume of the flue gas, it comes 12.148 meter cube at 0 degree C and 760 millimeter mercury. Now, this volume is also 13.482 meter cube at 20 degree C and 735 millimeter mercury. At all the temperatures and pressures, you can calculate this volume also. This is what the problem, which I thought, you will do yourself. Now, another problem I would like to give you is that, I will partially solve and partially solve yourself. Now, the problem is as follows.

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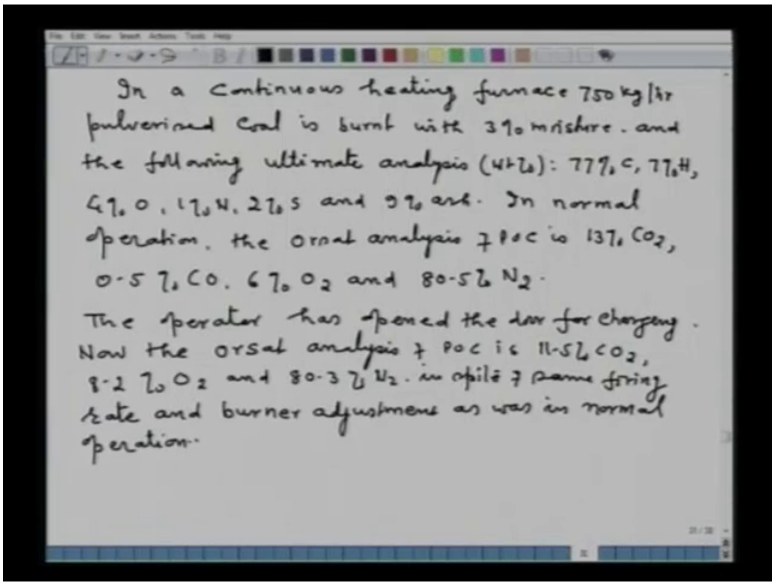


In a continuous heating furnace, in a continuous heating furnace, 750 kg per hour pulverized coal is burnt with 3 percent moisture and the following ultimate analysis, ultimate analysis is given on weight percent. Now, in case it is not mentioned, it is always given on percent; that is 77 percent carbon, 7 percent hydrogen, 4 percent oxygen, 1 percent nitrogen, 2 percent sulphur and 9 percent ash. In normal operation, in normal operation, the Orsat analysis, the Orsat analysis of P O C is 13 percent C O 2, 0.5 percent C O, 6 percent O 2 and 80.5 percent nitrogen. Now, the operator has opened the door for charging. What the operator has done? The operator has opened the door for charging. He observes that, the analysis of P O C is changed. Now, the Orsat analysis of P O C is 11.5 percent C O 2, 8.2 percent O 2 and 80.3 percent Nitrogen, in spite of same firing rate, in spite of same firing rate and burner adjustment, and burner adjustment, as was in normal operation.

What he has done, he has just opened the door and he analyses the P O C, by the Orsat operators; he finds that, the analysis is changed. He thinks that, he has not changed the firing rate; he has not changed the burner adjustment; nothing he has done, but he is surprised that, the analysis of P O C is changed. Now, he has approached to you, and he wants to clear the doubts. What he wants to know?

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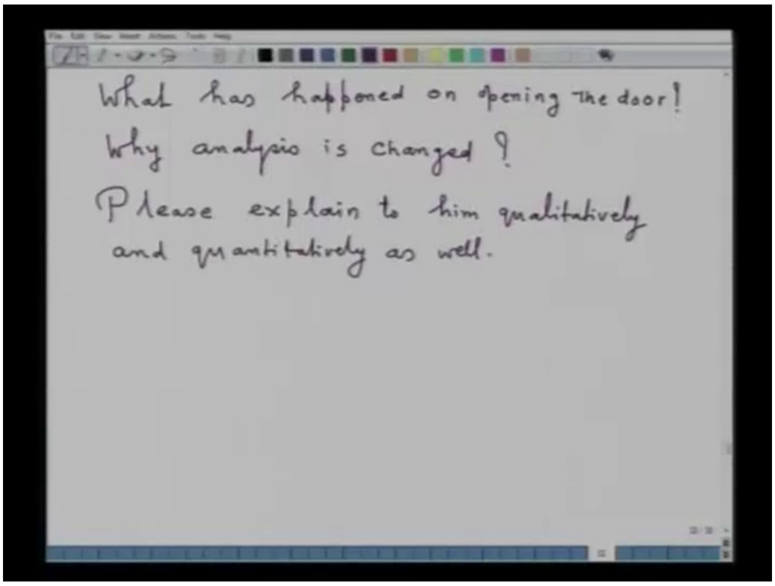


He wants to know, Sir, what has happened, what has happened on opening the door. He is surprised; he has not changed the burner adjustment; he has not changed the firing rate. Everything was similar, as it was earlier. Now, he says that, his analysis has changed. He wants to know, what has happened sir, on opening the door? Then, he also wants to know, why analysis is changed, why analysis is changed. He also wants to know, why analysis has changed, because now, the analysis of P O C now, does not contain any amount of C O. In the normal operation, it was 0.5 percent C O. Now, there is no C O in the volume of P O C.

He is surprised, what has happened. So, please explain to him, please explain to him, qualitatively; you know, he is operator; he is a very sharp person; he wants to know the figure from you; he wants to know the amount. So, explain to him qualitatively, and quantitatively as well, and quantitatively as well. You just cannot, escape by telling him some bullshit. You have to give him the figure that, this has been happened and these are the values. So, this is what the problem before you. How would you approach, to solve this problem? Now, first of all, is the note. What has happened on opening the door? When he has not changed the firing rate, when he has not changed the burner adjustment, then, only thing on opening the door has happened is, the amount of air has rushed into the furnace chamber. So, on opening the door, the air has rushed into the furnace chamber. Now, the furnace chamber has air from the two sources; one, air, which has come through the opening of the door, or, you can call air leaked; and another source of air that we were already supplying, during the normal operation.

Why analysis is changed? Now, since, if you see the analysis of products of combustion in the normal operation, you will note that, it contained the 0.5 percent C O; that means, the combustion was not complete. You note also, the combustion was not complete, in spite of having 6 percent of oxygen in the product of combustion. You recall from the earlier lecture, I have said that, you always require excess amount of air to obtain complete combustion; and the problem says also that, you have 0.5 percent carbon monoxide with 6 percent oxygen in flue gas; that is, even, you are burning coal with the excess air, still the combustion is not complete and that is a fact. You have to supply the excess air. So, why analysis is changed? The reason for this, in the normal operation, the insufficient amount of air; so, carbon was combust into C O 2 and C O; now, extra amount of air is available; on account of that, now, the combustion is complete and on account of that, you do not have any incomplete combustion product in the flue gas, or in the P O C. And, that is what you are observing that, you have 11.5 percent C O 2 and 8.2 percent of oxygen; that is what, your amount of C O was there in the normal operation, now, it has disappeared. That is the answer for why analysis changed.

Now, you have explained to him. Now, you have to calculate the quantitatively, whatever you have said to him. You have said to him two things; first, you have said to him, air has leaked. So, he wants to know, what is the amount of air that is leaked? Then, he wants to know, or what is the amount of air that is leaked, he wants to know, in terms of theoretical air. So, on the quantification front, what you have to calculate, first, you have to calculate, when the door was opened, opened, how much amount of air has leaked into, and this air leakage, you have to express in terms of theoretical air. So, again, you can solve this problem with the help of the input output box, or material balance. Simple material balance, you have to do it. So, the first of all, you have to do the carbon balance. Now, note, in the carbon balance, because the coal contains sulphur and carbon; you know that, in the Orsat analysis, S O 2 is not separately reported. So, while doing the carbon balance, you have to take carbon and sulphur both, and that is equivalent to the amount of C O 2. So, I just give you the hint.

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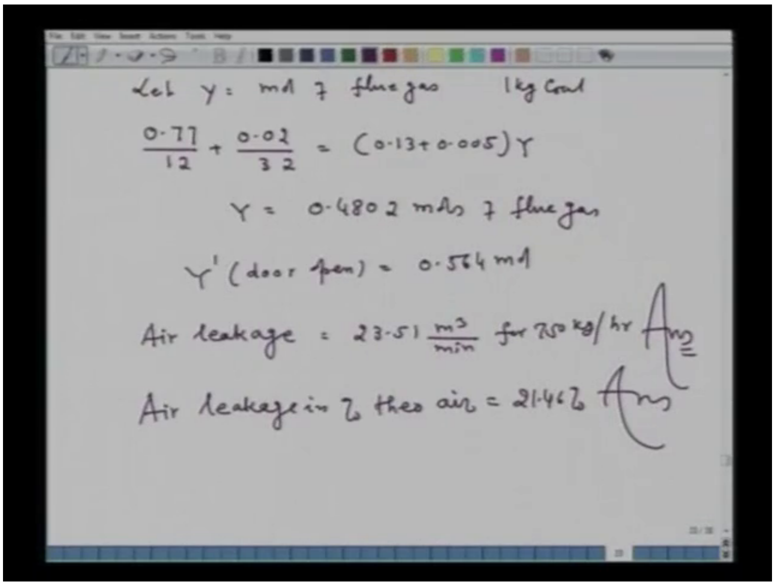


So, let y is the moles of the flue gas. Now, if I do the carbon balance, then, carbon balance will be on mole 0.777 divided by 12 plus 0.02 upon 32; that is equal to 0.13 plus 0.005 into y. Now here, the basis of calculation is 1 kg coal. So, if I calculate y, y will be equal to 0.4802 moles of flue gas. Now, once I know, when doing the normal operation. Now, when the door was opened, I am again given with the analysis of the product of combustion; so, I can calculate now, again, y dash, when the door was opened, door was opened. So, this, it will be equal to 0.564 moles. So, I can find out now, air leakage by doing the nitrogen balance. So, you can perform yourself. So, air leakage, now, you have to find out, from the nitrogen balance, the air in both the cases. So, if you do that, you will get 23.51 meter cube per minute for 750 kg per hour coal. Now, you have to express this air leakage in terms of the theoretical air; what you have to do, calculate the (( )) amount of oxygen, or theoretical amount of oxygen, by complete combustion. So, air leakage in percent theoretical air, that will be equal to, 21.46 percent, and it is the answer. And, that is answer and now, you have satisfied the operator. The operator also feels good and you also feel good.