Solar Energy Technology
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Lecture - 32
The phi bar-f chart Method, Tank Losses and Finite Heat Exchanger

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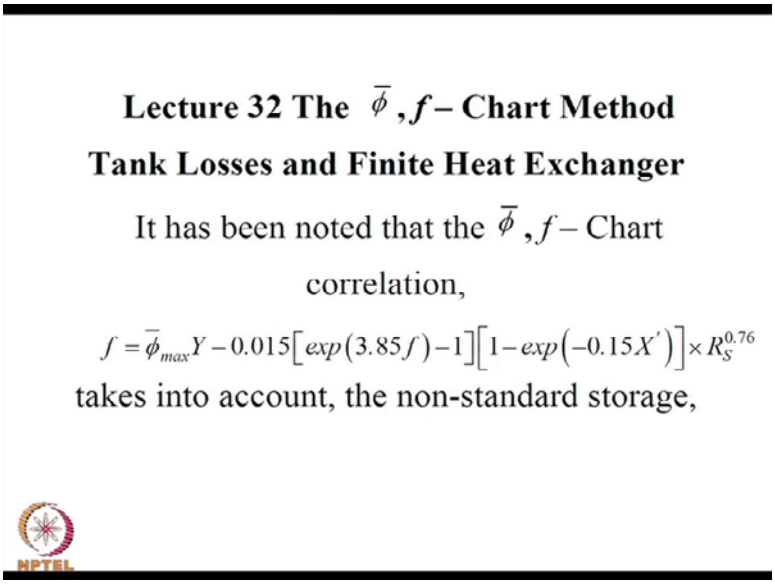

So, today in this lecture, we shall proceed how to account for solar tank losses in the solar energy system, which is being calculated by the phi bar f chart method as well as the finite heat exchanger.

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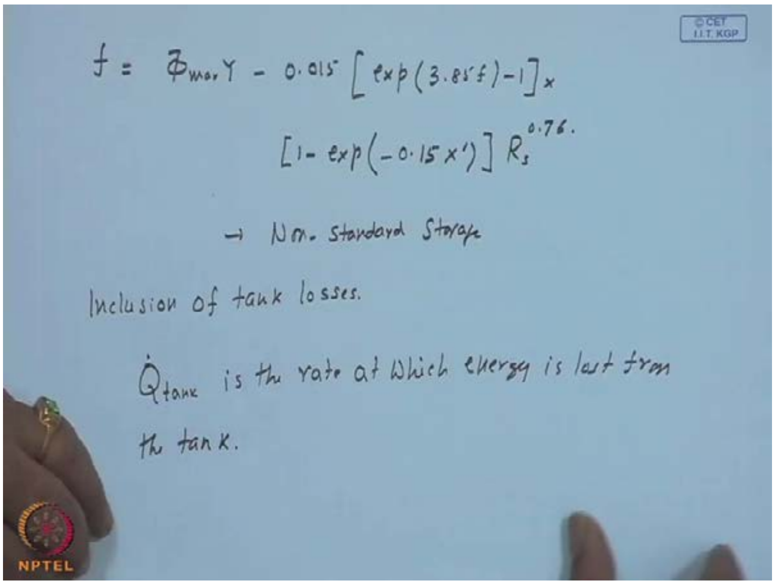

So, we shall just recall the correlation f in phi bar chart method is given by phi bar max y minus 0.015 exponential 3.85 f minus 1 times 1 minus exponential minus 0.15 x dash times stranded storage to actual storage ratio raise to the power 0.76. So, this takes into account as the non-stranded storage. So, now how do we include the tank losses? If the tank is at an average temperature of T, it will be losing heat at a particular rate depending upon the overall loss coefficient of the tank multiplied by the surface area of the tank, times temperature difference of the type T tank minus surrounding T a dash. Initially, we do not know what is the tank temperature? But let us say Q dot tank is the rate at which energy is lost from the tank.

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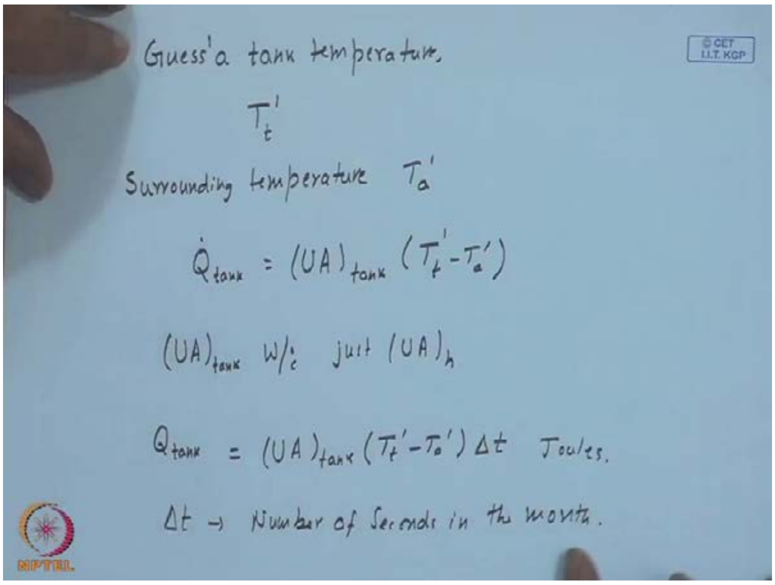

Since, I do not know the tank temperature, I will guess a tanks temperature which may require iteration. So, this I will call it guess 1 and let this be T t 1 and the surrounding temperature may be T a dash. Please note that this may be different from the ambient temperature since many times, the storage tank can be in the basement and the basement temperature produce heat could be quite different from the ambient temperature. So, we will call it to keep it general T a dash. So, Q dot tank is U A of the tank times T t 1 minus T a dash. So, this UA tank is the overall loss coefficient watts per meter square degree c multiplied by the surface area of the tank. So, it will be in watts per degree c just like which we have introduced in calculating in space heating, the building heat loss coefficient UA h.

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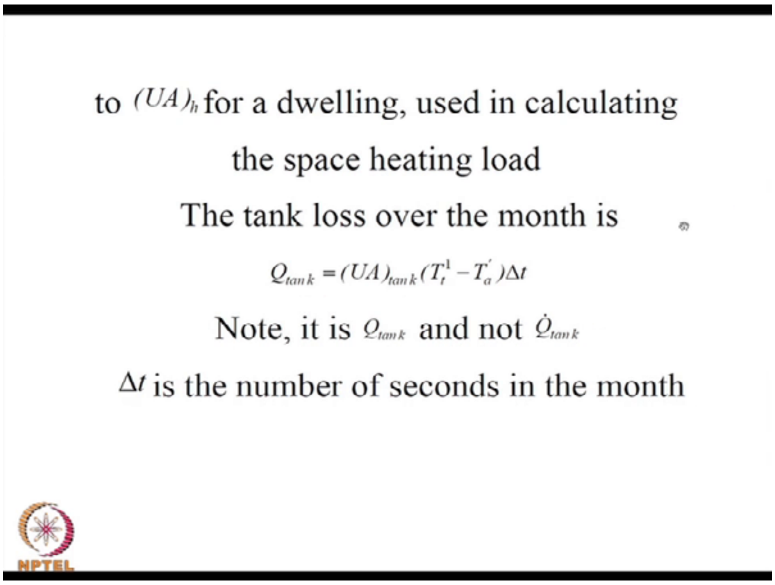

If I integrate this Q dot tank rate over the month and assume this T t dash and T a dash remains constant or some average value, I will get U A tank. It should not differ so much with the temperature T t 1 minus T a dash times delta t, where delta t is the number of seconds. This makes it joules. If U is watts per meter square degree c, this will be so many joules number of seconds in the month.

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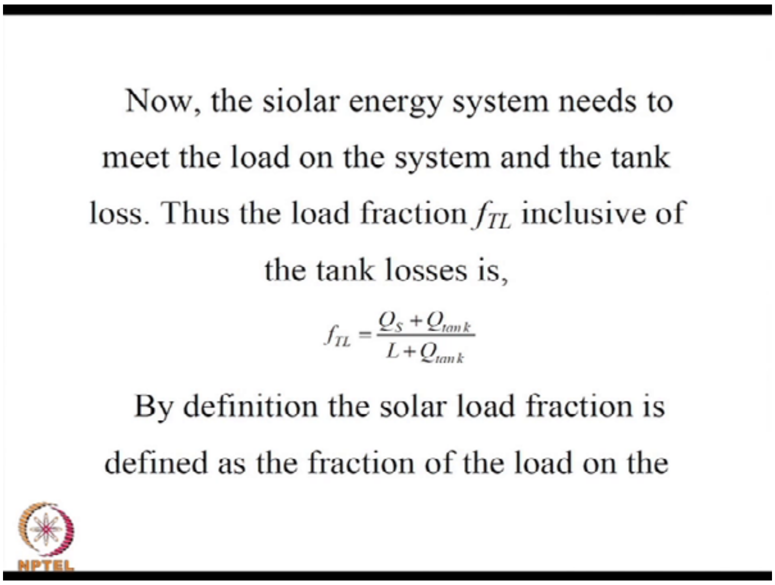

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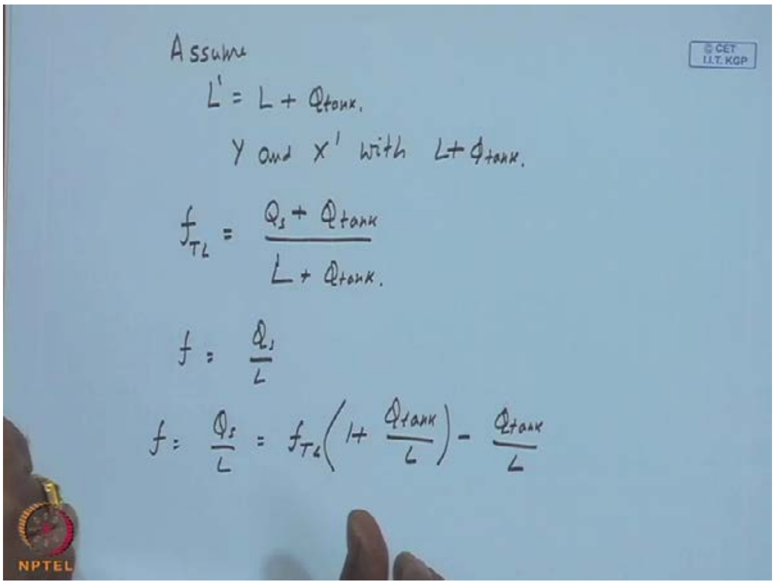

So, what I shall do is assume load now will be equal to, let me say L 1 equals to L plus Q tank. The affect of the tank loss as far as the solar energy system is concerned; it looks like an additional load. So, if I calculate my Y and X dash with L plus Q tank, I do not want to complicate things unnecessary calling L1, L 2, L 3 etcetera. So, it is a actual load on the system plus the last one tank. I will get the solar load fraction, but I shall qualify it as f TL, that is inclusive of the tank losses. So, what I get this number is Q system by Q tank by L plus Q tank.

We have not deviated from our original definition except we realize that Q tank has been fully met and has to be fully met the load on the system is L, and Q is the amount of energy that is going to meet the load on the system. So, consequently the slow load fraction that I obtain will be Q s plus Q tank by the total load now being L plus Q tank, but actually my f solar is Q s by L. So, from this I can find out f is equal to Q s by L. Just divide throughput with L, then I will get as f TL times 1 plus Q tank by L minus Q tank by L, right. Q s by L will be f and then Q tank by L will be here and L by L is 1 plus Q tank by L. So, that goes onto f TL minus Q tank by L. So, this is nothing but you respect the tank losses. You fully need that and then remaining amount of energy goes to meet the load.

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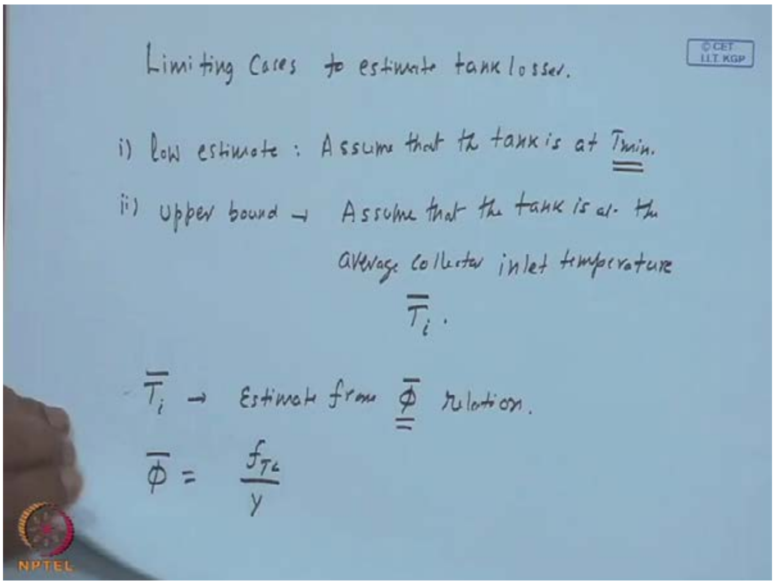

Now, there are two limiting cases because I must have a way of correcting the T t 1 limiting cases to estimate tank losses. One is a lowest estimate. Assume that the tank is at T minimum because the system is supposed to deliver energy at about the temperature T minimum. The tank temperature cannot be lower than T minimum and a upper limit is assumed that the tank is at the average collector inlet temperature. This is essentially equal the outlet temperature because when once it stops increasing, the pump is cut off. So, this I will call it T i bar.

Now, this T minimum is no problem. This is known is specified. This T i bar, I will estimate from phi bar relation. Since, this is corresponding to be a inlet temperature of the collector. Based upon this inlet temperature, there is a term utilizability phi bar and if there is a certain utilizability, what the t i bar temperature is. Now, this is where this phi bar is. I am deliberately not writing phi bar max, just phi bar. It is essentially f TL upon y. In other words, if y is the non-dimensional (()) energy and f TL is the load fraction and include all the tank losses, then that corresponds to some sort of a phi bar y equal to f TL. As I was telling phi bar max into y is the maximum solar load fraction. Some average utilizability multiplied by y should be my solar load fraction with the tank losses.

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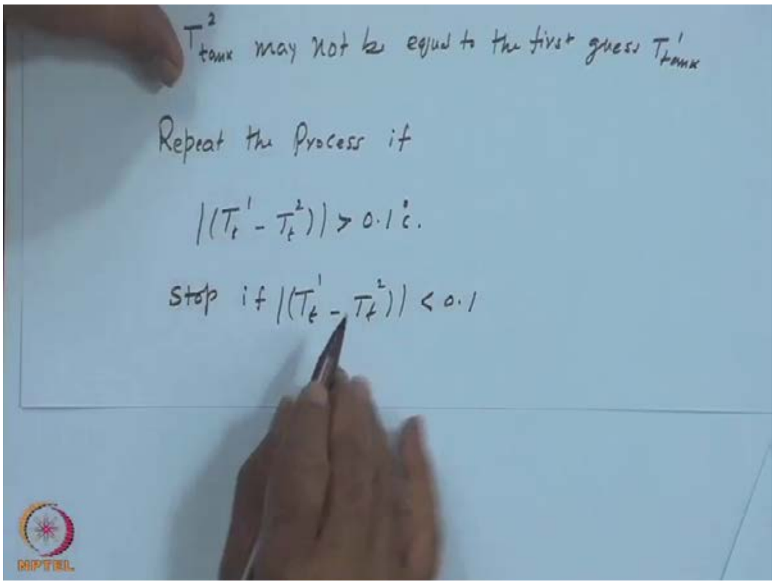

So, now the new tank temperature, at least I have whatever. Basis should be somewhere in between these two numbers. T tank 2, I will call it T i bar plus T minimum by 2. Now, this T tank 2 may not be equal to first guess T tank 1. So, repeat the process. If T tank 1 minus T tank 2, we make sure modulus is, let us say greater than 0.1 degree c or stop, if T tank 1 minus T tank 2 mod is less than 0.1.

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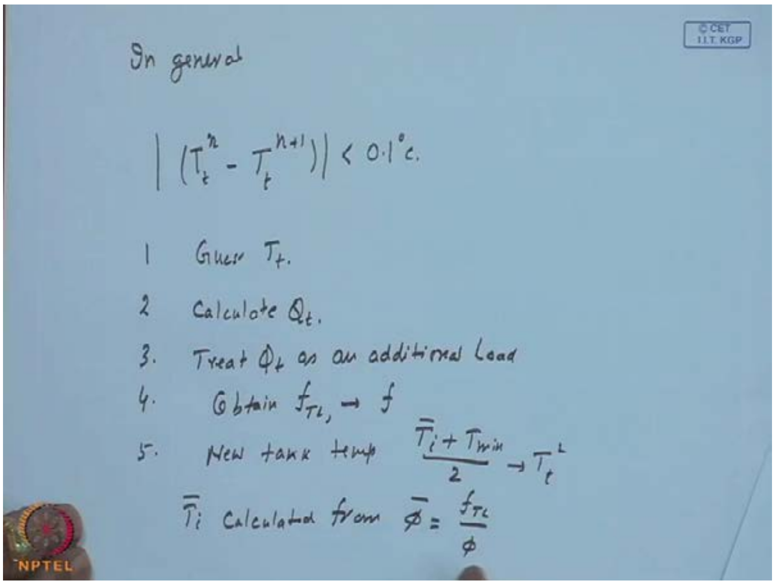

In general, if we continue iterate, I can write it as modulus of T tank n minus T tank n plus 1 mod is less than 0.1 degree celsius. So, you continue this calculation n number of times until the difference in that estimated T i bar and T minimum by 2 is pretty close to the previous value you guessed as the tank temperature. So, let me quickly go through this again step by step.

1. Guess T t

2. Calculate Q tank

3. Treat Q tank as an additional load

4. Obtain f TL inclusive of the tank losses from which you can calculate f solar in meeting the load on the system, and

5. New tank temperature is T i bar plus T minimum by 2 which may be your T t 2. T i bar is calculated from phi bar equal to f TL by y because this is the function of explanation a plus b times X c bar plus c X c bar square. I will find out a X c bar. From that X c bar, I will find out a T i bar, ok, f TL by y. I am sorry.

So, this process is continued iterating n number of times until the temperature difference that you assume, the tank temperature and this final average tank temperature which is an average between upper estimate and the lower estimate of the losses is pretty close to each other. So, now the procedure is clear which shall become even more clear when we solve one example after sometime time.

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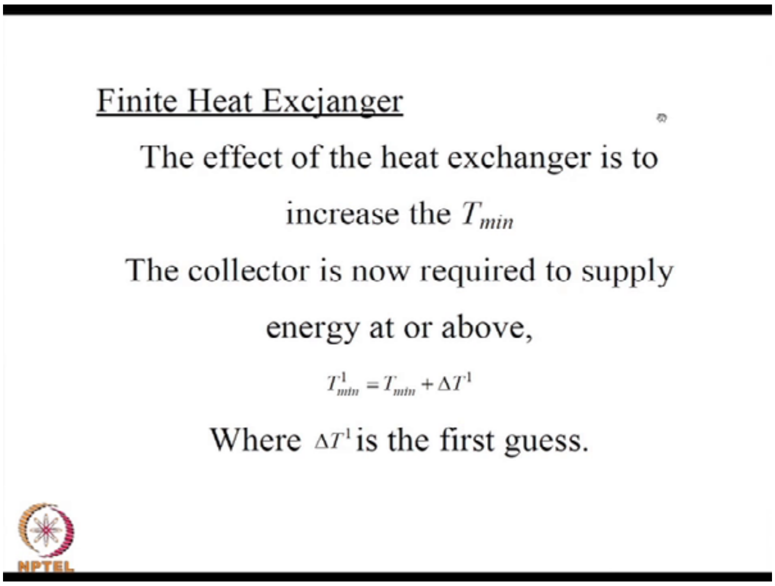

Now, Finite Heat Exchanger.

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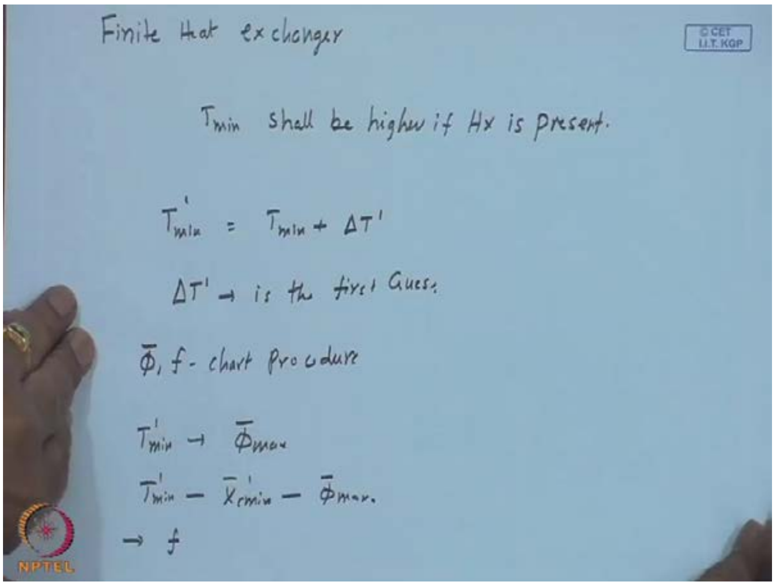

If you want to briefly say how the tank losses are accounted for, but to iterate the process and guessing, we might say that the effect of the tank loss is to enhance the load on the system by the amount that the energy is lost from the tank. Now, if you have a heat exchanger from the tank, it goes to the heat exchanger to meet the load. So, if you are calculating about the back flow, the T minimum, the temperature at which the energy is to be (( )) be the collector shall become higher if H x is heat exchanger is present, right. That will be some delta T is required. That delta reflex in the tank temperature, that tank temperature reflex in the T minimum are the outlet temperature from the collector which needs to be delivered in order that it finally suppress energy originally desire T minimum.

So, once again I will assume that T min guess 1 equal to T min plus some delta T 1 which may be 4 degrees, 3 degrees like that. So, delta T 1 is the first guess. So, we follow f phi bar f chart procedure. What do we mean by this? T min 1 correspond to some phi bar max or in between if you want T min 1 corresponds to X c bar min 1 corresponds phi bar max, then I will get my solar load fraction. Y index are straight forward to calculate because they do not depend upon T minimum.

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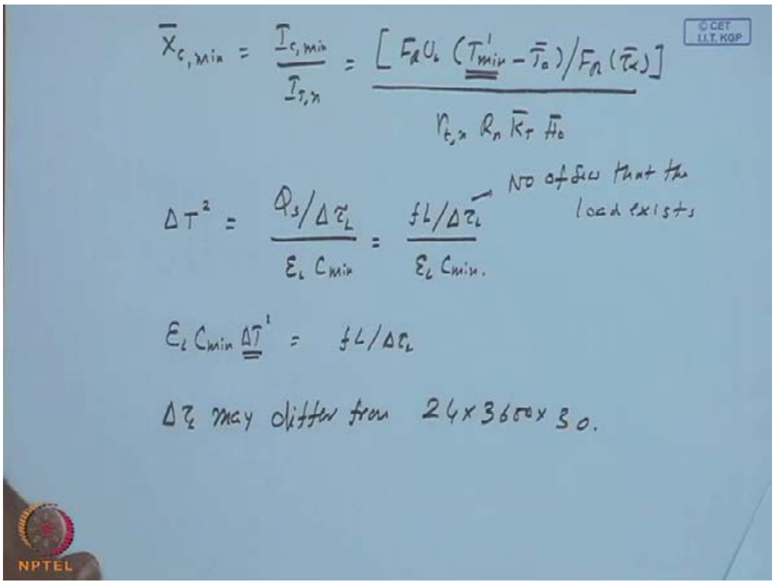

When once if you want, you can now X c bar minimum rewritten will be as I C minimum by I T noon equal everything is a same F R U L. Write T min guess minus T a bar by FR tau alpha bar over r t, n R n K T bar H 0 bar. This is nothing but the same previous definition except I am replacing the minimum temperature at which energy delivery is desired by T minimum plus some delta T because of the presence of the heat exchanger.

Now, if f is the solar load fraction that means phi bar, I have already calculated X c corresponding phi bar max X c bar minimum and we know y index dash and we know f. So, if f is the solar load fraction that multiplied by y is the useful energy that is being sent. So, that will be equal to Q s by, I will explain again, delta tau L by epsilon l C minimum. The energy that is going to meet the load on the system is f product by delta tau L. We will make this is number of seconds that the load operates that the load exist; it may not be 24 hours. It may be let us say, 12 kilo watts or 12 hours a day by epsilon l C minimum.

So, this is a rate at which the energy delivery is made upon epsilon l C minimum and you will be very comfortable if you look at the equation as epsilon l C minimum. Delta T 2 is nothing but the energy transferred by the heat exchanger, right because this is the minimum of the heat capacitance rates of the heat exchanger fluids on the two sides of the heat exchanger multiplied by the effectiveness of the heat exchanger multiplied by the delta T available across the heat exchanger, ok. This is nothing but f L upon delta tau L. So, f L is the total amount of energy supply over a period of delta tau L.

So, this is the rate at which the energy is supplied and that should be matched by the heat exchanger of effectiveness of epsilon L and the minimum capacitance of T minimum with a temperature difference of delta T 2. So, why I emphasis in delta tau L may differ from number of seconds in the month, right. Now, you might ask me the question why did we do not do this upper Q tank estimate. The loss from the tank always takes place, whereas if there is no load heat exchanger does not operate. That is the reason why energy this is a rate epsilon 1 C minimum is the rate at which the heat exchanger is going to supply energy. This is rate at which they load on the system.

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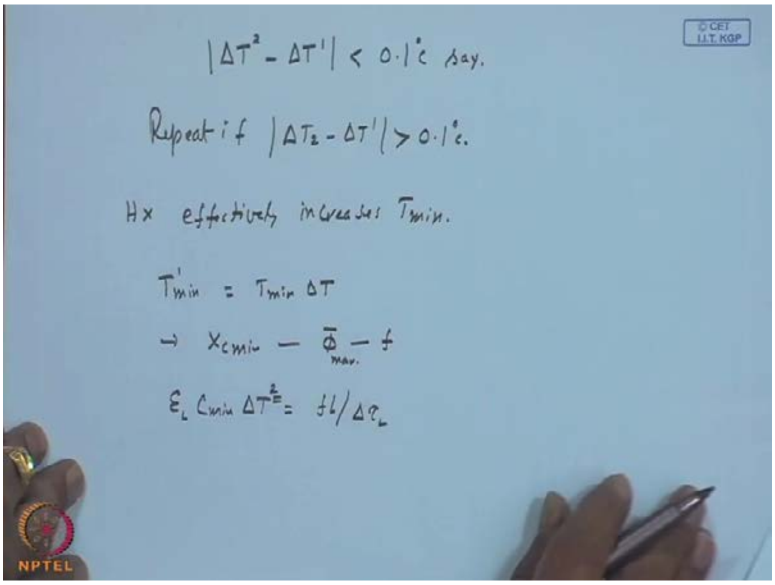

So, again we will set up the same condition. First, guess the difference between these two should be let say 0.1 degree c or else repeat if is greater than 0.1 degree c. So, you always come out with delta T 2, and then go and re estimate your X c bar minimum and then the solar load fraction, ok. So, in a nutshell that once again the heat exchanger effectively increases T minimum. So, the procedure is T min equal to T min plus delta T which may change it to X c minimum from where you calculate phi bar from where (( )) f. So, from this epsilon l C minimum times delta T 2 should be equal to f into L by delta tau L. So, this is the governing equation. How? Please do not follow in the context. These are not delta T squares delta T 2, but I suppose those of you who have held by repeatedly saying that you would not make that mistake.

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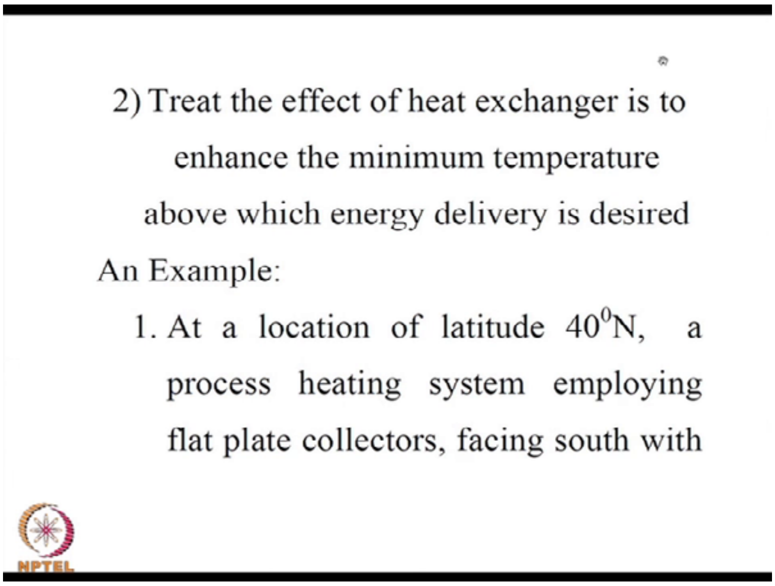

So, this is what I have again summarized. Heat tank loss at the additional load of the system, T the effect of heat exchanger is to enhance the minimum temperature above which energy delivery is desired. So, if you remember these two things in physical terms, it is more easy to automatically follow the procedure. Only in the case of tank temperature NU estimate of the tank temperature is T i bar plus T minimum by 2. So, the T i bar being coming from the average utilizability concept. Now, we shall to consulate these ideas, we should take up an example and we shall see how much we can do.

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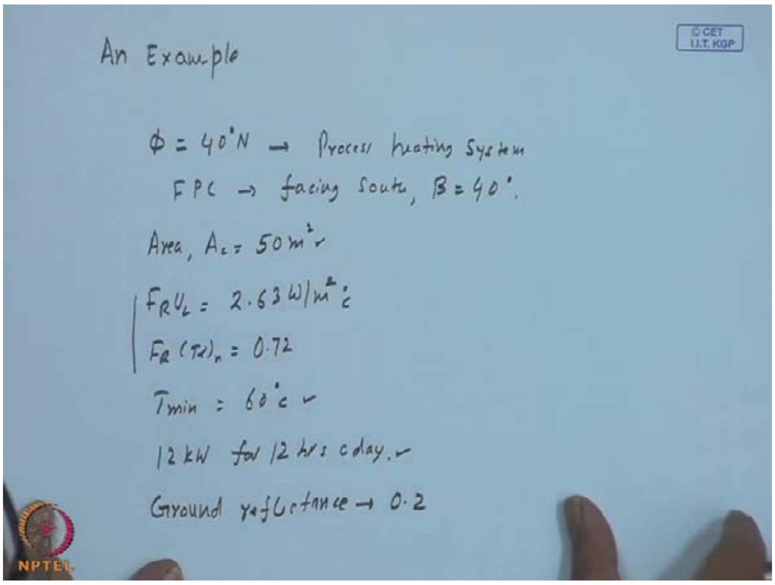

I am deliberately giving many relations which we have gone through earlier. In fact, if you solve this problem, more or less, almost all the method that we have covered would be covered. So, the location is the latitude of 40 degrees and in fact, this example is from the text book by Duffy and Beckman except few things, I have charged here and there and this is for a process heating system, this is to bring out certain details, and flat plate collectors facing south and the slope beta is equal to 40 degrees, area is equal to 50 meter square and The collector parameters are FRUL is 2.63 watts per meter square degree centigrade, and FR tau alpha are normal. In fact, these values we have used in other publications also, this is sub T minimum is 60 degrees of 12 kilo watts for 12 hours a day.

Now, for our calculations, you may assume ground reflectance to be 0.2. So, the characteristics you should know of course the location slope flat plate collectors, the collector parameters, and then the minimum temperature and the total load and of course, this is the area that we have provided. What is the solar load fraction that comes out which may not know.

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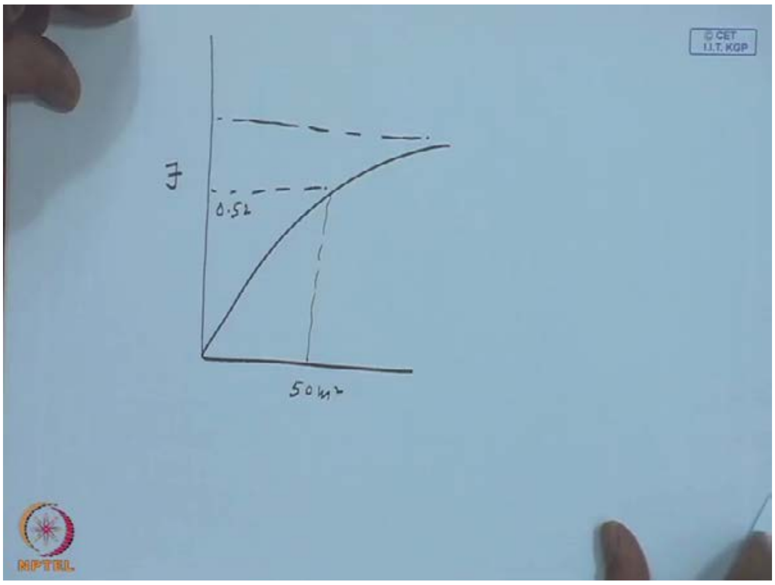

We do not know appropriately. The idea is to calculate and if you plot the annual solar load fraction, it may be something like this, and if you have this 50 meter square, this may be 0.52 whereas, if you make any one monthly calculation, so for January, it may be less. For June, it may be more because the solar radiation is more and the load on the system is constant is 10 kilo watts for 12 hours a day.

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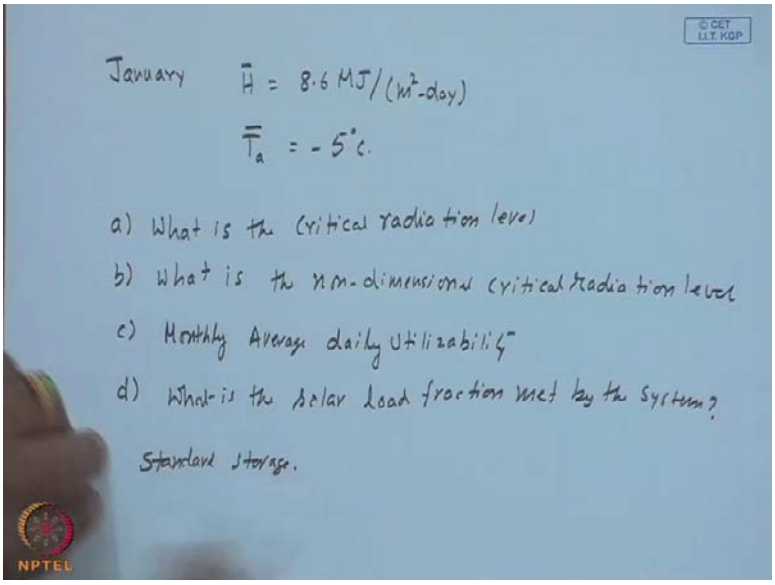

So, I take the data of January which you can calculate for the T m by 2 also, H bar is 8.6 mega joules per meter square day. In other words, there is no ambiguity. The monthly average daily radiation on a horizontal z phase is 8.6 mega joules per meter square day and the ambient temperature is T a bar is equal to minus 5 degrees c.

Now, only difference is if you take a location from India, typicality T a bar may be 10, 15, 20 whatever even in the month of January. So, first since we know we are going to use phi bar of chart method, my question will be what the critical radiation level is, so that I try to put it in the form that you could see it, so that the methodology is remembered. What is the non-dimensional critical radiation level and then you have, c, monthly average utilizibility, and what is the solar load fraction met by the system. Have I forgotten anything? Yeah, I think let us assume standard storage. It is 350 kilo joules degrees c.

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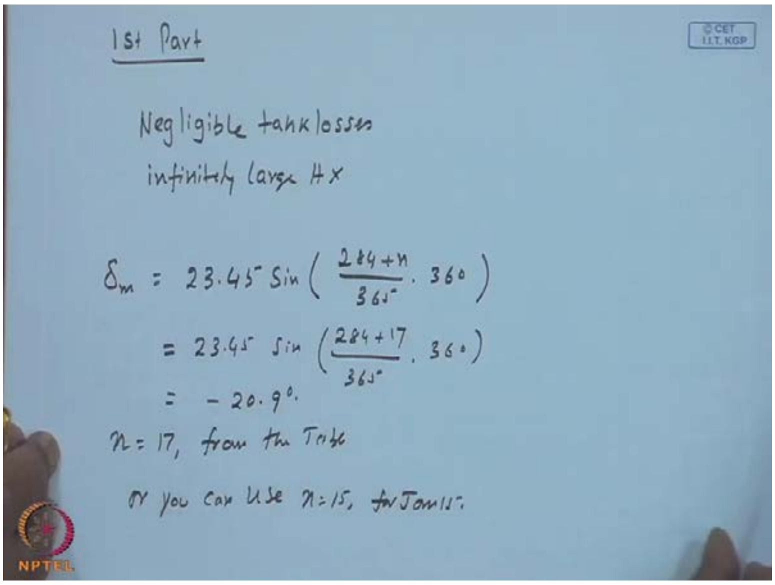

These are one by one we try to calculate. Also, first part is negligible tank losses and infinitely large H x. I suppose, those few are familiar with heat transfer. You would not find it surprising when I say infinitely large heat exchanger. It is nothing but saying that delta T is 0 across the heat exchanger, ok. So, first we need the mean declination. You can see this almost one of the very first relations we have written, 23.45, the whole idea of 284 percent by 365 into 360. That will be equal to 23.45 times sin 284 plus 17 by 365 into 360. Of course, n is equal to 17 from the table or you can use n is equal to 15 for January 15. Without much, it does not make, second would be that should be minus 20.9 degrees. It may be 0.88 or 0.92. I do not know (( )).

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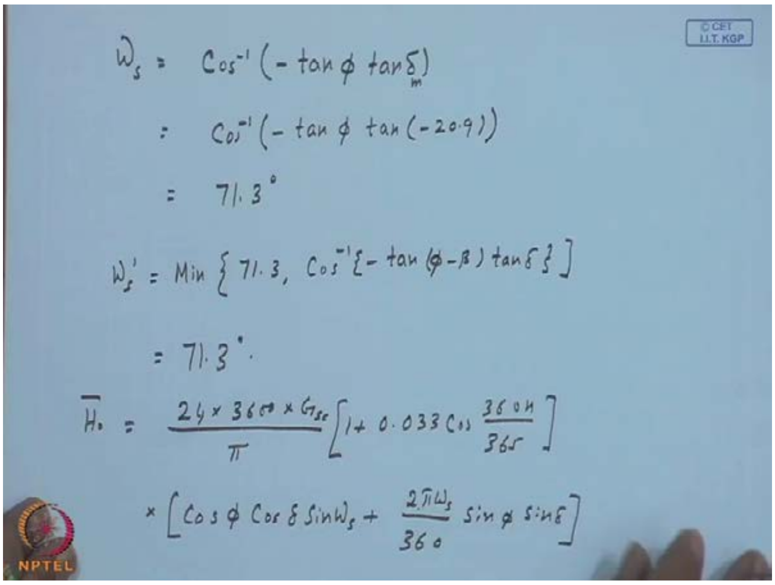

So, this is the main declination from which we calculate the sunset or angel omega s which is once again cos inverse minus tan phi tan delta, which is do not worry about this delta and delta m. We are making only mean day calculation. So, you need to forget that subscript, it means the single number in this problem. This comes out to be 71.3 degrees. So, this is lower than 90 as can be expected fairly high latitude and the January, it will be less than pi by 2 lower value and omega s dash for the south facing surface we know trigonometry. Obviously, this will be lower than that (( )). However, you can calculate by minimum of 71.3 and cos inverse minus tan phi minus beta tan delta which is 71.3. What next because all my correlation will be in terms of the a clearness index. I need H 0 bar which will be 24 into 3600 times Gsc, the solar constant by pi times 1 plus 0.033 cos 360 n by 365 times cos phi cos delta sin omega s plus 2 pi omega s by 360 times sin phi sin delta.

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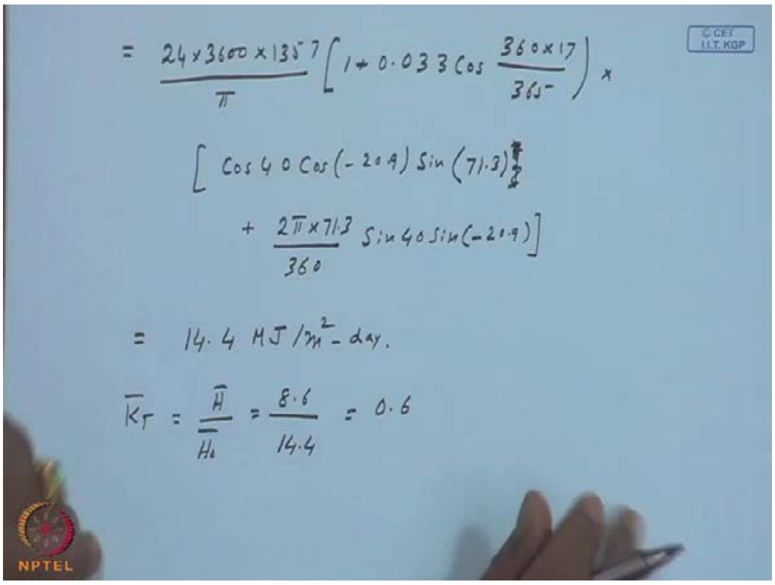

Please see this factor 2 pi by 360 same as pi by 180 because omega s I am going to put in degrees. That is once again 24 times 3600 times 1357 north 63, as the guess may be by pi times 1 plus 0.033 cos 360 into 17 by 365 times cos 40 cos minus 20.9 sin 71.3, fine. It is all right. Not necessary, plus 2 pi into 71.3 by 360 sin 40 sin minus 20.9. You can check up with your relation which you have given n number of times that comes to 14.4 mega joules per meter square d. So, the monthly average clearness index is H bar by H 0 bar which is 8.6 by 14.4 equal to 0.6.

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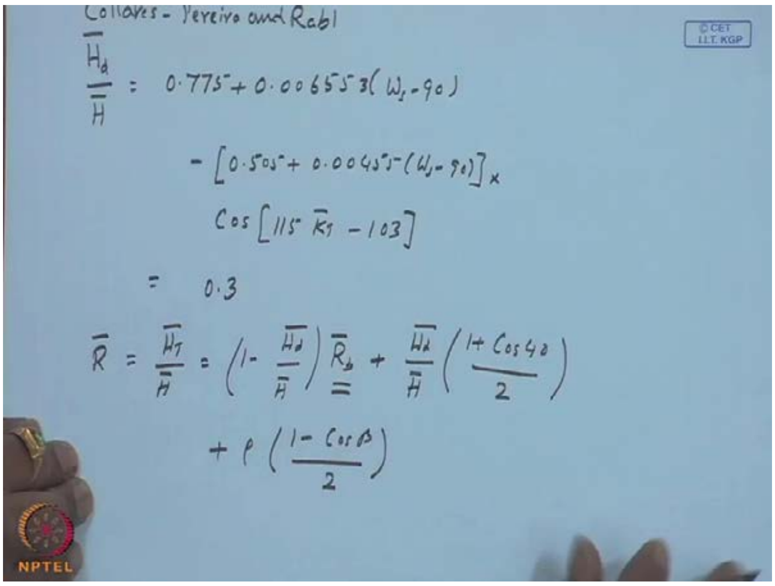

So, from this, we can calculate again monthly average daily diffuse fraction. This is Collares-Pereira and Rabl co-relation again which is 0.775 plus 0.006553 times omega s minus 90 minus 0.505 plus 0.00455 times omega s minus 90 times cos 115 K T bar minus 100. Now, please check the equations and the brackets. I think I am copying all right, but sometimes there may be mix up. 0.3 is reasonably expected in the bar per value. So, R bar will be H T bar by H bar which can be written as 1 minus H T bar by H bar. Now, you understand why we calculated this times R b bar plus H T bar by H bar times 1 plus cos beta by 2 plus rho which is 0.2 minus cos beta by 2.

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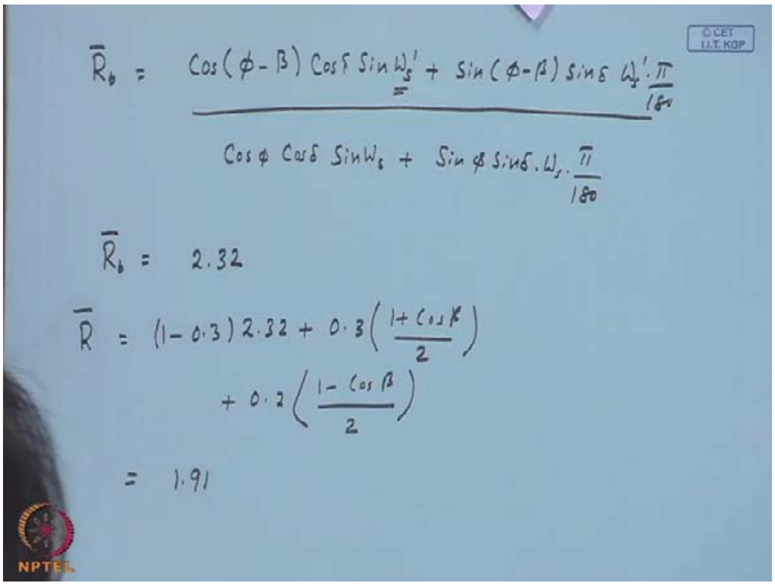

This detailed factor for the entire radiation, this is the beam component, direct component, this is diffused, and this is the ground refraction and you have your R b bar cos phi minus beta cos delta sin omega s dash plus sin phi minus beta sin delta omega s dash into phi by 180 by cos phi cos delta sin omega is plus sin phi sin delta omega s into pi by 180. Please note that the numerator is with the appearance, sunrise, sunset or angles. So, I am deliberately writing omega s dash and omega is dash and the denominator is with respect to the actual sunrise or sunset or angle omega s. So, simply because these are numerical equal, do not interchange. That will become a bad habit.

So, this R b bar if you calculate it, it is 2.32 and R bar will be 1 minus 0.3 that is H d bar by H bar into R b bar 2.32 plus 0.3 times 1 plus cos beta by 2 plus 0.2 into 1 minus cos beta by 2, which is 40 and this comes out to be 1.91. Let us just halt for a while. So, in the course of these problems so far we used how to calculate the declination, how to calculate H 0 bar and the clearness index, and then the diffuse fraction and the parameter R bar. So, tilted radiation, diffuse fraction, extra (( )) variation and declination, these relations has come so far.

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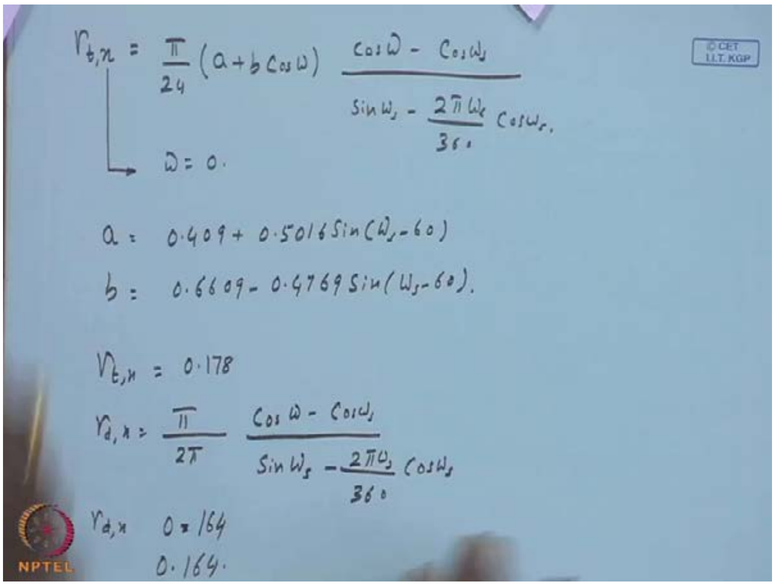

Now, we go for estimating r t at noon time because what was the first question. The first question was what the critical radiation level is. If I am about to, I can calculate FRUL into T i minus T a be something from which we have to calculate the non-dimensional critical level. If I want to calculate the non-dimensional critical level, we need the noon time radiation on the average day, r t n is phi by 24 a plus b cos omega. Again Collares-Pereira and Rabl, these relations which you had it earlier, cos omega minus cos omega s by sin omega s minus 2 pi omega s by 360 cos omega s. This is to be calculated noon means omega is equal to 0. Typically, it may not be at times. However, we will do it at omega is equal to 0. Assume solar time is the same as the local time that is one part and there are certain, where omega may not be equal to 0. K 0.409 plus 0.5016 sin omega s minus 60 and b is 0.6609 minus 0.4769 times sin omega s minus 60. So, if you calculate r t n will be 0.178, ok.

Now, you start developing a feel for the numbers, your r factors, r b factors, higher r factors will be less because that will be multiplied by 1 minus H d by H. So, this is 1.91 r bar and r b bar is 2.32. Later on when we make a calculation and similarly for summer, then my r b bar and r bar factors will be smaller than what you have got for the winter months. So, r t n is 0.178. This is about the noon time. That means 11.30 to 12.30 and that is almost 0.178. That means 20 percent of the total radiation. It can be expected, though it is only 1 hour and the total hours are less than about 11 hours 90 degree, 90 hours corresponds to 610 hour that is 10 and 10 and half hours. So, 20 percent can be expected in one single hour because there is around the noon time.

So, this one way you can check whether the numbers that you get are reasonable or not. For example, r t n should be higher than the proportionate amount around a noon time, and it will be lower than that means, there are 10 hours or each one will be 0.1, but around noon time, it is almost 0.2 and r d n is simpler that a plus b cos omega is also not there. Cos omega minus cos omega s by sin omega s minus 2 pi omega s by 360 cos omega s, this is 0.164. Let me repeat 0.164.

Now, you may wonder the diffuse radiation r d n, the fraction also is 0.164. Pretty close to 0.178, but you should remember this is 20 percent of the diffuse radiation whereas, this is about 20 percent of the global or the total radiation. So, these numbers looks similar out of magnitude. They do not differ much because one is normal as with respect to the global radiation and the other is normal with respect to the diffuse radiation. So, I am just trying, so that you can develop patience of field for the numbers that you get. It cannot be 10 to the power 6 and 10 to the power minus 3 or so.

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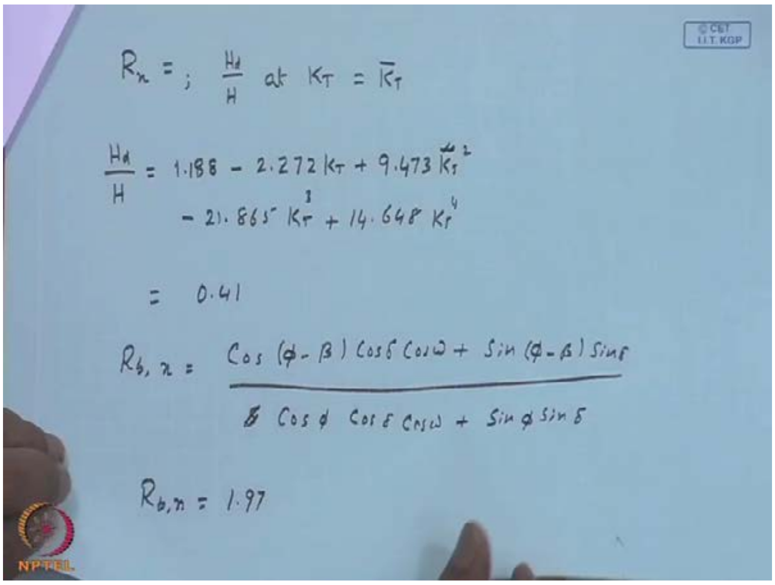

Now, we are emphasizing for some reason or the other, R factor at the noon time in calculating the non-dimensional critical level. I need H d by H, right at clearness index daily is numerical equal to average clearness index, ok whereas, when we calculate R bar and R b bar, we used H d bar by H bar whereas, when we are going to calculate R n, I will use H d by H. Again, the Collares-Pereira and Rabl correlation, but the individual daily diffuse fraction correlation. There may be different theories, there are explanations for these. One simplest could be this may be working better as a correlation.

The other reason could be since the critical level is going to be found out on the moon time equal to this solar radiation on the mean day, no matter what, it is mean day, a single day, so we shall use the single days diffuse fraction. In other words, for equating it, it will be individual diffuse fraction that matters. Incidentally, KT bar is a number. That is all. See this bar I should have not drawn it plus 14.648 K T to the power 4. So, if you calculate, this is 0.41.

So, at the given numerical values, at least in this way, it looks like the daily diffuse fraction is higher than the monthly average diffuse fraction. That is sometime back also I had explained, H d by H bar is not summation of H d by H divided by n, but it is summation of H d by summation of H. R b at the noon time cos phi minus beta cos delta plus omega plus sin phi minus beta sin delta by cos phi cos delta cos omega plus sin by sin delta. So, R b noon will be 1.97.

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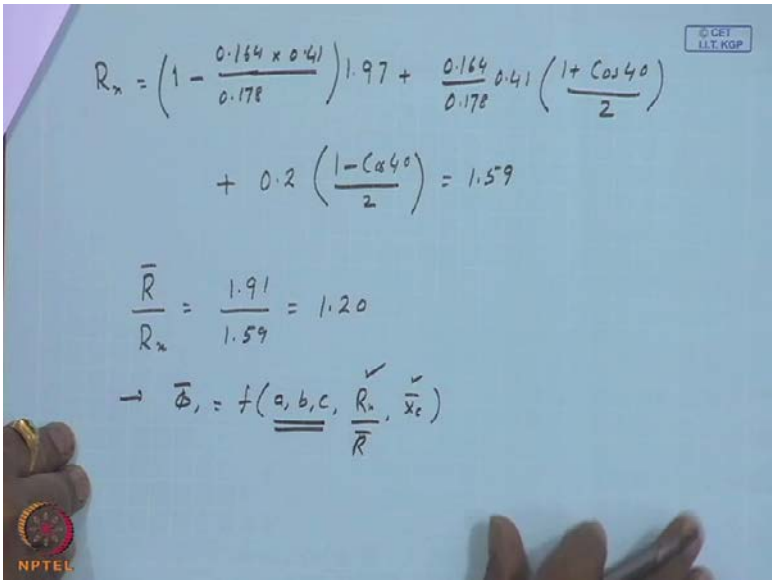

So, R n as I have explained 0.164 by 178, that is R d by R t into the diffuse fraction 0.41 times 1.97 that is R b noon plus again R d by R t times the diffuse fraction 41 times 1 plus cos beta which is 40 by 2 plus the ground effectance 0.2 into 1 minus cos beta by 2. This comes to be 1.59. So, R bar upon R n equal to 1.91 by 1.59 equal to 1.20, right. So, this is one parameter I need in calculating phi bar. In addition to this is a function of, of course that a b c and then R n by R bar R by R n does not matter and X c bar. So, this we have obtained. This can be calculated straight forward from the clearness indices.

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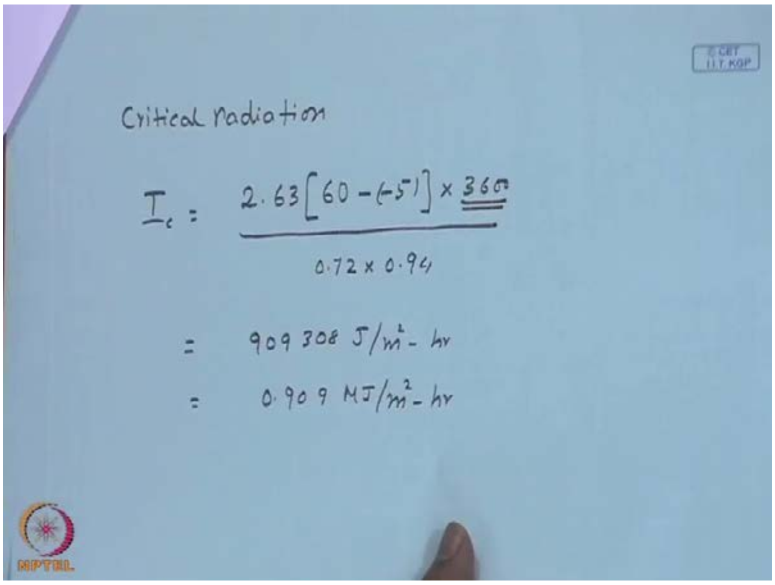

Now, the critical radiation. I c FRUL to T min minus T a times; time is important that is what I was telling. We have to put that factor by 0.72 into 0.94. This now you will have in 909308 joules per meter square in that hour. That will be 0.909 mega joules per meter square root hour, ok. So, this is, otherwise you will get a very small number. It should be watts per meter square, but then I had to adjust the other thing also accordingly.

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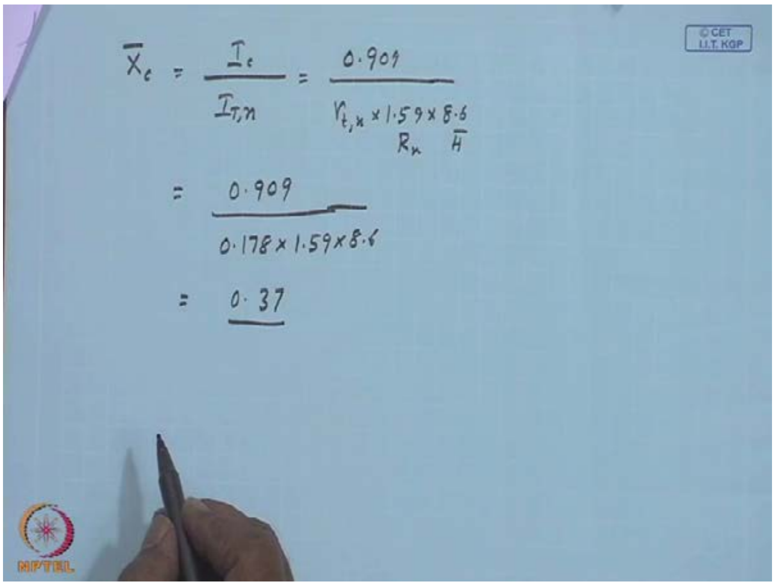

So, non-dimensional critical level will be X C bar will be I C by I T noon time, that is equal to, now we got 0.909 which is r t n into R n into H bar. This is H bar R n and r t n. So, this will be 0.909 by 0.178 into 1.59 into 8.6. This is mega joules, this is also mega joules. I have no problem, 0.37. So, we calculate up to the non-dimensional critical level, then we will go to the calculation of the utilizability and the solar load fraction met.

Now, I think many of the relations which we have developed or studied empirically or analytically, they are already under use. So, if you solve one problem on phi bar f chart, almost all the relations you will recall. We shall continue next time.

Thank you.