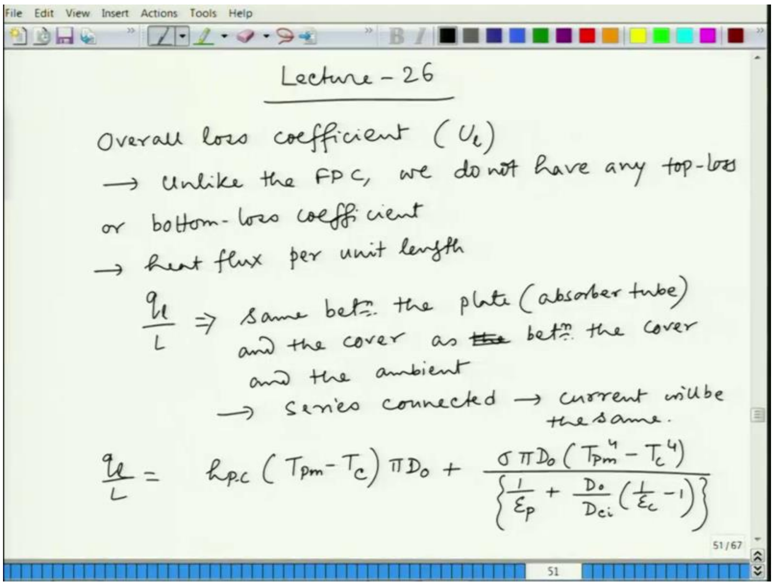
Elements of Solar Energy Conversion

Prof. Jishnu Bhattacharya
Department of Mechanical Engineering
Indian Institute of Technology, Kanpur

Lecture - 26

Hello and welcome back to this series of lectures on Elements of Solar Energy Conversion. Today here, we are at lecture number 26.

(Refer Slide Time: 00:26)



So, up to the last class, what were we doing? We were analyzing the parabolic trough collector; we have finished the part up to which we have derived the useful heat gain by the parabolic trough and the efficiency of the same. Now, here, there are few things that are missing in a sense, like we have assumed that this U_l or the overall loss coefficient we have we know that, that is what we assume, but in reality, we have to calculate it. How to calculate it?

So, we will look at how we can get this overall loss coefficient for a parabolic trough collector. So, here we have to go back to the drawing board that means we have to find out the thermal circuit again, and then only we will be able to find out this overall loss coefficient.

So, here unlike the flat plate collector, we do not have any top-loss coefficient or bottom-loss coefficient. So, this is a circular tube which is carrying the working fluid, and we have a concentric circular tube of transparent material which acts as the cover. So, there is no top and bottom, but we have a single loss coefficient which is U_l. Now, if we look at the heat flux at a different level so, the first one is so, let us say heat flux per unit length right.

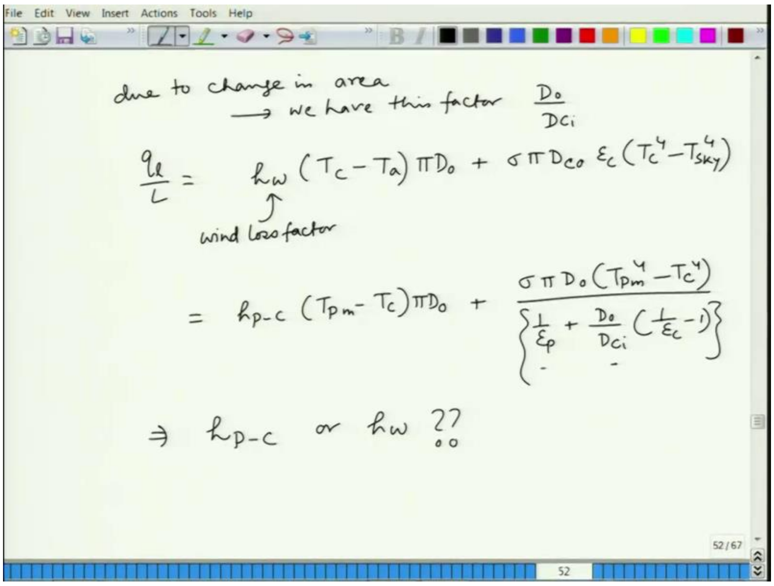
So, we are not considering how the heat flux is changing along the length. So, what are we doing? This q_l is the heat loss divided by L. Now, if we look at and this will be the same so, this will be the same between the plate and the cover or yeah, let us say plate, which is basically the absorber tube, not the plate, but just to be consistent with the terminology that we have used for flat plate collector, we are using the same terminology plate.

So, that heat flux between the plate and the cover will be the same as the as between the cover and the ambient right because the current will be the same as their series-connected, the current will be ok. So, what can we write? We can write first this between the absorber tube and the cover; we can write that the heat transfer coefficient between the plate and the cover is multiplied by the temperature gradient, which is the mean plate temperature minus the cover temperature.

$$\frac{q_l}{L} = h_{pc}\left(T_{pm} - T_C\right)\pi D_o + \frac{\sigma \pi D_o ({T_{pm}}^4 - {T_c}^4)}{\{\frac{1}{\varepsilon_p} + \frac{D_o}{D_{ci}}\left(\frac{1}{\varepsilon_c} - 1\right)\}}$$

$h_{pc}\left(T_{pm} - T_C\right)\pi D_o$ this is the convection part. Now, we will have the radiation part as well. $\frac{\sigma \pi D_o ({T_{pm}}^4 - {T_c}^4)}{\{\frac{1}{\varepsilon_p} + \frac{D_o}{D_{ci}}\left(\frac{1}{\varepsilon_c} - 1\right)\}}$ this is the radiation part.

(Refer Slide Time: 06:05)



So, here, what we see that due to change in the area because as the diameter changes, the area also changes that is why we have this factor $\frac{D_o}{D_{ci}}$ which is not present in the case of a flat plate collector. When we have two parallel plates, the area across the heat transfer direction does not change, but here it changes; that is why you have this factor.

Now, this $\frac{q_l}{L}$, the same current flows between the cover and the ambient. So, there what are the factors? The first one is what is happening through convection. So, we have this term. Here, this h_w is we call it to wind loss factor; this is nothing but the coefficient of heat transfer due to wind because the cover is losing heat to the ambient because of the wind flow right.

And the other part will be the radiative part, and here we have D_{co} which means, the outer diameter of the cover tube multiplied by the emissivity of cover material multiplied by the

4th power of cover temperature, absolute temperature minus the effective sky temperature raised to the power four.

So, this is the same current flowing, and that is why these two quantities you can equate that means this thing will be equal to $h_{pc}(T_{pm} - T_C)\pi D_o + \frac{\sigma \pi D_o ({T_{pm}}^4 - {T_C}^4)}{\{\frac{1}{\varepsilon_p} + \frac{D_o}{D_{ci}}(\frac{1}{\varepsilon_C} - 1)\}}$. So, these two quantities you can equate, and you can find what the is $\frac{q_l}{L}$?

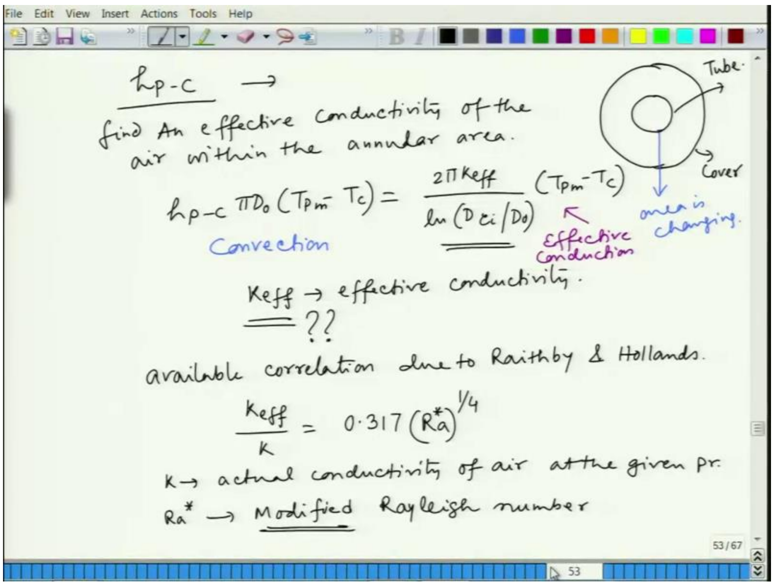
But now, the question arises that what are the values of this h_{pc} or h_w ? These things we do not know and the typical way of finding out for the flat plate collector would not work here; why?

Because the flat plate is a geometry where you have the coefficients available easily, but for the parabolic trough, we have these concentric tubes, and the flow over a tube is completely different than flow over the flat plate that is why we have to use separate coefficient or separate correlations for finding out these factors.

So, now let us try to see how we can determine them. Other than that, if you look at these equations, there is nothing unknown. Of course, the temperatures are unknown, which are actually basically, you are trying to find out, but other than that, everything is a material property and the geometry such as the diameters and then, material properties of emissivity and all.

So, there is nothing unknown, but the heat transfer coefficient between the tube and the cover and then the from the cover to the ambient, which is through wind-heat loss factor.

(Refer Slide Time: 10:28)



So, let us first try to get this heat transfer coefficient between the tube and the cover. So, what can we do? We can find so, basically what is the geometry here we have the tube, and here you have the cover with the concentric circle or cylinder rather. So, this is the cover, and this is the tube ok, and you can see that the area is getting changed as you go towards the cover; the area is changing. So, what can we do? We can find effective; we can find effective conductivity of the air within the annular area.

So, in that case, if we get that, then we can write that this heat transfer that is happening because of the natural convection, this we can equate it to as if the conduction is happening and an effective value you know. So, for the heat conduction, you know when the area changes because of the circular geometry; what you have the relation, is this ok? this you have learned in your conduction heat transfer coefficient.

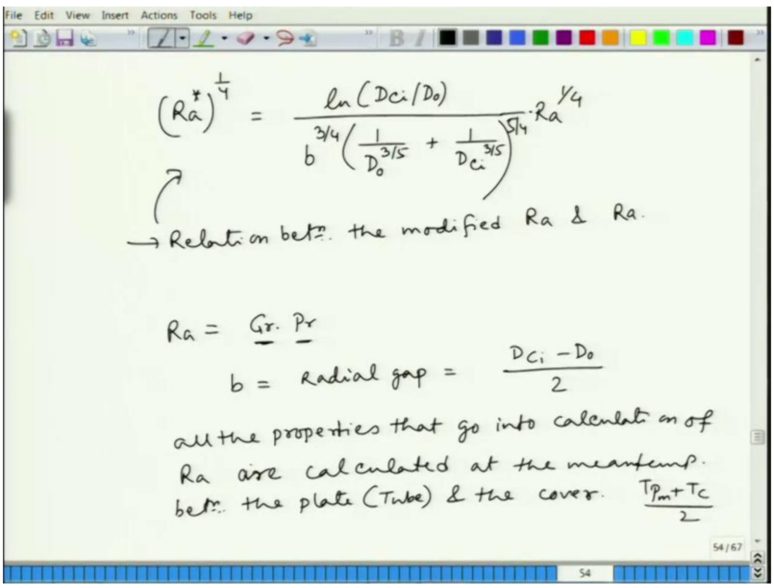
Particularly, this natural log comes because of the change in the area, and here, you see that we have used this effective conductivity. So, what we did? We did that we equated this convection term with the right-hand side effective conduction term, isn't it? Now, the onus comes on us to find out what effective conductivity is, and for that, we have to use some standard correlation that has been derived and obtained by rigorous experiments.

So, how to find this effective conductivity? So, the available correlation is due to Raithby and Hollands, and if you are interested in looking at the reference paper, please look at the textbook that we are using, which is by Sukhatme and Nayak. So, this effective conductivity divided by the actual conductivity, the conductivity of the enclosed air is obtained by this correlation; this is the modified Rayleigh number to the power one-fourth.

So, here k is the actual conductivity of air at the given pressure because you also can evacuate this portion. So, you can change the pressure within this annulus space, and that is actually done. You have looked at the evacuated tube collectors while we were talking about the flat plate collector, and here also, it is done for the parabolic troughs.

So, you have to be careful what the conductivity is at that pressure level because, for gas, pressure determines the conductivity value, and this Rǎ, it is the modified Rayleigh number. Why did we call it modified? Because it is related to the conventional Rayleigh number like this.

(Refer Slide Time: 15:52)



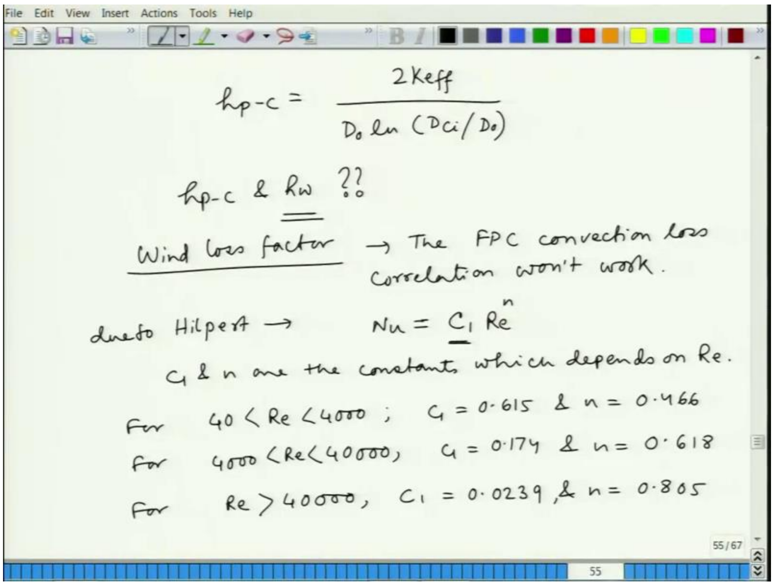
So, Rå raised to the power 4; this is related to the conventional Rayleigh number, and what is the conventional Rayleigh number? So, let me write it here first, the conventional Rayleigh number is nothing but the Grashof number multiplied by the Prandtl number. Grashof number you know for the; natural convection and Prandtl number is the thermal diffusivity and the viscous diffusivity right. So, that is the normal Rayleigh number.

Now, for this case, we are modifying it, and here comes the effect of the geometry in the form of a natural log of the ratio of the inner diameter for the cover system and the outer diameter of the absorber tube multiplied by this b to the power three-fourth which I am going to tell you what is b and D naught to the power three-fifth plus one over D_{ci} to the power three-fifth and this whole thing powered five by four, and that multiplied by the normal Rayleigh number to the power one-fourth.

So, this is the relation basically between the modified Rayleigh number and conventional Rayleigh number. Now here, we have introduced this b, b is nothing but the radial gap of this annular space, and this is $\frac{D_{ci}-D_o}{2}$ and of course, all the properties that go into the calculation of Ra that means the viscosity, thermal diffusivity, everything is calculated or rather are calculated at the mean temperature; between the plate or tube, absorber tube, and the cover.

That means, this $\frac{T_{pm}-T_c}{2}$ that is the mean temperature between the tube and the cover and all the properties that you are calculating that should be at that mean temperature; then only you can find out. So, Rayleigh number, if you know that, then you go back and find out what is effective conductivity, and that is how you can find out what is the $h_{p\text{-}c}$.

(Refer Slide Time: 19:26)



So, with all these, the heat transfer, convection heat transfer coefficient between the plate and the cover

$$h_{p-c} = \frac{2K_{eff}}{D_o \ln(\frac{D_{ci}}{D_o})}$$

So, basically, we were after this h_{p-c} and h_{wind}. We did not know that for the whole analysis, we needed them, and now, we know what the heat transfer coefficient between the plate and the cover is.

Now, what is left is this wind loss factor. So, wind loss factor how to get that? Again, the flat plate collector convection loss correlations would not work here right because the geometry is different, and all the correlations are strictly or critically dependent on the geometry. So, that is why you need to be careful about using which correlation you are using and where.

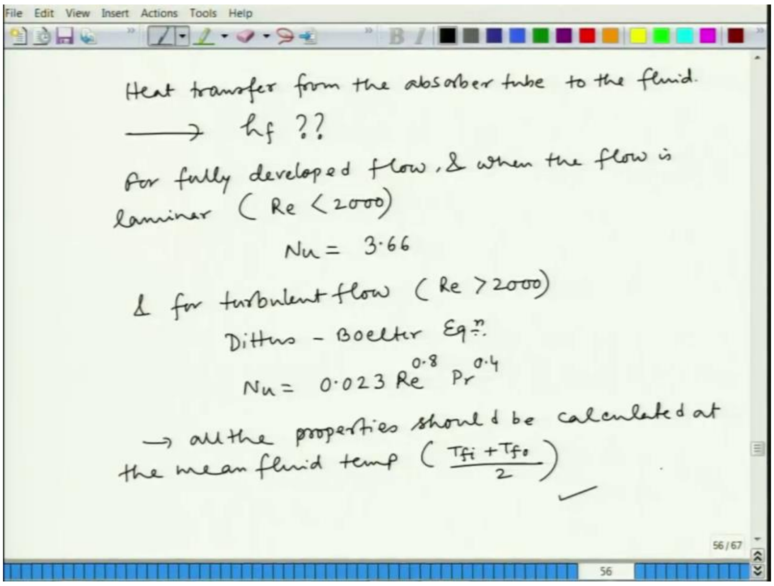
So, the correlation that we use is due to Hilpert, and that correlation is in terms of the non-dimensional number. All the time, the correlations are written in terms of non-dimensional number because you can use it for different size of the same geometry that is why it is non-dimensionalized, and that is a function of the Reynolds number to some power of n, and you have a pre-exponential function or number which is C_1.

So, here, these C_1 and n are the constants, which depend on Reynold's number, the range of Reynold's number C_1 and n will depend. So, what are they? So, for Reynold's number between 40 and 4000, we get C_1 equal to 0.615 and n equal to 0.466.

For the next range between 4000 and 40000, we have C_1 equal to 0.174 and n equal to 0.618, and for the even higher range, Reynold's number greater than 40000, which very rarely you will encounter in a parabolic trough collector Reynold's number above 40000 is almost never used. So, I mean, this is the natural convection. So, in the case of natural convection, going up to that high Reynold's number is typically impossible. So, that is how you find the h_w or the wind loss factor.

So, when you know the h_{p-c} and h_w, then you will be able to find out the U_l and everything else will fall in place, the heat removal factor, collector efficiency factor, and you can find the overall efficiency of the collector, the useful heat gain, all the required quantities you can find.

(Refer Slide Time: 24:12)



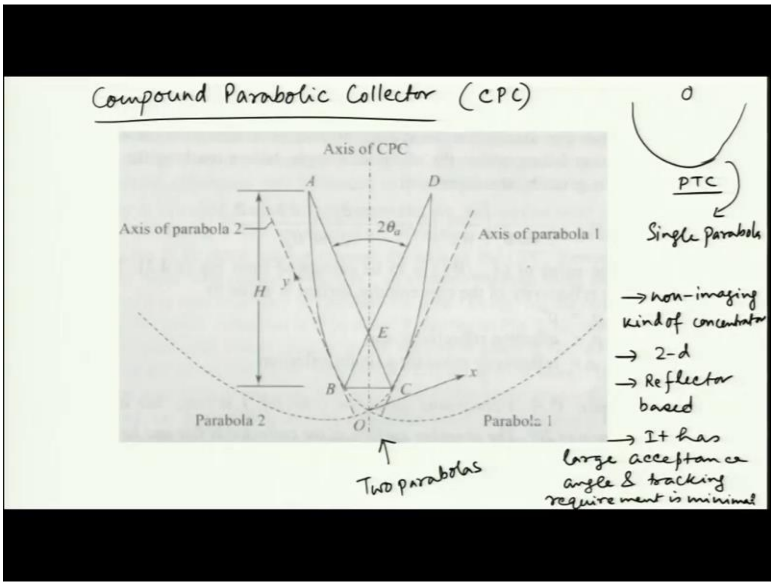
And only one thing is remaining here is to look at how the heat will be transferred from the absorber tube to the fluid. So, from the absorber tube to the working fluid or the heat transfer fluid, which is carrying out the heat. So, now, and for that, we require the heat transfer coefficient h_f.

So, here, the typical correlations are available; I am just repeating it because this is a pipe flow. For pipe flow, you know for the for fully developed flow, when the flow is laminar; Flow is laminar so; usually, Reynolds number less than 2000, the Nusselt number which is the non-dimensional heat transfer coefficient is basically constant right, this you have learned in the heat transfer course for convective heat transfer.

And for turbulent flow or rather for Reynold's number greater than 2000, we have the well-known Dittus-Boelter equation, and there the Nusselt number is a function of Reynold's number as well Prandtl number. So, this is the pre-exponential factor, and then you have Reynold's number to the power 0.8 and Prandtl number to the power 0.4. So, these are the standard coefficients from which you will be able to find out what the hf is.

So, here again, all the properties should be calculated at the mean fluid temperature. And that is your $\frac{T_{fi} \mp T_{f0}}{2}$ that means the inlet and outlet temperatures of the fluid, the average of them. So, that is how we know all the relevant heat transfer coefficients and the thermal analysis for parabolic trough NCR.

(Refer Slide Time: 27:32)



The next thing we are going to look at is the other concentrating collectors, parabolic trough, and flat plate collectors. Flat plate collector is the non-concentration version, the most common non-concentrated version of solar heat collector, and for the concentrated ones, the parabolic trough is the most commonly used geometry, and we have analyzed it fully in terms of the optical analysis as well as in terms of the thermal analysis.

Now, the next thing we are going to look at is what is called the compound parabolic collector, or more commonly, it is abbreviated with CPC, Compound Parabolic Collector. So, why do we call it compound?

Compound because it is not a single parabolic surface anymore, which was in the case of the parabolic trough. In the parabolic trough, what did you see? We had a single parabola, and you had a collecting tube or absorber tube at the focal point of that parabola.

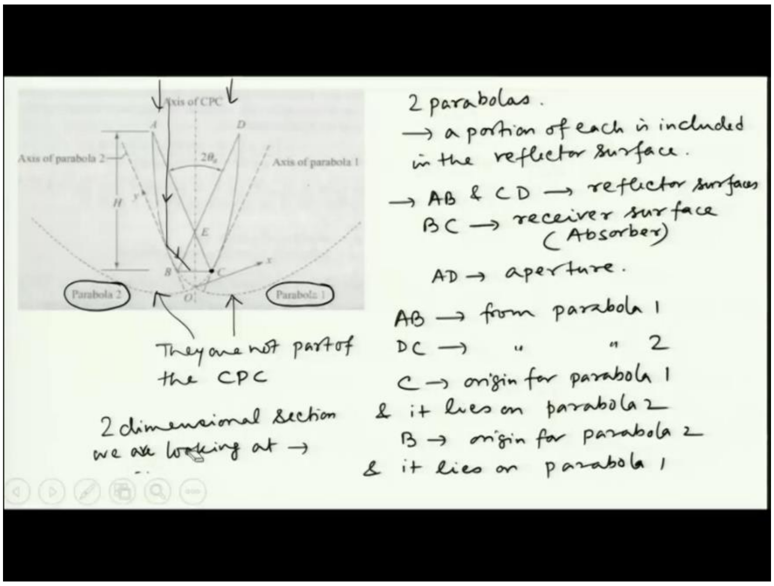
So, in this case, so, this is for PTC, and we had a single parabola, but for CPC, we have more than one parabola, and you can see here that we have two parabolas, and they are actually making up the surface of reflection. So, before I go into its detail, what is it? It is again a non-imaging kind of concentrator; then it is also so, we have looked at the different classification of this concentrating geometries right.

So, imaging, non-imaging was one, linear, non-linear, or linear volumetric was the other which is also 2D or 3D. So, this one is non-imaging, this one is again 2D because you are not focusing on a line, but you are focusing on a plane rather or rather it is not a point focusing thing; it is a line or plane focusing thing. So, it is a 2D geometry 2D concentrator, and the third classification we looked at is the reflector based right; it is not refractor based, but it is a reflector based concentrator.

Now, why we use it? Because it has a large acceptance angle and tracking is tracking requirement I would say is minimal that means, unlike the parabolic trough collector and the other collectors as you see later, where the tracking has to be perfect, it has to be two-dimensional or rather two-axis tracking, and the surface has to, or the aperture surface has to track the sun perfectly.

But in this case, for the compound parabolic collector, we do not need that. So, that is the particular advantage of this compound parabolic collector, and we will see how it works.

(Refer Slide Time: 31:57)



So, here, you can see that there are two parabolas; one is parabola one, and the other one is parabola two so, there are two parabolas and a portion of each; a portion of each is included in the reflector surface. So, here, you see that from A to B, first let me write what the reflector surface AB and CD are; these are the reflector surfaces while BC is the receiver surface or the absorber surface, and AD is the aperture.

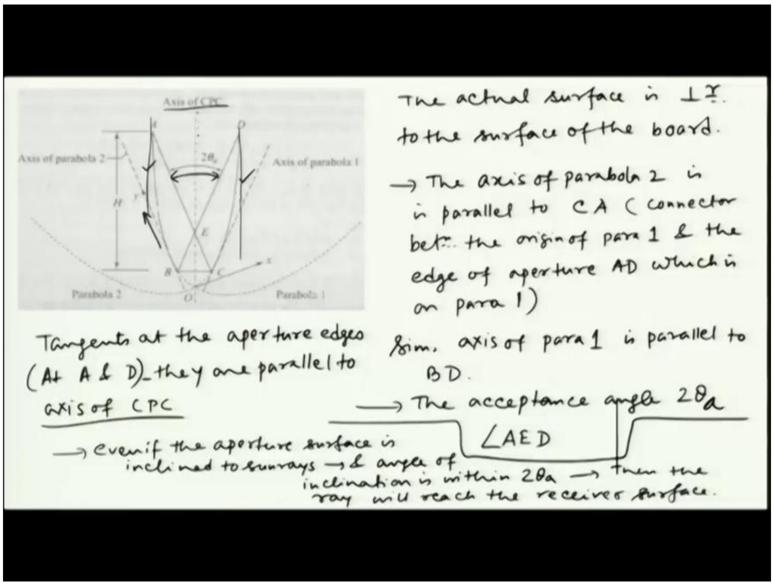
So, you see that sun rays are coming through this aperture AD and they are getting reflected at so, suppose a particular ray is coming like this so, it is getting reflected here when it reaches the reflector, and due to parabolic nature of the surface, it will be coming towards the absorber ok and similarly for other rays. So, this is the geometry.

And here, you see that the AB portion of the reflector surface is from parabola one, and the DC part of the reflector surface is from parabola 2, isn't it? So, the dotted portion here, as you see, the dotted portion from both the parabolas, are not part of the compound parabolic collector.

Now, another thing you notice that point C, C is the origin for the 1st parabola. So, C is the origin for parabola one, and that origin lies on parabola 2. C is part of parabola 2, but it is the origin of parabola 1. Similarly, B is the origin of the origin for parabola two, and it lies on parabola 1.

So, that is how both the parabolas are interconnected, one's origin is part of the other surface, and this is the two-dimensional cut that we are seeing. So, the 2-dimensional section we are looking at and the actual collector is going into the board perpendicular to the surface of the board. So, perpendicular, let me write in the next slide.

(Refer Slide Time: 36:19)



So, the actual surface is perpendicular to the surface of the board. So, this is very interesting geometry, isn't it? These two parabolas are interconnected, and the common part you are taking as they reflect reflecting the surface. Also, note here that the axis of the parabola; axis of parabola 2 is which one? Axis of the parabola 2 is this line right, and that is parabola two is parallel to this CA line, CA is what?

The connector between the C, C is the origin of parabola one so, this is the origin of parabola one, and the edge of aperture AD and A is on parabola 1. So, that is how this is connected. So, the axis of parabola 2 is parallel to the connector between the origin of parabola one and the aperture edge, which is on parabola 1.

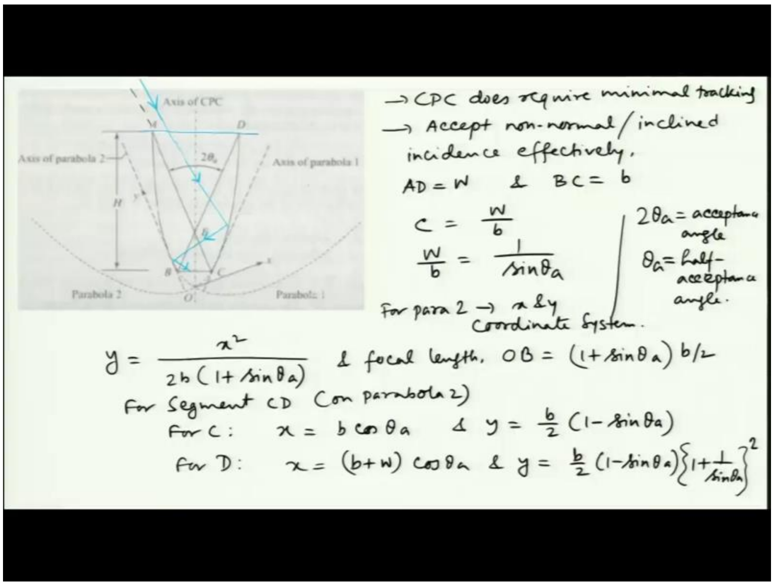
So, aperture AD, edge of aperture AD which is on parabola one and similarly, you have the axis of parabola 1 is parallel to BD isn't it? B is the origin of parabola two, and D is the aperture edge on parabola two, and here, you also notice that the tangents so, tangents at the aperture edge or rather aperture edges which are at A and at D, are parallel to the axis of CPC. So, this is the axis of CPC right you see.

And if you draw a tangent here at D, which will be like this, and at A, which will be like this, both this one and this one, these tangents will be parallel to the axis of CPC. So, thus, this geometry is symmetric, and it is very interesting because now, you have an acceptance angle that is much larger.

So, let me write it here. So, the acceptance angle is this 2θa that you see in the diagram that 2θa how you are getting? It is the angle AED. An acceptance angle we have talked about it earlier, what does it mean? It means that you have even if the aperture and the sun rays are inclined to each other, they do not have to be always normal.

If they are inclined to each other, and that inclination angle is within this 2θa, then that particular sunray will actually reach the receiver that is the concept of acceptance angle. So, even if the surface or yeah, even is the aperture surface is inclined to sun rays and the angle of inclination; angle of inclination is within this 2θa which is the acceptance angle, then the ray will reach the receiver surface.

(Refer Slide Time: 42:11)



So, that is very interesting because in that case, you can say that if some sun rays so, if you in increase this angle, now if some sun rays coming like this. If the sun ray is coming like this and this is your aperture plane, and you can see that it is not normal to the aperture plane.

But still, it will heat the reflector here, and it will, maybe it will have multiple reflections, it will be reflected back again, and the sunray will actually reach the receiver. So, that is how this angle of acceptance is increasing your range for which the rays will be accepted, and it will reach the receiver.

So, that is why CPC does require minimal tracking; that is why it is called minimal tracking. It can accept non-normal incidence effectively. It can accept non-normal or inclined incidence effectively. And often, the compound parabolic collectors are not fitted with any tracking mechanism; it is not possible to go into detail of compound parabolic trough a compound parabolic collector in this course.

But it can be shown that for the whole year, you can fix a particular position of a CPC, and you can get the effective concentration up to 4, 5, and for 8 hours a day that is possible without doing any tracking. So, that is the beauty of it. Now, if we try to analyze it in more quantitative form, then what we can write is let say that this AD is our width, width of the aperture W, and BC, which is the width of the receiver b.

So, the concentration ratio that we get here is $/b$, the aperture area divided by the receiver area that is the concentration ratio hereafter, and so, it can be shown that these W/b are one over $\sin\theta_a$. So, $2\theta_a$ is the acceptance angle, and θ_a is called half acceptance angle. So, this can be shown.

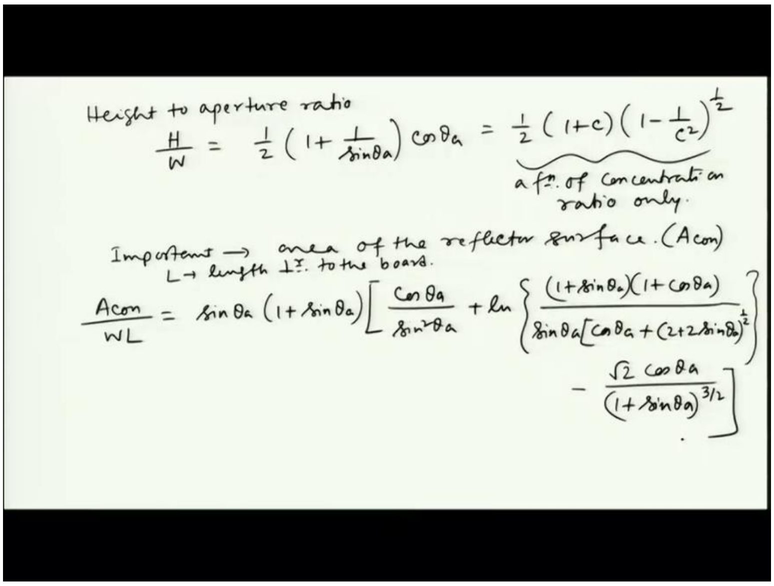
And for parabola 2, we have this x, y coordinate system; for parabola 2, look at the figure we have this x, y coordinate system, and from there, what can we write?

$$y = \frac{x^2}{2b(1 + sin\theta_a)}$$

The focal length is OB. So, OB is $(1 + sin\theta_a)^{b/2}$. So, this you can find.

So, now, for segment CD, which is on parabola 2, you can write the coordinates for C, the x coordinate is $bcos\theta_a$ and the y coordinate is $\frac{b}{2}(1 - sin\theta_a)$ and for point D, the x coordinate is $(b + w)cos\theta_a$ and the y coordinate is $\frac{b}{2}(1 - sin\theta_a)\{1 + \frac{1}{sin\theta_a}\}^2$.

(Refer Slide Time: 47:56)



So, once we know the coordinates of C and D, what can we write? So, whenever we know the coordinate of C and D, we can write the height to aperture ratio that will tell us how much reflector surface will need, and all right. The geometry if we want to find, then we need to know what is the height to aperture ratio.

So, that is

$$\frac{H}{W} = \frac{1}{2}\left\{1 + \frac{1}{sin\theta_a}\right\}cos\theta_a = \frac{1}{2}(1 + c)(1 - \frac{1}{c^2})^{\frac{1}{2}}$$

You can write it in terms of the concentration ratio itself because the concentration ratio is $\frac{1}{sin\theta_a}$.

So, whatever concentration ratio you want will determine what will be your half acceptance angle and what will be your height to aperture ratio. Now, another important quantity is to know what is the area of the reflector surface. Area of the reflector surface why is it important? Because the reflector surface is where you are going to put the reflecting coating, and which is the most costly thing in this whole arrangement.

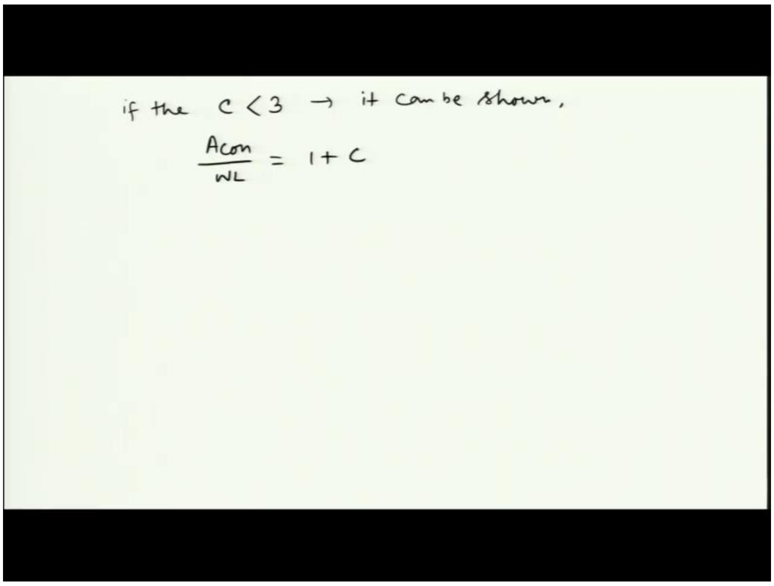
So, you have to use the super reflector, and which will stay for a long time so, that coating how much of that you will require will depend on what is the area of the reflector surface, and that is why it is known, it is important to know. So, let say that is an area of concentrator or reflector A_{con} and that $\frac{A_{con}}{WL}$, L is the length perpendicular to the board.

So, that one you can write, or it can be shown so, L let me write L is the length perpendicular to the direction of the board. So, this expression is

$$\frac{A_{con}}{WL} = sin\theta_a(1 + sin\theta_a)[\frac{Cos\theta_a}{sin^2\theta_a} + \ln\left\{\frac{(1 + sin\theta_a)(1 + cos\theta_a)}{sin\theta_a[Cos\theta_a + (2 + 2sin\theta_a)^{\frac{1}{2}}]}\right\} - \frac{\sqrt{2}Cos\theta_a}{(1 + sin\theta_a)^{\frac{3}{2}}}]$$

So, this is a long-expression, and we can simplify it significantly.

(Refer Slide Time: 51:51)



So, if the concentration ratio is less than three, then it can be shown; it can be shown that

$$\frac{A_{con}}{WL} = 1 + C$$

So, we will see from here in the next class.

Thank you.