Elements of Solar Energy Conversion
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Lecture - 24

Hello, everybody; welcome back to the series of lectures on Elements of Solar Energy Conversion. So, far we have looked at the background that we require for this solar energy conversion technique; then, we started looking at the flat plate collectors, which are the basics basic of all kinds of collectors.

And, then we have looked at few variations of that we did a detailed thermal analysis. And, in the last class, what we started is the concentrating collector, and the first topic we took was the theoretical limit of concentration ratio. How much maximum concentration can we think of? Then any practical device can be weight according to that theoretical limit.

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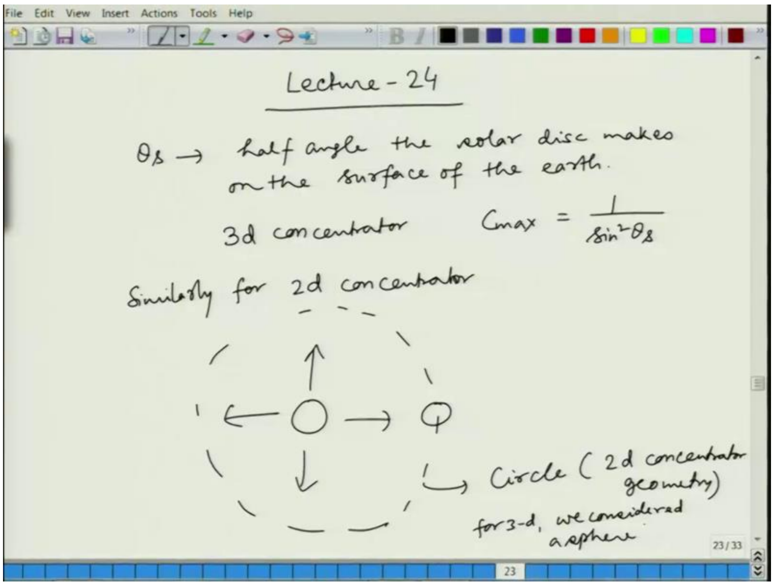

So, we are here at lecture number 24.

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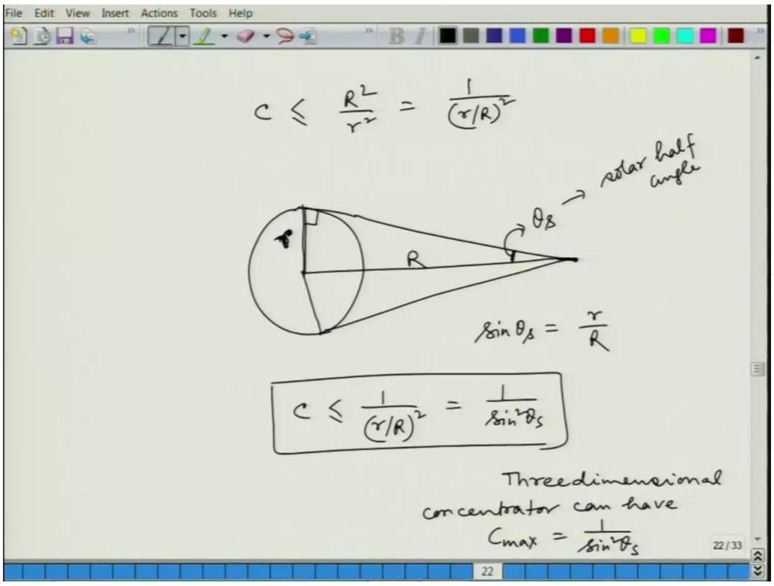

So, in the last class what we have seen? The three-dimensional concentrator can have $C_{max} = \frac{1}{sin^2(\theta_s)}$. That means that is the θ_s is the half-angle that the solar disk makes on the surface of the earth. So, these θ_s let me just repeat that it is the half-angle the solar disk makes on the surface of the earth. And for 3d concentrator, we have $C_{max} = \frac{1}{sin^2(\theta_s)}$.

And, we have used the thermodynamical limit, and that is why it's called thermodynamic limit or theoretical limit for concentration ratio. Similarly, for a two-dimensional concentrator, two-dimensional concentrator means what? Suppose you have a this is the sun, and it is radiating all around. So, you can think of a two-dimensional plane which is a circle, and the earth is somewhere on that circle.

So, instead of a sphere, this is a circle for 2d concentrator geometry. So, for 3d, this is a sphere; we considered a sphere around the sun. So, this time we are considering a two-dimensional circle.

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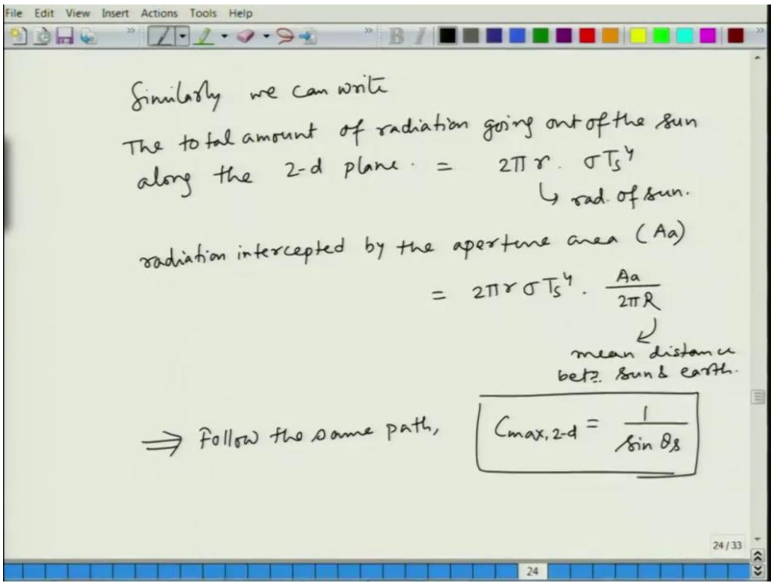

So, the again similar way we can think of, we can write the total amount of radiation going out of the sun along the 2d plane. So, that would be your $2\pi r\sigma {T_s}^4$, 2πr is what? The circumference of the circle. Earlier, we have used $4\pi r^2$ which is the total area of the sphere; in this case, what we need to do? We have to take the circumference of the circle, and that is 2πr, r is the radius of the sun. And, the rest part the sigma ${T_s}^4$ remains the same.

So, similarly, what we can find the radiation intercepted by the aperture area, A_a subscripted with a is $2\pi r\sigma {T_s}^4$ this is the total amount across the circumference. And, you have a fraction of that in the absorber, which is $\frac{A_a}{2\pi R}$ this R is the radius or the mean distance between the sun and earth.

So, in the exact same way, we are handling the fraction of radiation that is getting intercepted by the aperture area. So, following the same path, which of course, I am not going to repeat the C max now let me subscript with 2d will be $\frac{1}{Sin(\theta_s)}$ instead of $sin^2(\theta_s)$, we have $\frac{1}{Sin(\theta_s)}$. So, that is the theoretical limit for a two-dimensional concentrator.

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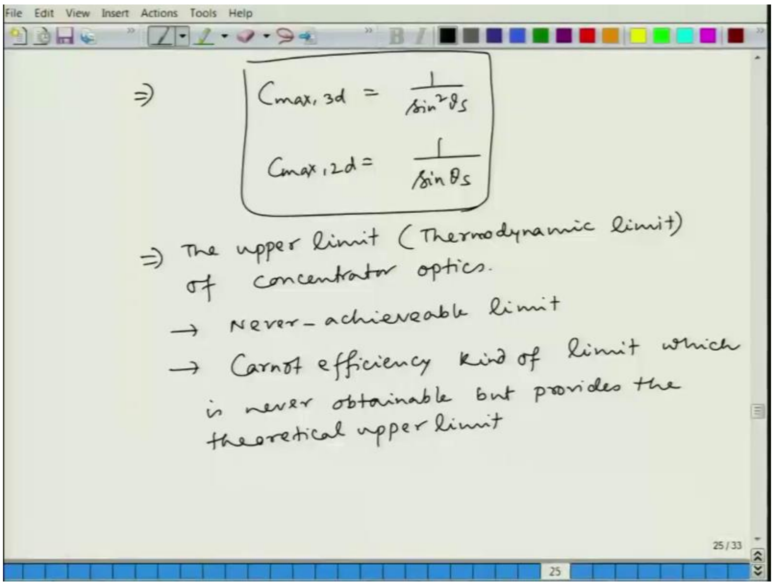

So, here we must remember that $C_{max,3d} = \frac{1}{sin^2(\theta_s)}$ and $C_{max,2d} = \frac{1}{sin^1(\theta_s)}$ both of these give the upper limit or thermodynamic limit of concentrator optics. So, this is kind of a limit that can never be reached because it requires that the receiver reaches the same temperature as the sun, which is impossible to achieve.

So, a never achievable limit that can be used to compare the different concentrator optics so; means it's like a Carnot efficiency kind of limit which is never obtainable but provides the theoretical upper limit. So, just to say that, if somebody says that some very large number. Let us say that 100000 times concentration ratio is achievable, whether you can believe him or not. So, that kind of limit this particular value puts.

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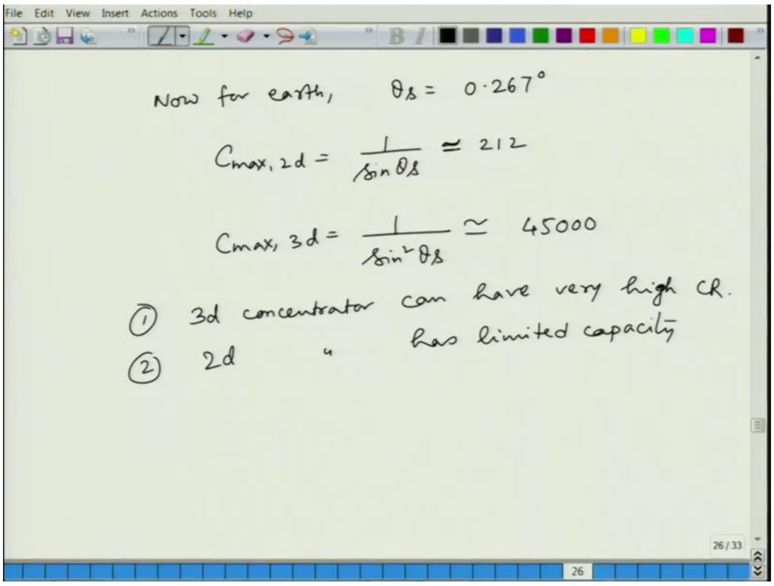

So, now for the earth, this θs is which is the half-angle that the solar disk makes that is 0.267˚. So, on mars, it will be different because it depends on the mean distance between the sun and that particular planet. So, for the earth, it is 0.267˚; there is a slide variation as the distance between the sun and earth changes, but it is negligibly small. So, we can take the mean value, which is 0.267 degrees.

So, what we can see the $C_{max,2d} = \frac{1}{sin^1(\theta_s)}$ you can substitute this value, and you can see the approximate value will be 212. And, similarly, $C_{max,3d} = \frac{1}{sin^2(\theta_s)}$ and that is approximately 45000. So, two very important points here we need to make that the three-dimensional concentrator can have a very high concentration ratio or CR and 2d concentrator has a limited capacity of concentration, 212 is the theoretical maximum.

So, in reality, you can not get beyond 50. And for a three-dimensional concentrator, the theoretical limit is 45000, so; you can go well above 2000, 3000 you can go easily to that level. So, if you really want to have some serious concentration, you have to go to a 3-dimensional concentrator.

And, again here these numbers, if you have some sense of these numbers then you will have like if somebody says I have a parabolic trough which is a two-dimensional concentrator and by that, I am achieving a concentration of 500. You just say that you are lying; that is simply impossible; the theoretical limit is 212. So, you cannot go beyond that whatever you do. So, that kind of intuition is important, and I hope that you can inculcate that from this course. So, that is all about the theoretical limit.

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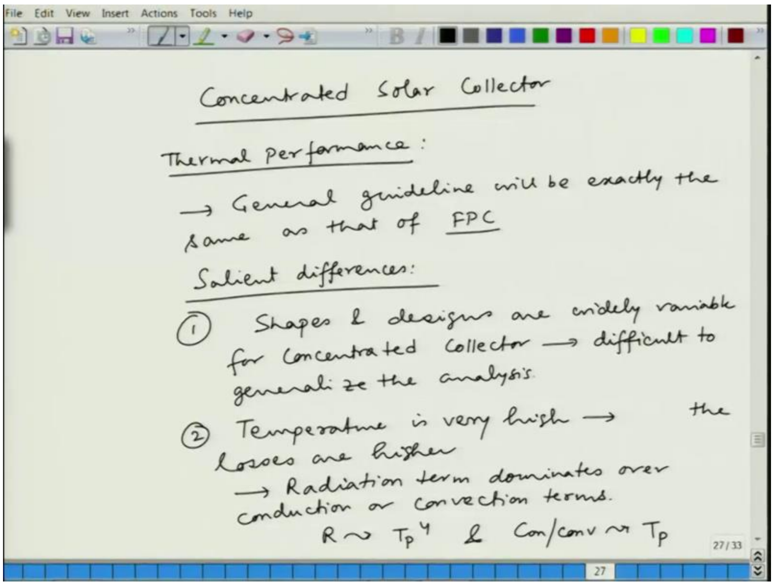

Now, for the concentrated solar collectors, if we do the thermal performance analysis, what things will be different because the flat plate collector, even including the air heater we have covered in very detail. But, here we are not going to cover all the details, but we need to find what are the salient features are or what the salient differences; if you consider a concentrated solar collector and a flat plate solar collector.

So, thermal performance, if we want to see, the general guideline will be exactly the same as that of a flat plate collector, because again you are having some absorb radiation, you have some losses, and you have some useful heat. So, the general guideline will be the same only the intensity is much higher. So, what things will be different? So, salient differences if we want to say the 1st one is the shapes and designs are widely variable for concentrated collectors.

So, shapes and designs, that means geometry is important; we have seen that while we have looked at the liquid flat plate collector and the air heater, and the differences we have looked at. So, if for concentrated collectors you have wide variability in terms of shapes and designs, then those will be different as well. I mean, that will tell you what would be the thermal resistance circuit and all those things.

So, that thing is there so, is the first thing is that it is difficult to generalize. In the analysis or flat plate collector, we have certain predictability of what will be the design if it's a liquid collector or if it is an air heater. But, for a concentrated collector, the designs are so variable that general formulation is difficult. 2nd salient feature is the temperature is very high compared to the flat plate collectors, and; that means both the losses. So, first of all, the losses are higher.

Because the temperature is high, that means the loss to the emit will be higher. And the radiation term dominates over conduction or convection terms. What do we mean by that? You have several losses; one thing is conduction through the edges, convection through the air layer, and you have radiation term. Now, the radiation term depends on the fourth power of temperature right.

And, both conduction and convection terms depend on the first power of temperature, so; that means when the temperature is higher, the radiative term will be dominating right because this radiation is T_p to the power four and conduction or convection both of them are T_p to the power 1. So, that is why the radiation term will be dominating.

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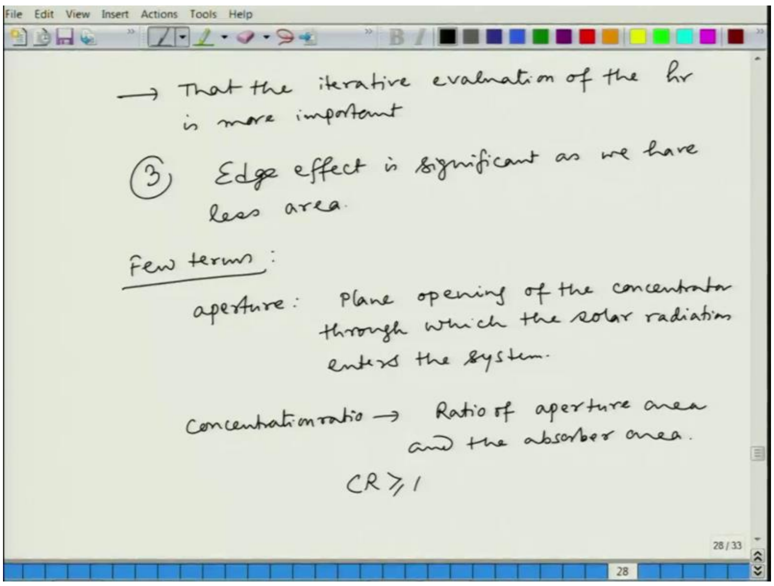

So, what would be the consequence? That the iterative evaluation of the radiative heat transfer coefficient, which is hr is more important. So, you have seen that whenever you have a radiative term, you have to guess the temperature of the plate. And then you find the radiative heat loss from there. And, then you come back, find the temperature again and see how much did it change, and this iterative procedure is more important when the radiative term is dominating.

So, in this case, you have to do several more steps of iteration, then only you will have a converged heat transfer coefficient for radiation. Then, the 3rd point, the 3rd differential, the edge effect is significant, as we have less area. So, what is the point of concentration? The absorber area is much reduced; that is the point of concentration.

Otherwise, if you have a very large absorber, then you can as well use a flat plate collector geometry; no concentration is required. So, when you reduce the area and that area reduction depends on the concentration ratio, the edge effects will be more important because the edges constitute a significant portion of the total area. So, these are the major differences.

Now, before we proceed, we should have a clear understanding of few terms, which are particular to the concentrated solar collector first thing is aperture. Aperture is what? It is the plane opening of the concentrator through which the solar radiation enters the system. So, it's just like the aperture of a camera, the area through which the light comes in the camera that is called the aperture, and you can control it depending on the amount of light you want inside the camera.

Here also, an aperture of a concentrator means the plane that is allowing the solar radiation to come into the system. Then the concentration ratio is nothing but the ratio of aperture area and the absorber area. And the whole point is that it has to be greater than 1. So, the CR is greater than equal to 1; when it is equal to 1, we do not call it concentrator concentrated collector; we call it flat plate collector.

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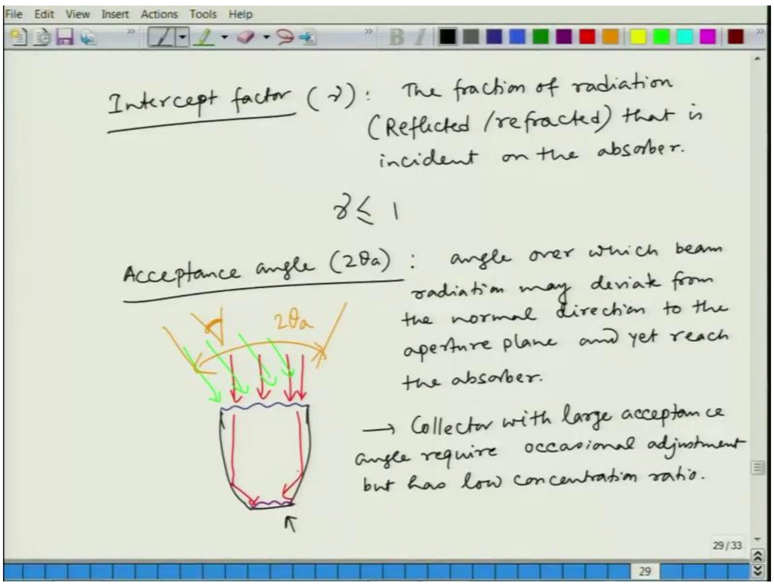

The next term is called the intercept factor; often, we designate it with the symbol ϒ. What is that? It is the fraction of radiation; by that it is, I mean the concentration can happen through different optical phenomena major are refraction or reflection. So, whether it is reflected radiation or refracted radiation ok, that is incident on the absorber.

So, we will see that it will be important that all the radiation that is getting going through the aperture and then getting refracted or reflected to be focused to the absorber may not reach the absorber. So, only a fraction of that will reach. So, ideally, we want all the radiation that is passing through the observer reaches passing through the aperture to reach the absorber.

But, in reality, this intercept factor will be less than equal to 1 so, this will be less than equal to 1. Another important jargon for the concentrator is the acceptance angle; we call it $2\theta_{a,}$ just like θ is, which is the half-angle subtended by the solar disk here; we have $\theta_{a,}$ which is half-angle or half acceptance angle. So, the acceptance angle is $2\theta_a$. So, it is the angle over which beam radiation may deviate from the normal direction to the aperture plane and yet reach the absorber.

So, what does it mean? So, there is one particular geometry which we called compound parabolic dish, where you have the this is the aperture area, this is the aperture plane, and this is the absorber plane. So, it depends, I mean, of course, if the solar radiation is normal to the aperture plane. It will get reflected here, and it will reach the observer. But, the acceptance angle is what if the direction of the ray is like this; even then, a fraction of it will reach the observer.

So, the angle between the normal and the actual solar beam direction that the particular collector is can accommodate, the particular collector can accommodate that is the acceptance angle. So, basically, the acceptance angle here would be the total deviation that it can accommodate, and that will be $2\theta_a$, and half of that will be θ_a. So, here we can say that a collector with a large acceptance angle requires occasional adjustment but has a low concentration ratio.

So, one limit we can think of the flat plate collector, which is already familiar to you. So, flat plate collector, you have the acceptance angle to be 180 degrees. So, from whichever angle it comes, it can absorb a portion of it. So, their acceptance angle is huge, but you can keep it fixed; you can have occasional adjustment, but the concentration ratio is the lowest, that is 1. For this particular example that I have seen here, I mean shown here, here also you can have concentration ratio about 6, 7, 10.

A low concentration ratio and it has it gives you a certain acceptance angle which is less than 90˚, but significantly higher than 0˚. But, most like the parabolic trough or parabolic dish, they have 0 acceptance angle because you have to have normal radiation on the aperture. Then, only the concentrator or the reflector or refractor will work and deviate the sunlight in such a way that it reaches the absorber.

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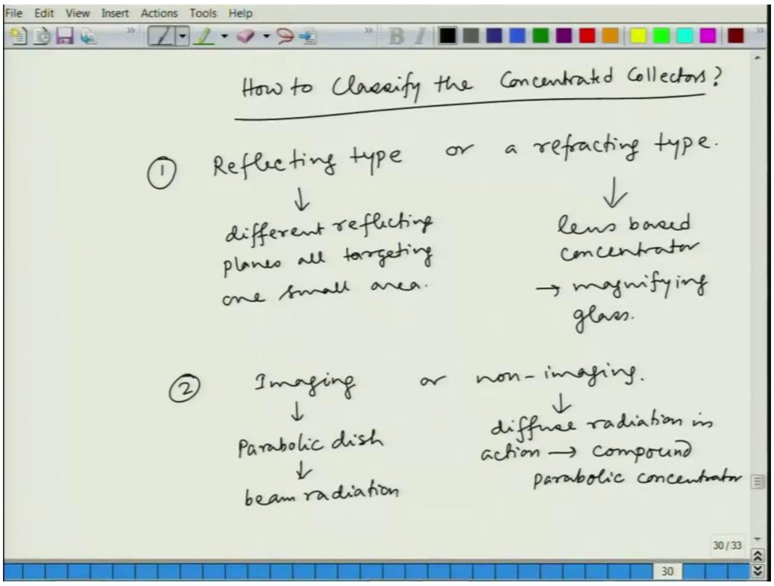

Now, how to classify these concentrated collectors, there are several possible ways how we can classify ok. The 1st one we already talked about whether it is a reflecting type or a refracting type. So, it is possible that there are lots of reflectors, and all of them are reflecting a certain point; that is how the concentration is getting achieved or a large surface each portion of the surface is reflecting the solar radiation to a certain point a certain area. So, that is how the concentration is achieved.

So, the basic principle of different, reflecting planes all targeting one small area. That is how the reflecting type concentrator works, and refracting type is very common; you have seen that when in your childhood I am sure you have done this experiment, that you put a magnifying glass under the sun and you concentrate it in such a way that you can even burn a piece of paper or a piece of cloth.

So, this is the lens-based concentrated basic version; you can see in the case of a magnifying glass. If you have not done that experiment in your childhood, please go back and collect a magnifying glass and do that its really fun. The 2nd kind of classification that we can have is whether it's imaging or non-imaging. Imaging means you will actually form an image of the sun on the absorber after whatever you are doing reflection refraction.

There will be an image formed on the absorber, and non-imaging means it's all blurred; you do not have an image of the sun. So, whenever you have diffuse radiation inaction, you have a non-imaging thing because diffuse radiation does not give you the exact direction, so; that means you do not form a clear image of the sun.

So, such as the compound parabolic trough or compound parabolic collector, parabolic concentrator that is a non-imaging kind. An imaging kind you can say that any parabolic dish, you can say and it works only with beam radiation. The diffuse radiation does not take part in the concentration, and that is why it forms a completely clear image.

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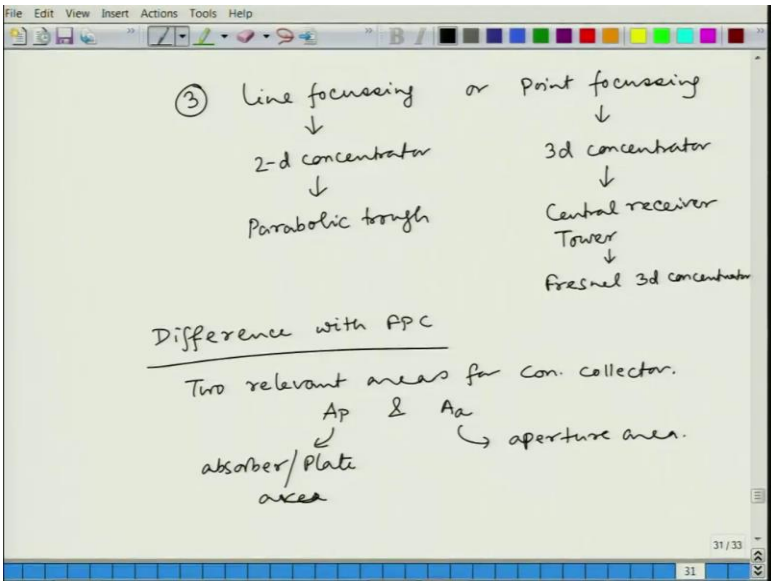

The 3rd kind of classification we can have is line focusing or point focusing, which is also called line focusing, which means it's a two-dimensional concentrative. We have talked about it earlier; when we have looked at the theoretical limit of the 2-dimensional concentrator and 3-dimensional and point focusing, it is your 3-dimensional concentrator.

And 2-dimensional if you want to take the example, you can take it as parabolic trough, which will see just after this one. And three-dimensional concentrator is something of a point concentrator; you can say the central receiver tower, or you can say Fresnel 3d concentrated. So, these are different ways you can classify the concentrator optics.

And in case of the difference with the flat plate collector, you can have that we have two areas, two relevant areas for a concentrated collector; what are they? One is the absorber area or plate area A_p, and the other one is the aperture area or A_a. So, this is the absorber or plate area, and this is an aperture area. So, if you remember the flat plate collector, we had only one area, A_c the collector area, or we have also written A_p. So, there were no different areas.

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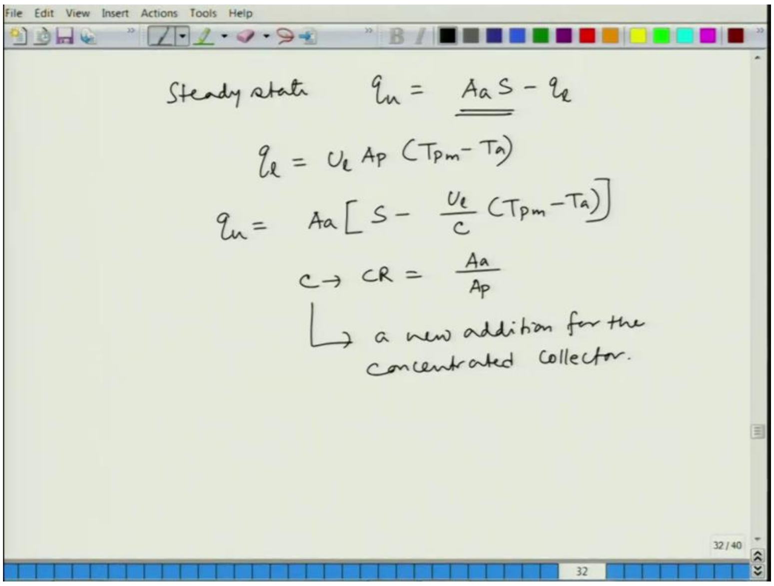

So, what would be the difference? Under steady-state, we have seen that the useful heat gain the rate heat was A_aS minus the rate of heat loss through the overall area. So, here the absorption that is happening or the amount of radiation that is coming in is multiplied by A_a or the aperture area. So, here the q_l is your U_l *A_p because now the loss is happening from the absorber area $T_{pm} - T_a$.

So, now, if you put that in the above equation and you can have $A_a\left(S - \frac{U_l}{C}\left(T_{pm} - T_a\right)\right)$. So, C is the concentration ratio which is nothing, but $\frac{A_a}{A_p}$.

So, that factor this factor is a new addition for the concentrated collector, is not it, earlier you had only one area, and you did not have any factor C for flat plate collectors. So, now we will do the analysis for the most common parabolic trough collector, which is the most common concentrating collector.

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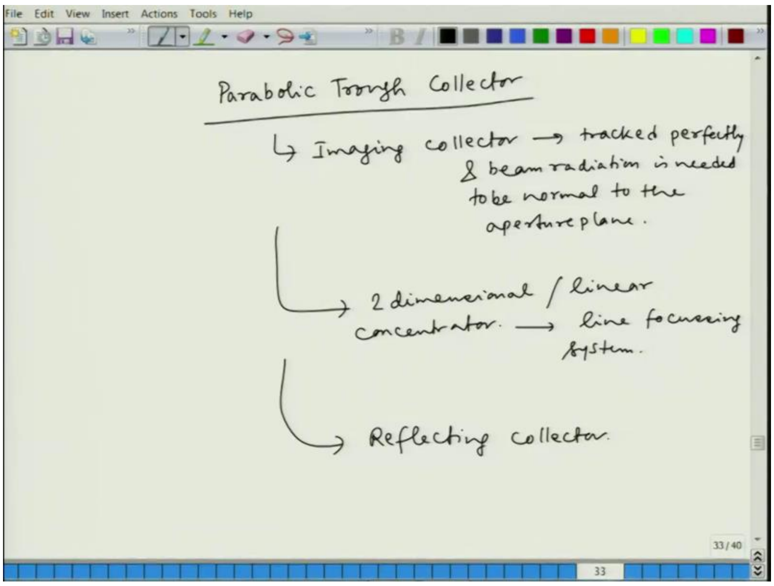

So, we look at the parabolic trough collector. So, first, let me show you how does it look.

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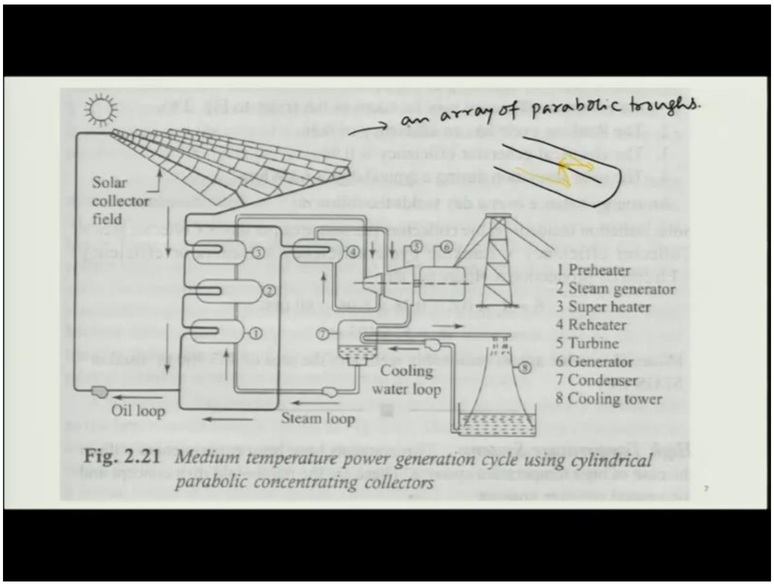

So, here you can see this is an array of parabolic troughs. So, how do they look? You have the parabolic surface, which is long, and at the focal point, you have the tube which carries the fluid and gets heated by the collector ok. So, what is happening here? You have these solar rays are falling on this and then getting reflected onto this focal plane, where the pipe is running; that is how the parabolic trough collector works.

So, now, what kind of collector is that? It is an imaging collector because it does not allow the defuse radiation to dictate the concentration, it is it has to be tracked perfectly. So, for any imaging collector, it has to be tracked perfectly, and beam radiation is needed to be normal to the aperture plane.

And another way you can say it's a two-dimensional or linear concentrator. Because all of them, all the radiation is being focused on a line where the collecting tube is there, but it's not focused to a point. So, you can also call it a line focusing system. And, also it is based on the principle of reflection ok. So, it is a reflecting collector, not on the principle of refraction, but the aperture is nothing but a plane that is reflecting.

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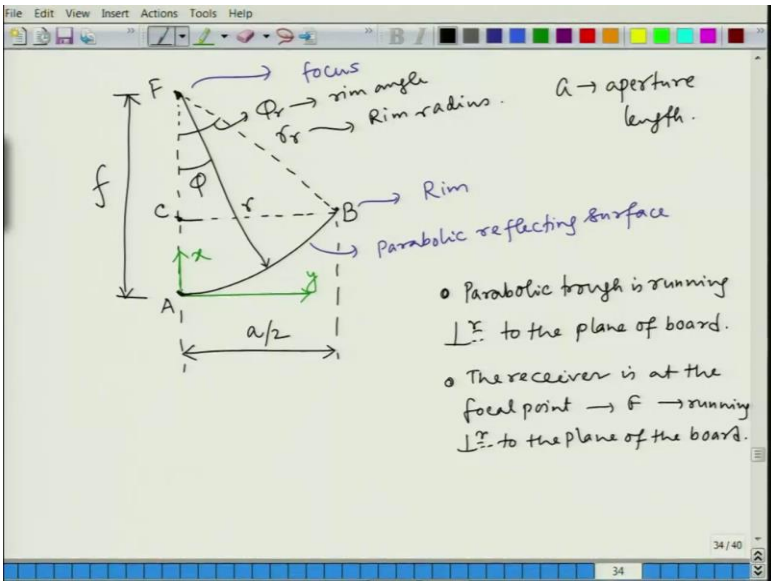

Now, if we do the optical analysis of that first thing, we can draw that let us see that this is the parabolic surface, and this is the point of focus. So, let us say this point to be F and the midpoint of that surface, I am just drawing half of it, and the other half will be symmetric so, if this is the parabolic surface, parabolic reflecting surface. And, this is the focus of the parabola. Now, let us say that B is the endpoint of it so, this point B is called the rim.

Rim means the farthest point from the center. So, this is the rim, and the radius at the rim is called r_r; that means rim radius. At any other point, you can draw, and that radius is r, and that r is changing depending on whether you are on the parabola. Similarly, the angle that the rim point subtends is called the rim angle, and at any other point, you can draw the angle, which is 5.

And let us name these so, this is the focal distance f and if we draw up a perpendicular from the rim point to this focal line, let us name this point to be C. And, also let us say that this is the x-direction and this is the y-direction. So, here what is the aperture? Aperture is this BC. So, we can so this is half aperture actually we have drawn half of the parabola, and this is half aperture, let us say this is a by two where a is our aperture length.

And, please note that this figure that we have drawn is the plane is actually running perpendicular to the plane of the board, and that is why it's a two-dimensional figure. We have just drawn a slice of that extended plane, and that is a two-dimensional plane. So, let me write that the parabolic trough is running perpendicular to the plane of the board. And the receiver is at the focal point F. So, again, the receiver is also running perpendicular to the plane of the board.

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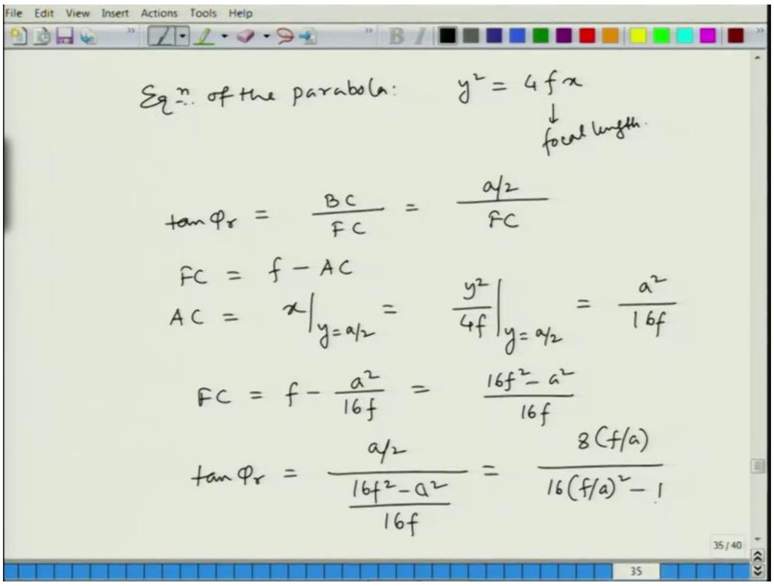

So, now what we can write this equation of the parabola from the drawing we can directly write this will be $y^2 = 4fx$, f is the focal length, this is the focal length. Now, you can see that the tan(ϕ_r) so, the tangent of the rim angle ϕ_r which is nothing, but $\frac{BC}{FC}$. So, BC is this one, and FC is this one. $tan\varphi_r = \frac{BC}{FC} = \frac{\frac{a}{2}}{FC}$.

So, now we need to find FC, which is nothing, but $f - AC$ you can see here f is AF that is the small f. And FC is small f minus AC, and AC is what is x at y equal to a by 2; let us see that. So, AC is nothing, but x is in this direction x at y equal to a by 2, is not it? So, now, what can we do? We can put this f value which is $\frac{y^2}{4f}$ that is from the equation of parabola at y equal to a by 2. So, that gives us a square divided by 16f.

So, we have obtained AC, which means, $FC = f - \frac{a^2}{16f}$

$$\tan(\varphi_r) = \frac{8\frac{f}{a}}{16\frac{f}{a}^2 - 1}$$

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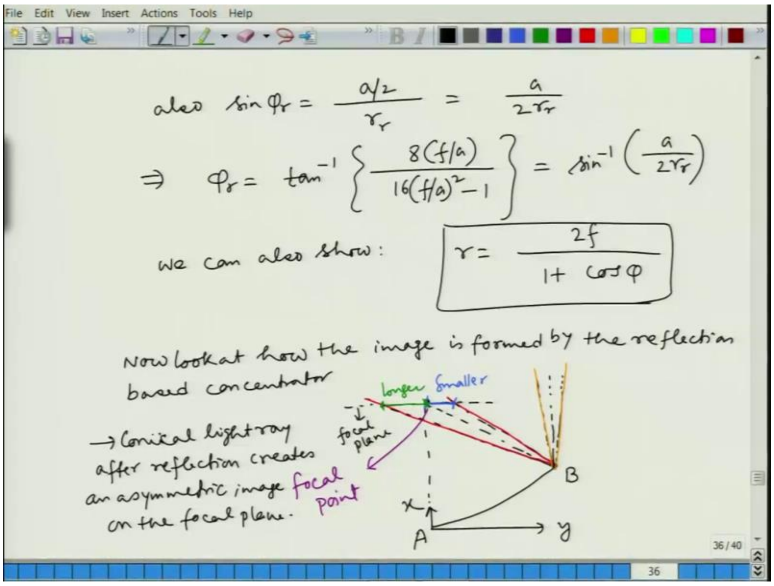

And, also sin(ϕ_r) you can find which is a by $\frac{a}{2r_r}$. So, not only the rim angle but the rim radius, we want to know. So, let us involve r_r here. So, what can we write? ϕ_r either you can write in terms of $tan^{-1}\left(\frac{8\frac{f}{a}}{16\frac{f}{a}^2-1}\right)$Or you can write $sin^{-1}(\frac{a}{2r_r})$. And, we can also show that these radii at any place you can write in terms of $\frac{2f}{1+\cos(\varphi)}$.

So, this is the relationship between the radius of the parabola and the angle of that particular angle corresponding to that particular radius. Now, look at how the image is formed by the reflection-based concentration. So, suppose we have this particular parabola; as we have seen earlier, this is x and y. We have certain here; let us say the focus point is here.

So, let us say we have a plane at the focus point, so, at the last point or the rim point let me make them smaller. At the rim point, what we have? We do not have a single solar ray coming on to this point. We have a cone 3-dimensional cone that is coming on the rim point; because the sun is a circle sun looks like a circle from that point B, this is point B, this is point A.

So, at point B sun looks like a circle; at any other point, it will have a cone of light that is falling on that. And that cone, when it gets reflected, will maintain that cone form a conical form. So, what will it do? So, let us say this is the reflected cone, and this is the incident cone. So, you can see that across the focal point, the distance at which these plane carts are different; this is a smaller distance compare to the other side. This is a larger distance or a longer distance.

And this is the focal point. So, if you look closely, the conical light ray after reflection creates an asymmetric image on the focal plane, is not it? This is the focal plane; this is our focal plane. So, what would be; what would be its consequence if we have a certain receiver there so the image that will be created will be asymmetric across the focal plane.

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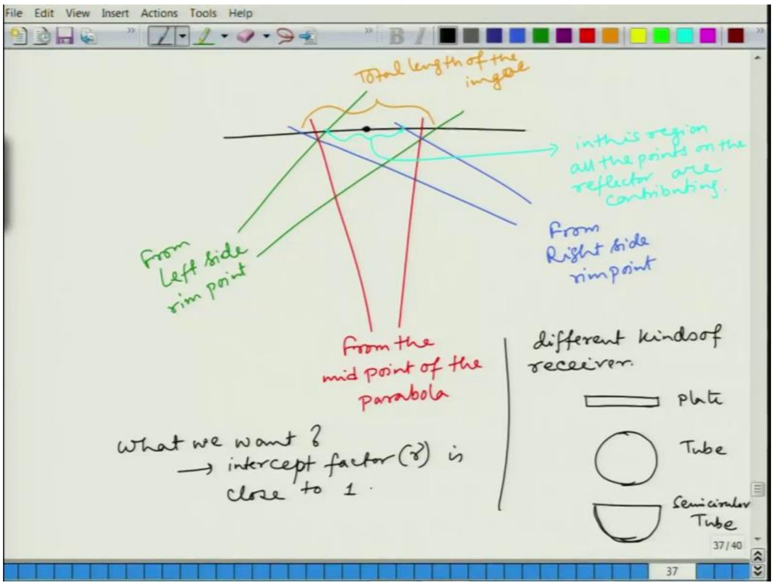

So, now, if we just look at that focal plane so, from one side one rim angle, it will have let us say this is the; this is the cone that from the right-hand side focal point. And, there will be another one which will be from the left-hand side focal point. So, this is left side rim point, and this is from; this is from left side rim point, and this is from right side rim point right, and from the middle, you will have in between these two.

So, this is from the midpoint of the parabola. So, you can see that ultimately, if you have a two-dimensional parabolic trough, then the image that will form will be symmetric. But, from one point, if you look at it, the image will be symmetric because now you can see the length of that image the total length of that image will be this right.

So, the total length of the image, but you can see that in this region. So, in this region, all the points on the parabolic reflector are contributing. So, here in these in this region, all the points on the reflected are contributing is not it, but beyond that, all the points are not contributing few points are contributing. So, the intensity will be different. You have an image formed on the focal plane, but the intensity will not be equal everywhere; at the middle, it will be higher, and towards the edge, it will be less.

Now, you can have different kinds of the receiver. So, on the image focal plane, how the image form we have written, but now you can have either a plate kind of receiver, you can have a sphere kind of receiver or not sphere, but circle and semicircle that is also possible. So, this is the plate, this is the tube, or this is a semi-circular tube. So, these different kinds of receivers you can have.

And what we want? We want that the interception is maximum so, we want the intercept factor ϒ to be close to 1. That means all the radiation that is getting reflected from the parabolic trough should reach or should intercept the receiver. So, we will see all these details of how the image forms on the focal plane and how the different receivers will affect the next class in detail.

Thank you very much for your attention.