Elements of Solar Energy Conversion
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Lecture - 14

Hello and welcome back to the series of lecture on Elements of Solar Energy Conversion. So, we have done 13 lectures so far and this is the lecture number 14 ok.

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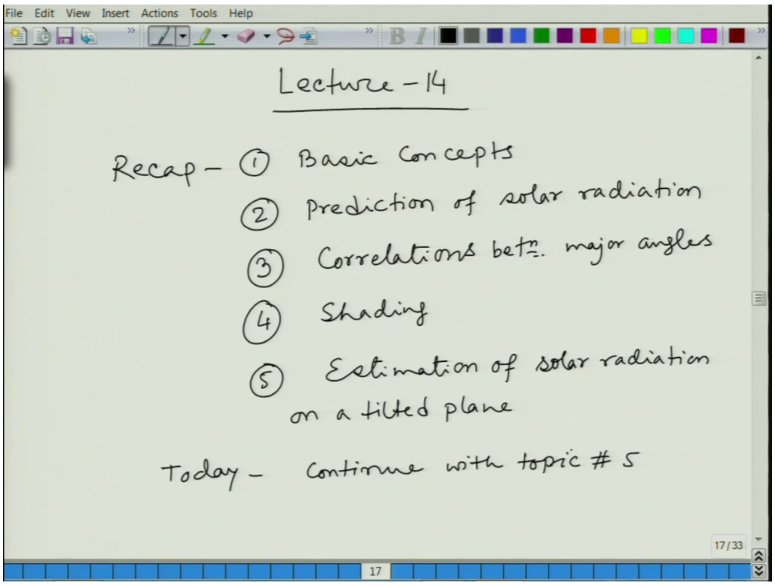

So, what we have covered so far like any other class we will just mention them. So, that we know where we are, but we will mention them short in short notations not going into detail. So, first we covered basic concepts then prediction of solar radiation third thing we covered the correlations between major angles ok, that we derived.

And then we have looked at shading, how it affects the solar energy conversion systems and then we have started looking at the estimation of solar radiation on a tilted plane. So, in the last class we have covered about half of it and today we are going to finish that part ok.

So, today we will continue with topic number 5, as mentioned here ok. So, that is the plan and if we have enough time left we will go to the next topic which will be looking at the solar collectors ok. So, that is the interesting part where you will actually see how this collectors work and all, but before that we have to build up the background that this collector study requires.

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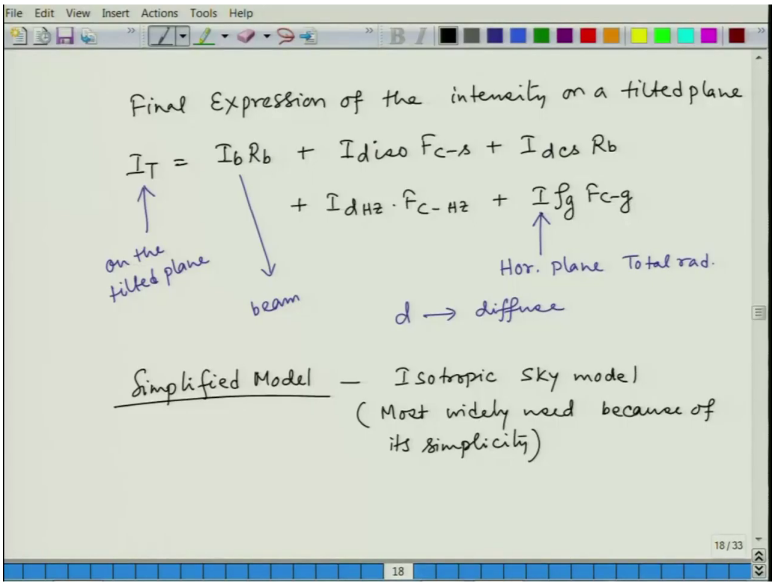

Horizontal plane value to the tilted plane value and then we had few component of the diffuse radiation first one was the isotropic sky. And we have introduced the view factor which connects from the collector to the sky that F c s plus, the next diffuse component was termed as circumsolar which is designated with the subscript c s.

And again we introduced or we used this conversion factor which takes from the horizontal value to the tilted plane value ok, that is the circumsolar part and the next part was the horizon brightening part right. So, I d H Z, which is horizon brightening diffuse radiation and the view factor was from the collector to the horizon area ok.

Plus I into rho g into F c g this last term it represents the reflected part, where I is the reflected part from the ground the horizontal plane around it. And I here stands for the horizontal plane value of the total radiation and rho g is the reflectivity the average reflectivity of the ground plane and the corresponding view factor which is F c g. So, this is where we stopped in the last class.

So, I again want to emphasize that this I without any subscript this is for the horizontal plane total radiation ok. This IT that is on the tilted plane right this I b stands for the beam radiation and whenever you have a subscript small d, that means, its diffuse ok. So, just to remind you.

Now, the next step would be to actually find out these values ok. So, we have formulated what would be the form of the equation, what would be the major terms ok that is coming from the concepts. Now, what we need to do we need to put values corresponding to these different now this symbols right. And for that we need to make some assumptions ok.

So, let us first take a simplified model, which often serves the purpose completely. So, we do not need any further complications to be introduced. So, simplified model what it does? It does not differentiate between the isotropic diffusion diffuse radiation, the circumsolar diffuse radiation or the horizon brightening diffuse radiation ok, what it does it takes only the isotropic sky.

So, the simplified model we call isotropic sky model which is actually the most widely used model most widely used because of its simplicity ok. And it does not call for any more complication until and unless we require for or we thrive for further accuracy. So, if we get reasonable accuracy for our purpose then we stick to such simplified model with isotropic sky ok. So, if we take the isotropic sky only what we will get?

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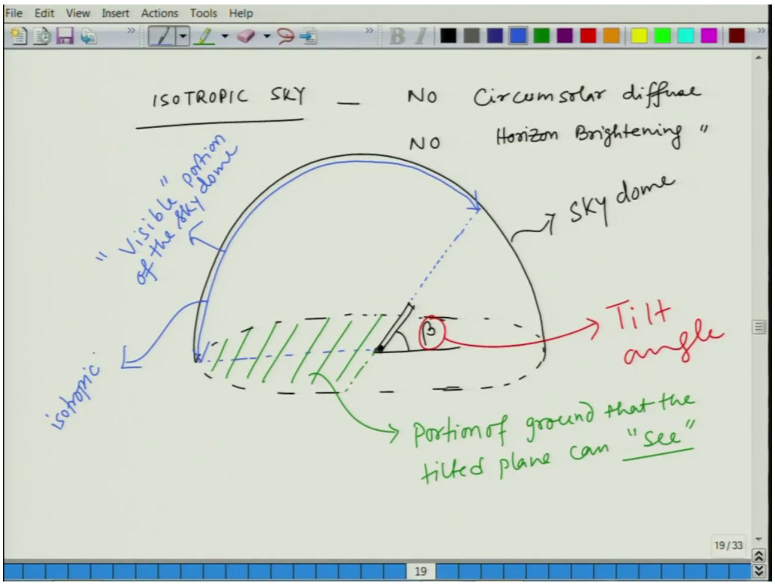

So, isotropic sky assumption, it tells that no circumsolar diffuse radiation as well as no horizon brightening diffuse radiation ok. So, what we are left with? So, let us say that then what we are left with ok. So, if we have this is the point where we have the collector and we have a tilted plane. Suppose this is the plane that we are interested in looking at the radiation intensity ok. So, what does a sky dome look like?

So, sky dome will look like this right and so, this is the sky dome and this angle the collector makes this angle is the tilt angle beta right. So, you can see that the plane it sees portion of the sky dome right. So, this portion of the sky dome the collector sees behind the collector the portion is not visible to the collector.

Visible, what do you mean by that? The collector does not have a eye, but visible means that the radiation can directly reach to that collector from this blue colored portion only ok. So, this is visible and I am putting some inverted commas. So, that you know what the visible means visible portion of the sky dome ok.

And what else does this particular collector sees it sees the portion of the ground right. So, let us say this is the portion of ground that the sky dome sees ok. So, this is the portion of ground that the tilted plane can see, again see means from where the radiations can directly reach on the surface of the collector ok.

And this beta is the tilt angle ok. So, if this is the case and under the isotropic sky assumption what we are assuming that this whole portion whole portion is this blue portion is isotropic. It has certain intensity which is coming equally from all parts of the dome.

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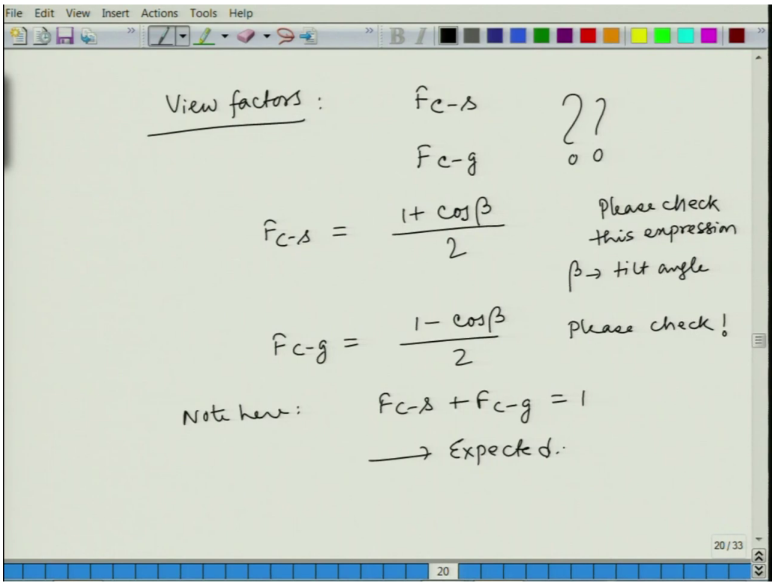

So, first we need the view factors ok. View factors are from the collector to the sky and the other view factor is from the collector to the ground right. So, what would be these view factors and now we are not going to calculate this view factors or find out which is a geometric concept which you have learnt how to do it in case of radiation heat transfer.

So, what we will do we will just state what these view factors will be. So, this collector to sky view factor will be 1 plus cos of beta divided by 2 ok. So, I insist that please check this expression whether it is true or not from the consideration of geometry please check this expression and here beta is the tilt angle ok.

So, that is the view factor from the collector to the sky and from the collector to the ground is 1 minus cos beta over 2 ok very simple expression, but you can check that again please check ok. Now note here that these two view factors add up to one right and that is what they should do.

From the view factor algebra you know all the surfaces that is visible from a particular surface the view factors will add up to unity right. So, that is why here also we see that. So, this is kind of expected, but it is good to verify that this is true. Now, if these are the view factors the expression that we are we have written which will be simplified in terms of the isotropic sky as well as we will put these view factors into the expression.

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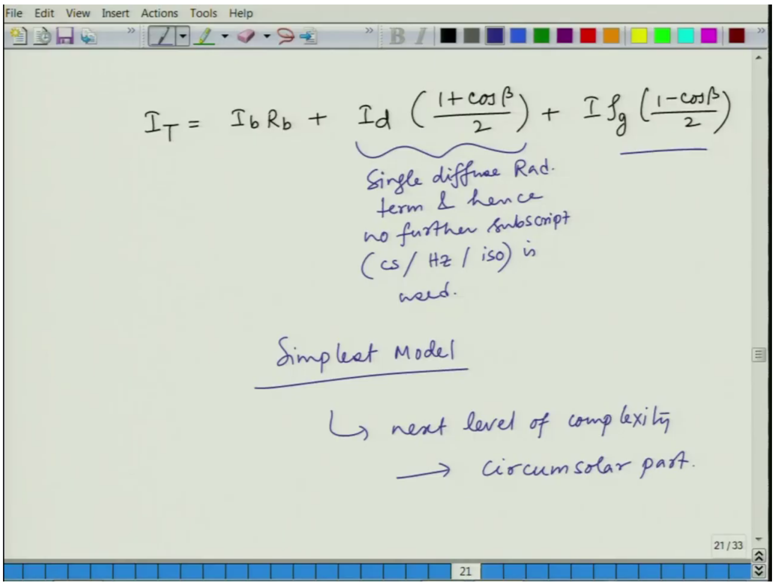

And what will we get? We get this particular expression where the beam part is unaffected because we did not make any changes to that and the diffuse part. Now we have gotten rid of all the different diffuse parts like isotropic, circumsolar or the horizon brightening part we can only write I d, which will tell you the isotropic sky diffusion intensity and that is a single value.

And the view factor is 1 plus cos beta divided by 2 ok. So, that is the total diffuse radiation coming from the sky dome plus the ground reflected part, where we will use the view factor with the ground ok. So, this is the expression that we get under isotropic sky.

So, here you note that single diffuse radiation term and hence no further subscript, such as your circumsolar or horizon brightening or isotropic etcetera are used no further subscript is used ok. Only I d will tell you that is the all diffuse radiation that we have ok and this is the last term is the ground reflected part.

Now, that is the simplest model ok, simplest model. Now, if we want to introduce little more complexity to that. So, next important complexity to introduce next level of complexity is introduced through the circumsolar part ok. And circumsolar part we know that it is related to the beam radiation direction and we use the same factor R b which is used for the beam radiation part ok.

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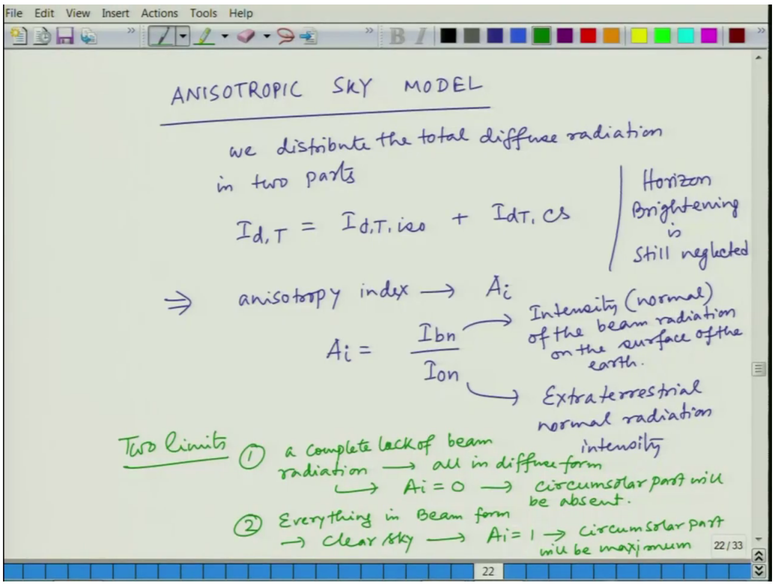

So, now we will look at anisotropic sky model ok. Anisotropic sky means it is not uniform throughout the sky it has a background thing which is isotropic. And then for the circumsolar part or where the sun lies around that we have certain enhanced intensity, which will include in the circumsolar part ok.

So, what we do we distribute the total diffuse radiation in two parts. So, I d T, T stands for the tilted surface and I d stands for the total diffuse radiation that is I d T isotropic plus I d T circumsolar ok. So, here the horizon brightening is still neglected we did not introduce that ok. So, if we have these two parts then we need to have some distributing factor, how we are going to distribute between isotropic and the circumsolar?

And for that we introduce this anisotropy index ok, an anisotropic index is designated as Ai you can see anisotropic and that is why Ai. And Ai is defined to be Ibn divided by Ion, what is that? So, and ok first the most basic thing that Ion is our extraterrestrial normal radiation intensity right, o means outside the atmosphere; that means, the extraterrestrial value.

And it does not depend on whatever be the atmospheric condition, whatever be the weather condition cloud is there or not, it does not depend on that. So, that is why we base our anisotropy index in terms of Ion. And what is in a numerator? It is the intensity and again I should say normal intensity of the beam radiation on this surface of the earth ok.

Whenever we do not have the index or subscript o, that means, we are measuring it on the surface of the earth not outside the atmosphere surface of the earth ok. So, here you can see that what does the this anisotropy index tries to capture. It captures how much of the extraterrestrial radiation is available in terms of beam radiation.

So, it is kind of tells you that lets look at two limits. So, first one is a complete lack of beam radiation. That means, all the radiation that is available is in the diffuse form ok all in diffuse form. So, there you can see that, whether I mean basically it means it is a completely cloudy day you cannot see the sun, then how can you have anything specially bright portion around the sun. So, circumsolar part will be completely absent right.

So, this means that when Ai is 0 then the circumsolar part will be absent right that is intuitively makes sense right. And the second limit that you can see when everything that is available is in the beam form ok. So, everything in beam form or beam radiation, that means, a clear sky condition right.

And in that case Ai will be 1 and the circumsolar part will be maximum do not you agree. So, these two limits tell us that ok the anisotropy index gives you certain distribution when the circumsolar part will be higher or lower that is what we are trying to catch through this anisotropy index.

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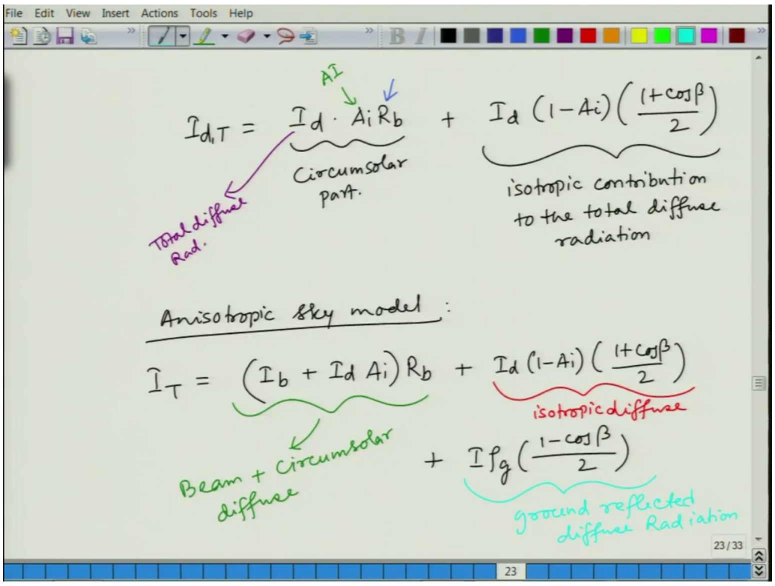

Now, if we introduce this anisotropic index then we can write this total diffuse radiation on the tilted plane will be equal to two parts. One will be circumsolar part right, this is the circumsolar part which you can see that it has this signature R b which stands for the factor which is related to the beam radiation right and it also has this anisotropy index ok.

And this I d is the total diffuse radiation ok. So, I d is total diffuse radiation. So, it tells us the factor which will be circumsolar in which includes the anisotropy index as well as which includes the R b the beam factor ok. And the second portion is the isotropic part, which will be where we have this factor 1 minus Ai.

That tells that 1 minus Ai is the other than what you have other than the circumsolar part ok. And we have of course have this view factor ok, view factor for the sky. So, this gives you the isotropic contribution to the total diffuse radiation is that clear. So, we have now introduced little more complexity and we have now divided the diffuse radiation part into two parts one is isotropic contribution, the other one is circumsolar contribution.

And to find out that circum that distribution we have introduced 1 parameter, which is called anisotropy index. And it depends on the cloudiness or the aerosol content of the atmosphere or rather the condition of atmosphere dictates, what the anisotropy index will be, ok.

So, under this anisotropic condition or anisotropic sky model what we finally, get the total radiation to be IT will be equal to I b plus I d into Ai. And we can club them together the beam part as well as the circumsolar diffuse part in one term and where both of those terms include R b plus the sorry isotropic part of the sky radiation 1 plus cos beta over 2 ok plus the ground reflected part which stays as is ok.

So, this is the beam plus circumsolar diffuse ok, this is the isotropic diffuse part ok and the last term is the ground reflected. And again it is diffuse radiation as we are assuming that the ground is not a specular reflector, but a diffuse reflector ok. So, again this is diffuse radiation ok. So, that is what the anisotropic sky model gives us.

Now last bit of complexity that we. So, far did not consider is the horizon brightening part. So, let us include that one as well.

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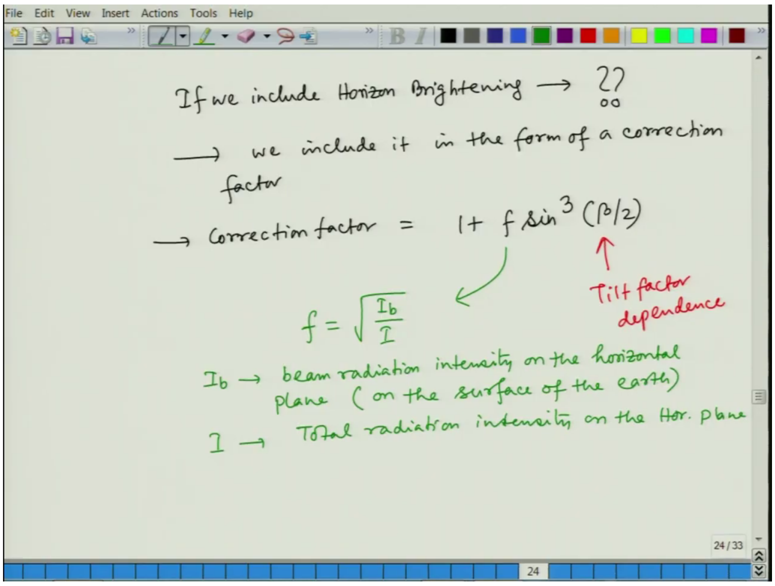

So, if we include horizon brightening, what changes the model will do ok. So, what we do we include it in the form of a correction factor ok. We do not include it absolutely independently or we do not include it in the form of a separate term, but we include it as a correction to the diffuse radiation that we are already taking. And this correction factor we introduce is 1 plus f multiplied by sin cube beta by 2 ok or sin beta by 2 cubed.

So, you can see that this correction factor depends on the beta or the tilt angle ok tilt angle will tell you, how much the horizon brightening will be effective because if you have a horizontal surface it will see very small portion of the horizon, but if you have a tilted surface then it will see one portion of the horizon very directly right. So, that is why the tilt factor dependence is there. So, please note this ok.

And the other thing that we see here which is not so far introduced is a factor f ok. And what this factor f, f is found by this quantity I b divided by I and square root of that. Now, how this is derived and validated? For this you have to look at the proper or the appropriate reference papers and the derivation of this are of course, beyond the scope of this course ok.

So, but you note the physical significance of this because this tells us I b is your beam radiation intensity on the horizontal plane. And of course, whenever there is no o we have on the surface of the earth ok. And I is what? I is the total radiation intensity on the horizontal plane.

So, again it is a relation or a ratio between the beam radiation and the total radiation ok. So, and the square root of that gives you the correction factor. Now if we include that correction factor in our expression.

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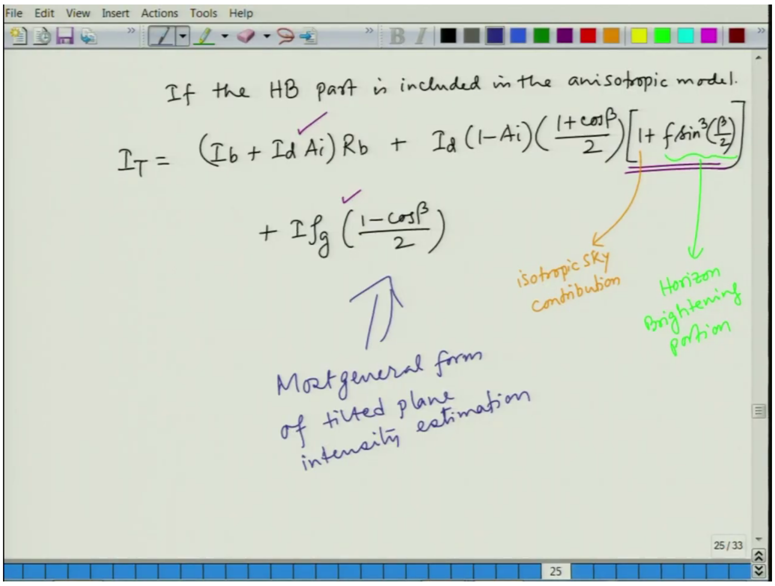

Then, if the horizon brightening part is included in the anisotropic model then the final expression that we get is the total radiation on the tilted surface, that is I b I d, Ai multiplied by R b just like the previous expression that we had then I d one minus Ai this is the isotropic term we are writing up to this we have seen earlier right.

Now, for the horizon brightening, what we are doing? We are multiplying this whole thing by the correction factor ok. So, you can see here ok let me just finish it first plus I rho g 1 minus cos beta divided by 2 ok. So, the these two terms the first and third terms they are exactly the same only difference we have is here right in the second term.

Where what we what difference we have, this one is giving you the isotropic sky part, sky contribution ok and the other one this part is giving you the horizon brightening portion ok. So, basically we have not written it in separate form, but we corrected the anisotropic or the isotropic sky term for the diffuse radiation with this factor which includes the effect of horizon brightening ok.

So, this is the most general form of tilted plane intensity estimation ok which includes everything, but again I should stress here that such complicated model is not often used. Rather we use the simple isotropic sky model which does not include the circumsolar or horizon brightening portions and even then we are very close to the actual estimation.

So, let us go to the next topic which is related to of course, this particular tilted plane radiation intensity estimation and that we call the radiation augmentation.

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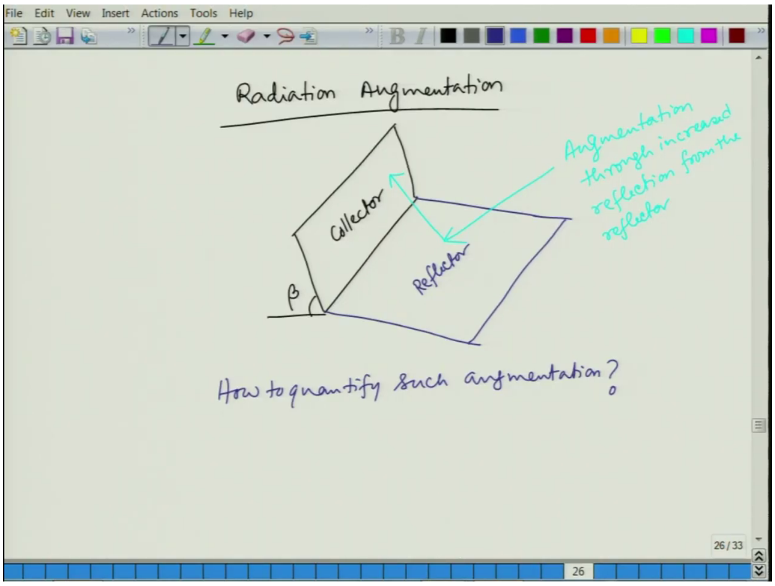

Augmentation means what? To enhance, to increase right, to add, to the radiation that we had. Now, whenever we want to add something we need to put some extra effort right. So, if you just place the collector at certain location at certain tilt angle then whatever is available you will get. Now, if you want to add this, what we do we place certain kind of reflectors in proper positions. So, that the intensity on the collector increases that is what is called radiation augmentation.

So, suppose we have a collector here ok inclined to certain angle beta with the horizontal. So, if this is our collector we can increase its radiation on it by placing a augmenter ok, this is what this is nothing but a reflector. So, even if you do not have it the ground under it will reflect some portion of the radiation to the collector.

But the ground reflectivity is much lower right. So, if you place a reflector which has higher reflectivity. So, what you will have, you will have certain radiation that is coming here that will be reflected to the collector and that is how we are augmenting, augmentation through increased reflection from the reflector ok.

Now, why are we saying that the reflector is placed on the ground? We can place it somewhere else so that the reflection increases right. But in that case we are going to block certain portion of diffuse or beam radiation as well right. So, if we place that reflector on the ground the other portions of the radiation that is reaching on the collector is not going to be affected. Only thing we are increasing the ground reflectivity to increase the total radiation ok.

So, that is the idea of augmentation and for that how to quantify such augmentation ok. So, for that we need to find out how much of this reflected radiation from the reflector will actually reach the collector right. That will be the added part to this reflection or to this total radiation right. So, for that we need to quantify this view factor between these two.

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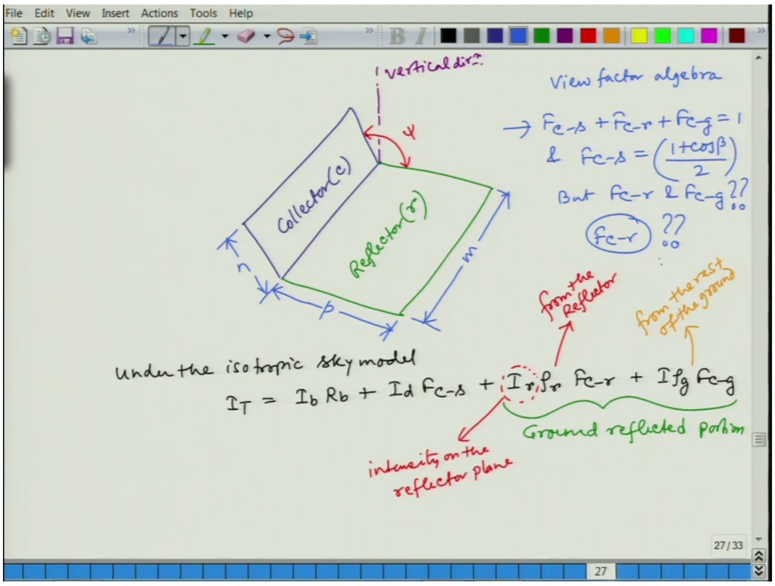

So, let us now take some dimension, so that we can find out the few factor. So, this is the collector, this is the reflector ok and let us say, yeah. So, this is collector will designate it with c and this is reflector we designate that with r and the dimensions here this is we say this is n ok, this is p ok and this particular dimension is m.

And let us say this angle. So, of course, if reflector is on the horizontal plane on the ground this will be your vertical direction ok and the angle between these two let us say this is psi ok. So, if this is the dimension then. So, under the isotropic sky model which is the simplest one, what we have seen?

That IT can be written as I b, R b plus I d, F c s, which is the view factor from the collector to the; so, the sky plus I r rho r this is from the reflector right plus I rho g F c g ok. So, basically what we are seeing here that the ground reflected portion is now broken into two parts. So, one is so this is ground reflected portion now has two parts.

One is from the reflector right and the second one is from the rest of the ground right. So, now the whole ground is not in the same reflectivity or same condition. So, what we do the rest of the ground is separately dealt with and the reflector is separately dealt with ok. And here you see that I r here is the, this I r is intensity on the reflector plane ok, that you have to estimate first right.

Now, here we can write that the view factor view factor algebra tells us that F c s. So, from collector to the sky plus F c r which is collector to the reflector plus F c g that is collector to the ground, all three must add up to one right. So, that is what the view factor algebra tells us and F c s we have already mentioned in earlier portion of this lecture, what we wrote this is 1 plus cos beta divided by 2 right, but what about this c r and F c g, F c g and c r we do not know right.

So, either of them we have to know if we know one then the other will be obtained from this summation rule ok. Because among three terms we know two the third one we can get now how to. So, let us try to find out how this we can find this F c r ok.

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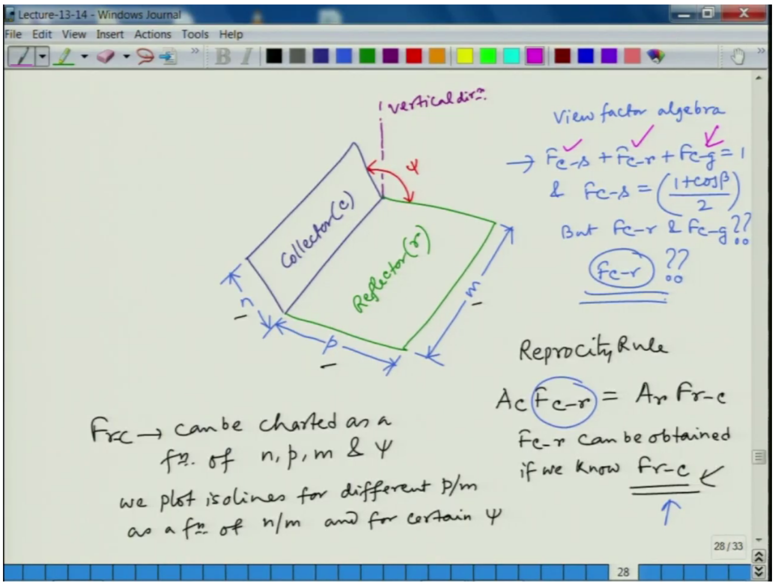

Ac into F c r will be equal to A r into F r c right that is the reciprocity rule for the view factors. Now, if we are after F c r can be obtained if we know F r c right because areas are anyway known. So, let us try to find this F r c. So, this F r c can be charted as a function of these different of parameters right n, p, m and psi ok. These 4 parameters will tell us what would be the value of F r c. And that can be obtained I mean purely from geometry ok.

So, what we can do what is usually done is that this n, p. So, we plot isolines for different p by m ratio as a function of different n by m ratio and for certain psi ok. So, that way we take care of the all the 4 parameters that F r c depends on.

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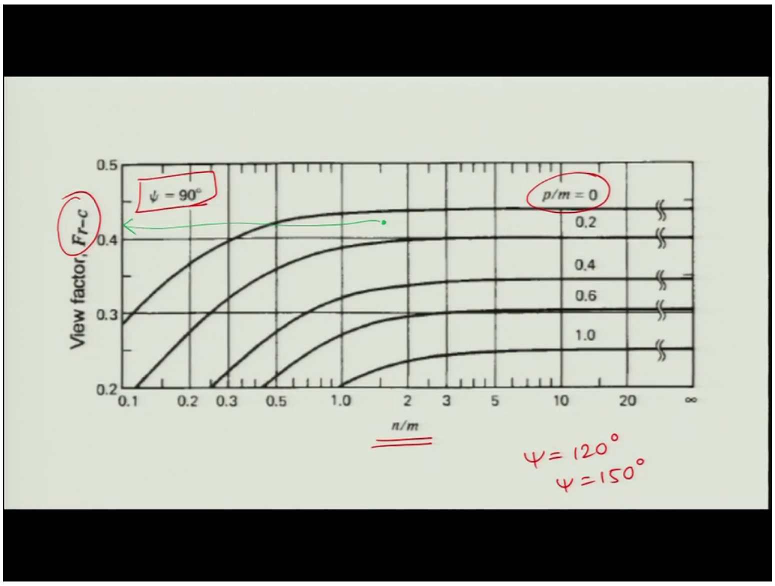

So, let us look at such a chart ok, here is such a chart where we are trying to find out this F r c ok, the view factor from the reflector to the collector. And here we are plotting it for different n by m. And what we are plotting? We are plotting isolines for different p by m ok and everything we are doing for a certain psi ok.

So, that is how we can plot for psi equal to 120 degree psi equal to 150 degree and all ok. So, that way we plot this F r c and if you have something some particular variables which fall in between as you know that you have to interpolate right. So, if something happens to be here like here. So, you have to interpolate between these two lines and then you will get a particular value ok for F r c.

So, that is how this F r c is found and once this F r c is found the other things are easily found out ok. So, once this F r c is found then F r c is found and then we can find this F c r ok from the reciprocity rule and from there when F c r is known rather when this F c r known F c s is already known that is 1 plus cos beta by 2 and then we can find the F c g.

So, that tells us all the required view factors and we can place them in the expression of IT and we can obtain the value for the augmentation that happens due to the reflector.

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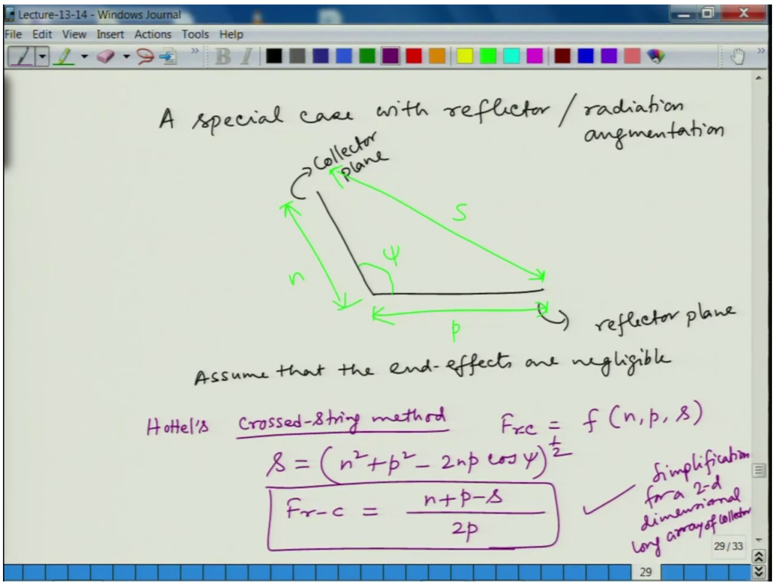

So, last thing that we are going to talk about today is a special case a special case with reflector or radiation augmentation. So, why do you call special case because often we see that rows of solar collectors are placed very long distance ok. So, if you look from side view it will be somewhat like this. So, suppose these are the solar panels which are placed perpendicular to the plane of the board and you have a reflector associated with it ok.

So, this is the collector plane and this is the reflector plane ok and we can assume that the end effects are negligible because it is almost a two dimensional case when you have one dimension very long and that is how its effect is negligible. So, what we have here also we can take this to be of length n and this to be of length p ok. And if we assume or if we write this length we can write it to be s ok.

So, this angle as earlier will designate with psi. So, this is exactly same as the earlier case, but here the m thing is absent and we are assuming that this is infinitely long perpendicular to the direction of the board ok. So, here what we get is that we will use Hottel's crossed string method. If you are not familiar with this please go back to the radiation heat transfer book and look at this particular method then you will find that this F r c can be obtained in terms of this n, p as a function of n, p and s ok.

Now, first we have to find what that s will be because that will depend on n, p as well as the psi. So, n will s will be this is a pure geometry problem you can find this out by yourself. So, s will be n square plus p square minus 2 n, p cos psi whole to the power half, that means, square root.

And when we have s then F r c will be nothing, but n plus p minus s divided by 2p ok. So, that is how you get for a long panel of solar collector with radiation augmenter we will have F r c little simplified then looking at the chart that will be n plus p minus s divided by 2p ok. So, this is the simplification for a 2 d dimensional long array of collector ok.

So, here we stop for today and in the next class we will start with flat plate collectors, which is the most basic form of solar collectors. So, so far we have covered all the basics that are needed for your solar energy conversion. Now, we are going to see from the next class we will actually see the conversion devices.

Thank you very much for your attention.