Elements of Solar Energy Conversion

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Lecture - 27

Hello, everybody and welcome back to this series of lecture on Elements of Solar Energy Conversion. Today, we are here at lecture number 27, ok.

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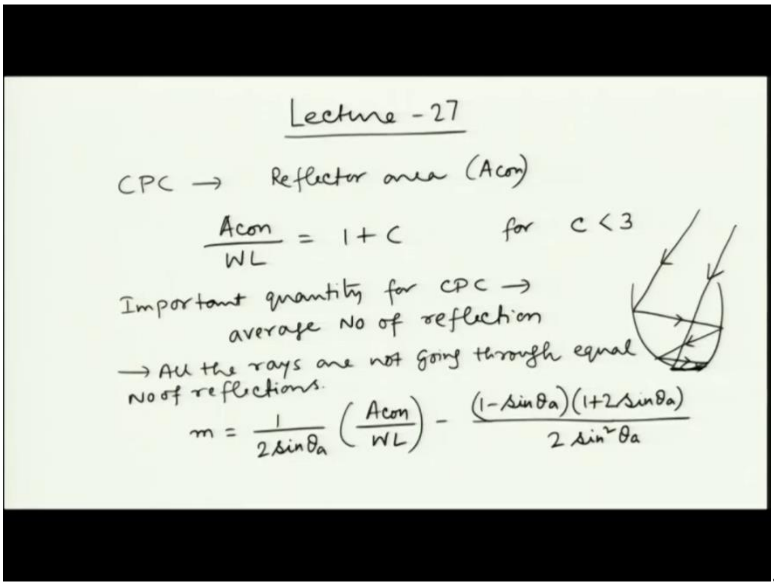

So, we were looking at the compound parabolic collector or CPC and in the last class, we have derived the expression for the reflector area which is also called concentrated area, because concentration is happening here through reflection. So, this expression we ended up with. And this simple expression is valid only for small concentration ratio which is less than 3.

Typically, this compound parabolic collectors are used where the requirement of concentration ratio is not that high, but the requirement that you do not need to use the tracker that is even more important. And that is why for small concentration ratios, we use this CPC and the concentrator area or reflector area is expressed like this. Now, another important quantity to know for CPC is the average number of reflection, ok.

So, if you look at the CPC geometry, some ray may go multiple number of reflection before they reach the receiver surface or some ray may directly come to the receiver surface. So, all the rays are not going through equal number of reflections.

So, what is the average number of reflections? That is important because that will tell us what would be the intensity due to these multiple reflections. If suppose the reflectivity is 0.9. So, 90% of the ray will be reflected and the 10 percent will be lost or absorbed or something, ok.

Now, if you have 2 reflections, then 0.9×0.9 will be the effective fraction, that will be available to the receiver. Now, if you have 3 reflections, then it will be 0.9^3, that is how the average or the number of reflections will change the intensity for that particular ray.

Now, it can be shown that this average number of reflections is dependent on again the acceptance half angle, which is the quantity related to its geometry. And that is the thing that all the important parameters related to CPC are dependent on this acceptance half angle, ok.

So, average number of reflections is,

$$m = \frac{1}{2\sin\theta_a}\left(\frac{A_{con}}{WL}\right) - \frac{(1-\sin\theta_a)(1+2\sin\theta_a)}{2sin^2\theta_a}$$

In case you are interested in the derivation of this expression, you have to go to the original sources, the research paper where these have been derived and you will find the relevant reference from the textbook which is by Sukhatme and Nayak, ok.

We are not going through the derivation here, we are just mentioning the formula. So, that you can design, or you can find the relevant quantities related to the designs, ok.

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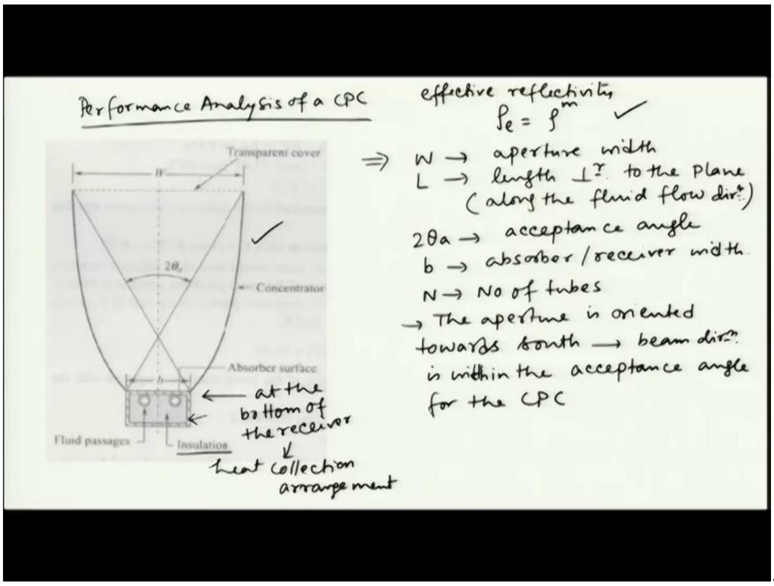

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Now, so this is concentrator and this average number of reflectivity or the effective reflectivity of the collector will be the reflectivity of the surface to the power this average number of reflections, ok. So, this is an important quantity that you will require. Now, we have looked at the optical part of it. What would be the area? What would be the geometry? How it can accommodate larger or inclined incidence on the aperture plane?

So, now, what we are going to do is, we will look at the performance analysis of a CPC, ok. So, in this figure you can see that we now have the CPC and at the bottom (at the receiver part), we have this heat collecting arrangement. So, at the bottom of the receiver we have this heat collection arrangement. Typically, as we have seen for flat plate collector, we have the tubes that are running below the absorber plate and we have this insulation and the whole thing is put in a box.

So, that is how the heat is collected from the CPC, ok. So, first let us put some symbol for all the relevant quantities. So, W you have already looked at it is the aperture width, L is the length perpendicular to the plane or you can say length along the fluid flow direction, right and $2\theta_a$ is our acceptance angle ok, b is the absorber or receiver width, ok.

So, let us say that N is the number of tubes, which are collecting the heat from the receiver plate, ok. And, we can assume that the aperture is oriented towards south direction (south for northern hemisphere again) and it would be north for southern hemisphere. So, basically towards the equator. And the beam direction is within the acceptance angle for the CPC, ok. Then only it will reach the receiver portion, ok.

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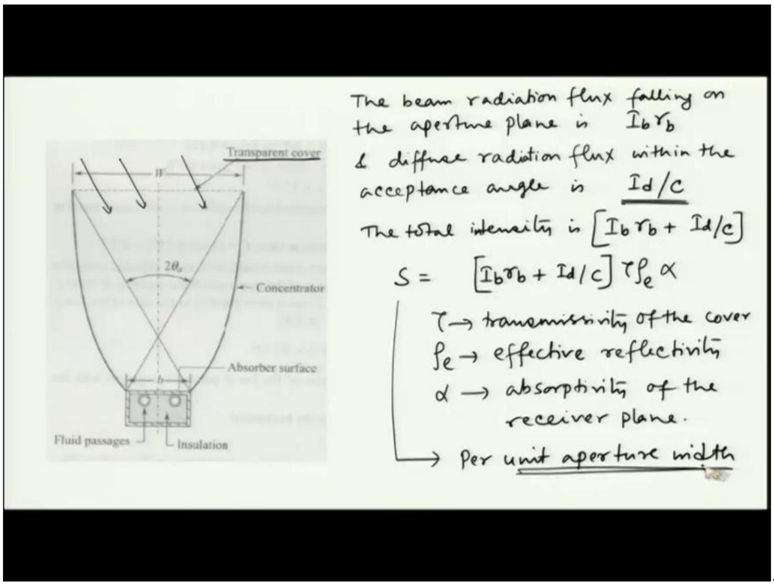

So, if this is the case then what we can write, the beam radiation flux falling on the aperture plane is $I_b r_b$, right? I_b is the beam radiation intensity on a horizontal plane and r_b is the conversion factor, which takes the tilt into account, ok. This you have seen earlier so, you know how it comes. As the concentration ratio for CPC is not that big usually it is within 5 or maximum 10.

So, the diffuse radiation concentration will also be important for this low concentration ratio CPC, ok. For higher concentration ratios such as parabolic trough or parabolic dish, we will see next. There the beam intensity is so intense that you do not need to include diffuse radiation it does not make any significant difference. But here we include diffuse radiation because beam intensity is not that big.

So, the diffuse flux within the acceptance angle is I_d/C. Why we call it divided by C? Because, the diffuse radiation is coming from all kinds of direction, right and only a fraction of that which is coming inside the aperture is being coming on the receiver plane. So, we have to divide it by concentration ratio (C), ok.

So, again this particular expression involves a long derivation, which we are not being able to cover here; you can look that up from the original papers, ok.

So, the total intensity is $[I_b r_b + I_d/C]$, right. Now, when we know the intensity, we know what is the absorbed radiation per unit area? So, that is the total intensity multiplied by the transmissivity of the cover. So, we are assuming that we have a transparent cover at the aperture, ok.

So, that transmissivity will come into picture and then you will have this effective reflectivity? Whatever intensity is coming in the aperture, they will be reflected and the effective reflectivity ρ_e will be multiplied for the absorbed radiation part. And, then the other factor is α; α is the absorptivity of the receiver.

So, here let me write, this τ is transmissivity of the cover, ok. ρ_e is the effective reflectivity (as we have seen few minutes ago) and α is the absorptivity of the receiver plane. So, here you see that instead of flat plate collector, the expression of S has changed little bit and we have to incorporate that in our analysis.

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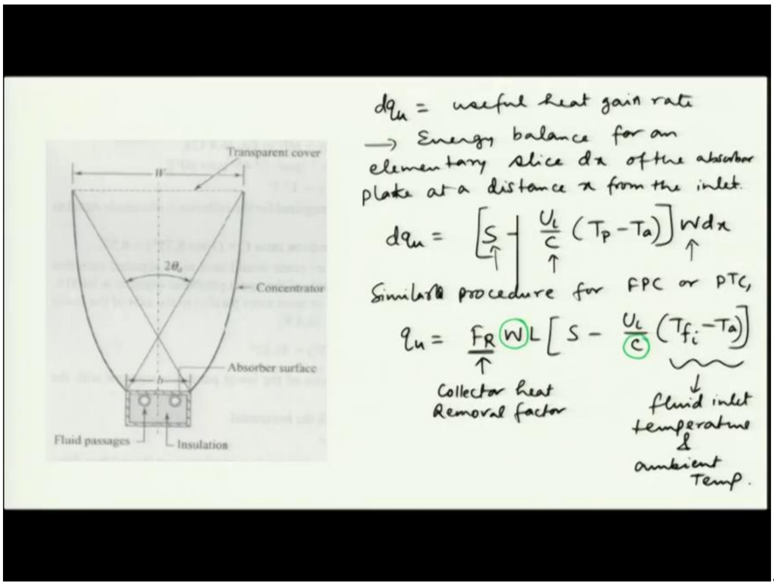

Here this S is per unit aperture width, because everything we have talked about it is on the aperture, ok. So, S will also be normalized per unit aperture width not per unit receiver width. So, that you have to pay attention to, ok.

Now, this dq_u, if we say that useful heat gain rate and how we will you will get it? By energy balance for an elementary slice dx of the absorber plate at a distance x from the inlet, ok. So, as you have seen earlier it will be,

$$q_u = \left[S - \frac{U_L}{C}\left(T_p - T_a\right)\right] W\, dx$$

For concentrating collector, you have this U_L/C factor, which is unlike the flat plate collector, ok.

And this is multiplied by aperture width $W\, dx$, because this S is per aperture width. So, U_L which is the effective loss coefficient that also we are taking in terms of absorber width or absorber plane, ok. So, we are skipping all the steps, we can just say that similar procedure for flat plate collector or what we have seen the parabolic trough collector earlier. What will we get? This q_u will be,

$$q_u = F_R W L \left[S - \frac{U_L}{C}\left(T_{fi} - T_a\right)\right]$$

When you have this collector heat removal factor involved, you can write in terms of the fluid inlet temperature and the ambient temperature. This you have seen earlier, only thing you need to pay attention is here. So, here you are using the aperture width not the receiver width, ok. And here, we introduce the concentration ratio, ok. So, these two you need to pay attention to which is unlike the previous cases, ok.

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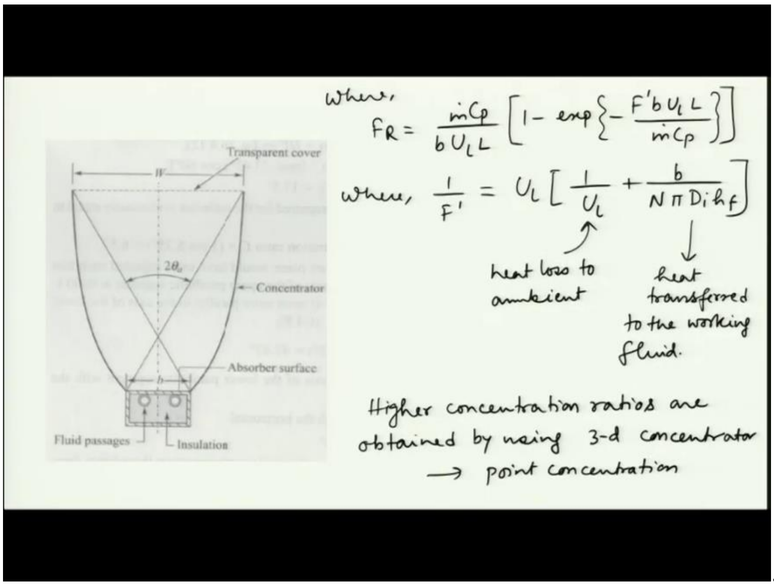

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So, here in that expression,

$$F_R = \frac{\dot{m}C_p}{bLU_L}\left[1 - exp^{\left\{-\frac{F' b U_L \mathrm{L}}{\dot{m}C_p}\right\}}\right]$$

So, b here is the receiver width, ok. Here in the heat removal factor the receiver width b is coming into picture, but in the expression of q_u the useful heat gain rate we have W, which is the aperture width, ok.

So, F' is collector efficiency factor, right. So, this collector efficiency factor can be expressed as,

$$\frac{1}{F'} = U_L \left[\frac{1}{U_L} + \frac{b}{N\pi D_i h_f}\right]$$

So, you can see that this is for the heat loss to ambient that is how this U_L is related to and this part is heat transfer to the working fluid. So, the working fluid details came into picture, N is the number of tubes, πD_i is the inlet perimeter and h_f is the heat transfer coefficient inside the fluid, and b is the width of the receiver. So, that is how we can get the heat transfer to the fluid from the compound parabolic collector, ok.

So far we have looked at the two-dimensional parabolic collectors, one is PTC which is the parabolic trough collector and the next one we have looked at is compound parabolic collector, which is nothing but the combination of two consecutive parabola and they are put according to certain algorithm. And that is how we receive less tracking requirement produces significant amount of concentration.

Next what we are going to look at the higher concentration ratio if we target, then we have to go for 3-dimensional or 3-d concentrator. So, higher concentration ratios are obtained by using 3-d concentrators or what we often call point concentrator. Instead of a line we now concentrate in a point. So, that is how we increase the concentration ratio.

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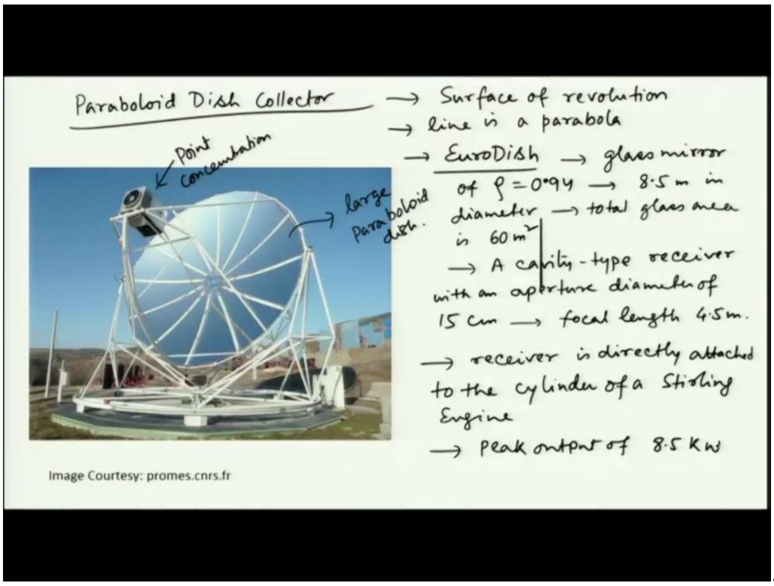

So, first thing here the most common is called the Paraboloid dish collector. The line that we are revolving that is a parabola. Line is a parabola or rather part of a parabola and we are revolving that around an axis and that is how we get the paraboloid shape and parabola dish collector is giving you a point concentrator.

So, the image that you are seeing, this is for an actual parabola dish collector which is named EuroDish, ok. So, this was a major event happened in Europe around 2010 where, few countries came together and designed this particular solar collector, where you can see that this is a large paraboloid dish. And where you are concentrating?

You are concentrating at a small area I mean in principle you are concentrating at a point, but of course, in practical you have practical limitation that you have to have a significant amount of area.

So, you can say that this is where the point concentration is happening, ok. So, the rays that are falling on the aperture are getting reflected and reaching that point concentration where we have some either the heat is being collected by some fluid or that heat is being used in some engine itself.

So, in case of this EuroDish what we have the glass mirrors of high reflectivity 0.94, and we have that the diameter is 8.5 meter, ok. So, you can imagine it is a big paraboloid and total glass area is 60 meter square, ok. And, we have a cavity type receiver here with an aperture diameter of 15 centimeter, ok.

So, you can see the large area 60-meter square is the mirror area or the aperture area, that part is getting concentrated into a small area of 15 centimeter diameter, ok. So, you can imagine the concentration ratio there, you can calculate as well and here the focal length is 4.5 meter, ok. Now, in this receiver here some fluid is not flowing to take that heat away. So, the receiver is directly attached to the cylinder of a Stirling engine.

Stirling engine is the typical solar engine which runs on external heat. So, any temperature difference it can convert into power and please look that up how a Stirling engine works, but for this paraboloid dish it is often used along with some Stirling engine. And, this particular EuroDish gives you the peak output of 8.5 kW, ok. So, this 8.5 kW of energy you can get almost free.

So, installation cost is of course there, but there is no fuel cost, right. So, that is why these solar paraboloid dish, they are very popular. And, we also have one very good example in our country in India.

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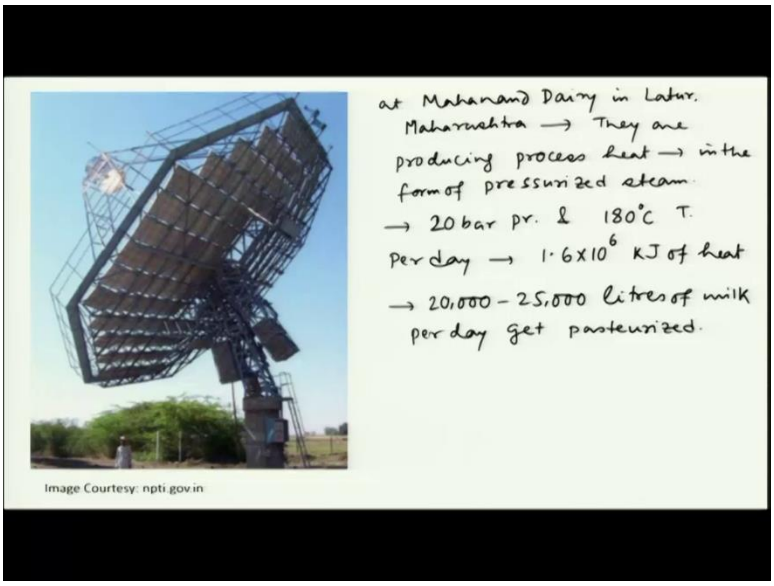

So, the figure that you see here is at Mahanand Dairy in Latur, Maharashtra, ok. So, this is a dairy farm and they have installed this particular paraboloid dish and they are not producing power with it, but what they are doing? They are producing process heat in the form of pressurized steam, ok.

So, for milk industry or dairy industry, what you need? You need to have process heat at certain pressure and temperature for the milk processing, ok. So, for pasteurization you need to have the heating at certain pressure, you cannot go below that pressure, because then the pasteurization process does not happen, ok.

So, in this case what they are having is 20 bar pressure and temperature of about 180 °C, ok. So, that kind of heat it is generating and per day it can deliver $1.6 \times 10^6\ kJ$ of heat, ok. That is a large amount of heat that it can produce again just free, it is just converting solar energy into this. And what can it do? It can pasteurize 20,000 to 25,000 liters of milk per day, ok. So, that is very practical example that we have.

So, this is also quite old, but there are new paraboloid dish collectors which are coming up for many agricultural industry, other industries, chemical or even dyeing industry, textile industry where process heat is a big part. And earlier we used to burn fossil fuel, gas or coal, but for this green push, now what we are trying to do? We are using the solar dish and we can get it almost free, ok.

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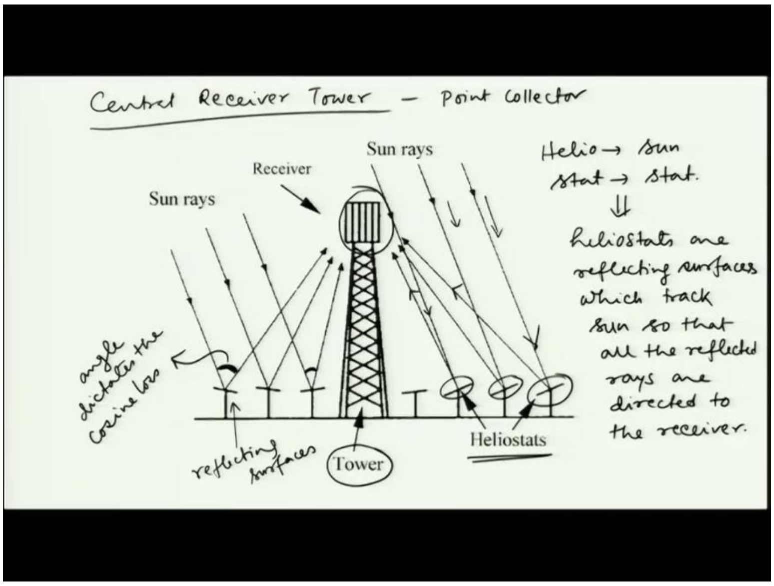

So, now the next concept we are going to discuss is called central receiver tower, ok. Again it is a point collector, and what it does? In a big field, in the middle of that field you put a tower, ok. Tall tower and on top of that you have some collector, ok. And around it in circular positions, you put lot of these reflecting surfaces, ok. These are reflecting surfaces. So, here you see, these are called heliostat.

Heliostat means what? Helio means sun and Stat means static. So, basically with respect to sun it does not move it is static. So, what it means is that it perfectly tracks the sun. So, that with respect to sun that position of the reflector is static. So, what it does? From whichever direction the sun rays are coming the reflectors they are individually tracked.

So, they ensure that whatever ray is falling on it, it is reflected back to a central point ok, that is how this central receiver tower works. And all of these are doing the same thing, ok. They are reflecting the sun rays to a central point and you have to put this central receiver at some height, then only all these receivers will be able to work without interfering each other without shading or blocking each other, right.

So, that is how a central receiver tower works. So, basically this means that these heliostats are reflecting surfaces, which track the sun so, that all the reflected rays are directed to the receiver, ok.

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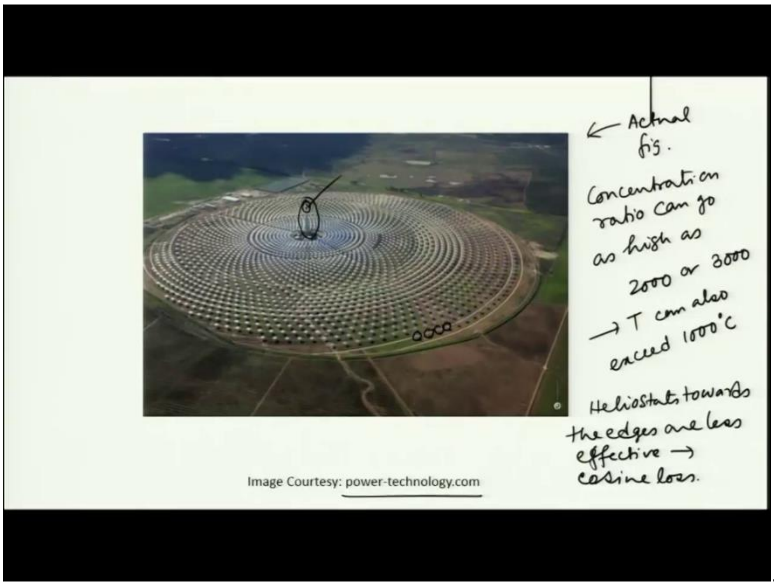

Now, you can see an actual figure for this central receiver tower, ok. So, again this is actual figure, and you can see here, that the central tower is here and receiver is at the top of it. And all these reflecting surfaces, individually you can see all these and there are lot of them, ok.

And all of them are oriented in such a way, that their reflected ray reaches this point. That is how you can generate a huge amount of concentration ratio. So, the concentration ratio can go as high as 2000 or 3000, ok. It depends on the design and the concentration ratio can go really high, but if you go that kind of high concentration ratio, the temperature that you can reach can also exceed 1000 °C.

So, when you increase the temperature, you know the kernel efficiency increases and the efficiency of the of the power plant increases, because temperature signifies the quality of heat. When the temperature is higher that heat is more useful, the quality of heat is more. So, in a heat engine it will produce more power, ok.

So, that is why for high temperature even super critical power cycles, we cannot use the parabolic trough or these things, but we can use this central receiver tower, where the temperature can go really high, ok.

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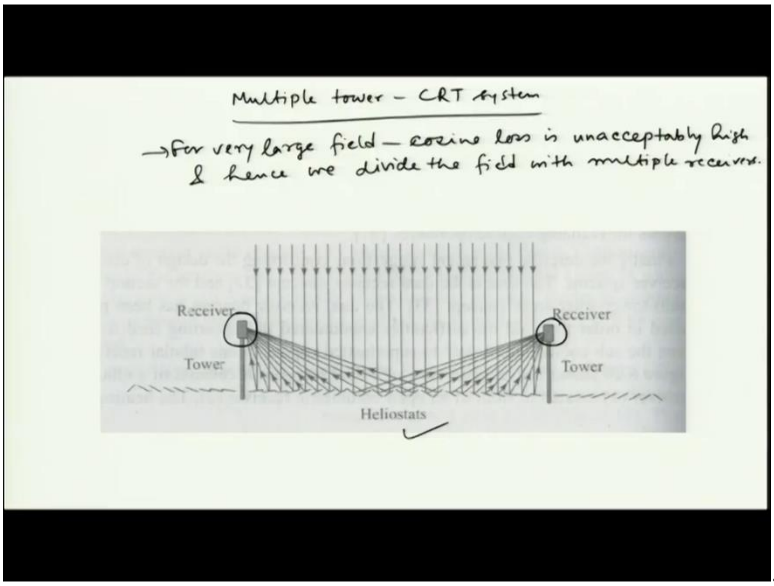

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Now, another variation you can have with these things with multiple towers, with multiple receivers. So, multiple tower CRT system, ok. So, that is also possible why do you need it? We do not have enough time to go in details of designing of this central receiver tower or heliostat field layout, there is a complete theory of that, but what we can say heliostat towards the edges are less effective because of cosine loss. So, when the receivers or the heliostats are forced to make the angle change a lot by reflection. So, the angle between the incoming ray and the reflected ray tells us that what would be the cosine loss. ok.

So, in the previous figure you can see here that this angle is more for the heliostat, which are towards edge, ok. Which are near the central tower this angle is smaller, ok. And this particular angle actually dictates the cosine loss. So, when that angle is larger you will have less amount of contribution from the heliostat towards the edges. So, that is why we cannot go for very large field, then the effective contribution of the edges will be low.

So, in that case what we do? We divide the field with more number of receivers. So, for very large field, cosine loss is unacceptably high and hence we divide the field with multiple receivers, ok. So, this is why this multiple tower CRT system is used, ok.

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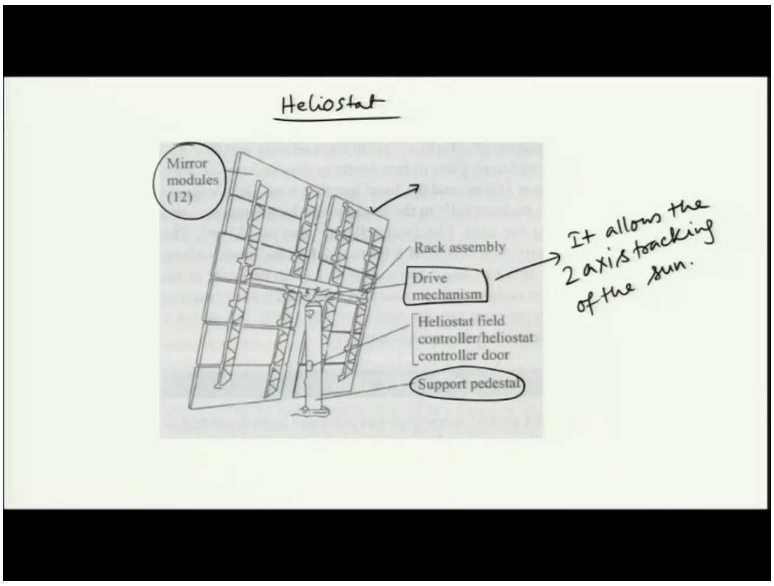

And if we look at a particular heliostat, then what you will find that a large reflecting surface which is this. So, large surface with lot of mirrors placed on it. So, these mirror modules they are placed on them and you have a support pedestal here and this whole thing is connected to some drive mechanism, ok. So, this drive mechanism what it does? It allows the 2-axis tracking of the sun, ok.

Of course, it is automated depending on the location of the sun it orients itself, so that it reflects properly to the receiver tower, ok.

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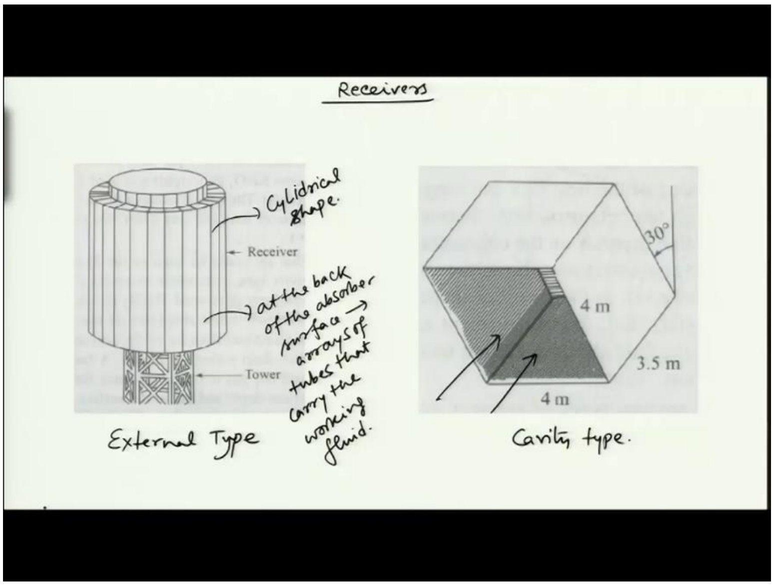

That is how a heliostat would look like and in the receiver part what we have is the tower and on top of that we have the receiver. So these are receivers and there can be two different kinds of receiver. One is called external type and other one is called cavity type, ok.

So, external ones, how do they work? Usually, they are of a cylindrical shape and the outside is the absorbing material. You have some coating which can absorb all the radiation it gets and at the back side you will have arrays of this tubes which are taking the working fluid. So, at the back of the absorber surface, we have arrays of tubes that carry the working fluid, ok.

And in case of cavity type what you have, you have not the external surface, but you allow the concentration happening inside a cavity. So, a small cavity is there through which all the rays go inside and there you have this array of tubes carrying the working fluid, ok.

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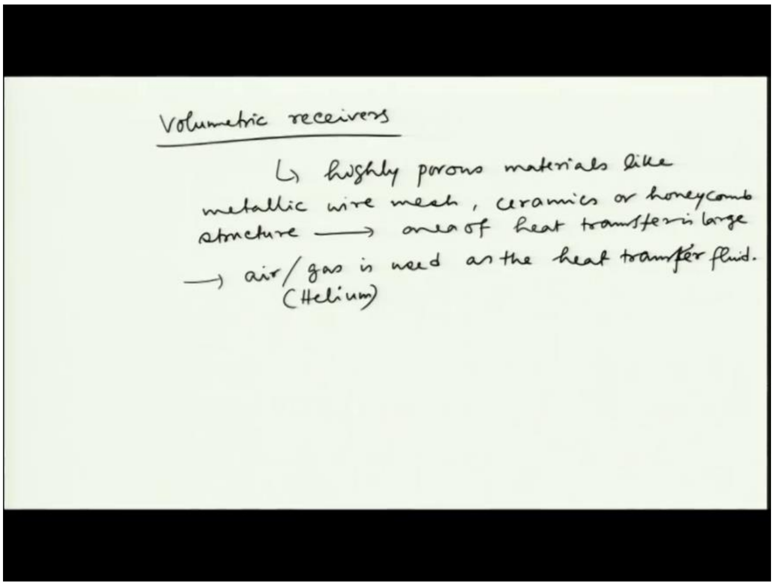

And another kind we can have which are now getting developed which are called volumetric receivers, ok. Other than the external or cavity type, we have these volumetric receivers. Where, we have this highly porous materials like metallic wire mesh or ceramics or honeycombs structure. These are all for the purpose of increasing the area of heat transfer. So, area of heat transfer is large and air or some gas is used (often helium is used for its desirable properties) as the heat transfer fluid, ok.

So, these are different kinds of receivers, the heliostat field geometries. Now, if we want to quickly analyze it, let us assume this CRT analysis, ok.

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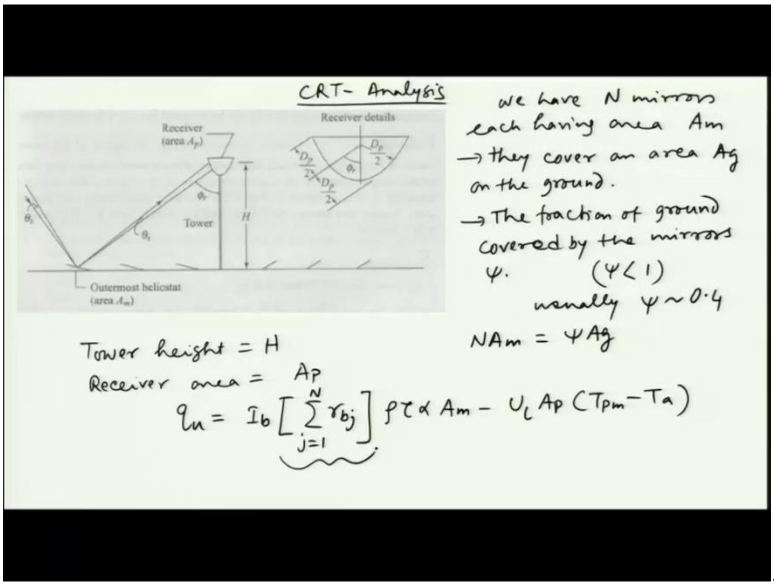

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So, let us assume that we have N mirrors each having area A_m, m stands for mirror and A stands for area, ok. And they cover an area A_g on the ground. So, you can see that the heliostats cannot be placed continuously, you have to put gaps in between, because otherwise the incoming rays we will be blocked by a neighboring heliostat or the outgoing ray or the reflected ray we will be blocked by the neighboring heliostat.

So, we have to keep these gaps between the heliostats and that is why the area, the whole heliostat field area only a fraction of that is getting used as the reflector area, ok. So, the fraction of ground covered by the mirrors is ψ that we can say because ψ is always less than 1 and it is usually much less than 1.

Usually, ψ is around 0.4, only 40 percent of the ground is covered by the mirror area. So, now, what we can write,

$$NA_m = \psi A_g$$

So, mirror area, only ψ fraction of it will cover the ground, ok.

Now, if we have this tower height (as in this figure) to be H, ok. And the area of receiver is A_p, then what we can write this,

$$q_u = I_b\left[\sum_{j=1}^{N} r_{bj}\right]\rho\tau\alpha A_m - U_L A_p(T_{pm} - T_a)$$

So, rest of the thing is very familiar only thing we do not know is this part, right. So, why that is coming?

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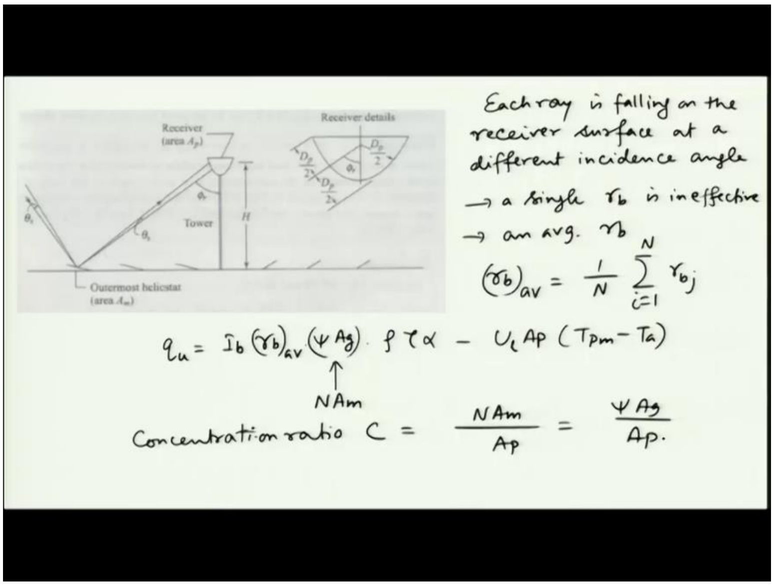

Now you will see that each ray is falling on the receiver surface at a different incidence angle. So, earlier we have seen for the plates and other receivers, we have a constant receiving angle, or the incidence angle, but here you can see all these different reflector, they are putting the rays back into the receiver and the incidence angle is continuously changing for each of the heliostat contributions.

So, that is why we cannot take a single r_b. So, a single r_b is ineffective, what we need to have? An average r_b, ok. And how we can find? That average r_b is,

$$(r_b)_{av} = \frac{1}{N}\sum_{j=1}^{N} r_{bj}$$

So, that is the major thing. So, what you can write now,

$$q_u = I_b(r_b)_{av}(\psi A_g)\rho\tau\alpha A_m - U_L A_p(T_{pm} - T_a)$$

So, ψA_g is equal to $\mathrm{N}A_m$ (total mirror area), τ means the transmissivity of the cover surface and α is the absorptivity of the receiver surface, T_{pm} is the mean plate temperature and T_a is the ambient temperature. So, that is how this heat balance is done, ok.

And here, I should mention the concentration ratio C is,

$$C = \frac{\mathrm{N}A_m}{A_p} = \frac{\psi\, A_g}{A_p}$$

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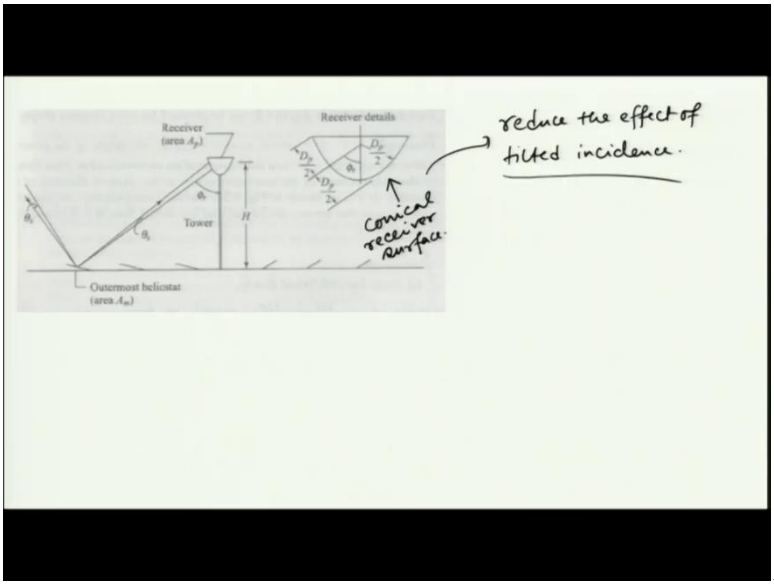

Now, we can have this kind of receiver where you have a conical receiver surface, ok. Which will basically reduce the effect of tilted incidence. So, that is often used. Now, we are not going to detail how those receivers are designed and all, that should be part of your further reading not in the part of the course.

So, here up to this course, today we are at 27th lecture. Upto this what we have completed is all the background that we require for solar energy conversion and all different kinds of or rather major kinds of the thermal solar energy converters, in terms of flat plate collector or the concentrating thermal collectors including the central receiver tower which are used for large scale solar thermal power plants, ok.

Now, from the next class onward for the rest of the lectures, what we are going to do is the photovoltaic part which you often see, which is the most commonly observable solar energy conversion device, the photovoltaic panels. How do they work? We will look at the basics of them from the next class.

Thank you so much.