Elements of Solar Energy Conversion
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Lecture - 22

Hello and welcome back to the series of lectures on Elements of Solar Energy Conversion. Today, we are here at lecture number 22. So, what we did? We have developed the background that you require to understand these different solar energy conversion devices, how to analyze them and all. And, then we started with the basic solar energy conversion device which is a solar flat plate collector, ok.

We have seen the most common configuration of it which is liquid flat plate collector and the variation of it which is evacuated tube collector and then we also have looked at the air heaters which is little bit different in terms of the design of the geometry because air is a poor conductor of it and that is why you require large area for heat transfer. So, that is the portion that we have covered.

So, the next thing that we are going to discuss in this class is the Overview of different Solar Thermal Collectors and we will switch to the mode which are concentrating solar collectors. Concentrating solar collectors where you have some concentrating optics to increase the incident intensity on the absorber and that absorber can be a photovoltaic panel, it can be a heat absorber like a black plate and whatever be the case the intensity is much-much higher than the normal solar radiation.

So, that is the concentrating part. So, before I go to that I need to provide an overview of different kinds of solar collectors.

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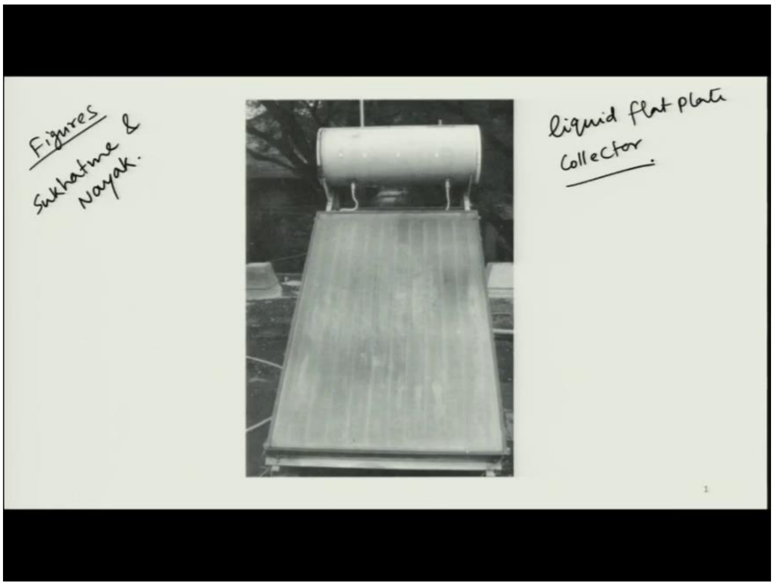

So, let us start with. So, this one (you have seen earlier) is the liquid flat plat collector. I should mention here, all the figures are taken from the book by Sukhatme and Nayak, ok. So, if you look at that book you will find different photographs of these collectors and also few schematic diagrams which are very illustrative. So, this is the most common liquid flat plate collector.

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And, then we have seen that when you have a requirement of higher capacity of the solar heat collection as well as if you have some higher temperature requirement, then a single flat plate collector with a tank may not serve the purpose and that is why we need array of flat plate collectors.

Here you see that there are multiple such collectors all of which are connected through common inlet manifold and outlet manifold, ok. So, that is how the array of flat plate collectors are used.

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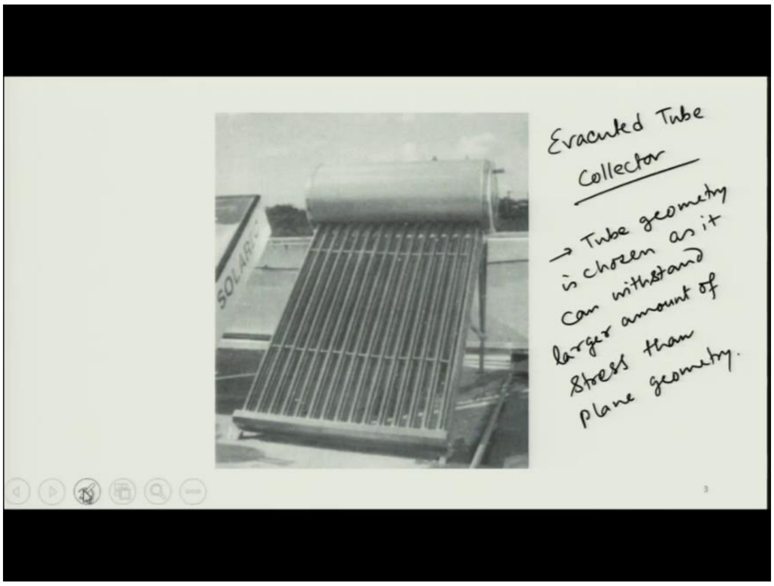

Now, we have also looked at the evacuated tube collector where we have introduced vacuum in between the cover system and the absorber plate, ok. So, to reduce the convection loss that happens as a part of the top loss coefficient, ok. So, why we have used the tube geometry? Because it can withstand larger amount of stress than a plane geometry, ok.

So, tube geometry is chosen as it can withstand larger amount of stress than plane geometry that is the only reason and this is the most commonly used geometry or configuration for liquid flat plate collectors and we have also looked at air heaters from here.

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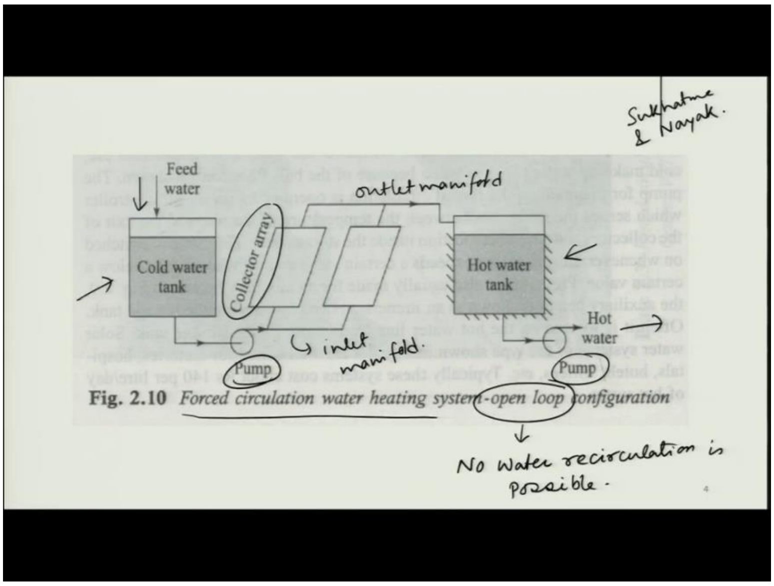

Now, we can look at few schematics where more and more complications can be introduced. This is taken from Sukathme and Nayak. So, please refer to that book, you collect that book and look at these figures and its explanation. It will be very helpful for you to understand the underlying principle.

So, here what we have seeing that this is a schematic of a forced circulation water heating system where you have an array of collectors and everything is connected through this outlet manifold and here you have inlet manifold, ok and this pump is pumping the liquid through this array of collectors.

And, you have two tanks which are separated one is hot water tank which is connected to the outlet manifold and you have a pump where this hot water is taken and gets delivered to the point of use. And, on the other hand you have this cold-water tank where feed water comes in and get stored whenever it is required by the inlet manifold the pump takes it from the cold water tank.

So, here you see that instead of the basic geometry of a single tank where water is circulated again and again, we have separated that hot water tank and cold water tank and we are not relying upon the natural convection, but what we are relying upon is forced convection. We have two pumps – one to push liquid from the cold water tank to the array of collectors and another pump which takes liquid from the hot water tank and puts it into the place of use, ok.

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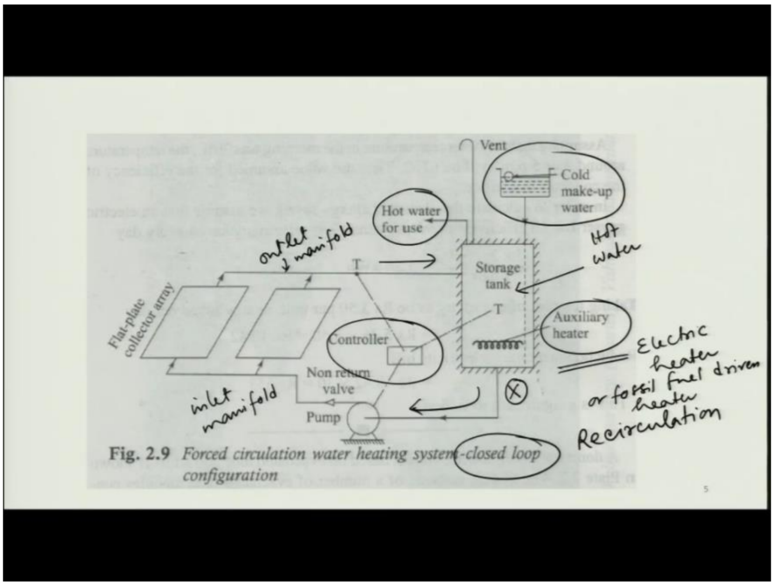

Now, you can introduce more complication to this by allowing water recirculation, ok. So, if we look back at this particular figure. Here is the system is open loop, ok. So, no water recirculation is possible. So, what does that mean? Water will flow only one time through any collector.

So, whatever chance it gets to get heated up that is the only chance it gets and once it reaches hot water tank, there is no way you can increase its temperature, ok. So, that is why it is called an open loop configuration and you do not have any recirculation option here.

But, you can have the recirculation option if you have a close loop. So, you have a recirculation option when you have a close loop. What you are doing? You are again using a storage tank, ok. So, this is hot water tank, because what it does, it is connected both to the inlet manifold as well as outlet manifold, ok. So, this is what? This is your inlet manifold and this is your outlet manifold, ok.

So, what you can do, once the hot water goes here, if you want to increase its temperature further you can let that water pass through the collector array once again, ok. So, that is how you can do it and what it does it requires a controller which will tell you at what point you switch on the pump for recirculation and at what point you do not do that, ok.

And, you can also have some auxiliary heater. Suppose the temperature that you wish to achieve is not being possible even after multiple recirculation due to low amount of solar intensity on a particular day that can happen any time. If you have a cloudy day the intensity will be low and you will not be able to reach the desired temperature.

In that case what you can do? You can put an auxiliary heater which can be an electric heater or you can burn some fuel to heat it up or fossil fuel driven heater. Whatever it may be but it is not solar. So, you can have that auxiliary option, only when you require it you can switch it on, ok.

So, the rest of the cycle does not get affected that is why the auxiliary heater is used. Now, when you have reached the desired temperature then you do not need to do any recirculation, ok. What you need to do? You just take that hot water for use, and then whenever you take it there has to be a cold water feed, right, otherwise the levels will fall, ok.

So, that is what this cold water feed does. It supplies water when you have taken out water for the use. So, this is one possible close loop configuration with the same principle of flat plate collector.

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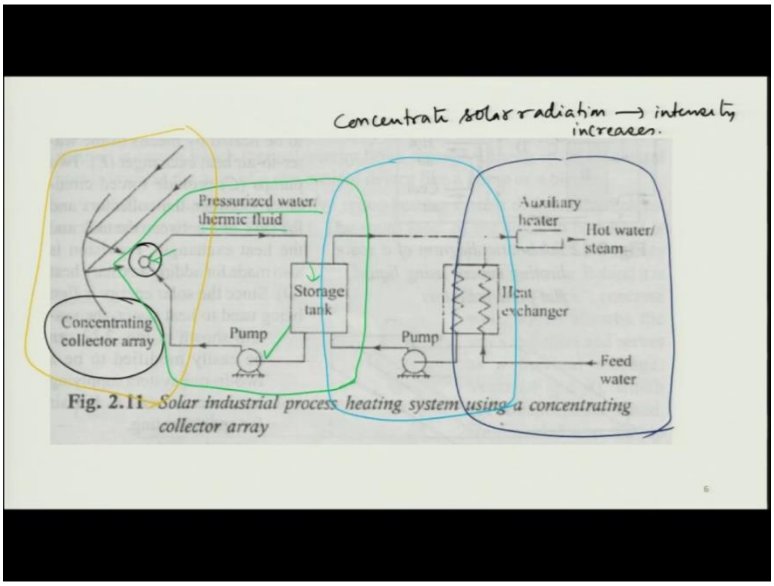

Now, if you really want to increase the efficiency of this collector, what we do? We concentrate, ok. Whenever we concentrate solar radiation the intensity increases, right and depending of what kind of concentrator you are using and what kind of optics you are using to achieve that concentration, you can vary the concentration ratio. It can go from as low as 2, 3, 4 up to 2000, 3000 that is also possible.

So, you can see that if 1000 W/m^2 is the normal solar intensity ok and if you go for like 100 concentration ratio you will have 100,000 W/m^2 on the absorber plate, ok. So, the intensity can be really pushed up by using a concentrator optics.

Now, I am not going into detail of this concentrator optics I will do in the subsequent lectures, but what I you want you to understand that a small absorber of whatever shape can get much more intensity and that is how you can get huge amount of useful heat as well as huge amount of temperature that you can achieve.

So, what you can do? If you just look at separately, this is nothing but the close loop or you can say close loop or open loop, it has a single storage tank. So, it should be close loop solar heating system, ok. It has a pump and you can have this pressurized water or any other thermal fluid which can carry the heat from these absorber to the storage tank, ok.

Now, once you do that? You can use another loop which are intercepting which takes the storage tank heat to another heat exchanger and you can use it or you can send it to another loop which will use that hot water and if you can reach significantly high temperature and pressure you can use it to run a ranking cycle, ok.

In that case, this whole solar heating system will be called a solar furnace, ok. Exactly in a thermal power plant when we burn coal and get that high temperature and get high pressure high temperature steam. Here also it is possible, but for that you have to increase the intensity by significant amount then only you can do that, ok.

So, this concentration that you require why it will be concentrated because, you have to use certain optics. You have to redirect or change the direction of the solar rays in such a way that the rays which were now falling on a large amount of area they get deviated and they focus on a particular point or a much smaller area that is how it is possible, right.

And, whenever that is the case, the direction of the sun rays is very critical there. A concentrator optics can only work if you have a known or predetermine direction of the solar radiation falling on that concentrator, ok.

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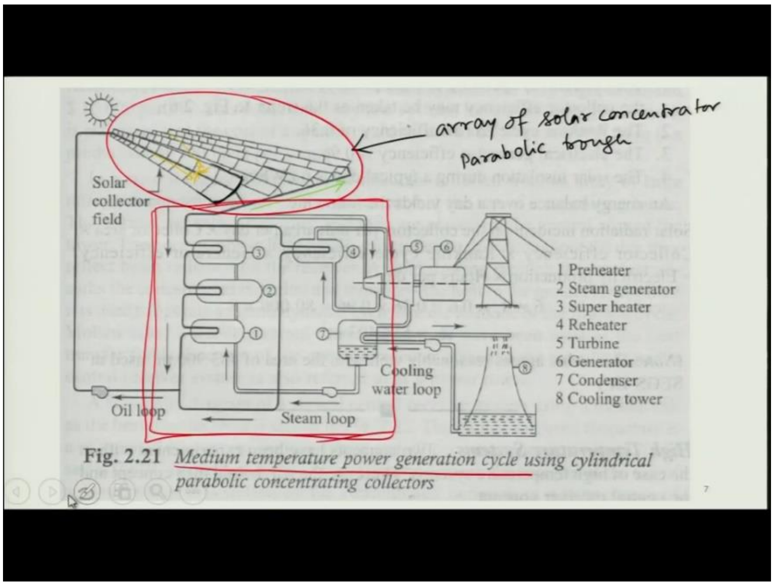

Let us look at some other examples also, here also you can see. So, this is an array of solar concentrator and these are called parabolic trough, ok. If you look at this closely, these are actually parabola and going in these direction you have a long 2-dimensional parabola.

So, whenever the sun rays are falling on that all these are directed to this pipe that is at the focus, i.e., focal point if you place a pipe and run fluid through it that concentrated sunlight will heat up that pipe and the fluid inside it. And, when you have an array of it, when you have a multiple number of such parabolic trough concentrators, you can raise the temperature significantly.

And, that is how you can see that this is nothing, but a medium temperature power generation cycle. So, this is basically you are replacing the coal burning furnace with a solar furnace, ok. So, you are collecting all the heat that these parabolic trough collector arrays are providing. This is nothing, but a boiler, this part is a solar boiler you can see where exactly the same functions are performed as a boiler does, ok. So, that is the level of concentration you can get.

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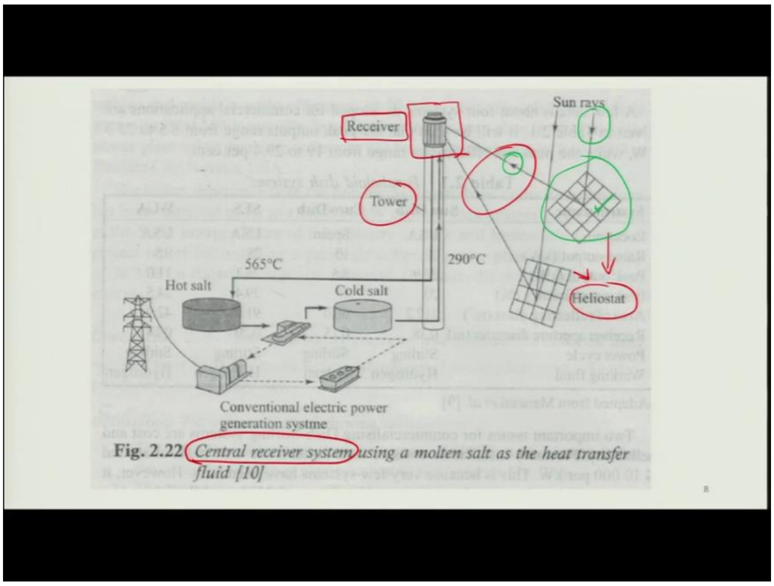

Now, you can also have even more amount of concentration by using this central receiver system. What does it do? It puts the receiver on top of a tower. So, this is the tower and this is the receiver ok and you place lot of reflectors (which are called heliostat) all around that particular tower, ok. So, if you have a large field of different heliostats and all of them track the sun and concentrate or focus all the solar radiation falling on that field on to that particular receiver.

So, if you look at this receiver everything is getting pointed out to that particular point. So, these are heliostats, and all of them are radiating or focusing sun rays on to a particular point. So, the bigger amount of heliostat field you use bigger amount of concentration ratio you can reach.

So, my point of giving you this overview of different concentrating optics is that, that for all this concentrator to work, you require perfect tracking of the sun. So, for example, if you take this particular heliostat and this is the general direction of sun rays that are falling on it.

If sun position changes it always changes right, if this heliostat cannot track the sun, it will not be able to direct the sunlight in this fashion, right. So, a perfect tracking of the sun is mandatory for any concentrating optics to work, ok.

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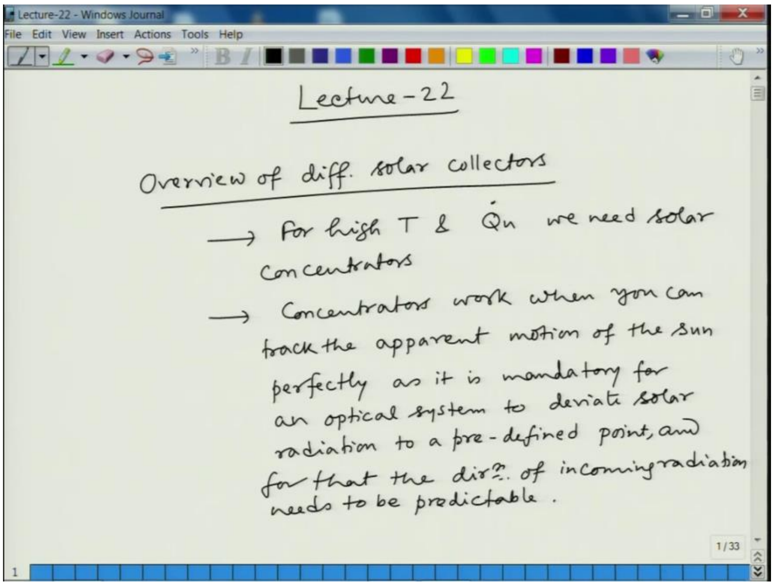

Now, so, what we have learned let me write the lecture number here as well. So, we are here at lecture number 22, ok. So, from this overview of different solar collectors what we get is that for high temperature and rate of useful heat gain, we need solar concentrators, ok. Simple flat plate collector will not give you that amount of high temperature or high heat capacity.

If that is the case, now each of these concentrators work when you can track the apparent motion of the sun perfectly as it is mandatory for an optics or optical system to deviate solar radiation to a pre-defined point. It is mandatory for an optical system to deviate solar radiation and for that the direction of incoming radiation needs to be predictable, right.

Otherwise, what you will end up with the direction of incoming radiation changes and if your optical system does not track it, it will keep the same orientation and the deviated ray will go somewhere else which you do not want.

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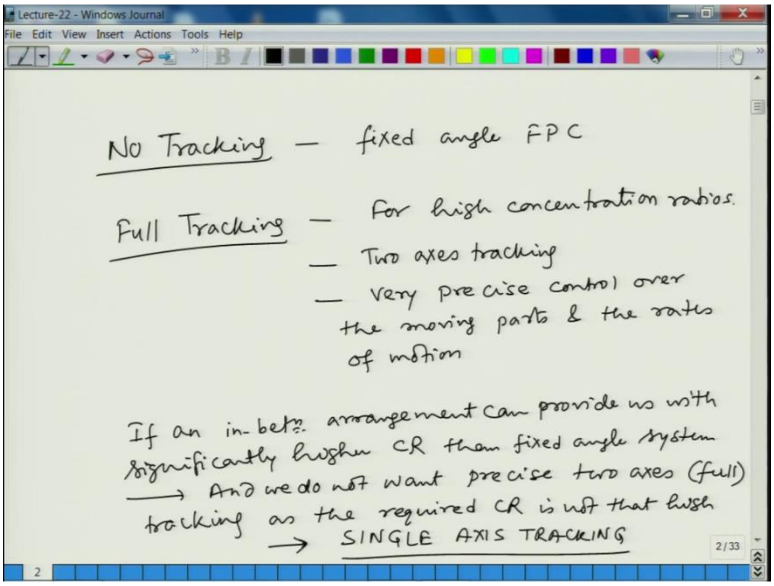

Now, what we can see that if we do not track, so, let us say, no tracking. We have seen such a case right, the fixed angle solar flat plate collectors. We have seen they are not changing; they are not tracking the sun wherever it is you are placing it is taking the solar radiation as it is available. So, it is not trying to optimize it.

So, that is one option and other option is full tracking, where you need or where this is needed for high concentration ratios, ok. And, for this full tracking what you need? You need two axis tracking, two axis motion ok, because apparent motion of the sun has two different orientations that change – one is from east to west which is the diurnal motion the other one is from north to south which is seasonal motion, right.

So, as sun is moving in two different orientations, your tracking system also should have two different orientation motions and then only you can track the sun perfectly. So, that is required and for that you need very precise control over the moving parts and the rates of motion, ok that is indeed possible and we regularly do it, but it requires high amount of precision, it requires parasitic power consumption, ok.

So, we do that only when we require it. So, do we have anything in between? Can we have something between no tracking and full tracking? ok. So, if an in between arrangement can provide us with significantly higher concentration ratio CR, then fixed angle system we would love it, right? We require that kind of system and we do not want precise two axis, or which is often called full tracking (two axis tracking) as the required CR or concentration ratio is not that high.

So, if we want something in between, what option do we have? We have single axis tracking, ok. So, that option is single axis tracking. So, we will move our collector or reflector in a single orientation and whatever concentration ratio it will give us we will take it, that is the idea, ok. So, in between compromise but now you can choose different possible orientations of that tracking and the motion, right.

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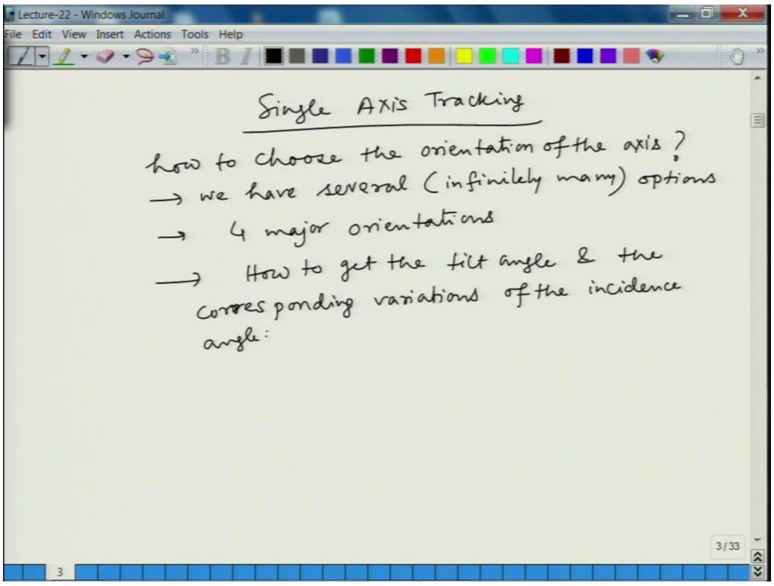

Now when we have this single axis tracking, so, first question we will have how to choose the orientation of the axis? Because, a full tracking you have to do it whatever orientation you do, one will be perpendicular to the other and in each time it will focus to the sun.

So, that is easy in the sense you do not have to optimally choose the angles. Whatever orientation of one axis you take, the other orientation will be perpendicular to that, ok. Now, for a single axis tracking, you can choose several orientation of the rotating axis and how often you are going to give motion to that and with that choice the amount of optical concentration ratio that you can get will vary, ok.

So, we have several choices (actually infinitely many, mathematically). You can choose any axis you want, and people have seen that there are 4 major options which we are going to use and which will give us the optimal performance under different conditions.

So, we are going to use those 4 major modes and see how the tilt angle changes with these modes of orientation and the incidence angle changes accordingly. So, our question will be how to get the tilt angle and the corresponding variations of the incidence angle, ok.

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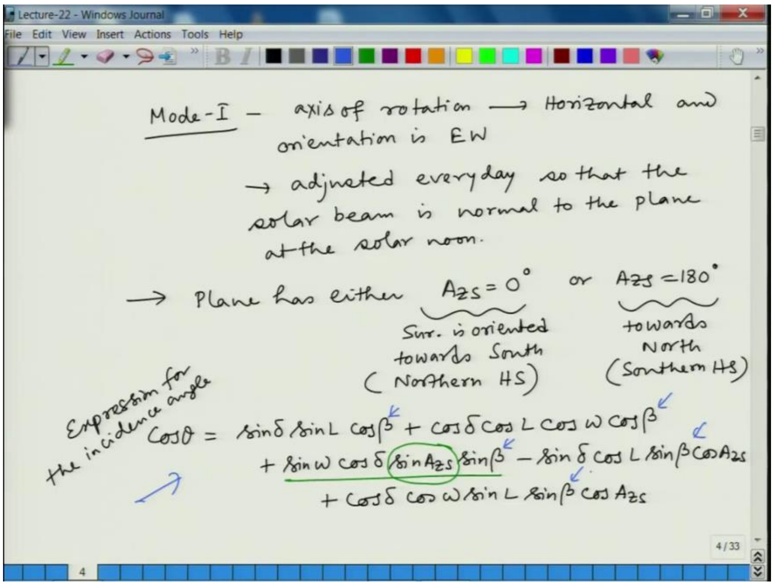

So, let us first look at mode I

So, what is mode I? Here we are choosing the axis of rotation to be horizontal and orientation is east-west, ok. So, on all these things and later also whenever you are going to use any solar concentrator or any tacking system you have, it is very critical that you can visualize the motion, ok.

So, whenever I say in mode I, we are choosing horizontal axis and orientation of that axis is east west. So, wherever you are, you can imagine that in east west you can put the axis and you can put it horizontally, ok. So, please visualize it and again what we are going to do, we need to give the frequency of changes also (frequency of motion).

So, every day we are going to adjust it so that the solar beam is normal to the plane at the solar noon. So, what we are going to do? We are choosing this horizontal east west axis and we are going to adjust it once a day. We are not going to give motion all through that diurnal motion of the sun, we are not going to do it. We are going to adjust for a day, we are going to place it in such a tilt angle, so that at the solar noon, the beam will be exactly normal to the plane of the collector, ok.

So, if that is the case then the axis of the rotation is horizontal east west, but the plane can have different orientation right and we have seen that a plane is optimally oriented when it is oriented towards the equator. So, for the northern hemisphere, the orientation will be towards south and for the southern hemisphere, the orientation will be towards north.

So, plane has either this surface azimuth angle to be 0 degree or surface azimuth angle to be 180 degree, ok. Surface azimuth angle means what the projection of the of the surface normal it makes on the horizontal plane with the south direction, right. So, when it is 0, that means, the surface is oriented towards south and this means towards north, ok.

So, towards north is 180 degree and this you will find for the northern hemisphere and the other one will be for southern hemisphere. So, all through this course what we will use? We will do the derivations for northern hemisphere and the same thing can be done for the southern hemisphere, ok. So, we will skip the southern hemisphere part more often than not, ok.

Now, from your earlier derivations what you got the expression for the incidence angle what we obtained was,

$$\cos\theta = \sin\delta\sin L\cos\beta + \cos\delta\cos L\cos\omega\cos\beta + \sin\omega\cos\delta\sin A_{zs}\sin\beta - \sin\delta\cos L\sin\beta\cos A_{zs} + \cos\delta\cos\omega\sin L\sin\beta\cos A_{zs}$$

This long expression we have derived earlier, and this is the expression of the incidence angle on a plane with respect to different important angle such as the declination angle, latitude tilt angle, hour angle surface azimuth angle, ok.

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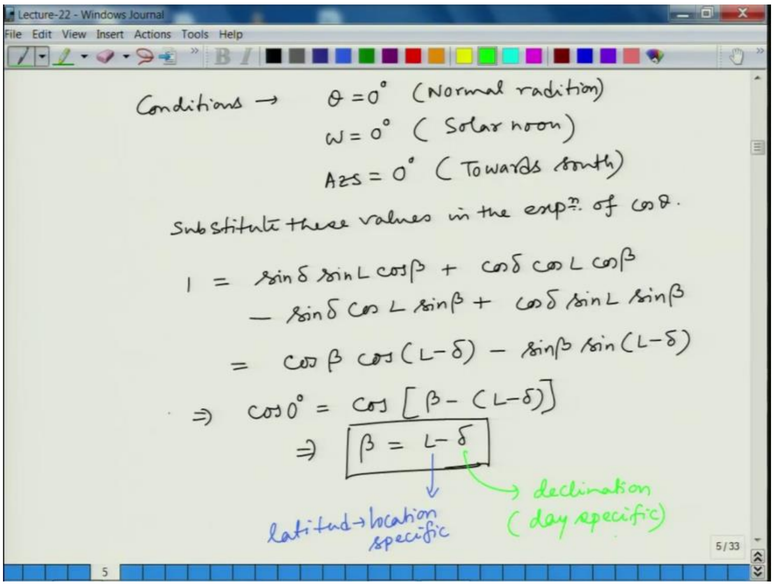

Now, what condition did we put? We have put that this θ will be 0 degree, that means, it is the normal radiation. So, solar beam will be normal to the surface plane, ok. Now, and when will this happen? At solar noon, that means, when hour angle is 0 degree. So, this means solar noon ok and here we are working for the northern hemisphere. So, the surface orientation will be towards south, so, A_{zs} will be 0 degree as well. So, this means towards south, ok.

Now, if we put these conditions on the expression of $\cos\theta$, what we will get, first of all? So, substitute these values in the expression of $\cos\theta$, ok. So, when θ = 0, $\cos\theta$ = 1. So, what you can write?

$$1 = \sin\delta \sin L \cos\beta + \cos\delta \cos L \cos\beta - \sin\delta \cos L \sin\beta + \cos\delta \sin L \sin\beta$$

because cos ω = 1, as ω is 0 degree at solar noon.

So, this is the simplified expression you can see here we have this particular term get 0 because we have this sin A_z in it and sin A_z= 0, so that term vanishes; other four terms are simplified in this particular fashion, ok. Now, what you can see that this is nothing, but you can take cos β common and you can have $cos\ (L - \delta)$ and for the other term you can take sin β common and you will have $sin\ (L - \delta)$, simple trigonometric algebra we are using, ok.

So, what does it mean that this left hand side is our cos 0 degree and this right hand side is nothing, but $cos\,[\beta - (L - \delta)]$, right. So, what it means? That your tilt angle of the plane has to follow this relation. It has to be latitude minus declination angle, ok. So, if we want to have in mode I, we have the axis orientation is east west and the axis is horizontal.

Then, at solar noon if you want to get the beam radiation perpendicular to the surface ok you will have to choose a tilt angle which is nothing, but the difference between your latitude of that place and the declination on that particular day. So, here what this is the location specific. So, this is latitude (location specific) and the other one δ; δ is the declination angle which is day specific, which day you are adjusting it for that the δ will change, ok.

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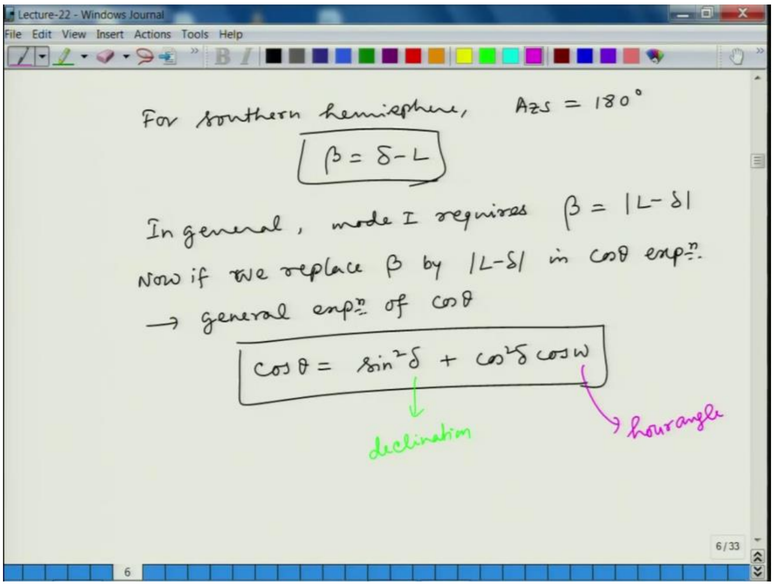

So, if that is the case and for southern hemisphere, we will just mention it.

For southern hemisphere,

$$A_{zs} = 180°$$

And in that case, you can show that,

$$\beta = \delta - L$$

Earlier here we have seen it is L − δ and for southern hemisphere it will be δ − L.

So, in general what you can say that mode I requires the tilt angle,

$$\beta = |L - \delta|$$

So, which covers both plus and minus values, ok. So, here in this particular expression, now you know what these β's are, right for that mode I orientation.

So, as you know that, what you can do? You can replace this β there and you can find an expression for $\cos\theta$. So, if we replace β by this mod of $|L - \delta|$ in $\cos\theta$ expression what we get? We get the general expression for $\cos\theta$ which will tell at any time what will be your incidence angle, ok.

And, what is that expression? We are not going to derive it, but we are going to state it,

$$\cos\theta = sin^2\,\delta + cos^2\,\delta\, cos\,\omega$$

So, please derive it by yourself. It is simple trigonometric algebra that you have to use. So, please derive it and what does it tell? Like in mode I, you have chosen a certain single axis tracking system which will be adjusted only once in a day, ok. In the morning itself you change it and in the next morning we change it, that is how it works.

So, in that case for any point of time what will be the incidence angle on that plane that is very important to know, then only you will be able to understand or calculate what would be the incidence intensity, ok. So, here you can see that it is dependent on only two things – one is the declination, the other one is the hour angle. So, what is the time of the day that gives you the hour angle and declination is the which day you are.

So, those are the only two things – all other dependence like the orientation of the plane, the β, latitude, etc., everything is now boiled down to this particular expression of $\cos\theta$, ok. So, that is the mode I single axis tracking.

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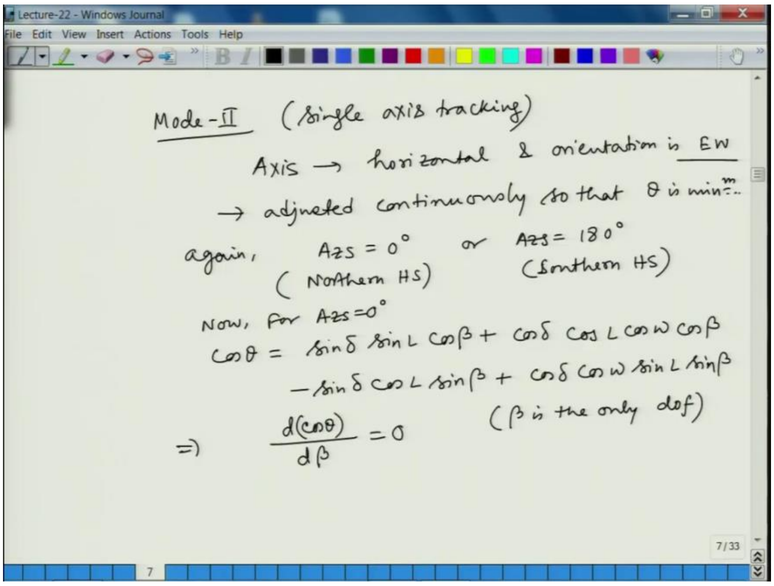

Let us look at the next mode II of single axis tracking. Again, we have to first tell what is the angle of the axis itself with horizontal and then what is the orientation of that axis and how often you are going to rotate it with respect to that particular axis. So, here again, we will have the axis to be horizontal just as in case of mode I and the orientation is also east to west ok, but what is the difference?

It is adjusted continuously. Earlier we are adjusting only once a day; now, we are moving it continuously so that this θ is minimum. What does it mean? The θ is minimum means your incidence angle is minimum that means, the intensity is maximum. And, earlier we are doing that only at solar noon we are getting perfectly normal incidence, but at other point of time we are not getting it perfectly normal or we are not even trying to minimize the θ angle or the angle of incidence. Here we are continuously adjusting it, so that the θ angle is minimum.

So, let us see what would be the implication of this mode II tracking system. So, again these A_{zs} is either 0 degree or 180 degree, ok. So, this is for northern hemisphere and this is for southern hemisphere, ok. Now, what we have? Now θ is not 0 degree at solar noon. So, we cannot write that kind of expression. Only what we can do for northern hemisphere now, let us say for A_{zs} = 0 degree that value we can put directly and the expression of $\cos\theta$ will be the following, ok.

So, this again I would insist that please check that by yourself, ok. Simply in the general expression of $\cos\theta$ what we did, we have put A_{zs} to be 0 degree, ok. Now, what we want this $\cos\theta$, θ to be minimum; that means,

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

Because β is the only degree of freedom here, right that is the tilt angle that is what we can change. So, with respect to β, this $\cos\theta$ derivative should be 0 that is how we find the minimum point.

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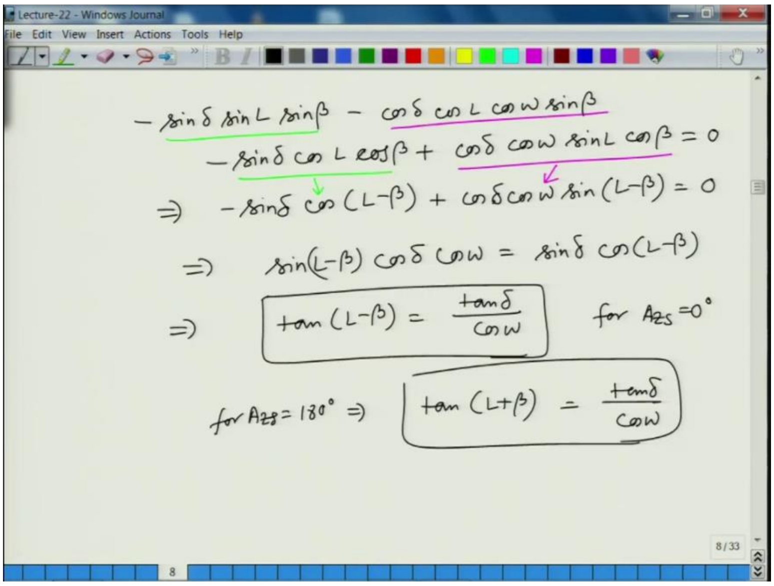

So, now let me just write the derivative of $\cos\theta$ expression with respect to β and what you will get is this,

$$sin\delta\ sinL\ sin\ \beta - \ cos\ \delta\ cos\ L\ cos\ \omega\ sin\ \beta\ - \ sin\ \delta\ cos\ L\ cos\ \beta$$
$$+ \ cos\ \delta\ cos\ \omega\ sin\ L\ cos\ \beta = 0$$

That is the condition of θ minimum. And, then if you simplify this expression what you can do you can get this −sin δ cos (L−β). So, if you take these two terms sin δ sin δ these two terms will give you this, ok and then you can have cos δ cos ω and sin (L−β). So, the other two terms this one and this one if you take cos δ cos ω common and then you will have sin (L−β) to be 0. So, that will be equal to 0, ok.

So, basically that gives us,

$$sin\ (L - \beta)\ cos\ \delta\ cos\ \omega\ =\ sin\ \delta\ cos\ (L - \beta)$$

And that gives you,

$$tan\ (L - \beta) = \ tan\ \delta / cos\ \omega$$

And, this is for A_{zs} = 0 degree and the same expression you can get or for A_z= 180 degree you will get this,

$$tan\ (L +\ \beta) = \ tan\ \delta / cos\ \omega$$

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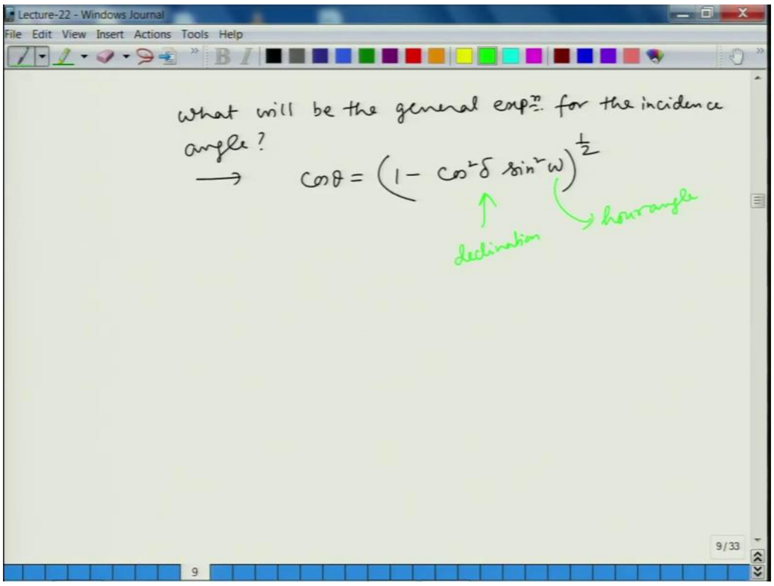

So, just like the earlier case what we want to know, what will be the general expression for the incidence angle, ok? What is the condition of minimal that we have obtained, but what would be the incidence angle, ok. So, again you can derive I am not going to derive it. You can show that,

$$cos\ \theta = \sqrt{1\ -\ \ cos^2\ \delta\ \ sin^2\ \omega}$$

So, again you see that it depends on two angles declination which changes from day to day and this ω which is hour angle which changes from point to point. So, that is how you get it and that is the mode II single axis tracking, ok. So, we will complete the other modes of single axis tracking in the next class. Here we will stop.

Thank you for your attention.