Fuels, Refractory and Furnaces

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Lecture No. # 29

Transport Phenomena in Furnaces: Heat Transfer and Refractory Design

We will take applications of heat flow equations to lining design, some of the applications I have already done in my earlier lecture.

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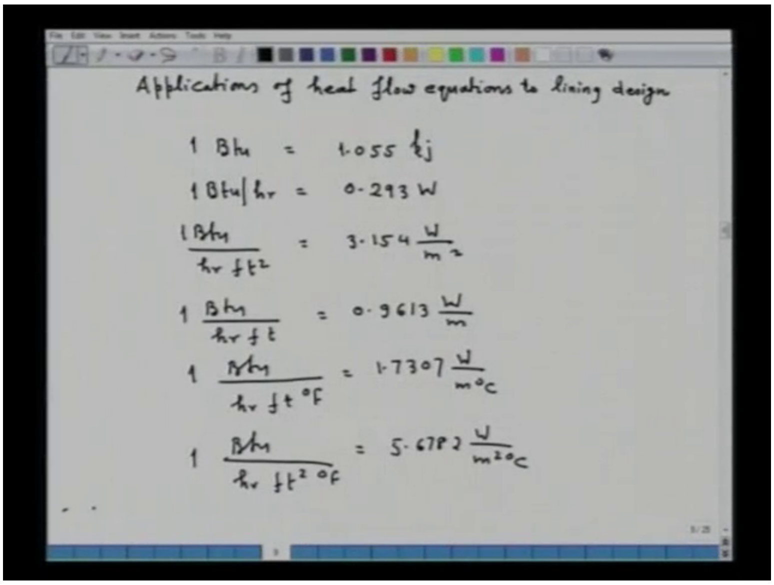

Now, today what I have thought I will try to illustrate the use of the equation in different units also, so that your conversion with the units of various variables. So, I will give of the say conversion values of the units say for example, 1 B t u that is one British thermal unit that is equal to 1.055 kilo joule, 1 B t u per hour that is equal to 0.293 watts, then 1 B t u upon hour feet square that is equal to 3.154 watt per meter square. Then 1 B t u per hour feet that is equal to 0.9613 watt per meter, then 1 B t u per hour feet degree Fahrenheit that is equal to 1.7307 watt per meter degree Celsius that is unit of thermal conductivity. Then 1 B t u per hour feet square degree Fahrenheit that is equal to 5.6782 watt per meter square degree Celsius that is unit for heat transfer coefficient.

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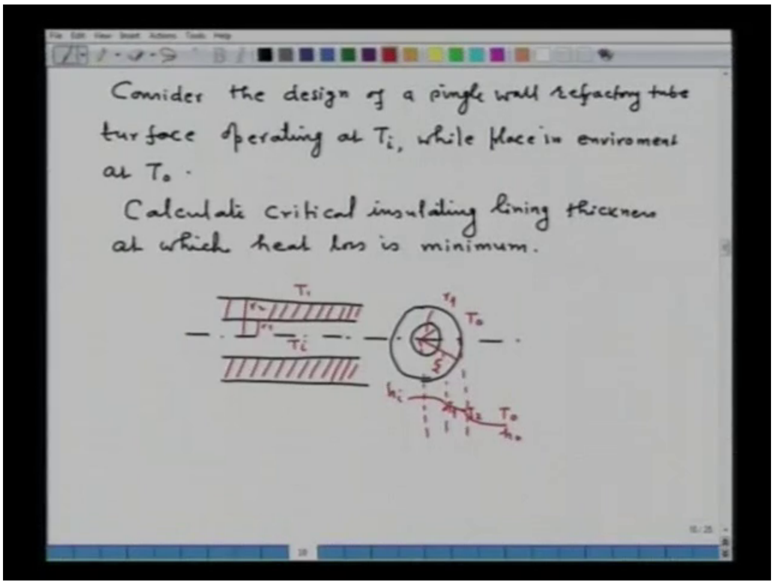

Now, with this let us take another problem. Consider the design of a single wall refractory tube furnace which is operating at temperature T i, while placed in environment at temperature T 0. Now, you have to calculate critical insulating lining thickness, at which heat loss is minimum. Now, this problem I have given with the view that we always perceive that as you add more and more refractory lining, there will be a lower and lower heat loss that is what the perception of the lining of the furnace heat. It appears that it is not, so that you go on adding the refractory lining the heat loss will continuously decrease.

Now, let us see, what are the factors that are responsible. So, in fact the problem under consideration can be represented for example, this is the tube furnace and this is the lining and this is the interline and this is the another view. So, we have let us consider this diameter as r 2, this diameter as r 1, this temperature as T i and this is same here as r 1, this is r 2 and this is the refractory lining, this is the refractory lining. And, if we wish to represent, say this temperature is T 0, this is the environment temperature not the temperature of insulating environment interface.

So, if you wish to draw, so called thermal gradient. Then, from here we have, say this temperature say this temperature let us say this is T 2, this here T 0 this temperature is T 2, this temperature is T 1 and here we have the so called, this one is and this. So, this is the h i and here is the h 0, they are the respective heat transfer coefficient. So, here the temperature is given of the environment temperatures T 0, so let us see how we get this concept of critical insulating thickness.

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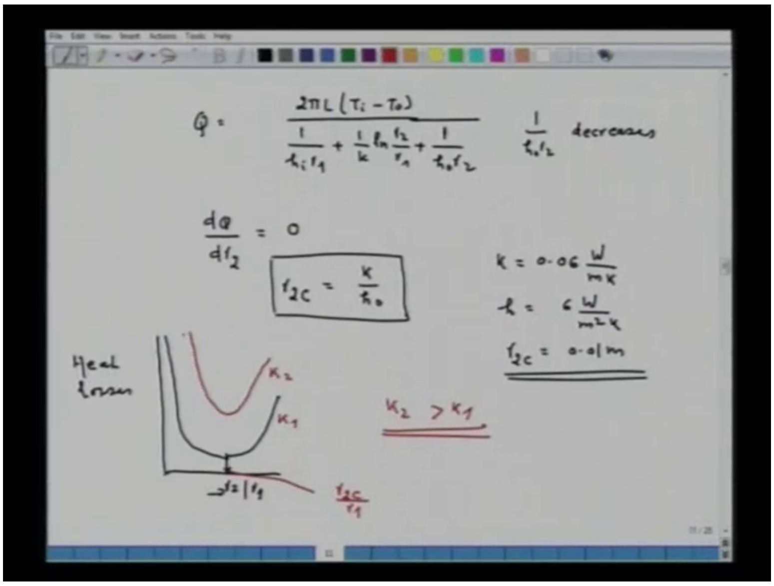

Now, for this geometry, now say radial flow through the furnace wall we already found say Q that is equal to 2 pi L T i minus T 0. Now, where this L, this is the L is the length of the furnace upon 1 upon h i into r 1 plus 1 upon k l n r 2 upon r 1 plus 1 upon h 0 r 2 that is what we have already derive this equation. And, now if you look at this equation r 2 it will present the distance from the center of the furnace to the insulating lining. So, as r 2 increases, then the value of 1 upon h 0 into r 2 it decreases. That is, this 1 upon h 0 r 2 is the thermal resistance. So, as r 2 increases the thermal resistance occurred by the heat transfer coefficient from lining to the surrounding decreases, but at the same time the thermal resistance offered by the refractory lining it increases.

So, you see if one parameter increases another parameter decrease, so there has to be somewhere and minimum value of clue, so how we will go find out. So, you have to differentiate the, this heat loss with the outer radius d r 2 and we said the differential equation to be equal to 0 and from there, that this you can do yourself, this is not a very difficult. And, here we get r 2 c that is equal to k upon h 0. So, this relation represents that well there is a critical layer thickness above which the heat loss will increases rather than it decreases. So, prevailing concept that increase the lining thickness and you will decrease the heat loss, that is not true. There is critical insulating thickness which depends upon the thermal conductivity of material and heat transfer coefficient from the outer surface of the furnace to the surrounding.

Now for example, if we take k is equal to 0.06 watt meter Kelvin and h we take 6 watt per meter square Kelvin, then we get r 2 c that is equal to 0.01 meter. So, what does it mean? That beyond the critical layer thickness of 0.01 meter that is, if we increase the insulating thickness layer beyond 0.01, the heat transfer or the heat flow or the heat loss will increase rather than it decrease. So, for example if you plot, say if you can plot here say heat losses, we take ratio r 2 upon r 1. So, when r 2 is equal to r 1, then the heat losses will be very high, so as we increase the value of r 2 upon r 1, then what will happen? The heat loss will decrease and at some critical value beyond it further increases, so this value is the so called r 2 c upon r 1.

Now, this value it depends upon the thermal conductivity of material k 1, now if I have another material which has a thermal conductivity higher than k 1, then naturally this curve is going to have this particular way, where k 2 is greater than k 1. So, this is a very very important concept in the refractory lining design particularly for tube furnaces, that beyond the particular thickness the heat losses in fact they increase. Also, if you couple this information with the thermal conductivity of the material, now you can also have a idea of selection of material with reference to heat losses.

Say for example, they if you have the different material of different thermal conductivities, this is the one way. Then you select the material of lower conductivity or if you have a material of one thermal conductivity, then you can optimize with the increase layer thickness. So, what is important here is the concept of critical insulating thickness and the role of thermal conductivity of the material that is if you want to decrease the heat losses beyond r 2, then you have to change the value of thermal conductivity, that is what this equation says.

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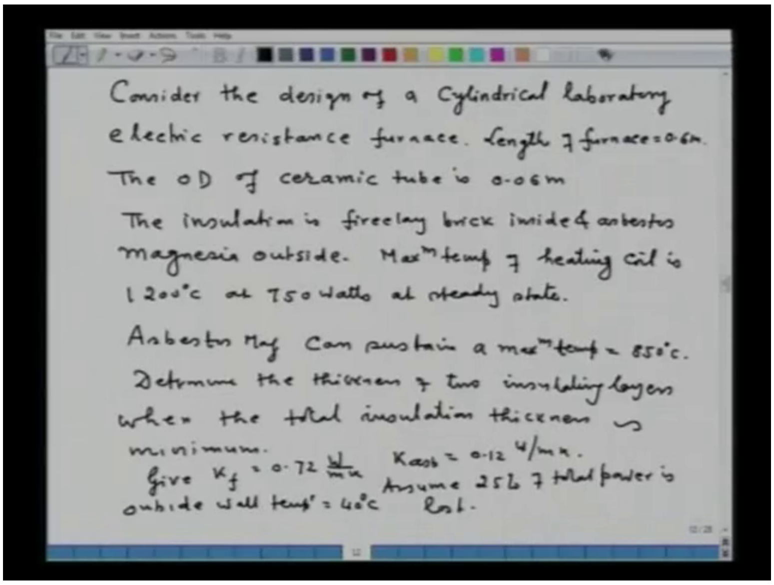

Now, let us take another example say consider the design of a cylindrical laboratory electric resistance furnace that you must have done in your courses. Because heating of the material in laboratory, we always use the tube furnaces; they are design in laboratory by winding a Chantal wire on experiment tube. So, length of furnace is 0.6 meter. The outer diameter of ceramic tube is 0.06 meter, because you wound or you wind the heating element on the outer diameter of the tube. The insulation is fireclay brick inside and asbestos magnesia outside. Maximum temperature of heating coil is 1200 degree Celsius at 750 watts, at steady state.

Now, it is also given that asbestos magnesia can sustain a maximum temperature equal to 850 degree Celsius. You have to find out or determine the thickness of two insulating layers, when the total insulation thickness is minimum. Now, that is very important that is you have to find out, the thickness of both layer at which the total thickness is minimum that is where the key of the problem lies. Also, it is given say k fireclay it is given to you 0.72 watt per meter Kelvin, k asbestos magnesia is given 0.12 watt per meter Kelvin. Also, assume 25 percent of total power is lost and also outside wall temperature of the furnace assume at 40 degree Celsius. So, what you have to calculate? The total thickness at which the insulation thickness is minimum. So, what we have to do now again, we have done already the composite cylindrical shell and we can write these equation.

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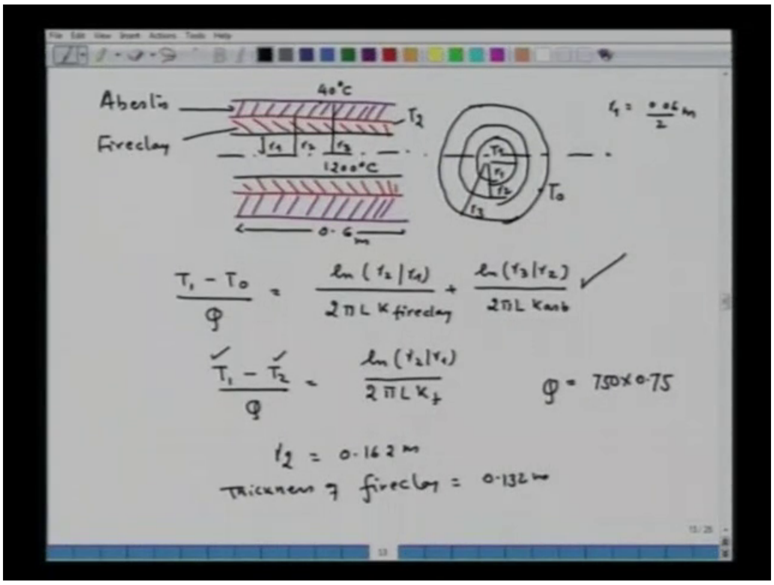

For example, if I represent it, this is what required to be done. This is the tube furnace, this is ceramic tube and this is your fireclay brick, this is the fireclay brick lining and here this is the asbes magnesia lining. (No audio from: 18:10 to 18:19) And, say if you represent another view here, then this is our furnace tube, this is the fireclay brick lining and this is the asbestos brick lining. So let us take it, that this is as r 1 this is as r 2 and this one as r 3. So, similarly we can also say this one is here r 1 this is r 1 and this is r 2 this temperature is given 40 degree Celsius and this temperature is given is at 1200 Celsius, that is the maximum heating element temperature.

And, the length of the furnace that is given to you is 0.6 meter, r 1 is equal to, r 1 is given to you how much? That is outer diameter that is the 0.06 upon 2 that is meter that is, so we know this equation at T 1 minus T 0 upon q that is equal to l n r 2 upon r 1 upon 2 pi l k fireclay plus l n r 3 upon r 2 2 pi l k asbestos, where here this temperature I am taking as T 1 and this temperature is T 0. Now, mind you here we do not need the value of heat transfer coefficient because the temperature directly at the interface is given. So, that is why I have not used the interface, the heat transfer coefficient.

Now, it is said that the asbestos magnesia can sustain a maximum temperature of 850 degree Celsius. This one is the asbestos magnesia and this one is fireclay. So, when this can sustain, this asbestos magnesia can sustain maximum of 800 degree Celsius; that means the interface temperature between asbestos magnesia and fireclay is 800 degree Celsius. So with this we can write down say T 1 minus T 2 upon q that is equal to l n r 2 upon r 1 2 pi l k fireclay. Now, this temperature, the interface temperature I have represented as T 2. Now, all that I have to substitute these values, then I will be getting so T 1 is 1200, T 2 is 850, just now we have discussed, what is the value of Q? Q will be equal to 750 watt supply, 75 percent is used that is the value of Q. So, we can substitute all the values, so we will be getting r 2 is equal to 0.162 meter.

And hence, thickness of fireclay that will be equal to 0.132 meter because r 2 value is from here to here, so we have to subtract the value of r 1, so that is what you can get. Now, since the value of r two is known to us, now we can use of this particular expression, r two is known to us. We have to find out the value of r 3, rest everything is known, you substitute the values of all.

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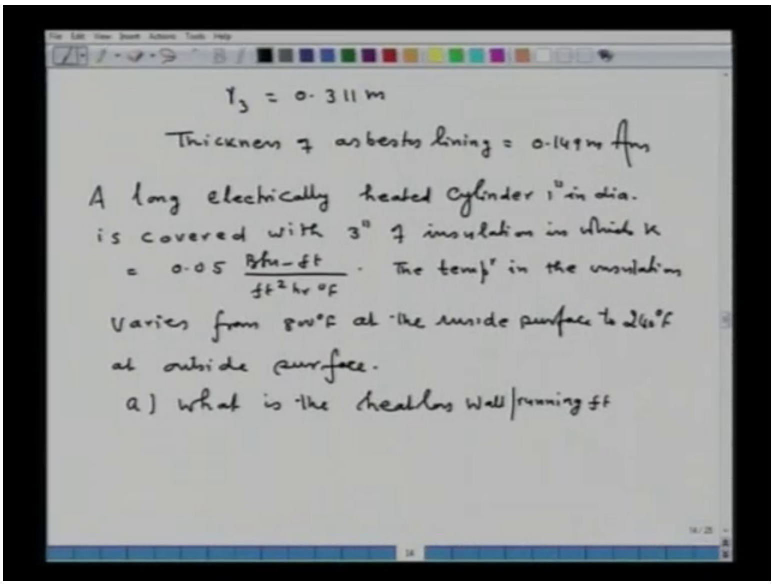

Then, you will be getting r 3 that will be equal to 0.311 meter and so thickness of asbestos lining that will be equal to 0.149 meter, so that is the answer. Now, what is require in this problem to think? One as the problem says that you have to find out the thickness of two insulating layer when the total insulating thickness is minimum. Now, this particular means if you note that the value of k asbestos, say k asbestos is very much less than value of k fireclay. So, that means if total thickness has to be minimum, then the lining of asbestos magnesia has to be higher, number one. Number two problem important points in this particular problem, that the maximum temperature which asbestos magnesia lining can sustain is 850 degree

Celsius and this particular information directly tells you that the temperature at the asbestos magnesia and fireclay interface is 850 degree Celsius. And, these are the two important things that are data I mean hidden in this particular problem, unless you dig out it will be difficult to solve the problem. So, that is what this idea.

Now, let us take another problem, say a long electrically heated cylinder say 1 inch in diameter. Now, I am illustrating a problem in British units is covered with 3 inch of insulation in which k is given to you 0.05 B t u feet, feet square hour degree Fahrenheit. The temperature in the insulation varies from 800 degree Fahrenheit at the inside surface to 240degree Fahrenheit at outside surface. Now, find what is the heat loss in watt per running feet? Now, purposely I have mixed the various units so that you bring here attention while solving the problem and at the same time, you are conversion with the different types of units.

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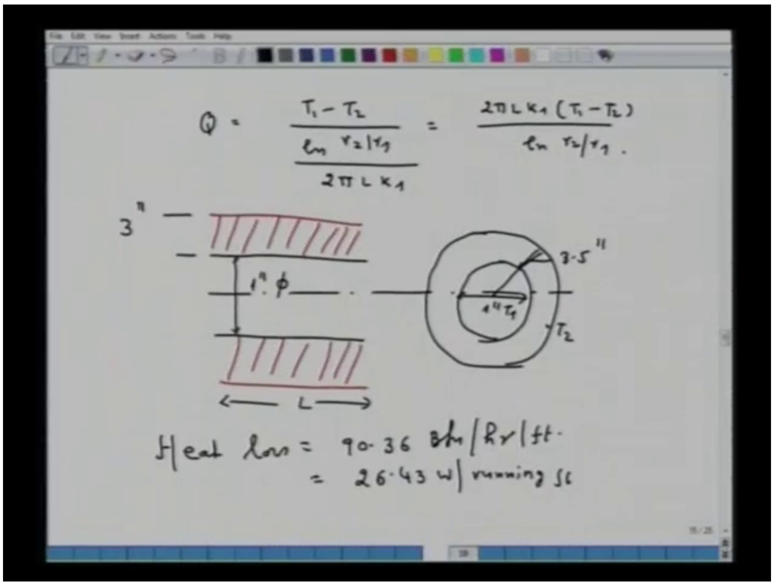

Now, I have to solve this problem is very straight forward, because here you have to use the simple expression that is the heat flux or other heat loss Q that is equal to T 1 minus T 2 upon l n r 2 upon r 1 divide by 2 pi l k 1 or you can also put it that is equal to 2 pi l k 1 T 1 minus T 2 upon l n r 2 upon r 1. Now, if you want to represent very simple, say this is the furnace and here we have the insulation, this is the insulation. Now, this is given as 1 inch diameter and this is given 3 inch insulation thickness or if you wish to represent somewhere here, then this the furnace tube and this is the insulation. So, this diameter is 1 inch and from this thickness or from center line this is 3.5 inches.

So, you have given this temperature is T 1 and this temperature is T 2 and this length is L. So, I have written this expression, all that you have to substitute and the heat loss will be equal to 90.36 B t u per hour which is that will be equal to 26.43 watt per running feet, B t u per hour per running feet. So, that is how you can solve this particular problem.

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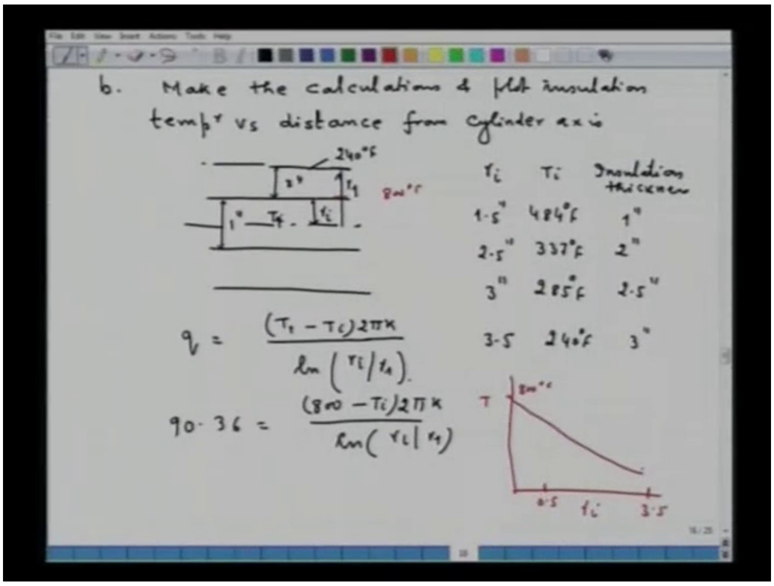

Now, as an extension of this problem part b, I would like you to calculate say make the calculations and plot insulation temperature verses distance from cylinder axis. So, what is require is that let suppose, this is 1 inch and this is the (( )) 3 inch as given, this is 1 inch. So, what is required, you have to plot, you have to I mean calculate the temperature at various distances in the lining and then you have to plot. For example, if we take this is 1 inch, this is 3 inch, we have to use the formula you know this that q that is equal to T 1 minus T i into 2 pi k upon l n r i upon r 1. So, what I represent. I am representing this is as r i and this is as r 1, so that is what I am representing over here. And, this is as your T 1 and sorry this is as T 1 and we have to calculate T I, we have to calculate T i as a function of the distance of the cylinder axis.

So, what we will do? We will simply we know the value of q of course, this is per meter, so we have calculated q 90.36 that is equal to 800 minus T i into 2 pi k upon l n r i upon r 1. So, I will substitute the various values for example, I take r i and I calculate T i and then the insulation thickness. Because insulation thickness you have to subtract the diameter of the tube, so r i if I take say 1.5 inch, take here 2.5 inch and 3 inch. So, T i become 484 degree Fahrenheit, 337 degree Fahrenheit and 285 degree Fahrenheit. Insulation thickness will be 1 inch, here it will be 2 inch, here it will be 2.5 inch and at r i is equal to 3.5, insulation thickness is 3 inch, what will be the temperature? This is that 240 degree Fahrenheit that is given, so this temperature is given as 240 degree Fahrenheit.

So, now, all that you have to plot well, you should plot on a graph paper. So, if you plot here, say let us take here temperature and here we will take the, so called value of r i. Then, at r i is equal to 0.5, the value of T is 800 that is, here the value is given to you 800 degree Fahrenheit. So, at value 0.5 this is 800 degree Fahrenheit, so that somewhere here is 3.5, so at 3.5 I have value of 240. Then, I can plot and it appears to me somewhere a slightly known linear nature is (( )) to be there. So, that is what you can also plot and see all the values are varying. Another let me illustrate now the important, the role of air gap as I have told in my lecture that I have illustrate it for a problem.

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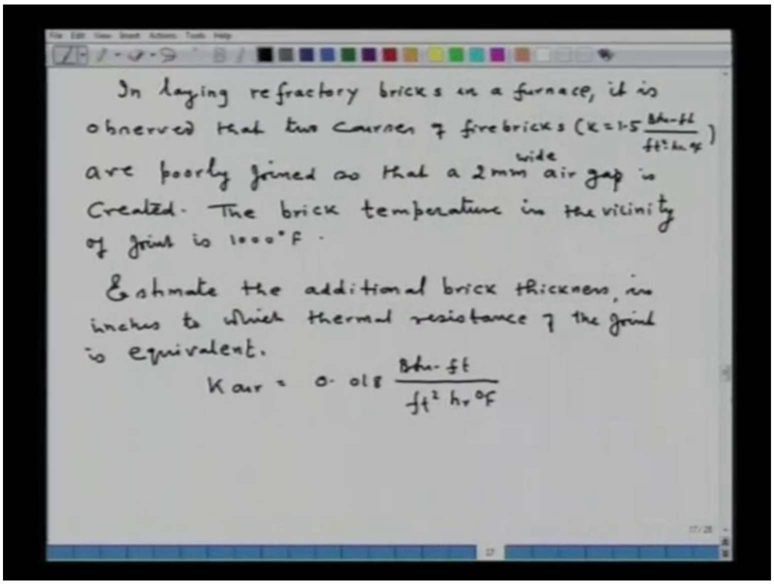

So, let us see, say in laying refractory bricks in a furnace, it is observed that two courses of firebricks k that is equal to 1.5 B t u feet square into hour into degree Fahrenheit are poorly joined. So, that a 2 millimeter air gap is created, because when you make a wall then the you lay one brick after other and the next brick and next brick, that is what the furnace wall is. So, in laying the two bricks sometimes because of the roughness or whatever mistake you have done, a space between two brick is left and that has a width of 2 millimeter. So, that a 2 millimeter wide air gap is created. The brick temperature in the vicinity of joint is 1000 degree Fahrenheit. Now, estimate the additional brick thickness in inches to which thermal resistance of the joint is equivalent.

Now, you are laying two bricks and in between there is an air gap. So, what that air gap can do? Because of the very poor thermal conductivity of air gap, the temperature is drastically fall between the brick, so as a next brick, if we cannot sustain the sudden temperature fall then this brick collapse. So, that is what the importance of air gap. And, the air gap which is left over for example, in this particular problem 2 millimeter, how much amount of thermal resistance it is equivalent to; that we can calculate now. It is given; k air is given 0.018 B t u feet upon feet square hour and degree Fahrenheit. Now, you can calculate this particular problem by two ways, either you take the thermal resistances of air gap, thermal resistance of the brick and calculate the thickness or you can also calculate the heat flow through an air gap and heat flow through the refractory.

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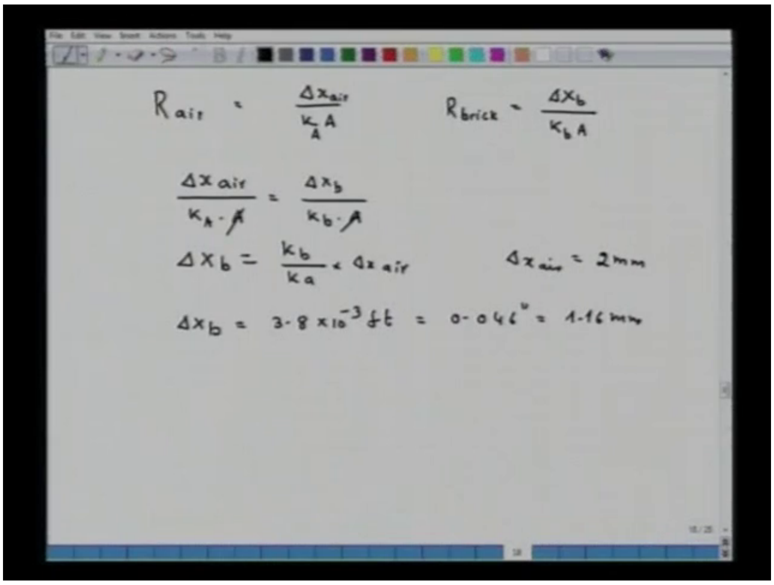

So, either of the ways is o k. so, let us take it now, let us take the thermal resistance of air that will be equal to delta x upon k into A. That is what the definition of thermal resistance, delta x that of the air. Now, the thermal resistance of brick that is equivalent, that will be equal to delta x brick upon k brick into k, that this is k of air. So, this delta x b is an equivalent thermal resistance, so therefore, you can have delta x air upon k A into A, that is equal to delta x b upon k b into A. So, from here we can calculate say, then we can calculate delta x b A A gets cancel, that will be equal to k b upon k A into delta x air.

Now, delta x air that is equal to 2 millimeter, we have to convert into inches. k b and k A they are all given, so we can find out delta x b that is equal to 3.8 into 10 to the power minus 3 feet, that is equal to 0.046 inch, that is equal to 1.16 millimeter. So, an air gas of 2 millimeter thickness is corresponds to an additional resist, an additional brick of 1.16 millimeter thickness. So, that is what the importance of, now.

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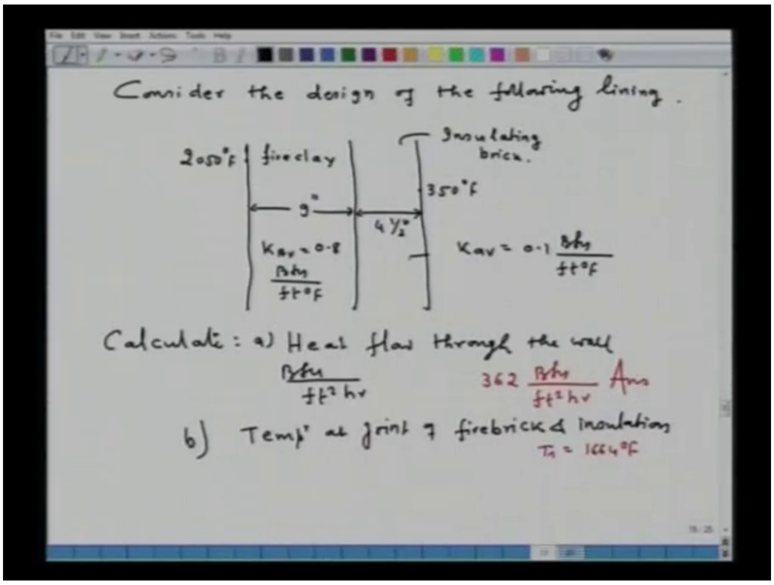

Last problem I will like to say or I will like to illustrate, say consider the design of the following lining. Now, this is a composite wall construction, the composite wall. So, we have this is the refractory wall, this is another refractory wall. Say, this refractory wall consists of fireclay and this one is insulating brick. Now, this has thickness nine inch and this has thickness four and half inch. Now, here k average is given to you 0.8 B t u feet degree Fahrenheit and the k average is given here 0.1 B t u feet degree Fahrenheit. What I, this is composite wall construction and a composite wall made of two types of refractory brick, one is fireclay which is nine inch thick and another is insulating brick which is four and half inch thick.

Now, the temperature of the fireclay brick facing the combustion chamber of the furnace, that is the temperature of combustion chamber and fireclay interface, that is here is given to you 2050 degree Fahrenheit. With this it means you do not require heat transfer coefficient value, because this is the temperature at the combustion wall, at the combustion chamber and a fireclay interface.

Now similarly, at the insulating brick and environment interface, the temperature is given that is here 350 degree Fahrenheit. We do not require any heat transfer coefficient value, so this is the problem. And, now what you have to calculate? Say calculate heat flow through the wall, of course, in units B t u per feet square hour. Naturally, you have to assume here 1 feet square you have to calculate, so you can do this problem and the answer of this problem will be 362 B t u feet square hour and this is the answer of this particular problem, this is a. Calculate temperature at joint of firebrick and insulation, so the answer for this question, for this part will be T 1 or t that will be equal to 1664 degree Fahrenheit.

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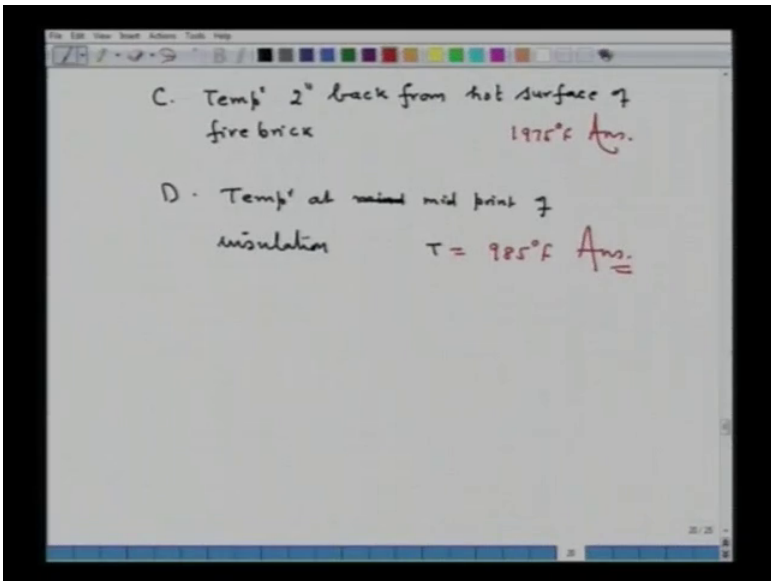

Temperature 2 inch back from hot surface of the firebrick, so this will be, answer will be 1975 degree Fahrenheit, that is the answer, temperature at mid-point of the insulation, so this temperature will be 985 degree Fahrenheit, so this is the answer. So, with this illustration, I have sufficiently illustrated the use of heat flow equation for design of the furnace lining now. By now you must have gotten a feel the important role of heat transfer. What you have learn so far is that how to optimize the lining thickness and integrate it with the available material of different conductivity. The heat losses in the furnace lining design can be minimized either by increasing the value of thickness or decreasing the value of k.

Now, which one, whether you will decrease the heat loss by lining increasing, by increasing the lining thickness or by decreasing the value of k, it will depend upon the availability of the material and the cost consideration. Because if you want to have a material of low thermal conductivity, it has to be produced, it is porous and it may be slightly expensive. You have a material of high thermal conductivity; well those materials should be used where the temperature requirement is also important.

So, what I mean to say here that there are several factors which must be optimize in order to come a particular refractory lining design. And, on the top of it, it is also important that the phases which are in contact with the refractory material is also an important issue.

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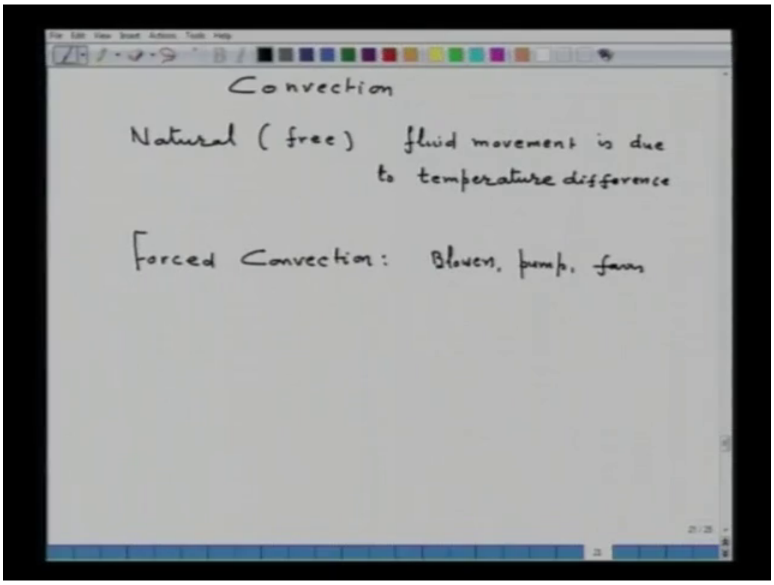

So, this is what I was able to illustrate. Now, the next topic that I would like to go on, convection. Now, another mechanism of heat transfer is convection, as already I have mention in my introduction that convection is essentially fluid flow. In heat transfer by convection, fluid flow is important; depending on the type of flow heat will be transfer faster or at lower rate.

So, the faster movement of fluid, the faster transfer of energy, so, the convection is associated with fluid motion. In fact when a packet of fluid of fire velocity transfer, it goes to the lower velocity than the heat transfer will again occur by the conduction. So, in fact the mechanism, if we talk of the mechanism of heat transfer, then even in convection on a molecular level it is again the heat is being transfer by conduction; in fact the role of convection is in the fluid flow.

So, the convection is associated with fluid motion, so accordingly, which have we have natural convection which is also called free convection. Natural convection, now here the fluid movement is due to temperature difference. Now, for a furnace design, a natural convection is important from the heat loss, from the wall of the furnace to the surrounding, higher is the temperature of the wall, higher will be the heat loss. Then, there the heat loss, the dominant mechanism on the heat loss from the wall of the furnace to the surrounding is by natural convection. Another is say called force convection. Now, as name suggests we are forcing the fluid to move, we are applying some type of force. Naturally, the fluid flow will be faster and as the fluid flow is faster or the velocity is faster there will be faster mechanism of heat transfer.

So, for example, blowers, pumps, fan all they rather induce the fluid to move and as if and as a result of which the transfer of heat occurs. Now, say one of the important thing in case of convective heat transfer or in the application of the conductive heat transfer is to know the temperature. Because if we know the temperature, we can determine the heat loss and so on. Now, there are say several, there are few ways in determining this temperature, one of the way is to do the differential energy balance and couple it with the Navier stokes equation. This is the most fundamental approach, but this approach will require the numerical solution of the coupled equation, because you have to couple the fluid flow equation that is the Navier stokes equation with the energy equation. Then, you can find out the temperature and from the temperature you can find out the so called the heat losses or whatever you can want, you can do whatever you like to do it.

Another approach is based upon the heat transfer coefficient. Now, for most engineering calculation involving convection, the concept of heat transfer coefficient is very often employed in order to determine the heat losses. In several cases for example, the heat transfer from P O C or products of combustion to the charge, there you may not require detailed knowledge of convection. But all that you require how much amount of heat is being transferred. Similarly, a body of the gas is flowing over the liquid or flowing of the surface, we may not, we do not require or we may not be requiring a detail knowledge of convection mechanism so on. But what we are requiring is simply by how much amount of heat is being transferred. So, for all these purposes, the approach of heat transfer coefficient has been found to be very very useful.

Now, as such in the detail study of convection as applied to furnace design, we will be taking the approach of utilizing heat transfer coefficient to estimate the heat losses. Now, here there must be exercise that heat transfer coefficient is an empirically determine constant. Mind you it is not a constant like density, like thermal conductivity, like it is not a property of the fluid. It is an empirically determine constant which depends upon so many factors geometrical arrangement of the surfaces, cooling behavior, temperature difference, all these are the important factors which govern, the so called heat transfer coefficient. The further application of the heat transfer coefficient we will take in the next lecture.