Elements of Solar Energy Conversion

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Lecture - 23

Hello, everyone. Welcome back to this series of lecture on Elements of Solar Energy Conversion. Today, we are here at lecture number 23.

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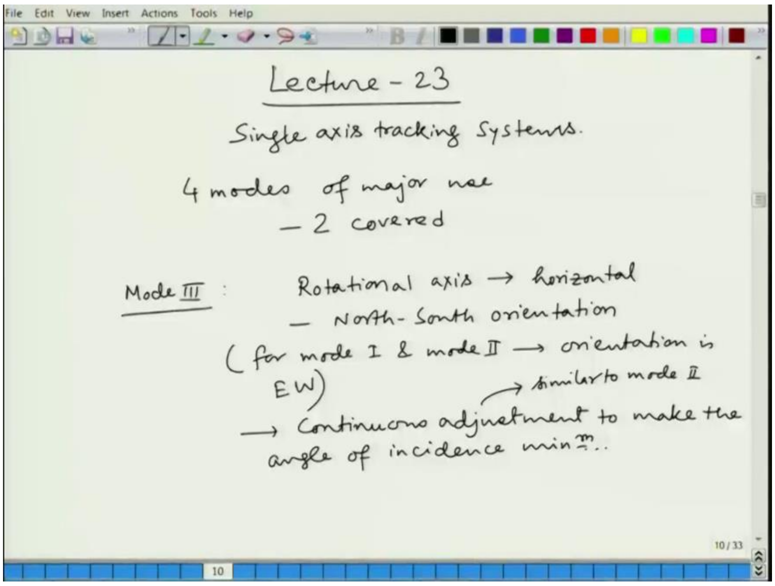

So, in the last class we have started looking at the single axis tracking options, ok. Why do we need to do this single axis tracking? Because it is a middle path between the fixed position solar collectors and the fully tracked solar collectors. Fully tracked means it has to be two axis tracking system then you can actually track the sun and perform the concentration through properly refracting or reflecting solar rays to a focal point.

So, in the single axis tracking system what we do? We use a compromise between these two extremes: two axis tracking and no tracking. And that is how we increase the amount of radiation that we can get and also we reduce the amount of complication, the maneuverability issues and all that is related to the full tracking system, ok.

So, we are looking at the single axis tracking systems and we mentioned that there are 4 major modes of single axis tracking that are used. There are infinitely different possible configurations that you can use (in principle). It is important to note that you choose the orientation and the position of the axis and how frequently you rotate it, there are infinitely many possibilities. But, the 4 modes that I am going to discuss here are the ones that are majorly used and it has its reasons why those are the modes that are used, ok.

So, there are 4 modes of major use and in the last class we have covered 2 of them and today, we are going to cover 2 more, ok. So, let us start with mode III, ok. Now, first thing for any mode we need to find, or we need to know the rotational axis position.

So, it is again horizontal and now, we have North– South orientation of this axis. So, for mode I and mode II we have seen the orientation was East-West. So, just let me remind you for mode I and mode II, the orientation is East-West, but this time for mode III what we are going to use is North–South orientation, ok. But, these mode I, II and III, the axis is horizontal that similarity is still there, but we have North South orientation, ok.

And, what we are doing? We are doing continuous adjustment to make the angle of incidence minimum, right, that is the goal of any tracking mechanism to minimize the angle of incidence and here also we are doing the same and we are doing that continuous adjustment.

So, in this sense, this continuous adjustment is similar to mode II that we have discussed. In mode I what was the issue? We have adjusted once daily. So, for a single day it has a fixed position. Next day when the declination angle changes then you again change the β or the tilt angle, but you do not do continuous adjustment that is for mode I and for mode II and mode III we do continuous adjustment to ensure the angle of incidence is minimum, ok. So, this is the configuration.

Now, similar to mode I and mode II, what we can do? We can find that under different condition how you derive the equation of β. The β is the one that is changing right, the tilt angle. So, that you can do and from that you can put that β value in the incidence angle expression cos θ expression and you can find out how the incidence angle will vary under different conditions or during the diurnal motion of the sun, ok.

So, for all these different modes, we are not going to do all the derivations. I leave that to you to actually perform the derivations I am going to give you the results, ok. So, one derivation I have shown you for mode I and you will follow you will get the clue from there and you can continue doing that.

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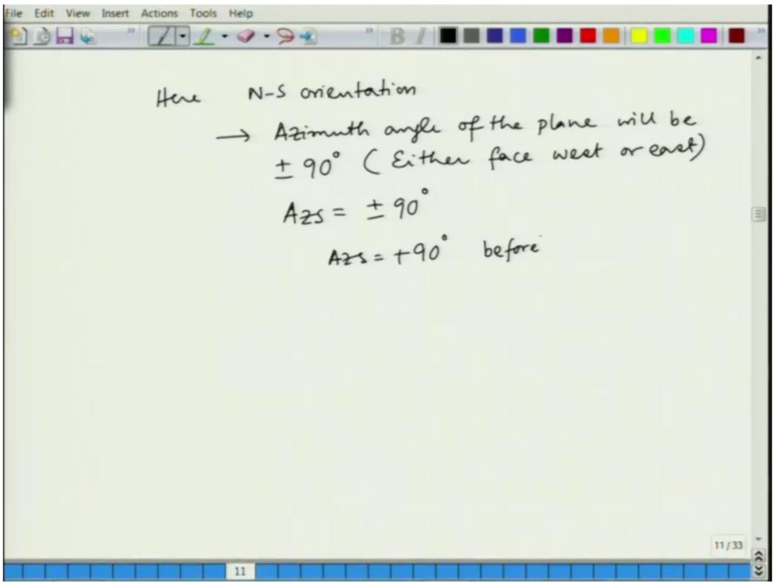

So, here what we have North – South orientation, right. So, if you see that this is the axis, if this is North – South, then the plane that will move to East and West, right. If this is the plane and this is the axis which is North – South and the plane will move to East–West, right.

So, what we can say the azimuth angle of the plane will be ± 90°. What does it mean? It will either face East or West. I should say West or East because plus 90 means it is West, right and minus 90 means East. So, this is the major difference.

In mode I and mode II in both the cases this A_{zs} was 0° or 180°, you remember? If you do not remember, go back to the previous video and look at the distinction because it is very important to actually visualize. You should close your eyes and should be able to visualize how the single axis tracking will work, ok. So, here the major distinction is A_{zs} or the azimuth angle for the plane is ± 90°, ok.

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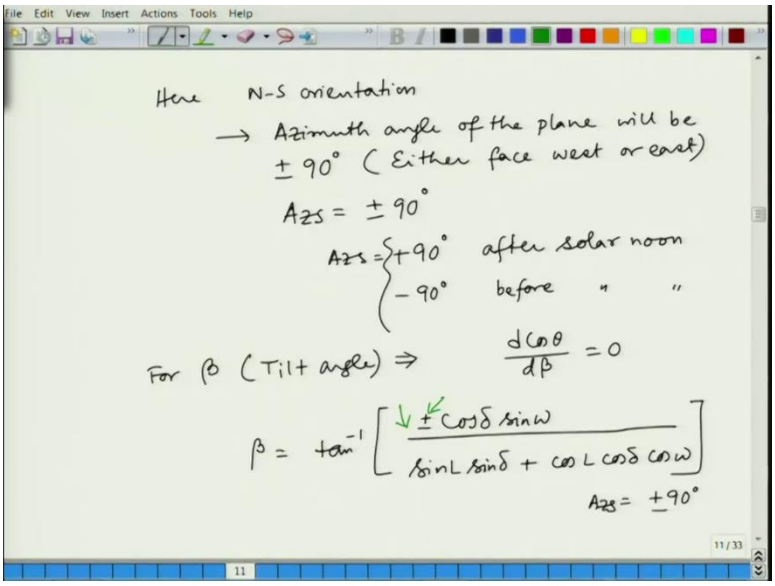

So, when this is 90°. So, I should say $A_{zs} = +$ 90° after solar noon, right because you know sun rises in the East and goes to the West, ok. So, plus 90, that means, towards West the orientation should be after the solar noon, ok and this will be -90 before solar noon in the morning hours, ok.

So, now, for β or the tilt angle, you can derive that again by doing this thing,

$$\frac{\mathrm{d}\cos\theta}{\mathrm{d}\beta} = 0$$

Because you are going to minimize the θ angle (the angle of incidence) with respect to β or the tilt angle. So, if you do that, what you get? You will get this β will be

$$\beta = \tan^{-1}\left[\frac{\cos\delta\sin\omega}{\sin L\sin\delta + \cos L\cos\delta\cos\omega}\right]$$

This you will get for $A_{zs} = +$ 90, and same expression you will get with a negative sign here, ok. So, I should say plus or minus and here correspondingly when A_{zs} or the surface azimuth angle is + 90 °, then you will have a positive sign here and if you have A_{zs} to be minus 90, then you will have the negative sign here, ok. So, that is how β is determined.

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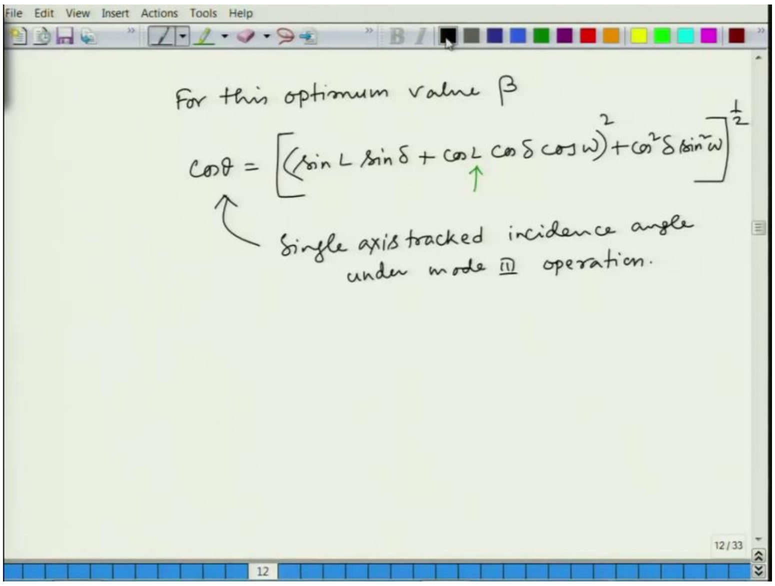

Now, for this optimum value of β we need to know what is the angle of incidence? Because that will tell us what would be the intensity on the tilted surface? right. So, for this optimum value of β, you can show cos θ will be,

$$\cos\theta = \sqrt{(\sin L \sin\delta + \cos L \cos\delta \cos\omega\ )^2 + cos^2\delta\ sin\ ^2\omega}$$

So, this is nothing, but the single axis tracked incidence angle under mode III operation, ok. Now, here you see that it also depends on L, ok. So, in earlier case you did not see the dependence on L it was dependence on the declination and the hour angle right, but in this case you have dependence on latitude or the location of the solar collector, ok. So, that is mode III for you. Now, mode IV is little more interesting.

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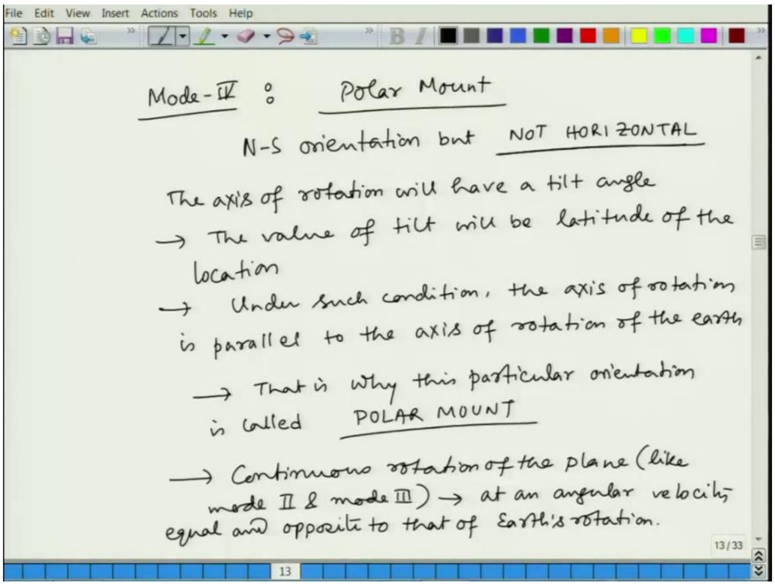

Mode IV, ok and it is often called polar mount, ok. We will see why it is called polar mount and it is also very a widely used option of a single axis tracking system. So, here what is the configuration? We have North – South orientation just like mode III ok, but the axis is not horizontal this is the critical part, ok.

Earlier in all three modes the axis was horizontal your plane can have different tilts, but the axis itself can have the horizontal orientation ok, but in this case, it is not true. So, what would be the tilt angle? So, if it is not horizontal it will have a tilt angle by itself, the axis will have a tilt angle.

So, the axis of rotation will have a tilt angle here because it is not horizontal and that value of tilt will be latitude of the location. It is very interesting, ok. You see that the tilt is location specific, it is the latitude of that particular location, ok. So, why we are doing all these kinds of tricks ok?

So, the idea is, under such condition, the axis of rotation is parallel to the axis of rotation of the earth, ok. You know that the North South axis against which the earth itself rotates that is under a certain tilt with the orbital plane right and that tilt is 23.45°, right.

So, here by orienting the single axis tracking axis of rotation in North – South direction and giving it a tilt of latitude of that location, what we are doing? We are essentially making the angle of the rotation axis parallel to the axis of rotation of earth, ok. So, that is why this particular orientation is called polar mount, polar mount means it is getting mounted parallel to the polar axis.

And, how we are going to move it? And, again like the mode II and III, mode IV will also have continuous rotation of the plane, ok. Just like mode II and mode III, ok and how we are going to do it. The continuous rotation will be at an angular velocity equal and opposite to that of earth's rotation.

So, why do we see the sun to move from morning to evening? Because earth itself is rotating against its own rotational axis, right. So, that is the reason why sun appears to move from East to west. So, earth is actually moving from West to East, ok. So, here we are trying to track the sun. So, we have to give the equal amount of opposite rotation to the collector axis so that it can exactly track the sun all the time during the day, ok.

So, that is why we are giving an angular velocity which is equal and opposite to that of earth rotation, ok. So, this is a very interesting mode of single axis tracking where you have a very simple relation for the angle of incidence, ok.

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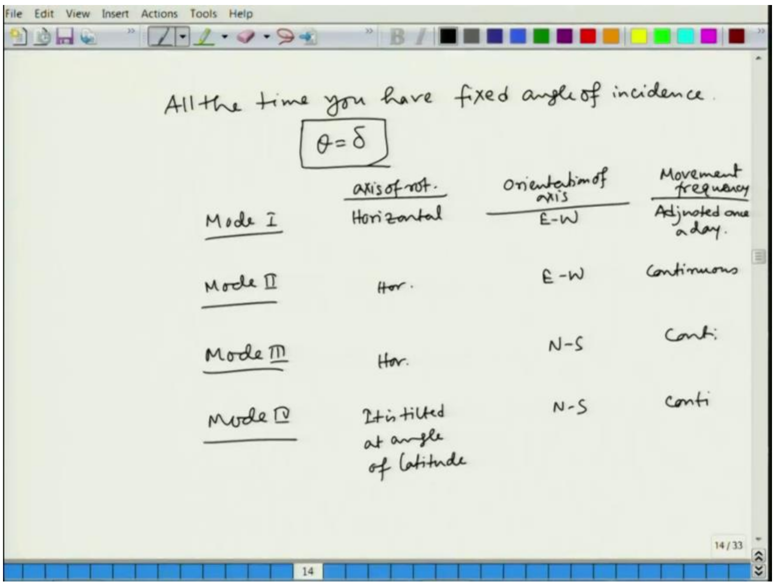

So, here all the time you have fixed angle of incidence which is equal to the declination of that particular day, ok. So, on a particular day you have a single declination value and if you have a polar mount system which is moving the collector in equal and opposite velocity as that of the earth rotation then what you will get? The angle of incidence will be exactly equal to the declination of that particular day.

So, this is the simplest kind of relation and you have a fixed angle of incidence. It is very easy to determine all kinds of intensity plot and everything which is fixed for that particular day, if you have a polar mounted single axis tracking system, ok. So, that is why I give more stress on this one because it is in principle very interesting, ok. So, these are the 4 modes we have covered. So, let me just summarize it once.

So, mode I, mode II, mode III and mode IV, ok. So, all for three modes, the axis of rotation is horizontal, but for mode IV it is tilted at angle of latitude, ok. So, it is a location specific angle of tilt to the axis, ok.

And, now the orientation of axis, in this case it is East – West, for second mode also it is East – West and for the III and IV mode, we have North – South orientation of the rotation axis ok and what else do we have ok? The movement frequency, right. So, for first mode it is just adjusted once a day.

So, for the first, you have only one value for the tilt. And for rest of it they are continuously adjusted, ok. So, this is an overview of what kind of different modes of single axis tracking we use, ok.

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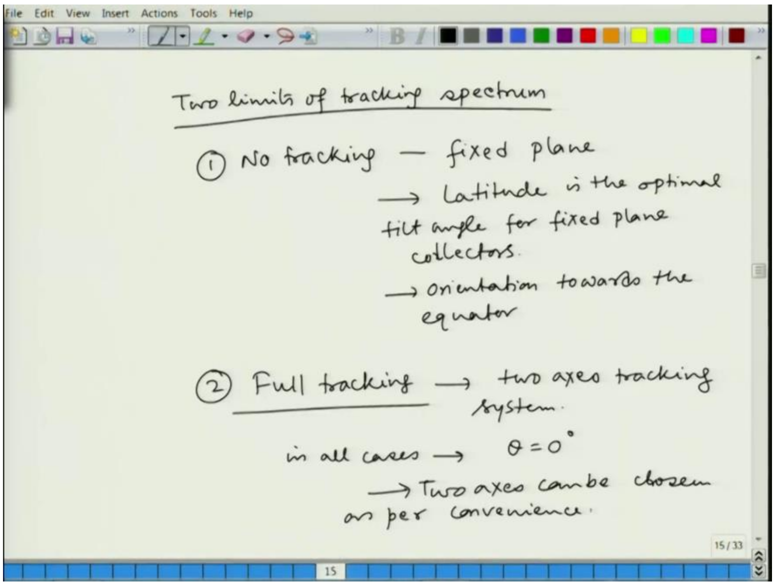

And, as we are saying the single axis tracking, we should also mention in this slot that two extremes- one where no tracking you are using (that is fixed plane).

And, you have seen that most often the solar panels that you see here and there on the different rooftops or the solar water heaters that you see on your rooftop, mostly they are fixed plane ones. And, until and unless you have some industrial setting of solar collector small scale domestic settings, they are all a fixed plane solar collector, ok.

And, there also it is important to note how to choose that particular fixing angle, ok and there what we choose is the latitude that also can be shown. So, that requires a long derivation that you can show to choose the optimal fixed angle for a solar collector maybe a solar panel.

What angle you should choose? You should orient that to the South direction. So, this is for the northern hemisphere. So, basically you orient that to the equator and keep the tilt same as the latitude, ok. Latitude is the optimal tilt angle angle for fixed plane collectors, ok.

So, I am here at Kanpur, for me it will be 26.5° with the horizontal angle, ok. Wherever you are you have to choose the fixed angle to be equal to the latitude and the orientation has to be towards the equator. What does it mean? So, for any location in the northern hemisphere, your fixed angle collector should look at the South direction, ok and latitude will be the optimum tilt angle, ok.

And, in the Southern hemisphere any location, it should always look towards the North direction and again the latitude of that particular place should be the angle of tilt. And, the other extreme of the tracking spectrum is full tracking.

So, whenever you are doing full tracking as we discussed earlier also that we have to have a two-axis tracking system, a single axis cannot give you full tracking. And these two axis you have the flexibility to choose how you are going to move. You can completely follow the diurnal motion in one axis and the declination angle in the other axis, ok.

The North – South which is the declination angle in the other axis or you can have any other combination. So, if you choose that in one axis you are going to do the East West tracking then it will move much faster compared to the other axis because other axis will only change daily and it is also very small, ok.

So, in case of full tracking system, you have to have a two-axis tracking system. So, that means, that those two-axis you can choose any way you want. One option is you can choose one axis to track the diurnal motion of the sun ok; that means, it will go from East to West and if you have like 8 hours of sunshine that you are going to track, all those 8 hours it will move in one direction from East to West, ok.

And, for the other direction, the other axis will rotate in the North – South orientation; that means, it will track the collector by following the declination changes, ok. So, that is one option or any other option of two axis motion you can choose. How much you have to move, at what rate you have to move – these things will change and become more complicated if you deviate these two axis from East – West and North – South.

But, it is possible in principle, and in all cases what is the goal? This incidence angle is always 0°; I mean if it is a perfect tracking system incidence angle will be 0°, if little imperfection is there, it should be as close to 0 as possible ok that is the goal, yeah.

So, I should write here as well that these two-axis can be chosen as per convenience, ok. There is no restriction how you need to choose that. Now, that ends the single axis tracking system and we discussed that if we want just the simple solar radiation that is available to use it for the collection then we need to use either single axis tracking or a fixed plane collector, ok.

But, if we have a concentrating optics to increase the intensity by many folds 1000 folds, 2000 folds, if that is the purpose, then we have to have some concentrating optics and we have to have a full tracking, ok. So, this we discussed.

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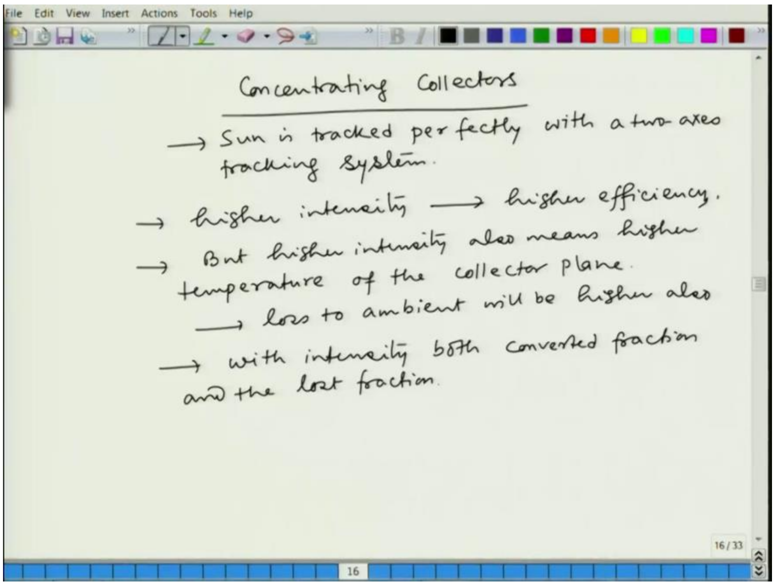

So, now what we are going to do? We are going to start this concentration optics and concentrating collectors. So, here we assume that the sun is tracked perfectly with a two-axis tracking system, ok and we need higher intensity that is why we are doing this concentration ok and that leads to higher efficiency as well, ok.

Higher concentration means larger amount of solar radiation is coming onto a smaller area, ok. So, that leads to higher efficiency, but here we need to note that higher intensity also means higher temperature of the collector plane, right. Now, if we have higher temperature; that means, the loss from that collector plane to the ambient will be higher as well, ok.

So, this means loss to the ambient will be higher also, right and if you have a photovoltaic converter, photovoltaic collector, we will see that if you go high in temperature the efficiency drops. So, if you have a thermal collector there also if the temperature is increased you have higher loss to the ambient.

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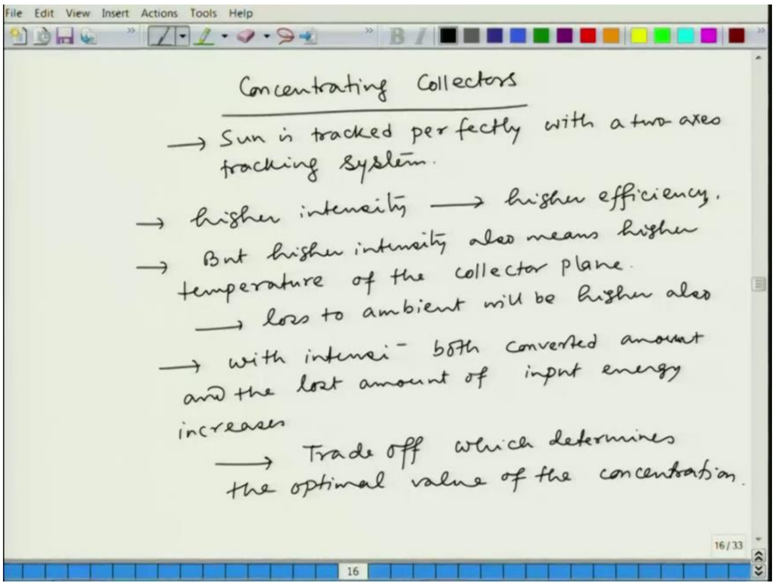

So, with intensity both converted fraction and lost amount of input energy increases, ok. So, what we need to do? We need to have a tradeoff. So, there lies a trade-off which determines the optimal value of the concentration. How much concentration you need? If somebody asks, then you have to know how to choose that optimal concentration value, ok.

So, that is the first general idea I am trying to impart. Now, when we know the optimum value, there also we should know how much maximum value we can get, ok.

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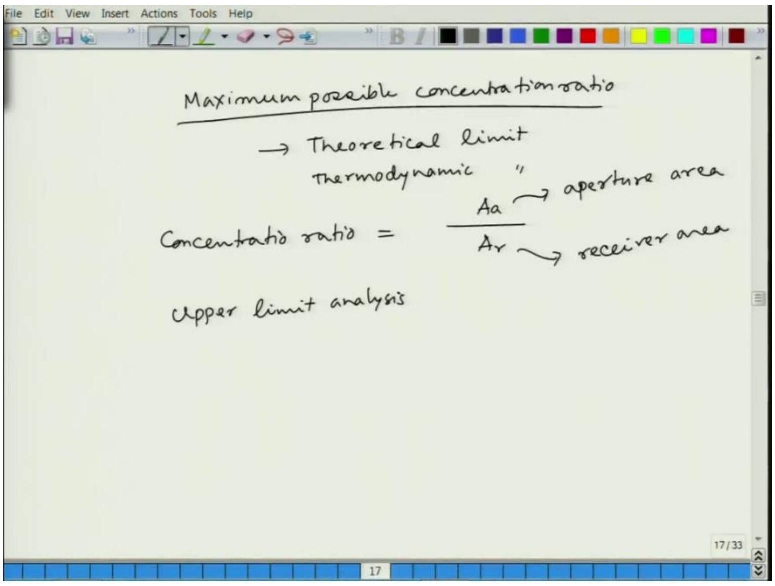

So, maximum possible concentration ratio it is important to know for any particular system what would be the maximum possible value that we can try or we can achieve. So, that is called the theoretical limit or we also call it thermodynamic limit. What it tells us that the maximum possible concentration ratio that we should try to achieve. Here I am using this term maximum or optimum.

So, I should first define it what is a concentration ratio. Concentration ratio is nothing, but the aperture area divided by the receiver area, ok. This is the aperture area which means the area which is allowing the sun rays to come into the system that is the aperture and the receiver area the effective area which is actually doing the conversion process, ok. It may be a photovoltaic chip or it may be a black painted plate which is absorbing the solar heat, ok.

So, the ratio of aperture area and the receiver area is our concentration ratio. So, if you have a large aperture and a small receiver then your concentration ratio is higher, ok. So, now, we are going to do this upper limit analysis.

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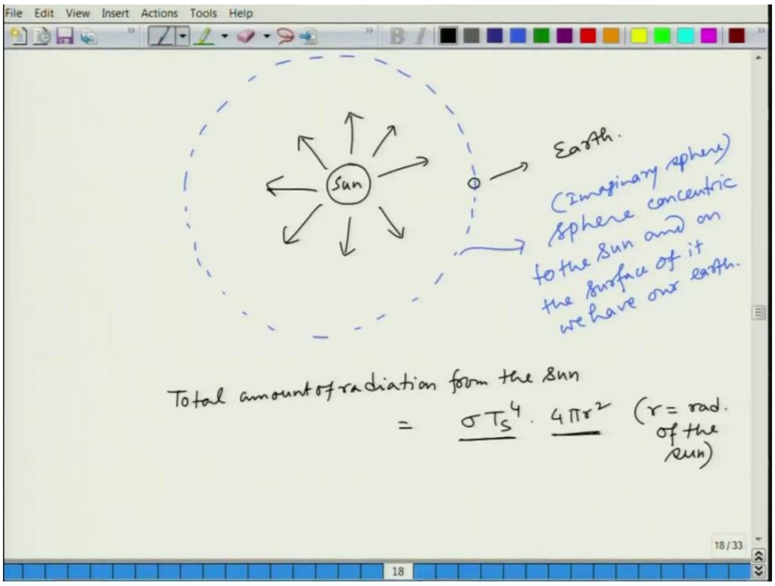

So, let us say we have the sun here and what it does? This is the sun, what it does? It is radiating equally in all directions. It does not know where earth is, it does not know where anything else is, it is simply radiating equally in all directions, right. Now, there happens to be an earth which is lying somewhere here in a long distance.

So, now let me draw the earth little closely, ok. So, let us say this is the earth. Now, if you think of a sphere on the surface of which the earth is residing, ok and the sun is at the center of it. So, this is the sphere concentric to the sun and on the surface of it we have our earth, ok. So, that we can imagine. This is of course, an imaginary sphere, ok.

Now, you can think of the amount of radiation. So, total amount of radiation from the sun whatever the sun is radiating and that is the Stephen Boltzmann's constant multiplied by the effective surface temperature of the sun multiply to the power four, right and this is happening for the whole of sun, that is $4\pi r^2$ and r is the radius of the sun, right.

So, this is per unit area, it is radiating. And this is the total amount of area of the surface of the sun, ok. So, that is the total amount of radiation from the sun.

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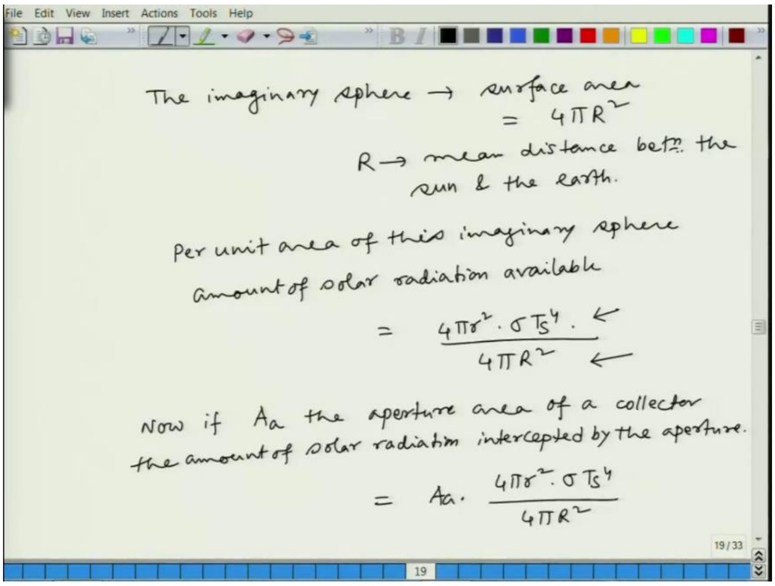

Now, you can think of the imaginary sphere, what is the area?

$$surface\ area = 4\pi R^2$$

where this R is the mean distance between the sun and the earth, right, that is the total amount of area.

So, per unit area of this imaginary sphere, the amount of solar radiation available is nothing, but the amount that is getting radiated from the sun,

$$Amount\ of\ solar\ radiation\ available\ = \frac{4\pi r^2 . \sigma T^4}{4\pi R^2}$$

So, numerator here is the total amount of radiation coming out of the sun and you are dividing it by the total amount of surface area of that imaginary sphere. So, this is the ratio that tells us that per unit area of that imagine sphere we have this much amount of solar radiation available, is it not?

Now, if A_a is the aperture area of a collector, then how much of this available solar radiation will be intercepted by this aperture area? So, the amount of solar radiation intercepted by the aperture is nothing, but the ratio that we just obtained in which is per unit area multiplied by the aperture area, right.

$$amount\ of\ solar\ radiation\ intercepted\ by\ the\ aperture = A_a . \frac{4\pi r^2 . \sigma T^4}{4\pi R^2}$$

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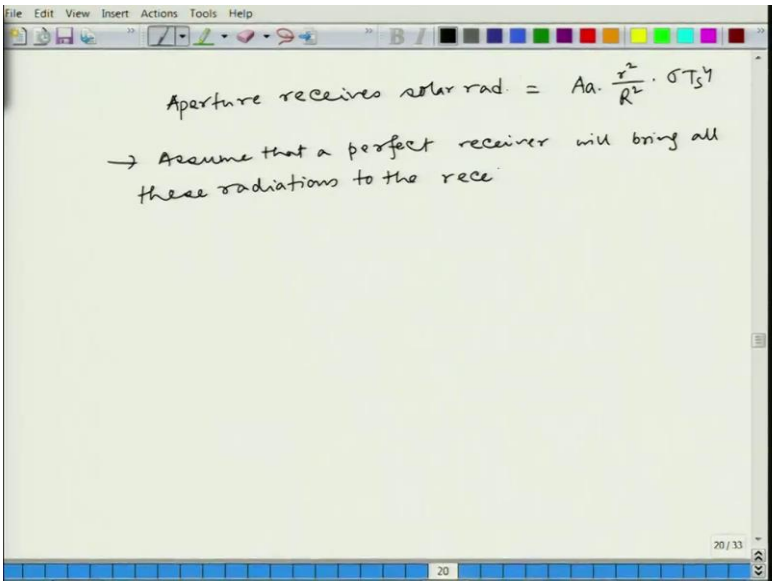

So, the aperture receives solar radiation how much? That is $A_a . \frac{r^2 . \sigma T^4}{R^2}$. So, that is the amount of solar radiation received by the aperture.

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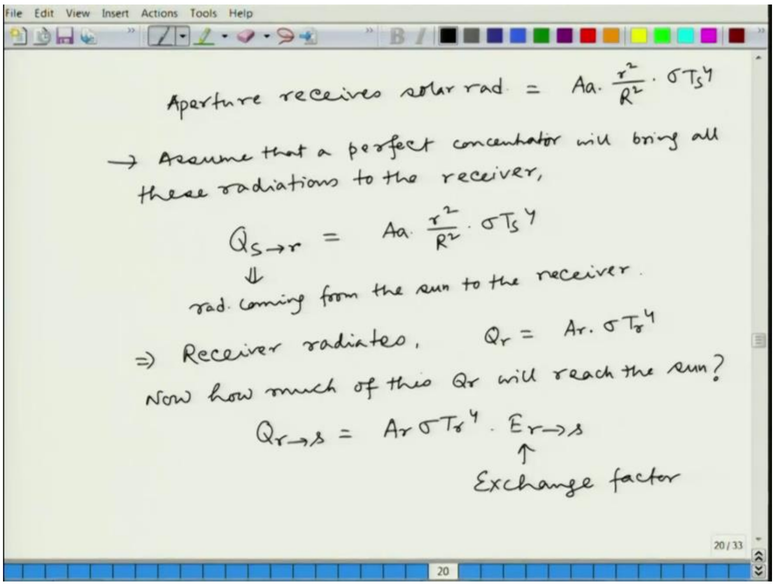

Now, assume that a perfect concentrator will bring all these radiations to the receiver, right. So, it will not allow anything that is coming on to the aperture go waste right, a perfect concentrator will bring everything to the receiver, ok.

So, in that case we can write the heat that is coming from sun to the receiver, s-r that is this total amount of radiation that aperture receives right, ok. This is radiation coming from the sun to the receiver. So, perfect concentrator will not allow anything to go waste, ok, clear?

Now, you come to the receiver and think of a situation where the sun and the receiver are exchanging radiation, ok. That is what is happening from sun to receiver. What is the radiation that we have quantified? Now, if receiver radiates, what would be the quantity that will be the total receiver radiation that will be,

$$Q_r = A_r . \sigma T_r^4$$

where A_r is the area of the receiver, T_r is the temperature of the receiver (absolute temperature)

Now, how much of this Q_r will reach the sun that is a legitimate question to ask, right? The sun radiates and a fraction of that is getting radiated to the receiver. Now, the receiver also is radiating and a fraction of it will reach the sun, ok.

So, let us say this Q_{r-s}; that means, from receiver to the sun we have. This is the total that is coming out of the receiver and we have a fraction E_{r-s}, that we do not know what fraction is that, but let us say that is an exchange factor you can also call it a view factor, ok. So, this exchange factor which tells us how much of the receiver radiation will reach the sun.

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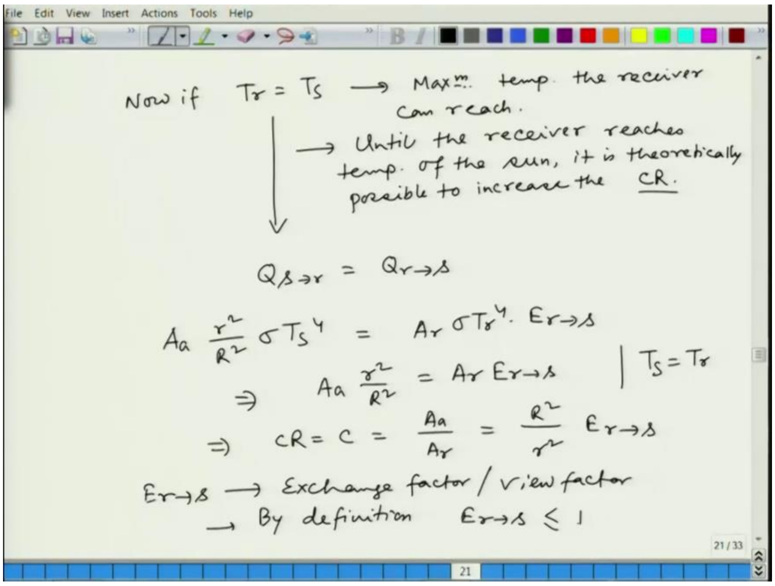

Now, if $T_r = T_s$; so, if receiver reaches the temperature of the sun that is the maximum point of your concentration, it cannot go further. So, this is the maximum temperature the receiver can reach by exchanging or getting heat from the sun, it cannot go beyond that. So, until the receiver reaches temperature of the sun, it is theoretically possible to increase the concentration ratio, I am going to abbreviate with CR, ok.

So, that is possible, I mean practically whether you will be able to do it or not is a secondary matter we are now trying to see what is the theoretical limit of this, ok. So, practically you need certain material which can withstand their high temperature and there is none, ok.

So, if these two temperatures are equal then,

$$Q_{s-r} = Q_{r-s}$$

The radiation that is coming from the sun will be equal to radiation that is coming from the receiver to the sun. So, now, if you put the values that you have determined. This is the value for Q_{s-r} and this is the value you determine for Q_{r-s}.

Now, you can simplify it by removing the common terms here the assumption is $T_s = T_r$. So, you could remove the $\sigma {T_r}^4$ and $\sigma {T_s}^4$, ok. Now, what is CR or C if you can say it is,

$$C = CR = \frac{A_a}{A_r} = \frac{R^2}{r^2}.E_{r-s}$$

So, now, this E_{r-s} is what? This is the exchange factor or view factor between the receiver and the sun and by definition it is less than equal to 1, it cannot be more than 1, right.

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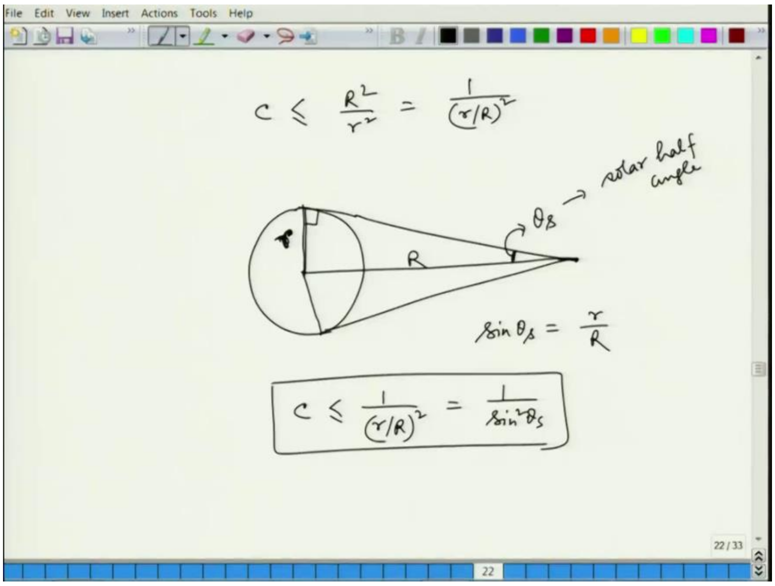

So, what we get?

$$C \leq \frac{R^2}{r^2} = \frac{1}{\left(\frac{r}{R}\right)^2}$$

Now, if you see this this is the sun and this is the aperture area. So, this is our r; that means, the radius of the sun and this is our R, and this angle is 90 °.

So, what you can write this angle which we call θ_s or the solar half angle. So, the solar half angle,

$$\sin\theta_s = \frac{r}{R}$$

So, what we can write,

$$C \leq \frac{1}{\left(\frac{r}{R}\right)^2} = \frac{1}{sin^2\theta_s}$$

So, that is the theoretical limit of concentration ratio. This concentration ratio cannot go beyond $\frac{1}{sin^2\theta_s}$; θ_s is the half angle, ok.

So, let us stop here and we will discuss about it again in the next class. We will discuss it and again we will see if we have a 3-dimensional concentrator or the 2-dimensional concentrator how that will affect the theoretical limit in the next class.

Thank you for your attention.