Fuels, Refractory & Furnaces
Prof. S. C. Koria
Department of Materials Science and Engineering
Indian Institute of Technology, Kanpur

Lecture No. # 31
Transport Phenomena in Furnaces
Convection and Radiation Heat Transfer
Role of Refractory

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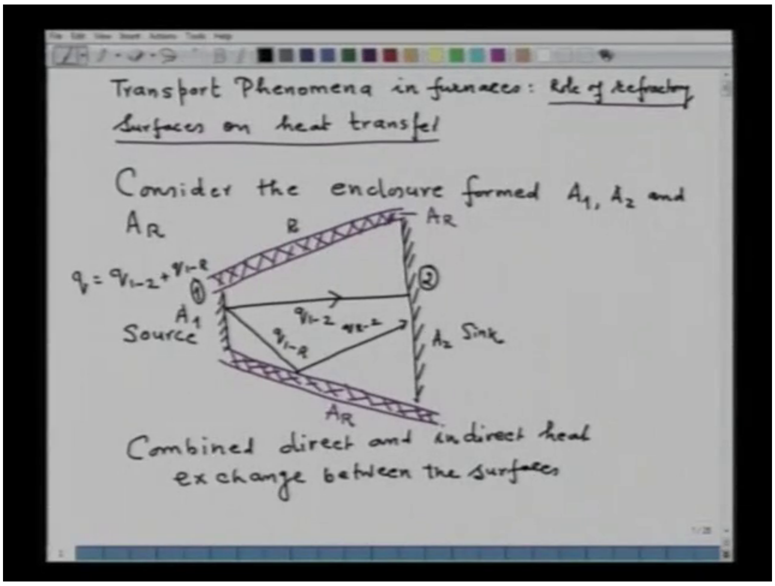

Today, in the series of lectures on transport phenomena in furnaces, I will be talking on the role of refractory surfaces on heat transfer. As in my introductory lecture, I said that a furnace is a thermal enclose. The thermal encloser is formed by the lining of the refractive material. So, refractive materials have several functions in the furnace. One of the important functions of the refractory surfaces is to enhance the radiation heat exchange and to keep heat within the furnace.

When fuel is burnt in the furnace, flame is produced. Now, heat transfer from flame to the charge and to the furnace enclosure, it occurs by mechanism of convection and radiation. Among them, radiation is the most important mechanism. So, it is here. Today, we will be considering, what is the role of refractory surfaces on radiation heat exchange and how it keeps the furnace hot. So, now, for that let us consider the enclosure, which is formed by A 1, which is the source and A 2, which is the sink. It is bounded by refractory surfaces whose area is A R. As such, that no radiation energy escapes from the furnace, that is from the refractory surface of the furnace.

So, something like this, I can represent. This is the source. Let us say, its area is A 1. This is the sink, say whose area is A 2 and this is now bounded by a refractory wall, whose area is A R.

So, this is the refractory wall. So, on this side, this refectory wall area is A R. Now, A 1 we call as a source and A 2, we call as a sink. Now, what will happen? As A 1 radiate its heat, so the total amount of heat, that is q, if I call this surface is one and this surface is two and refractory, I denote it by R, then q, that will be equal to q 1 2. That is, a direct heat exchange will occur. The source will radiate its heat at the rate of q 1 2 plus, as we will see in the course of the derivation, plus some of the heat will be intercepted by refractory wall, that is q 1 R. So, total amount of heat, that plus q 1 R. So, now let us derive what is the role of refractory surface in the heat transfer, when the refractory surface is present.

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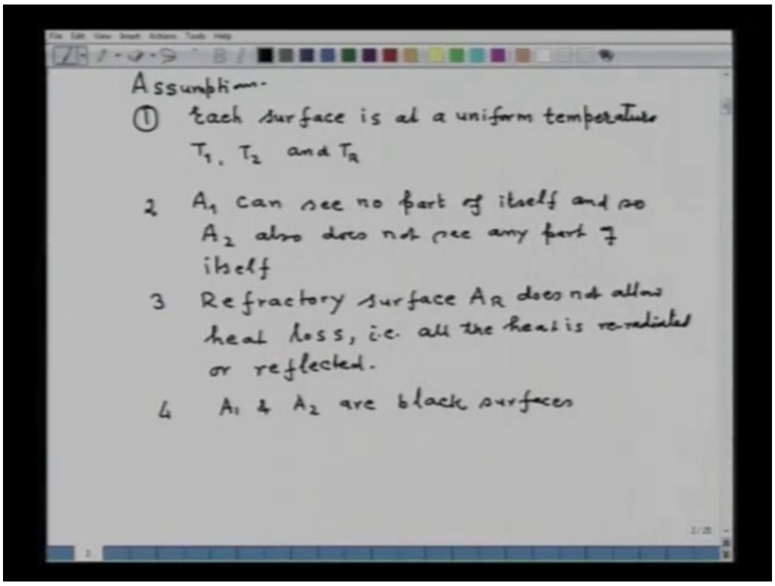

Now, for that, we will make certain assumptions. Number one assumption is, each surface, we consider each surface is at a uniform temperature and characterized by T 1, T 2 and T R.

That is, T 1 is the temperature of the source, T 2 is the temperature of the sink and T R is the temperature or inside temperature of the refractory surface.

Second assumption is, now since we already know that in radiation heat transfer, the fraction of the surface, which is seen by the sink is important because, that will be only heated up. So, our assumption number two, A 1 can see no part of itself. So, we will also assume, A 2 also does not see any part of itself. That is the assumption number two. The assumption number three is that, refractory surface A R, whose area we have represented by A R, it does not allow heat loss.

That means, that is, all the heat is re-radiated or reflected. That is, essentially we are considering a refractory surface is an adiabatic wall, which does not allow any heat to be transferred from inside of the furnace to the outside. So, that means, whatever amount of heat which falls on the area A R, it will be either re-radiated or reflected. The fourth assumption at the moment is, A 1 and A 2 are black surfaces. So now, what this figure represents is, this is a combined direct and indirect heat exchange between the surfaces. How it is direct?

Say, a source, it will radiate its energy q 1 2, that is the direct heat exchange between the source and the sink and part of the heat will be reflected by refractory surface, which is emitted from source one. So, this is q 1 n R. Similarly, when A 2 gets heated up, it will also radiate its energy and an account of it, we will say this one is q R 2. That, I will be explaining this thing further.

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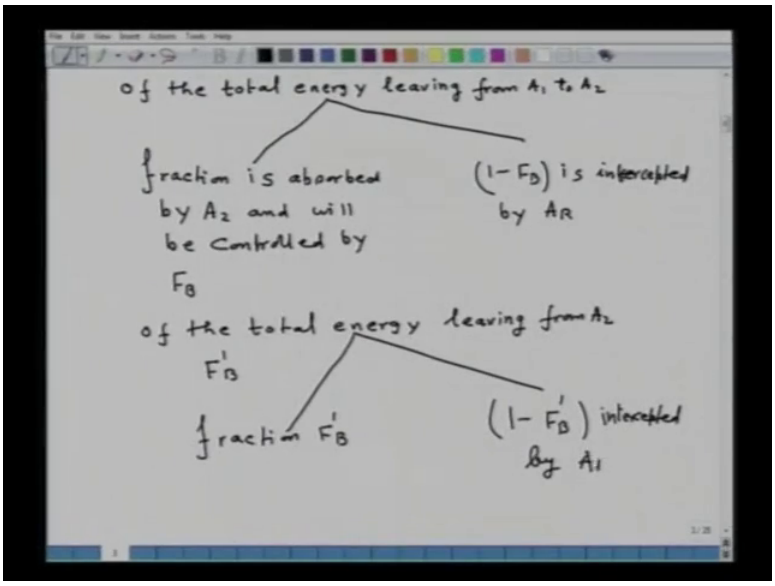

So now, let us see now, say of the total energy leaving from A 1 to A 2 because, A 1 is at higher temperature, which is a source and A 2 is the sink. So, the amount of energy will leave from A 1 and we will strike at A 2. So, what will happen? Out of this total energy, say some fraction of energy is absorbed by A 2 and will be controlled by, which factor? By the view factor. Let us say F B, where F B is the fraction of energy, which is absorbed by the surface A 2. So, F B, in fact, is a geometrical view factor considering the black surface. So, F B, in fact, will control the amount of energy that is absorbed by A 2, as a result of radiation from the source A 1.

So, that is the FB. It is a very important factor. As I said, this is the view factor between the surface A 1 and A 2. In physical sense, it is the fraction of the surface which is seen by A 2, by the radiation which is coming from A 1. So, when FB energy is absorbed; that means, 1 minus FB is intercepted by A R. Now, this energy will be emitted by A 1 to A 2. A 2 will absorb the energy and it will also be heated up.

So, after a while, A 2 will also begin to radiate the energy. Again in the same way, we can write, say of the total energy leaving from A 2, again fraction will be absorbed by A 1 and rest will be intercepted by refractory surface A R. Now, as F B is the view factor from A 1 to A 2, similarly we say that, let F dash b is a view factor as seen by A 1 with reference to A 2. So, that way, the fraction F dash b is absorbed by A 1 and 1 minus F dash B, that will be intercepted by A R. Now, there is a relation between F B and F dash b.

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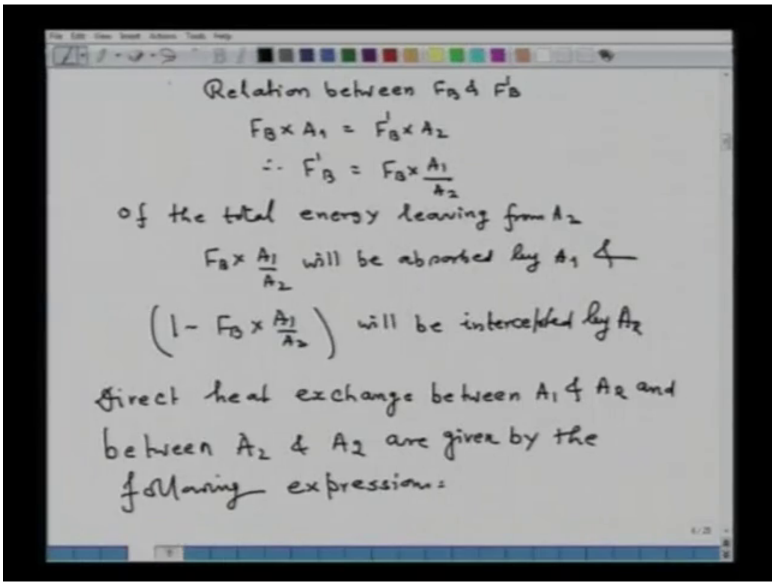

So, the relation between F B and F dash b is F B into A 1 and that is equal to F dash b into A 2. Therefore, F dash b can be expressed in terms of F B, that is into A 1 upon A 2. So, with this it means, as of now, of the total energy leaving from A 2, say F B into A 1 upon A 2 will be absorbed by A 1 and 1 minus F B into A 1 upon A 2 will be intercepted by refractory surface A R. Now, we are seeing that the role of refractory surface. So, accordingly, the direct heat exchange between A 1 and A R and between A 2 and A R are given by the following expressions.

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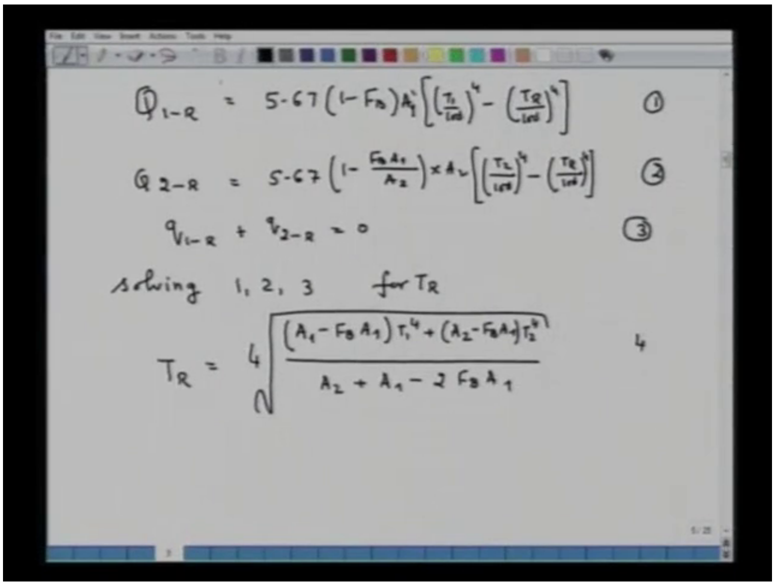

So, we can write down now, say q 1 to R and that will be equal to 5.67 1 minus FB into A 1 P 1 upon 100 to the power 4 minus, remember here it is T R, because we are considering an exchange between A 1 and A R, 100 rest to the power 4. Let us call this expression to be number one. Similarly, q 2 to R, that will be equal to 5.67 1 minus F B into A 1 upon A 2 into A 2, this will be A 1, T 2 upon 100 rest to the power 4 minus T R upon 100 rest to the power 4. Let us call this expression is number two.

Now, we have assumed that there is no heat flow to the refractory. That means, there is no heat loss from the inside of the refractory to the environment. That means, we have considered adiabatic valve. The result of this assumption, we can write down q 1 to R plus q 2 to R and that is equal to 0. This is our expression number three. So, we can solve now, solving equation 1 2 and 3 simultaneously for T R, this exercise, I leave it to you. Please do it.

So, we can get the value of T R and that is equal to fourth root of A 1 minus F B into A 1 T 1 to the power 4 plus A 2 minus F B A 1 T 2 to the power 4 divided by A 2 plus A 1 minus 2 F B into A 1. This is expression number four. So, this particular expression gives you the temperature of the refractory surface, which is due to net exchange of heat from A 1 to A 2 and A 2 to A 1.

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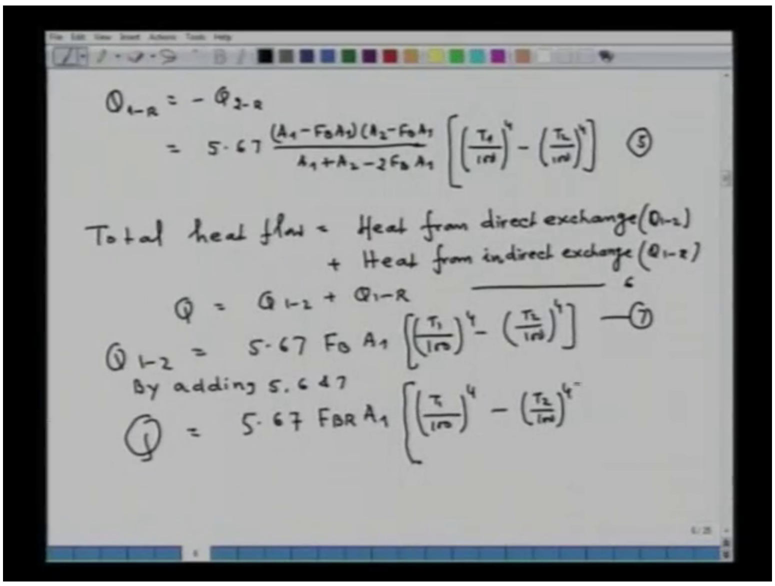

So now, then, we can now, further we can write down, say q 1 to R and that is equal to minus q 2 to R and that is equal to say 5.67 into A 1 minus F B into A 1 A 2 minus F B into A 1 upon A 1 plus A 2 minus 2 F B into A 1 T 1 upon 100 to the power 4 minus T 2 upon 100 to the power 4. Let us call this expression number five. Now, this particular equation five says that, this is the additional indirect heat exchange between A 1 and A R.

That means, this particular expression suggests you that, there is an additional heat exchange will occur from the surfaces A 1 and A 2, which is obtained by reflection and re-radiation by A R. So, the role of refractory surface now becomes very clear. It gives you the additional amount of energy by reflection from surfaces A 1 and A 2. So now, the total heat flow that will be equal to heat from direct exchange, that is equal to q 1 to 2 plus heat from indirect exchange heat.

So, that will be, let us say equal to q 1 to R. So, therefore, total amount of q, that will be equal to q 1 to 2 plus q 1 to R q 1 to 2 that is equal to 5.67 F B A 1 T 1 upon 100 to the power 4 minus T 2 upon 100 rest to the power 4. So, let me call this is expression number six and this is expression number seven.

Now, if I add five, six and seven, now I have to add it, and then I will be getting the amount of heat that will be equal to, that is by adding by adding five, six and seven and re-arranging we get, 5.67 into F B R into A 1 T 1 upon 100 to the power 4 minus T 2 upon 100 rest to the power 4. Let this equation be number eight.

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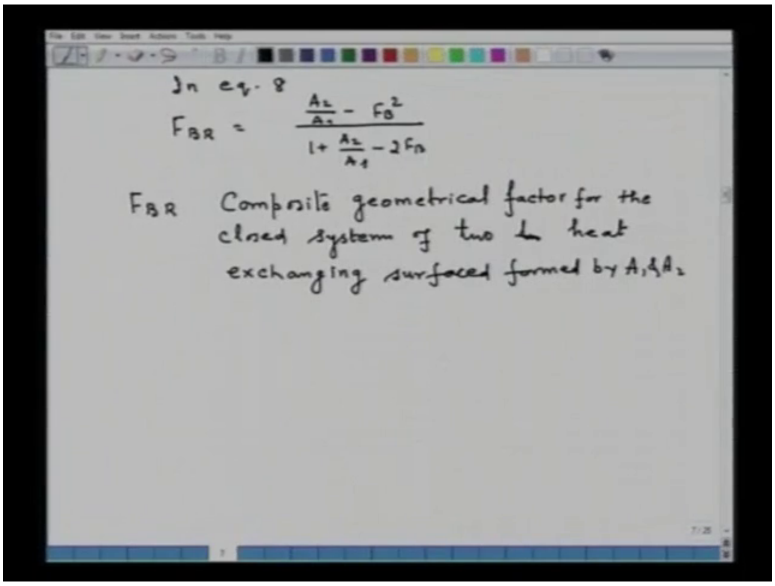

So here, in equation number eight, F B R, that is equal to A 2 upon A 1 minus FB square upon 1 plus A 2 upon A 1 minus 2 F B. This is called, so F B R is a composite geometrical factor for the closed system of two heat exchanging surfaces formed by A 1 and A 2.

So in short, what this F B R has a physical meaning is that, it rather modifies the view factor as formed by surfaces A 1 and A 2. So now, the role of refractory surface is very clear. That means, the refractory surface, it provides an additional amount of heat exchange or which is coming through re-through, re-radiation or by the reflection from the refractory surfaces. Therefore, the refractory surfaces are very important.

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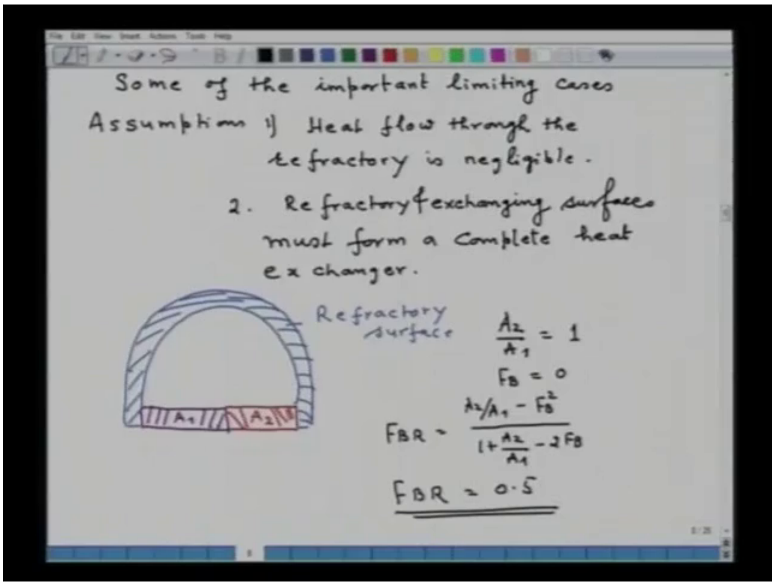

So, from here, we can derive some of the, say important limiting cases. So, we can derive now, say some of the important limiting cases. Now, what we can, from here we can see, what is the role of refractory surfaces. Now, let us take an example. Now, before this, the assumptions of deriving this information for some of the important limiting cases, there are certain assumptions. Assumption number one, heat flow through the refectory is negligible. That is the assumption number one. Second is, refractory and exchanging surfaces must form a complete heat exchanger.

So, under these two assumptions, if we consider some of the limiting cases, let us see what are these limiting cases could be. Now, for example, let us consider, this is, say one surface A 1 and this is the another surface A 2. Now, this is, say, enclosed by a refractory wall or a refractory surface. So, this is a refractory surface and which encloses, say surface A 1 and another surface is A 2.

Now, let us take, say in this case, let us take for example, A 2 upon A 1, if that is equal to 1. Both the areas are the same. So, in that case, F B, that is equal to 0 because, both cannot see each other. So, in that case, we can derive the value of F B R, that is FB R, that is equal to, we have just now derived the formula, A 2 upon A 1 minus F B square upon 1 plus A 2 upon A 1 minus 2 F B. So, we substitute A 2 upon A 1 is equal to 1 and FB is equal to 0, then we get the value of F B R and that is equal to 0.5. So, you see, the value of F B R, it also depends upon the area ratio of A 2 and A 1 and also, it depends upon what is the value of F B. That is, what fraction of the surfaces can be seen by A 2 with reference to A 1 or A 1 with reference to A 2. This is one particular example.

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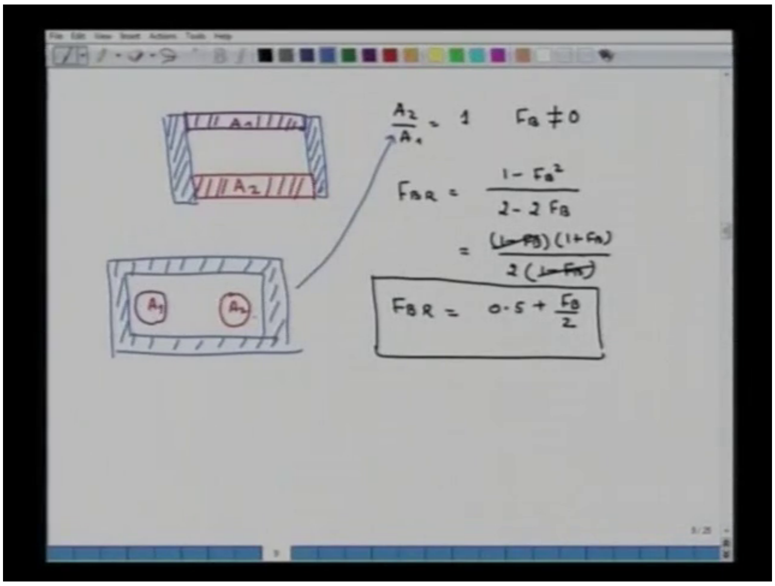

Let us take another example. Say, in this case, let us take this one is the area A 1 and this is area A 1 and take this is area A 2. They are enclosed by a refractory wall. This is a refractory wall and the area, that the A 1 and A 2 are enclosed by the refractory wall. Now here, we have say A 2 upon A 1 is still equal to 1. Now here, F B is not equal to 0, because of the arrangement of the two surfaces. So, therefore, it is equally important how the two surfaces are arranged, in order to get the beneficial effect of refractory surface.

So here, if F B is not equal to 0, then we can calculate again, say F B R that will be equal to, say 1 minus FB square upon 2 minus 2 F B. All that I have to do is, substitute the value of A 2 by A 1. So, if I solve this thing, that will become 1 minus F B into 1 plus F B upon 2 into 1 minus F B. So, 1 minus FB cancels out. So here, F B R, that is equal to 0.5 plus F B upon 2. So, you see, the value of F B R, now here it further depends upon F B. That is how the two black surfaces or how the two source and sink, they are arranged with reference to each other. Now, this situation can also be perceived to be, say this the area A 1 and this is a area A 2 and enclosed by a enclose, the refractory enclose. Here also, A 2 upon A 1 is equal to 1.

So here also, the same relationship between F B R and F B holds good. Now remember, this F B, it concerns to the black surfaces. That means, the emissivity of a black surface is equal to 1. We have not yet considered the influence of emissivity of the real surfaces.

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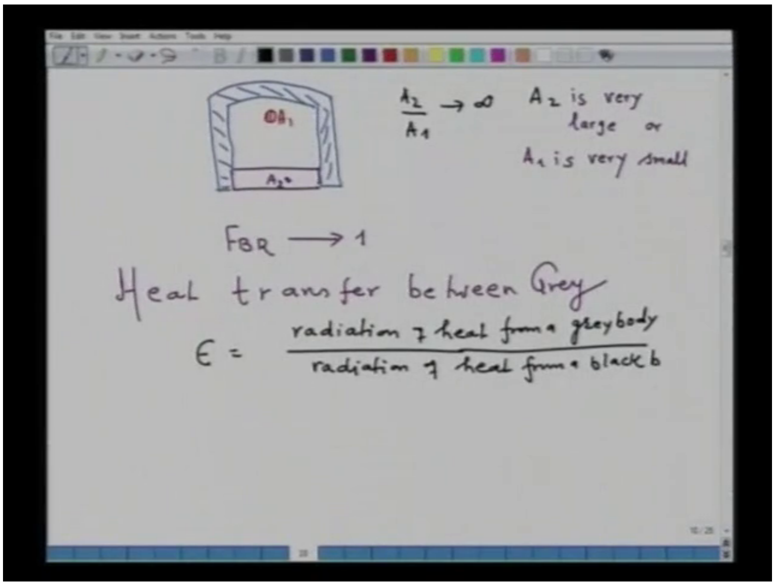

Now, let us take another example. Say for example, I take now, say this is the A 2 and somewhere here, I have A 1. It is enclosed by a refractory like this. This again is a refractory encloser. So here, let me consider, now in case where A 2 upon A 1, that is equal to infinity. That means, either A 2 is very large, say I mean this is A 2. So, A 2 by A 1 infinity means, either A 2 is very large or A 1 is very small. In both cases, A 2 by A 1, it tends to infinity. Now, if we substitute these values into our expression, F B R is equal to, so on and so forth, so, we will be getting F B R equal to 1.

So, these are the, say some of the limiting cases of the arrangement of source and sink within the refractory enclosure. Now, so far we have considered the black surfaces only. Now, if you want to consider the real surfaces, then you have to define a term which is called emissivity. Now, as I said, so far, we have considered black surfaces. That surface A 1 was black and A 2 was black. Now, let us consider the heat transfer between grey surfaces and that is defined by, the surface is defined by, say a term emissivity. This emissivity, that is equal to, say radiation of heat from a grey body divided by radiation of heat from a black body.

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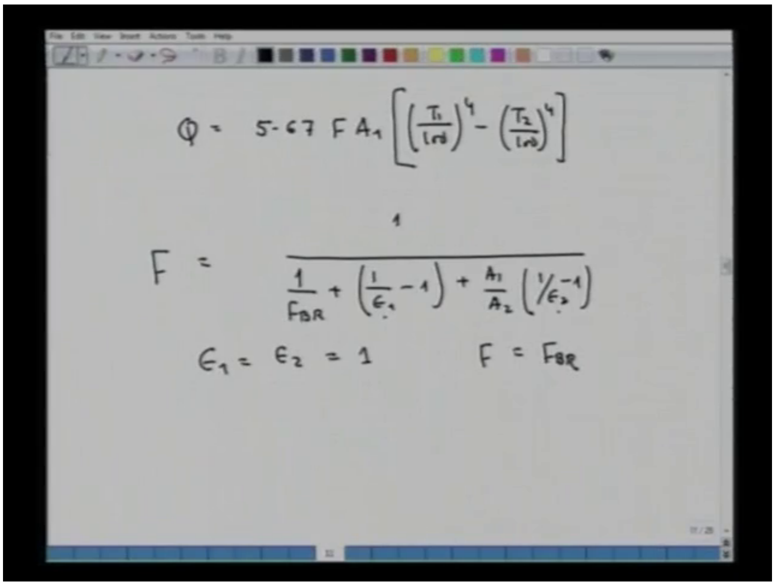

So, by introducing the term emissivity, we can determine an expression for heat transfer between two grey surfaces. That we will write as, say q, that is equal to 5.67 into F into A 1 upon T 1 upon 100 to the power 4 minus T 2 upon 100 to the power 4.

Now remember, here the effect of emissivity of surfaces, we have embedded in a parameter F, which is the view factor. We are now considering that view factor will also be influenced by the presence of emissivity in such a way, so that, the value of F, that is equal to 1 upon F B R plus 1 upon epsilon 1 minus 1 plus A 1 upon A 2 1 upon epsilon 2 minus 1, where epsilon 1 and epsilon 2 are the emissivity of the surface 1 and surface 2.

Now, whether this expression is correct or not, if we put, say epsilon 1 equal to epsilon 2 equal to 1, that is that of the black body, then our expression F, that is equal to F B R. Hence, we can say that, what formulation we have made for the calculation of F is correct because, it is giving us the value of F that is equal to F B R, when the A 1 and A 2 are enclosed by black surfaces.

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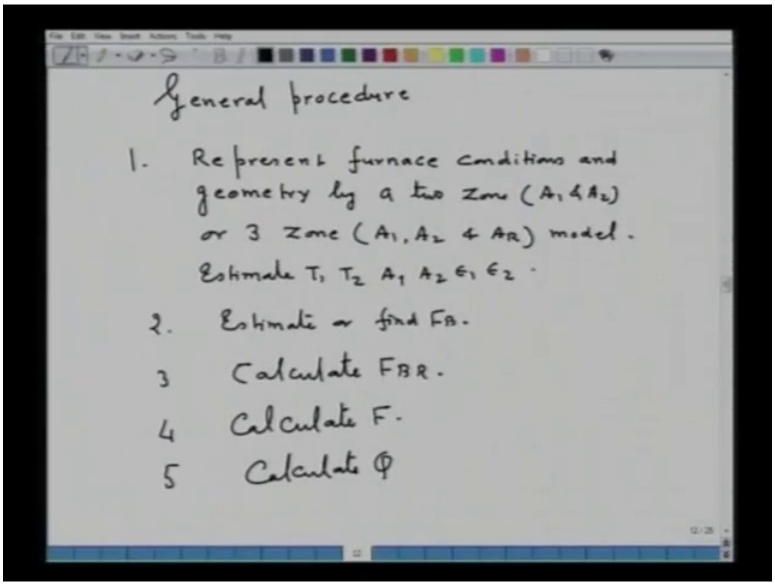

So, what is involved in calculation of heat transfer by radiation? So, what we can do now, a general procedure to calculate the rate of heat transfer between the two surfaces within the furnace.

We can do this way. That is, number one, first of all, we represent furnace conditions and geometry by a two zone system, which incorporate A 1 and A 2 or three zone, which incorporate A 1, A 2 and A R, two zone or three zone model. We estimate T 1, T 2, A 1, A 2, epsilon 1 and epsilon 2.

Second, we estimate or find the value of F B. Once you know the value of F B and A 2 by A 1, then calculate FBR. Once you calculate F B R, now you can calculate F. Once you know the value of F, then you can calculate q. However, this is the way in which you can calculate the heat transfer between the two real surfaces enclosed by the reflective surface. However, I will try to illustrate with a problem. We have to calculate the heat transfer.

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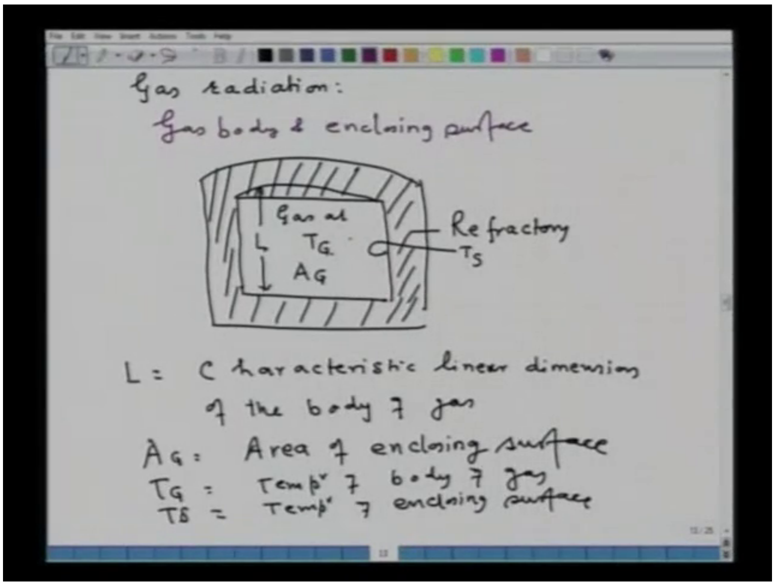

Now, so far, we considered heat transfer by radiation. Now, in this, is also important about the heat gas radiation because, flame is a product of combustion. It is well known that, all di-atomic gases like nitrogen, oxygen, they neither radiate nor transmit any amount of energy. So, heat transfer by all di-atomic gases, it occurs by the mechanism like convection. Whereas, all tri-atomic gases, they emit or radiate heat within certain wave length. So, in considering the heat transfer by radiation from products of combustion, it is important to consider the radiative heat exchange between a body of gas and a black enclosing surface. For example, so what we will be considering, so, let us consider a body of the gas at temperature T G, which is enclosed.

This is a refractory. This one is the body of gas, which is at temperature T G and the refractory surface encloser has a temperature T S. Area of the body of the gas, let us say A G and this L, so, what we say, L, that is the characteristic linear dimension of the body of the gas. A G is the area of enclosing surface and T G is the temperature of body of gas, whereas T R at T S, that is equal to the temperature of enclosing surface.

So, in fact, this diagram is the gas body and enclosing surface. The heat transfer or heat radiation will occur on the gas, which is at temperature TG and it will heat up the enclosure. Now remember, this heat transfer by radiation is important only when the products of combustion contain tri-atomic gases. Because, the tri-atomic gases like CO2 and H2O, they emit or radiate heat within the particular wave length. Nitrogen and oxygen, they are transparent and they neither emit nor radiate. So, the only, so, in a flame which consists of the nitrogen oxygen, H2O and CO2, they emit or radiate the amount of energy. That point is to be important. Only tri-atomic gases, they emit or radiate the energy within particular wavelength. That is, the temperature is also an important issue.

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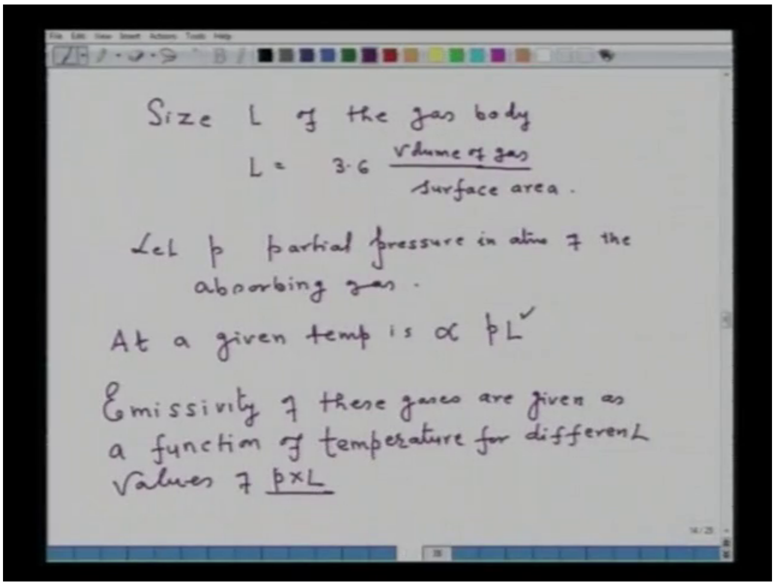

So, in order to define, what we, in order to calculate, what we do is that, we calculate size L of the gas body. This size L is given by 3.6 upon volume of gas divide by surface area. Now, once we have found out from the volume of gas and surface area the value of L, then let us consider P, that is the partial pressure in atmosphere of the absorbing gas. Now, the proportion of radiant energy observed will depend upon the number of molecules in the path of the beam.

That means, depending on the number of molecules of the gas, naturally the amount of radiation will depend upon how many numbers of molecules of that particular gas is present. For example, if you have a mixture of CO2 H2O N2 NO2, so we have to find out how many number of molecules of CO2 is present because, only those numbers will decide what is the amount of heat is being transferred.

Now, at a given temperature this number of molecules that determines the heat transfer by radiation is proportional to P into L, where P is the partial pressure of that particular gas. That means, from the composition of the products of combustion, you will determine, what is the value of partial pressure of that particular gas. That is, the total pressure is equal to 1. We will find out the concentration of CO2 or H2O and then, find out the partial pressure of CO2. If CO2 is under consideration, H2O, if H2O is under consideration. Then now, from here on, one has to use the plots. That means, now once you have found out the value of P and L, that is for water or for H2O, then from here, the emissivity of these gases are given as a function of temperature for different values of P into l.

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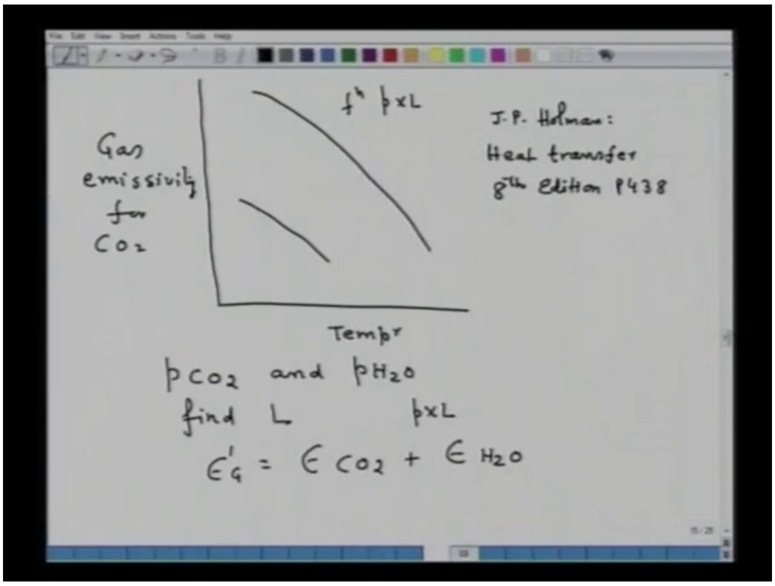

That means, the plots, they are something like this. That is, the plots are there, whereas a gas emissivity, for example, or CO2, that is as a function of temperature and I am just showing the schematic. So, these plots are like this. They are shown as a function of P into L.

Now, for the exact nature of the plot, I will request you to consult a book by J P Holman heat transfer, eight edition, and page 438. These diagrams are given and from these diagrams, the value of emissivity can be determined. How will you determine? That is from a composition of products of combustion, you will be determining first of all, P CO2 and P H2O. From POC, this can be easily determined. Now, once you determined this, then find out the value of L from the relation, which I have given you earlier.

Make product P into l, and then consult the plots for gas emissivity for CO2, as well as H2O. As a function of temperature, you will, as a function of temperature and for a given value of P into CO2 P into L, that is P CO2 into L, you will read the value of emissivity of CO2.

Similarly, same way you can do emissivity of H2O. However, you have to consult the CO2 and H2O independent diagram. So, therefore, then epsilon dash d, that will be equal to epsilon CO2 plus epsilon H2O.

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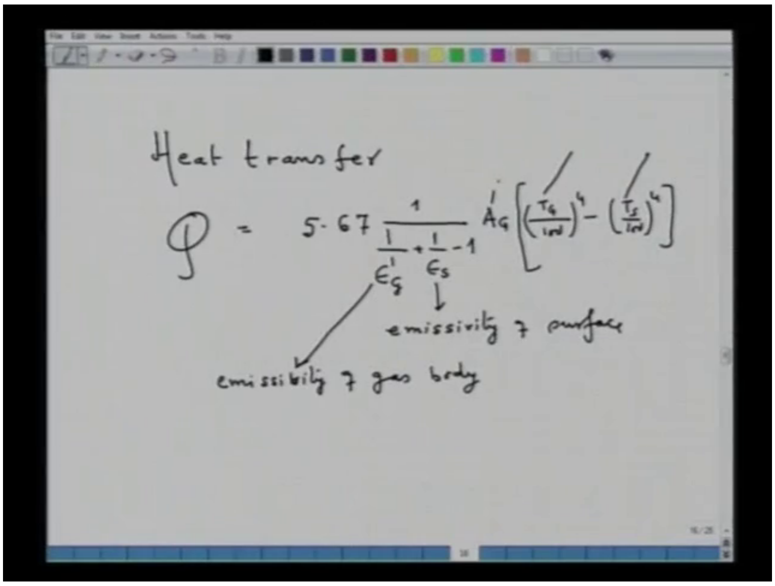

In case of when products of combustion consist of CO2 and H2O, then the heat transfer Q, that is equal to 5.67 1 upon 1 upon epsilon dash g plus 1 upon epsilon s minus 1 into A G T G upon 100 to the power 4 minus T S upon 100 to the power 4, where epsilon s is the emissivity of surface, and epsilon dash g is the emissivity of the gas body. T G is the temperature of the gas and T S is the temperature of the sink and A G is the area of the gas body.

So, utilizing this expression, one can find out how much amount of heat will be transferred from the products of combustion, when it consists of CO2 and H2O. That is, you can find out the rate of heat transfer or rate of heat radiation or radiative heat transfer from gas to the body. In the next lecture, I will be considering the problems and their solution depending on the use of these expressions.