Fuels Refractory and Furnaces

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Lecture No. # 19
Heat Utilization in Furnaces: Heat Recovery Concepts and Illustrations

I will continue my lecture on heat utilization in furnaces. Today, I will be illustrating role of heat recovery devices. As already you have learned that, heat recovery devices are the devices which recover the heat. In this connection the efficiency of heat recovery devices is important. Unless, they are able to recover the high amount of heat, they will not be able to impart that heat to for example, incoming air. So, we have also seen, the relative efficiency and efficiency limit of the heat recovery devices, we have defined all those things and we have learned the concept and how to use these heat recovery devices.

Now, I have also said that, there are two important heat recovery devices, one is the regenerator, another is the recuperator. Which one will be suitable, that will depend upon the temperature of the discharge gases. If the temperature of the discharge gases is very high for example, of the order of 800, 1000 or 1200 degree Celsius, then the recuperator is not useful, because recuperator their essential construction is that of metallic part. However, for higher temperatures, regenerators are used and regenerators essentially, they have brick checker work. In that, hot flue gas are allowed to flow and in that first cycle, where the hot flue gases flow, the brick checker work gets heated up.

In the next cycle air passes and it recovers the heat from the brick checker work and gets heated up so, essentially regenerator or recuperator, both are heat exchange devices. So, today I will be illustrating the efficiencies of heat recovery devices and their integration with the furnace, as I have also said it is very important to integrate the furnace with the heat recovery devices, because heat recovery devices will essentially heat the air and that air will pass to the furnace.

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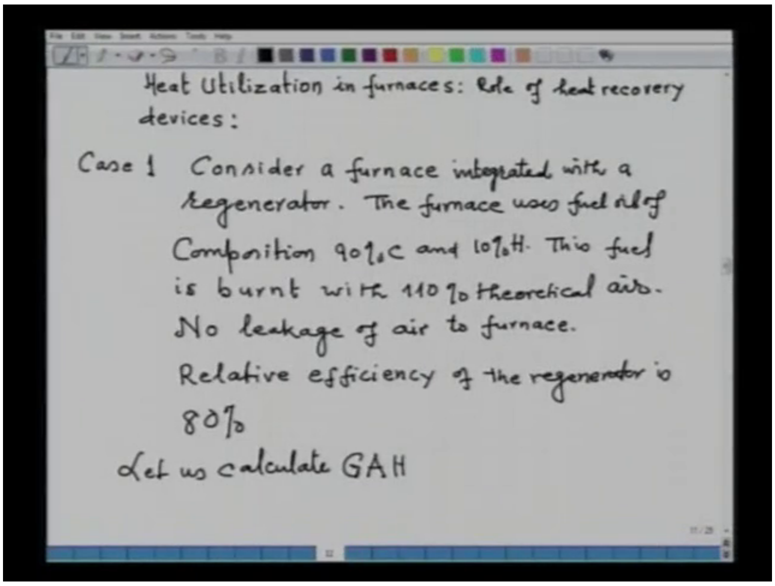

So, let us; let me illustrate it with an example. I will consider, say case 1, let us consider a furnace integrated with a regenerator, the furnace uses fuel oil of composition, 90 percent Carbon and 10 percent Hydrogen. This fuel is burnt with 110 percent theoretical air, in case 1, we observed no air leakage, no leakage of air, to furnace. We also assume that, the relative efficiency of the regenerator is 80. Now, let us calculate for this case, let us calculate gross available heat for this case and understand the concept of different efficiencies which I have introduced in my earlier lecture, in order to calculate gross available heat. Later on we can also correlate this with the fuel consumption and as well as fuel saving.

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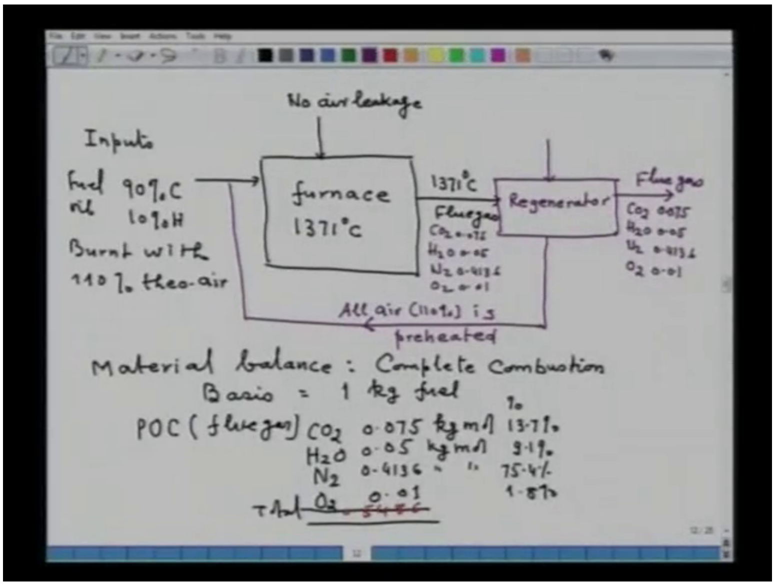

Let us see, the same thing I will be representing in a block diagram and the block diagram is it is this way. Say this I will consider, as a furnace which is operated such that, the flue gas temperature is 1371 degree Celsius. So, invoking the concept of critical process temperature, we assume that, the furnace is operating at 1371 degree Celsius. So, as such flue gases are also discharged at 1371 degree Celsius, that is, what a concept of critical process temperature means. You should also understand that a critical process temperature similar to flue gas temperature, that means, a very uniform meeting, it is an idealized representation of the problem, in actual practice this may not happen.

In actual practice, the flue gas temperature may be somewhat lower or maybe somewhat greater, which depends on the rate of heat demand as already I have enlisted. But for the sake of illustration, let us take critical process temperature is that of the flue gas temperature so, here flue gases. So, now the input inputs are we have fuel oil, whose composition 90 percent Carbon, 10 percent Hydrogen and this is burned with 110 percent theoretical air. We have also assumed that, In this case, no air leakage and now we are integrating with the so called regenerator. So, this is a regenerator which will be heated by the heat of the flue gas and later on the cool flue gas will be discharged.

Now, we are also considering that, all the 110 percent theoretical air is being preheated and this preheated air is supplied to the furnace. So, we have since there is no air leakage in the furnace. So, all 110 percent theoretical air, it will be preheated to a regenerator and that preheated air will be transferred to the furnace. So, what we are assuming here, all air here 110 percent is preheated. So, essentially we are supplying here, preheated air into the furnace. So, if we want to calculate the gross available heat, as I have repeatedly said in my earlier lectures on combustion that is lecture 9 to 13.

The first and the foremost requirement of doing heat balance or calculating anything with relate to gross available heat or net available heat, material balance is most important. So, first we have to do material balance, material balance we will assume there is complete combustion that is, there is no conformation in the flue gas. Now, we have to perform the material balance and for that basis, we will be using say 1 kg fuel. Well I will not do here for you material balance calculation, since you have already done this exercise in earlier lectures. If you understand those and try to do material balance, take 1 kg of the fuel, do the Carbon find out the stoichometric reactions and write down the various products of combustion.

So I have done for you and what I am straight away writing, the products of combustion or they are also called flue gas, both are one and the same thing. It is a carbonaceous fuel, it contains Carbon and Hydrogen and it is burned with excess air and our assumption is complete combustion. So, that tells us straight away, that the products of combustion will consist of CO_2, H_2O, Nitrogen and since there is an excess air so, there will be oxygen also in the flue gas. So, I am calculating in kg moles Co_2 is 0.075 kg moles, H_2O is 0.05 kg moles, Nitrogen 0.4136 kg moles and Oxygen is 0.01. So, we have this material balance before us.

Well, in terms of percentage, so, the total P O C, total P O C is 0.5486 total P O C. So, percentage will be 13.7 percent Carbon dioxide, 9.1 percent H_2O, 75.4 percent Nitrogen and 1.8 percent Oxygen. So, we know now, this is our P O C composition and this particular flue gas, it consists of air. Now, we can straight away write over here that CO_2, H_2O, N_2 and O_2 of the respective moles, say 0.75, 0.4136 and 0.01. They will be entering to the regenerator and the output will also be CO_2, H_2O, N_2 and O_2. CO_2 will also be since, they are not consumed so, their moles will remain the same 0.4136 and 0.01.

When these moles of flue gas, they are passed into the regenerator, remember moles are not at all consumed, it is the only heat transfer occurs. Only on passing through regenerator the flue gas which exists the regenerator will have a temperature lower than the entry temperature of flue gas. So, further we calculate, we also will need the amount of dry air.

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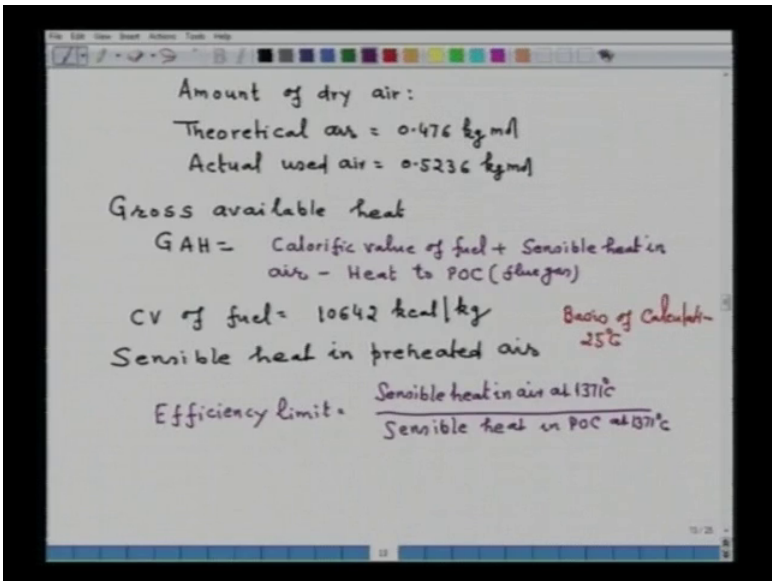

So, we calculate now the amount of dry air. So, first you can calculate the theoretical amount of air, simply C plus O 2, C O 2 all of you know theoretical air or if you have any problems in calculation refer to my lecture 9 to 12. Theoretical air, that will be equal to 0.476 kg mole and since 110 percent excess air is used. So, the actual used air that will be equal to 0.5236 kg moles so, now we have a complete material balance before us. We know that much amount of air would be required and that much amount of air will be preheated into the regenerator that much amount of flue gas will pass into the regenerator. Now, we are in a position to calculate heat related quantities.

So, we have to calculate now gross available heat and as we all know gross available heat that will be equal to Calorific value of fuel, plus sensible heat in air minus heat to products of combustion or flue gas both refer to the same meaning, you should not confuse in any way. Now, in order to calculate gross available heat, we should know, what is the calorific value of the fuel? Now, if calorific value of the fuel is not given, then calorific value of the fuel can be calculated by the so called dulong formula which I have done in the lecture number 2. So, the calorific value, if I use the dulong formula, then the calorific value of fuel that is equal to10642 kilo calorie per kg.

Now, we have to calculate sensible heat in air, because air is preheated in the regenerator so, first we will have to calculate the so, called sensible heat in preheated air. Now, for all calculation on heat, our assumption say basis of calculation, as I have pointed out at several places is 25 degree is our base temperature that should be clear. Now, sensible heat in preheated air, it can be calculated by the various efficiencies which we have defined in the earlier lecture. So, if you recall, we have defined the so called efficiency limit. So, this efficiency limit, I am writing once again, efficiency limit that is equal to sensible heat in air at hot flue gas temperature and in our case the hot flue gas temperature is 1371 degree Celsius.

I am straight away writing upon sensible heat in P O C at same temperature, that is the efficiency limit. So, here first of all we have to find out what is the sensible heat in P O Cat 1371 degree celsius or sensible heat in P O C means, how much amount of heat P O C is taking with it. So, we have to calculate now the heat to P O C or sensible heat in P O C.

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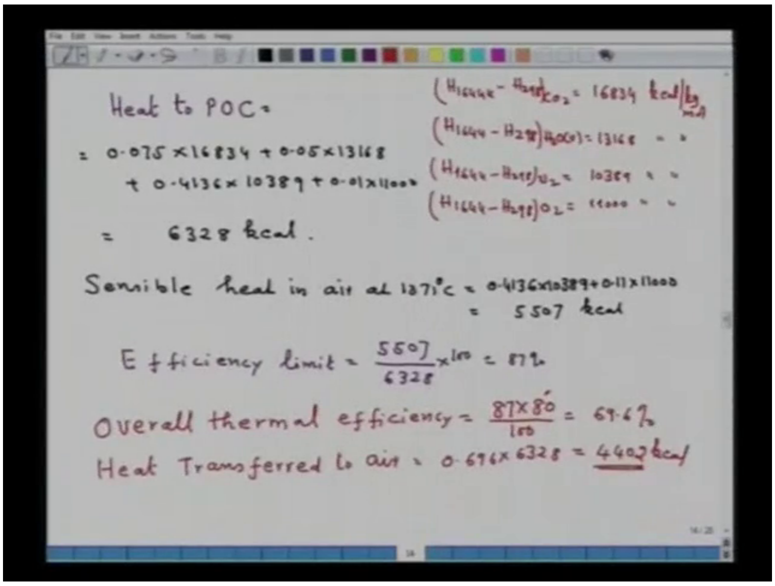

Now we have to calculate heat to P O C. Very straight forward M C P into delta t. You can calculate taking C P is equal to A plus 2 bt plus C by t square as already I have said or for easy calculation not listed. What I am using, I will be writing here, the Enthalpic content at the temperature of interest on the basis of reference temperature. So, I am writing here the Enthalpic content for example, H 1644 kelvin minus H 298, for C O 2 that is equal to 16834 kilo calorie per kg mole. Similarly, H 1644 kelvin minus H 298, H 2 O vapor, that is equal to 13168 kilo calorie per kg mole and H 1644 minus H298, Nitrogen, that is equal to 10389 kilo calorie per kg mole and H 1644 minus H 298, O2, that is equal to 11000 kilo calorie.

Now, straight away we can calculate heat to P O C all that you have to multiply kg mole with the respective Enthalpic content. So, heat to P O C that will be equal to 0.075 into 16834 plus 0.05 into13168 plus 0.4136 into 10389 plus 0.01 into 11000. So, if I sum total it, then this will give me heat to P O C, 6328 kilo calories. Now similarly, I know now the amount of air, air consists of 71 percent Nitrogen, 21percent oxygen. So, I can also calculate now the sensible heat in air at 1371 degree celsius that will be equal to 0.4136 into 10389 plus 0.11 into 11000. So, this is the sensible heat in air at 1370; 1371 degree Celsius so, that will be equal to 5507 kilo calories.

Now, I can calculate relative; now, I calculate the efficiency limit. So, you take the calculator and calculate it, that will be equal to 5507 upon 6328 into 100. So, that will be giving you 87 percent, this is the 87 percent is the efficiency limit of the regenerator. Now, I can calculate the so called overall thermal efficiency, you know that is equal to efficiency limit into relative efficiency. So, if I do that efficiency limit it is 87 percent relative efficiency is given to 80 and if I divide by 100, now, this 80 percent relative efficiency is given, so, that is equal to69.6 percent.

So, this overall thermal efficiency of 69.6 percent tells you, that only 69.6 percent of the heat, of the flue gas will be available to preheated air that is the meaning of overall thermal efficiency. So, in this particular problem the heat transferred to air as the amount of air passes through the regenerator, that will be equal 0.696 into 6328 and that will be equal to 4402 kilo calorie. So, this is how you will be calculating the amount of heat that is obtained when the amount of air passes through the regenerator. Now, if you consider the heat balance of a regenerator only, then the following picture emerges.

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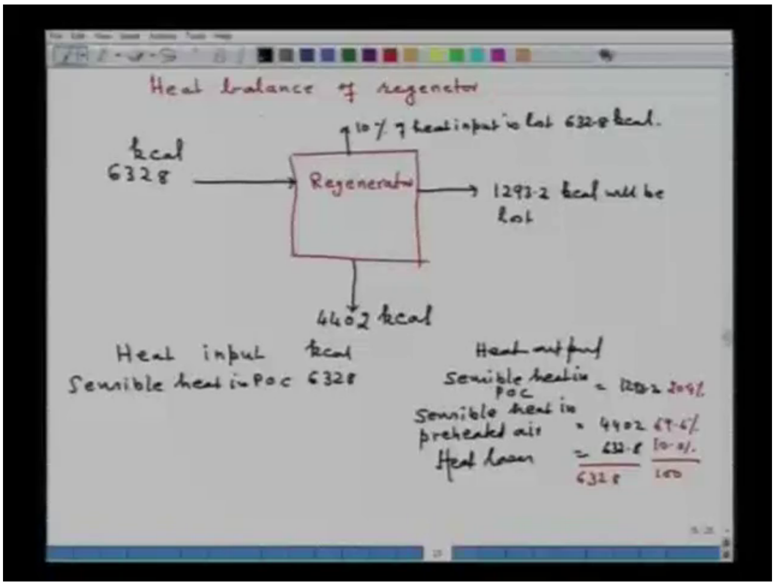

Now, we consider the heat balance of the regenerator and I draw a block, a box so, that is a regenerator amount of heat which is entering 6328 kilo calorie. Now, we consider now let us say, 10 percent of the heat input is lost, that means, 632. Kilo calorie is lost. We could recover, 4400 kilo calorie is recovered in the form of preheated air which will be supplied to the furnace and the rest 1293.2 kilo calorie will be lost to the surrounding. So, if you make the heat balance so, heat input is 6328 kilo calorie. I will write down the heat balance so, heat input and heat output.

Say heat input is sensible heat in P O C, that is how you will be doing the heat balance also 6328 kilo calorie and there is no other heat input. Now, output, the sensible heat in P O C, that is equal to1293.2 and in percent 20.4 percent. You see that still 20.4 percent heat is being lost, sensible heat in preheated air heat, that is equal to 4402 or that is equal to 69.6 percent. And heat losses, that is equal to 638.8 and that is equal to 10.0. So, this makes again 6328 and this is equal to 100 percent. So, why I have given the heat balance, from here you can get a clue, what should be done, if you want to improve the efficiencies of the regenerator you know 20 percent is going to lose, 10 percent is the heat losses. Maybe you could do something more in order to improve the design and construction of the regenerator.

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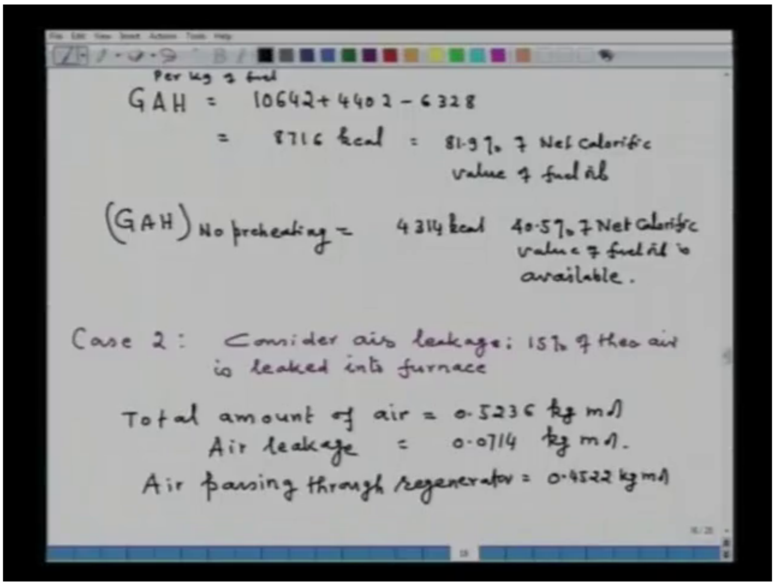

Now, we can calculate the gross available heat, that is equal to calorific value to the fuel as I have said, you calculate from dulong formula. For this gross available heat, we are calculating is per kg of fuel 10642 plus 4402 minus 6328. So, this gross available heat is 8716 kilo calorie or that is equal to 81.9 percent of net calorific value of the fuel oil, had there been no preheating, so, gross available heat not preheating. This will be equal to 4313 kilo calorie, that means only 40.5 percent of net calorific value of fuel oil is available.

So, you can see the importance of integrating a heat recovery device. You are able to increase the gross available heat almost 55 times and to that tune you will be able to save almost that much amount of fuel, if you preheat and if you want the process to be carried out at 8716 kilo calorie. So, that is, it shows that how integrating the heat recovery devices. In this example, we have taken regenerator, how it helps? It helps in many ways, one way it helps to decrease the fuel consumption. Had there been no preheating and if you will be requiring around 18; 81 percent of the heat, then you have to burn more amount of fuel.

Another thing is that, whatever heat you are adding or whatever heat you are expecting from the flue gas, you are also producing the emissions, that is, thermal addition to the environment. So, this particular example illustrates not only fuel economy, but, also illustrates how to reduce the thermal emissions. So, in this sense this example has to you that fuel economy and thermal emission reduction, these heat recovery is that very very important. Now, let us take again another case, now let us take case 2, we just extend this example further to illustrate some of the more important thing.

So, let us take case 2, in the case 2, we consider air leakage. In case 1 mind you, we have not considered air leakage now, we are considering air leakage. We consider 15 of theoretical air is leaked into furnace, all other operation are same. We have not changes any other operation, other than there is now an air leakage. We are operating the furnace 110 percent air, fuel oil is same composition, early we are integrating with the regenerator. The only difference between case A and case 2 is that 15 percent of the theoretical air is leaked into the furnace. And let us see, how this air leakage affects the gross available heat and so on and also regenerator efficiency.

Now, what does it mean is the air is leaked? Since, you have decided to work with 110 percent theoretical air. In case 1 all 110 percent air was rooted through regenerator and a preheated air was taken into the furnace. Now, 15 percent air is being leaked into the furnace. Now, only 95 percent of the air will be passing through the regenerator, could you get the thing which I wanted to convey? Out of 110 percent total amount of air since 15 percent has leaked into the furnace. Now, the amount of air which will be taken to the regenerator for heating is only 95 percent. That means, 95 percent of the heat, 95 percent of the air will now be preheated into the regenerator, this calculation we will do.

So, now with the air leakage, the following scene emerges. Earlier we have calculated the total amount of air will be same, now, that was earlier we have calculated 0.5236 kg mole. Air leakage that is equal to 0.0714 kg mole, now, air passing through regenerator, how much it will be? You have to subtract 0.5236 from 0.0714 that will be equal 0.4522 kg mole.

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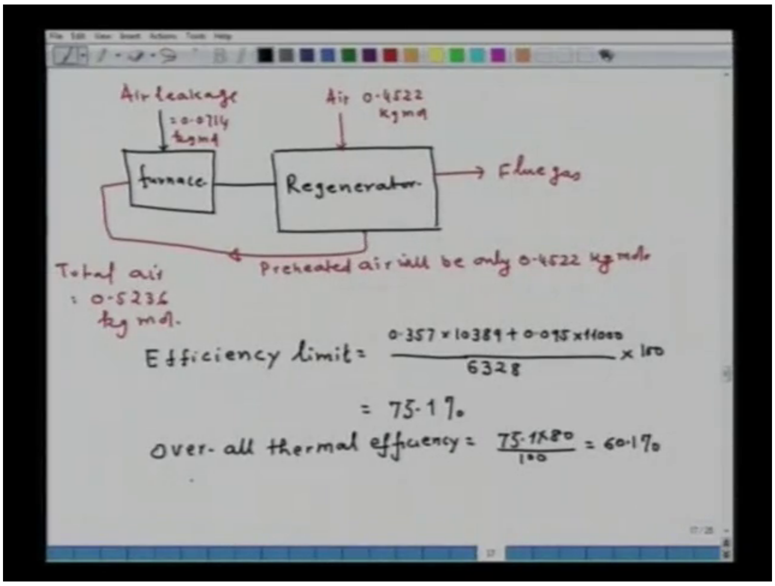

So, now again if I do a block diagram for balance, then it appears as follow this is the regenerator and I will make it this is the furnace. So, in the furnace, air leakage that is equal to 0.0714 kg mole. Total air is equal to 0.5236 kg mole. So, here only air or preheating will be 0.4522 kg mole, the rest air is leaked directly into the furnace. Of course, here is the flue gas and the preheated air so, preheated air will be only 0.4522 kg mole that is what, it shows it now. Now for this case, again if you want to calculate the gross available heat, you have to perform the same calculations as you have done earlier.

We have to find out what will be the sensible heat in preheated air. Again we are assuming the same thing, relative efficiency is also 80 percent. Though you may argue, sir, little bit amount of air is decreased. Because earlier it was 0.5236 kg mole was passing through the regenerator, now, it is 0.4522 kg mole is passing only to the regenerator. Velocity of the air will be somewhat lower than the earlier case. Relative efficiency of the regenerator could be slightly higher, it is possible. Then for the sake of calculation, we are considering the relative efficiency same as that was in case 1, that is the 80 percent.

So, let us calculate now efficiency limit, you have to calculate a fresh sensible heat in air at hot flue gas temperature. So, I have given already the values of Enthalpic content, I am simply writing down 0.357 into 10389 plus, 0.095 into 11000. And heat content in flue gas is the same as that we have calculate earlier you have to multiply it by 100. So, you see now, the efficiency limit has gone down to 75.1 percent, earlier it was 81 percent. So, as a result of decreasing the efficiency limit, what will happen to the overall thermal efficiency? Overall thermal efficiency, that will be equal to 75.1 into 80 upon 100, that is equal to 60.1 percent.

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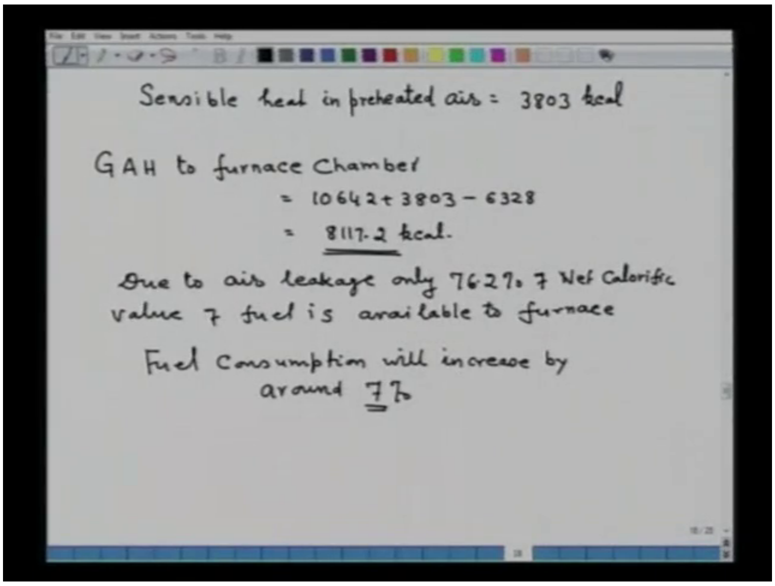

Now, that means, the sensible heat in air, sensible heat in preheated air, how much it will be? It will be 60.1 percent of the heat of flue gas. So, that will be equal to 3803 kilo calories. So, you can make out, what is the effect of air leakage? Now we can calculate gross available heat to furnace chamber. So, gross available heat that will be equal to 10642 plus 3803, that is the sensible heat in preheated air, minus 6328, that will be equal to 8117.2 kilo calories. Now, so due to air leakage, only 76.2 percent of net Calorific value of fuel is available to furnace.

Now, this now, slightly less amount of heat will be available to the furnace and what it will lead to, if you operate this furnace. At the same amount of gross available heat as that of case one, what will happen now? Can you think of? Because, now, the gross available heat in presence of air leakage has decreased. But you want to operate the furnace in the same amount of gross available heat for case A. So, naturally, the fuel consumption will increase. So, in this case, fuel consumption will increase by around 7 percent so, that is what the role of air leakage into the furnace. So, air leakage is a very detrimental to the fuel economy.

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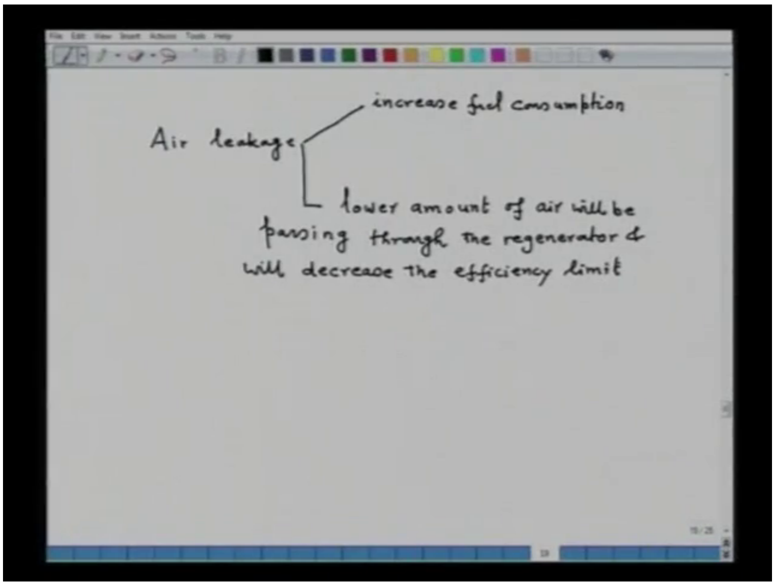

So, in short we can say that air leakage, it will increase fuel consumption, how it will increase? Because whatever amount of air, that has leaked into the furnace. It will take the heat of the furnace and in order to compensate that heat, you have to supply extra amount of energy, that is, the one detrimental effect of air leakage. So, for all fuel economy purposes or for fuel saving purposes, it is at most important that air leakage in the furnace should be as minimum as possible.

Now, another important effect of air leakage is when a furnace is integrated with a heat recovery device then, lower amount of air will be passing through the regenerator and will decrease the efficiency limit. And when it decreases the efficiency limit, naturally, it will also decrease the overall thermal efficiency. And as a result of decrease in overall thermal efficiency, the amount of heat which is transferred from flue gas to air will also be lower. So, in fact the air leakage affects in two ways broadly speaking. One way it increases the fuel consumption, because naturally now, air is leaking and a part of the heat will be taken by the air to heat to that particular temperature. So, common sense says, the fuel consumption will increase, therefore, all arrangement must be made, so that air leakage remains to a minimum.

Another effect of air leakage when the furnace is integrated with the heat recovery device or regenerator or recuperator, and if the furnace operates with the same total amount of air, as it was initiated in the design stage. Then, a lower amount of air will not be passing to the regenerator as a consequence, you are unable to utilize the efficiency of the regenerator also. Therefore, all efforts must be made to see that, the air leakage remains to the minimum.

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