Solar Energy Technology
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Lecture - 19
Concentrating Collectors

This lecture, so this lecture deals with Concentrating Collectors. Before we go ahead with the concentrating collectors, one or two topics that were left out in the previous lecture are in connection with flat plate collectors or in fact, some of them are common to concentrating collectors also, we will deal with it.

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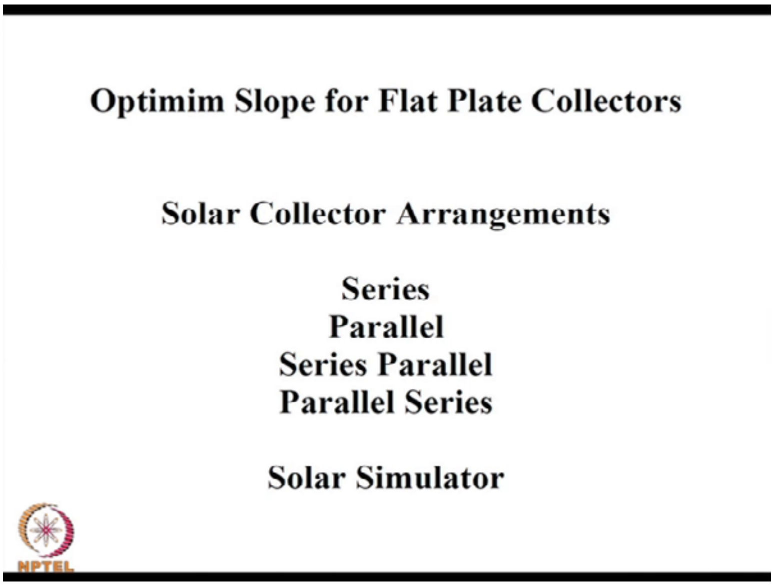

First, we discuss the optimum slope for flat plate collectors; the best way is to calculate the total radiation received by the collector in the year, even based upon the monthly averages. And depending upon your objective, you maximize the total radiation received over the year or whatever is the application that demands.

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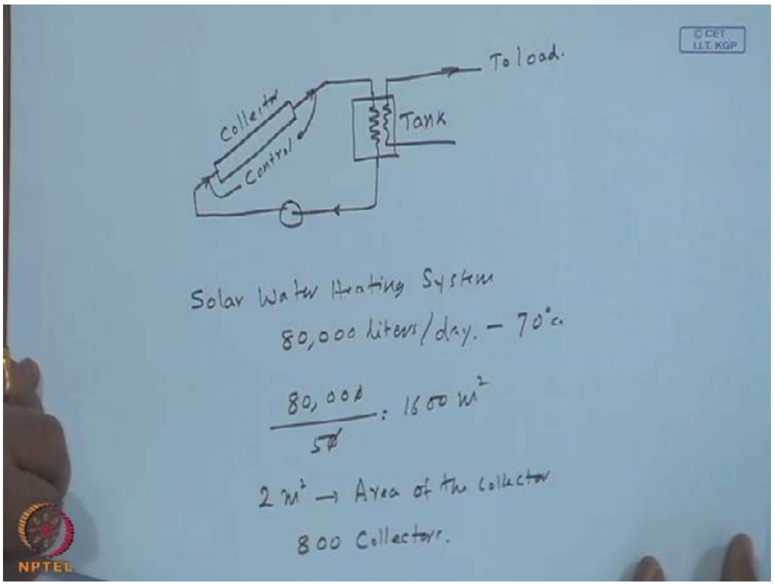

Now, the other thing, when we talk about a single collector, in a class room type of situation or it may be going here into a tank and it may be re-circulated through a pump, through this. We can say here is a sort of a heat exchanger, very simplified system diagram, this is the collector, still if I want, I may have a control, which ensures that the exit temperature is higher than the inlet temperature from here, I may take it to the load.

So, there is no heat exchanger I can assume, effectiveness to be unity, that will come to about it is simulators, simulation later. So, it is very nice to talk about one collector and then, also people say, why not we use the optimum angle every month, change it once a month. So, it may not be a very bad idea but, now imagine a solar water heating system something like let us say, 80,000 liters per day.

I am not exaggerating or I have no larger systems than this, which I will mention a little later, supplying energy at about 70 degree centigrade. So, this will require approximately if I am may say, so 80,000 divided by 50, that comes to 1600 meter square. At 70 degree centigrade, I am assuming 1 square meter collector area will deliver about 50 liters per day so, this comes to about 1600 meter square.

So, if you take 2 square meters as the area of the collector, there will be 800 collectors, all of them connected to each other. So, it is not a easy thing to change a slope every day and every month consequently, depending upon the application, we find the optimization that is, what we were trying to say in the earlier topic, that we considered. Now, the solar collector arrangements, how do I connect these 800 collectors or just let us talk about a less number, for the convince of drawing may be 12, 13, 9 or 16 collectors.

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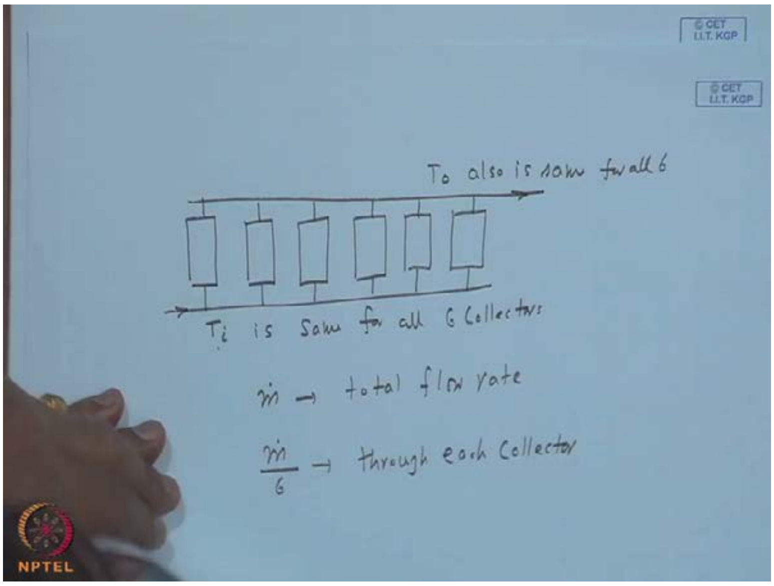

One way is, I will take it for the time being just 6 collectors, so let us say, there is a large header connected to this, connected to this, connected to this and all the 6. Then, again the delivered hot water will come out through these 6 collectors and I have some sort of a pressure balancing.

So that, the flow through each collector is uniform in addition to the headers and risers that, we discussed providing uniform flow in the collector, this is one arrangement. So, T i is same for all 6 collectors and similarly, T o also is same for all 6 where, assuming that, there is a uniform flow rate and all the collectors are same efficiency consequently, nevertheless, it will enter at T i and come out with T o. So, the flow rate, if this is m dot total, we have got m dot upon 6 through each collector, so the corresponding the pressure drop will be that, due to m dot by 6.

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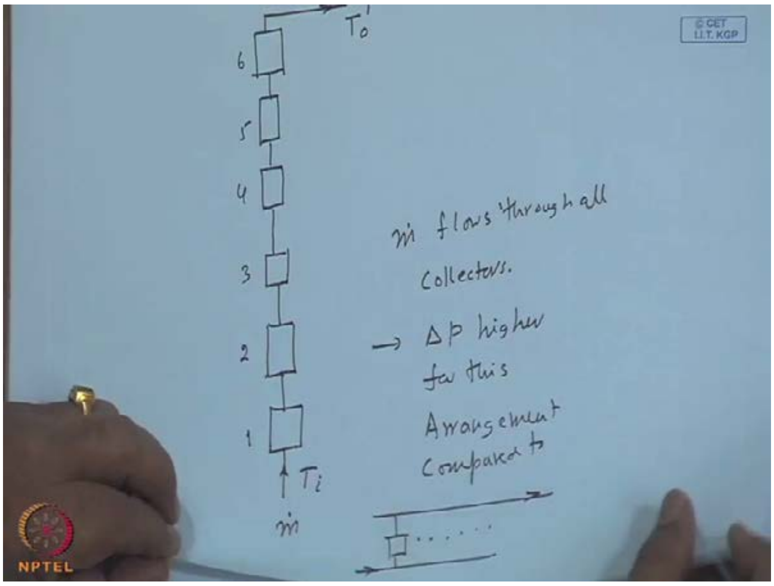

Instead, I will have the arrangement like this, they have become little smaller because, I have to adjust it in the height of the paper, in the landscape mode, one more, that is it. So, this enters at T i, in general this may go out at T o dashed, which may be different from T o, when they were all in parallel, this is collector number 1, 2, 3 and 6, m dot. So, m dot flows through all collectors, so this has got the advantage of a uniform flow rate perhaps better maintained through all the collectors.

But, a 6 times of flow rate will be going through each collector, so I can expect delta P higher in this arrangement, for this arrangement compared to a parallel, whatever we have discussed earlier. So, we can see that, this is one extreme and this is another extreme, this has got the little bit of disadvantage of poorer heat transfer and less higher chance of non-uniform flow rate. The last collector imagine 800 collectors, we may not get the same flow as the first one, whereas here the pressure drop is higher.

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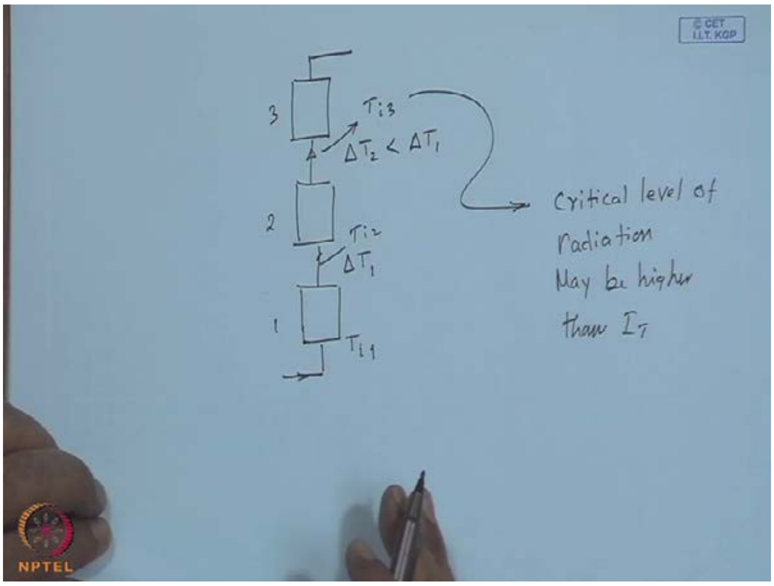

One more thing, which is often ignored or not really taken into account, when you have got series collectors, again we will discuss in little bit in detail, when we consider the critical radiation level. Let us say, this is T i and this adds the delta T 1 and this adds a delta T 2 obviously, less than delta T 1 since this is at a higher temperature and hence, higher loses. So, technically the efficiency of each subsequent collector will be lower than the previous one now, it so happen, may so happen that, this T i 3 , this will be T i 2, this i may call it T i 1. So, T i 3 is much higher consequently, the so called critical level radiation may be higher than the solar radiation falling on the collector.

In other words, a stage will come where, the last of the collectors may not be able to provide further heating to the fluid that, they receive. So, this is one danger, one has to wrecker with, when the collectors are in series compared to in parallel bottom.

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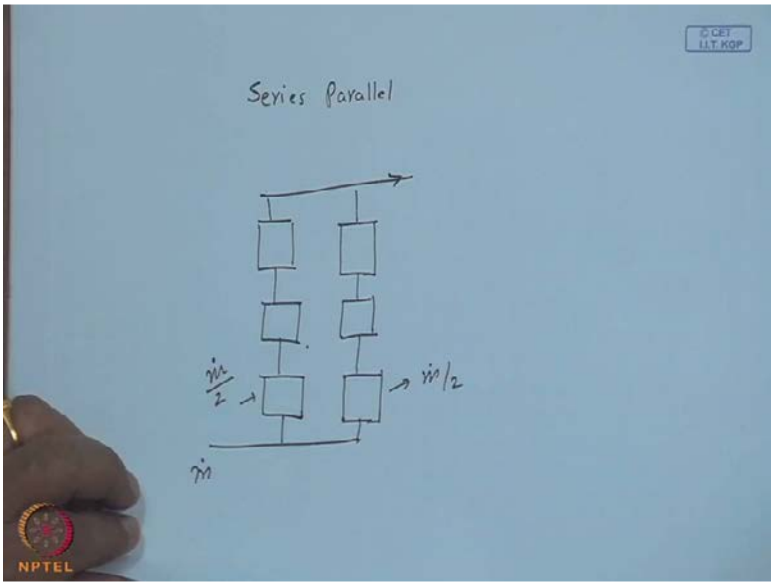

So, one can think of a combination of these things, series, we have considered parallel, we have considered and series parallel. So, 3 collectors over here, they are in series and they are in parallel with another 3 collectors that means, my original six collectors have been connected like this. So that, if this is my m dot, this will have m dot by 2, this will be having m dot by 2.

Compared to m dot, had they been completely in series, you know that, the pressure drop is highly non-linear with the flow rate so, there will be a significant reduction, if you make it a series parallel.

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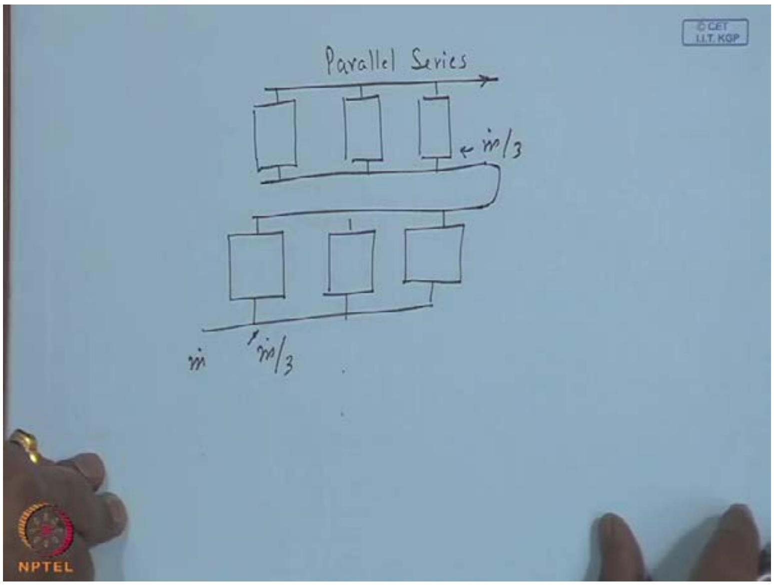

The other variant could be parallel series though, technically they are distinguished but, the idea is the same these are in parallel then i have so, this is. So, it is a question of, I have deliberately chosen 6 so that, I can make 2, 3 of them in parallel with 2 series and 3 of them in series with 2 parallel called a parallel series or series parallel. Now, it is very difficult to say, which one have a higher pressure drop but, you can see that, the total flow rate is m dot. But, through each will be m dot by 3 and here also, m dot upon 3, compared to m dot upon 2 in the previous case 2, 3 collectors. So, i can expect, this to be having a lower pressure drop though, one has to worry about the additional piping that, this may require.

So, these are the issues, when you talk about not a single collector like in the class room, we have a larger system supplying thousands of liters of water, which may have 2000, 3000 square meters of area, of collector with about 1000 to 2000 collectors, of each 1.5 to 2 square meters of area. For n number of divisions say, one has to connect in parallel or in series, or series parallel combinations.

If they are all in series, first of all the land area geography or topography has to be something of course, not that I cannot put it side by side and still make it series but then, the one has to worry about the losses through the pipes also. Apart from the land restrictions, one has to really work out through a simulation or a calculation procedure, what gives you the optimum heat transfer enhancement or advantage these are the additional pumping requirement.

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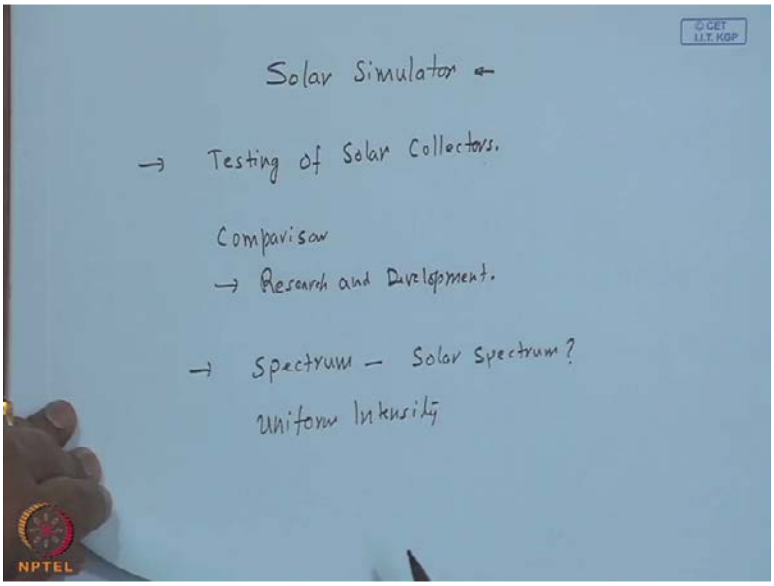

Then, I will just touch upon a solar simulator, this is for testing of solar collectors of course, one can go ahead and do the outdoor testing. But, no matter, how careful one can be, the conditions cannot be identical, when the tests are conducted on different days. So, if you want to compare two designs then, outdoor testing, if the difference in the efficiency is 10 percent, 8 percent, one can take cognizant of but then, if it is 1 or 2 percent, the uncertainties owing to the different climate conditions may be larger than the difference in the efficiency that, it is shown.

Consequently, it may be a little tough to take a decision about, which collector is superior in case, apart from the class consideration, one is 37 percent tested in February and the other is 39 percent tested in summer, i really have no idea, which one is really superior. So, it is, it is very difficult to assess that type of a small defects 30 to 40 years, the difference may not be 10 percent but, the higher one is likely to be higher.

So, for comparative purposes, number one you can say, for comparison and for indirectly research and development, after all you propose 2 or 3 designs, you test it under identical conditions and come out with this, this design is better than the other. Then, invariably solar simulators are used in addition to the advantages, that not only you can have a controlled solar radiation, it can be done indoor and it can be done all the 365 days of the year or without worrying about rain, high wind or any cloudy condition, etcetera.

If you consider or account for all these things, you may not have more than 200 days of clear days, of less than that, in fact to test a solar collector under the recommended testing conditions. So, solar simulator could be a alternative but, the compromise is spectrum, will the solar simulator give the solar spectrum that is, question number one. Secondly, uniform intensity, after all though the sun is at a large distance from the earth, the size also is pretty large and intensity of the solar radiation on collector is can be expected and is uniform. Whereas, if you have a solar simulator, depending upon the distance, from which you keep the solar collector and the simulator, you may have a difference in the intensity on the collector surface.

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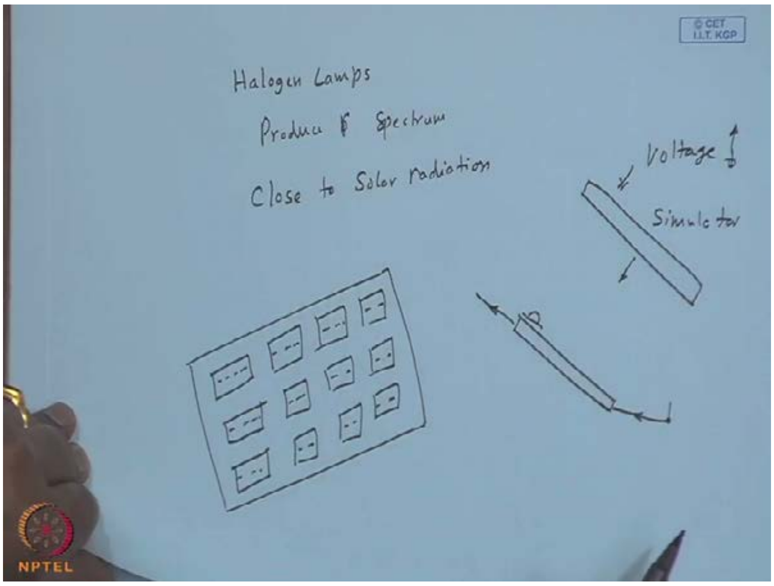

So, usually halogen lamps produce a spectrum close to solar radiation so, one can think of a bay of halogen lamps or Philips makes them in India, may be you may have about 12 or 14 as the case may be. And you arrange them at distance, best decided by trial and error, each one is about may be a 1 kilo watt. So, simpler element can be made that, the angle can be changed, this is the one, you may keep your collector parallel to this, with your of course, flow and other instrumentation. This is your simulator and you use a pyranometer on the collector surface and ensure, whether the intensity is uniform or not.

And if it is within plus minus 5 percent or so, it is ok and you can bring down if necessary, move it nearer, if you want a higher intensity, move it away that is, one way or change the voltage. Voltage applied through a variac can be up or can be down of course, within 220 volts supply limitations and then, you can go down to 100 and then, once again the problem is that, of the spectra. If the voltage is lower, it may not produce the same spectrum as that at the fluid but, simulator results can be depended upon to the extent of establishing relative performance of different collectors.

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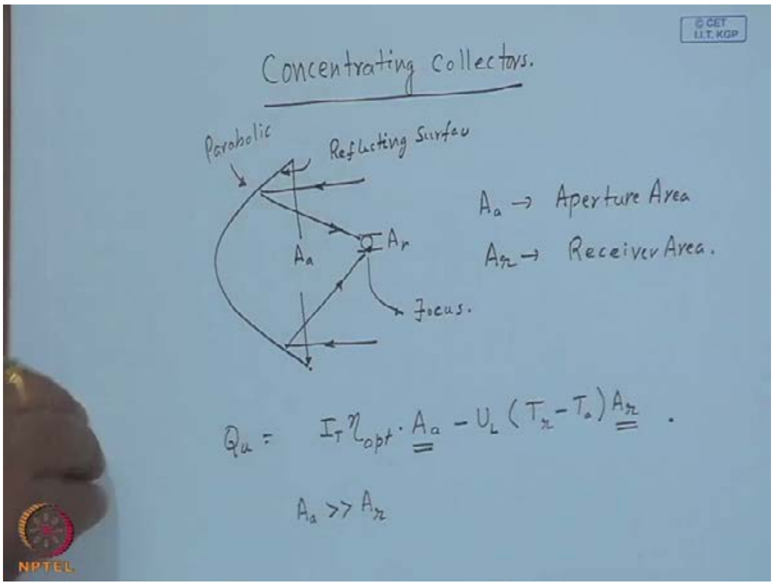

So, we go on to the next topic of concentrating collectors so, we explode improving the efficiency or the operating temperature for the flat plate collectors through 1 or 2 or more glass covers, platter insulation and even evacuation though, it may or not be practicable or to have a completely evacuated flat plate collector. So, the next idea is to have, what we call concentration and the very early type of concentration, you can see it in the form of mirror boosters.

So, if you have, I will first give you the configuration so that you will understand the whole idea suppose, i have a parabola, this is a reflecting surface and this is a focal point. So, all there is falling on the reflector, will be reflected on to this now, to fix the idea let this be A a, i will give you the name. Let this projected area be A r, A a is the aperture area and A r the receiver area so, whatever radiation is received by this aperture, is reflected on to A r.

Now, if i write the energy balance Q u should be equal to I t times some optical efficiency, i will call it for the time being, times A a. So, my solar radiation I t is based up on the unit area of the collector or the aperture area sorry minus the looses that, will be taking place from the receiver at temperature T r and the ambient temperature T a multiplied by A r.

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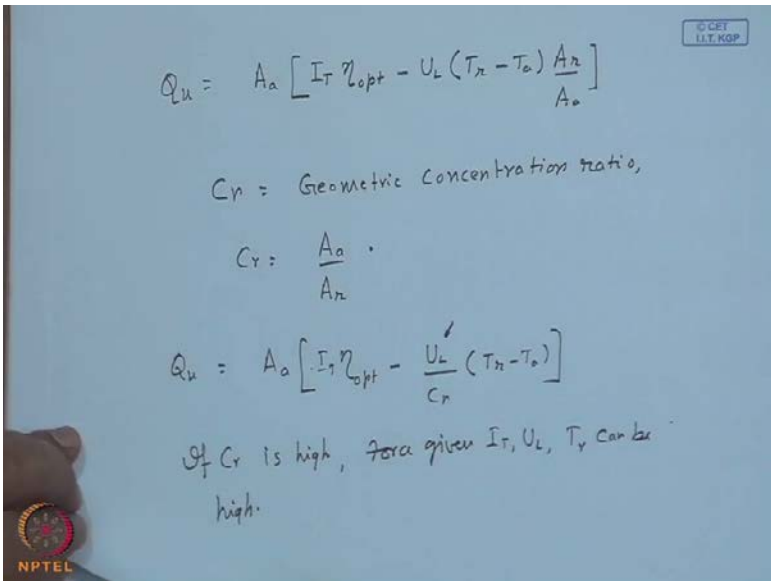

Now, the collection is through A a and the losses are through A r, which A a is let us say, much greater than A r. So, now, if we try to write it per unit area or write in the standard form, I can write it as A a times I t eta optical minus U L times, T r minus T a times, A r upon A a. Now, if I define C r, a geometric concentration ratio A a by A r so, Q u can be put in this particular form, A a times, I t eta optical minus U L by C r times, T r minus T a.

Now, this clearly shows, if C r is high of course, it is greater than unity in order that, there is concentration and not diffusion. If C r is high, I can have for a given T r can be high, if you compare with a flat plate collector, if i choose this concentration ratio as something like 10, i may have a delta t 10 times larger, for a given U L at the corresponding critical level. So, this is essentially, increasing the effective intensity of solar radiation on a receiver area, A r collected from an aperture area A a.

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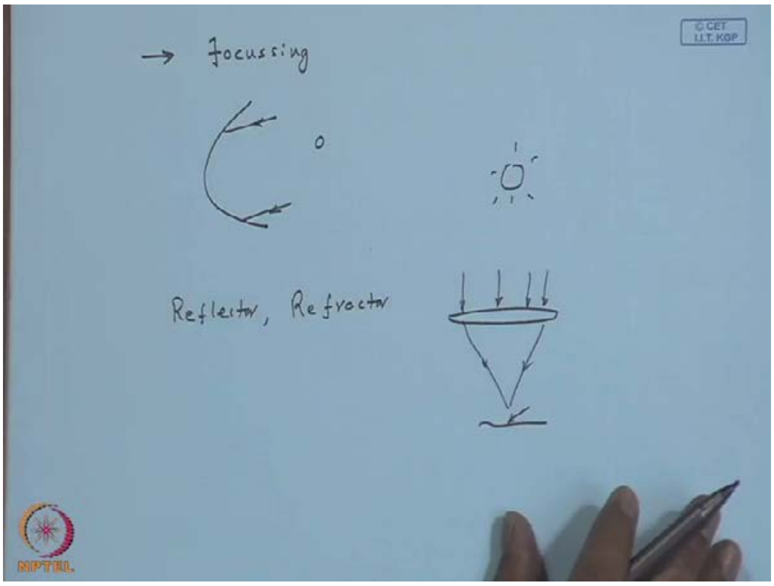

So, this receives what you need is, focusing so, the solar radiation that is coming on to this parabolic reflector should be always parallel to its axis. Otherwise, it will be not be concentrated at the receiver where, it is kept at the focal point so, this also can be done with a reflector, as we have discussed R with a refractor. Many of us might have had experience in trying to burn a paper with a convex lens and sun's rays childhood and then, paper and it gets burnt because, all these rays are concentrated at a finitely small area.

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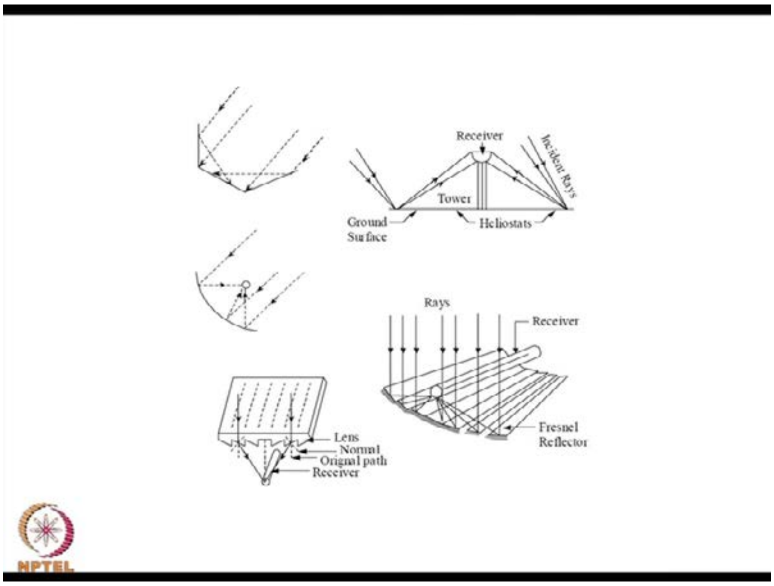

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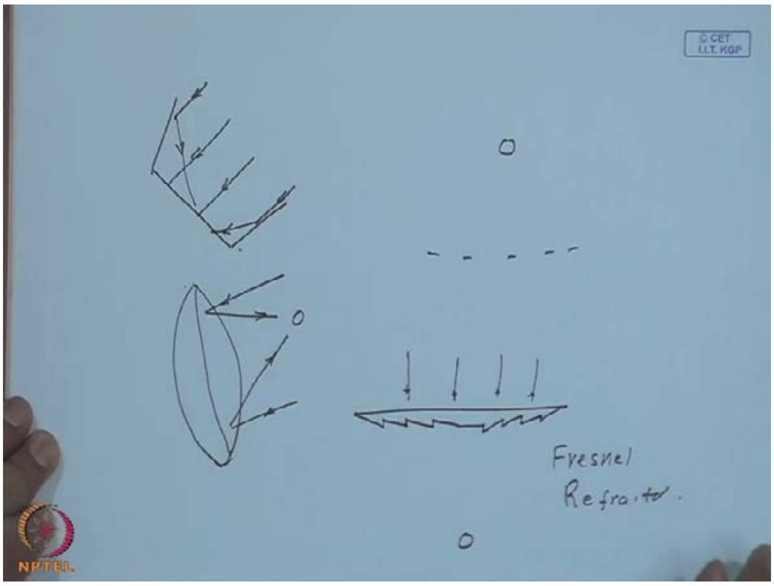

So, here are certain pictures that, will show you different concentration methods, the first one is almost like the mirror booster, which we have discussed. Basically these two are the boosting surfaces, which will come over here, this will directly receive and this will be reflected, this will be reflected onto this. And of course, which we have discussed, this parabolic or it could be even a paraboloidal, if you see the dish antenna, it will be of the same shape. And here is the focal point and the sun's rays coming onto this, it will be reflected on to the receiver.

So, when the size is a limitation people have, you can see a heliostats, smaller mirrors or lenses focusing onto a central receiver, so that breakage of one does not bother the remaining ones. So, you can have a finer lens that is, essentially something like this at k micro Grosse, this may be up and then, what is it gook. So, whatever is through the…

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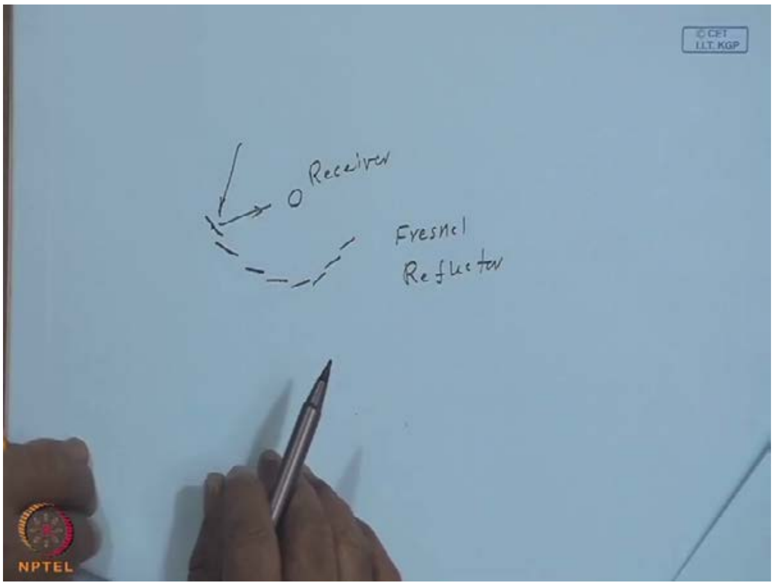

Similarly, you can arrange even the mirrors like this and on to a central tower so, so you have sun's rays reflected on to this. Now, the advantage of this type of smaller reflectors, as we have shown in the case of heliostats or this fresnel reflector. Each one of them can be tilted depending upon the sun's position so, this is a receiver, not to get confused with the sun. So, you need some sort of a orientation or tracking of smaller pieces of reflectors than one large piece.

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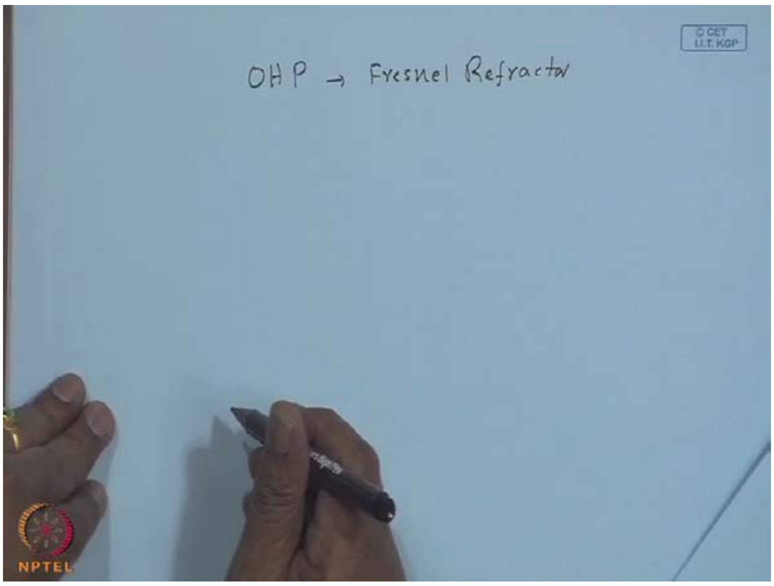

And let me ask a question, can you give me any device where, there is a fresnel refractor your OHP, over head projector has a fresnel refractor. If you look through the top of the over head projector, you will find something like your high school experiment of a newton's rings that is, a fresnel lens that is, with a die minutely varying angles of groove that will make the focus and then, reflect the object or the paper that, you place on the over head projector.

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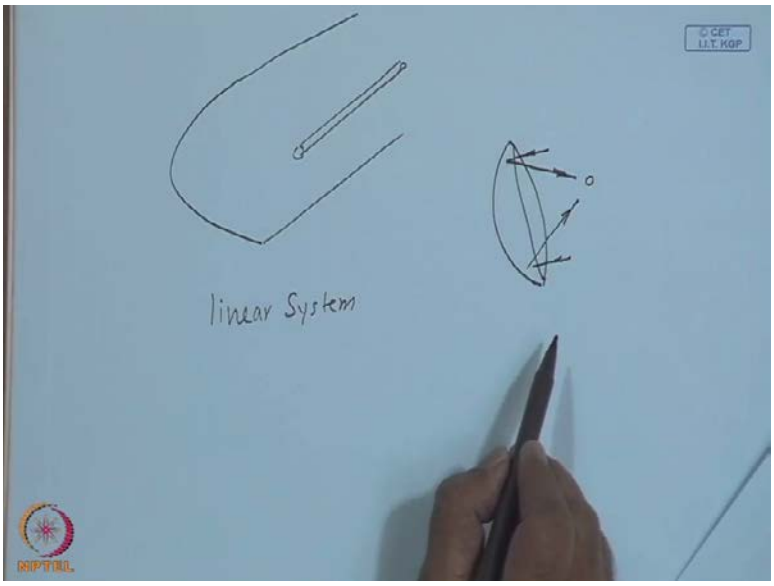

So, if I have something like a parabola so, in a two dimensional view something like this, this will be my tube. So, I might call this a linear system in other words, in the limit the reflected rays will fall on a line though, that width of the line is finite for different reasons. So, parabolic reflector comes into the first category and the paraboloidal in the second category, this in principle is a point though, that point is finite, being sun casting a finite disk size, I cannot have anything smaller than a particular size by virtue of the sun subtending an angle of 27 minutes at the earth surface.

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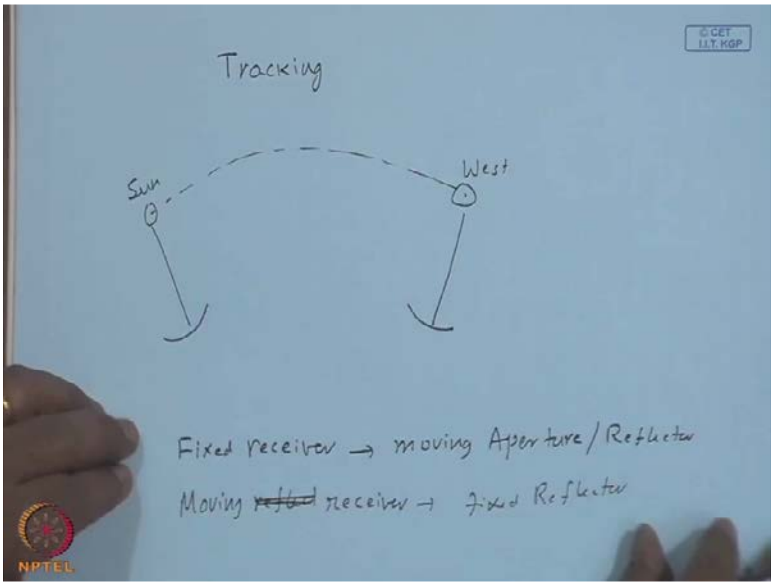

Now, so far so good but then, I have to see that, the rays are parallel to the reflector axis so, this requires continuous tracking that means, my collector as the sun goes from east to west, my collector should turn from here, it does not move but, just to emphasize this is here and this is here, normal the aperture plane. So, this has to turn from east to the west, whatever may be the angle that, we do not know still so, this requires tracking otherwise, it does not work. So, you may have a fixed receiver and a moving aperture that means, the reflector or you may have a moving reflector, moving receiver sorry I am writing only on the other side and a fixed reflector.

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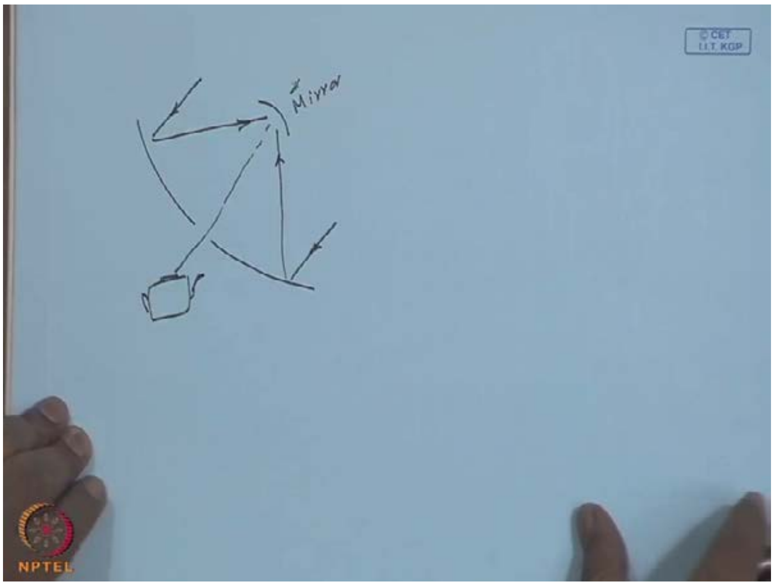

And there is one more configuration one can think of so that, one does not come in the way of reflected sun's rays let us say, it is a paraboloidal and this is a mirror, this is also a mirror. They will be reflected onto this mirror and it will come over here then, you may have a pot, may be a tea kit. So that, when you are handling this, you are not in the path of the sun's rays otherwise, you look here, it could be quite serious.

So, ideally, if I want to follow the sun's rays all the time, my reflector has to have a two axis tracking from east to west and keep rotating up and down, because the sun goes from east to west along an arc and that, arc angle depends upon the season right. So, if you have a surface, you will be going from let us say, east to west in that process, it may be also swiveling in order that, the sun's arc will be in the plane normal to the aperture.

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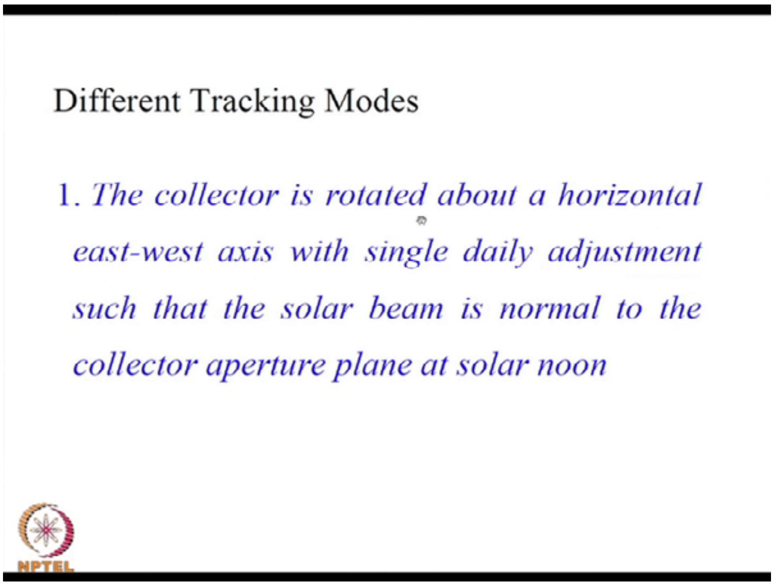

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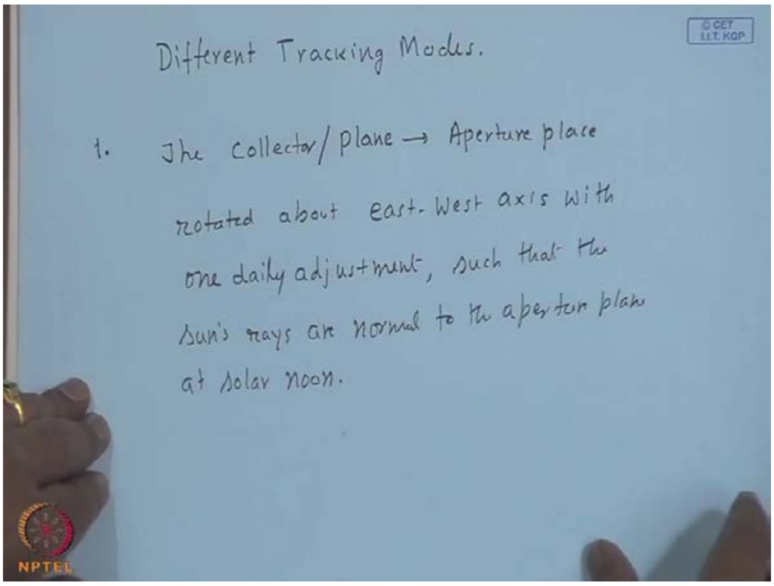

Now, we will consider different tracking modes so, mode one, the collector or we shall in future differ it as the plane, which essentially means the aperture plane. Because, whether it is parabola or paraboloid, whatever is the radiation passing through the aperture plane, will reach the reflector there by getting reflected or the refracted to be refracted. So, the collector or the aperture plane rotated about east west axis, with one daily adjustment such that, the sun's rays are normal to the aperture at solar noon so, this is only one adjustment per day simplest.

Though, we will see whether that is sufficient or not, for what kind of concentrating collectors, this will do the job. So, if you want me to demonstrate it let us say, this is the aperture plane, there is a parabola behind it or to my left is the east and to my right is the west. So, I make one simple adjustment per day that means, the slope beta is chosen such that, sun's rays are normal to the plane at solar noon.

If for example, in December when the sun's rays will be pretty low, I will have a higher slope and in summer it will be steep sun so, I may have a lower slope. So, it becomes nearly near in the horizontal and nearly vertical in winter depending upon of course, the latitude. So, the idea is, this is the aperture plane, to my left is the east, to my right is the west and then, I will tilt it like this change the slope of this plane such that, the sun's rays are normal to the plane at a solar noon something like this.

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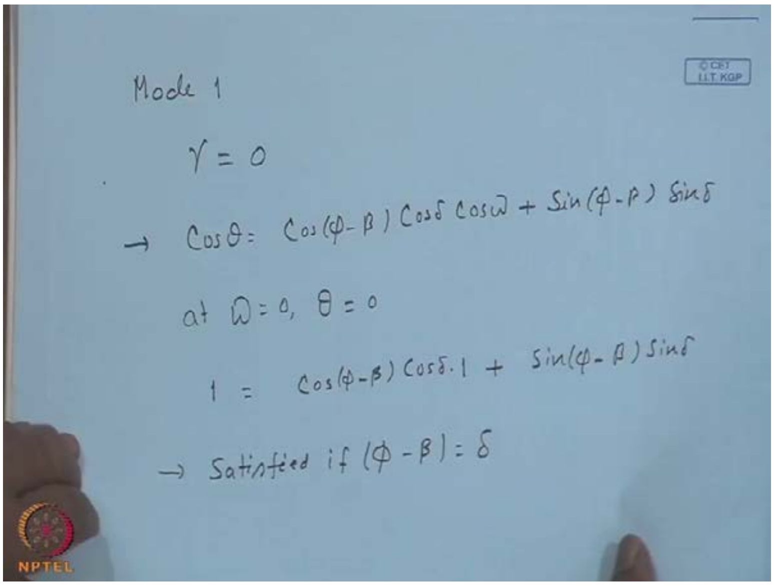

So, if you take for this arrangement, gamma is 0 because, it is the east-west axis so, it is south facing. So, my gamma is equal to 0. Consequently, my cos theta expression is simple, is cos phi minus beta cos delta cos omega plus sin phi minus beta sin delta, at omega is equal to 0, theta is equal to 0 right. The sun's rays being normal to the plane means, 0 angle between the outer normal to the plane and the sun's rays.

This means, this should be equal to cos phi minus beta cos delta, and cos omega is, at omega equal to 0 is 1 plus sin phi minus beta sin delta. So, this is satisfied, if phi minus beta is equal to delta right, then this becomes cos square delta sin square delta, cos square delta plus sin square delta is always equal to unity.

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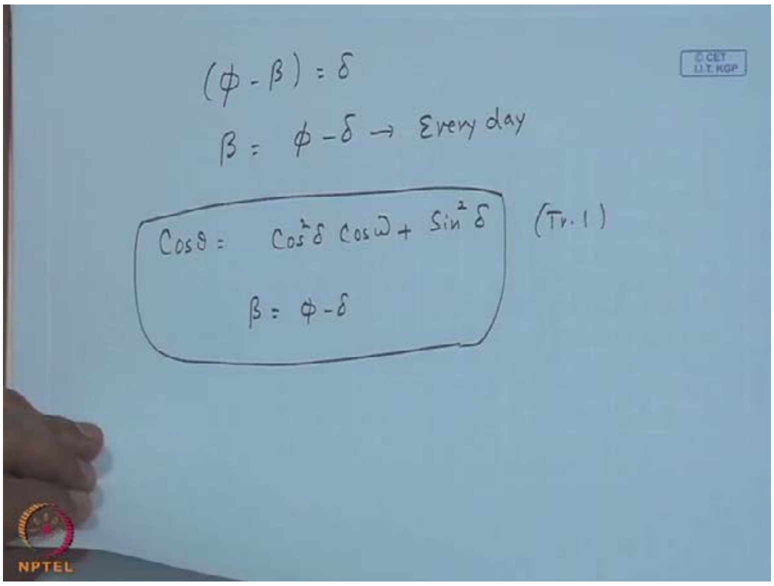

So, I choose phi minus beta is equal to delta or beta is equal to phi minus delta everyday that satisfies my tracking mode, the sun's rays are normal to the aperture at the noon time, providing the minimum angle at the noon time. Consequently, during the rest of the time, for a south facing fix surface for the day will be having a minimum of angle of incidence.

So, my cos theta is now, cos square delta cos omega plus sin squared delta so, tracking mode 1 and beta is phi minus delta, because if you look at the top equation, it does not contain phi, it does not contain beta so, in that sense, you will not have complete information, what you should do, about the tracking mode. But, this is basically, to tell that the aperture plane should be having a slope given by phi minus delta then, cos theta is given by this expression.

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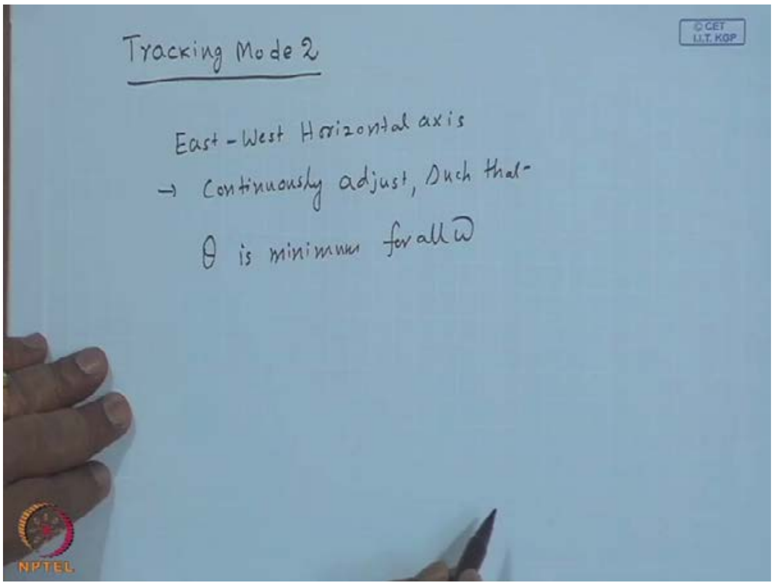

And you have got a tracking mode 2, we will do one step better than, what we have done, again a east west horizontal axis is the one single adjustment per day, continuously adjust such that, theta is minimum, for all omega. So, it is a east west horizontal axis surface, rotated about the east-west axis such that, the angle of incidence is minimum. In the previous case, the angle of incidence was the minimum and equal to your 0, when at noon time, which is satisfied by phi minus delta is equal to 1.

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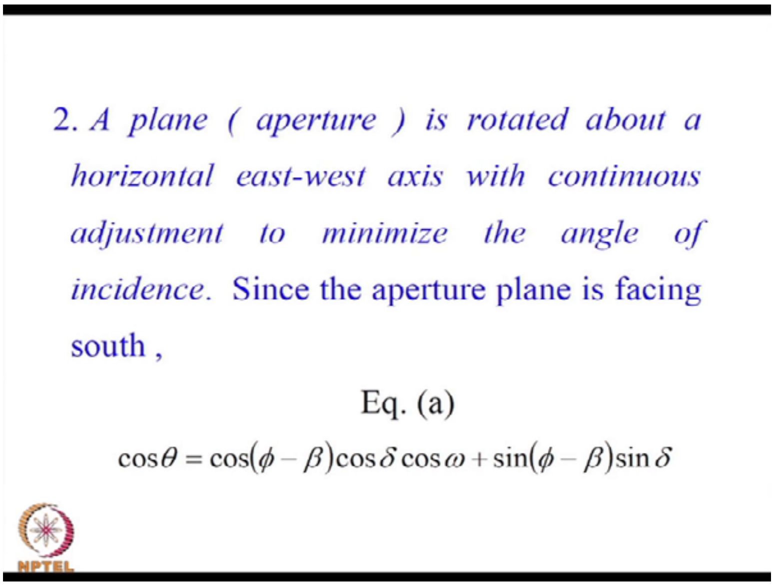

So, that is what, is written here, a plane is rotated about a horizontal east-west axis with continuous adjustment to minimize the angle of incidence.

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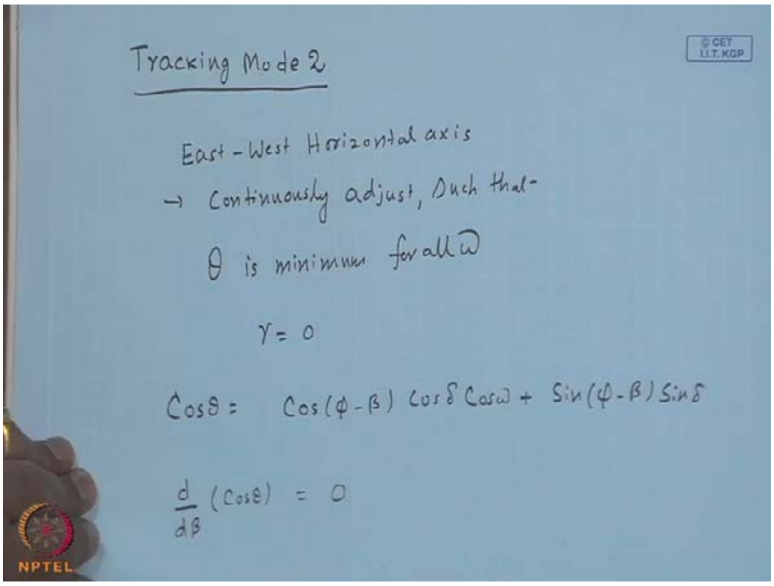

Since the aperture plane is facing south again, gamma is 0, my cos theta is given by the same expression cos phi minus beta cos delta cos omega plus, sin phi minus beta sin delta. Now, our objective is to make theta minimum so, what we do is, we do d by d beta of cos theta and equate it to 0.

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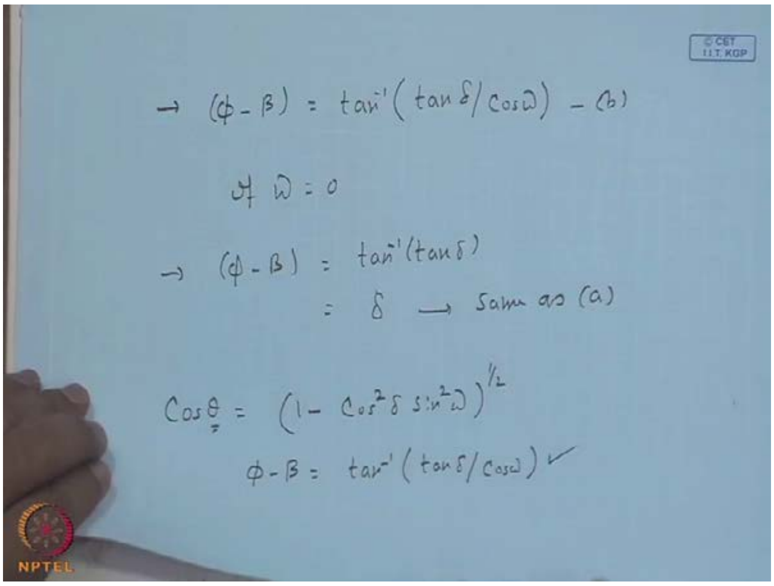

That will give me the condition, phi minus beta is given by tan inverse tan delta by cos omega so, this is b or the tracking mode 2. Now, let us see if omega equal to 0 this means, phi minus beta equal to tan inverse tan delta, equal to delta, same as a. So, tracking mode 1 condition that, the angle of incidence is a minimum at solar noon needs to be satisfied and it did, if phi minus beta is tan inverse tan delta by cos omega, at omega is equal to 0 and at any other time, I have to choose my phi minus beta, according to tan inverse of tan delta, upon cos omega.

So, if we substitute in that now, I will get my expression for cos theta, as 1 minus cos square delta sin squared omega, whole to the power 1 half right. So, again we have to mention phi minus beta is tan inverse of tan delta by cos omega so, you adjust beta with the time of the day, as given by this expression and then, you will have the angle of incidence being minimum, for this mode of tracking where, an aperture plane with a horizontal east-west axis is rotated about the east-west axis, such that beta is minimum in other words, it swivels around the east-west axis such that, beta is adjusted with this equation and your theta is a minimum. Theta will be 0 only at noon time but, theta will not be 0 at other times, for this mode of tracking, this is also a single axis tracking mode.

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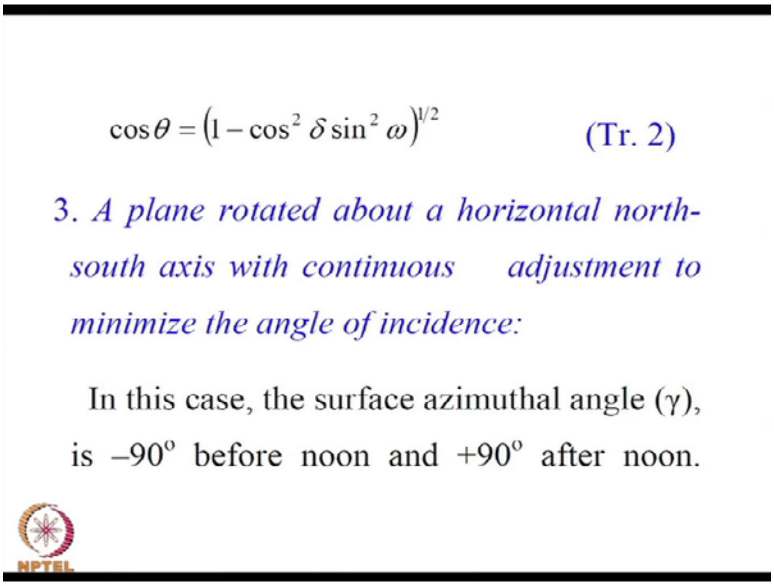

So, we come to the third tracking mode, which is a horizontal north-south axis with continuous adjustment, to minimize the angle of incidence. This requires a little bit of explanation, this is my aperture plane to my front is the south let us say, to my back is the north and this is east and this is west, to my right is west, to my left is east. So, if I face the aperture towards east and keep on rotating it about the north-south axis, which is horizontal, I will go from east to west.

And at each instance, I am changing the slope of the surface by certain amount, as given by the, whatever expression, we are going to get. So, previously we had a east-west axis now, we have got a north-south axis so, this should be rotated from east to west, as sun goes raises in the east, to sets in west. So, now, you can see from the definition of the azimuthal angle, if you take the projection of the outer normal to the surface, it will be always minus 90 that means, towards the east as long as the time is before solar noon.

After solar noon, it will be towards west so, my azimuthal angle will be plus 90 so, this as it is rotating, whether it is beta is 90 degrees or 80 degrees or 0 degrees or again the other direction 10, 20, 90 my outer normal from this direction, projected on to the horizontal plane, will be towards east consequently, you have a gamma minus 90.

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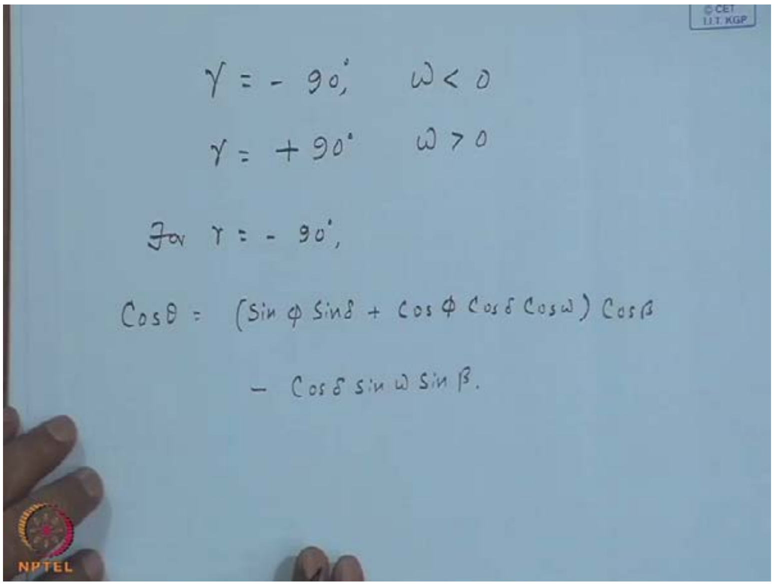

So, you have only two situations gamma equal to minus 90, for omega less than 0 and gamma is equal to plus 90, for omega greater than 0. So, the general equation for cos theta, if I choose to examine for for let us say, gamma is equal to minus 90, cos theta we have a general equation cos theta is equal to a cos omega plus b sin a plus, b cos omega plus c sin omega and in that, a b c are defined in terms of phi, beta, delta and gamma, and you put them and write it down, with gamma is equal to minus 90.

You will have a simpler expression, sin phi sin delta plus cos phi cos delta cos omega times, cos beta minus, cos delta sin omega sin beta. So, the third mode of tracking is around a horizontal north-south axis, the aperture plane being rotated from east to west and we realized that, the azimuthal angle is either minus 90 for fore noon and plus 90 for after noon. And the general equation for the angle of incidence will be in terms of, phi delta and omega of course, and the beta, now job.