Solar Energy Technology

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Lecture - 12
Theory of Flat Plate Collectors - Liquid Based (A)

In the last a few lectures we considered the processing of solar radiation, and calculating the optical efficiency or the transpotent absorbance product as applicable for flat plate collectors.

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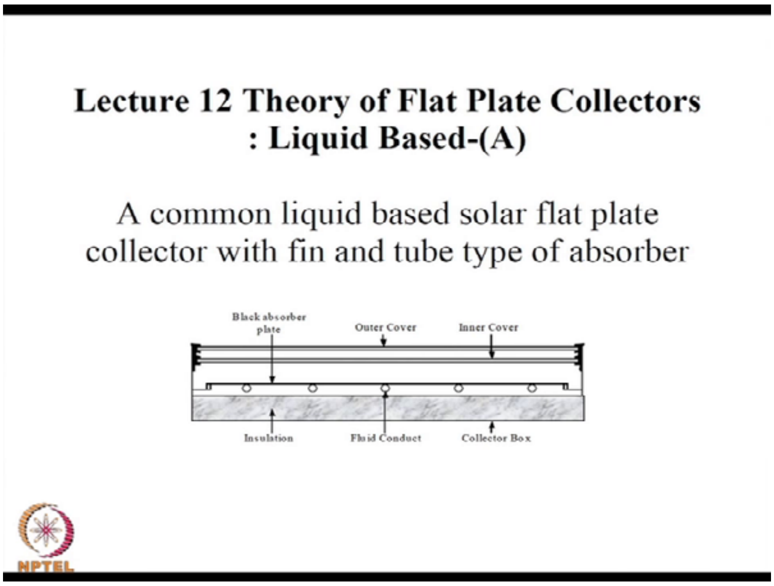

The time scales had been small like an hour and large like a day or even the monthly average day.

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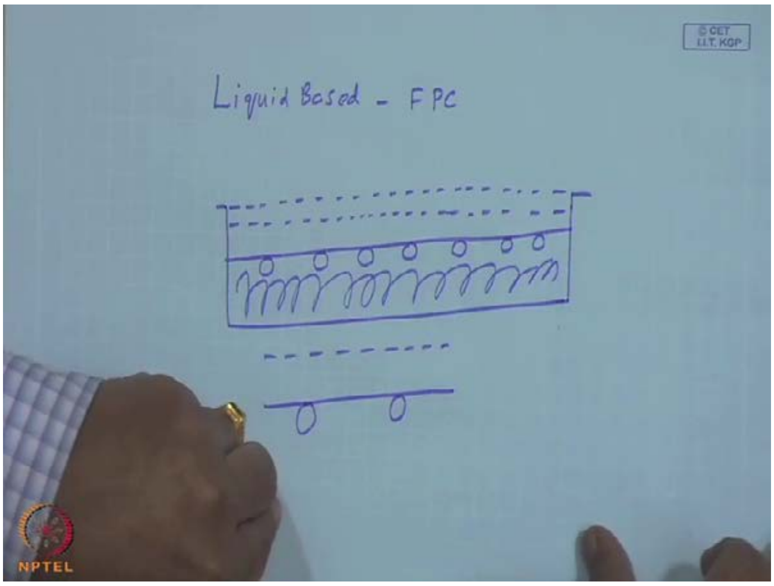

Today we shall go in detail with the theory of flat plate collectors, first we shall deal with the liquid based flat plate collectors. Why I said in general liquid based is it may be water in general, but it could be an anti freeze solution too to take care of colder climates, we already have gone through the basic collector configuration. The idea being to make the absorption process of solar radiation efficient, and less emission and less of convictive heat losses, which typically has an absorber plate with tubes as shown here; they can be soldered or wended to the bottom of the absorbing plate, and this is housed a box and the bottom is insulated.

So, that the bottom conduction losses are minimized, and top we have one or two attempts durably three glass covers. So, that convictive and radiative losses are minimized. Other configurations are possible this fin and tube arrangement I have shown in a is nothing but the same the tubes are attached to the bottom.

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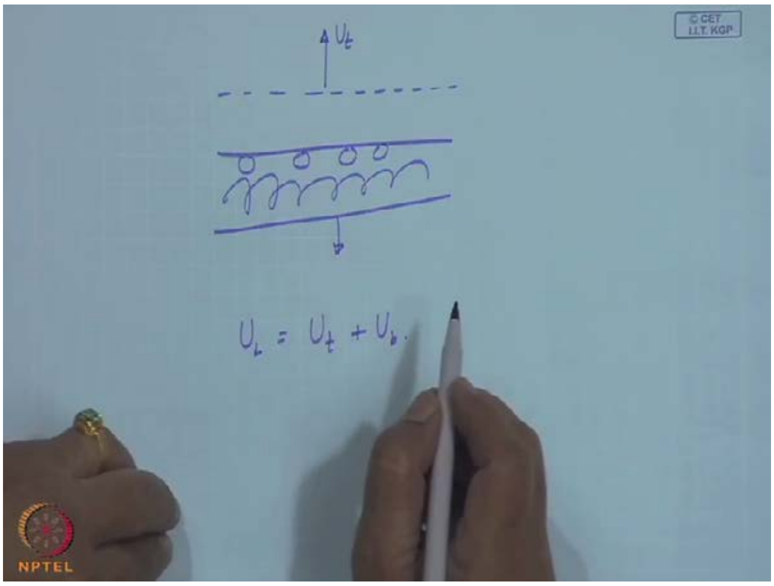

And you may characterize the system to be comprising of a top loss coefficient, and bottom loss coefficient, in general overall loss coefficient will be equal to the top loss coefficient plus the bottom loss coefficient, though it may not be true all the time, we will see the exceptions a little later.

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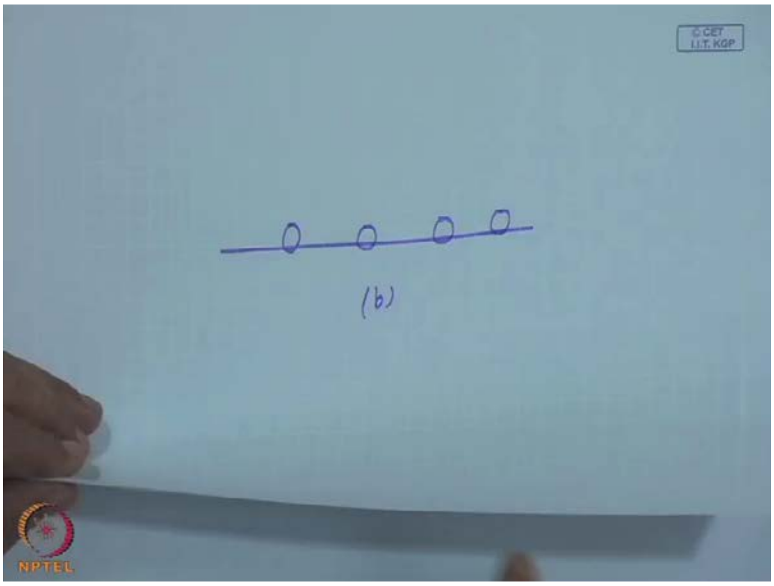

Now, the absorber can be also having the tubes on top of the absorber plates, like this with the argument being the a blackened absorbing tubes will be directly exposed consequently they will absorb more transfer heat to the fluid more directly, this is the configuration b.

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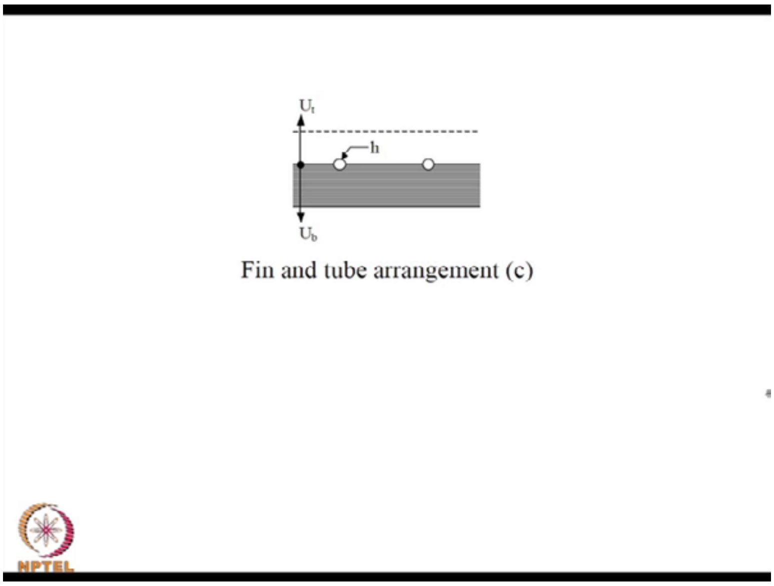

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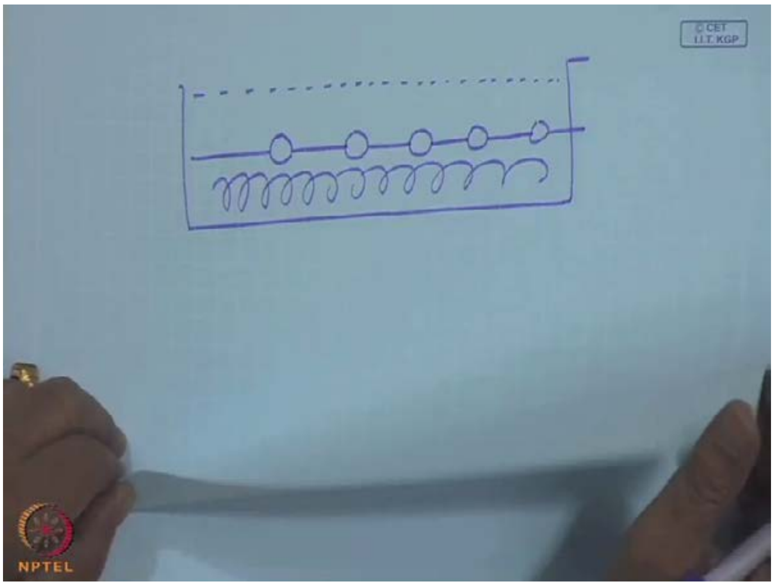

You may also have a configuration c, where the tube is in the middle separated by a flat plate which we call the fin little later so on and so forth. Again one or two glass covers and you have the box with an insulation; these are the fin and tube type of absorbers with their tube arrangement being slightly different one from the other. Each one have its own advantage or disadvantage and the expressions that we are going to have they slightly differ. The performance may not be all that much different form one thing to the other, it is a question of manufacturing convenience.

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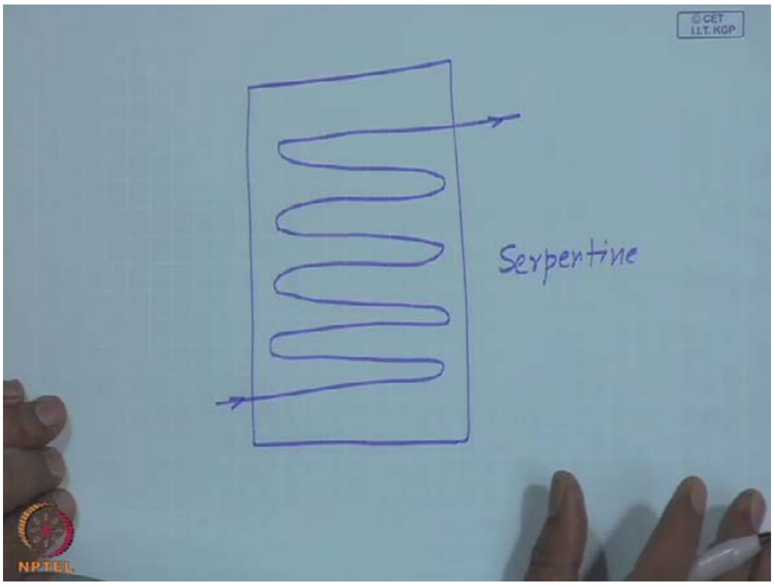

Now, you can think of other configurations also you may have the entire absorber plate with a sort of serpentine tube arrangement soldered or welded to the absorbing plate, and goes out between at low temperature may enter here may lay here, this is a serpentine absorber. The difference between these two is the total flow rate is divided equally among the number of tubes in the configurations we have shown earlier, and in this case the entire flow goes to the tube. So, this may lead to a higher pressure loss though there may be some other advantage in terms of heat exchange.

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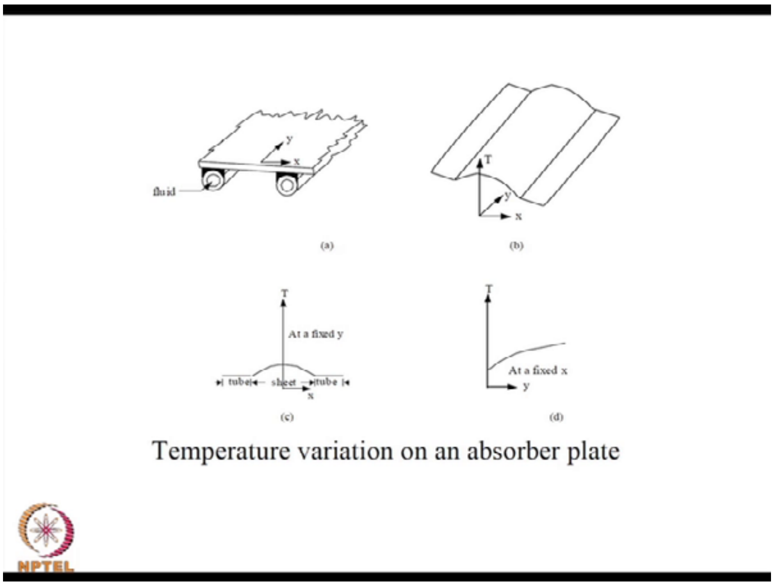

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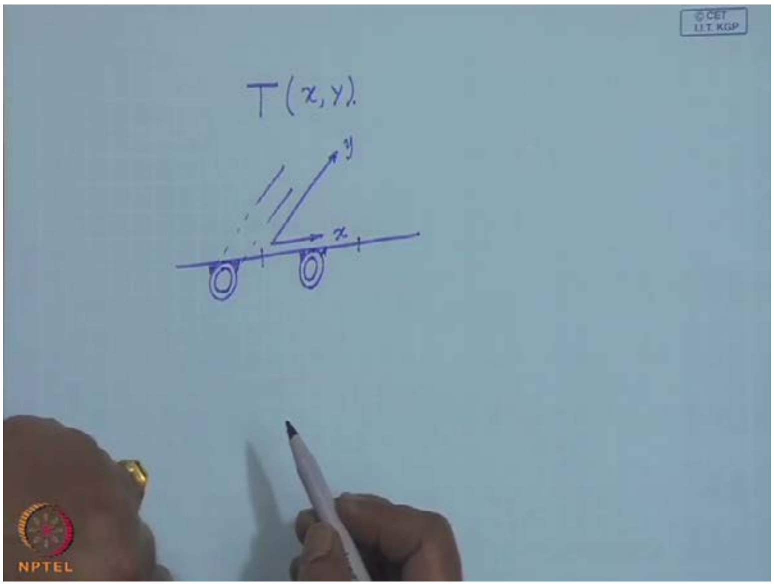

Now, if you want to make an analysis we should know in general the temperature on the absorber as a function of x and y, where we have shown that if I may show the detail that this may have an inner diameter and an outer diameter d i and d o, and this is soldered welded with a bond material. So, that the thermal contact is good, and the heat is transferred towards the fluid. Now, if I call this x the type of elements something like this half a fin to the left, and half a fin to the right of a tube is a repetitive element. So, this may be called x direction and this may be called y direction where you have these tubes running perpendicular to the plane as we have seen here.

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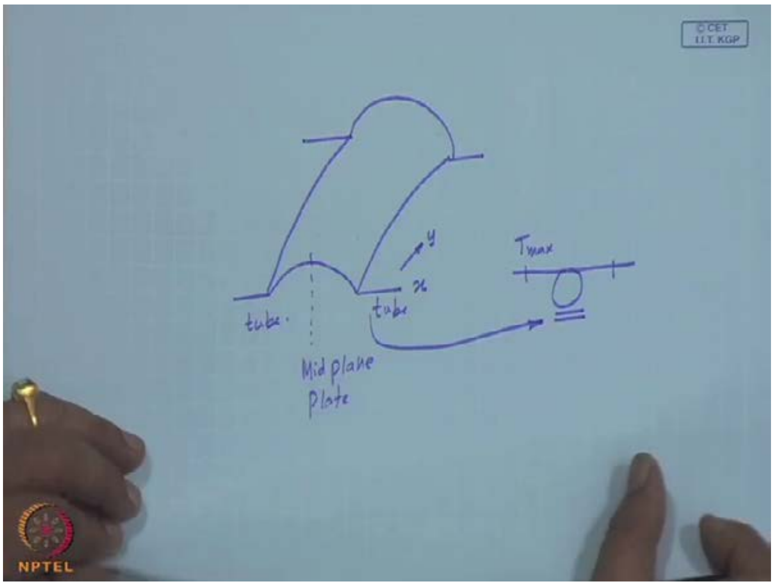

Next is qualitatively we can see if we plot the temperature, you will have something like this, this will be the middle of the mid plane of the plate, and this is the tube region tube region tube, and this is at any given X and this keeps on increasing as you go in the direction of y, and I will have again a picture something like this. In other words in the fin or the plate region the temperature varies with a maximum at the middle of the plate, if this is the element I am considering, this will be this is the T max, and the wave form portions pertains to the tube .

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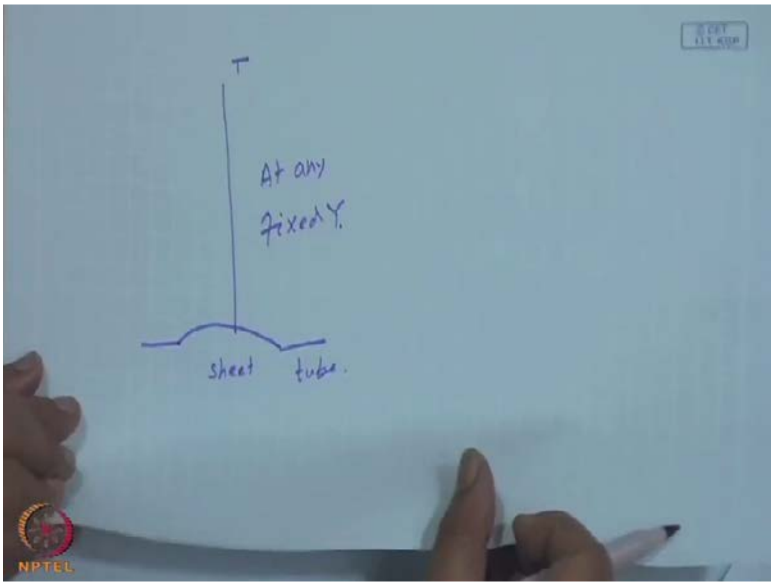

So, in a single dimensional plane, if I plot temperature T versus this is the tube, this is the fin, sheet rather this is what I have this is at any fixed Y.

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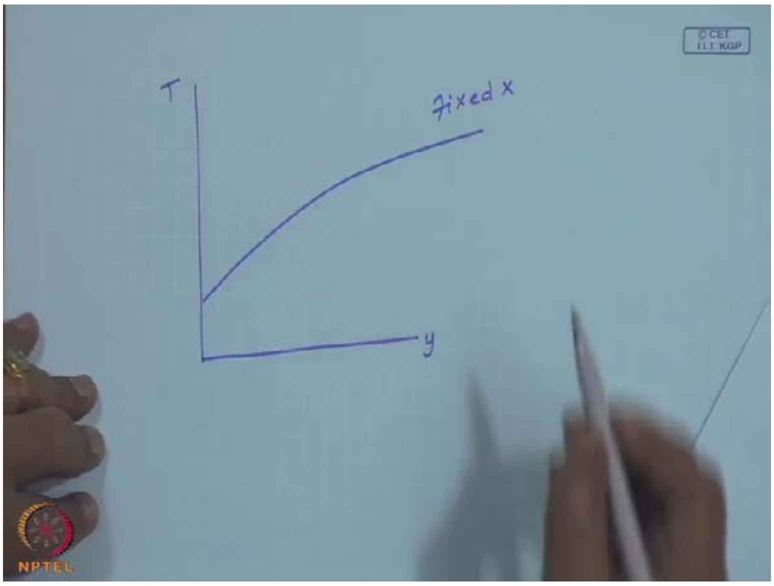

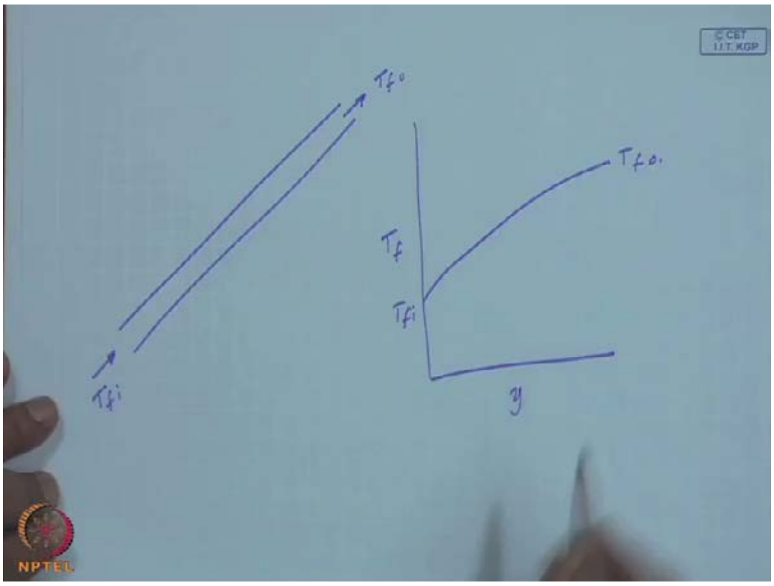

The same thing if I consider a fixed x, it will be increasing. So, to give you an idea, if this is one tube where the fluid is entering with T f i and it will be leaving at T f o, if I plot in the tube region it will start at T f i, and exits at T f o.

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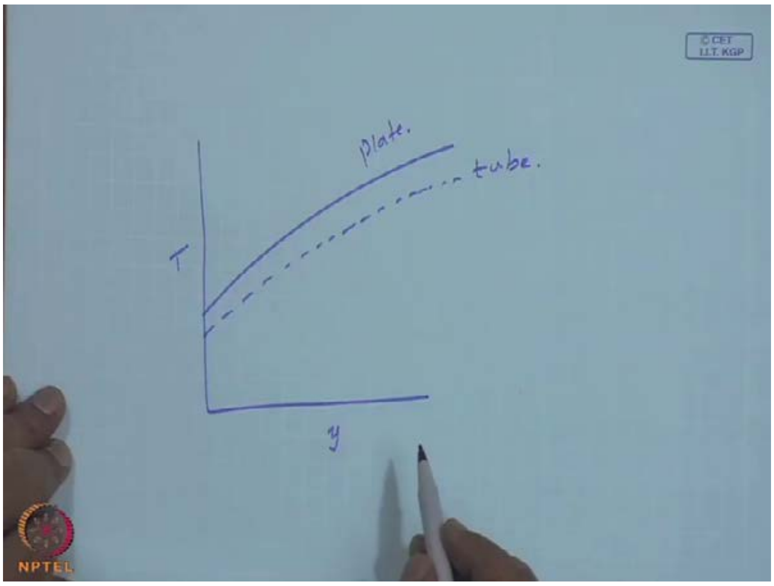

The location can be chosen not only the tube, but also anywhere on the plate, in general this is y and T, this is on the plate, this temperature will be higher than the temperature on the tube, because the heat is being transferred into the tube from the plate region.

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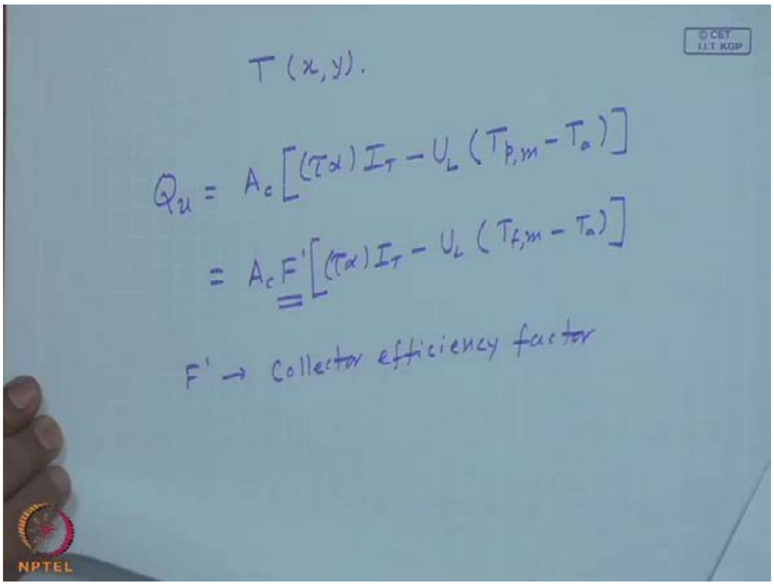

So, in general my temperature is a function of x and y, y being along the length of the tubes or the collector and x being across that. Now, we briefly mention that the useful energy gain for a collector of area A c can be expressed as transmittance of certain product multiplied by the solar radiation falling on the collector minus overall loss coefficient multiplied by I will pick up a mean plate temperature to represent the entire absorber plate. In other words it is a single node analysis, we will consider the entire flat plate to be at a temperature T p m. This of course, reasons we already mentioned as been modified as multiplied with a efficiency factor F dashed tau alpha times I T minus U L instead of T p m I choose T f m minus T a.

This gives a little more clear idea about the collector, if T f m is pretty close to T p m we can say that the collector is more efficient. In other words it is able to transfer the energy to the fluid to reach almost the plate temperature, then this factor f dash will be close to unity. So, this f dashed is called the collector efficiency factor, which we have already defined.

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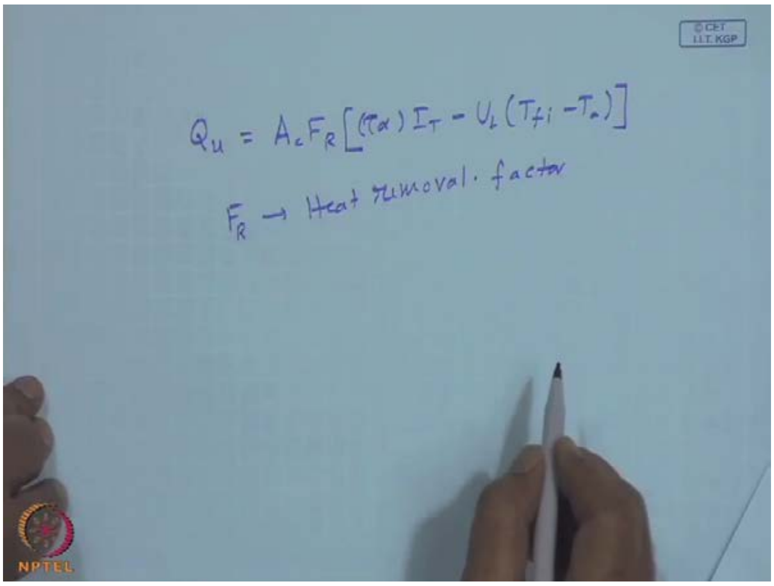

And even to avoid the uncertainty of defining T f m, Q u can be expressed in terms of the inlet temperature of the collector, this is a single point temperature. So, there cannot be any ambiguity about it. And the factor F R we already defined as heat removal factor which is in a way analogous to your heat exchanger effectiveness.

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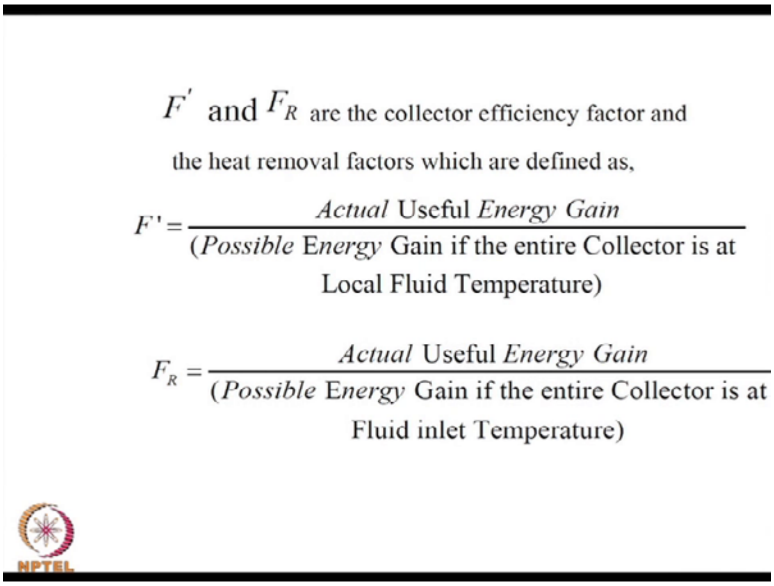

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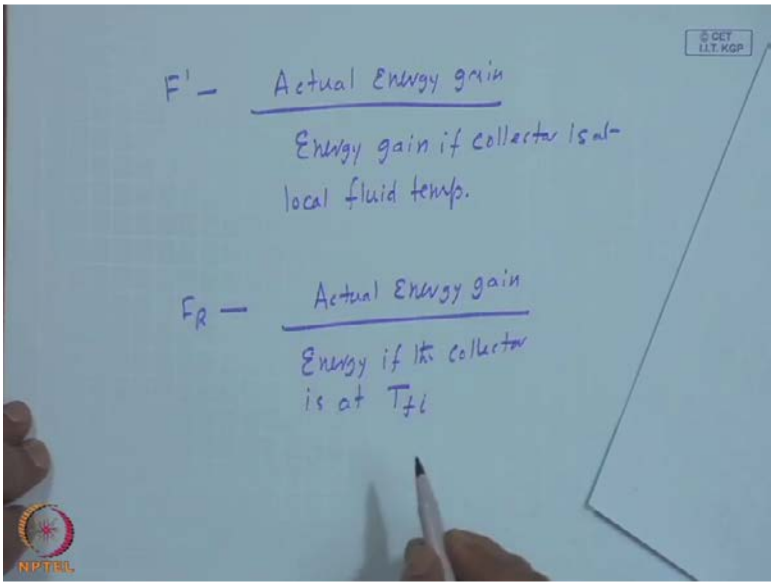

So, we recall the definitions of F dashed the collector efficiency factor, and F R the heat removal factor as the ratio of actual energy gain I write in brief by energy gain, if the collector is at local fluid temperature. Similarly, F R is defined as actual energy gain by energy gain, if the collector is at collector fluid inlet temperature here T f r right. In other word this is the temperature which causes the minimum of the losses, and hence the maximum possible energy gain.

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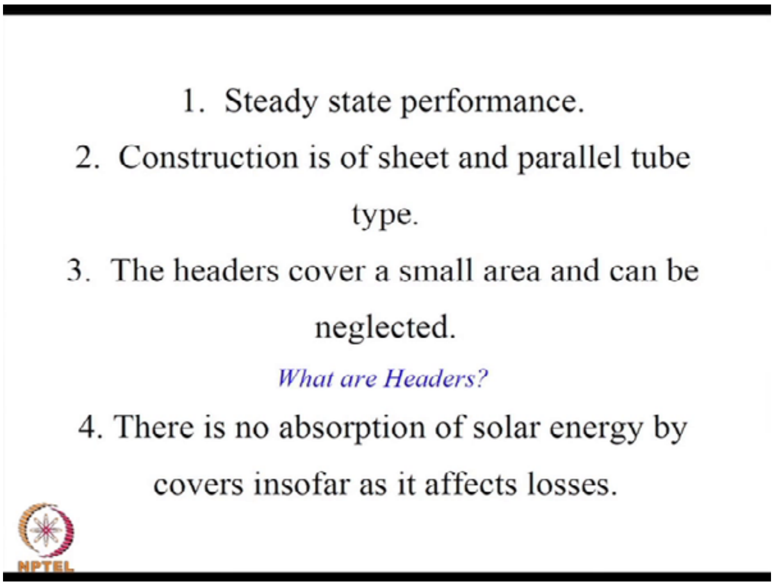

Now, before we proceed with the analysis we make a large number of assumptions, the list of assumptions one can really remember, but the implication is very important; particularly in solar collectors often in heat transfer we make the assumption steady state etcetera, but in the case of solar collectors and in general environmental systems, the steady state has got an implication and a deliberate assumption.

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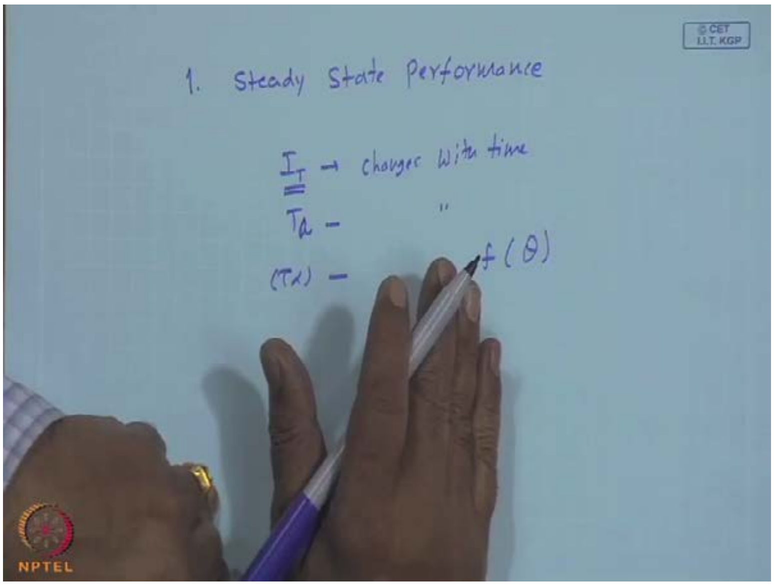

First in steady state performance, we are going to obtain the performance of a solar collector liquid based for the time being under steady state conditions, which means things do not change with time, but we know for example, I T changes with time and then you have got T a ambient temperature also changes with time. And even tau alpha changes with time being a function of angle of incidence, and if in particular if you want to be very specific even the overall loss coefficient may change with the time, because of the temperature dependence. However, we assume the performance to be in steady state, in other words we are trying to obtain what shall be the useful energy gain if a certain intensity of solar radiation or in a short term scale I T remains fixed. So, there had been sufficient warm up period, and the collector has reached steady state, and if everything else continued to be so what will be the useful energy gain; that is what we are going to do even though we know that solar radiation is going to change with time.

And hence we may calculate n number of times depending up on hour or half an hour each being steady state, and the subsequent hour being a continuation of the previous steady state.

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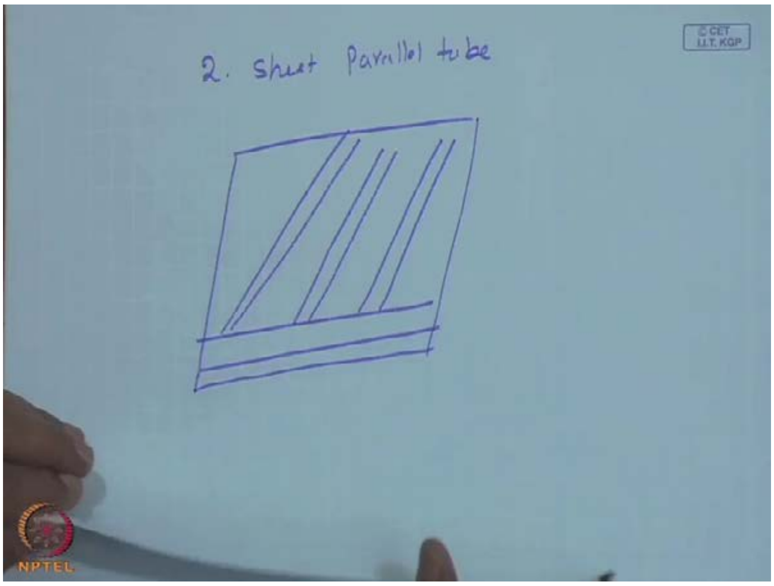

Of course, the second one is construction is of sheet and parallel tube guide. In other words, if we have if I show as a sort of skeleton, here is one pipe a series of pipes are joined to this, and this entire thing is on a plate welded or soldered as the case may be in the collector box.

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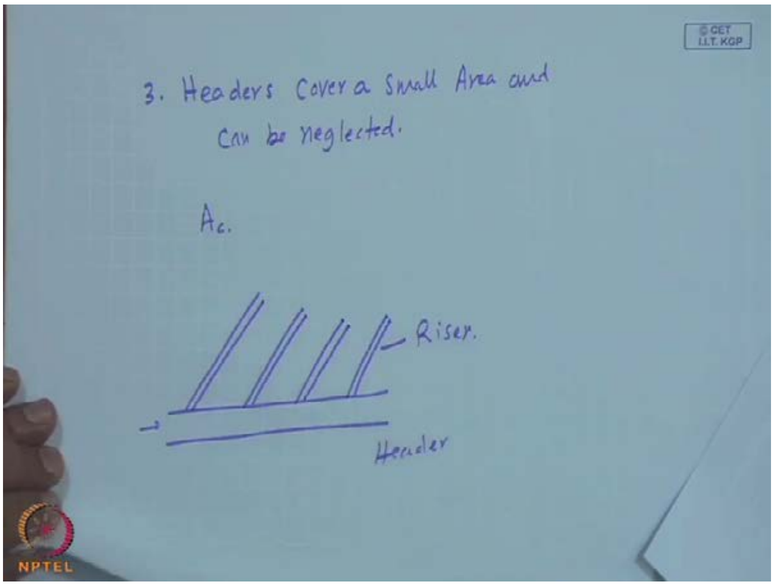

Now, next important next assumption rather headers covers small area, and can be neglected. So, there is always the question what is the area A c is it the glass cover area or is it the total box area or is it the absorber area, and does it include the headers or not. What are headers? Headers are those things that being in the fluid into the collector from where it is distributed through the relatively smaller tubes as we have shown earlier; there is a reason why the headers are larger, and then they so called this is a header, and this is a riser.

So, this provides tries to provide a uniform flow into the risers, we shall see a little while later or why it is larger diameter helps. And the there is no absorption of solar energy by covers in so for as it is as it affects the losses.

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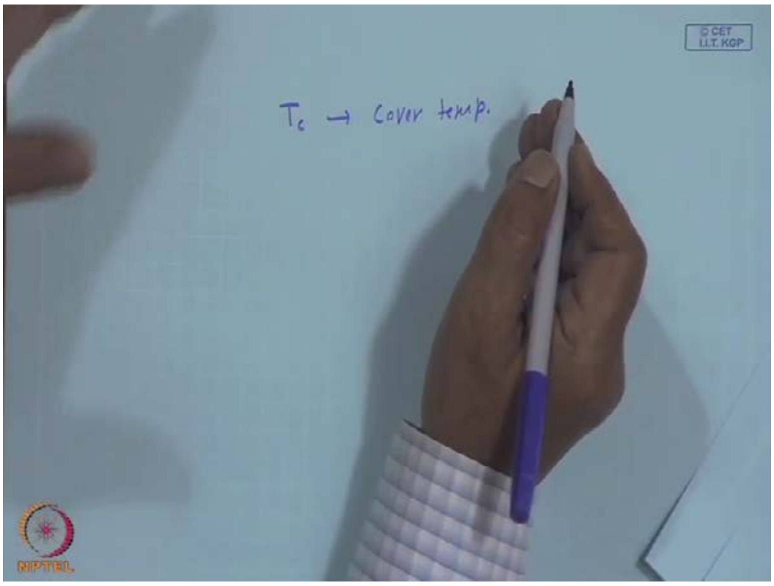

So, if T c is the cover temperature, it is a result of whatever conviction is taking place from another cover or the plate, and not necessarily the absorber energy. In other words, we will consider the solar radiation to be transmitted through the glass cover or reflected and not absorbed, the temperature increase is not due to absorption, but by a convictive heat exchange only.

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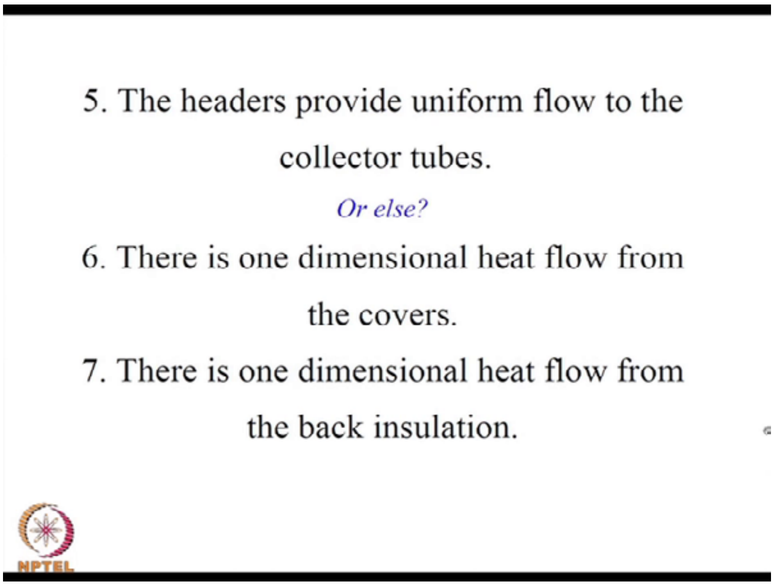

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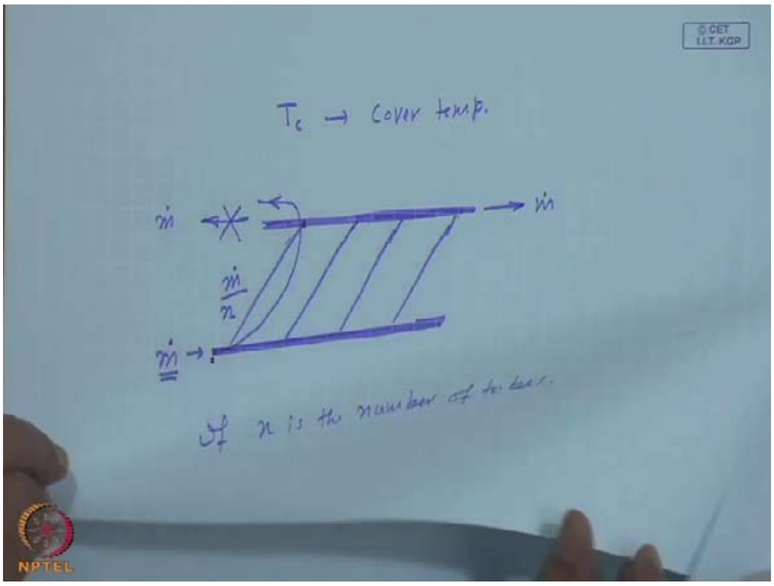

The headers provide uniform flow to the collector tubes. Now, I shall simplify this, this thicker line is my heater and these thin lines are my risers, they are connected over here like this, again there is another header. So, the assumption is these headers provide uniform flow. So, if there is m dot entering through this, and this will be m dot by n through each if n is the number of tubes. So, if the header is larger delta p across the header is negligible compared to delta p across the riser. So, consequently you will have almost the same head available for the tube number one to the last tube. So, they provide a uniform flow or alternately.

If you take m dot to be inputted over here, this will be coming out as m dot and not this, if we choose the second alternative it enters on the same side and leaves the same side then there is likely to be a short circuit and most of the flow will be going through first few pipes rather than uniformly up to the last one. In addition to providing a negligible pressure drop thereby providing a uniform flow, you balance the path length of one tube plus the header, and the last tube plus the header here is the larger portion somehow delta p is more or less the same trying to provide uniform flow to the tubes.

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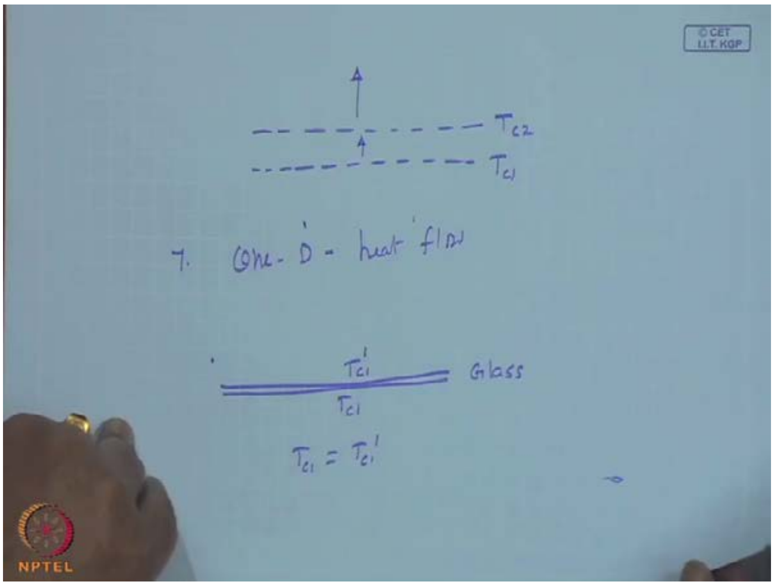

There is one-dimensional heat flow from covers, what essentially it means is that if this is a cover, this is from cover one to cover two, and I can consider it to be at single temperature T c 2 and T c 1. Similarly, there is one-dimensional heat flow from the back insulation. So, in general I can say there is only one-dimensional heat flow either through the top or through the bottom.

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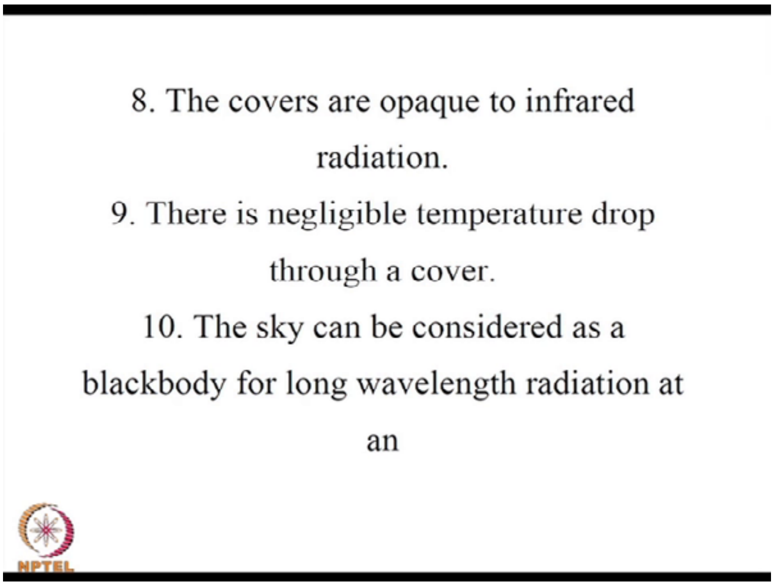

The covers are opaque to infra red radiation. So, if the covers are opaque to infra red radiation, please remember that the solar radiation effectively is within the wavelength of zero to four microns, whereas after the plate is heated the temperature may be 100 120 and the corresponding lambda max t lambda max may correspond to much higher than four microns. So, that will be in the infra red range and the covers are opaque precisely creating what is called the green house effect inside the collector. Then negligible pressure drop through a cover, if there is a thickness for the glass we do not see this is at T c 1 and the top is at T c 1 dashed. We assume T c 1 equal to T c 1 dashed, in other words the temperature across the glass plate is uniform. This is an important thing all of you should pay little attention.

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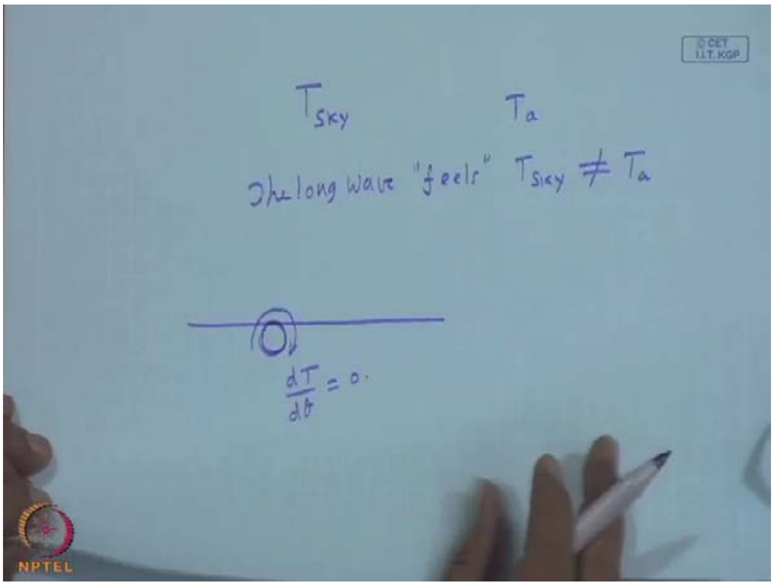

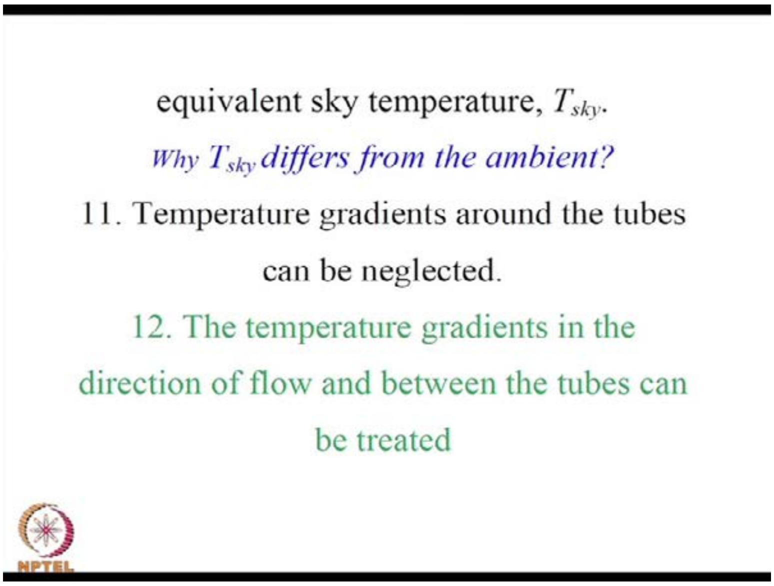

The sky can be considered as a black body for long wave radiation at an equivalent sky temperature of T sky. So, the radiation leaving as a loss from the solar collector will eventually see the ambient at T a, then the loss is from whatever is the glass cover to the ambient temperature, but what we are trying to say is the long wave feels T sky which is not necessarily equal to T ambient. We will give a simple example, suppose you measure the temperature of the ambient and the temperature of water in a bucket the water in the bucket will be at a lower temperature in the evening or night though it may be little higher than the ambient temperature during day time, if it receives solar radiation. Why does in the night the temperature be less than the ambient temperature .

If that is true there will be a heat transfer from the surrounding ambient to the fluid until the temperature becomes equal to ambient temperature or it is losing heat to a temperature not the immediate surrounding at T a, but to some other far off place which is at a lower temperature that is what we call the sky temperature T sky. So, temperature gradients around the tubes can be neglected. Now, in this type of analysis we do not worry about d d theta d T d theta is zero, it does not change in the peripheral direction of the particular tube. So, entire tube is at uniform temperature.

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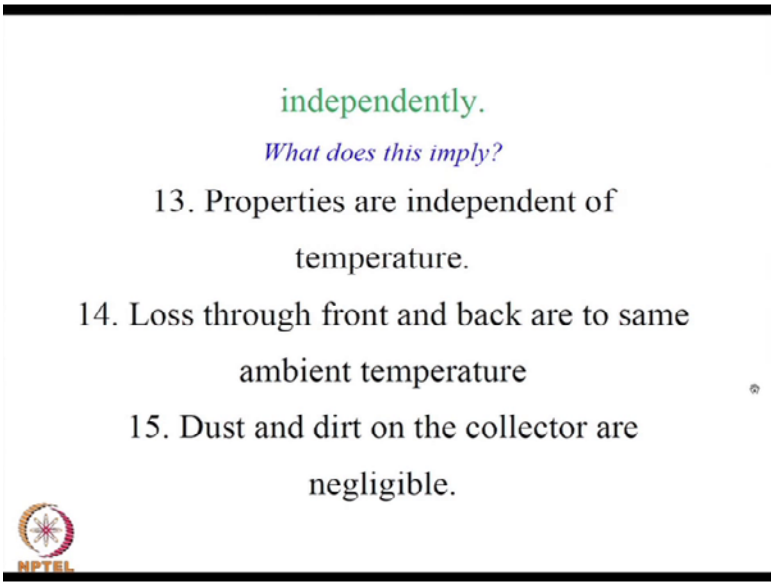

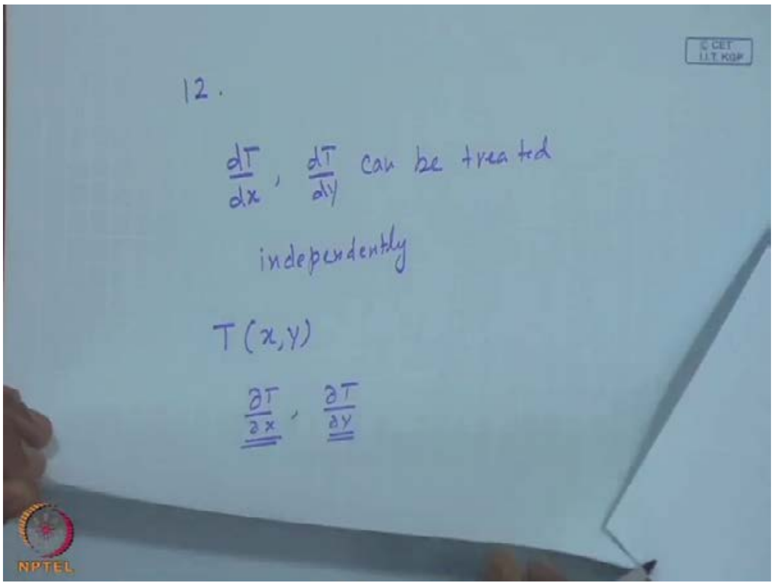

Now, this is a what should I say one very significant feature the temperature gradients in the direction of the flow and between the tubes can be treated independently; that means, d T d x and d T d y can be treated independently. If we remember if we treat T as a function of x and y. So, I have a partial derivative of d t by d x and a partial derivative of d T d y. Now, what we are suggesting is that this changes in the x direction be treated independent of the changes in the y direction.

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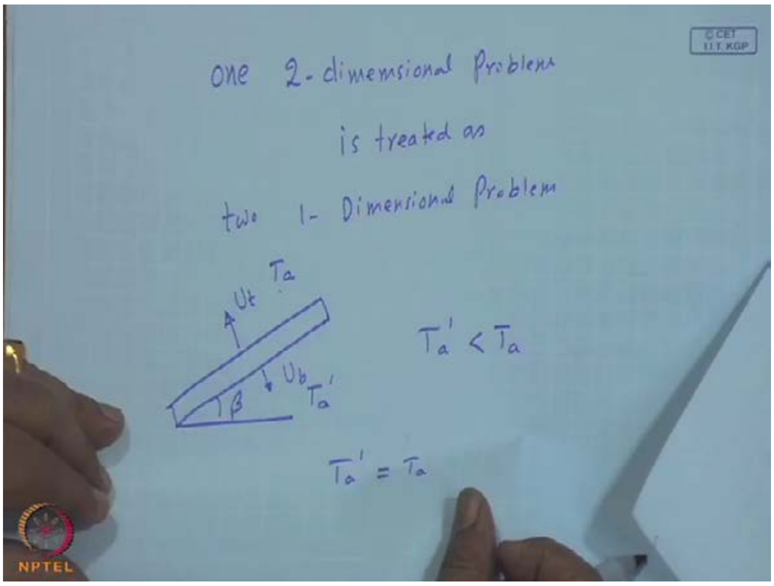

So, in a mathematical language a one two-dimensional problem is treated as two one-dimensional problems. The consequence is that we have two ordinary differential equations; one in the direction of x and the other in the direction of y, and they can be solved independently. Properties are independent of temperature, and this is a very common assumption in heat transfer in fluid mechanics, and as long as the temperature changes or not too large; one can assume this and loss through front and back are to the same ambient temperature.

So, if this is my solar collector with some slope beta, this will be to the top loss this will be my bottom loss. So, some people argue if this is T a, and the bottom of the collector will be at some T a dash, generally T a dash being less than T a. So, this is a shaded region. So, the back losses will be in principle different or different the temperature through which the top losses are taking place, but we assume T a dashed equal to T a dust and dirt on the collector are negligible. So, we assume somebody cleans them at regular intervals.

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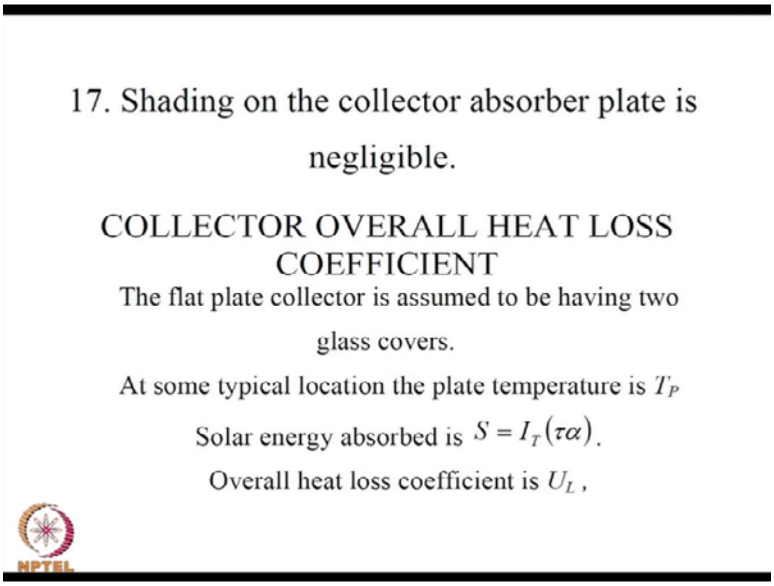

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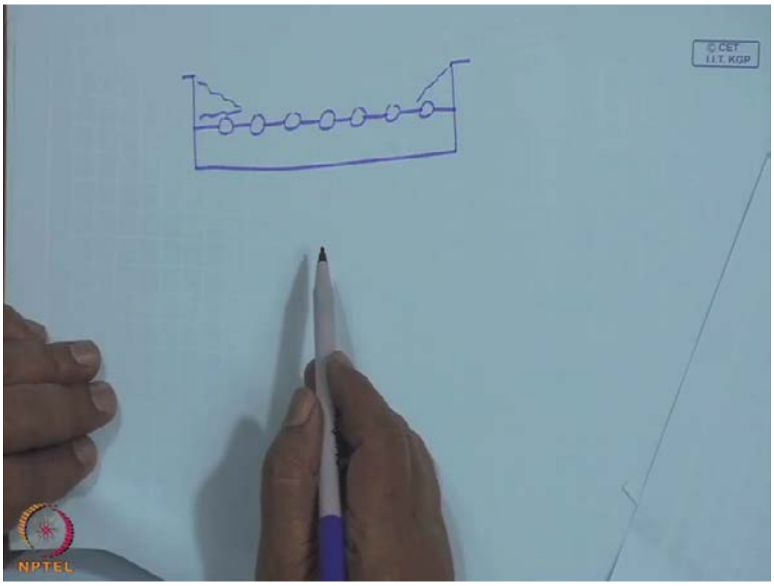

Shading on the collector absorber plate is negligible. So, one thing is the shading because of its own box, like if we have two glass covers; the height of the box could be considerable compared to the level, where the absorber is mounted. So, this may cast a shadow depending upon the time of the day, but we are considering that it is negligible. And similarly of course the installation is such that there will be no shadow cast by neighboring building or neighboring structure on to the collector array or the solar collector. So, these are the important things or assumptions that are made a number of them, main thing is the steady state performance though we know that the solar radiation is changing. Secondly, the two-dimensional problem is treated as two one-dimensional problems and uniform flow is provided through the risers.

And in so far as solar radiation is concerned the glass covers do not absorb the radiation, they are opaque to infra red radiation and the other common things that we have mentioned.

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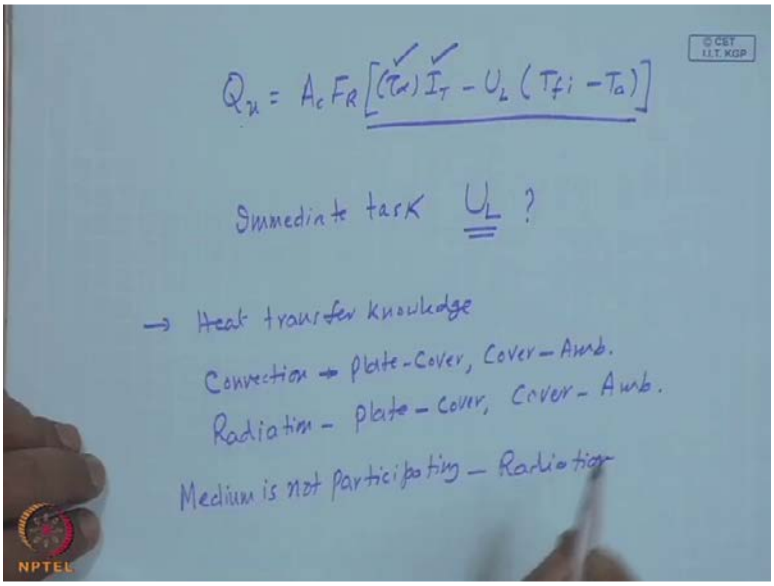

So, we recall Q u A c we will put F r tau alpha times I T minus U L into T f i minus T a. So, we know methods to calculate I T for an hour or a day or a monthly average day though we may not be able to submit for other reasons which will come at a little advanced stage, and we also know how to estimate tau alpha comprising of diffused sky, diffused radiation, direct radiation, and the ground reflected radiation. And F R will depend upon my actual energy gain for which I should find out, what is this Q u? Upon the maximum possible if the entire collector is at the inner temperature as given by this term, it can be experimentally determined or it can be theoretically calculated which we will see in a little while, but our immediate task is to calculate. How do you find out the overall loss coefficient U L; of course, this may depend up on heat transfer knowledge conviction between plate to cover and then may be cover to the ambient, if there is two covers again cover to cover and then the radiation from the plate I shall be using this plate and absorber synonymously.

So, when new say collector plate temperature it is the same as the absorber temperature, and then to the cover similarly cover to the ambient. So, we have knowledge of convection to find out to have our heat transfer coefficients and radiation depending up on the temperatures, and if you assume that the medium is not participating for radiation transfer. We can deal with the Stephen Boltzmann law applied between two surfaces at temperatures T 1 and T 2 or whatever the temperatures is…

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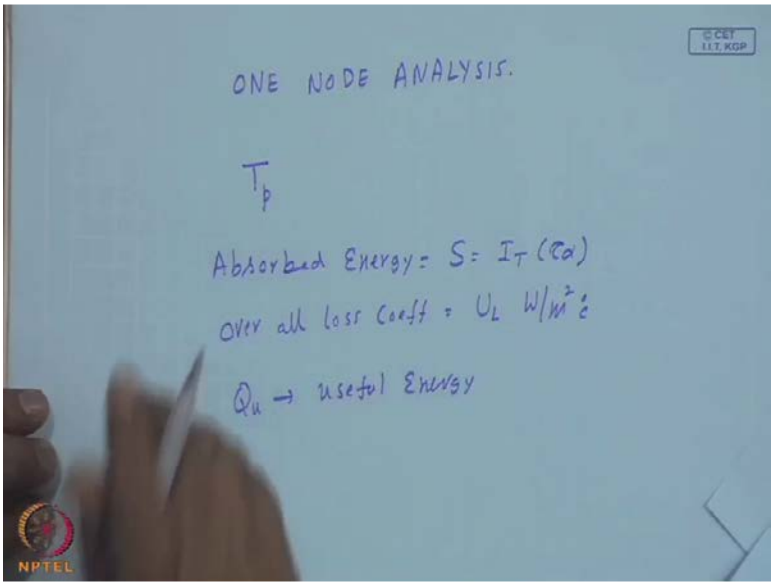

So, now, this is a one node analysis. So, let the plate be at some temperature T p it could be at a point or a mean plate temperature then the absorbed energy is S I T tau alpha, and the of course the overall loss coefficient U L watts per meter square degree centigrade. So, Q u is the useful energy, we will try to put down the thermal network, and then calculate overall loss coefficient U L in terms of the thermal resistances.

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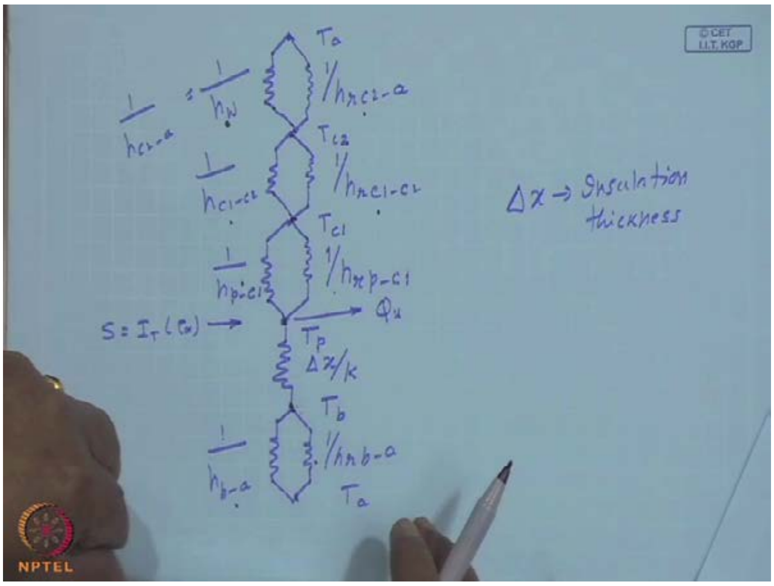

If the plate can be represented by this point the absorber energy S equal to I T times tau alpha will be entering, and Q u will be the output and this is at temperature T p. Now, then let us say the first glass cover for a two glass covers is at a temperature T c 1, the second glass cover is at a temperature of T c 2, and then there is a ambient to which my temperatures or heat loss takes place. Then again I may have a temperature of T b at the back of the collector then again a T a.

So, now the picture is the absorber is at a plate temperature of T p and incoming absorber radiation S equal to I t into tau alpha falls on that, and useful energy gain that you obtained will be Q u. Now, rest of it is losses the difference between these two is the losses which goes in the top direction starting from the plate to the cover one; cover one to cover two and cover two to the ambient. Similarly from the back of the or the bottom of the collector from the plate temperature to the box bottom of the collector, and then from there to the ambient.

So, now we have two paths a conviction path and radiation path. So, this will be having a resistance of 1 by h r p to c 1. So, h r is sort of a radiative heat transfer coefficient and p to c 1 is from the plate to cover one, this will be 1 upon h p to c 1, just plate to the cover one the convictive heat transfer coefficient. Similarly, we have two parallel paths which is one upon h r c 1 to c 2 and one upon h c 1 to c 2. In other word this is a convictive heat transfer coefficient between the plate, and the cover one and h c 1 c 2 is the convictive heat transfer coefficient between cover one, and cover two whereas the h r contour parts are the radiative heat transfer coefficients. From here we have got again a radiative loss h r c 2 to the ambient, then a convictive loss by wind which is 1 upon h w or you can call it one upon h c 2 to ambient.

So, this is a wind heat transfer coefficient or in general terminology from cover two to the ambient, at the bottom there will be simply a conduction given by a resistance of delta x upon k if the thickness of the insulation is delta x is insulation thickness, do not be confused with the x direction it has nothing to do with it, it could have been l by k and then we have a convictive loss one by h back to ambient and a radiative loss 1 by h r back to ambient.

Now, let me because this is an important thing to understand let me recapsulate an absorbed energy of s equal to I T, and tau alpha is absorbed by the plate at temperature T p giving out the useful energy gain Q u. The loss will be from the plate to the cover one by radiation and by conviction, and again from cover one to cover two by radiation and by conviction. And you have from the cover to the ambient by radiation and the wind velocity or the wind heat loss coefficient, from the bottom you have a conduction loss through the insulation and again a conviction and radiation from the back of the solar collector to the surrounding temperature T a which we assumed equal to the ambient temperature T m.

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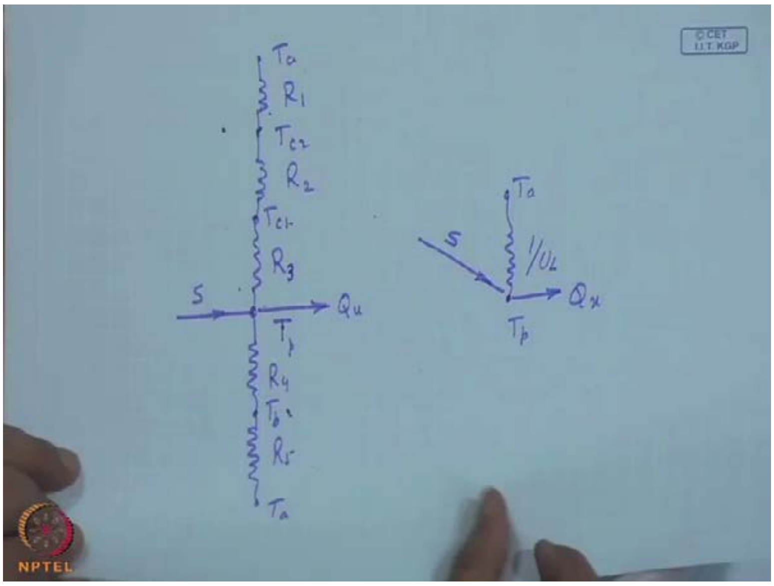

So, this can be simplified those two all parallel resistances can be combined into one, and we have a simplified picture S flowing out at T p Q u the useful energy gain, this is T c 1, and a resistance of R 1, this is T c 2 and a resistance of R 2, I am sorry this is R 3 T a this will be R 1. You have the conduction resistance this will be R 4, and the overall due to conduction conviction and radiation R 5 from the back temperature T b to T a. This overall can be further simplified as you have got T p, and you have got Q u the loss is T a 1 upon U L, and the incoming radiation is absorb radiation S. So, we have to find out U L or one upon U L.

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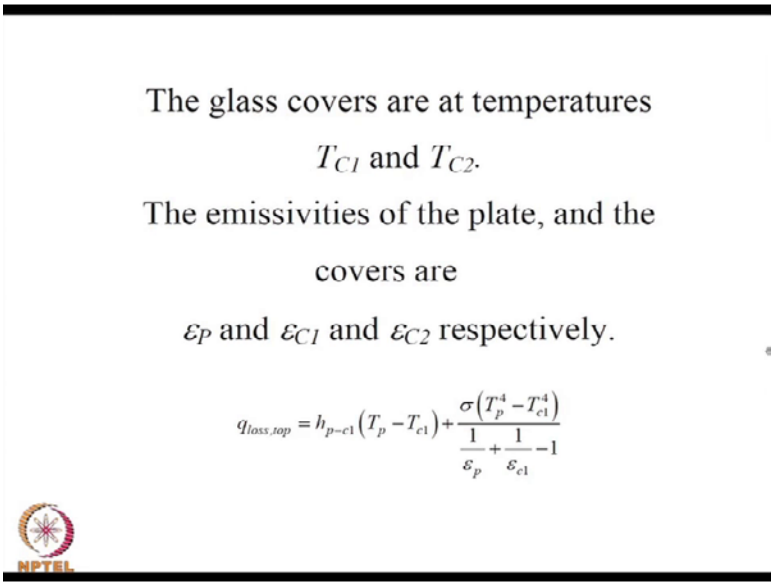

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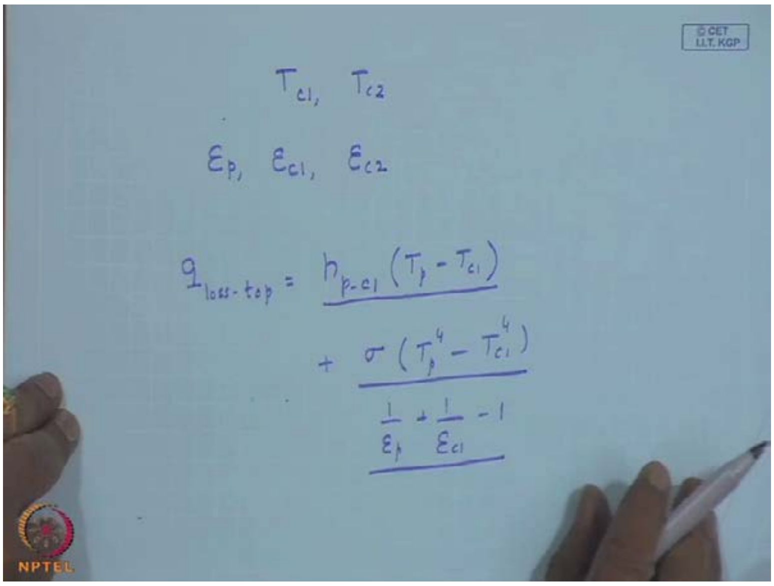

So, first we shall evaluate these resistances one by one, the glass covers are a temperatures T c 1 and T C 2. Let the emissivity's of the plate be epsilon p, cover one epsilon c 1, and cover two epsilon c 2. So, I can express q loss top should be equal to h p c 1 into T p minus T c 1, this is the convictive loss from the plate to the cover one plus sigma T p to the power 4 minus T c one to the power 4 upon one upon epsilon p plus one upon epsilon c 1 minus 1. So, we are treating them as the infinite parallel plates at temperatures T p and T c 1 and the corresponding emissivity's are epsilon p and epsilon c 1. So, this is the radiative loss and this is the convictive loss. So, the same amount of loss should go from cover one to cover two and eventually to the ambient.

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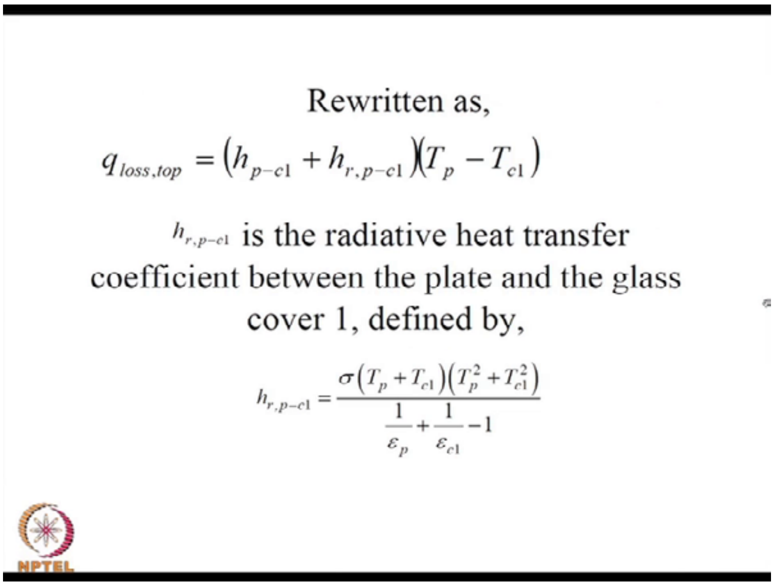

So, this can be re written as q loss top h p c 1 plus h r p c 1 into T p minus T c 1. Now that radiative loss is expressed in terms of a radiative heat transfer coefficient multiplied by just a temperature difference, not the difference of the fourth powers of the temperatures. So, h r p to c 1 is defined as sigma T p plus T c 1 into T p square plus T c 1 square by 1 upon epsilon p plus 1 upon epsilon c 1 minus 1, there is no magic if you just multiply with T p minus T c 1, it will be nothing but sigma into T p to the power minus T c one to the power 4 upon 1 upon epsilon p plus epsilon c 1 minus 1, this you have done in your under graduate heat transfer course in the radiation part.

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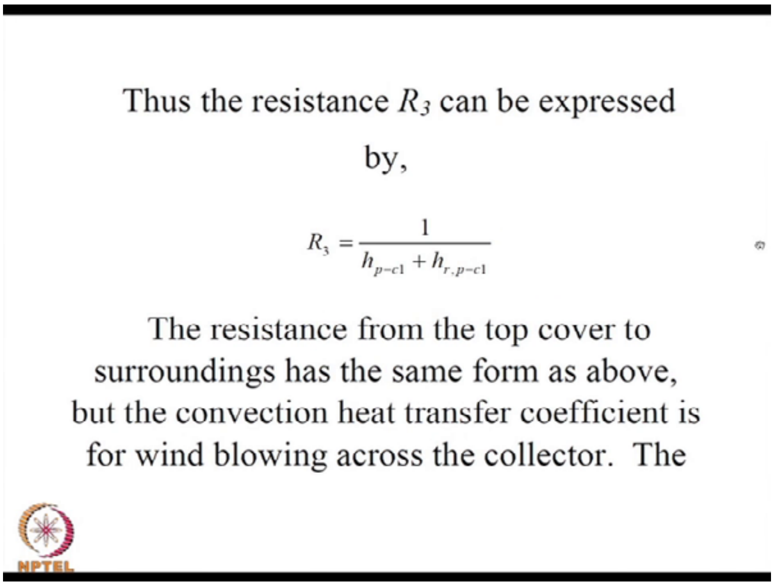

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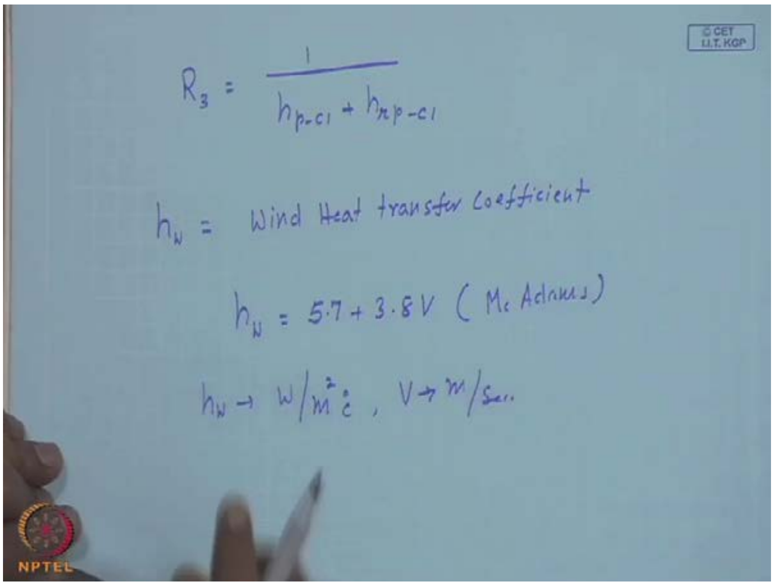

So, now my resistance R 3 is given by 1 upon the summation of the conductance's h p c 1 plus h r p c 1. So, the resistance from the top cover to surroundings has the same form as above, but the convictional heat transfer coefficient is for wind across the collector, right. Now this is R 3.

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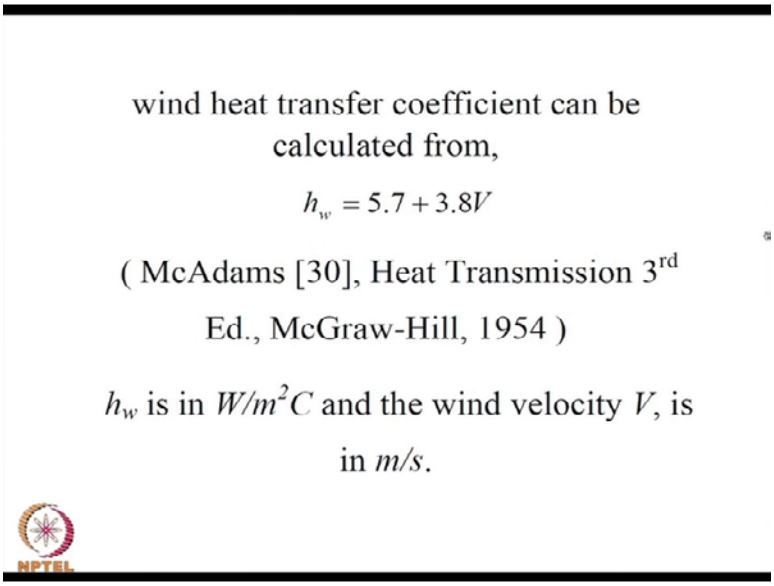

So, what is h w? This is the wind heat transfer coefficient, h w is 5.7 plus 3.8 v, where h w is in watts per meter square degree c, and v is the wind velocity in meters per second. This relation is due to Mc Adams.

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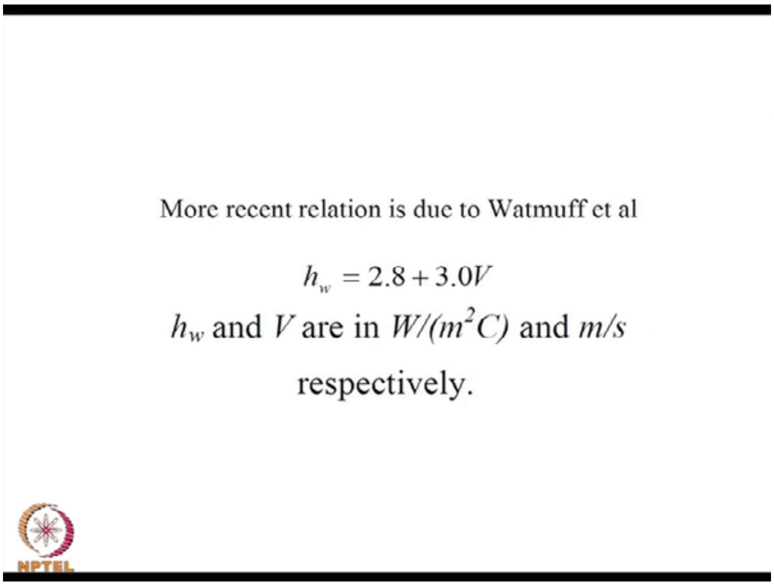

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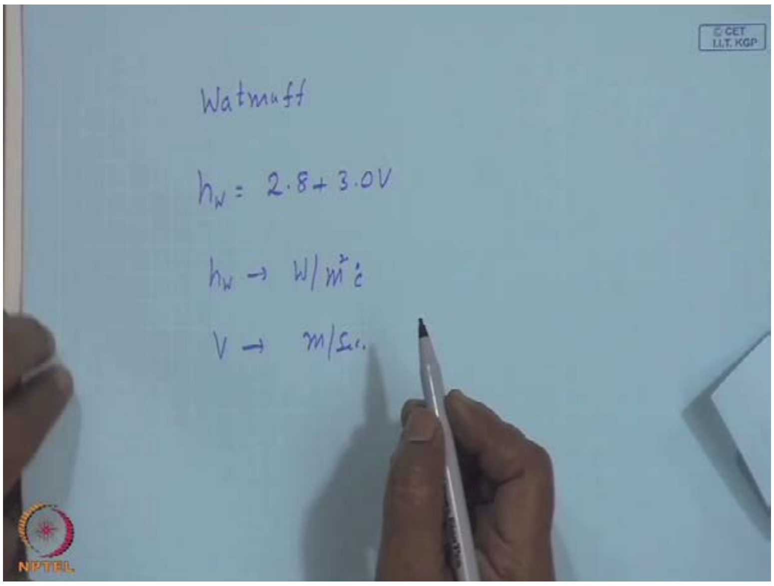

Subsequently more recently rather relatively, Watmuff (( )) suggested this h w be calculated as 2.8 plus 3.0 v again, h w is watts per meter square degree c, and v is in meters per second. So, you can see that the Watmuff's relation gives a lower value for h w compared to the value one would obtain by Mc Adams relation for a given wind velocity or it is suggested that apparently perhaps the radiative loss also has been included in the Mc Adams relation.

So, this is what we… So far have introduced the theory of liquid based collectors flat plate collectors, a basically they comprise of a sheetened tube the arrangements can be different, it may contain even one cover or two glass covers, the idea is to find out the overall loss coefficient under a set of assumptions; the assumptions had been mainly the steady state temperature and the problem can be treated as two one-dimensional problems instead of one two-dimensional problem. And then a thermal network has been written and losses from the top will be from the plate to the cover one, cover one to cover two then cover two to the ambient.

From the bottom by conduction through the insulation, and then again by radiation and conviction to the ambient. So, with this terminology we also have a relation for the wind heat transfer coefficient proposed obtained by Mc Adams or Watmuff and more recently Watmuff is being used a more often than the Mc Adams relation, because of its expected accuracy and Mc Adams relation is may be provides a conservative estimate, because h w is a larger. So, subsequently we will go about how to find out U l, we have expressed all the resistances now we need to find out what is the overall heat loss coefficient.