

Radiative Heat Transfer
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Module - 8
Lecture - 39
Concentrated Solar Connector

Hello friends, in the previous lecture we discussed how the atmosphere affects solar energy reaching the earth surface. Now, this surface solar irradiation can be harnessed to generate energy, electric or mechanical in a number of ways. We all are familiar with solar photovoltaic, rooftop solar photovoltaic, solar thermal plants, where solar energy is converted into thermal energy.

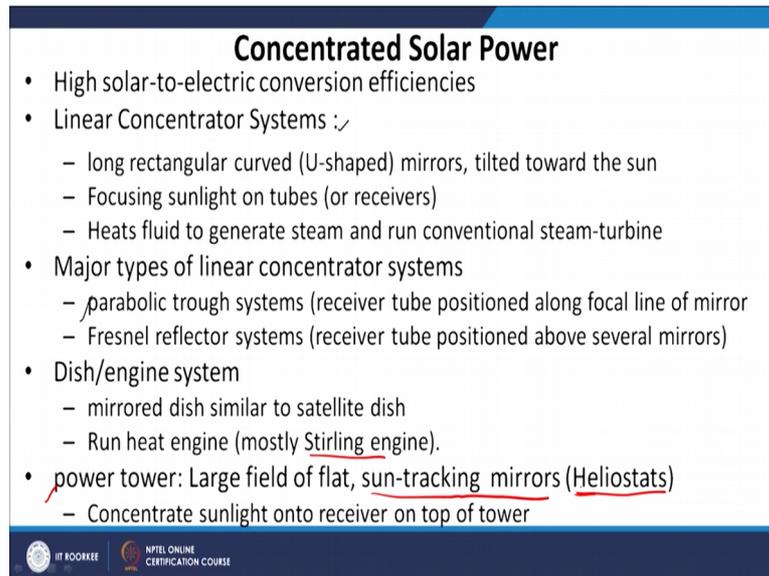
The, In this class, we will learn about concentrated solar collectors which is a special type of solar power where solar energy is concentrated in high intensity. And that high intensity solar energy is basically used to heat water, to generate steam. And then, this steam is basically used to run turbines. So, solar concentrated collectors or power plants, they have certain advantages. In certain places, lot of emphasis has been given to solar concentrated power.

But overall, the popularity of solar photovoltaic is much more than solar concentrated, because of the associated cost. But here in this lecture, we will discuss about the details. So, what are the peculiarities of concentrated solar power. So, here we are using some mechanisms. In your childhood, you must, might have also done this experiment by taking a lens and focusing solar energy through that lens on a page or a piece of paper and burning it.

So, what basically this lens does is, it concentrates solar energy in high intensity. And then increases the temperature of the object on which the energy is basically concentrated on. Now, why we want to do it in our energy application is because it gives you very high energy, have very high conversion efficiency compared to normal solar photovoltaic or other devices where the temperature is very low.

So, these devices give you higher efficiency and that is the point solar concentrated power plants are basically gaining importance. There are number of configurations in which these power plants are basically designed. They are linear concentrated system.

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Concentrated Solar Power

- High solar-to-electric conversion efficiencies
- Linear Concentrator Systems : ✓
 - long rectangular curved (U-shaped) mirrors, tilted toward the sun
 - Focusing sunlight on tubes (or receivers)
 - Heats fluid to generate steam and run conventional steam-turbine
- Major types of linear concentrator systems
 - parabolic trough systems (receiver tube positioned along focal line of mirror)
 - Fresnel reflector systems (receiver tube positioned above several mirrors)
- Dish/engine system
 - mirrored dish similar to satellite dish
 - Run heat engine (mostly Stirling engine).
- power tower: Large field of flat, sun-tracking mirrors (Heliostats)
 - Concentrate sunlight onto receiver on top of tower

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In this we have long rectangular curved mirrors. So, we use mirrors which are long and curved. And they are tilted towards the sun. What they do is, they focus sunlight on a series of tubes. And these tubes basically carry fluid. Maybe water or it may be some other fluid. And as a result of heat transfer through this concentrators on these tubes, the temperature of the fluid rises.

And either they are converted into steam or if some other material is used as a fluid, then lot of heat transfer takes place. And we basically use this heat to generate power through some thermomechanical means. In this category, we have 2 important configurations. The first is parabolic trough concentrated system. In this, the tube is at the focal point of the mirrors. And the other is Fresnel reflector system, where we have number of mirrors and a tube which is positioned above the mirrors, not necessarily at the focal point of the mirrors.

The first one, parabolic trough system is the most popular. Although there are few power plants in the world which are basically designed based on the Fresnel refracted system. The second in this category is dish system. We here we have a form of dish antenna which focuses sunlight. And this focused sunlight basically raises the temperature of a fluid which is used to run some kind of engine.

And mostly we have Stirling engines used in these applications. So, these are also used in small scale solar concentrated systems. These dish antennas are manufactured for small applications. And the third is basically concept of power tower or solar tower. Where we have

a large field of a solar concentrated system and there is a huge tower. And the light falling on these mirrors on a large field is focused on the tower.

And in the tower, it is used to generate some kind of steam. If water is the working fluid, some kind of here a mechanism is used to generate steam. And then, steam is used to run turbines. There may be other substance other than water which may be used as a working fluid to generate power. Now, these mirrors in the solar tower system are basically tracked by some tracker, so that they are always pointing towards the sun.

So, we have called them sun tracking mirrors. And these are also called heliostats. Okay. So, these sun tracking mirrors are called heliostats. And a large field of heliostats basically focus solar energy onto a onto a tower.

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So, these are some of the figures for these type of applications. These are, these is called basically parabolic trough. So, we have parabolic mirrors in lines. And there are tubes at the focal point. And through this tubes, water is basically being passed. And this concentrated power basically heats the temperature of the water significantly. And then, this heated water can be converted into steam.

And that steam can be used to generate power. Then we have dish type system. We have a dish antenna which focuses the solar energy onto this receiver. And then, this is a solar tower, where we have a large field of solar reflectors. And they all reflect the radiation towards this tower in which now the steam is basically generated.

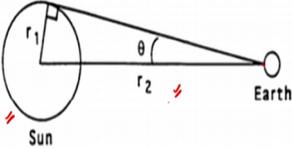
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Law of Maximum Concentration

- ❖ Solar irradiance decreases as $\frac{1}{r^2}$
- ❖ At orbit of earth

$$I_2 = I_1 \left(\frac{r_1}{r_2} \right)^2 = I_1 \sin^2 \theta$$

- ❖ 2nd Law of Thermodynamics forbids: $I_2 > I_1$



$C I_2 \leq I_1$

$C \leq \frac{1}{\sin^2 \theta}$

$C \leq \frac{n^2}{\sin^2 \theta}$

$C \leq \frac{n^2}{\sin^2 \theta}$

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Now, before we go to the analysis of these type of mirrors, from radiation point of view. We should understand the law of maximum concentration. We will derive the same result from 2 points. 1 is thermodynamic point of view and the second is the radiation point of view. So, let us understand the thermodynamic or second law point of view. So, let us say we have sun. Okay.

The sun, the intensity of the sun, we know that intensity does not change but the heat flux, basically the energy per unit area changes from point to point. If we go from, far from the sun, the amount of energy per unit area will decrease. Okay. And the decrease is proportional to 1 upon r square. So, solar irradiance or energy per unit area decreases with distance. And the decrease is proportional to, inversely proportional to r square.

So, if let us say the intensity at the surface of the sun is I_1 . The r_1 is the radius of the sun. And the intensity at earth outer atmosphere; so, here we will just look at the outer atmosphere only, because we do not want to go into the details of how the atmosphere basically interacts with intensity. So, if let us say at the outer atmosphere the radius is r_2 , then, and the intensity is I_2 , then the relation I_2 upon I_1 is r_1 upon r_2 square.

Where r_1 is the radius of the sun and r_2 is the distance between sun and the earth. Now, this r_1 by r_2 from this triangle is simply = sin theta. So, we get I_2 is = I_1 sin square theta. So, the intensity of the sun or intensity of solar radiation basically decreases as sin square

theta. Okay. Now, as per second law of thermodynamics, So, what does second law of thermodynamics basically says; that I_2 cannot be $> I_1$.

So, that is the second law limitation. That means, heat cannot transfer from a low temperature body to a high temperature body. That is the limitation of second law of thermodynamics. So, what it says is that the intensity of radiation, because the sun is a source of this radiation and the intensity at the surface is I_1 . So, this intensity cannot become greater than I_1 . So, I_2 cannot be $> I_1$. That is the thermodynamic limitation on this.

Now, how can I_2 increase. As per this relation I_2 will always decrease. The farther you go from the sun, the intensity should decrease. So, what are the mechanism by which intensity can increase? The mechanism is concentration. Okay. So, we can concentrate solar radiation by either mirrors or through lenses. So, by focusing through mirrors and lenses we can concentrate, but the thermodynamic limitation says that C times I_2 should be $< \text{ or } = I_1$.

So, that is the limitation of the second law of thermodynamics. That even after concentration, even after a increasing the intensity of solar radiation by means of lenses or mirrors, you cannot increase the irradiance more than the irradiance at the surface of the sun. And by substituting the value of I_2 by I_1 , we get C is $< = 1$ upon \sin^2 theta. If we have a medium with refractive index n , then C is $< = n^2$ upon \sin^2 theta.

So, this is the maximum concentration you can do. So, you can design any mirror, you can design any lens, but you cannot increase the concentration by this factor. So, 1 upon \sin^2 theta is the limit by which you can increase the concentration of the solar radiation.

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Problem

- ❖ Calculate the maximum concentration factor for sunlight in Earth's orbit
- ❖ Distance of Sun from Earth = 149.6×10^6 km ✓
- ❖ Radius of Sun = 695,508 km ✓

$$C \leq \frac{1}{\sin^2 \theta}$$
$$C_{max} = \frac{1}{\sin^2 \theta} = \frac{D^2}{R_s^2} = \underline{46,265}$$
$$C_{max} = \frac{n^2}{\sin^2 \theta} = \underline{1.5^2} \frac{D^2}{R_s^2} \approx \underline{100,000}$$



Now, let us do some number calculations for our earth and sun system. The distance of sun from the earth is given by 149.6 into 10 to the power 6 kilometer. This is the distance between earth and the sun. And radius of the sun is 695,508 kilometer. If you substitute these values in our relation, $C \leq 1$ upon sin square theta, we get C max. That is the maximum amount of concentration is 1 upon sin square theta.

D square upon R s square, where D is the distance and R is the radius of the sun. We get 46,265. So, the maximum amount by which you can concentrate solar energy is 46,265. If you are trying to focus this energy, if you are trying to concentrate this energy in a medium with refractive index, let us say 1.5, then it can go up to 100 thousand or 1,00,000. So, concentration can increase up to 1,00,000 if you are dealing with a medium with refractive index $n = 1.5$.

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Concentration Ratio of Devices

Device	C	Temperature	Efficiency	Power MW
Parabolic Trough	60-80	500 °C	< 20 %	20 -100
Linear Fresnell	60-80	500 °C	15 %	10-50
Dish	1000	1600 °C	30 %	50 kW
Power Tower	600	800 °C	20 %	200-500
Solar Furnace	10,000	2000 °C	Application in laser, space propulsion, material processing	

Now, let us look at some of the devices. So, parabolic trough, they are typically designed for concentration of 60 to 80. So, we have this parabolic concentrator that can focus energy and increase the irradiance by 60 to 80 times. The temperature of these devices is around 500 degree C. The efficiency is < 20 percent. And they are designed to, so far, the parabolic trough have been used as a technology to design power plants with the range of 20 to 100 megawatt.

Linear Fresnel collectors concentrated power plants, they are very few in number in the world. And they are basically in the same concentration range, same temperature range. Efficiency is also very similar. Okay. It is just a different technology. There is a maximum 50 megawatt power plant that has been designed in this category. Now dish based power plants are very very much less in size.

They have concentration of around 1,000. The temperature can reach up to 1600 degree C for these type of applications. The efficiency is high, 30 percent. So, for local applications dish type solar concentrators are very useful. And they are used in number of places. Typically, 1 dish type concentrator can give you around 50 kilowatts. The power tower where we have a field of concentrator.

They have a concentration of the order of 600 temperature, 800 degree C, efficiency around 20 percent. So, they are useful when we want to utilize them for large power projects. So, 200 to 500 megawatt if you want to design a power plant, these type of power tower concepts are

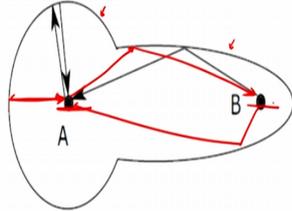
very useful. Now, solar furnaces are an upcoming concept. In solar furnace, the concentration is really very high, around 10,000.

The temperature can reach up to 2000 degree C. So, these type of a concept have applications in lasers, space propulsion and material processing like in furnaces and all. So, solar concentration has wide applications and you can focus the energy in different amounts for different type of application.

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Ellipse Paradox

- Objects A and B are at focal point of ellipse
- A at the center of sphere
- All radiation leaving A comes back to A if it hits the sphere
 - Small fraction reaches B
- Most radiation leaving B reaches A
- A heats up and B cools down
 - Violation of second law of thermodynamics
- Resolution:
 - A and B cannot be point object



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Now, before we go into radiative analysis of these concentrator, let us just focus on ellipse paradox. Okay. So, let us say we have point source. Okay. And we have 2 mirrors. 1 is spherical mirror and 1 is elliptical mirror. So, 2 mirrors are there. Now, A is the center of this sphere. And B and A are at the focal point of this ellipse. So, we have ellipse which has focus point A and B. And we have a sphere which has center at A.

Now, let us say all the radiations; so, whatever radiation leaves A, it will hit the surface. Now, let us assume that the surface of sphere and ellipse are perfectly reflecting. And they are specular. So, whatever radiation basically hits the surface will come back to the sphere center itself. So, nothing will basically go to the ellipse. However, any radiation that leaves in this direction will hit the ellipse and it will go to B.

So, we see that only a small fraction of the energy emitted from A will go to B. Most of the energy will basically come back to A. On the other hand, whatever energy is emitted from B will actually go to A. So, it means, if you look at this, more amount of energy is basically lost

by B than A. And from thermodynamics point of view A should get heated up and B should get cooled.

So, initially if we assume that both A and B are at the same temperature. And A is losing less energy and B is losing more energy, the temperature of B will basically decrease and temperature of A should increase. Now, from thermodynamics point of view, it is not possible. In thermodynamics, you cannot transfer heat if the 2 bodies are at the same temperature. Then, how basically this is happening?

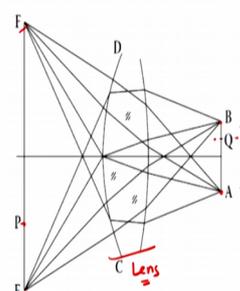
And this is called ellipse paradox. Okay. And the answer to this question is that transfer of heat from A to B and B to A is possible only if A and B are not points, only if they are extended surfaces. Okay. That means, if they are represented as a point, then heat transfer cannot take place the way we have basically defined it. So, point objects is not possible in radiative heat transfer.

There cannot be a surface which is point like, which is 0 dimension in its shape. So, in radiative heat transfer, there cannot be any 0 dimensional shape. There cannot be any point surface which basically emits or absorb radiation. And that is the difference in the theory that we are going to discuss in this lecture.

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Concentrator

- To transmit maximum amount of energy to absorber
- **Image versus Non-Image Optics**
- Image Optics: ✓
 - Lens/Mirror, object and image
- Non-imaging optics
 - Lens/Mirror, Light source, receiver
 - No image of the source is formed
 - Required irradiance achieved at the receiver/absorber
 - AB may or may not represent image of EF
 - IF AB is image : Q may not be an image of P (Aberrations)






So, what is a concentrator? Now, here there are 2 points. 1 is imaging device and 1 is non-imaging device. In imaging device, we call it optics. So, you all have studied optics in class twelfth. What we have is, we have a object E and F. And there is a lens. This is the lens. And

it forms an image AB. Okay. The image of EF is basically the image of AB. Okay. That is basically we have learnt in optics. Okay.

So, optics basically comprises of lens, mirrors, object and image. That is basically the optics. Now, the point here is that, what you have learnt so far in optics is not necessarily true. So, optics is a branch where you can produce, reproduce images of certain objects. But these images are not sharp. They are subjected to aberrations. So, I will not go into the details of optics here in this lecture.

The point that I want to emphasize here is, it is not possible to reproduce a sharp image of EF onto AB. So, as an example, if you have a point P in between EF, then Q will not be its image. It is not possible. Suppose you have made an image EF as AB. Then point P will not have its image Q. It will be either shifted on this side or that side. So, there will be aberrations. There will not be a sharp image.

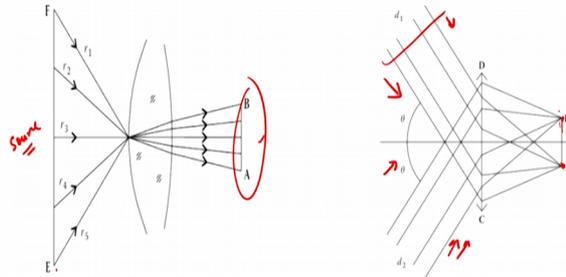
So, we cannot use principles of optics to design our solar collector. The concentrated solar collector, we cannot use the concepts of optics. But the point is, we do not need the knowledge of optics to design solar concentrator. And that is why the branch has been developed and this called non-imaging optics. So, what basically it say that, we do not need to form the image. Okay.

We, what we want is, we have a light source coming from sun. And most of the radiation coming from the sun, we want to concentrate on a small object which will generate energy in the form of steam or whatever. Okay. So, what we want to basically do is, we want to, let us say this is the light source EF. Okay.

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Concentrator

- Infinitely displaced source (Sun)
- Half angular aperture
- Device designed to concentrate rays (d_1) onto A and rays (d_2) onto B
- All radiation (angle $<$ half angular aperture angle) passes through AB



So, EF is the source from which the radiation is come. So, we are not interested whether AB is a image of EF or not. So, we do not want to answer this question, whether AB is an image of EF or not. You must have done this in your childhood also. Where you take the lens away and closer, the image becomes sharper. So, when you bring the lens closer, the image becomes little sharper. If you take the lens away, the image becomes little blurred.

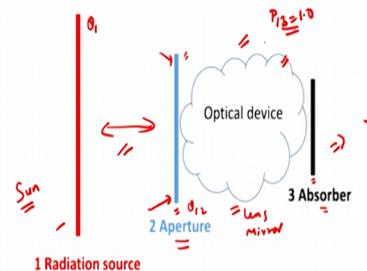
So, but the point is, we are not interested in whether the AB is image or not. What we are basically interested in is that all the radiation coming from EF should pass through AB. Whether AB is image or not does not matter. So, all the radiation coming from EF should pass through AB. So, that basically what we want in solar concentrator. So, we want to design optics such that all the radiation coming from let us say in this direction d_1 should focus on A.

And all the radiation coming from this direction should focus on B. Then whatever radiation coming from intermediate direction will focus between A and B. If radiation coming from this direction focuses on A. And radiation coming from this direction focuses on B. Then whatever radiation comes between these 2 directions will pass through AB. Whether it focuses on between AB or not does not matter. It may focus here, it may focus here, does not matter. But it will pass through the line AB. And that is basically the logic behind the design of this concentrated system.

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Maximum Concentration

- Objectives: collect maximum amount of energy with minimum area of the collector/absorber (maximize C)
- Design of suitable optics/non-imaging optics
- $C = \frac{A_2}{A_3}$
- $C =$ Geometric Concentration ratio



So, let us see how we can design this using the view factor algebra that we have discussed. So, let us say we have a radiation source. In this case, we will be having sun. We have an aperture. So, we will put some aperture through which the radiation will enter. Then we will use some optical device, maybe lens or mirrors. And what these lens and mirrors will do? They will focus all the energy onto this absorber.

So, this is the plate on which we want to focus all the energy. So, our objective is to design this. Okay. The concentration is defined as A_2 by A_3 . So, amount of radiation that we actually collected is = the area A_2 of the aperture. That is the total amount of radiation we have collected. All the radiation that passes through A_2 we have collected. And all this radiation we have focused onto a small area. A_3 may be actually very small. Okay.

We have seen that it could be a difference of 1,000. If we have concentration of 1,000. It could be 10,000 for certain applications. So, what we want is, we collect maximum amount of energy. We want this aperture to be as big as possible, to collect as much amount of energy as possible. And we want to focus this on a small absorber. So, that is basically the concept of concentration.

And we define concentration as the ratio of A_2 by A_3 . The aperture area divided by the absorber area. That is defined as the concentration. Now, we will use the calculation of view factor to find out the concentration A_2 by A_3 . So, from this image, just look at it; the amount of radiation coming from the sun Q_{12} and received by the aperture Q_{12} is = Q_{13} .

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Governing Equation

$$Q_{12} = Q_{13}$$

- Let us assume all surfaces are black and at same temperature

$$Q_{12} = Q_{21} \quad \text{Thermodynamics}$$

$$A_1 \sigma T^4 P_{12} = A_2 \sigma T^4 P_{21} \quad =$$

- P_{12} : fraction of energy leaving surface 1 received by surface 2 after reflection and refraction by optical system

$$A_1 P_{12} = A_2 P_{21} \quad -D$$

- Rule of reciprocity

That is what we want. So, whatever radiation is received by the aperture should basically fall into absorber. Now, from radiation analysis point of view, we assume all surfaces are black and at the same temperature. Such that, Q_{12} is = Q_{21} . So, that means, if instead of sun, the surface 1 which is sun. Surface 2 is radiating. Then whatever energy is radiated from 2 should go to 1. So, Q_{12} is = Q_{21} from thermodynamics.

So, this is from thermodynamics. If both are same temperature, then from thermodynamics point of view, Q_{12} should be = Q_{21} . And all that bodies are at same temperature. Now, Q_{12} can be written as area 1 sigma T to the power 4 P 1 2. Now, P 1 2 is equivalent to view factor. It is not necessarily the view factor. I will explain what is P 1 2. And this will, the right-hand side becomes A 2, area of the surface 2 sigma T 4, because temperature is same and P 2 1.

Now, we have discussed in this course view factor. So, view factor is the fraction of energy emitted from 1 surface and received by another surface. That is view factor. Then we discussed exchange areas. Direct exchange area is the amount of energy emitted by 1 surface and received by another surface, but the energy may be subjected to absorption by the gas intermediate gas. Now, P 1 2 is basically the amount of energy emitted by surface 1 and received by surface 2 after undergoing whatever optics basically falls in the way.

It may be reflection, it may be concentration, whatever. So, P 1 2 is basically a fraction of energy leaving surface 1, received by surface 2 after reflection, refraction, whatever optical system that basically falls on the way. So, in this way, we have defined the this factor P 1 2.

So, now from this relation, we cancel out sigma T to the power 4. So, we get $A_1 P_{12} = A_2 P_{21}$. This is the same reciprocity rule that we have discussed many times. Okay. So, reciprocity rules holds true even for the optics that we are discussing here.

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Governing Equation

- Similarly

$$Q_{13} = Q_{31}$$

$$A_1 P_{13} = A_3 P_{31}$$

$$A_1 P_{13} = A_3 P_{31} = A_1 P_{12} = A_2 P_{21}$$

$$C = \frac{A_2}{A_3} = \frac{P_{31}}{P_{21}}$$

- Generally, P_{21} cannot be manipulated as it depends on position of the sun
- Need to manipulate P_{31} with proper optics to optimize concentration $P_{31} \rightarrow 1$

$$C \leq C_{\max} = \frac{1}{P_{21}}$$

Same thing we can do for surface 1 and 3. So, amount of radiation coming from sun and falling on absorber is Q_{13} . And because they are in thermodynamic equilibrium, so it should be $= Q_{31}$. And we get $A_1 P_{13} = A_3 P_{31}$. And combining this equation, let us call this equation 2 and this as equation 1. So, combining 1 and 2, we get this relation $A_1 P_{13} = A_3 P_{31} = A_1 P_{12} = A_2 P_{21}$.

Now, from this, this relation and this relation, we can write down concentration ratio $C = \frac{A_2}{A_3} = \frac{P_{31}}{P_{21}}$. So, the concentration is basically $= \frac{P_{31}}{P_{21}}$, where P_{31} is a kind of exchange factor between the absorber and the sun or the source. And P_{21} is basically the exchange factor between the aperture and the source. So, generally P_{21} , you cannot manipulate the P_{21} , because P_{21} is basically decided by the sun and the aperture.

So, you cannot manipulate, sun cannot change its position, while aperture is also fixed size. So, you cannot manipulate P_{21} . So, P_{21} is the exchange factor between sun and the aperture, which you cannot manipulate. But you can manipulate the absorber by designing optics. So, if you look at this image, you cannot define what is happening here, you cannot alter it. Because sun is fixed and aperture is also fixed.

So, you cannot change what is happening in this region. But you can change what is happening in this region by designing a suitable optical system. So, we will design mirrors, we will design lenses in such a way that this is maximized. So, P_{13} is = 1. So, we will design optics in such a way that P_{13} is = 1. So, P_{31} is = 1 that gives you the maximum value.

So, we need to manipulate P_{31} with proper optics to optimize concentration. And the maximum concentration from this relation is when P_{31} is = 1. And we get this value as P_{21} . Okay. So, maximum concentration is = P_{21} .

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Hottel's Cross String Method

- Two dimensional plates
- Exchange factor

$$P_{21} = \frac{(AD + BC) + (AC + BD)}{2CD}$$
- Source at infinity: $\Delta\theta \approx 0$
- $AC=AE$; $AC=BD$; $AD=BC$

$$P_{21} = \frac{2(AD - AC)}{2CD} = \frac{DE}{CD} = \sin\theta$$

$$C_{max} = \frac{1}{\sin\theta}$$

Now, we will use the Hottel's cross string method which we have discussed earlier also. So, Hottel cross string method says that the exchange factor or view factor between 2 surfaces. Now, assuming there is no optics in between, we can use Hottel's cross string method. So, exchange factor P_{21} is = the diagonal elements, diagonal string AD and BC and side elements AC and BD.

So, sum of diagonals + the AC + BD. So, we, and then divided by 2 times CD. This is the Hottel's cross string method that we have discussed. Now, in this case, we want to find out the value of P_{21} . So, this is what we want to find out. So, 2 is the aperture and 1 is the sun. And we know sun is located at very far distance. So, when sun is very far, the angles delta theta in this geometry will be very small.

So, delta theta will be very small. And we can approximate AC is = AE. So, AC, this length is = AE, this length. And AC is = BD by symmetry. And AD is = BC. So, by symmetry, this is = this one. So, using this relation, now this should be -. So, using this relation, P 2 1, the exchange factor is = 2 times AD - BC upon 2 CD or is = DE. DE is the distance this distance upon CD. And from this triangle DE by CD is sin theta.

So, you get C max is = 1 upon sin theta. Now, what we got this relation from thermodynamics, we got C max from thermodynamics as 1 upon sin square theta, right. The maximum concentration you can do is 1 upon sin square theta. That was from thermodynamics point of view. But here we get a relation 1 upon sin theta. So, why there is a difference of square from thermodynamics and this relation?

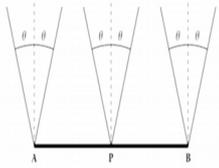
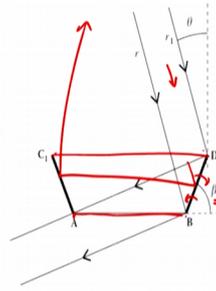
The reason is, this is only for 2D geometry. In this we have assumed that the plates are infinite in the plane of the board. While this relation is for 3D. So, this relation is true. Both the relations are correct. This is for 2D. And C max is = 1 upon sin square theta if it is 3D. So, the same relation that we derived from thermodynamics, we have also derived from the radiation point of view. And it says that C max is = 1 upon sin square theta for a 3-dimensional geometry.

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Compound Parabolic Concentrator

- Concentrate maximum radiation
- Flat mirrors at angles β
- Angle β be as small as possible to maximize aperture
- Minimum limit on β : radiation reflected towards mirror C

$P_{31} = 1.0$
 $C_{max} = \frac{1}{\sin^2 \theta}$

Source: Introduction to Non-imaging optics, Julio Chaves




Now, how do we design a parabolic concentrator such that P 3 1 is = 1. Now, this is the our objective. We want to design optics in such a way that the P 3 1 is = 1. And our C max becomes = 1 upon P 2 1 or = 1 upon sin square theta. So, this is how we want to design our

system. So, how do we do? Let us say we have a absorber plate, a flat absorber plate. So, AB is a absorber plate. This could be a simple silicon plate or whatever.

So, we have a flat plate. And it receives radiation over an angle 2θ . So, solar radiation is coming onto this plate within this angle 2θ . Now, how do we do, how do we maximize it? So, we want, if you do not use any optics, if you do not use mirrors, then the total amount of radiation received is = is proportional to the area AB. If you do not use optics, the direct expose this to solar radiation.

Then the total amount of radiation basically received by this absorber plate is = or proportional to its own area. So, in this case, the irradiation or energy absorbed by this plate Q_{13} is proportional to area of the plate AB. Okay. So, this is going to be very less. So, normally this plates are not very large in dimension. So, this is going to be very less. And we want to maximize it. So, how do we maximize it?

So, we want to maximize it by putting a larger aperture such that this is our absorber and this is the aperture. So, what you want net? On small absorber, all the radiation falling on this aperture should basically pass through. So, all the radiation that is coming through this aperture basically should pass through this absorber plate. And how do we do that? We put mirrors. So, let us say this is the plate, absorber plate.

We put 2 mirrors BD and AC adjacent to it. Now, what could be the angle of this flat mirrors? Let us say β is the angle of this flat mirrors. If we decrease β ; that means, if we move the mirror this side, what is going to happen? Our aperture is going to increase. The aperture size is CD. This is the aperture size. If we increase, if you decrease β , aperture is going to increase. So, that is good thing.

We want aperture to be as large as possible. So, we should have β as small as possible. If we decrease β , aperture will decrease. So, we do not want β to be large. We want β to be small. But if we keep on increasing β , what will happen is, the radiation will not pass through A. Rather it will pass through AC. It will fall on this and then here. And then it will be refracted back. And this is something we want to avoid.

So, what you want is, radiation coming from this side should be reflected onto A or focused onto A. No radiation coming from this side should fall beyond A. So, there is a limit on the value of beta. Beta cannot be small enough so that the radiation coming from the direction r_1 falls on mirror AC. Okay. So, there is a limit on AB. Now, once we have decided what will be the minimum angle of beta, we have fixed the aperture size. Now, we want to increase more. So, we can add more mirrors.

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Compound Parabolic Concentrator

- Ray r_2 after reflection at point D_2 should hit the absorber at A in extreme position
- Mirror size can be small to make a parabolic concentrator
- The shape of parabolic concentrator starts concaving inwards:
 - Reducing aperture
 - Shadowing the cavity

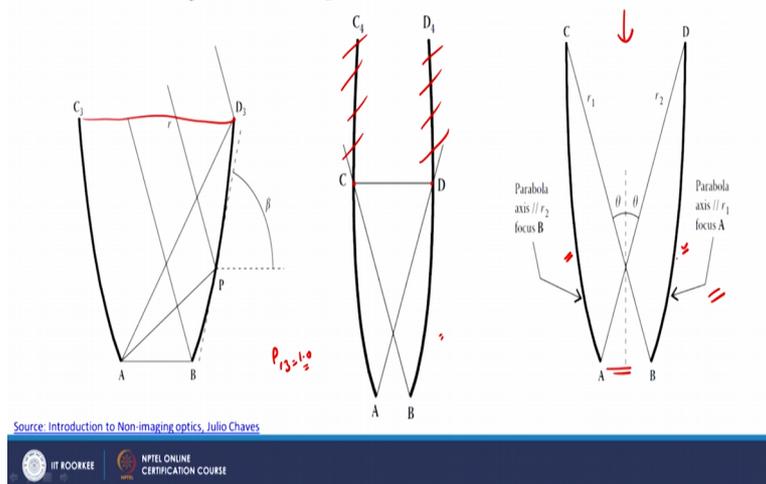
Source: Introduction to Non-imaging optics, Julio Chaves

So, in this case, we have added more mirrors. Again, we decide what angle should be there. Now, here what we decide is, whatever radiation coming from direction r_2 should pass through A again. Okay. So, that it is not reflected back. If it is $>$ this value, then it will fall onto it and it will be reflected back. So, whatever radiation falls, the extreme radiation falls onto this mirror, should be coming to A.

So, we have added 2 layers of mirrors and whatever radiation coming from this direction, all the radiation is basically passing through AB. And no radiation is actually falling onto the mirrors AC 1 or AC 2. So, we do not want any radiation to be reflected out of this cavity. So, we keep on adding mirrors.

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Compound Parabolic Concentrator



And we assume that the mirrors are very small in size. So, what we get is a parabolic geometry. So, this is a parabolic geometry. Okay. And this is the aperture. So, we have focused all the radiation coming from sun at a certain angle theta coming through this aperture CD. And all the radiation that enters through this aperture into this mirror cavity, basically passes through AB. And such a device is called perfect concentrator.

The P 1 3 for such a device will be = 1. Because it concentrates all the radiation. Now, 1 thing you should observe is, in the intermediate figure; so, these 2 are basically parabolas and these parabolas starts to concave inverse. So, this is the maximum distance, maximum separation distance between these 2 parabolas. And after that the distance basically starts decreasing or the aperture stars decreasing.

So, we do not want aperture to be decrease we want aperture to be as large as possible. So, we cut the top version. So, this portion we cut. And we keep the geometry from A, B, C and D. So, this is the final geometry of the parabola. This is the final concentrator. So, what is this constructor doing? In this concentrator, we will orient this concentrator towards sun at a certain angle.

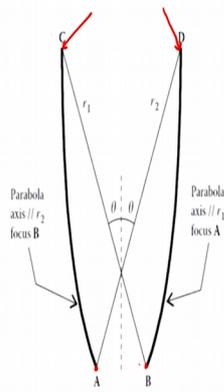
All the radiation that enters this cavity basically will be focused onto AB. And no radiation will be basically reflected out. So, whatever radiation enters the cavity basically will be focused on to AB. So, that is basically the concept of parabolic, compound parabolic concentrator. Why compound? Because we have 2 parabolas. This is parabola 1 and this is

parabola 2. So, we have 2 parabolas. And that is why this is called compound parabolic concentrator. Okay.

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Compound Parabolic Concentrator

- Characteristics:
 - Two parabolic mirrors
 - Arcs—AC : axis parallel BC (tilted θ to the left) and focus A
- Edge-ray principle:
 - Rays coming from edges of source of radiation deflected onto receiver's edges





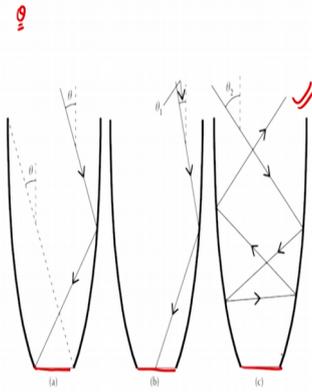

So, we have 2 parabolic mirrors. Okay. And the principle of edge-ray is basically, whatever radiation comes and falls on the edge should basically focus on this edge. Whatever radiation comes on this edge should focus on this edge. That is the principle of edge-ray principle. And this type of concentrated design is called compound parabolic concentrator. Okay.

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Compound Parabolic Concentrator

- $\theta_2 > \theta$: all rays are reflected out
- Acceptance
 - Fraction of rays hitting the receiver
- The compound parabolic concentrator gives maximum possible concentration

$$C_{max} = \frac{1}{\sin \theta}$$

$$h = A \frac{1 + \sin \theta}{2 \tan \theta}$$


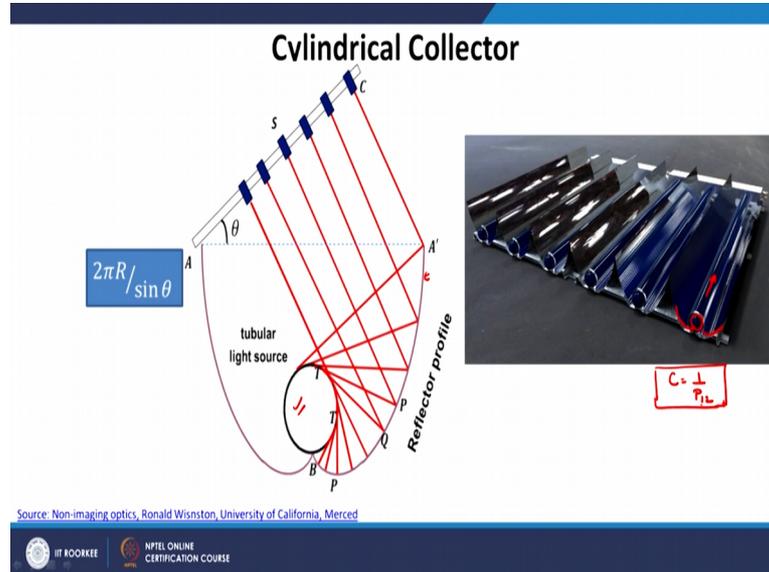
Source: Introduction to Non-imaging optics, Julio Chaves




So, all the radiation that comes at an angle theta; so this, all the radiation focus is here. If the theta is large, you see that radiation coming from large theta basically reflects multiple reflection. And some of the radiation is basically going outwards the cavity. So, this is basically a compound parabolic concentrator for theta decided by the solar angle. And all the

light coming from the sun should be within a small angle range. And once it is that, it is a perfect collector. And $P_3 = 1$; sorry. If the angle is large, sum of the radiation will be basically reflected out and the collector efficiency will decrease.

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So, this is the, I have shown you the design of parabolic trough in the previous slides. There is a second configuration which has now become very popular. That is cylindrical collector. In this case, we do not have a flat collector. As you see here, we have a flat collector. This is the collector plate. All the radiation is absorbed on this plate. There is a new configuration that is coming up, that is basically the cylindrical collector.

In this, we do not have a flat collector, we have a cylindrical collector. This is the cylindrical collector. And when we apply the same principal for designing this mirror, this is the mirror. This basically is involute of the cylinder. This is a involute kind of configuration. And this is the design of the collector. So, we have tubes which carry water inside. And then we have this involute types of collectors.

And these collectors basically provides the 100 percent collector efficiency or concentration. So, C comes out to be 1 upon P_1 in this case. So, this provides you the maximum concentration for this cylindrical type of collector. So, we end this lecture on solar collectors, solar concentrated collectors here. In this lecture, we have discussed how the principles of view factor, how the principles of view factor algebra can be used to design a good concentrator for different type of absorber plates, whether a flat plate, absorber plates or a parabolic absorber.

So, solar concentrator is a upcoming technology because of its high-efficiency. Many many applications we find lot of power plants are coming up which use this technology to concentrate large and large amount of solar energy onto absorber and increase the temperature of the fluid to very high temperatures where we can achieve high efficiency. Thank you. We have only a few lectures left. So, we will focus on the experimental methods in the next lecture. And that will be the last lecture of this course. Thank you.