Solar Energy Technology
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Lecture - 15
Mean Temperature and Heat Capacity Effects

So, before we go to the next topic on mean temperatures, I shall continue and complete, what little bit has been left out, about the experimental method, to determine the efficiency of the solar collectors.

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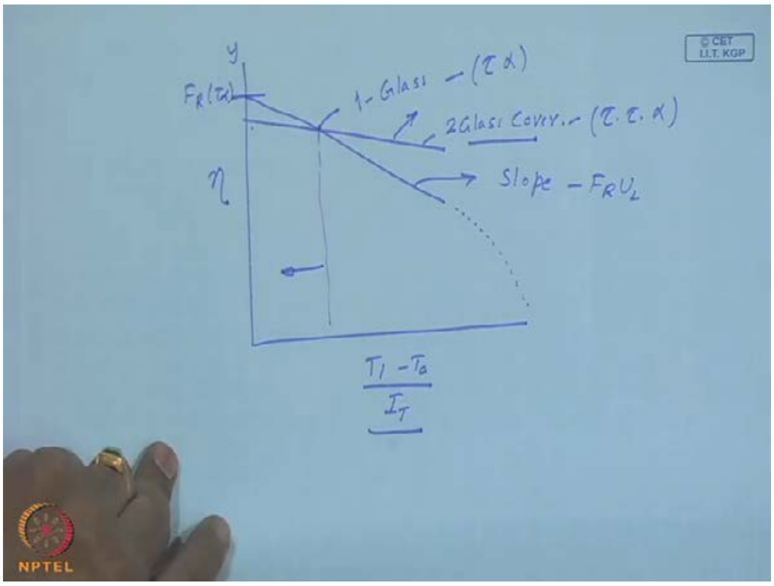

So, we found that the efficiency varies linearly, with the parameter T I minus T a upon I T, and here is efficiency, and you will have best straight line fit, and beyond this point, it may be non-linear, decreasing quickly. And this if I say if it is for one glass, we may have something like this, for two glass. Note that two glass cover efficiency is a bit lower, at low values of this delta T upon I T, and it is higher for higher values. In other words, if the operating temperature is high, in the case of two glass covers, I lower U L is beneficial. Whereas if the operating temperature is low, there will be some sort of a reduction in (( )) sort of product, compared it to one glass cover. Remember this has got effectively tau, times tau, times alpha whereas, this is only one tau into alpha, though effective part will come into the picture.

So, there is a cut off temperature between one glass cover, and two glass covers, and below which of this value of the parameter, you have a one glass cover performing better, than a two glass cover, so this is a typical curve. And normally we hope to operate in the range, before U L variation becomes so large, and this line becomes non-linear. Now if you look at that equation, this is going to be your F R tau alpha intercept, and the slope of this will be, minus F R U L. In addition to determining the efficiency of the collector, if you find the efficiency curve, fit a best straight line. The intercept on the y axis will give you the property F R tau alpha, and the negative of the slope of the collector will be, F R U L.

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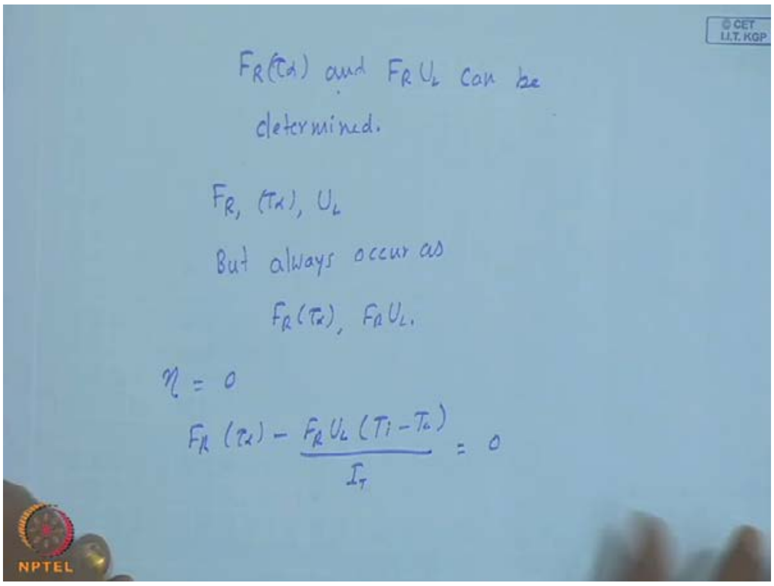

So, the collector parameters F R U L, can be determined from the experimental points. Now, actually there are three parameters F R, tau alpha, and U L, but always occur as two F R tau alpha product, and F R U L product. So, the two parameters can be determined from the efficiency test. Now if efficiency is equal to 0, assuming that the line continues, it will lead to a certain value of I T; that is F R tau alpha minus F R U L times T i minus T a by I T equal to 0.

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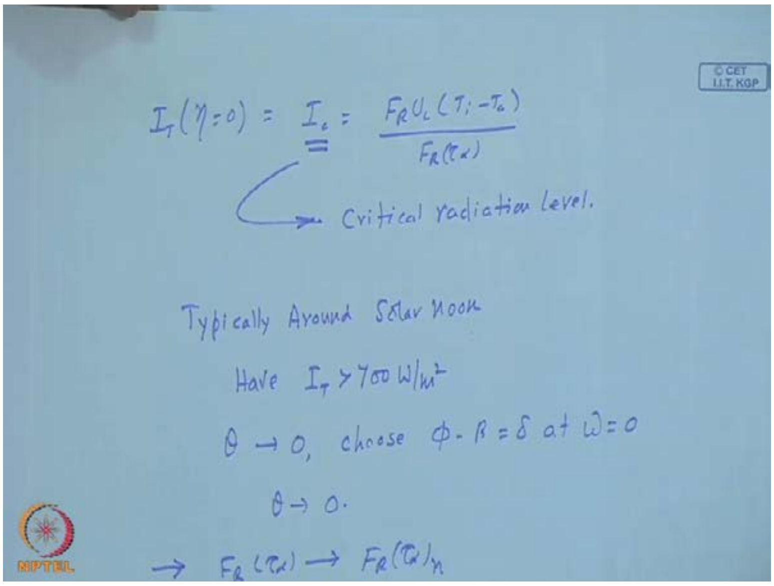

This leads to a I T, for eta is equal to 0, which I will call it I c equal to F R U L times T i minus T a by F R tau alpha. So, this is a sort of what we call critical radiation level. So, it implies that the incoming radiation on to the collector, should be above this number I c, in order that there is heating of the fluid and in the collector. Now there are certain recommendations for the experimental procedure. This is done typically around solar noon, have I T almost greater than 700 watts per meter square, and theta close to 0; that means, if you choose for example, phi minus beta equal to delta at omega equal to 0 theta is 0. This will ensure that F R tau alpha, will give you F R tau alpha normal. So, this is the basic parameter which depends upon the material properties, which can be obtained by conducting the experiment, around solar noon, with a high intensity level, and keep the angle of incidence close to 0; that means, normal to the sun's rays, which can be obtained around solar noon with a phi minus beta equal to delta, which we will see little later, when we talk about the tracking collectors.

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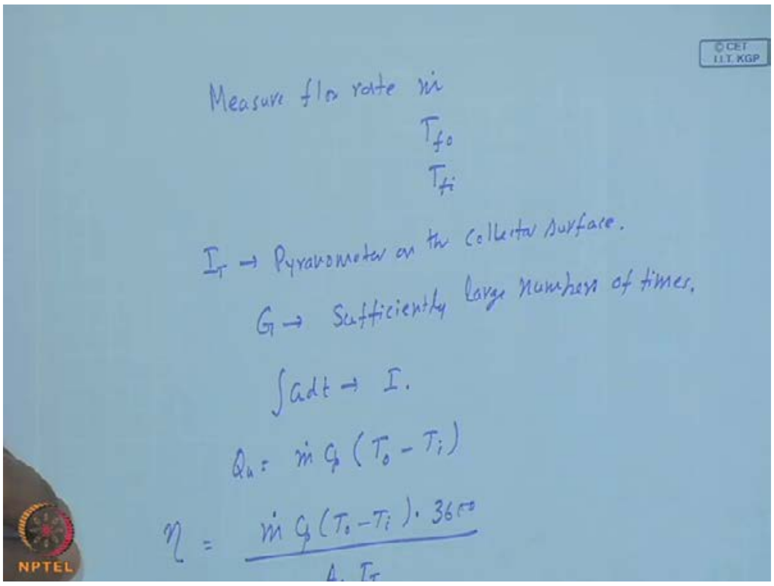

So, these quantities are already recorded over here. So, how do we do it, the actual measurements will be, measure flow rate m dot, and the out let temperature T f o, and the inlet temperature T f i, and directly I T mount the pyranometer on the collector surface. So, then we know other uncertainties, in converting from the horizontal surface, or any other surface, to the collector surface. Or if you measure g, then sufficiently large number of times, so that you have a meaning full integral G d t equal to I, and if you convert this into I T, there will be certain uncertainties. So, Q u is already known, in terms of the mass flow rate, outlet temperature minus the inlet temperature. So, efficiency measured can be m dot C p T o minus T I times 3600 by a c into I T, essentially 3600 is I T by 3600, to make it watts. So, we shall go to the next topic now, mean temperatures and heat capacity.

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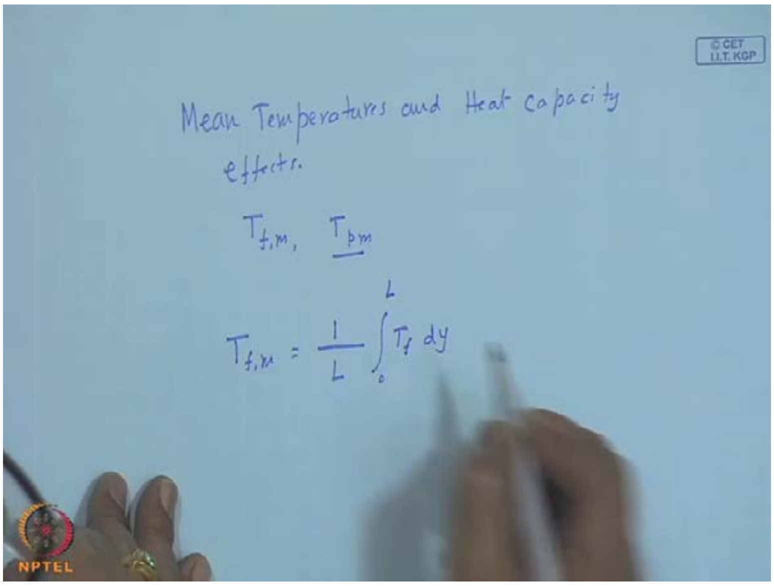

So, if the fluid temperature is varying between T f i to T f o, we may consider the collector to be operating at some mean fluid temperature of T f m. Similarly corresponding to T f, T p also will not be constant, it will be operating at T p m. It may be at the geometric mean point, or some sort of a weighted average of the plate temperature measured at different points, and in all the analysis we were representing the fluid with a single temperature, and the plate with a single temperature enlighten in the energy balance, though we evaluated for the sake of F R and f dashed variation of T in the x direction, and the variation of fluid temperature along the two. So, the mean fluid temperature, simply one upon the length of the two, integrated over 0 to L T f d y.

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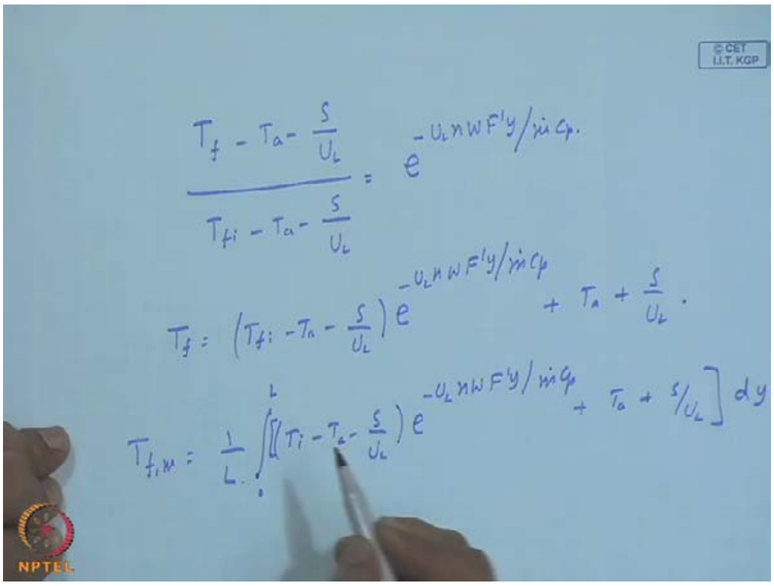

So, we have the temperature variation relation; T f minus T a minus S upon U L by T f I minus T a minus S upon U L is equal to e to the power minus U L n w f dashed y by m dot C p, where U L is the overall loss coefficient, n is the number of tubes, w is the spacing between center of the tube to the center of the tube, f dash is the collector efficiency factor, and m is the distance along the tube. So, one can express again T f is what any, is T f I minus T a minus S upon U L times e to the power minus U L and w f dashed y over m dot c p plus T a plus S upon U L. So, you put it in this T f m, will be one upon L integrated over 0 to L T f I minus T a minus S upon U L times e to the power minus U L and w f dashed y by m dot c p plus T a plus S by U L times d y.

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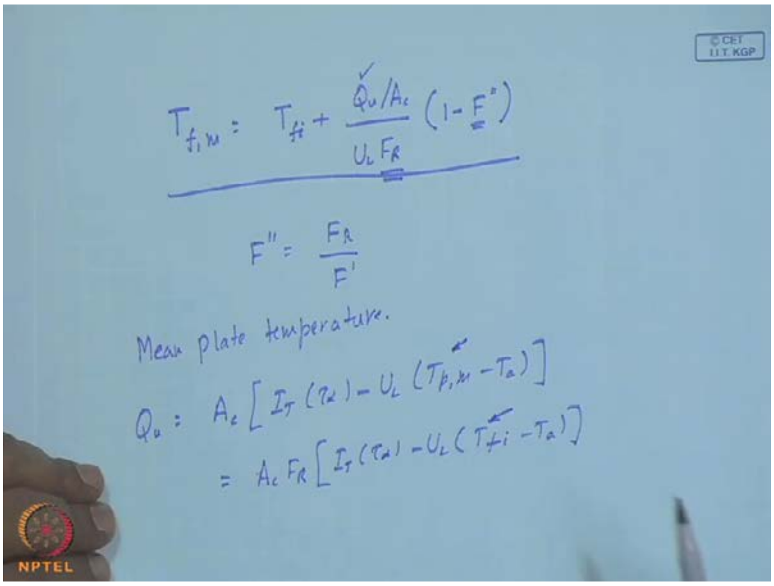

So, this is simple thing to integrate, exponential function only, and use substitute for F R which we already know. T f m simply given by T f i plus Q u by A c by U L F R times 1 minus f double prime. This f double prime is a flow factor; we will come to it little later again. So, if you know your F R, you can find out mean fluid temperature in terms of the flow factor, defined as F R by F dashed; that is for convenience to write in that particular fashion. Now we will try to evaluate the mean plate temperature. If you look at this equation, it looks that the mean fluid temperature is simply expressed in terms of Q u, if you know Q u, you can calculate the mean fluid temperature, and Q u is in terms of the mean plate temperature I T tau alpha minus U L into T p m minus T a, that should be equal to A c F R into I T tau alpha minus U L into T f i minus T a. Simply the energy gain return in terms of the plate temperature, and the energy gain return in terms of the fluid inlet temperature.

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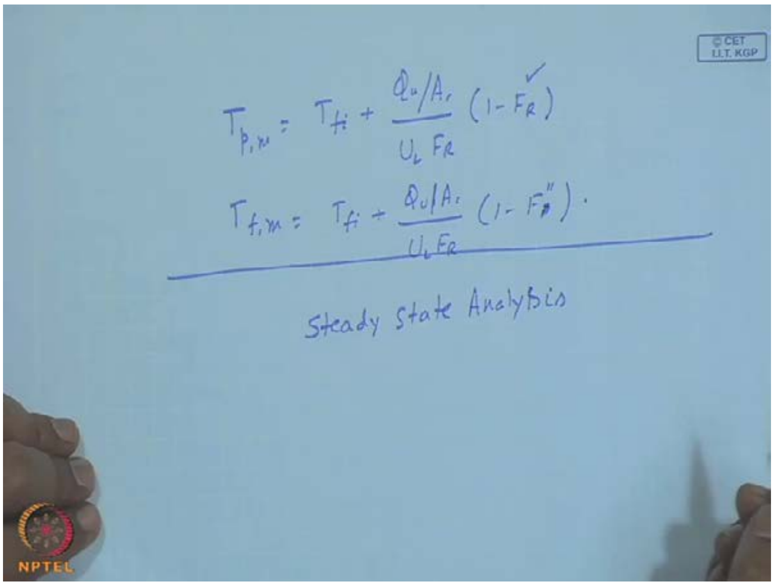

So, you have, from here simple straight forward relation. So, we have got T p m related to the heat removal factor, and T f m related to the flow factor. So, far we made a steady state analysis. In addition to treating as two one dimensional problems, instead of a two dimensional problem, we assumed that everything is constant, and steady state performance exist. So, this is not too bad, if you consider that continuously, the solar radiation is changing, ambient temperature is changing, but depending upon the heat capacity of the collector, a certain time will be required for the collector to respond, to the changes of the solar radiation. So, if you keep on applying this collector energy gain equation, over small periods of time. It may not be instantaneously followed, but it will follow, following a certain lag in time. So, your ultimate accuracy may not suffer so much, even if steady state assumption is made.

However there are in the text books, heat capacity of h r considered; that is mainly concerned, if you like you can apply the unsteady state equation, over a certain period of time and find out the temperature at the end of that period, used that as an initial temperature for the next period, and continue with the simulations or calculations. How do we distinguish between a collector, which is massive, heavy or m into c p is large, compared to a collector, which has got lower m into c p.

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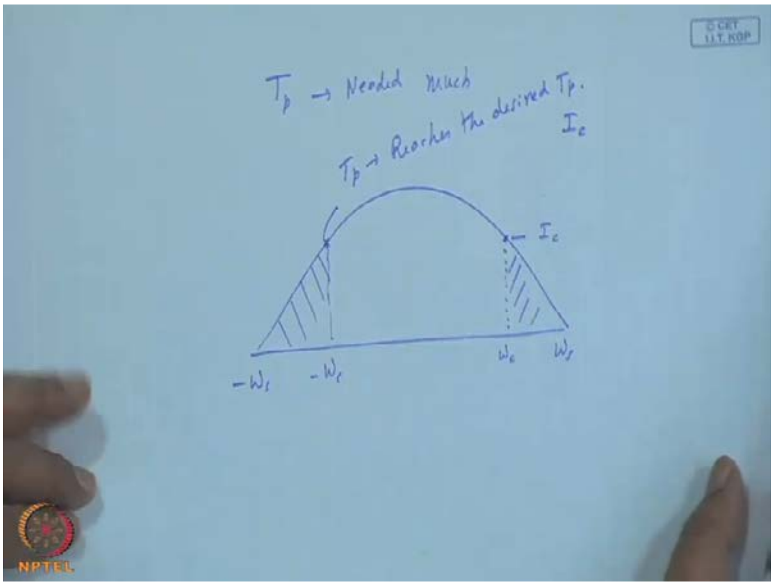

Now if there is a certain amount of solar radiation, not only does the high heat capacity collector responds slow, but it will reach a certain temperature T p, needed much later. If you have or comparing an absorber, which weighs 10 kilograms to a absorber, which weighs 2 kilo grams, with let us say specific is being almost the same, or one half or whatever the reason ratio, it is m C p ratios. Now if you got a m C p 10 times that of the m c p, then the energy required to heat the absorber, to the desired temperature, to deliver energy at the desired temperature, will be much large. So, if you are considering, solar radiation, some idealized distribution like this, from the sunrise to sunset, we have, of course calculated that I c, which will correspond to 0 efficiency. Unless my solar radiation level is above this critical level of radiation, there will be no heating of the fluid, which is un thing at a temperature T f i. Now suppose that occurs, this is 300 watts which may be corresponding to I c.

Now over this time period a minus omega c symmetric, 2 plus omega c, my collector can deliver energy at the temperature that is desired, provided at this particular point or before T p reaches the desired temperature. So, in other words, in the amount of energy, before from sunrise to before reaching the critical level, should be sufficient to heat the collector covers, and the absorber to the temperature that is required. Of course, unless the solar radiation is at the level of critical level of radiation I c, it will not deliver the energy at the desired temperature, but if the energy before that is not sufficient to heat, to the temperature required of T p, it cannot supply the energy at the temperature, even if I c is reached. The other way around is not possible, I mean it cannot heat before I c's occurred, because that also defines the temperature, which can be reached at that solar radiation level.

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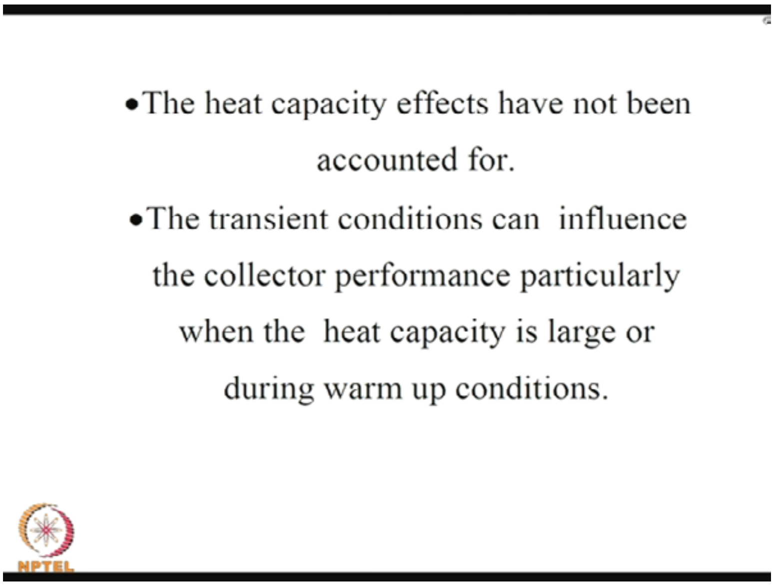

So, heat capacity effect is not necessarily, the accounting for accuracy of unsteady performance, but a necessity to determine also, the operating period. Even if you make certain assumptions in this analysis, subsequently you can apply this unsteady analysis with simplifying assumptions, a number of times, to get more or less time varying, performance of the solar collector, either by virtue of solar radiation varying, ambient temperature varying, or wind velocity varying.

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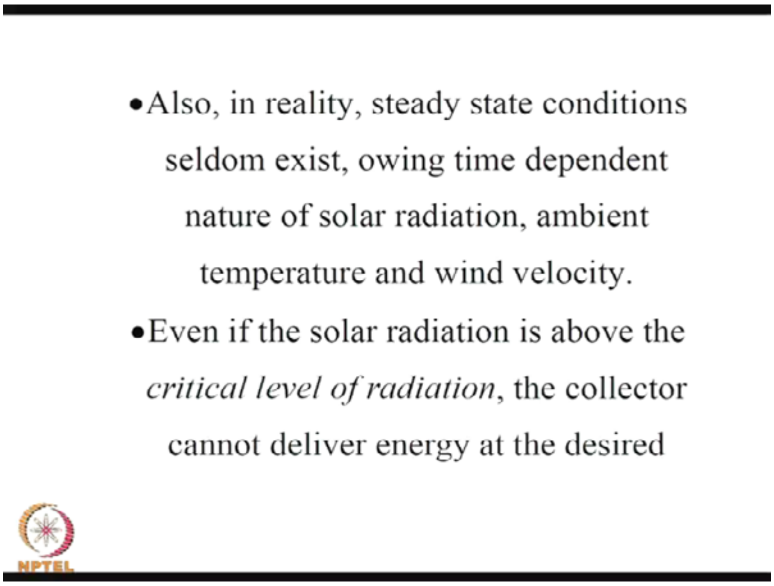

So, these are the radiation, I mean reasons which I have already stated, and is above the critical level of radiation, the collector cannot deliver energy at the desired temperature, unless the absorber reached the required temperature. So, this is, what is essential that the warm of period for the collector, should be less than the time required or equal to the time required, where the critical level of solar radiation is reached.

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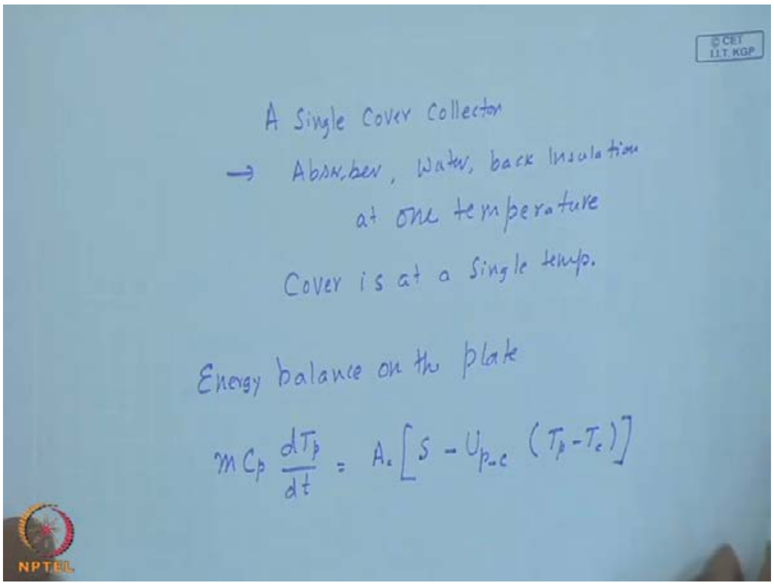

So, we assume a single cover collector, then we lump the absorber water in the tubes, and the one half of back insulation, to be at one temperature. The cover is at a single temperature. This is an assumption that we have been doing commonly, in other words, we distinguish glass cover as one unit, and the rest of the collector as another unit. So, if I make a energy balance on the plate, it will give me mass, time specific heat, times rate of change of temperature with time, should be equal to A c into the absorber radiation minus, whatever is the loss coefficient between the plate and the cover, to the temperature difference between the plate and the cover, so simple energy balance on the plate.

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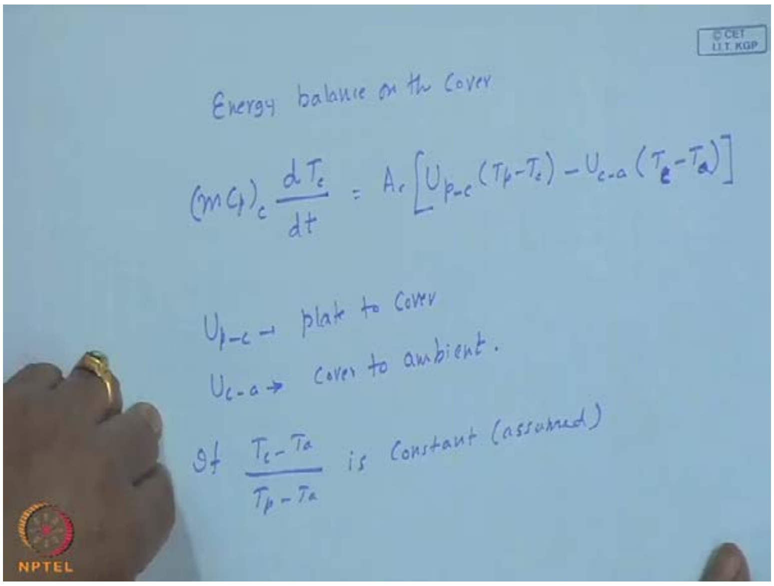

And similar energy balance on the cover, that given me m C p for the cover times d T c upon d T, should be equal to A c times, overall loss coefficient from plate to cover. This is what the glass cover is receiving, and it is losing U c 2 a times T a minus T c. This should be T c minus T a, because we have written as subtraction. So, these are the loss coefficients U p c from plate to cover, and U c to a is cover to the ambient. Now we make a. Of course, these are two simultaneously for T p and T c, one can solve them simultaneously, first order not very difficult, but a great simplification occurs if, T c minus T a upon T p minus T a, is constant assumed. T c is changing T p is changing T a is changing, so we assume that the ratio is constant, it is something like fully developed condition for the temperature field, though that is exact, and this is approximate.

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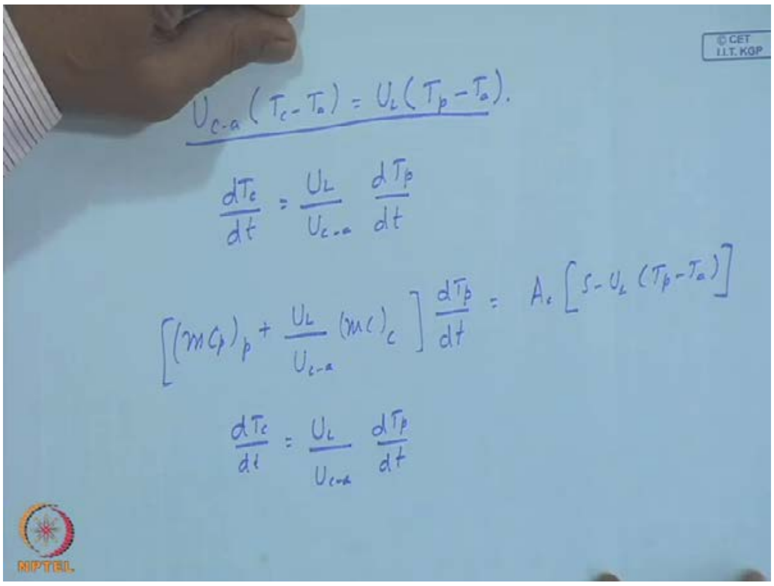

So, this means cover to the ambient times T c minus T a should be the loss in the steady state with T p minus T a. So, you can now find out d T c by d T equal to U L by U c a times d T p by d T. We have just differentiated the above equality, and you get the rate of change of the cover temperature, related to the rate of change of the plate temperature, multiplied by the ratio of the overall loss coefficient to the cover to the ambient plus coefficient. So, basically what it means is physically, we can understand if T p changes at a particular rate, T c should change at a corresponding rate, depending upon the loss coefficients. Now if you add those two equations, you will have m c of the plate, plus U L by U c a m c of the cover times d T p by d T is expressed in terms of d T c by d T a c times S minus U L into T p minus T a, and if you use this d T c by d T equal to U L by U c a d T p by d t.

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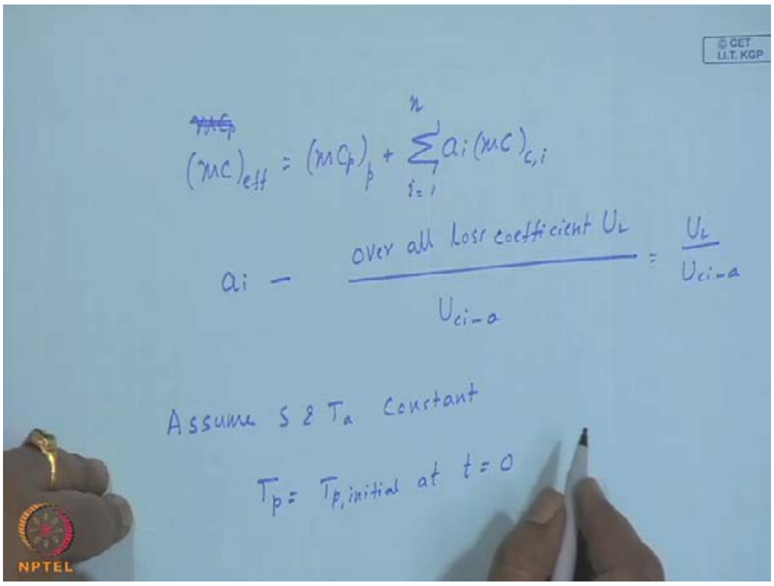

So, you already we have written that, we might write it as m c effective, sorry of the plate plus sigma a i m c recover i, i is equal to 1 to n. I have not generalized this relation of effective heat capacity, sorry mass into heat capacity, to n number of covers, not just one cover, where a i is the ratio of overall loss coefficient, U L to the loss coefficient from the cover in question to the sovereign, U c i to a. So, this is nothing, but equal to U L upon U c i to a. Now the equation is subjected to S and assumed, this is where again S and T a constant. So, it is a kind of quasi unsteady analysis, S and T are constant and, but because S is falling on the collector, your temperature of the absorber plate, and the cover plate will change, is nothing like a conventional system, exactly like a conventional system, where you are heating it, and the boundary condition or the initial condition would be T p is T p initial, at time T is equal to 0.

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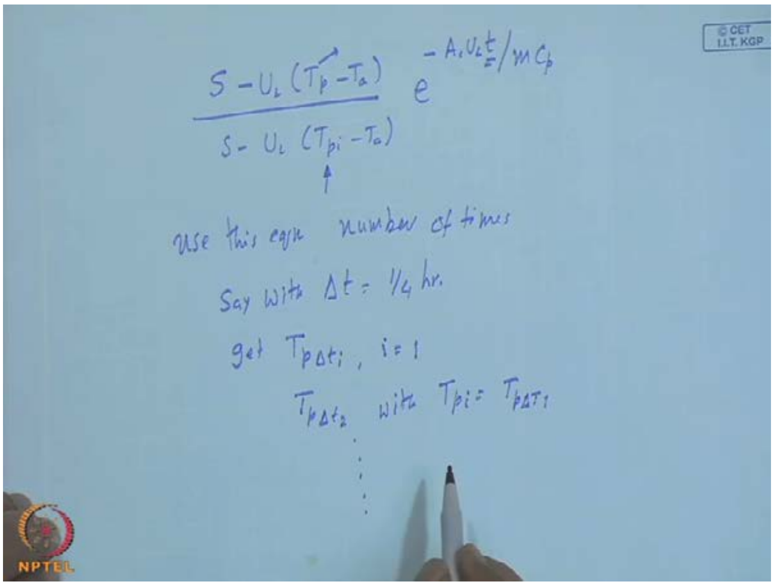

So, you will have S minus U L times T p minus T a upon S minus U L T p initial minus T a equal to e to the power minus A c U L time by m c p. So, this is how the temperature of the plate T p, from an initial temperature of T p i changes with time T, if the overall loss coefficient of the collector is U L, and the mass is m, and c p is this specific heat. So, what we can do is, though we made the assumption that S is constant and T as constant, use this equation, number of times, say with delta T is one forth hour, and get T p delta T i, i is equal to 1, and then T p delta T 2, with T p initial being T p delta T 1. So, like that you can continue, feed the temperature at the end of the time interval T p of delta T, as initial temperature for the next time interval, and continue the procedure, and in that process take in to account, your variation of the solar radiation and the ambient temperature. Consequently repeated use of this quasi steady or unsteady analysis, is likely to yield, acceptable unsteady state performance, and you are only assuming for the short period of 15 minutes or 10 minutes, the solar radiation to be constant, and particularly if m c p is large, the response will be slower, so you are liking to get a fairly accurate result.

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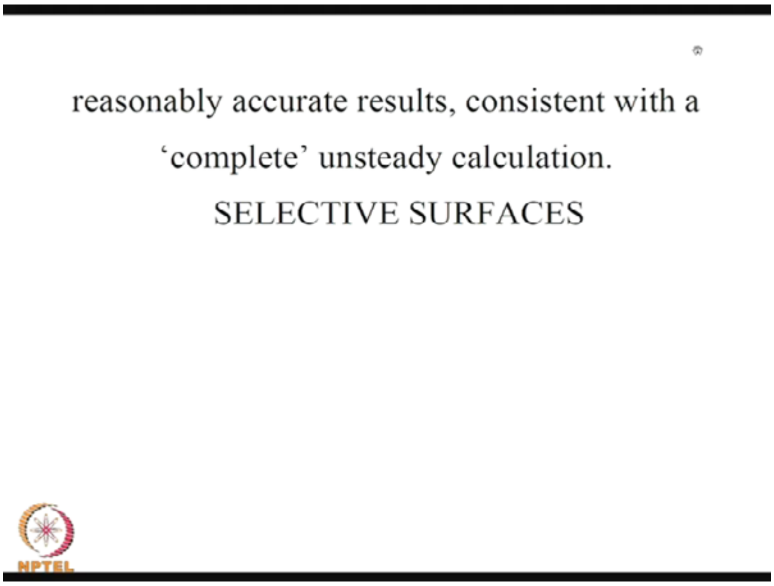

And this is most important, from the point of view of, whether the collector will reach the required temperature, before the solar radiation reaches, the critical level of radiation. It can be more, but it cannot be less, because the critical radiation level corresponds to the temperature at which, the energy delivery is desired by you, so the collector has to reach the temperature before the time.

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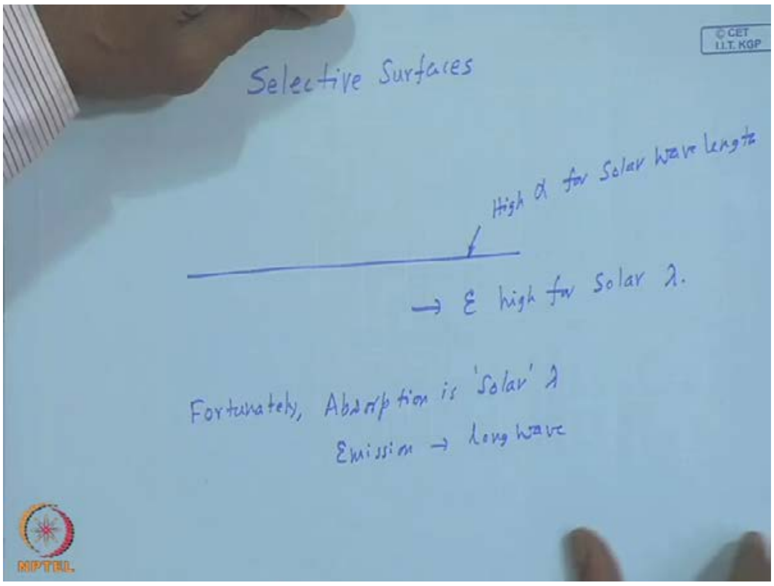

Now, when we were right the beginning, talking about basic principles of solar collectors. In general if there is any surface, we have using the methods of reducing conduction, convection, and radiation loss, and it should have; obviously, high alpha, absorbity for solar range. So, this implies, epsilon also high for solar lambda, but fortunately, absorption is solar wave length, and emission is long wave.

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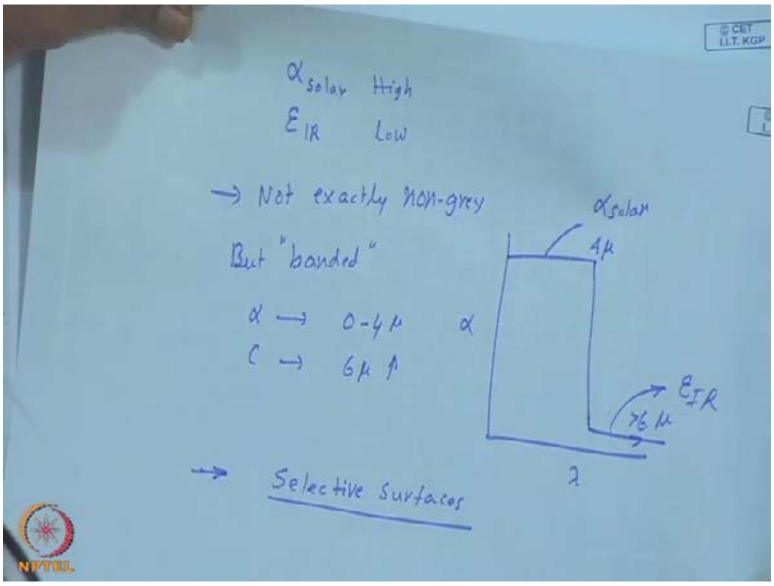

So, we do not violate the Kirchhoff's law, by choosing alpha solar, high epsilon IR low. This is not exactly non grey, but banded, alpha in say 0 to 4 microns, and epsilon say 6 microns and above. So, if you plot alpha versus lambda, you may have something like this. This may be 4 microns, and this is onwards 6 greater than microns. So, alpha is equal to epsilon is satisfied, but this is my epsilon IR, responsible for the losses, this is my alpha solar, for responsible for absorption. So, such surfaces, though they are dependent upon the wave length, there dependent upon two band widths separately, they are termed selective surfaces. So, selective surface in general is a non grey surface, but with a special feature, that the properties are in two bands of the wave length, in the solar range a high absorbity, and in the near IR or far IR a low epsilon. So, this is the material science research goes on.

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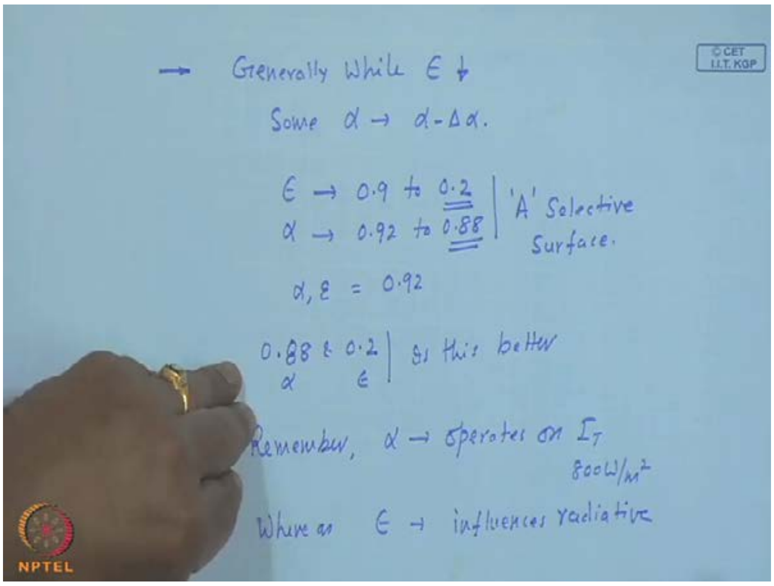

Generally, while epsilon is reduced, some alpha goes to alpha minus delta alpha. So, people will be sometimes tempted to be happy, that epsilon has gone down from 0.9 to 0.2, where as in the same process, alpha has gone down, gone from 0.92 to 0.88. This is a selective surface, no doubt it satisfies the criteria, that alpha IR is low, alpha, sorry solar is high, and epsilon IR is low, but if you consider the original thing that would have been alpha epsilon both 0.92, is this 0.88 and 0.2 epsilon, is this better. This is from a thermal energy point of view, not necessarily from the physics of how produce a selective surface, I thought it should be mentioned over here. Whenever you are producing a selective surface, there is some reduction in absorbity also. Consequently we have to have a estimate, whether that reduction in the absorbity, is compensated by the reduction in the emissivity or not. In this, at times it is convenient tempted, to think that 0.9 has gone down to 0.2, whereas, 0.92 has gone to only 0.88, so this should be ok, is a good surface, but we do well, if you remember, alpha operates on the incoming solar radiation; say 800 watts, whereas epsilon influences radiative part of the losses.

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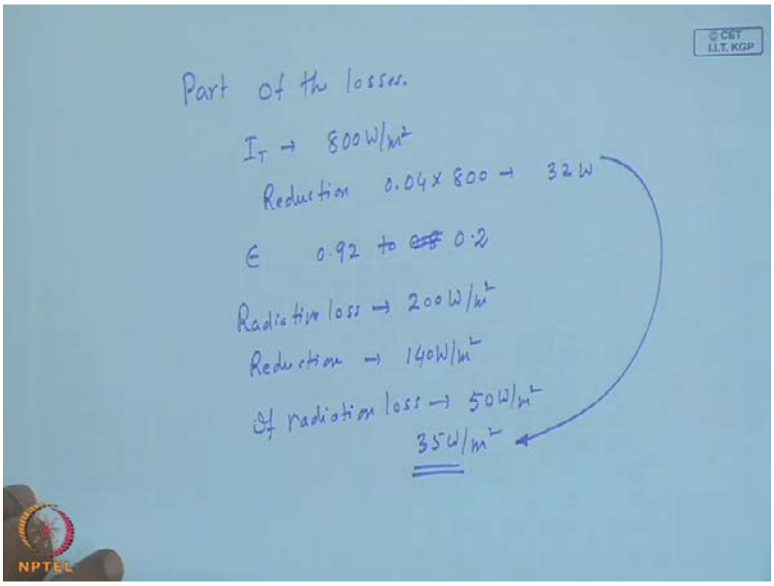

So, if you have got I T corresponding to 800 watts per meter square, and reduction would be, because of alpha, a 0.04 into 800; that is about 32 watts right 32 watts, whereas epsilon has come down from 0.9 to 2.8. Originally radiative loss, is let us say 200 watts per meter square, then this o this is 0.9 0.2. So, it is about 70 percent of this, reduction will be. If it is a part of that, or about 140 watts per meter square, this may be the, if it is a 200, if your total losses are 200, and if radiation loss, is only 50 watts per meter square, then my reduction will be of the order of 70 percent, 35 watts per meter square. So, this is comparable to this. So, if you are having a radiation component of about 50 watts, and a total of 800, a reduction of 0.9 to 2.2, is just about the reduction that may be, because of 0.92 to 0.88, for the absorbity. So, one should go for, the actual calculation, depending upon the operating condition, and make sure that the radiative component of loss is sufficiently reduced, because of the reduction, and it is more than the reduction and the absorb radiation, which is caused by some reduction d absorbity, in the process of producing a selective states.

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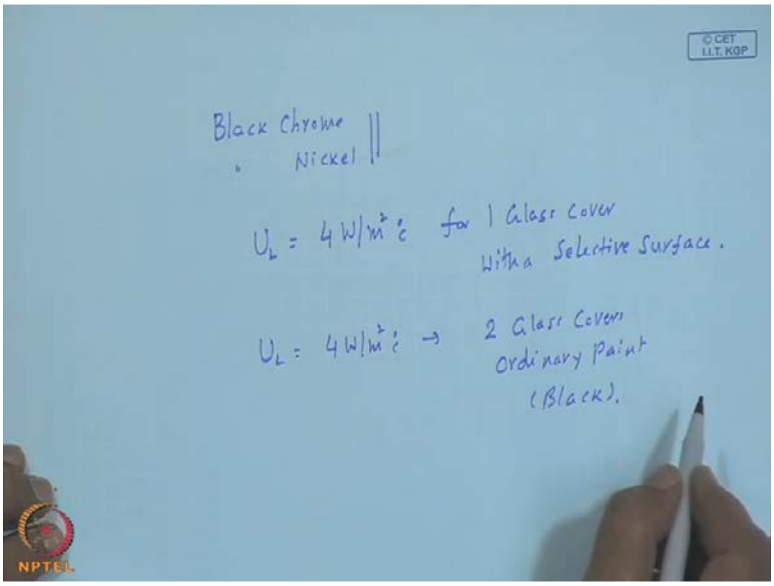

But assuming there are many recommended commercial available selective surfaces; like black chrome, and black nickel, these are the two stable coatings. There are number of processors to make a black chrome painting, or the black nickel coating, on copper or steel surfaces, and these are commercially available, and they have typically, they lead to a U L of 4 watts per meter square degree c, for 1 glass cover, with this selective surface. This you might compare, you will also, will be approximately 4 watts per meter square, for 2 glass covers, and ordinary paint, rather black paint. So, there is a dilemma, whether you go for the black chrome, black nickel selective surface, or the 2 glass covers, because the loss coefficients appear to be similar.

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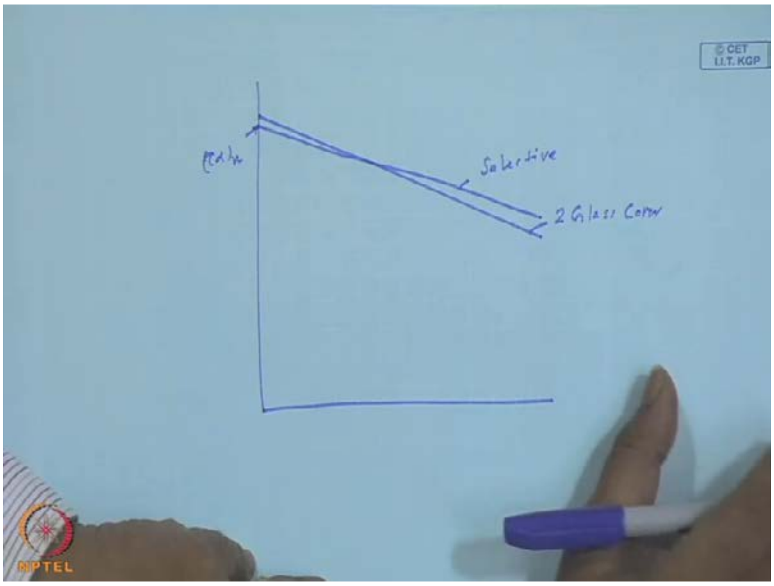

This is where your operating condition is going to come into the picture, just like we have drawn, for 1 glass cover and 2 glass covers. Now if I take a 2 glass cover performance, and selective performance. So, they are more or less of the same, but if it is at a low temperature, 2 glass cover maybe better, than a selective surfaces, since there is a slight reduction in tau alpha, normal in the solar range. So, this is one thing one has to keep in mind.

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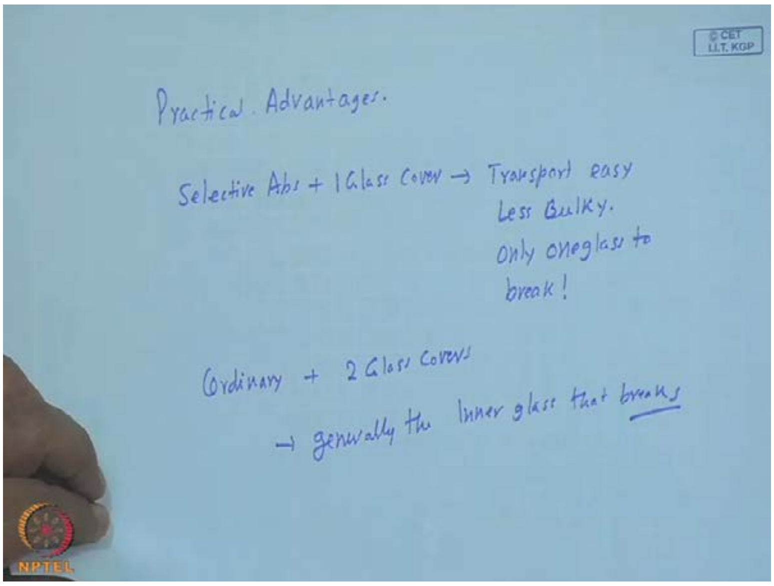

The practical advantages or disadvantages, if you have a selective absorber, assuming that the costs are comparable, generally they are, plus one glass cover, transport easy, less bulky in other words, and only one glass to break, this may sound a little hilarious, but there is reason for mentioning this. If you have got ordinary, plus 2 glass covers, it is generally the inner glass that breaks. In this instance we do not mean that somebody has thrown a stone to break the glass, but essentially by thermal expansion and contraction, and since the inner glass is at a higher temperature, the expansion and contraction will be more, and hence the chances of breaking are more. So, in that process, to replace the inner glass, you have to remove the outer glass also, consequently it will be a little more labor intensive, and that removing the outer glass may cause damage to the outer glass again. So, in that sense a selective surface with one glass cover, if the temperature of operation is right, is likely to be a better choice, than two glass covers.

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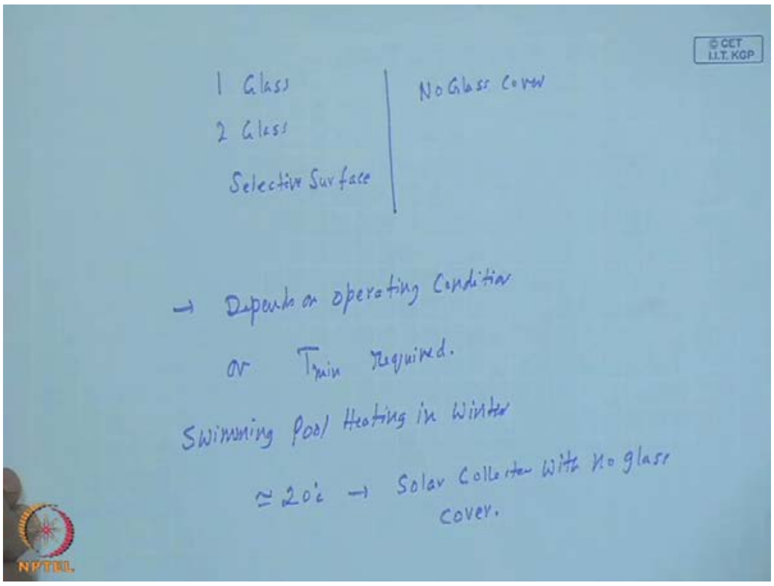

So, in short, it is not just a question of efficiency, we choose one glass, two glass, or selective surface, and in fact, you will be surprised even no glass cover, all this depends on operating condition, or your T minimum required. One example that comes to my mind is swimming pool heating, let say in winter. So, you can maintain a temperature of approximately 20 degree c, instead of 11 12 14, we do not consider lower temperatures, because then possibly people may not like to swim, unless it is indoor and this, and it can be easily heated, by a solar collector, with no glass cover. Of course, there are quite a few novel designs, where in the existence structure of sets, etcetera is made use of, instead of a separate collector system, being introduced or installed, for heating to a low temperature like 20 degree c.

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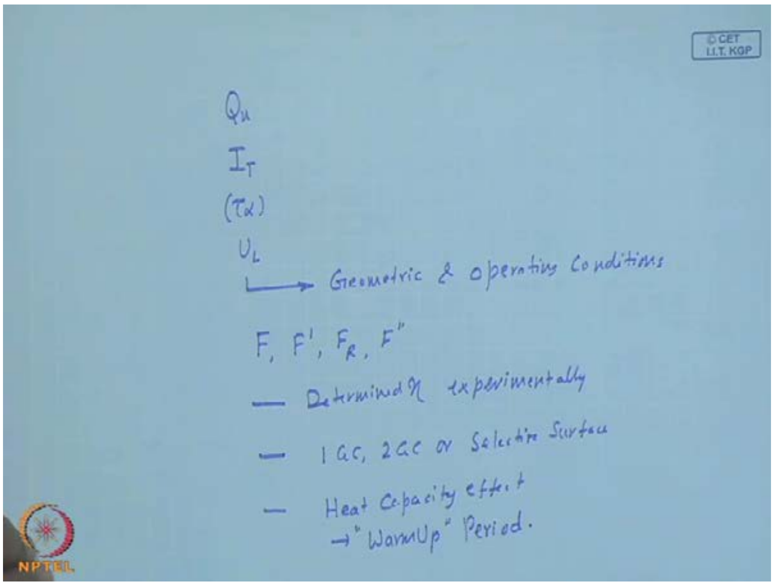

So, as for as the liquid heating collectors are concerned, we made such number of assumptions, obtained in equation for the useful energy gain, by energy balance, simple energy balance, then we know how to estimate I T, how to estimate tau alpha, how to estimate U L. And then related to our geometric, and operating conditions. In this process we defined a fin efficiency, a collector efficiency factor, and a heat removal factor, and a flow factor. So, these things in various capacities, represent our tellers how would the, a collector is. Then we determine the efficiency, experimentally; and based on that, we examined 1 glass cover, 2 glass covers or selective surface. Also we included heat capacity effect, which is mainly needed for warm up period.

In other words, it will tell you the operating time; if you have got a massive solar collector, which will require a lot of energy to reach the temperature required, to deliver the energy at the desired temperature, then it may operate for a very less time. Not only that, the unsteady equation can be, made use of repeatedly, to get reasonably representing unsteady state performance, from data being used over smaller and smaller time interface, may not be from the necessarily accuracy point of view, but to find out the effect of heat capacity, whether it is responding, how quickly, or not so how quickly, or to the changing environmental, or the metallurgical variables, that influence the performance of the solar collectors.

Thank you.