Elements of Solar Energy Conversion

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Lecture - 17

Hello and welcome back, we are going through the series of lecture on Elements of Solar Energy Conversion and today here we are at lecture number 17.

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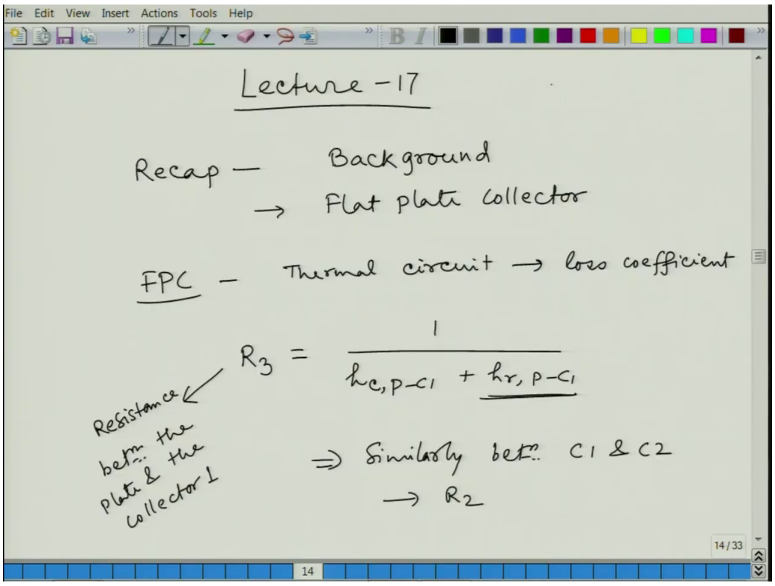

So, in first 16 lectures what we covered is the major background that you require for looking at the devices or any solar collecting system. In terms of the sun earth relationship the calculation of time, estimation of solar radiation, prediction of solar radiation and majorly the important angles and the correlations between them, ok.

So, these are the background we have created in the first part of the lecture series. So, we have done the background required for any conversion device and then what we started looking at is the flat plate collector. So, flat plate collector is the most basic form of solar energy collector and that is what we started looking at and we will go in details of it. And the major outline of the analysis will be the same for most other collectors that we will see subsequently, ok.

So, for flat plate collector, in the last class we derive the thermal network that is required for the loss coefficient, ok. That you require to find out to get the loss coefficient. So, the thermal circuit to get the loss coefficient, ok. So, please look back at the previous nodes because many of the symbols I am going to use will be the same as I used in the last class.

So, we stopped here, where we have derived the expression of the thermal resistance R 3 ok. R 3 is the resistance between the plate and the collector 1, ok. So, what we saw that it will be of two components, one will be for convection hc, between p and c 1 plus hr, between p and c 1, right. And we have also looked at how to find out this hc, p to c 1 and hr, p to c 1, ok.

You require a trick to convert the radiation heat transfer into radiation heat transfer coefficient equivalent to that, because it is not a delta t relation, but its t p to the power 4 minus t c 1 to the power 4. So, that conversion you had to do to get this hr, p to c 1 term, ok. Now, similarly between c1 and c2; that means, cover 1 and cover 2, we will get R 2 with very similar expression, ok. And both the convection and radiation terms will be there between c1 and c2 as well, ok.

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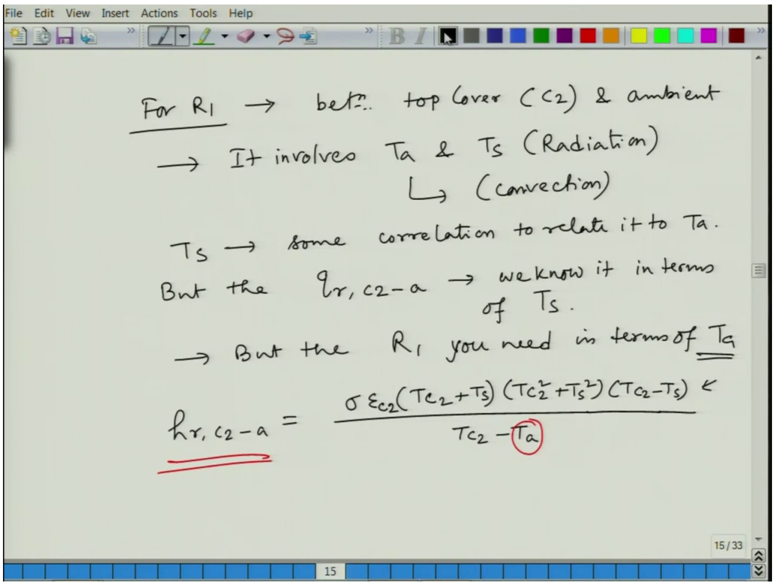

Now, for R 1 it is little different. R 1 is between, let me see the thermal circuit once again, yeah.

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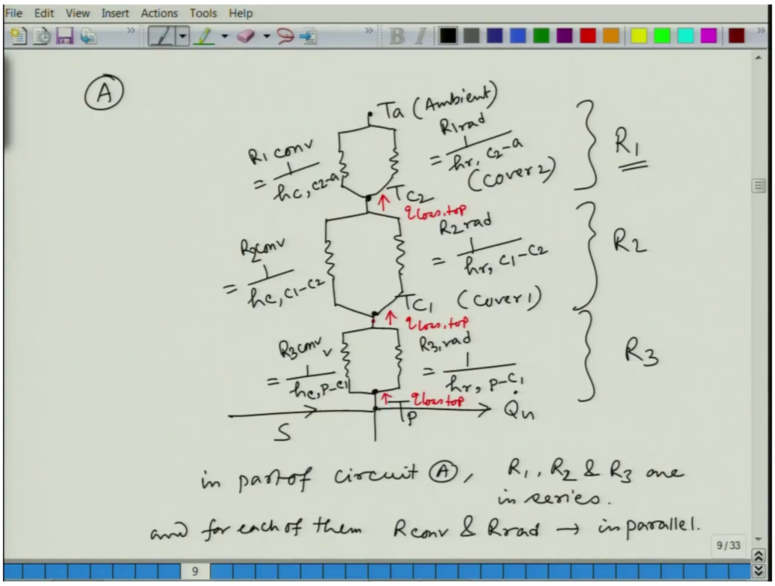

So, here we have the R 1, which is between the top cover and the atmosphere ok, so, between top cover, which we named cover 2 and ambient, ok. Here it is little different because we have ambient in picture as well as sky for the radiation heat transfer, ok. So, it involves ambient temperature T a and sky temperature T s. Sky temperature is for radiation and ambient temperature is for convection, right.

Now, this T s we use certain correlation, which you can relate to T a. So, some correlation and that depends on weather, location and all those things to relate it to and the exact form of the coefficient does not matter you have to find the effective sky temperature. But, the radiation heat transfer that is q r between c2 to ambient. This is we know it in terms of the sky temperature T s right, but the R 1, you need in terms of T ambient, right.

T s we do not use every term that we ultimately in the q useful equation you have seen that u l that relates the temperature gradient between the ambient and the plate to the useful heat. So, everything we have to relate to T a. So, what we need to do? We need to convert this T s dependence to T a dependence. And write the radiation heat transfer coefficient to be the radiation heat loss that will be Stefan Boltzmann constant sigma multiplied by the emissivity of the cover.

And then using the similar method, we can find out here it should be 2. So, similar method we can find out the relationship, this will be the heat transfer due to radiation from the top cover to the sky, right. So, how this comes, you have seen in the last class. Now, we have to divide it by the temperature difference between the cover 1, a cover 2 and the ambient temperature, ok.

So, please pay attention that this we introduced, so that we are at the same page in terms of the heat transfer coefficient both for convection and radiation, ok.

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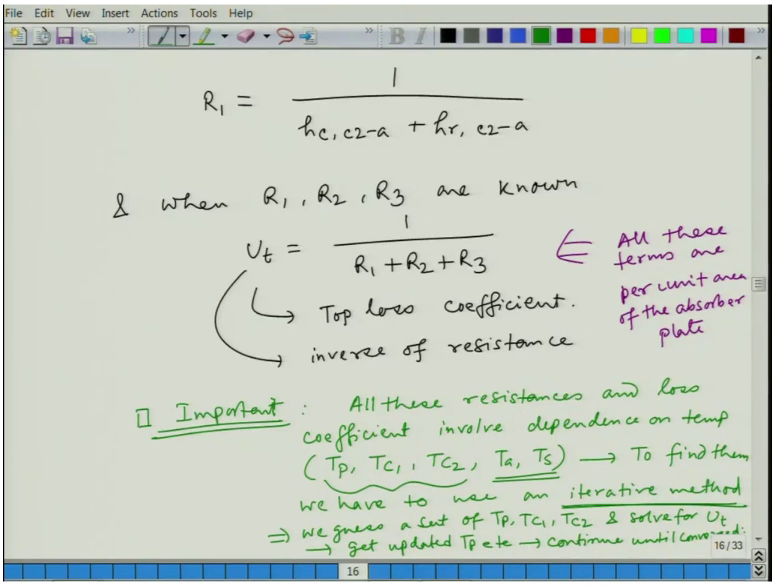

So, now, what we can write? This R 1 can be similarly written as, right. And when we have, when R 1, R 2, R 3 are known or at least the formulation is known what we can find? The top loss coefficient, which will be 1 over R 1 plus R 2 plus R 3. So, in these different steps where we are writing the thermal resistance for different between different layers of the solar collector, what if you are confused at any step?

I insist that please go back to your conduction heat transfer or the heat transfer textbook and look at how these different resistances particularly the series and parallel connection between these resistances are considered. Those things are not going to be discussed and you have it is assume that you already know them, ok.

So, this we get as the top loss coefficient and this is what? This is inverse of resistance, ok. This is equivalent to the heat transfer coefficient and one thing you note here that all these analysis, all these terms are per unit area of the absorber plate, ok. And ultimately this area comes into picture in the useful heat equation q u, so that is why the U t, R 1, R 2 everything you have to find out in terms of unit area.

Now, here I would like to mention a very important point, ok. So, please note that all these resistances and loss coefficient involve dependence on temperature, right. Like the plate temperature, the cover temperature ok, ambient, sky etcetera, right. Now, this ambient and sky they we can assume that they are not changing, but these three can change, right. And accordingly the resistance values will also be different.

So, as this temperature dependence is there to find them we have to use an iterative method, right. Otherwise for a certain temperature you find the heat transfer and then you solve it, it will have a different temperature then how can you rely that particular value for the resistance, right.

So, that is why we guess a set of T p, T c1, T c2 and solve for U t get updated T p etcetera, and continue until you see very insignificant change in temperature, that is how it is processed until continue until converged ok. So, that is the way to proceed about these resistances.

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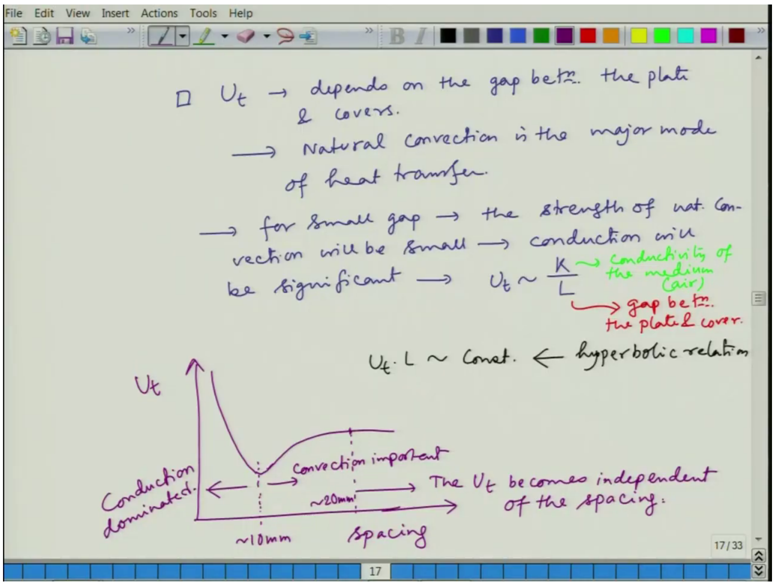

Another thing I need to mention here is that, this U t, it depends on the gap between the plate and the covers. So, between the plate and the cover you have certain gap right, and that is actually that will tell you the nature of flow the convection flow that will happen there, ok. So, basically here everything is happening in natural convection. So, natural convection is the major mode of heat transfer, ok.

So, natural convection is of course, weaker than the forced convection and when it is weaker the gap will significantly alter the flow structure and that is why you will have different U t for different gap. So, we can say that for small gap the strength of this natural convection will be small right, because it depends on the length scale.

So, if the natural convection is small then the conduction will be significant compared to the natural convection even the conduction will be significant. So, what we can expect? If the conduction if it is only conduction what will happen? In that case this U t will be close to this value, right.

So, this K is your thermal conductivity of the medium, here it is air and this L is the gap between the plate and cover, ok. So, if this is the case a natural convection is not so strong then what we can write? This U t L this will be a constant right, its conductivity a constant. So, what kind of relationship is this? This is a hyperbolic relation, right.

So, if you plot this U t as a function of this L then you will have a hyperbola. So, what we see in reality is the following that for small gap we have some hyperbolic dependence. And as the gap increases the natural convection become more and more strong. So, we will have natural convection dominate in terms of the overall heat transfer coefficient.

So, U t if you plot and this is the spacing or gap between the plate and the collector then we can see that up to a certain gap it is about 10 mm. Of course, it will depend on the air pressure inside that gap, the exact material of both the collect the cover and the plate. But, for a ball park value we can say up to 10 millimeter the conduction will be dominant and then the convection becomes important, ok.

So, in this region it is conduction dominated and up to a certain value of spacing you will have conduction convection to dominate and it will also be a function of spacing and beyond a certain value it will not be a function of spacing anymore. So, you will have a almost constant value. So, this is about 20 mm, when the U t becomes independent of this spacing, ok. So, this is another important point you should remember while designing a flat plate collector.

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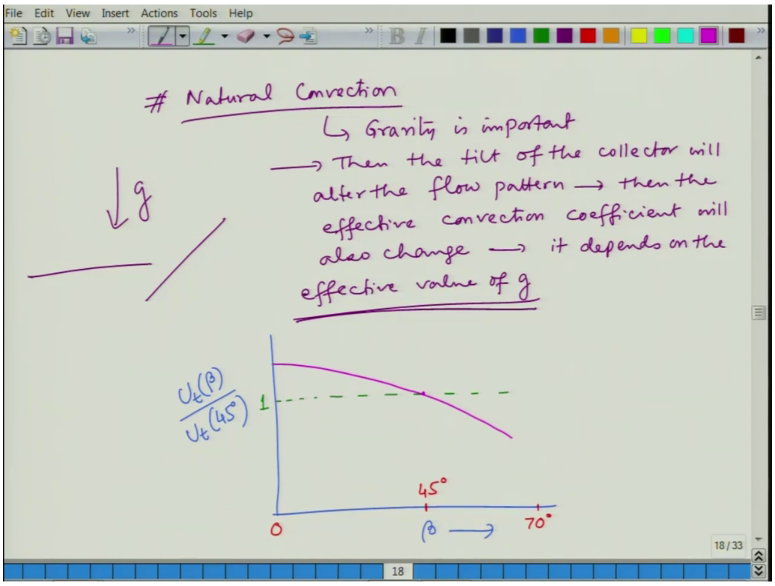

Now, here we note that we are talking about Natural Convection, right. So, natural convection depends on what? It depends on the buoyancy right and that means, the gravity plays a important role here. So, gravity is important for a natural convection process.

So, if gravity is important then the tilt, tilt of the collector will alter the flow pattern right. So, flow pattern means what? So, if your collector is horizontal or if your collector is somewhat tilted. So, in so for each case the gravity direction will be the same. So, only a fraction of gravity will influence the convection process.

So, that is how the tilt will change the flow pattern inside the gaps and when the flow pattern is changed then the effective conduct convection coefficient will also change, right. And that is why we can have. So, because it depends on the effective value of g, effective value of g, not the acceleration due to gravity 9.81 meter per second square that is not the g, at every tilt angle it will experience, right.

So, the effective value of g will tell you the strength of the natural convection. And so, similarly what we can do here? That we can plot this dependence on the tilt angle in terms of a ratio of the top loss coefficient at certain tilt angle beta and top loss coefficient at a fixed tilt angle 45 degrees, with the horizontal.

And if you plot it as a function of beta what you will get? You will get so, of course, this ratio 2 will be 1 at 45 degree. So, let us say here we have 45 degree, this is 0 degree and this is it never is used as 90 degree. So, let us say this is 70 degree, ok. So, if we plot this here it will cross it.

So, it will look somewhat like this, ok. So, it will be highest at 0 degree that means, natural convection will be highest at the horizontal positioning of the solar collector and it will be the lowest as you go up in the tilt angle ok, it will be going down with the increasing tilt angle ok. So, that is another important correlation that will require in your design phase. Now, so far we have talked all about the top loss coefficient.

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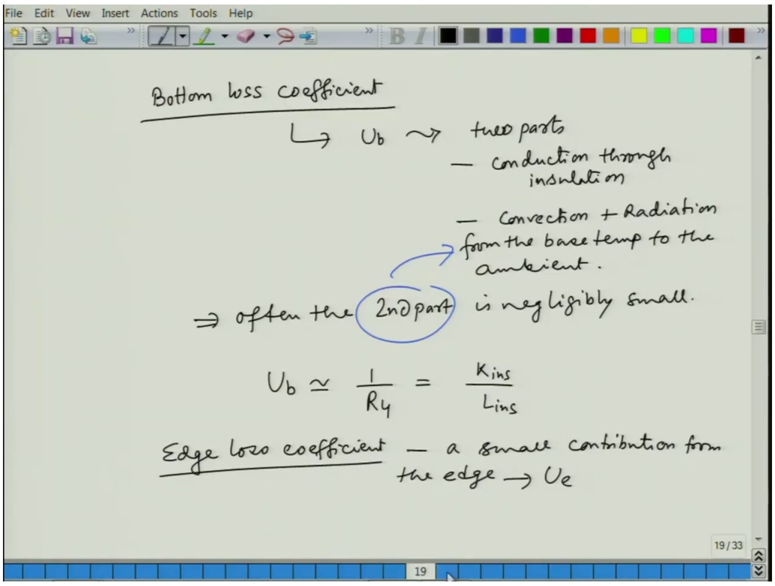

But, we also need to remember that there is a bottom loss coefficient, ok. So, if we go back and look at this figure, ok.

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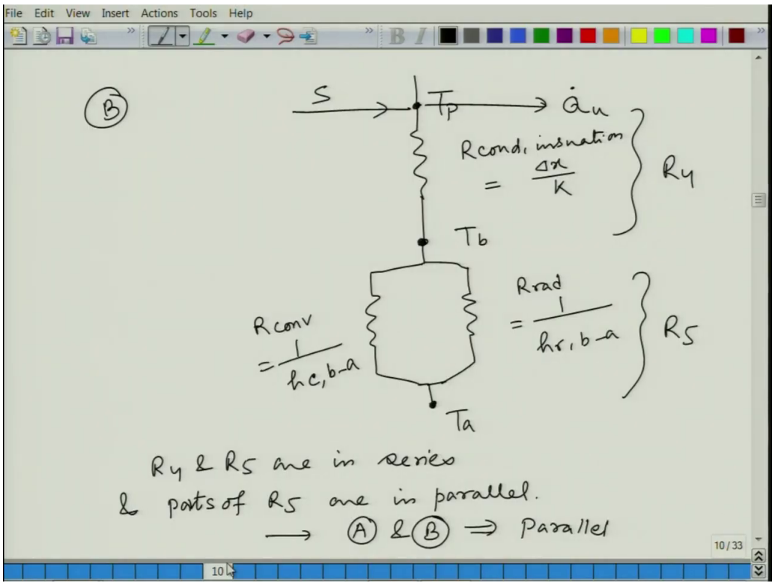

Here we see that the bottom loss coefficient consists of two major parts; one is conduction that is going through the insulation at the bottom and then from the base temperature T b the typical convection and radiation loss to the ambient, ok. So, two parts; so, for bottom loss coefficient U b, we have two parts, one is due to conduction through insulation, right. And second one is convection plus radiation from the base temperature to the ambient, clear ok.

So, often the 2nd part, 2nd part means, this one is negligibly small because, your insulation gives you the major resistance. So, the second part is negligibly small, ok. Then what we have? This U b we can write to be just one portion which is 1 over R 4, which is K insulation by L insulation; the conductivity of insulation and the thickness of insulation, the ratio of fluid.

So, bottom loss coefficient is little simpler than the top loss coefficient. Why is that? You think is intuitively because top loss we have double agenda there, why double agenda? You have to allow the sun raise to reach the plate then only the purpose will be served right, otherwise if you insulate it what is the purpose of having a collector.

So, we want to; we want to allow the solar radiation to reach the plate and heat it up, but as at the same time we do not want the plate to lose heat to the ambient. So, there are double agenda in the top part and that is why top loss coefficient is so complicated to derive, but the in the bottom what we need? We just want to stop leakage of heat from the plate ok.

Unless it is taken by the working fluid we want to stop the leakage to the ambient. So, we just insulate it, we do not care about anything else and that insulation will give you the resistance, ok. Now, another part we neglected to start with, but at some point we have to introduce it, right.

So, the edge loss coefficient. So, when we talked about the different assumptions we have assumed that the edge is contributing very small amount to the overall loss coefficient, but if it is not for any real design will have a small contribution from the edge. And edge loss coefficient is usually designated as U e.

So, U t is the top loss coefficient, U b is the bottom loss coefficient, and U e is the edge loss coefficient, but here I need to mention that there is a little trick to take the edge loss coefficient into the analysis of at the same framework with the base the bottom loss coefficient and the top loss coefficient.

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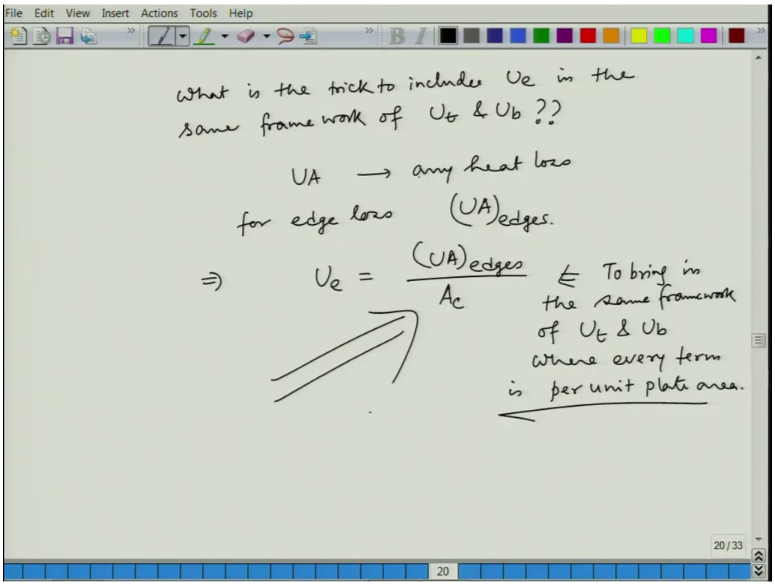

So, what is that catch? What is the trick to include this U e in the same framework of U t and U b? So, the trick is that whenever we find some heat losses, we find in terms of U into A, ok. Any heat loss will be will involve a coefficient loss coefficient U and an area A, ok.

So, here for edge loss this UA will be for edges, edges of the collector right, but that A or the area is different from the plate area, right. So, for the top loss and bottom loss coefficient we have talked everything in terms of per unit plate area. But, this edge loss does not fall into that category because the area is different here, ok.

So, what you need to convert? That this effective edge loss coefficient will be this UA for edges divided by A of the collector right, area of the collector that is the trick ok. To bring in the same framework of U t and U b, where every term is per unit plate area or collector area, ok. So, please remember this small change, otherwise it will be all hodgepodge when you actually implement.

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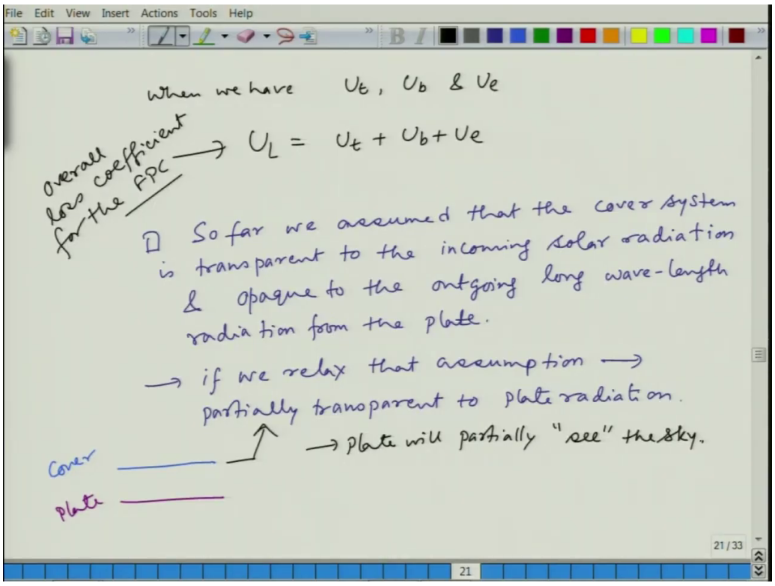

So, when we have this U t, U b and U e in terms of this per unit plate area, then what we can write this total U L will be just summation of these three, ok. This is the effective or overall loss coefficient for the flat plate collector, ok. So, this is how we get it, here two small points I need to mention that.

So, far we assumed that the cover system is transparent to the incoming solar radiation right and its opaque to the outgoing long wavelength radiation from the plate right, it is kind of a wishful thinking, ok. It is not like the cover system will completely be opaque to the short long wavelength radiation coming out of the plate, ok. We want it that way, but that will never be the case.

So, if we relax that assumption if we relax that assumption and say the cover system is not completely opaque, but it partially transparent or partially opaque you can say to the long wavelength radiation. So, it is partially transparent to the plate radiation ok. So, if you have done the radiation course you will appreciate that ok, if the cover system if this is the plate and this is the, this is the cover system.

Let me just assume for the time being that we have the single cover to make the concept clear, ok. So, if this is cover and this is your plate then if this particular cover is partially transparent, then the plate will actually be able to partially see the sky as well, right. So, the plate will partially "see" see means in terms of radiation, see the sky, ok.

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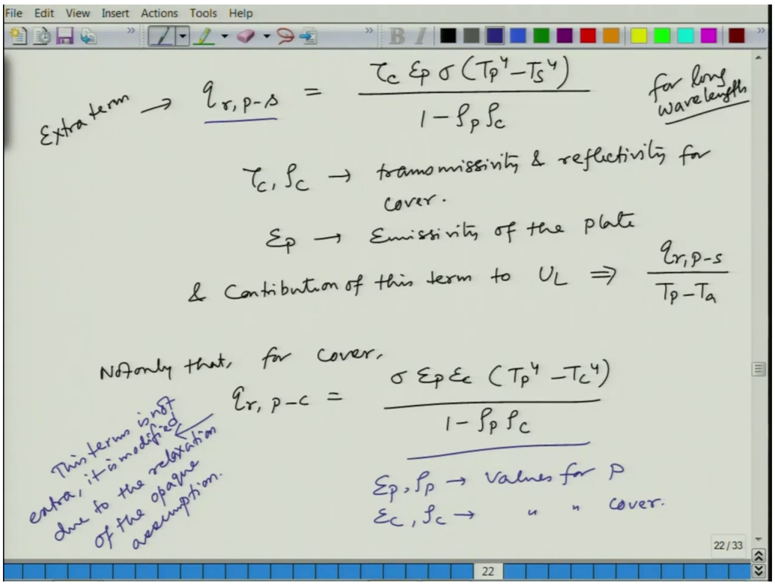

And what we can write then, this q radiation the rate of heat transfer through radiation from the plate to the sky. So, this term now introduced, because earlier we assumed its opaque, it cannot see the sky, the plate can see only the cover system, ok. Now, we have this extra term we can say, which was introduced due to this relaxation of the assumption ok.

So, what we can write? I am just writing the expression the derivation you can find it in any heat transfer book for partially transparent system, ok. So, what are these? This T c and rho c they are transmissivity and reflectivity for cover system, ok. And of course, this is for long wavelength, which is coming out of the plate and we know that is all these values transmissibility, reflectivity everything is a function of the spectrum or the wavelength of the radiation that is going through, ok.

And this E p is the emissivity of the plate, ok. So, earlier there was no term, which connects the plate temperature T p and the sky temperature T s, but now we have, we get this new term if we consider a partially transparent cover system, ok. Now, again to make it like; so, the contribution of this term will be this term to U L will be this thing right q r, p to s that will be divided by T p minus T a.

Again we have to convert it in terms of the dependence on the ambient temperature not the sky temperature. And not only that, what we have for the cover, this particular term will also change the extra term is there, but now we have a reduced amount of heat transfer between the plate to the cover right, because the amount of heat that is getting released from the plate a portion is directly looking at the see the sky.

And that is why it does not interact with the cover system. So, what we have the q r, p to c that term will also change like this, ok. So, we can say this term is not extra that we just consider here, but what it is? It is modified due to the relaxation of the opaque assumption. And that is why it is important.

Now, how to derive these things and all you will find it in your radiation heat transfer book, but again let me write that this whenever you have this E p and rho p these are values for plate. And this epsilon c, rho c they are values for cover ok, epsilon is the emissivity and rho is the reflectivity, ok.

So, we have looked at the all the different loss coefficient in detail under different kinds of situations. And now, we are in a position or now we can assume that somehow we have got a handle on the U L part.

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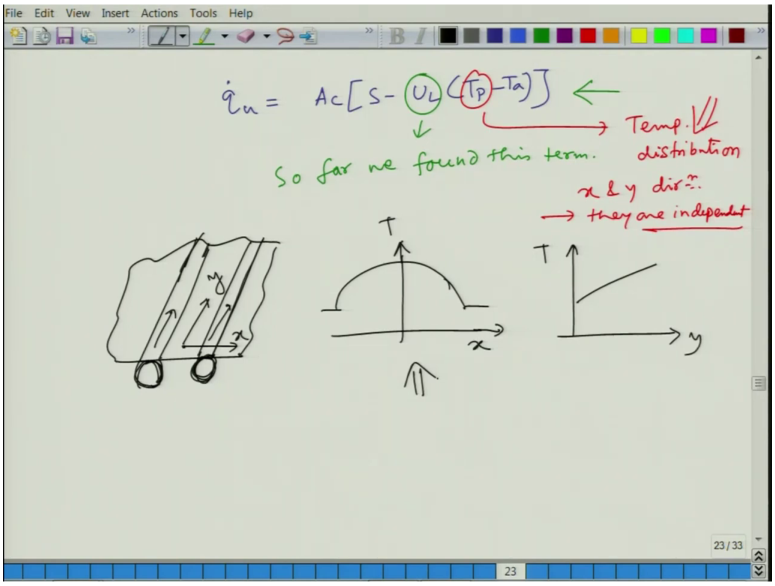

In the equation that we have written this A c S minus U L, T p minus T a right this equation you have written earlier. So, we were, so far we have got a handle on this. So, far we found this term U L ok. Now, we also said while we wrote this useful heat equation we also said that this is not a very useful equation and for that we need to find out the temperature distribution, which is this T p ok.

We need to have this temperature distribution and there also we have assumed that this x and y direction or two mutually perpendicular directions along the flow and perpendicular to the flow, we have assumed that they are independent, you remember ok. So, with all these let us now try to get this temperature distribution. So, a quick recap that we have shown you this particular figure earlier that the tubes are like this.

Of course, tubes are much thinner than I wrote here. So, this is the direction of fluid flow what we assumed, we have assume our coordinate system like this x and y. So, we have also seen that the temperature distribution will be somewhat like this for fixed y and temperature distribution will be somewhat like this for fixed x, this we have seen earlier. Now, let us look at let us look at this particular figure in the x direction temperature dependence in more detail.

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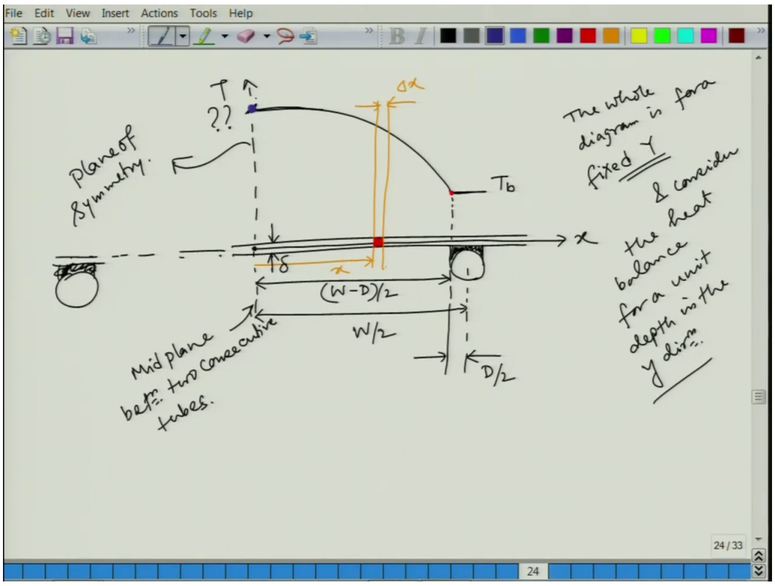

So, now, if we just draw half of it, let us say this is the plate and we have a tube here, which is bonded to the bottom of the plate with a high conductivity material a bond and. So, in the mid plane between the two tubes what we can write the temperature distribution will be somewhat like this, right. So, this direction T and this is the mid plane between two consecutive tubes, ok. So, basically you have another tube here, which is at equal distance from this plate, that is what it means, ok.

Now, let us put some dimensions as well. So, let us say that this dimension between the mid plane and the center of the tube is W by 2, why 2? Because W is the width between two tubes, so this is half way. So, that is why it is W by 2. And this is the diameter or radius of the tube that is D by 2 ok. So, what we are left with this particular distance where the temperature is varying this is W minus D divided by 2 is not it, ok.

Now, let us say that we have a thickness delta of this plate, ok. And for the temperature we have seen that we used this symbol T b which will be just on the area on the top of the tube, ok. So, that is T b and here we do not know what is the T ok, but we do know that this is symmetric this is the plane of symmetry ok. What does it mean? That across that plane the temperature distribution will be exactly the same on both the sides.

So, if this is your condition and ok. So, the whole diagram the whole diagram is for a fixed Y ok. So, I did not draw the, so here we have the x axis ok, this is for the fixed Y. And consider the heat balance for a unit depth in the y direction. So, the whole thing is considered for a unit depth in the Y direction and that is how we are going to look at the heat balance for this particular geometry.

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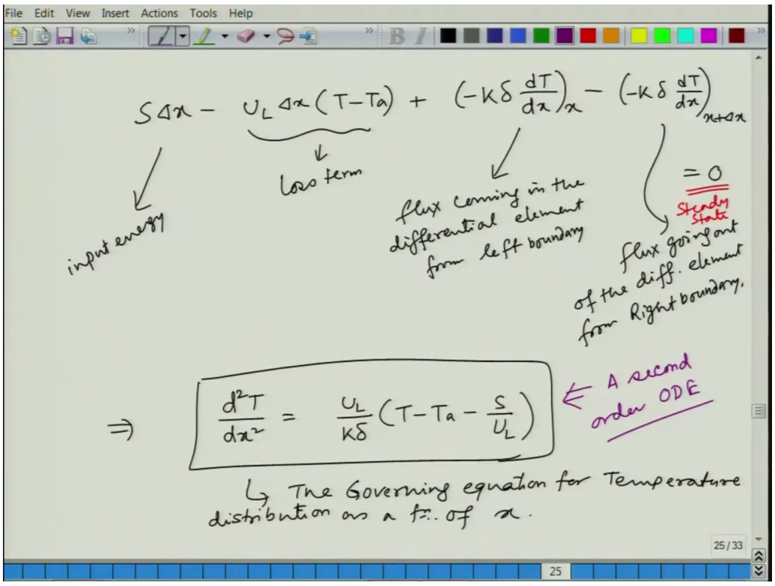

So, what we can write that the incoming let me just take a small slice here at any x. Let us take a slice delta x at certain value of x. So, what we can write the amount of radiation that is falling on this portion or getting absorbed rather S into delta x minus what is getting lost which is U L delta x multiplied by T minus T a. So, if we consider the temperature at that particular location x to be T then this is the effective amount that is getting absorbed, ok.

Now, these two terms will tell that for a particular slice here for the plate ok. So, we are looking at this particular slice and multiplied by a unit length in the direction perpendicular to the board, ok. Minus K delta dT dx at x plus delta x and this will be 0, why is that?

Let me just write that what are these terms this is the input energy right, this is the input absorbed energy for the plate input and this is the loss term, and this is what? This is the flux coming in the differential element from the left boundary, left boundary. And this term is what flux going out of the differential element from the right boundary and all these terms have to cancel each other in totality right, and that is why we have 0 and this is for steady state operation.

Otherwise, there will be some accumulation you will have some d capital T, d small t term right, but steady state assumption that right hand side is 0, ok. So, if we just get rid of this delta x term, what will we get? We get this particular differential equation T minus T a minus S over U L. So, just by simplifying that above equation what we can write is this ok.

So, this is the governing equation for temperature distribution as a function of x, in the x direction this will be the temperature distribution, and what is this? This equation a second order ordinary differential equation, right so, this is a familiar equation you have seen earlier many times in your undergrad mathematics course or even the heat transfer course during the conduction you have seen this equation.

So, I insist that you go back and find out, where you have learnt the solution of this equation and just get acquainted with the method again. Now, whenever we have a governing equation to solve the equation we need some boundary condition right. And this is a second order equation. So, you need two boundary conditions. So, 1st is- if we see at the right boundary, ok.

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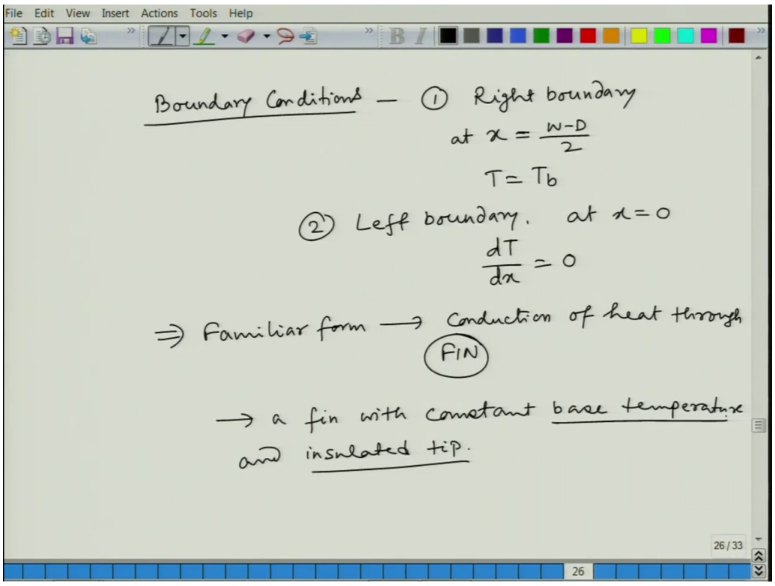

So, at the right boundary; that means, here what we have the temperature itself is given that is T equal to T b, ok. So, that means, at x equal to this is what is the distance that is W minus D by 2, this T equal to T b this is the right boundary, the temperature condition is given and at the left boundary, where x equal to so, left boundary is at x equal to 0.

So, let me see. At the left boundary that means you are here and we have seen that, this is the plane of symmetry. So, what does it tell? That both the sides will be the temperature distribution will be equal. That means, dT dx the slope of the temperature curve will be 0, ok.

So, that mean, the slope of the temperature curve here will be 0, ok. So, and two boundary conditions are required and both of them are given. Now, as I was telling you that this is a familiar form of equation that you are seeing here and that familiar form, where did you see it?

You have seen it in the conduction of heat through a FIN ok, this you have seen in your UG conduction heat transfer course and the same equation or similar I should say because the symbols will be different, the exact expression will be different, but the same form mathematical form of governing equation and the set of boundary conditions.

You have seen for a fin with constant base temperature and having an insulated tips, ok, why do you say so? Because insulated tip gives you this dT dx equal to 0 kind of condition and constant base temperature gives you this T equal to T b kind of condition, ok. So, this is a familiar form and you know the solution of this equation very well from your knowledge in FIN's.

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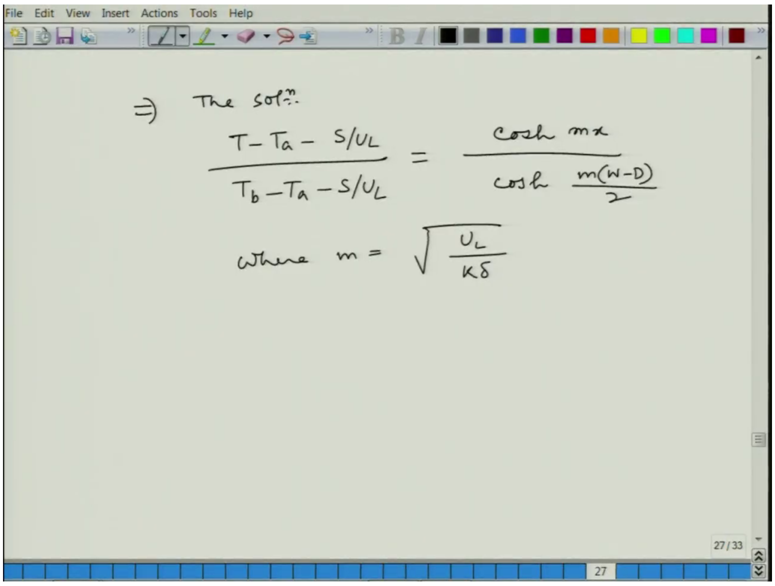

So, what, so the solution we are not going to do it because this is known and you can do it yourself. So, the solution is this T b minus T a minus S over U L. So, this T minus T a minus S over U L this part is different. It was in terms of the temperature of the FIN itself, but the solution is given in terms of this hyperbolic cosine of mx and divided by hyperbolic cosine of m W minus D by 2, ok and where this m you get as the square root of U L divided by K delta ok.

So, this you have seen earlier please go back, if you do not follow please do that derivation by yourself and find out that this is the solution for this equation. So, let us stop here at the for this class and we will continue working with this equation and its ramification in terms of the temperature distribution on a solar or on a flat plate solar collector.

Thank you so much for your attention.