Solar Energy Technology

Prof. V.V. Satyamurty
Department of Mechanical Engineering
Indian Institute of Technology, Kharagpur

Lecture - 22
Compound Parabolic Collectors

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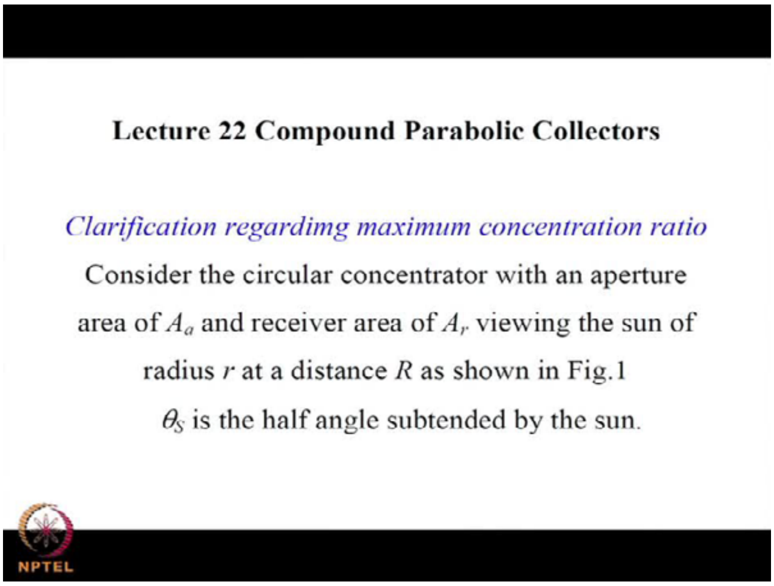

We should talk about, Compound Parabolic Collectors; last time we were dealing in general with concentrating collectors, it seems there is some confusion regarding the maximum concentration ratio, so I shall go through that very quickly.

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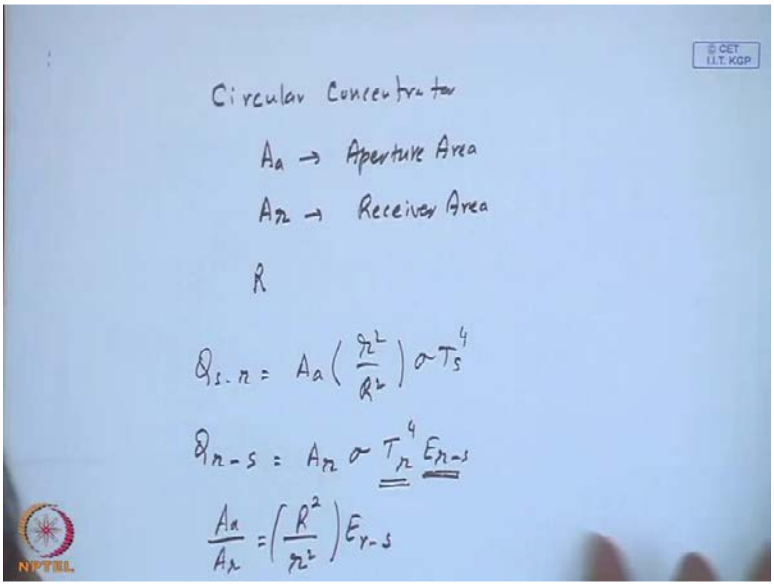

We will consider a circular concentrator of aperture area A, and the receiver area of A r, so whatever is the solar radiation, that passes through the aperture area gets reflected, or refracted, and gets focused onto the receiver of area A r as shown.

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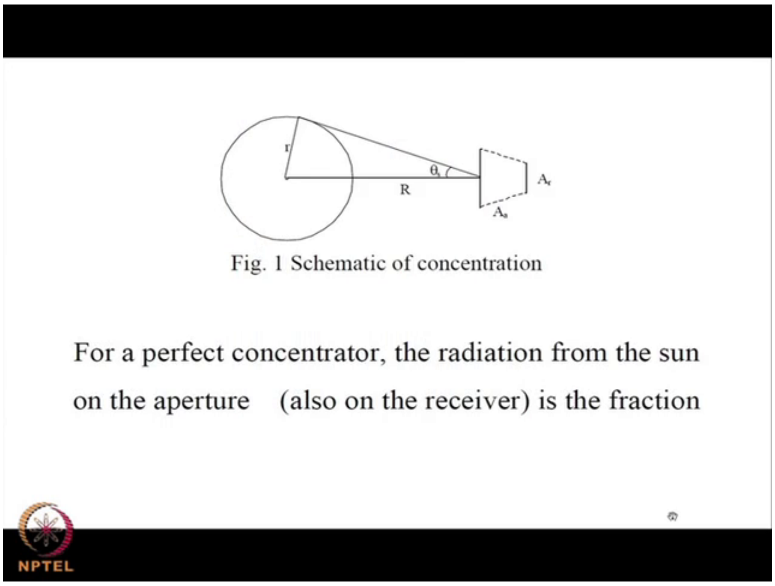

In figure 1, so that shows the sun from the distance of capital R from the earth, and of radius r, and the subtended half angle is theta s.

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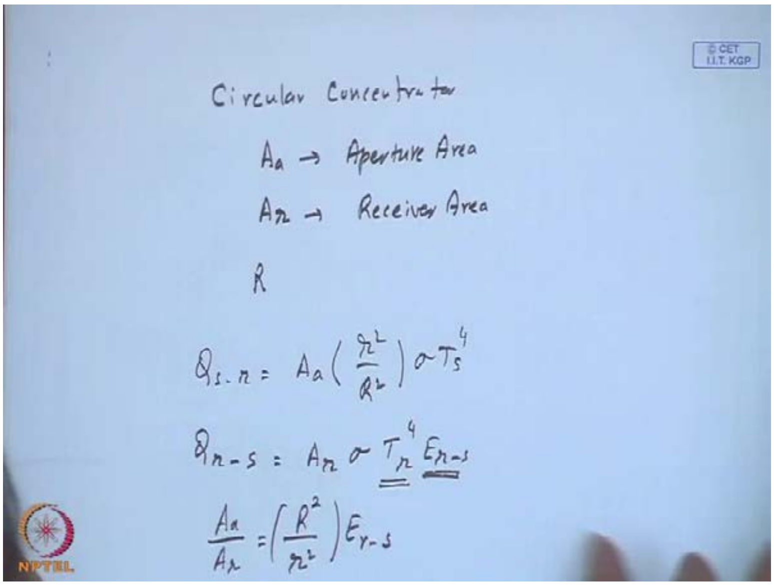

So, solar radiation emitted by the sun received on the earth is Q s r, area A a upon r squared by R squared sigma T s to the power of 4, where sigma is the Stefan-Boltzmann constant, r is the radius of the sun, and R is the distance between the sun and the earth, and T s is the effective temperature of the sun. So, if you write the emitted energy from the receiver to the sun, will be A r sigma T r to the power 4 into E r s; if T r is the temperature of the receiver, it emits. Assuming it to be a perfect emitter, sigma T r to the power 4 multiplied by the A r, the area of the receiver, and a fraction of it, a new factor will be, will be reaching the sun.

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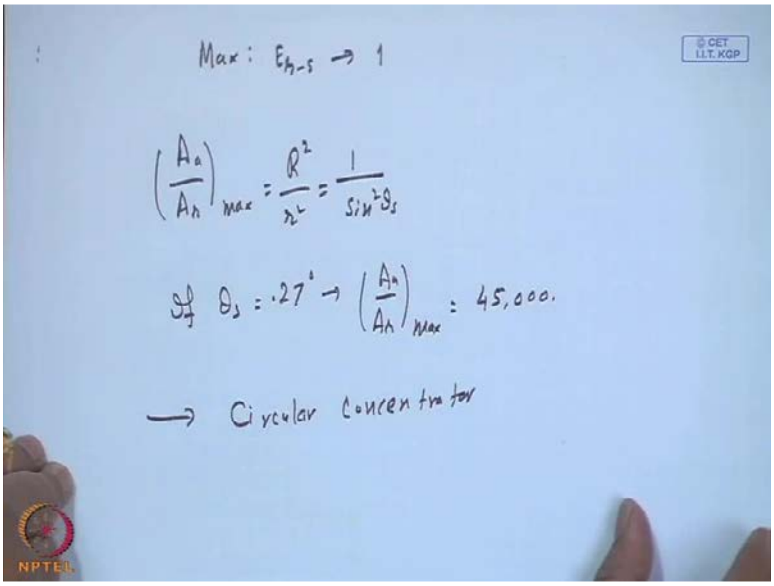

So, that you have the ratio A a upon A r as R squared upon r squared times E r s ,that is another equable evaluations, whatever is the solar radiations received by the receiver, must be getting emitted back, so that the temperature does not continuously increase. And if you assume maximum value for E r s can be 1, all the radiations emitted by the sun by the receiver can reach the sun, nothing more than that, consequently you have, A a upon A r max equal to R squared upon r squared equal to 1 by sin squared theta s, and if theta s is 0.27 degrees, that is the half angle subtended, then you have A a upon A r maximum equal to 45000.

This is for a circular concentrator, we had a confusion last time, but it is for linear, or concentrator, which I must responsible for it. Because in writing down, we started with derivation for the circular, but somewhere it is mentioned as linear, since it is sin squared theta s, it would be 45000 that will be the maximum concentration ratio possible, if you have a circular concentration.

Now, the question comes, why is it not infinity can r really focus onto a point? the answer lies in the fact, sun separates a finite angle no matter, how smaller it is 0.27 degrees with the earth, that makes the focus onto a finite area no matter how small it is, consequently this maximum concentration ratio.

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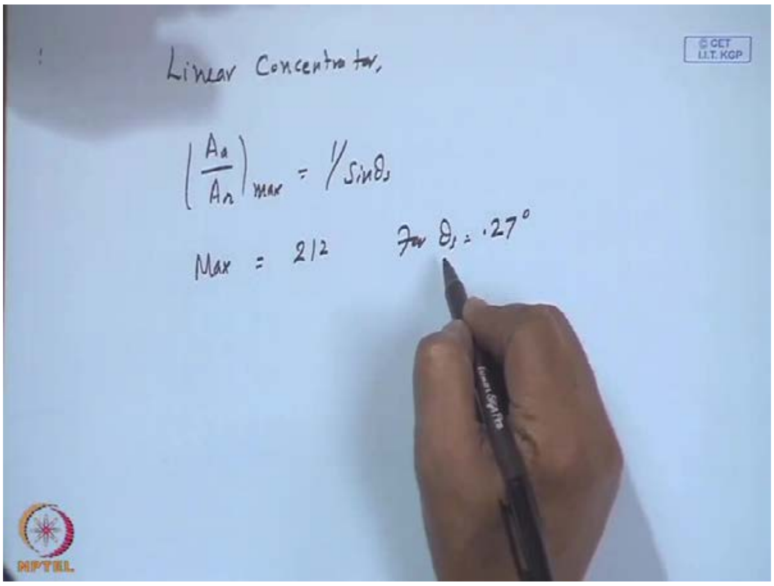

If it is a linear concentrator, you can see the text book by Kreek and Frieder, which is a very well written book. A a upon A r max will be 1 upon sin theta s the max will be equal to 212, if theta s is 0.27 degrees though, I am writing it as for theta s as 0.27 degrees, we have no option that is the angle, that sun subtends at the s surface. So you have a possible 45000 concentration ratio for a circular concentrator, and a possible 212 as the maximum for a linear concentrator. So, this is what was a bit confusing in the sense, last lecture I was mentioning as circular or linear interchangeably. The whole point is circular concentrator has a higher maximum possible concentration ratio, the maximum being 45000, and the linear concentrator has a maximum possible 212.

So, low at what you are design is, your concentration ratio will not exceed 45000 for a circular concentrator, and 212 for a linear concentrator. In other words, the circular concentrator is not a point concentrator, and linear concentrator is not mathematically a line concentrator, it has got finite width, no matter how small it is.

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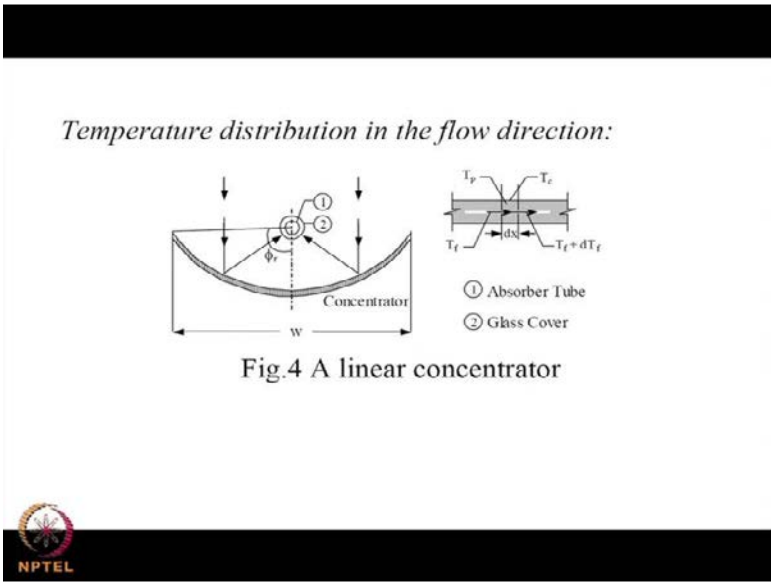

So, we have considered the temperature distribution, and expressed useful energy gain from a concentrating collector, why you have taken as an example as shown in figure 4. A concentrator parabolic with a outer diameter being d not, and inner diameter being b i and of the receiver tube which the diagram is self explanatory.

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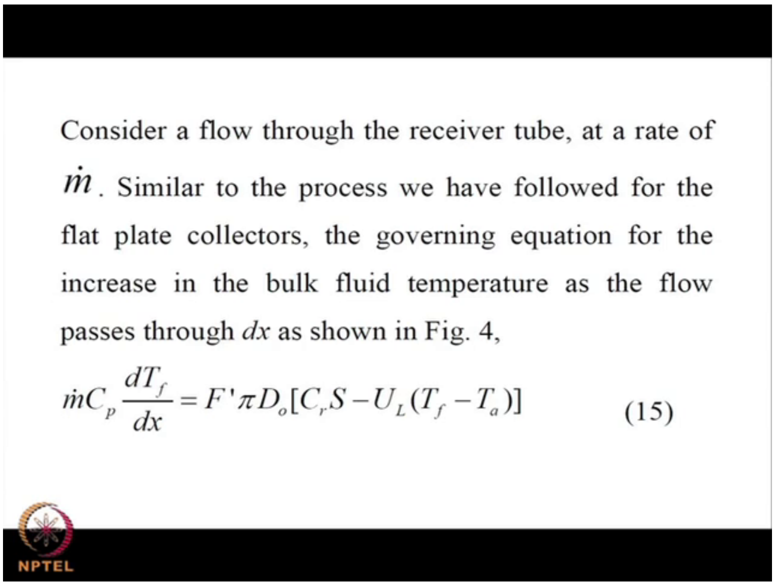

Except, I have skipped a certain portion to express the temperature of the fluid, and as it flows along the receiver tube, which is exactly similar to what we have in the case of flat plate collectors.

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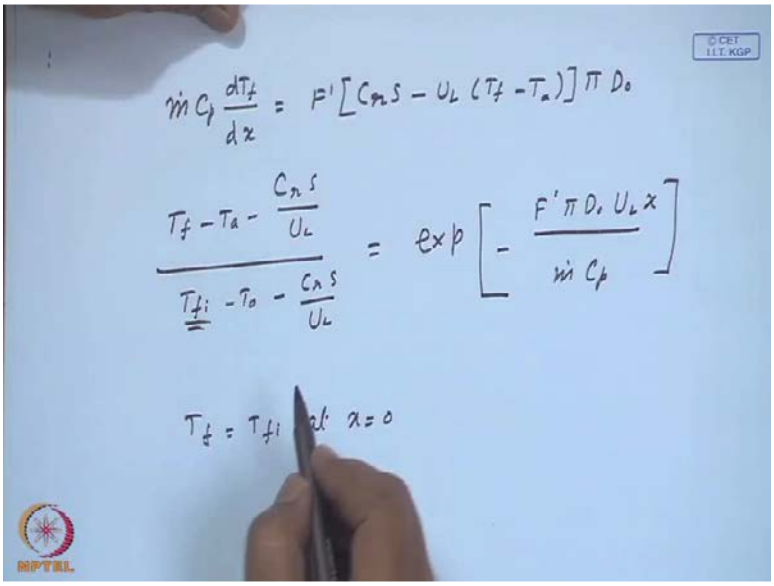

So, I should repeat, rather I should fill in that gap, if m dot is the flow rate through the receiver tube, and if you consider as shown in the diagram. An element length of d x, the temperature increase over d x multiplied by the mass flow rate; and this persecute is the energy gain by the fluid, flows through the tube of length d x should be equal to my F dash, the collector efficiency factor into concentration ratio times absorbed, energy minus U L into T f the fluid temperature.

Times your area, which is pi D naught into per unit length, since d x is over here, I will write it only pi D naught, and if I transfer onto the right hand side, you will have the temperature increase due to a length of d x.

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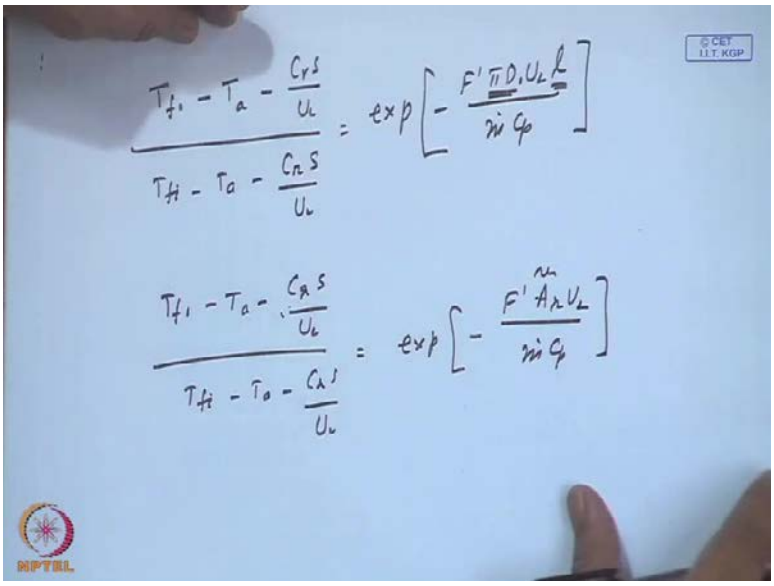

So, if you integrate this equation exactly, like we have done for the flat plate collectors, so the initial condition T f equal to T f i at x is equal to 0; so you can get exit temperature T f o by setting x as equal to l. You can notice that, pi D naught into l, like that of the absorber tube is nothing but the area of the receiver, which also can be re rewritten as… So this is in terms of the area of the receiver, and if you put c r equal to 1, you will have the same equation, we have had for the flat plate collectors.

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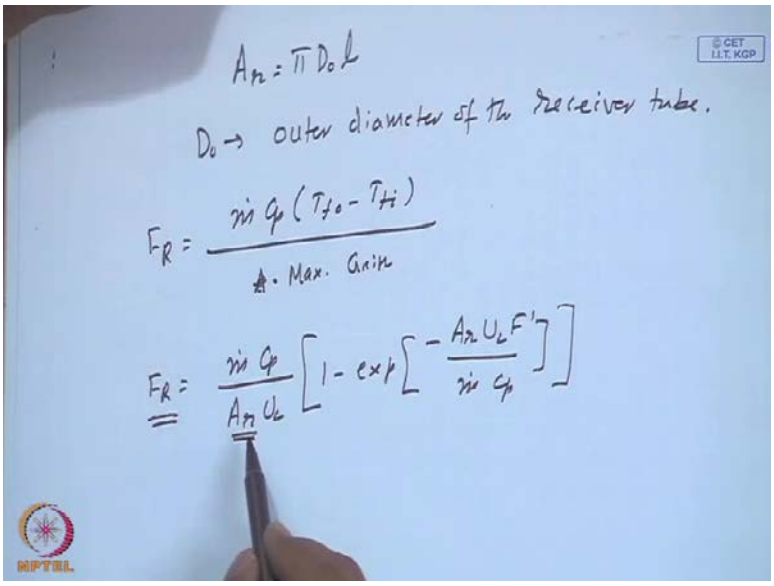

Now, just to be clear, area of the receiver will be pi D naught into l, where D naught is the outer diameter of the receiver tube. Now we have already derived, your heat removal factor should be equal to the actual energy gain, which is irrespective of the governing equations, or the balance equations is nothing but m dot c p into T f o minus T f i.

That is the temperature increase of the fluid, multiplied by the flow rate, multiplied by this this façade. So, this is the heat removal factor, and by max gain which we have already explained in terms of T f i; so we have got F r here, as m dot c p upon A r U L times 1 minus exp minus A r U L F dashed by m dot c p. So, the whole idea of little bit of this repetition is to say that, the area of the receiver comes to the picture, and where as in the case of flat plate collector, or we do not distinguish between the receiver area and the absorber area, which is exactly the same, and we call a c the collector area.

So, the solar radiation as received by the aperture area of A a gets reflected, and gets focused onto the receiver of area A r. And when we consider, the increase in the temperature in the receiver tube, it is the A r, that matters, that is consequently leads to the heat removal factor, being a function of A r being expressed in terms of A r.

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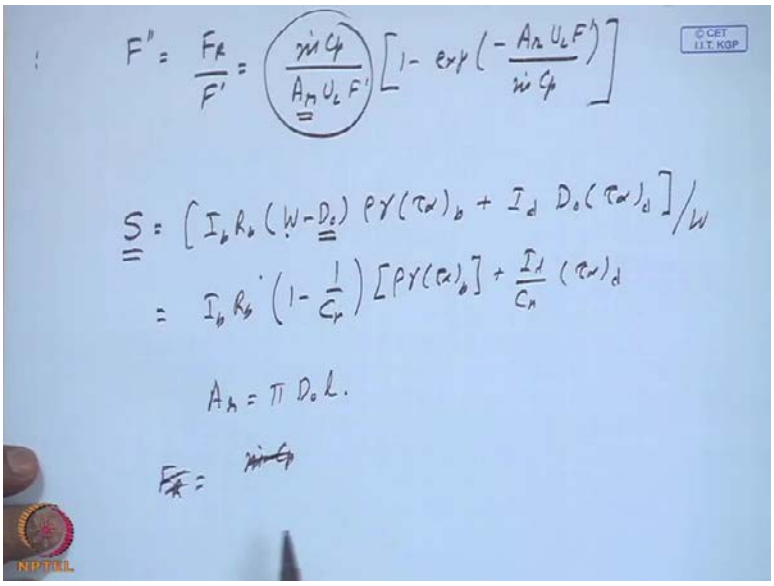

So, we will now you have the conventional pro factor defined as F r upon F dashed, which is nothing but m dot c p upon A r U L F dashed times 1 minus exponential minus A r U L F dashed over m dot c p. So the flow factor is again in terms of the non dimensional flow rate, which is expressed in terms of A r in the case of a concentrating collector.

Once again, if you look some books, you will have, that the absorbed energy, I thought I should give a clarification over here, I b R b times W minus D naught rho gamma tau alpha b plus I diffuse D naught tau alpha diffuse upon w. This is the solar radiation absorbed per unit area of the aperture, so W minus D naught, instead of W, which is a width of the absorber is due to the fact, there may be a shadow caused by the receiver tube onto the aperture area. And in this can be rewritten as I b R b times 1 minus 1 upon c r times rho gamma tau alpha direct b plus I d upon c r times tau alpha diffuse.

So, this is what you have got in terms of, if you consider this shading by the receiver tube, or to the aperture plane. And in many instances, if the concentration ratio is high may be 5 or 10, it becomes negligible; and consequently A r of course, is pi D naught L to reinforce the concept, so your F r will be, m dot c p, sorry this we have already done it, A r is pi D naught l.

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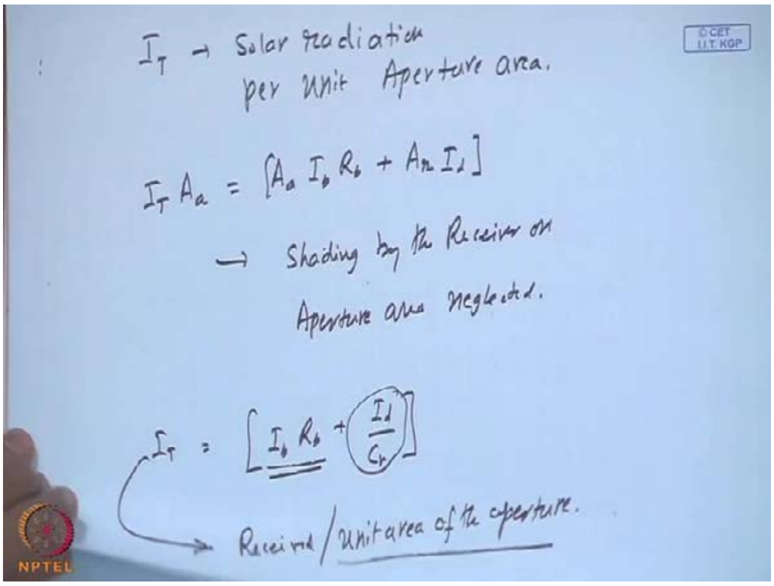

So, if I T is a solar radiation per unit aperture area, then I T times A a should be equal to a aperture, this is the direct component I b R b plus receiver area A r times the diffused component, this is shading by the receiver on aperture neglected. Consequently I T equal to I b R b plus I d upon c r, that is the received per unit area of the aperture, so if this is I b R b the set forward, but a fraction of the diffused radiation, that is directly collected by the receiver should be included in order to estimate I T, only thing is we are basing it on unit area of the aperture.

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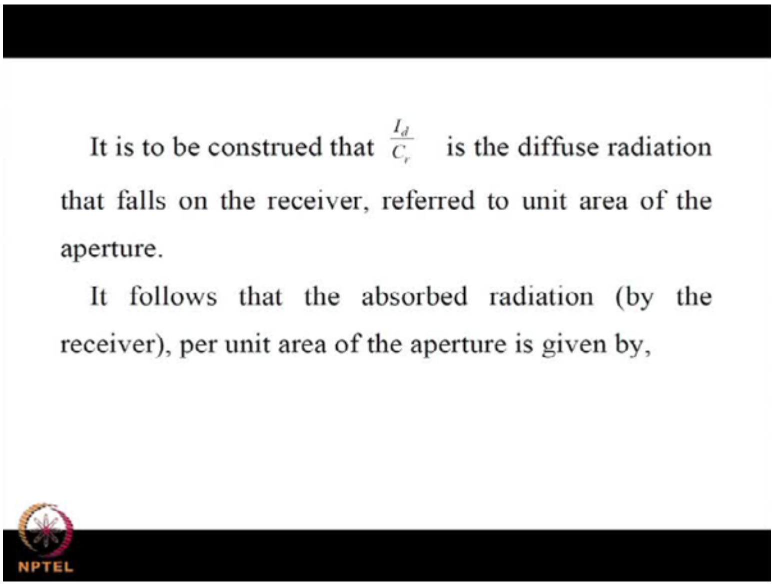

It is to be construed that $\frac{I_d}{C_r}$ is the diffuse radiation that falls on the receiver, referred to unit area of the aperture.

It follows that the absorbed radiation (by the receiver), per unit area of the aperture is given by, So, it is to be construed that I d upon c r is the diffuse radiation, that falls on the refer receiver, referred to unit area of the aperture.

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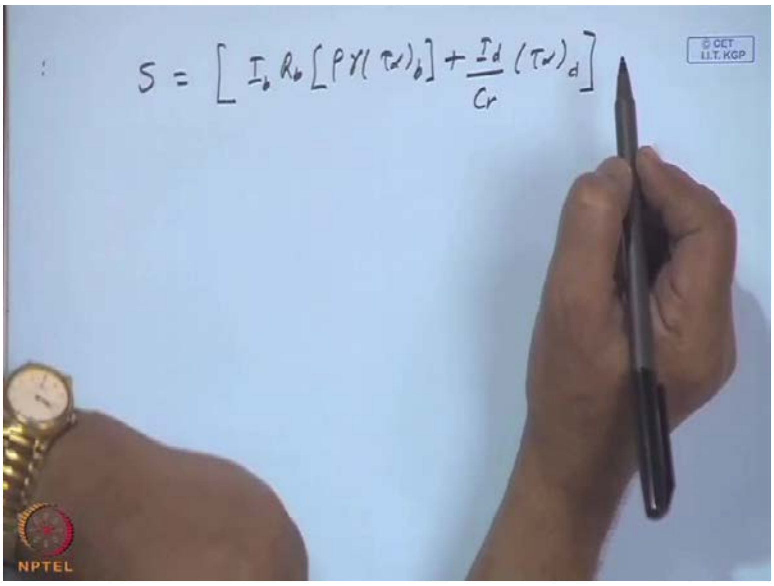

So, it follows reabsorbed area should be I b R b, the radiation received, multiplied by the optical factors, rho gamma tau alpha direct plus I d upon c r multiplied by tau alpha, for the diffused component of the solar radiation. So, we expressed basically the clarification regarding the concentration ratio, for a circular concentrator and the linear concentrator, and subsequently I have also included the derivation of the outlet temperature, from after flowing it, passing through the receiver tube of a concentrating collector, which is necessary to evaluate the heat removal factor, and the flow factor. Subsequently, we also said that, there are two ways of expressing the solar radiation per unit area of the aperture; some text books include the shading by the receiver tube onto the aperture plane.

So, that it will be W minus d not some do not, if c r is 10 5 that will be small factor; and the absorbed energy finally is expressed per unit area of the aperture as the direct radiation received multiplied by the optical factors plus a fraction of the diffused radiation, the fraction being 1 upon c r, where c r is the concentration ratio. And tau alpha d is the transmitter (( )) product for the diffused radiation.

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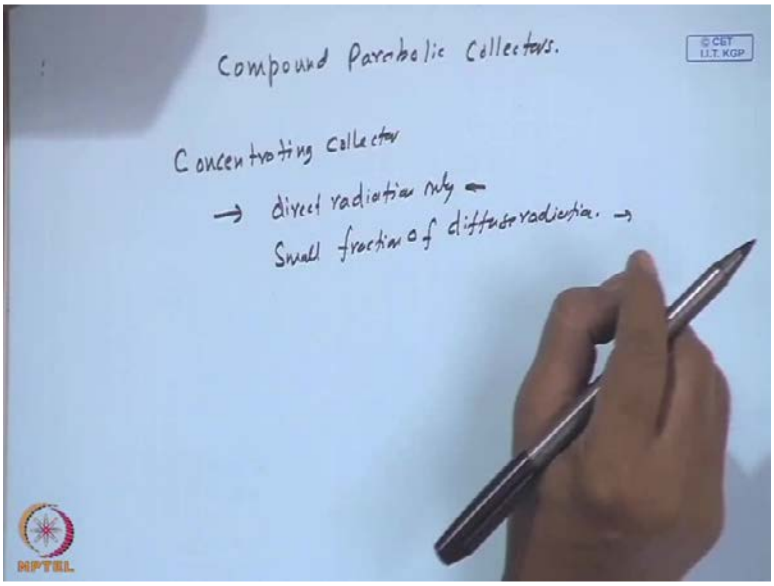

We also had a brief introduction, for what we call, compound parabolic collectors. Now, if you look the equations, that we have been discussing or arriving at for the concentrating collectors, it concentrating collectors dominantly take, the direct radiation plus a small fraction of diffused radiation.

So, we have got a gain, because you track the solar collector with the sun's path, or the sun's rays, and direct radiation falling on the aperture can be enhanced, no doubt, but you are losing a 20 to 30 percent, even on a bright day of diffused radiation. Because if the concentration ratio is high, the diffused fraction captured by a concentrating collector will be extremely small.

So, the issue has been can we do something, a design of a concentrating collector which has a concentration ratio, so that the solar radiation falling on the receiver is larger intensity, and it will not lose, because the receiver area is small but, also accepts diffused radiation which will be 30 percent of the total radiation.

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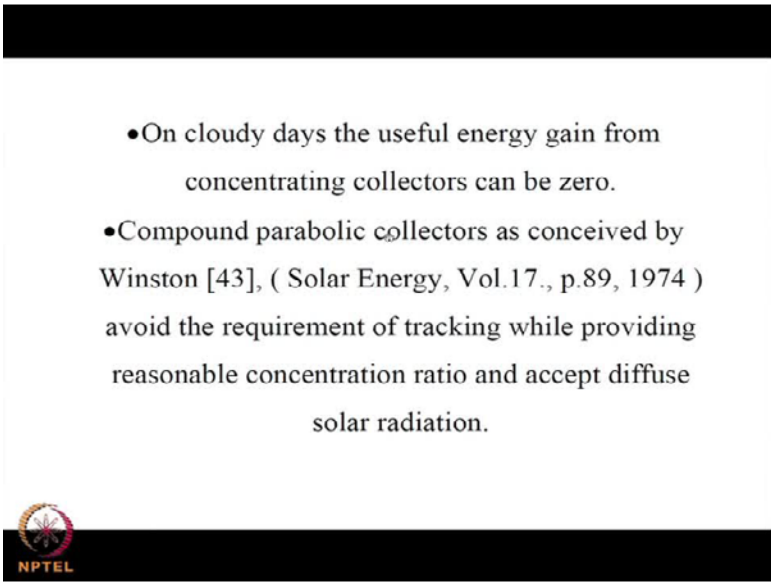

The other thing is disadvantages, on cloudy days, a c c may give you q u 0, if you have a very cloudy day, so it will does not accept diffused radiation, the useful energy gain may be almost equal to 0.

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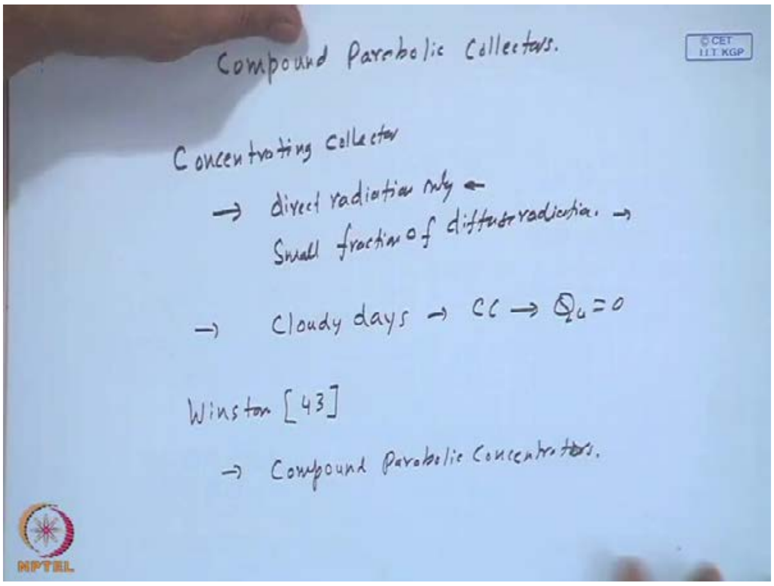

So, Winston professor Winston, as we have given the references 43, that you can see in the companion notes, and he conceived this so called, compound parabolic collectors.

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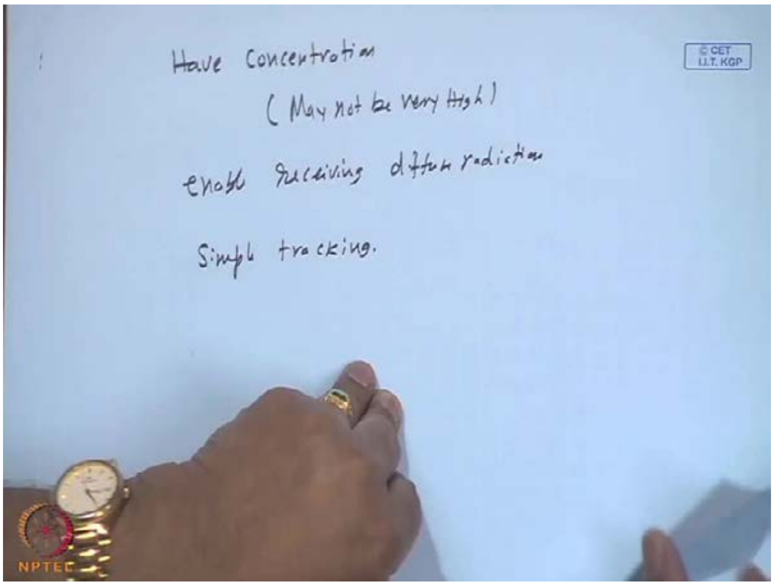

Whole idea is to have concentration, may not be very high, but enable receiving diffuse radiation, and simple tracking, you may call that we discussed, five cases of tracking. Simplest being east west axis with one single adjustment per day, such that 5 minus beta is equal to delta; the next one that 5 minus beta, you keep on changing, depending upon the time of the day, still the axis being east west. Of course, the other three deal with the north south axis, and a perfect tracker of the two axis.

So, if you have a simple tracking, and then the concentration ratio is not very high will be better way, combining the advantages of a flat plate collector, mainly of accepting diffuse radiation, and minimal tracking, ca e providing higher temperature working through it, that is being delivered by the concentrating collectors.

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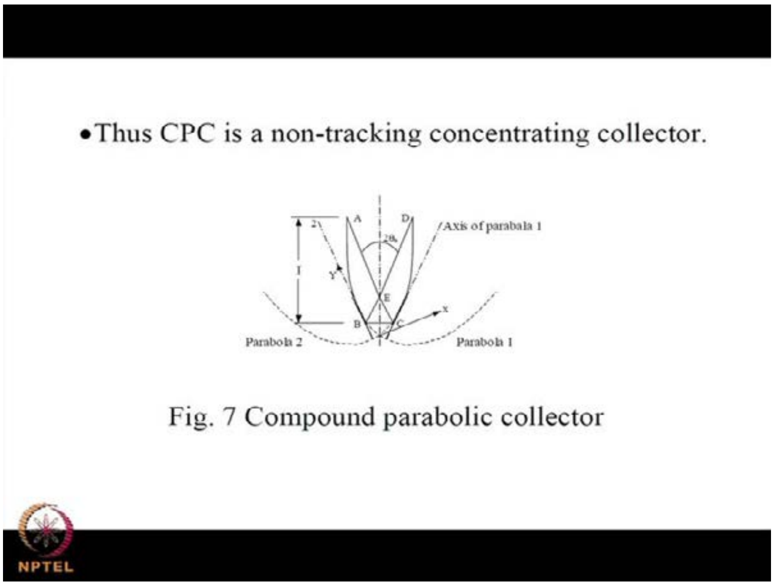

So, I have shown the picture of compound parabolic collector, basically it consists of this solid lines.

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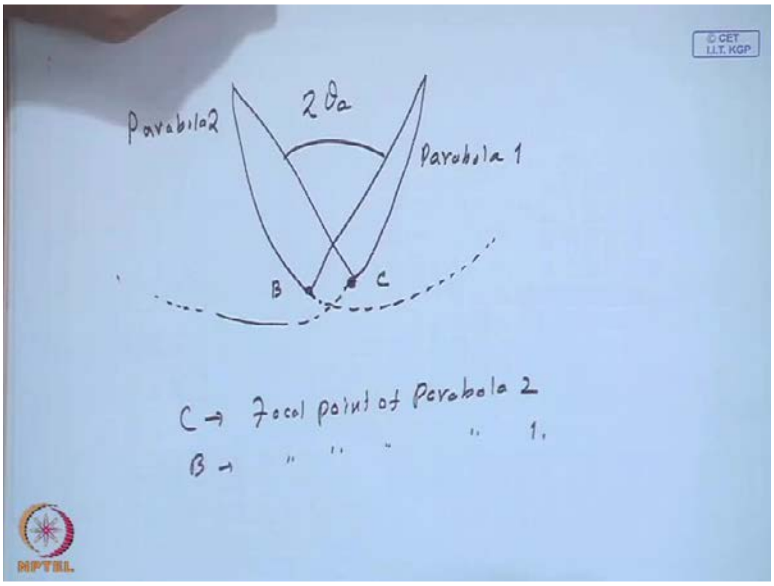

Let me redraw these, are two parabola’s either two part of parabola’s, this will be continuing like this, this will be continuing like this. So if this is parabola 1, and this is parabola 2, or this point over here, which I will call C, and this one B, C is the focal point of parabola 2, and B is the focal point of parabola 1. So, you have got a point on parabola 1, which happens to be the focal point of parabola 2, and the point B is the focal point of parabola 1, and you define if you cross join like this, 2 theta a.

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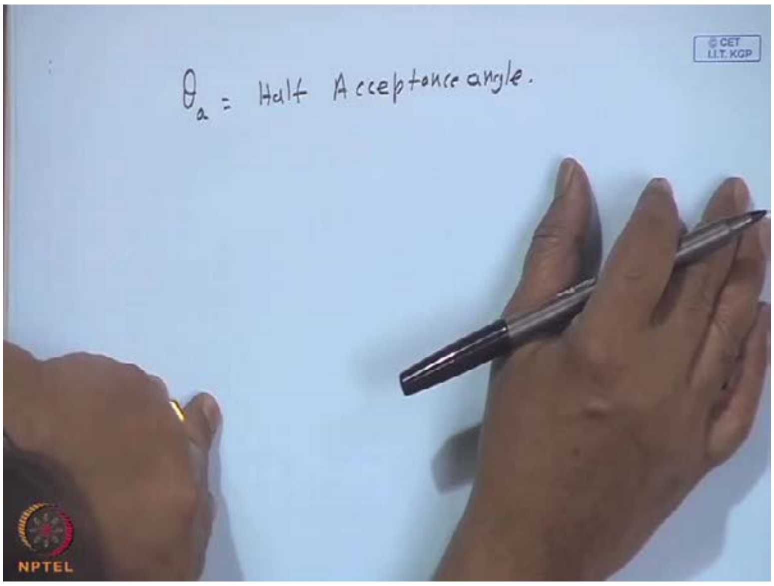

Where theta a is the half acceptance angle, it is called the acceptance angle, any radiation solar radiation coming beyond theta a, shall not be reflected from parabola 1 to parabola 2, or parabola 2 to parabola 1. In other words only those angles, that are within 2 theta a shall be accepted by the concentrating collector, and will reach eventually whatever is the focal point B, or C, as the case may be.

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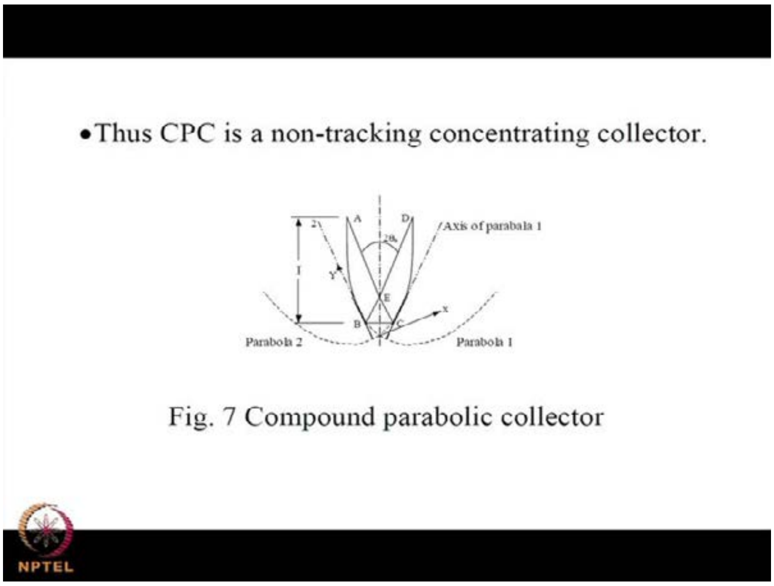

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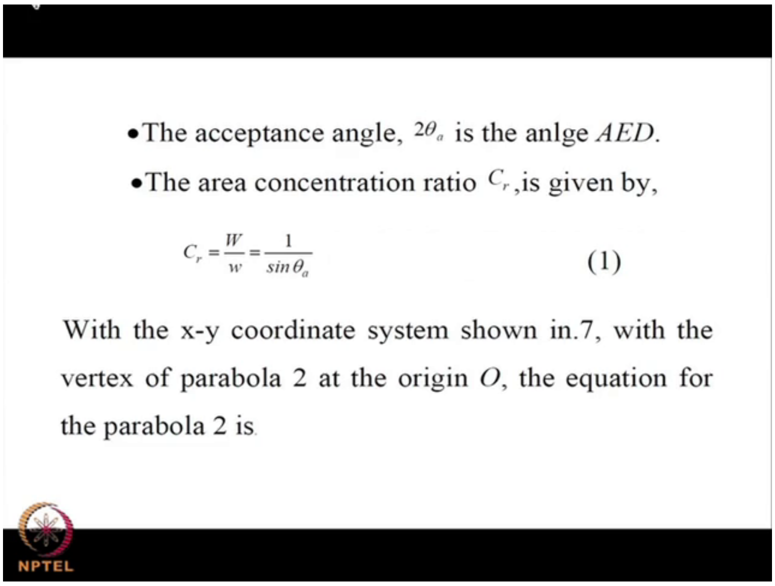

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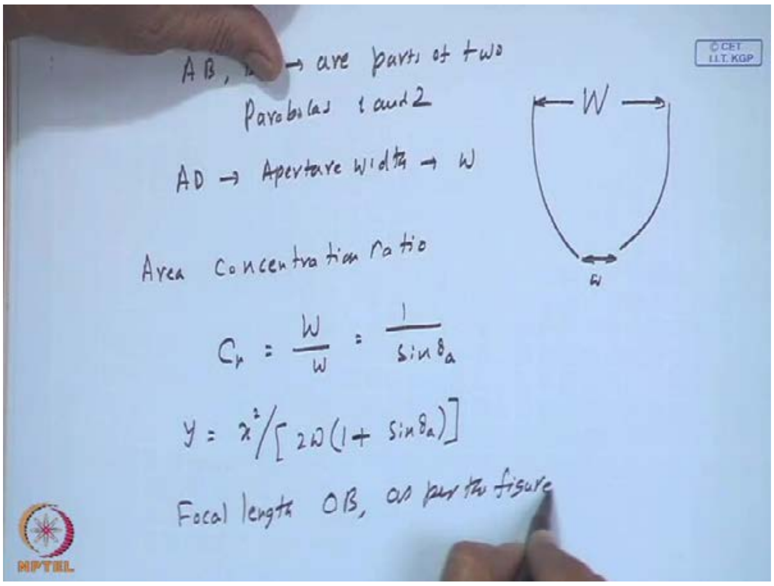

So, I also have shown the co-ordinate system in the direction of x, and the direction of y, and you have got the origin o. So in natural the two segments AB and DC are parts of two parabola’s 1 and 2, AD lets go back, and see AD is a aperture, can you show figure 7 of width W, you can refer to the figure.

Then the axes of the parabola’s are oriented in such a manner, that the focus of parabola 1 is the point C, and the focus of the parabola 2 is the point B, which we have already mentioned, and the angle is theta a 2 theta a, which were set, and the area concentration ratio, c r W upon w 1 upon sin theta a. So you can see W small w is the width at the a focal point at distance will be small w, the concentration ratio per unit length you can express simply as W upon small w and with the co-ordinate system.

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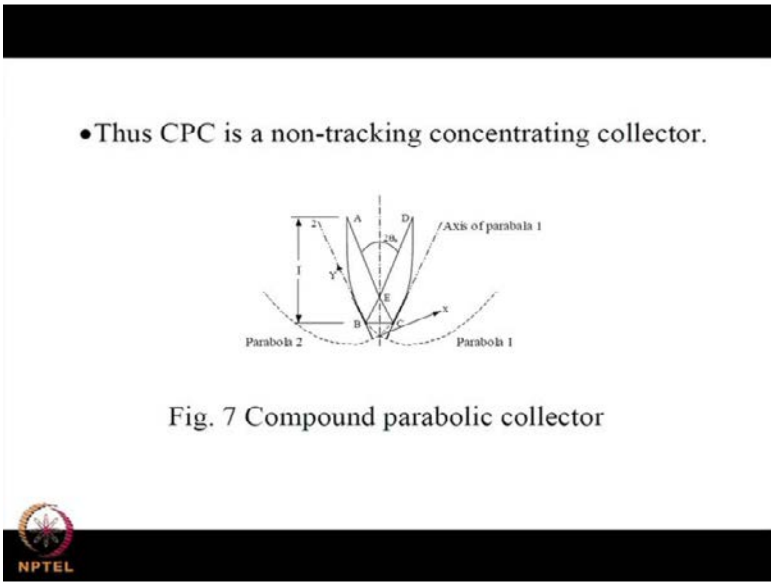

Which you can see in figure 7 right, you can take a time, little time to look at this picture, and copy or do whatever, you can express co-ordinate y as x squared, upon 2 w small into 1 minus plus, sorry 1 plus sin theta acceptance angle theta a, and the focal length as per the figure is o v, o is the origin, where the parabola 1, and parabola 2 they have the axes I mean vertex of the co-ordinate system.

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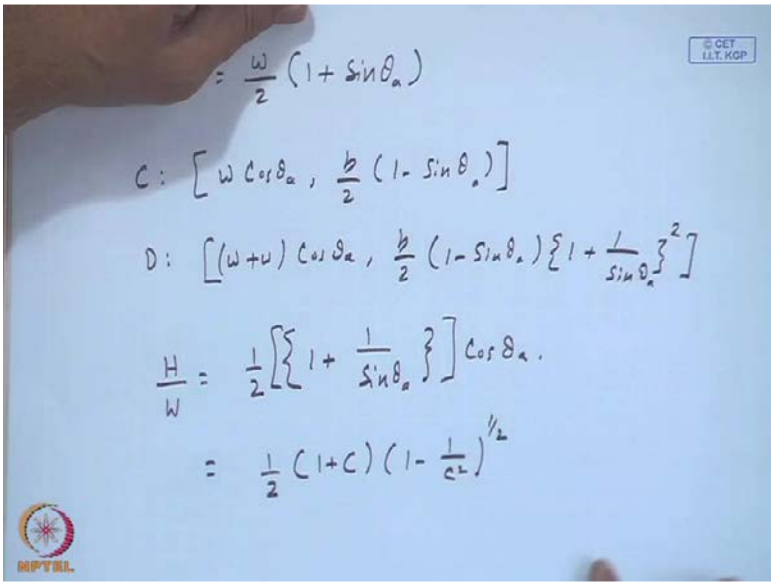

Simple trigonometric calculations will show you that o b will be equal to w by 2 times 1 plus theta a; so the points are C and D, once again I will show you the figure, C is the focal point of parabola 2, and B is the focal point of parabola 1, whatever and those co-ordinates are given by for C you have w cos theta a, the x co-ordinate and B by 2 times 1 minus sin theta a, as the y co-ordinate and for the point D, the co-ordinates are w plus w times cos theta a and b, over 2 times 1 minus sin theta acceptance ,multiplied by 1 plus 1 by sin theta a whole square.

So, you have know the co-ordinates of the points C and D, so basically for the purpose of design, you have got two parabola's identical in shape. But a part of parabola 1, part of parabola 2, plays in such a manner the focal point of parabola 1 will be the base of the vertex included of the parabola 2 and vice versa. Now the concentration ratio H upon W height to the width, which again I will refer to figure; so the total height is H, as shown over here that is between the points B to A or C to D. It looks like I but it is H half one plus 1 upon sin theta aperture times cos theta a, which is nothing but 1 by 2 1 plus c times 1 minus 1 by c square to the power 1 half.

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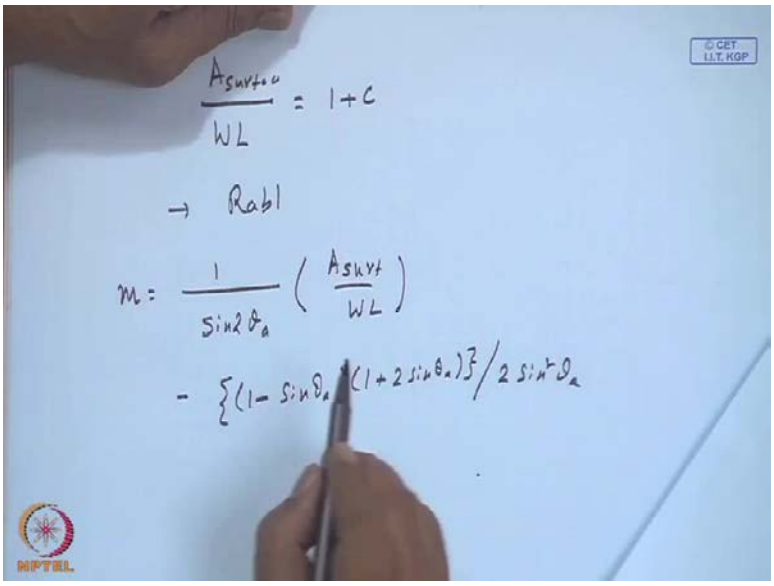

So that c should be the concentration ratio, which we are normally referring it to as c r but, nevertheless there is no confusion as far, this is concerned. So if you compare surface area to the aperture area, which is nothing but W L that should be equal to 1 plus c, so this is established by rabl of M I I T, and the details you can have from the solar energy general of 1977.

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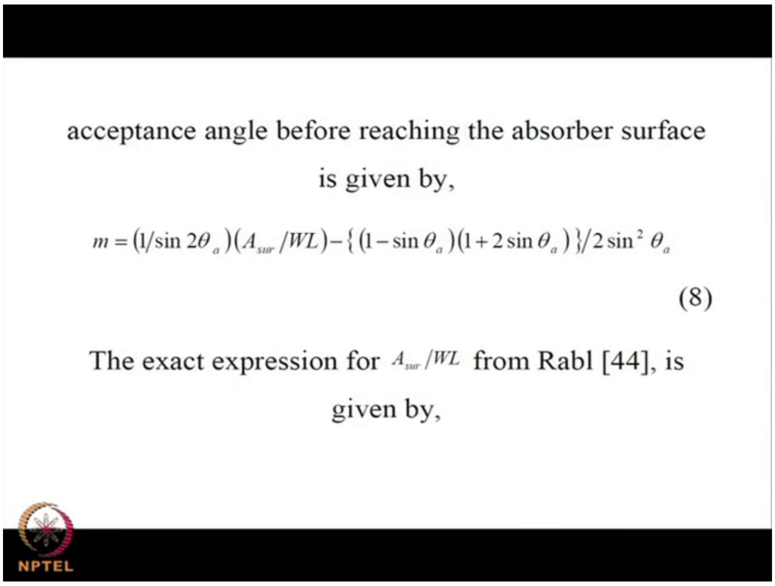

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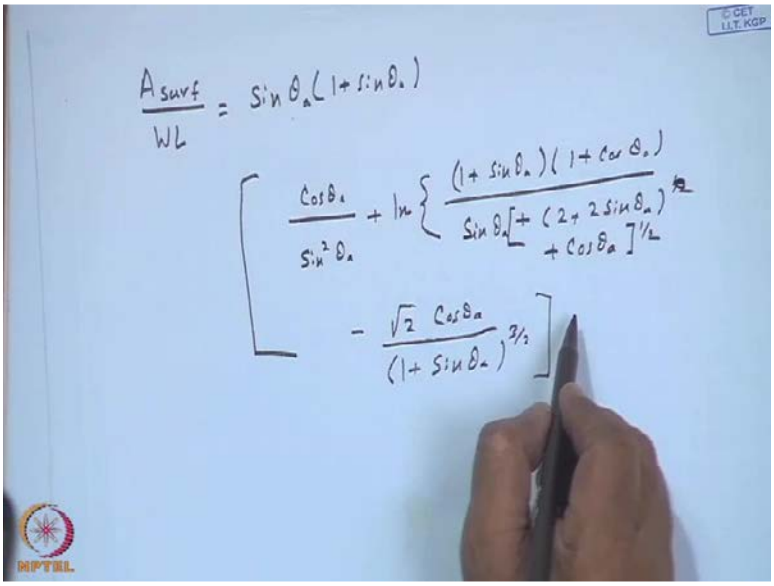

So if you have the acceptance angle before reaching the absorber surface, that can be expressed by 1 upon sin 2 times theta a, a surface by w l minus 1 minus sin theta a times 1 plus 2 sin theta a, upon 2 sin squared theta a well the that is an exp approximate expression, it is approximate exact expression surface area upon the aperture area w l will be sin theta a 1 plus sin theta a times big bracket cos theta a sin square theta a plus log 1 plus sin theta a times 1 plus cos theta a, upon sin theta a plus 2 plus 2 sin theta a to the power 1 half and theta a times, this should be a plus cos theta a over here, and this is over here minus root 2 cos theta a by 1 plus sin theta a to the power 3 by 2.

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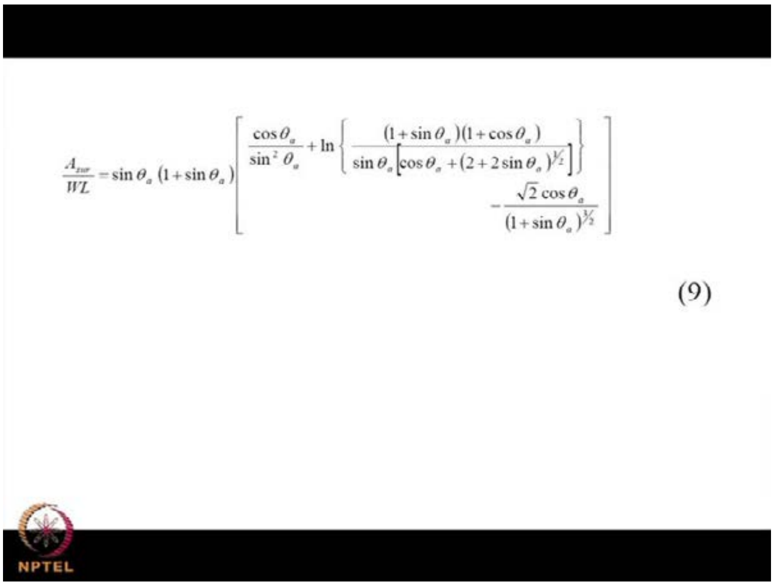

Now I would argue to take this relations as they are existing, what should be the surface area at the area ratio in the case of a compound parabolic collector, it is expressed in terms of the geometric factor, the angular acceptance theta a, so you can refer to any book including Duffin and Bakemann, by professor Duffin and professor Bakemann, and you can if there are any slight differences in plus minus signs, you can correct it though I believe I shall include a companion notes, as far as the equations is concerned are concerned, and you can have a look at the in case of my quick writing has some mistakes, it can be corrected.

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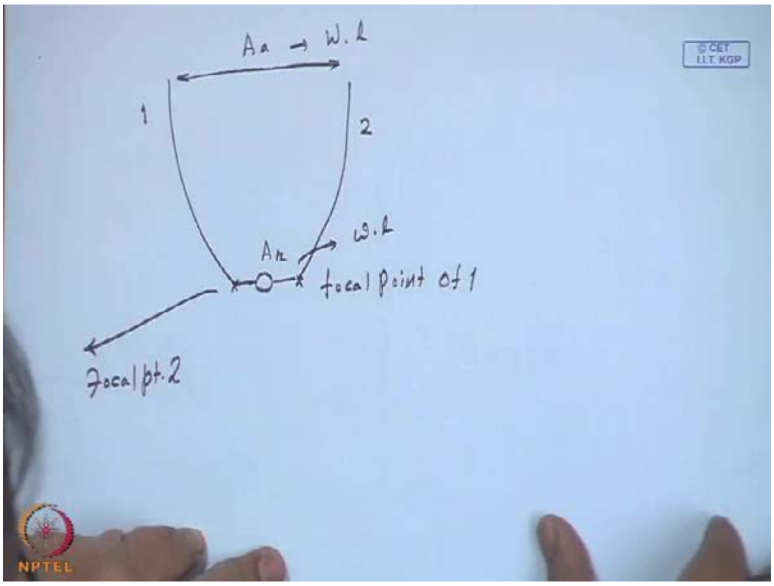

Now, you have got a compound parabolic collector, this is parabola 1, parabola 2, does not matter whether we called 2 and 1 the other way around, this is the focal point of 1, and this is the focal point of 2 so may have an observer with a ((two and a fin)) like this, so this will be my aperture area, effectively and this will be sort of my receiver area, which we have called w times l small w times l right, the point is parabola 1, and parabola 2 should be inside reflecting.

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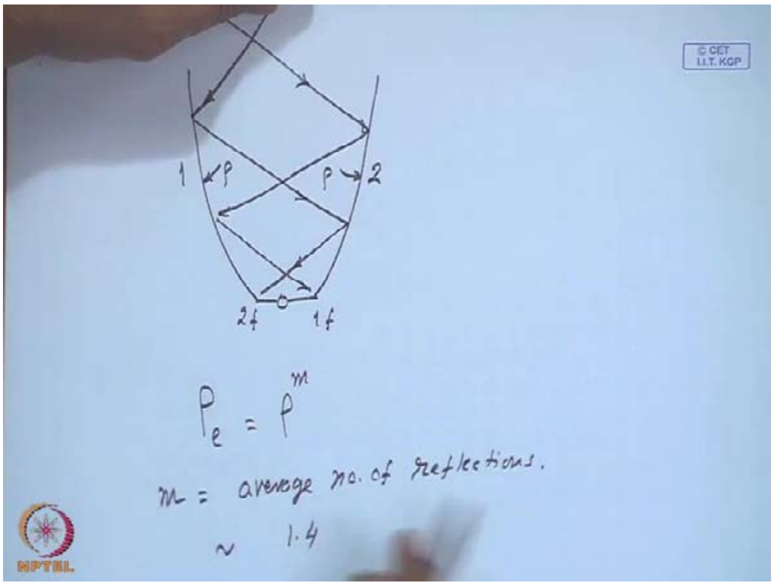

So, irrespective of this arrangement I have a ray, it should go over here because this is the 2 1 focal point of 2 and focal point of 1 similarly, any ray that is coming on to this after multiple pre reflections will reach, now focal point of 1 right.

So, depending upon the height length etcetera, how many reflections, it will be having so people have found rho effective should be relate to the rho of this surface, that is the reflectivity of the surfaces to the power m, where m is average number of reflections, this is sort of found out to be about 1.4, 1.5 right, how the fraction is you can easily imagine, if you consider a large number of rays, and then some of them may be having 2, some of them may have only 1, and the average turns out to be 1.4.

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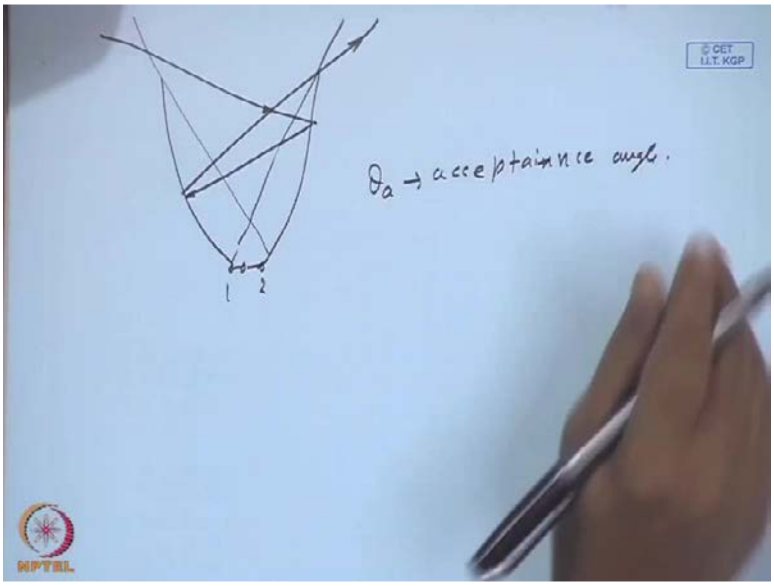

Then, the significant of the acceptance angle, any ray coming beyond, this will have a multiple reflection, and get out of the compound parabolic collector, consequently the theta a is called the acceptance angle.

So, solar radiation within theta a, only will be reflected re-reflected and goes to the concentrating point 1, or concentrating point 2, and then transfers energy to the fluid, so acceptance angle so that is a significance of the acceptance angle, so that you will know that any solar radiation ray coming, beyond that will not be focused onto the focal point 1 or focal point 2.

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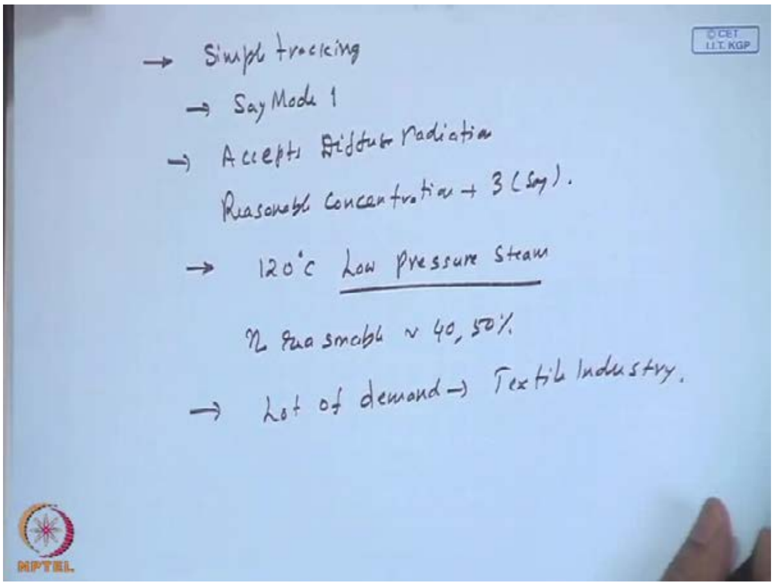

Now, so has the let us say advantages simple tracking, say mode one what we have considered as east-west horizontal axes with one single daily adjustment, then it accepts diffuse radiation, because whatever enters through capital W width, should reach also the receiver area a r, and reasonable concentration ratio, like it may be 3, now if you go for a very high concentration ratio with a so called compound parabolic collector, then your acceptance angle will become less and less, consequently it will not be accepting the alert of the solar radiation entering beyond those angles, so if something like 3 is ok.

Which is good enough for 120 degree c, let us say low pressure steam, at a reasonable efficiency, may be let us say 40 or 50 percent, and this also has got lot of demand particularly in textile industry.

So you got a reasonably efficient collector, without going to three glass covers and selective coating, through the flat plate but one single daily adjustment you do a compound parabolic collector, which will give you a reasonable ratio of 3 or 3 to 5 concentration ratio, which is good enough for generating the precious steam up to 120, 140 degree c with a reasonably high efficiency of 40 to 50 percent, and the applications are plenty particularly one mentioned I am making is a textile industry.

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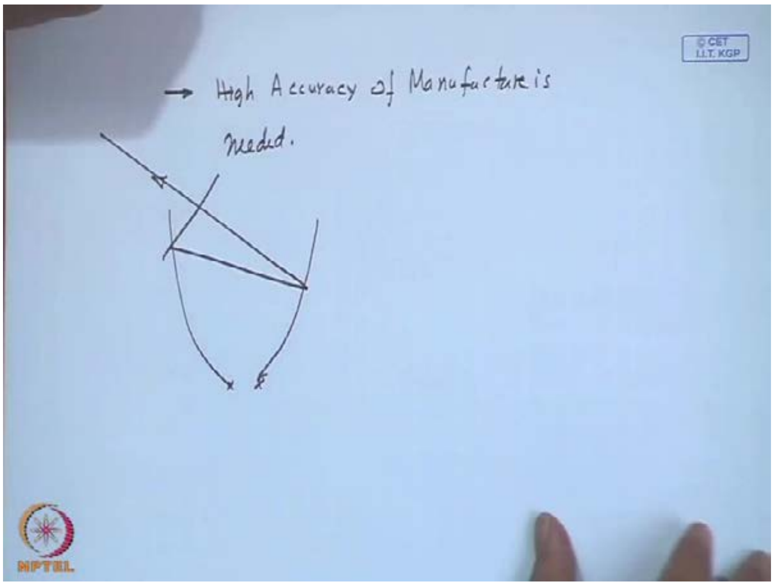

So, everything is so nice and there has to be somewhere, some hitch in this so this is one of the various successful designs but, a high accuracy of manufacture is needed, this is not to say that we need not have high accuracy for a flat plate collector or a regular concentrating collector but, the issue here is if you have got intercept reflectors, it may have multiple reflections, and get out and do not reach the focal point 1 or 2, so you need to have a good accuracy, in this optically look for the compound parabolic collector.

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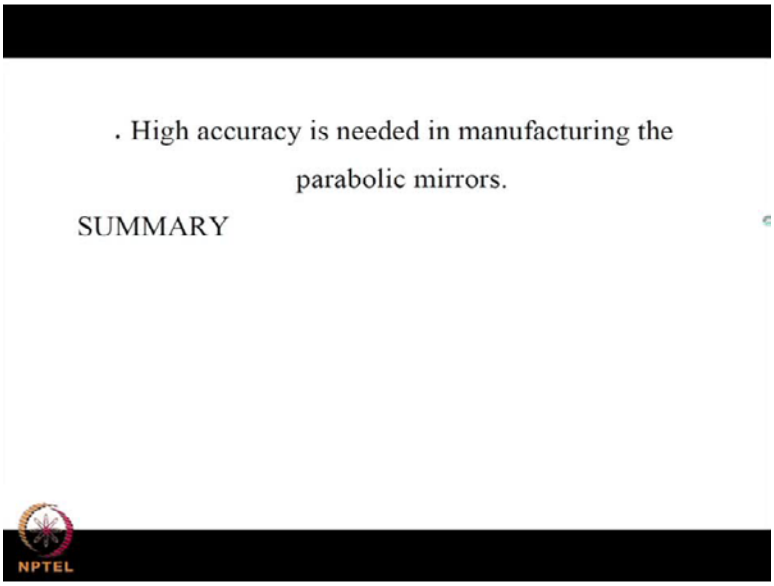

Otherwise, it is a reasonably quiet a bright idea to have a low concentration, and at the same time produce reasonably efficient low pressure steam, or whatever is the other fluid so this is what we have done, in the concentrating collectors, first we considered the several modes of tracking, and then the theory of a concentrating collector, through a parabolic concentrator, and then to avoid the disadvantages of a concentrating collector to combine the advantages of a flat plate collector.

We a suggestion by professor Winston had been a compound parabolic collector, which are also commercially successful and there are parts of 2 parabola's, 1 focal point will be at the base of the other parabola, and vice versa, that leads to a concentration of about 3, 4, 5 whatever, one nice to design and then you can have a simple this tracking mode, that is only a east-west horizontal axes with one single adjustment.

So this expects expected to be very promising, and quiet affluent relations are based upon the Winston collector, the slight disadvantage or the concern should be the high accuracy needed in the optics, otherwise the rays will not be reflected and going on to the focal points but, they may get out of the compound parabolic collector, that is it.

Thank you.