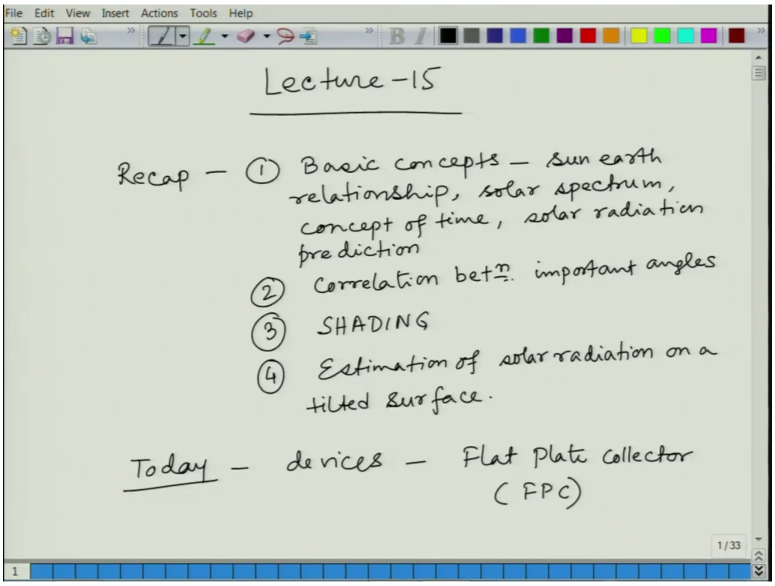
Elements of Solar Energy Conversion

Prof. Jishnu Bhattacharya
Department of Mechanical Engineering
Indian Institute of Technology, Kanpur

Lecture - 15

(Refer Slide Time: 00:27)



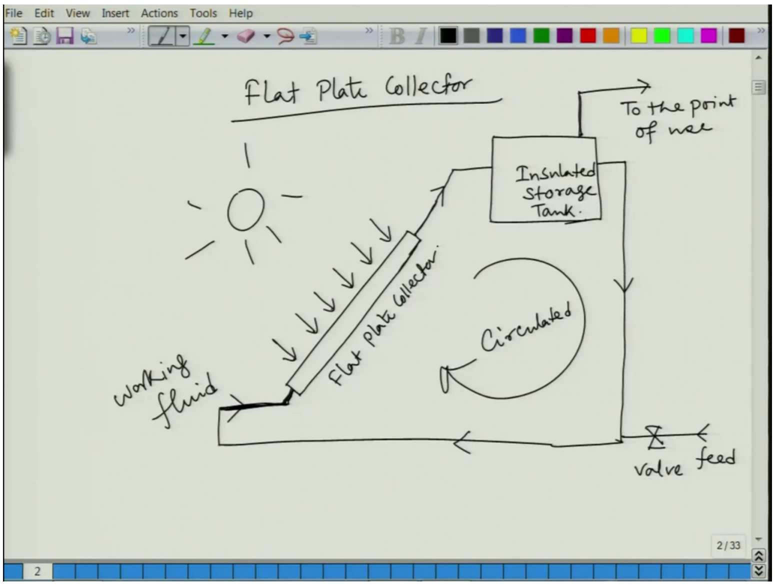
Hello and welcome back to this series of lectures on Elements of Solar Energy Conversion. Today we are at lecture number 15. So, here we are lecture 15. So, a quick recap for whatever we have covered in the first 14 lectures. 1st thing the basic concepts related to sun, earth, relationship, then solar spectrum, concept of time, solar radiation prediction. And then the major topic that we covered was the correlation between important angles.

We have derived most of the important correlations. Then we covered shading. From two aspects whether a particular location will be shaded by some nearby object or the overhang problem which also tells us whether the parallel rows of solar collectors will shade each other. So, that we covered. And then we covered the estimation of solar radiation on a tilted surface, ok.

So, these are the major topics we covered in first 14 lectures. And this builds the foundation that you require to actually look at the devices which are responsible for solar energy conversion or collection, ok. So, now, we are at this critical juncture where we are going to start the devices, ok.

The first, so today what we are going to do? We will look at the devices and the first most important device or the most basic device as well is the flat plate collector. This flat plate collector is often abbreviated with FPC, ok. And this is a very common abbreviation that is why you need to know that it is always FPC means flat plate collector, ok. So, that is what we are going to look at.

(Refer Slide Time: 04:02)



So, first let us look at the basic concept, the basic working principle of this flat plate collector before we go into analysis of it, ok. So, as the name suggests the collector you will be consisting of a flat plate.

So, let us say we have a flat plate like this, ok and let us put some width as well or depth as well because there are few components inside this flat plate collector. But basically, we have a flat plate which receives the solar radiation. Suppose we have sun here and this flat plate collector is receiving this solar radiation.

Now, this light or heat energy that is coming on to this flat plate collector where will that be going. So, there will be a fluid that will pass through this particular flat plate collector. So, there will be a fluid loop, ok.

So, fluid, we often call it working fluid which passes through this one and it absorbs the solar radiation that is collected by this flat plate collector and it delivers it to a tank, ok. So, this is you can say to save the heat and to reduce the loss you have to insulate that tank. So, let us say this is insulated storage tank, ok.

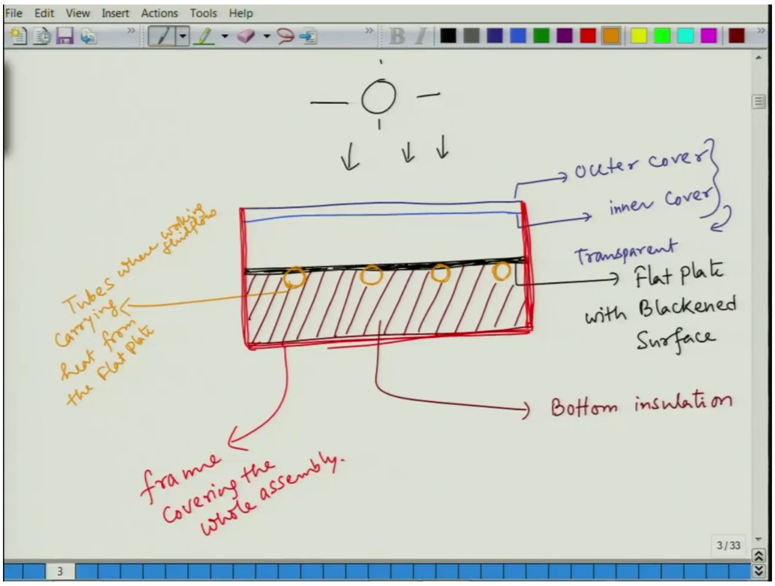
And what usually is done that this particular water itself is circulated few times through the flat plate collector as well as the storage tank, ok. And of course, you will be needing a feed here with a valve, ok valve and you will need to have a feed, ok. And from the storage you will have a line that will go to the point of use, ok. So, often this is circulated.

Now, you can see here that this is nothing but a water heating system, ok. If you keep a bucket of water under the sun then it will gain some heat from the sunlight, right, and from the morning to the afternoon if you see there will be slight increase in temperature as well, ok. So, this is in principle doing the same thing, ok. But here what we are doing? We are trying to increase the efficiency of that heat collection and we are also trying to reduce the possible losses that a bucket of heat is, bucket of water is undergoing, ok.

So, that is how this is like a water heating system, but much more efficient than placing a bucket of water under the sun, ok. And again I am saying this water heating, but you can use some other fluid as well. Often air is also used, but we will talk about the variations later. First let us try to understand the basic principle, ok.

So, here this is the flat plate collector, ok. So, this is the basic drawing for flat plate collector. Now, if we go to look at little more detail of that and zoom into the portion of this flat plate collector. What we will see inside it?

(Refer Slide Time: 08:59)



So, the heart of the flat plate collector is a flat plate, ok, literally a flat plate and it is blackened to increase its absorptivity, ok, oops, ok. So, this is the flat plate which is or with blackened surface, ok.

Now, if you have sun here, it radiates on it on the flat plate. Now, as soon as it starts gaining temperature by absorbing heat there will be loss as well because ambient is at lower temperature than the flat plate, so there will be a loss of heat to the ambient. So, to stop that, what we do? We put a cover, ok.

So, we put a cover here, and often what we do? We put two layers of covers. Why two layers why not or why more than one layer we are using? We will talk to it talk about it very soon, ok.

So, these are you can say this is outer cover and this is inner cover. So, ok fine you are placing them to reduce the heat loss from the flat plate and to minimize or negate the contact between the ambient air and the flat plate by pressing this cover, but they will also block the sunlight as well, right.

So, what you need to do? You need to have some transparent cover. So, both these covers you have to make them transparent otherwise the whole purpose of the flat plate collector is defeated. So, you are allowing sun rays to come in, but not the ambient air to be in contact with the flat plate collect or flat plate, ok. So, ok that is one thing.

The other thing is that you need to take out this heat as well, right. So, you make you are making this flat plate to be heated by the sunlight, but you want to take out the heat as well. So, how you are going to do it? So, you will place some tubes which will carry heat from this particular flat plate in terms of working fluid which is often water, ok. So, these are tubes carrying heat or tubes where working fluid flows carrying heat from the flat plate, ok.

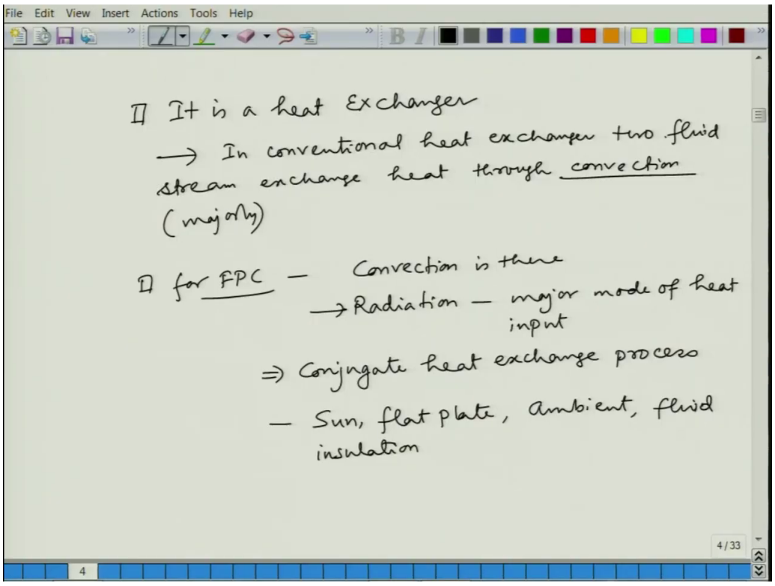
Now, if you see that again there is a big possibility of losing heat from the bottom of the flat plate as well as from the tubes, as tubes are carrying hot water, so heat will be lost from that. So, what we do? We put a very heavy thick layer of insulation at the bottom, ok. So, which covers the whole bottom including the tubes carrying heat, ok. So, that is we call bottom insulation. Usually this is pretty thick insulation to reduce the heat loss absolutely.

Now, what we need? We need to put it in some frame, right, so that everything is in place. So, here we have a frame that covers the whole thing, ok. So, this is the frame covering the whole assembly. But mind it that you cannot extend the cover for the top cover, right because or I mean you cannot extend the frame to the top cover because you have to keep it open to the sunlight, ok. So, this is the basic drawing for the flat plate collector.

So, what it does? To repeat what we understood. So, that the flat plate collector or this flat plate which is a blackened surface usually metallic surface for easy heat uniformity and it receives heat from the sun, but that reception happens through two layers of usually two layers of transparent covers, ok.

That reduces the top loss from the flat plate. And the useful heat that is taken away from the flat plate by the working fluid that are running through this tubes which are placed underneath the flat plate, ok. So, and the bottom of that is completely covered with some heavy insulation, ok.

(Refer Slide Time: 15:53)



So, before we proceed it is very important to have some physical sense of this system, ok. I mean we can do analysis and all, but the physical intuition that I always talk about is very important to carry with you even if you do not remember all the analysis steps. You can do it if you understand what is going on here very clearly.

So, first point one I want to mention is that it is a heat exchanger, right, ok. But usually in the heat transfer course the heat exchanger analysis as you have seen, we have seen there that the heat exchanger in a heat exchanger two differently heated liquids or fluids they exchange heat between themselves, right, through convection usually.

So, in conventional heat exchanger two fluid streams exchange heat through convection majorly, ok. I should say majorly; of course, conduction will be there, but convection is the major mode of heat transfer there.

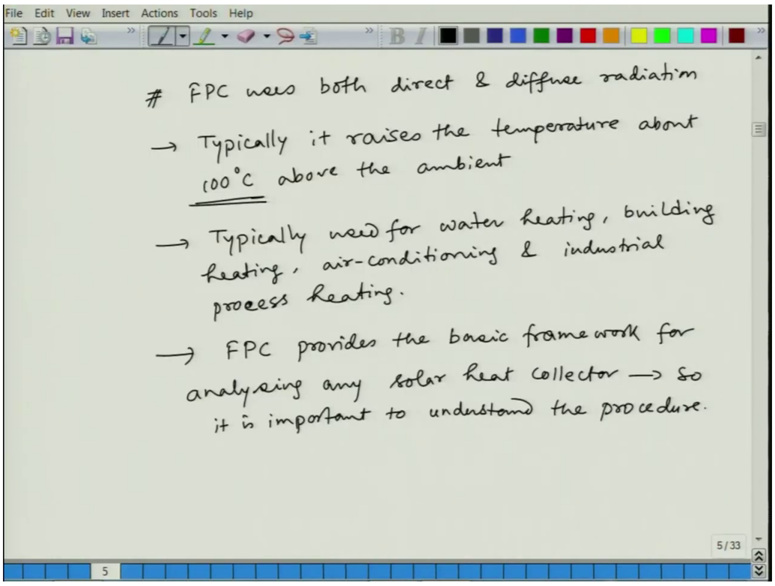
But here for flat plate collector what we see that convection is of course there, but major mode of heat input is through radiation. Radiation is the major mode of heat input, ok. And one of the bodies that is participating in this heat exchanging process is the sun ok, and it is participating through radiation, ok.

So, that is the major point which makes it different from other heat exchangers. And also, like we should say that this is a conjugate heat exchange process. What do we mean by that? It is not the heat exchange between two fluid streams or two bodies, ok there are multiple objects or bodies which are interacting with each other and it is a conjugate problem.

So, what are the bodies? Like, the sun is of course participating in the process, the flat plate which is participating in the radiation as well as convection to the ambient, ok and also we will see it has it interacts with the cover in a radiative mode, ok.

And the fluid that is taking away the heat from the flat plate as well as the insulation which reduces the heat flow. So, there are multiple things happening here and we need to analyze it very clearly to get make a sense out of it, ok.

(Refer Slide Time: 20:11)



So, please note what is the major differences between the conventional heat exchanger and a flat plate collector. And compared to other solar collectors which you will see later, ok. It uses FPC uses both direct and diffuse radiation, ok.

Flat plate collector is we when we say flat plate collector, we do not consider any concentration of the beam has happened, ok. We do not consider that its direct under the sun without any concentration we are considering flat plate collector and that is why it is not limited or restricted to the direct sunlight only, but it is also uses the diffuse radiation, ok.

And typically it raises the temperature about 100 degree centigrade above the ambient, ok. So, you should have some sense that if you install a flat plate collector on your rooftop what is the typical temperature you can expect, if you want to heat water through it, ok. So, typically it raises this about 100 degree centigrade. If you want to run a power plant which requires 500 or 600 degree centigrade as the input fluid you cannot use a flat plate collector. So, it is important that you know the limitations of a particular device.

And it is typically used for domestic water heating or building heating in the winter, ok. Particularly, if you are at a chilly location and also for air conditioning purpose and industrial process heating.

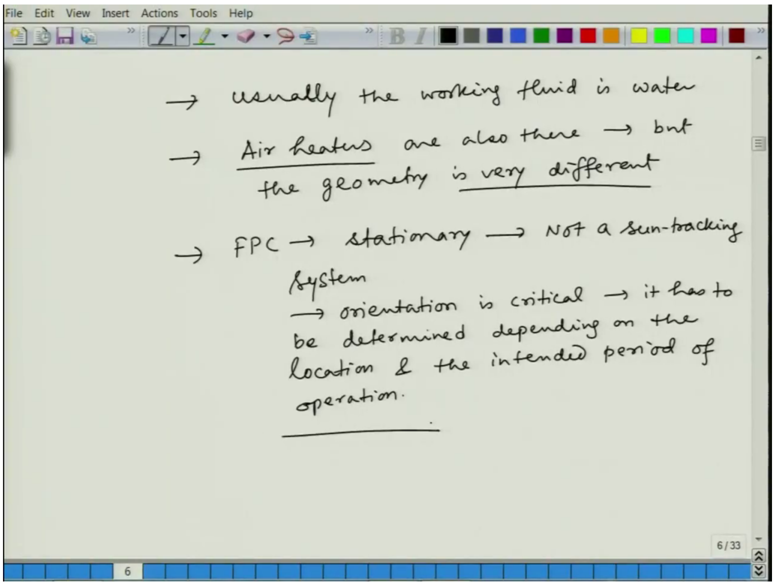
Often in agricultural and other sectors you require some heat very cheap source of heat at about 80 to 90 degree centigrade. There such flat plate collector can give you almost free heat for all those processes because sunlight is free. So, these are the typical application area of this flat plate collector.

And why I go through this flat plate collector slowly and with all steps shown? Because it gives you the basis the fundamental basis of all the different solar heat collectors as we see later, ok.

So, FPC provides the basic framework for analyzing any solar heat collector. So, it is important to understand the procedure how we; this is not a very trivial problem as the initial figure may tell you the, that this must be pretty easy its water circulating and water is getting heated, that is fine.

But if you want to analyze it you will see that it is not trivial. Particularly the problem is its conjugate nature, ok. All kinds of heat transfer are interrelated with each other and you cannot separate them out. You have to either solve it completely or if you or you do not solve it, ok. You cannot separate certain portion and solve it to get some idea that is the difference.

(Refer Slide Time: 25:06)



And again, continuing with the basic understanding that usually the working fluid is water, ok. And we will see that similar arrangement is used for air heating also. So, air heaters are also there, but the geometry is very different because instead of tubes we will require ducts to have reasonable like output or yield in terms of the working heat useful heat are very different, ok. We will see what are the differences later.

And it is important that these flat plate collectors are stationary. Stationary, what do you mean by that? It does not track the sun, it does not move, ok usually you keep it in a fixed position and let it run wherever the sun goes, ok. So, it is not all the time will be normal to the sun radiation, but it will try to optimize as much sun radiation it can absorb, and that will be decided by you who will decide what would be the inclination of that flat plate collector with the horizontal, ok.

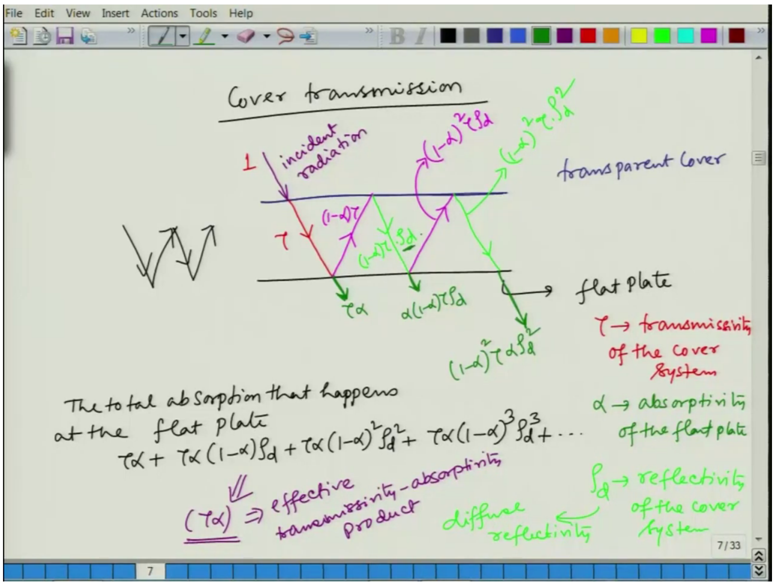
So, it is not tracked or rather not a sun tracking system, ok because sun tracking system involves lot of complications because it has moving mechanical parts and all, and you need regular maintenance it requires parasitic power to move that mechanical parts. So, if you as long as you can use a stationary system it is better to use it in fixed position, ok.

And here and whenever you use a stationary system then the orientation becomes critical, orientation is critical and it has to be determined depending on the location of course, and the intended period of operation. Why location is important is because it tells you what would be the solar motion or the motion of the sun will be with respect to that collecting site, ok.

An intended period of operation, what do I mean by that? Suppose you are installing a solar collector or flat plate collector for your winter water heating during winter you need to heat up water and for that you are using this solar collector. If that is the case then, what you need to do?

You have to look at the winter months and you have to choose a orientation which will be particular or optimized for that location or that intended winter operation, ok. And similarly, for other applications you have to choose accordingly, ok. So, that is true for any fixed position systems.

(Refer Slide Time: 29:20)



Now, first little technical thing that we are going to introduce is the cover transmission. What do you mean by that? We have seen that suppose we have a cover here which will be transparent of course, transparent cover, ok and the flat plate is at the bottom of it, this is the fat plate. Now, if we have a fixed flat plate collector, then most often or just a single time in the day the sun rays will be normal to the flat plate collector otherwise it will have an inclined entry, ok.

So, let us say that this is the incident radiation, there will be hundreds of or many of these solar arrows you will see solar ray arrows. But what will it do? It will; so, how can I differentiate it. Now, once it passes through the transparent cover the intensity will reduce and you can say even the; so, a portion of the incident radiation will come through and that portion if you say the total radiation is coming that value is 1. So, a portion of that let us say tau which will be the transmissivity of the cover that will reach at the bottom layer and it will ultimately reach the flat plate.

Now, what will happen to that? A portion of this will be absorbed. So, a portion; that means, alpha which is the absorptivity of the plate, ok. Here let me write tau is transmissivity, transmissivity of the cover system, and alpha is the absorptivity of the flat plate, ok. So, here only a fraction of that tau will be absorbed which is tau alpha. What will happen to the rest of it? That will be reflected, right.

So, it will be reflected and this will be 1 minus alpha into tau, right, because out of this tau tau alpha is absorbed in the flat plate and rest 1 minus alpha into tau will be reflected back to the cover system, ok. Now, from that cover system again there will be reflection. So, I have used another color. So, let us say we will have another reflection and now the reflection will be according to the cover system reflectivity, ok. So, that fraction will be 1 minus alpha tau multiplied by rho of g.

What is this rho of g? Rho of g is the reflectivity of the cover system, ok. You got it. Now, again a portion of that that reaches the flat plate will be absorbed. And what would that be? This will be alpha multiplied 1 minus alpha tau rho g, is not it. Now, again you will have another reflection where you will have portion 1 minus alpha squared and then tau rho g, this will be reflected, ok.

Again, a fraction will be coming back, so I should put the arrows here, so that you understand it clearly, ok. Now, how much will be this fraction? This will be 1 minus alpha square tau into rho g squared, is not it. I should use not rho g, but rho d because this is diffuse reflection, right and g stands for ground. So, let us not use that, ok. So, here also I should remove this to be d, ok. And this d stands for the diffuse reflectivity actually, ok. Back to the problem.

So, you can see what will happen, that there will be this multiple reflection and then coming back going up again. So, this kind of reflection will happen multiple times, but each time the intensity reduces, ok. So, you can see next time in the next layer what will be absorbed here will be this 1 minus alpha squared tau alpha rho d squared. Let me do this correction here as well, ok.

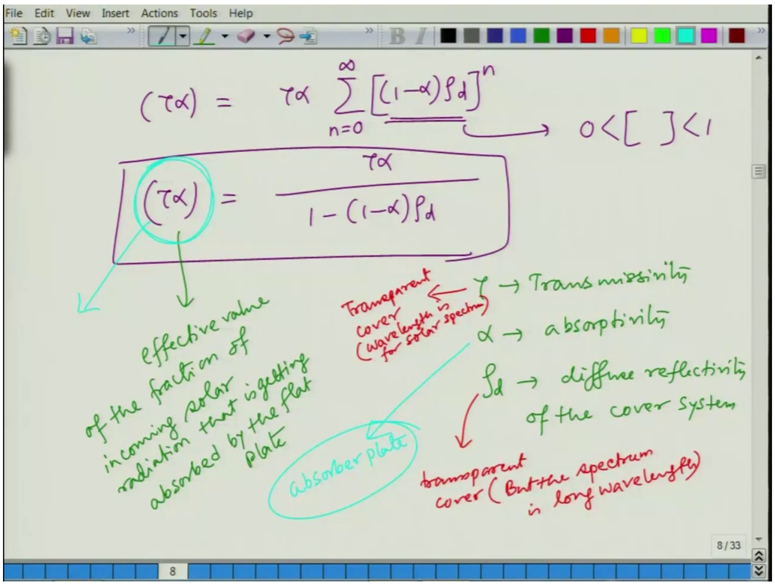
So, now and that will continue. So, what we can write? We can write that the total absorption that happens at the flat plate. You can write it as summation of this tau alpha plus tau alpha 1 minus alpha rho d plus tau alpha 1 minus alpha squared rho d squared plus, you can see, you can see this series coming, this will be tau alpha 1 minus alpha cubed rho d cubed, right and so on.

And at with each step the fraction is or the intensity is getting reduced because alpha is less than 1, so 1 minus alpha is also less than 1, and it is getting squared, cubed, and so on, ok. So, the value is reducing. Similarly, for rho d which is also less than 1 between 0 to 1, right reflectivity and it is getting squared, cubed, and so on. So, that is how the effective value of each term is getting reduced. So, this is kind of a infinite series that you get.

And what we do with it that we replace these particular infinite series with an effective value, we call it effective transmissivity absorptivity product, ok. And this parenthesis they tell you that it is an effective value, ok.

Not the transmissivity of the trans cover and the absorptivity of the flat plate if you multiply them that will not give you the effective value, you have to do this summation. So, this is called effective transmissivity, transmissivity-absorptivity product ok, which tell us what would be the fraction that will be utilized or absorbed by the flat plate, ok.

(Refer Slide Time: 39:42)



So, let me write it in concise form. This effective absorptivity transmissivity product will be tau alpha into summation of this 1 minus alpha rho d, this whole to the power n and this n will be from 0 to infinity, right. That would be the infinite series sum, right. You can concise way you can write it. And this is known you can get it for when this thing is less than 1 which it is because 1 minus alpha is less than 1 and rho d is also less than 1, so you will have some number which is between.

So, this parenthesis will be between 0 to 1, ok. So, for that condition what you can write this sum will be tau alpha 1 minus this, ok. So, this effective value you can write it to be this. So, note here that this effective value, this is effective value of the fraction of incoming solar radiation that is getting absorbed by the flat plate, is not it. That is the effective value. And this side we have tau this is transmissivity the absolute value alpha this is absorptivity and rho d this is diffuse reflectivity of the cover system.

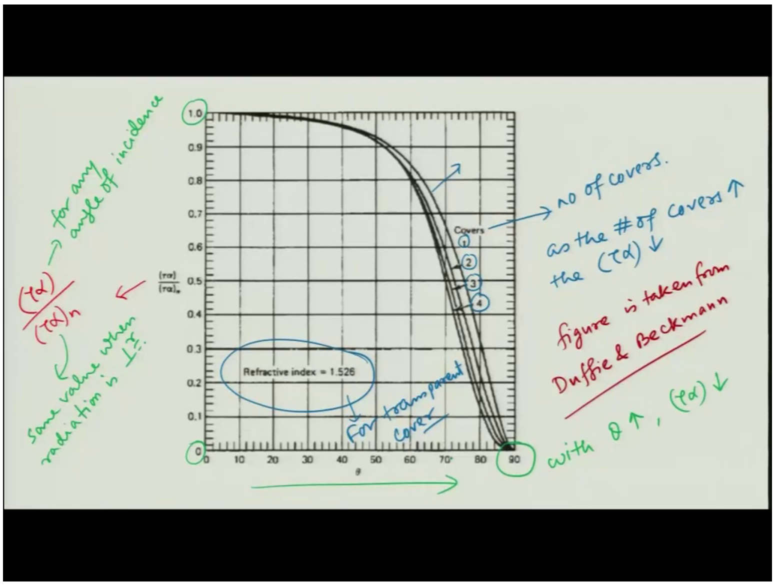
And this here there is a trick that we will go into detail later, but this row d is actually diffuse reflectivity for a particular spectrum range, ok for the solar radiation. Because what it is acting on is a diffuse radiation that is coming out of the flat plate if you see here that this rho d is acting on the diffuse reflection that is coming out of the flat plate.

So, the spectrum will be different than solar radiation, ok. So, it will be more of a longer wavelength radiation that this diffuse reflectivity will act on, not the shorter wavelength part of the solar radiation, ok. We will see to it in a while, ok. And these are individual values and you note that these are for different portions. This is for what? This is transmissivity for the cover system for the transparent cover and the wavelength range is the solar range, wavelength is for solar spectrum, ok.

But for this one this is again for transparent cover, but the spectrum is long wavelength or in the infrared region, ok. So, both are property of the transparent cover, but for different wavelength range. So, this is where the trick lies. And what else do we have here? This one, right, absorptivity and this is not for the transparent cover, but for the absorber plate, ok.

So, 3 different properties, 2 for the transparent cover and 1 for the absorber plate they all are contributing to this effective transmissivity absorptivity product, ok. So, it is not a simple product and whenever you see these brackets or parenthesis you will know that it is an effective value and you have to consider that, ok.

(Refer Slide Time: 45:10)



Now, if we look at the distribution of this effective transmissivity absorptivity product, then how does it look? Ok. So, here we are looking at a diagram which is giving you the ratio of this effective transmissivity absorptivity product to its normal incidence value, ok. So, what does it say? It is, this is for any angle of incidence and the bottom denominator is the same value when radiation is perpendicular to the collector, ok. So, that ratio will of course, be between 1 and 0, ok.

Now, that is what we see this is 0 and 1. And what we see here that we have several lines here which tells you covers. So, these are number of covers. So, as we see that we sometimes go with multiple covers on the transparent cover system. So, here you can see if we have 1 cover, you will have the line which will be this one, ok and then for 2, 3, and 4, ok.

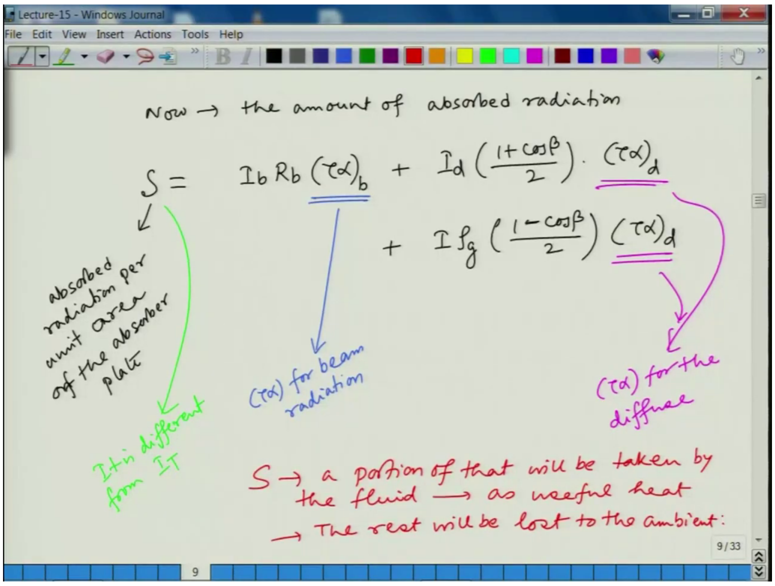
And you can see as the number of cover is going up the effective transmissivity absorptivity value is going down. And again, here it is not captured completely because the normal value the effective tau alpha subscripted normal that is also going down, right. So, the effective value that tau alpha is going down or by how much it is going down is much more than what you see here. And this is done for a certain refractive index. This refractive index is for transparent cover, ok.

So, before I proceed, I should put the image courtesy. So, this figure is taken from the book by Duffie and Beckmann, ok. So, this book is also referred to as one of the reference books, that we are using for this course and it is mentioned in the introductory video, ok. So, the figure is taken from there.

And one more thing I should discuss here is that you see the angle of incidence dependence. As the angle of incidence is going up it is the value is going down, ok because the amount of radiation that is going to be reflected back as well as the absorption that will happen all those values come down.

So, with theta going up this tau n effective value is coming down, and when the radiation is horizontal or parallel to the flat plate there will be no absorption at all, ok. That is what this point means, ok.

(Refer Slide Time: 49:39)



Now, we are in a position to see the amount of absorbed radiation, ok. Here the concept that we have developed for the total available radiation on a tilted plane will be directly utilized, ok and the concept we just saw this effective absorptivity transmissibility product that will also be used. So, let me write that expression, ok.

So, S, it is often designated as S which is the absorbed radiation per unit area of the absorber plate, ok and this acts on the beam radiation as well as diffuse radiation. So, how we will be use? For the beam radiation this I b R b part will be there and now with the intensity this is the beam intensity, right. Now, we have to multiply that with the effective absorptivity transmissivity product, but that again for the beam radiation.

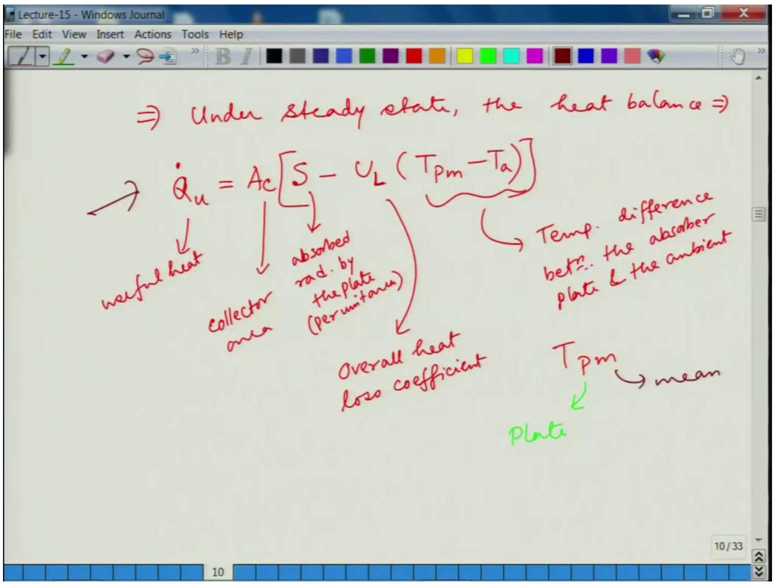
So, we will use the subscript b for this term. And then, for the isotropic sky what we have learnt? This I d diffuse multiplied by 1 plus cos beta over 2 which is the view factor from the collector to the sky and that will be multiplied by this effective absorptivity transmissivity product, but here with a subscript d, because the value will be different for diffuse radiation, ok.

And the third term will be from the ground reflected radiation which will be I multiplied by rho g which is the ground reflectivity and the view factor from the collector to the ground which is 1 minus cos beta over 2 multiplied by this tau alpha d. Again, this is this will be coming in diffuse form. So, that is why we use the subscript d.

So, let me just write it, so that you can see that again this is for the, this tau alpha for beam radiation or direct radiation, ok. And both of these are the same thing you have used twice, these are tau alpha for the diffuse radiation. And two diffuse radiations are coming, one from the isotropic sky that is the assumption again, and the ground reflected radiation, ok. So, that will give you the total absorbed radiation.

So, if you just get rid of this tau alpha terms from all the individual terms you will get the I T which is the total radiation that is falling on the tilted plane, ok. So, you note here that it is different from I T which you have learnt earlier, ok. This is one important thing. And you can also see here that S, a portion of that will be taken by the fluid, ok. That means, water as useful heat, that heat will be useful to you and the rest the rest will be lost to the ambient, ok.

(Refer Slide Time: 54:27)



So, now we are in a position to talk about this useful heat. We have introduced it a fraction of that will be used, but what we can write that under steady state the heat balance will be somewhat like this. What you can write? That the rate of heat that is carried out by the fluid which we call useful heat Q dot u that will be this absorbed radiation per unit area minus the loss, ok.

We can use that symbol U L which will be overall heat loss coefficient multiplied by the temperature difference between the absorber plate and the ambient, ok. And this whole thing will be multiplied by the area of the absorber plate, ok. So, let me just write this is useful heat, this is collector area, this is absorbed radiation by the plate, this is the overall here I should write per unit area, and this is U L is overall heat loss coefficient.

So, we do not know how to evaluate it till now. But what we are putting? Like a black box we are putting everything unknown to this term U L, over all heat loss coefficient. And what is this? This is the temperature difference between the absorber plate and the ambient, ok. So, T a is the ambient temperature and T pm. Why we call it pm? This T pm, let me just write what this individual subscript mean, p means plate, plate is referring to the absorber plate here and m means mean.

So, we will see that the whole plate will not be at the same temperature or it will not be same at certain temperature all the time, ok. So, we have to take some mean value of this. And that is where the difficulty of using this equation lies. And we will talk about it in the next class, and we will go into detail how we can determine this U L, the overall heat loss coefficient for individual losses that will try to understand, ok. Here I stop for this class.

And I thank you for your attention.